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Formation and evolution of the Chain-Kairali Escarpment and the Vishnu Fracture Zone in the Western Indian Ocean

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Abstract

Published models for the plate tectonic evolution of the Western Indian Ocean suggest that the Southern Mascarene Basin opened by oceanic crustal accretion between the continental margins of southwestern India and southeastern Madagascar. However, with the cessation of the Mascarene Basin spreading centre followed by a ridge jump resulting in the opening of the Carlsberg Ridge, almost all the traces of India – Madagascar divergence were carved away from the Indian Plate and attached to the African Plate. According to some recent studies, the Chain-Kairali Escarpment, a prominent feature on the southwestern continental margin of India, is possibly the only trace of India-Madagascar divergence that remained on the Indian Plate. But the exact conjugate correspondence of this feature on the Madagascar side is uncertain. Published plate tectonic reconstructions imply that the Vishnu Fracture Zone on the Indian side and the Mauritius Fracture Zone on the Madagascar side are aligned at chron C22ny (~49.04 Ma). Based on the near collinearity of gravity anomaly trends, the Chain-Kairali Escarpment appears to be the landward extension of the Vishnu FZ. However, at chron C34ny (~83.0 Ma), the Chain-Kairali Escarpment was in close proximity to the incipient Mahanoro Fracture Zone. In this study we investigate this incompatibility, using an up-to-date compilation of the tectonic elements from the conjugate regions of India and Madagascar and the latest available rotation parameters that describe India-Madagascar separation through a direct India-Seychelles-Madagascar plate circuit. Our revised plate reconstruction model suggests that the Chain-Kairali Escarpment was formed due to the strike-slip motion between the southeast coast of Madagascar and the then southwest coast of India during the initial stages of India-Madagascar breakup. The migration of the Chain-Kairali Escarpment from the proximity of the Mahanoro FZ and aligning with the Vishnu FZ was the result of several successive events. The first among those events was asymmetric crustal accretion in the Mascarene Basin due to ridge propagation, between chrons C34ny (83.0 Ma) to C33ny (~73.62 Ma). The Chain-Kairali Escarpment and associated crustal weak zones offshore India appear to have facilitated subsequent initiation of the Mauritius FZ and its conjugate Vishnu FZ during a plate reorganization at about chron C33ny (~73.62 Ma). The cessation of spreading in the Mascarene Basin and development of full extent of the Carlsberg Ridge, shortly after chron C27ny (60.92 Ma), resulted in the initiation of a long transform fault, coinciding with the Vishnu FZ, which connected the Carlsberg Ridge with the spreading centre of the Madagascar Basin. Therefore, the Vishnu FZ and the Chain-Kairali Escarpment are two independent features created during different episodes of evolution of the Western Indian Ocean and the Chain-Kairali Escarpment is not a landward extension of the Vishnu FZ.

Key words: India-Madagascar separation; Vishnu Fracture Zone; Mahanoro Fracture Zone; Mauritius Fracture Zone; Chain-Kairali Escarpment; Ridge propagation

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1. Introduction

The Western Indian Ocean (Fig. 1a) was formed due to rifting and drifting between India, Seychelles, Madagascar and Africa since the Late Jurassic. First-order plate tectonic evolutionary models depicting the relative motions of these continental blocks were provided by various researchers (Norton and Sclater, 1979; Morgan, 1981; Besse and Courtillot, 1988; Royer et al., 1992; Müller et al., 1993). According to those models the Southern Mascarene Basin opened between India and Madagascar, more particularly, divergence of the continental margins of southwestern India and southeastern Madagascar. Those models also suggested that all the traces related to the initial India – Madagascar divergence appear to exist only in the Mascarene Basin, since the opening of the Carlsberg Ridge closer to the Indian continental margin carved away almost all the oceanic crust and probably a part of the continental margin of India from the Indian Plate and attached them to the African Plate. In the absence of any oceanic domain constraint from the present day Indian continental margin, it is difficult to propose a confident India – Madagascar pre-drift juxtaposition by closing the Mascarene Basin alone. Some recent studies (Yatheesh et al., 2013b; Bhattacharya and Yatheesh, 2015) proposed that the Chain-Kairali Escarpment, a prominent bathymetric feature on the southwestern continental margin of India, is one such oceanic domain constraint of India- Madagascar initial divergence on the Indian Plate. Those studies suggested that the Chain-Kairali Escarpment demarcates the westward limit of an anomalous submarine terrace complex referred to as the Alleppey-Trivandrum Terrace Complex and represents a transform boundary that formed when the southwest coast of India moved past southeast coast of Madagascar during initial stage of the India-Madagascar separation. Further those studies in conformity with the model of Yatheesh et al. (2006) and Yatheesh (2007) predicted that in the India - Madagascar pre-drift juxtaposition, the Alleppey-Trivandrum Terrace Complex fitted into a bathymetric notch observable in the Northern

Madagascar Ridge and at the time of formation, the Chain-Kairali Escarpment was the precursor of the Mahanoro FZ.

The satellite-derived free-air gravity anomaly (hereinafter referred to as "gravity anomaly") map (Fig. 1b) suggests that in the present day setting the Chain-Kairali Escarpment is aligned with the Vishnu Fracture Zone (also known as the Chagos Fracture Zone). McKenzie and Sclater (1971) considered the Vishnu FZ as the transform segment to connect the long offset E-W trending magnetic anomalies located in the northwestern Arabian Sea with those in the region south of India. Whitmarsh (1974) suggested its possible northern limit at ~1°N latitude. The gravity anomaly map (Fig. 1b) shows that the Vishnu FZ is characterized by a ~ 1000 km long negative linear gravity anomaly trend between latitudes of 8°S and 1°N. Various reconstruction models (e.g. Norton and Sclater, 1979) demonstrated that the Vishnu FZ and the Mauritius FZ were conjugate fracture zones at chron C22ny (~49.04 Ma; Fig. 2a) and defined the southeastern limit of the Mascarene Basin. Two other later studies (Subrahmanyam and Chand, 2006; Nathaniel et al., 2008), noted that a gravity anomaly trend on the Indian continental margin (between ~6°N and 10°N along ~75°E) is nearly collinear with the Vishnu FZ, and suggested that this indicates northward continuity of the Vishnu FZ on to the Indian continental margin. Yatheesh et al.(2013b) have shown that this linear gravity anomaly trend corresponds to the Chain-Kairali Escarpment. Interalia the conclusion of Subrahmanyam and Chand (2006) and Nathaniel et al. (2008), implies that the Chain-Kairali Escarpment–Vishnu FZ complex is conjugate to the Mauritius FZ. But, the reconstruction models (Yatheesh et al., 2013b; Bhattacharya and Yatheesh, 2015) at chron C34ny (83.0 Ma) suggests (Fig. 2b) that the Chain-Kairali Escarpment was in close vicinity of the transform fault that later developed into the Mahanoro FZ. Thus, there is an ambiguity about the conjugate correspondence of the Chain-Kairali Escarpment on the African Plate and thereby the India–Madagascar pre-drift juxtaposition. This observation implies either the rotation parameters describing the India-Madagascar separation are incorrect or the Chain-Kairali Escarpment and the Vishnu FZ are not continuous features. Our study aims to resolve this ambiguity and we address this issue with plate reconstructions using an up-to-date compilation of tectonic fabric from conjugate offshore regions of India and Madagascar and improved rotation parameters that define India-Madagascar separation.

2. Data and Methodology

The main data used in the present study are magnetic anomaly identifications, fracture zones and the rotation parameters that describe relative motions among India, Madagascar and the other intervening micro-continental blocks. The magnetic anomaly picks were compiled from the published literature (Chaubey et al., 2002; Yatheesh et al., 2008; Eagles and Wibisono, 2013; Yatheesh et al., 2013a) and the rotation parameters were obtained from published sectoral reconstruction models (Royer et al., 2002; Yatheesh et al., 2008; Muller et al., 2008; Eagles and Wibisono, 2013; Bhattacharya and Yatheesh, 2015). The fracture zones that represent the traces of the plate motions were obtained from the global seafloor fabric database, published by Matthews et al. (2011) and later improved by Wessel et al. (2015). To extend / refine the fracture zones trends, we used the latest available (Sandwell et al., 2014) satellite-derived free-air gravity anomalies. To define the seafloor features of the study area, we used bathymetry contours from GEBCO digital database (IOC-IHO-BODC, 2003) and Yatheesh et al. (2013b). Two seismic sections along the profiles SST-17 and DN13-A were used to depict the basement characteristics of the Alleppey-Trivandrum Terrace Complex and the Chain-Kairali Escarpment. These sections were obtained from Yatheesh et al. (2013b) and Nathaniel (2013a), respectively. Plate tectonic reconstructions were carried out using the GPlates software (Boyden et al., 2011). All ages (Table 1) are based on geomagnetic polarity reversal timescale of Cande and Kent (1995).

3. Updated tectonic fabric maps of the conjugate regions off SW India and SE Madagascar

The southwestern continental margin of India and the southeastern continental margin of Madagascar are the conjugate regions that resulted from the India-Madagascar divergence. Therefore, most of the offshore tectonic elements existing in these conjugate margins and adjacent deep ocean basins can be expected to contain traces and evidences of that divergence. With an aim to arrive at better understanding of the genesis and conjugate relationship among these traces, we constructed updated tectonic fabric maps of these two conjugate offshore regions, by including the recently identified offshore tectonic elements.

3.1 Southwestern continental margin of India and the adjacent ocean basins

The tectonic fabric map (Fig. 3) of the southwestern continental margin of India and the adjoining Central Indian and Arabian basins incorporates the latest available information about magnetic anomaly picks (Chaubey et al., 2002; Yatheesh et al., 2008; Yatheesh et al., 2013a), associated fracture zones (Wessel et al., 2015), pseudofaults (Chaubey et al., 2002) and the other relevant offshore tectonic elements defined by the isobaths (IOC-IHO-BODC, 2003; Yatheesh et al., 2006, 2013b). The Alleppey-Trivandrum Terrace Complex, the Laccadive-Chagos Ridge and the Arabian, Laccadive and Central Indian basins constitute the major tectonic domains in this region.

3.1.1 The Alleppey-Trivandrum Terrace Complex

The Alleppey-Trivandrum Terrace Complex (Figs. 3 and 4a) is a large and prominent, nearly north-south trending bathymetric protrusion on the southwestern continental margin of India in the mid continental slope south of Cochin. This complex consists of two large contiguous terrace-like features, of which the larger southerly terrace is referred as the 'Trivandrum Terrace (TT)' and the smaller northerly terrace as the 'Alleppey Terrace (AT)'.The Trivandrum Terrace is characterized by the presence of a wide basement high in its central part, flanked on its easterly and westerly sides by thick sediment-filled grabens (Figs. 4c and 4d), referred as the 'TT-Eastern Basin' and the 'TT-Western Basin', respectively. A prominent linear gravity high is observed (Figs. 4a and 4b) in the central part of the Trivandrum Terrace and this nearly NNW-SSE trending gravity high appears to coincide with the apex region of the central wide basement high feature (Figs. 4c and 4d).

3.1.2 The Vishnu Fracture Zone and the Chain-Kairali Escarpment

The western limit of the Alleppey-Trivandrum Terrace Complex is defined by a nearly 500 km long steep linear escarpment (Fig. 4a), referred as the Chain-Kairali Escarpment (Yatheesh et al., 2013b). The Vishnu FZ was designated to a ~1300 km long scarp east of the Chagos Bank. The Vishnu FZ and the Chain-Kairali Escarpment are discernible (Fig. 1b) from the gravity anomalies. Both these features are characterized by negative gravity anomaly signatures, but the Vishnu FZ represents a much wider (~50-60 km) gravity low compared to the Chain-Kairali Escarpment (~15 km). Though the width of these features varies significantly, they are roughly collinear. The long linear topographic high existing west of the Vishnu FZ is the Laccadive-Chagos Ridge that consists of three segments, the Laccadive Plateau, the Maldives Ridge and the Chagos Bank.

3.1.3 Deep ocean basins

The deep offshore region located immediately west of the Chain-Kairali Escarpment is the Laccadive Basin (Fig. 3), which is a narrow triangular basin existing between the Laccadive Plateau (the northernmost segment of the Laccadive-Chagos Ridge) in the west and the continental slope of India in the east (Bhattacharya and Chaubey, 2001). Towards north, the Laccadive Basin appears to converge with the adjacent continental slope of India. Towards south, this basin appears to open into the Central Indian Basin and its eastern end, to a large extent, abuts the Chain-Kairali Escarpment. The deep ocean basin located west of the

Laccadive-Chagos Ridge is the Arabian Basin (Figs. 1 and 3). The magnetic lineations in the Arabian and its conjugate Eastern Somali basins show that the oldest magnetic lineations present in these basins correspond to chron C28ny (~62.5 Ma), which are located south of the Laxmi Ridge in the Indian Plate and north of Seychelles in the African Plate (Chaubey et al., 2002). The magnetic lineation pattern from chron C28ny (~62.5 Ma) to chron C20ny (~42.54 Ma) are characterized by the presence of oblique offsets, a diagnostic feature of propagating spreading ridge segments. The Central Indian Basin is located between the southern segments of the Laccadive-Chagos Ridge in the west and the Ninetyeast Ridge to the east. The magnetic lineations in the Central Indian Basin are divided into several compartments offset by fracture zones, where the Vishnu FZ marks the western boundary of the Central Indian Basin (Figs. 1 and 3). The fracture zone located immediately east of the Vishnu FZ is the Northern Boussole Fracture Zone (Patriat and Segoufin, 1988), also known as 73°E Fracture Zone (Kamesh Raju, 1993), which represents the conjugate of the Southern Boussole Fracture Zone in the Madagascar Basin, located immediately east of the Mauritius FZ (Patriat and Segoufin, 1988). The triple junction trace (TJT) divides the Central Indian Basin into the Eastern Central Indian Basin and the Western Central Indian Basin. The Eastern Central Indian Basin represents the conjugate of the Crozet Basin and they were formed at the 'Indian (now Capricorn)-Antarctic' (hereafter referred as Capricorn-Antarctic) plate boundary, while the Western Central Indian Basin represents the conjugate of the Madagascar Basin and they were formed at the 'Indian (now Capricorn)-African' (hereafter referred as Capricorn-African) plate boundary. The oldest magnetic anomaly identifiable from the Central Indian Basin corresponds to chron C34ny (83.0 Ma). The magnetic lineations corresponding to chrons C34ny (83.0 Ma) and C33no (~79.08 Ma) trend nearly NW-SE (Yatheesh et al., 2008; IFCPAR, 2010; Yatheesh et al., 2013a) while those corresponding to chron C33ny (~73.62 Ma) and its younger period trend nearly E-W (McKenzie and Sclater, 1971; Sclater and

Fisher, 1974; Kamesh Raju and Ramprasad, 1989; Dyment, 1993; Kamesh Raju, 1993; Yatheesh et al., 2008). The magnetic lineations from chron C34ny (83.0 Ma) to chron C31no (~68.74 Ma) of the entire Central Indian Basin were formed at the Capricorn-Antarctic plate boundary and therefore conjugate to the entire set of magnetic lineations segments are present in the Crozet Basin. The younger conjugate magnetic lineations corresponding to the Capricorn-Antarctic plate boundary are available in the Crozet Basin and those corresponding to the Western Central Indian Basin are available in the Madagascar Basin. Therefore, the western limit of the oceanic crust formed at the Capricorn-African plate boundary is limited by the Vishnu FZ in the Indian (now Capricorn) Plate and its conjugate Mauritius FZ in the African Plate. The Vishnu FZ is also considered to form part of the long transform offset system that connected the spreading centres of the Capricorn-African plate boundary with that of Indian-African (Seychelles - Laxmi Ridge) plate boundary (the Carlsberg Ridge spreading) sometime between chrons C27ny (60.92 Ma) and C26no (57.90 Ma).

3.2 Southeastern continental margin of Madagascar and the adjacent ocean basins

The tectonic fabric map (Fig. 5) of the southeastern continental margin of Madagascar and the adjoining ocean basins incorporates the latest available magnetic anomaly picks and fracture zone interpretations from the Mascarene (Eagles and Wibisono, 2013) and Madagascar (Yatheesh et al., 2008; IFCPAR, 2010; Yatheesh et al., 2013a) basins while taking into account the fracture zone trends detectable in the satellite-derived free-air gravity anomaly map (Wessel et al., 2015). The major tectonic domains in this region are the southeast continental margin of Madagascar, the Madagascar Ridge and the adjacent Mascarene and Madagascar basins.

3.2.1 Southeastern continental margin of Madagascar and the Madagascar Ridge

The eastern continental shelf of Madagascar is generally narrow, averaging about 25 km in width. The shelf edge is characterized by a fault scarp dipping steeply to 1800 m and the continental slope appears to lie along this scarp face, which exceeds 1000 km in length (Pepper and Everhart, 1963; Eagles and Wibisono, 2013). The gravity signatures suggest the presence of a strip of extended continental crust along the eastern continental margin of Madagascar further eastward of the continental shelf (Eagles and Wibisono, 2013). An anomalous bathymetric feature that exists adjacent to the southeastern continental margin of Madagascar is the Madagascar Ridge, which is a ~N-S trending elongated feature. The bathymetry map of the northern part of the Madagascar Ridge shows (Fig. 5) presence of a bathymetric notch defined by 2000 m bathymetry contour.

3.2.2 The Mascarene Basin

The tectonic fabric map (Fig. 5) shows that the Mascarene Basin consists of two distinct domains, a northern domain created by seafloor spreading between Madagascar and Seychelles during chrons C34ny (83.0 Ma) to C30no (67.61 Ma) and a southern domain created by seafloor spreading between Madagascar and India during chron C34ny (83.0 Ma) and ~60.25 Ma, i.e., shortly after chron C27ny (60.92 Ma). The magnetic lineations in the Mascarene Basin are divided into several segments, which are offset by long fracture zones. An interesting observation is that, unlike the distinctly straight fracture zones in the Madagascar Basin, the fracture zones of the Mascarene Basin on the Madagascar side are curved in nature (Fig. 5). The Mascarene Basin can be considered to consist of five major compartments, labeled as A through E, where A to D falls in the southern domain while E falls in the northern domain (Fig. 5). The compartment A is delimited by the Mauritius FZ in the easterly side and the Mahanoro FZ in the westerly side. The entire sequence of magnetic anomalies from chrons C34ny (83.0 Ma) through C27ny (60.92 Ma) is available in the southern flank but their conjugate sequences in the northern flank could not be mapped as systematically as in the southern flank, since the oceanic crust in the northern flank was probably obliterated by the Réunion hotspot volcanism that created the Mascarene Plateau. The magnetic lineations corresponding to the chron C33ny (~73.62 Ma) and its younger period are nearly NW-SE trending, while those corresponding to chrons C33no (~79.08 Ma) and C34ny (83.0 Ma) are nearly N-S trending. The extent of oceanic crust in compartment A is widest (~500 km) at its southernmost region and it gradually narrows down towards north, resulting almost 50% reduction in the width of the oceanic crust at its northernmost region. This compartment is further complicated by the presence of southern part of the Mascarene Plateau, which is considered (Duncan, 1990) to have been formed by Réunion hotspot volcanism. The compartment B is located immediately west of the Mahanoro FZ and this compartment contains almost the entire conjugate sequences of NW-SE trending magnetic lineations. The compartment C consists of the entire sequences of anomalies in the southern flank and the sequences of chron C32n1y (~71.07 Ma) to C27ny (60.92 Ma) in its northern flank. In the compartments B and C, the spreading appears to be less disturbed and nearly complete sequence of chrons C34ny (83.0 Ma) to C27ny (60.92 Ma) of the magnetic lineations are available. The magnetic lineations corresponding to chron C34ny (83.0 Ma) are oblique to the straight east coast of Madagascar. Though the entire magnetic lineation sequences could not be identified in the compartment D, the presence of magnetic lineation corresponding to chron C27ny (60.92 Ma) was mapped in this compartment. The magnetic lineation map suggests that, in compartment E, the magnetic lineation sequence from chrons C34ny (83.0 Ma) to C31no (~68.74 Ma) is available in the southern flank, where the location of the lineation corresponding to chron C31no (~68.74 Ma) is very close to the inferred extinct spreading centre in the northern Mascarene Basin. The magnetic anomalies in the northern flank of compartment E appear to be highly complex and this region does not contain identifiable magnetic anomalies.

3.2.3 Madagascar Basin

The region located immediately southeast of the Mascarene Basin is the Madagascar Basin, whose westerly boundary is delimited by the Mauritius FZ. The oldest identifiable magnetic lineation (Fig. 5) of the Madagascar Basin corresponds to chron C30ny (~65.58 Ma). The Madagascar Basin represents one flank of the oceanic crust formed at Capricorn-African plate boundary and its conjugate flank is available in the Western Central Indian Basin. The magnetic anomaly sequence of chrons C30ny (~65.58 Ma) through C20ny (~42.5 Ma) are divided into two segments by the Southern Boussole FZ, which is parallel to the Mauritius FZ. The Southern Boussole FZ on the Madagascar side and the Northern Boussole FZ on the Indian side represent conjugate fracture zones that define the Capricorn-Africa relative motion.

4. India-Madagascar plate tectonic divergence and evolution of its kinematic traces

The formation of the Western Indian Ocean is associated with the relative motion among India, Madagascar and Africa. The India-Madagascar reconstruction can be achieved by considering different plate circuits - either by considering movement of the Indian Plate directly to the African Plate (closing the Arabian, Eastern Somali, Madagascar and Mascarene basins) or indirectly by a combination of movements of Indian Plate to Antarctic Plate (closing the Central Indian and Crozet basins) and then the combined Indian-Antarctic plates to the African Plate (closing the Southwest Indian Ridge). The lack of availability of the adequate magnetic anomaly picks from the Mascarene, Madagascar, Eastern Somali and Arabian basins might have forced previous models to follow the Indian-Antarctic-African plate circuit to depict the motion of India relative to Madagascar since the Late Cretaceous.

Recently, Eagles and Wibisono (2013) provided a set of detailed magnetic anomaly picks and rotation parameters to describe the plate tectonic evolution of the Mascarene Basin. Using these rotation parameters that constrain India-Madagascar relative motion, along with the other available recent rotation parameters of the India-Seychelles-Madagascar circuit (Royer et al., 2002; Yatheesh et al., 2008; Müller et al., 2008), Bhattacharya and Yatheesh (2015) provided improved model for the early opening of the Arabian Sea from ~ 88 to 56.4 Ma. Since their model used constraints of many recently mapped regional scale tectonic features of the ocean basins off western continental margin of India, we basically adopted that model to examine the conjugate relationship among the various plate kinematic traces located on the Indian and Madagascar sides resulted due to India-Madagascar separation. However, we made slight improvement to that model by accommodating the updated constraints of the Mascarene, Madagascar and Laccadive basins.

4.1 Proposed model for India-Madagascar plate-tectonic divergence

We constructed plate reconstruction maps (Figs. 6a-h) in fixed Madagascar reference frame, for eight periods; 88.0 Ma (pre-drift), 83.0 Ma (chron C34ny), 79.08 Ma (chron C33no), 73.62 Ma (chron C33ny), 65.58 Ma (chron C30ny), 62.50 Ma (chron C28ny), 60.92 Ma (chron C27ny) and 57.90 Ma (chron C26no), to decipher relationship among the fracture zones located on Indian and Madagascar sides. The rotation parameters used for these reconstructions are presented in Supplementary Table ST-1.

4.1.1 Reconstruction at 88.0 Ma (pre-drift)

The timing of 88.0 Ma was selected since this age is inferred as the time when all the continental blocks/slivers under consideration were juxtaposed in their immediate pre-drift configuration. In the 88.0 Ma reconstruction map (Fig. 6a), the southern extent of the Alleppey-Trivandrum Terrace Complex fitted into the bathymetric notch in the Northern

Madagascar Ridge. The Chain-Kairali Escarpment is considered to have been initiated around this period due to a shear movement that occurred between the nearly straight southeast coast of Madagascar (Fig. 1) and the Alleppey-Trivandrum Terrace Complex region of the southwest coast of India, possibly triggered by the Marion hotspot. Shortly after 88.0 Ma, a seafloor spreading system developed between Madagascar and India which initiated formation of the Mascarene Basin.

4.1.2 Reconstruction at chron C34ny (83.0 Ma)

The reconstruction map (Fig. 6b) at chron C34ny (83.0 Ma) shows a scenario of coast-parallel segments of spreading centres between the northeast coast of Madagascar and Seychelles Plateau and coast-oblique segments of spreading centres, connected by en-echelon short transform offsets, between the east coast of Madagascar and India. Based on identification of several chron C34ny (83.0 Ma) picks within bathymetric notch of the Northern Madagascar Ridge it appears that, at that time a short spreading segment existed in the region between the tip of the Alleppey-Trivandrum Terrace Complex and the bathymetric notch in the Northern Madagascar Ridge. A relatively longer transform fault (TF1 in Fig. 6b) existed slightly northward of the notch. Data is insufficient to infer the situation in the southern part of the notch, but the short spreading segment of the notch perhaps was connected with TF1 through smaller transforms. As will be seen later, this transform fault TF1 will initiate the Mahanoro FZ and its conjugate in the southern and northern flanks of the Mascarene Basin, respectively and the Chain-Kairali Escarpment was in close vicinity of TF1. During this period, the Madagascar Basin did not exist and the conjugate oceanic crust of the entire Central Indian Basin was accreted in the Crozet Basin (Yatheesh et al., 2008; IFCPAR, 2010). Therefore, the easternmost spreading segment in the Mascarene Basin probably was connected directly to the westernmost segment of the Capricorn-Antarctic spreading centre (Central Indian and Crozet basins) as a single spreading segment without any transform offsets in between.

4.1.3 Reconstruction at chron C33no (79.08 Ma)

The reconstruction map (Fig. 6c) at chron C33no (~79.08 Ma) suggests that by this time the short central spreading segment existing between Alleppey-Trivandrum Terrace Complex and bathymetric notch of the Northern Madagascar Ridge gradually lengthened, probably by propagation, up to transform TF1.

4.1.4 Reconstruction at chron C33ny (73.62 Ma)

The chron C33ny (~73.62 Ma) reconstruction (Fig. 6d) suggest that, while spreading continued in the entire Mascarene Basin, a major reorientation of the spreading system had taken place since chron C33no (~79.08 Ma). The spreading direction, which was nearly E-W during chrons C34ny to C33no, very rapidly became nearly NE-SW at chron C33ny. Probably to accommodate this ridge reorientation, a new transform fault (TF2 in Fig. 6d) developed between the Mascarene Basin spreading centre and the Capricorn-Antarctic spreading centre. As will be seen later, this transform fault TF2 in due course will give rise to the Mauritius FZ on the Madagascar side and the Vishnu FZ on the Indian side. We believe, the pre-existing weak zones off the Chain-Kairali Escarpmentand the Alleppey-Trivandrum Terrace Complex regions might have facilitated initiation of the transform fault TF2. Further, from several picks we observe that at that time the ridge within the compartment A was a long segments panning from transform faults TF1 to TF2.

4.1.5 Reconstruction at chron C30ny (65.58 Ma)

Prior to chron C30ny (65.58 Ma), at around 68.5 Ma, a ternary rift system with a triple junction came into existence off the Saurashtra peninsula. Perhaps, this triple junction was developed contemporaneous with the earliest manifestation of Deccan Flood Basalt volcanism, triggered by the Réunion hotspot (Bhattacharya and Yatheesh, 2015). By this time the rift between the continental blocks of the Laccadive Plateau and the southern part of India also might have propagated some distance north and caused further crustal divergence creating the Laccadive Basin. Seafloor spreading continued in the Southern Mascarene Basin, but in the Northern Mascarene Basin spreading appears to have slowed down substantially after chron C30no (~67.61 Ma). During this period, the rift axis in the Laxmi Basin reached the stage of seafloor spreading commencing the formation of oceanic crust in the Laxmi Basin. Further, by this time the triple junction of Capricorn-African-Antarctic plate boundaries came into existence and the trace of this triple junction in the Indian Plate divided the Central Indian Basin into the Eastern Central Indian Basin and the Western Central Indian Basin (Fig. 6e). During this time, a new transform fault developed east of TF2. This transform fault (TF3) in due course gave rise to the Northern Boussole FZ located east of the Vishnu FZ on the Indian side and its conjugate Southern Boussole FZ located east of the Mauritius FZ on the Madagascar side. The mapped picks in the compartment A (i.e. in the areas between the Mahanoro FZ and Mauritius FZ) suggest asymmetric crustal accretion, at least during the period between chrons C34ny (83.0 Ma) and C30ny (65.58 Ma), with more crust in the Indian Plate side. Subsequently, at around 65 Ma the bulk of the Deccan Flood Basalt erupted as a result of Réunion hotspot volcanism.

4.1.6 Reconstruction at chron C28ny (62.5 Ma)

At around chron C28ny (~62.5 Ma), a new spreading centre (palaeo-Carlsberg Ridge) developed between the Laxmi Ridge and Seychelles (Fig. 6f). During this period, spreading in the Northern Mascarene Basin ceased, while spreading continued in the Southern Mascarene, Laxmi and Gop basins and crustal divergence continued in the Laccadive Basin.

4.1.7 Reconstruction at chron C27ny (60.92 Ma)

At chron C27ny (60.92 Ma), the spreading along the Laxmi Ridge-Seychelles, Capricorn-African, Capricorn-Antarctic and the Mascarene Basin spreading system and the crustal divergence in the Laccadive Basin continued (Fig. 6g). Shortly after chron C27ny (60.92 Ma), perhaps spreading in the southern Mascarene Basin also ceased and as a result, the entire Mascarene Basin became part of the African Plate.

4.1.8 Reconstruction at chron C26no (57.90 Ma)

Our reconstruction at chron C26no (Fig. 6h) shows, the entire Mascarene Basin spreading centre as extinct, while the Carlsberg Ridge as the new Indian – African plate boundary, which is connected with the active spreading axes of the Madagascar Basin through a long transform fault coinciding with the Vishnu FZ. We believe such a scenario had developed sometime earlier, perhaps contemporaneous with the time of cessation of spreading in the Mascarene Basin.

4.2 Spreading rates and spreading directions

The plate reconstruction maps presented in Fig. 6 suggest reorganization of the Mascarene Basin spreading centre, a major one at chron C33ny (~73.62 Ma) and a gradual one thereafter. To quantify these reorganizations, we constructed flowlines (Fig. 7a) and estimated half spreading rates and directions (Fig. 7b) for the relative motion between Madagascar and India between chron C34ny (83.0 Ma) and the inferred timing of extinction (~60.25 Ma) of the Mascarene Basin. These computations were made for a known location on the extinct spreading axis from compartment B of the Mascarene Basin, based on the stage rotations derived from the total rotation parameters used in the present study (Supplementary Table ST-1). This compartment was selected since this is less disturbed compared to the other compartments. Our estimates show that the half spreading rate was relatively low (~ 2.0 cm/yr) during chrons C34ny (83.0 Ma) to C33ny (~73.62 Ma) and it started increasing gradually from chron C33ny (~73.62 Ma) to reach a level of ~8.0 cm/yr around chron C29no (~64.75 Ma). Followed by this, the spreading rate shows a remarkably sharp drop from 8.0 cm/yr to ~4.0 cm/yr at around chron C28no (~63.63 Ma) and younger to this period, the spreading continued at around 4.0 cm/yr and finally ceased shortly after chron C27ny (60.92 Ma). During this period, a sharp drop in the spreading rate was also observed along the contemporaneous spreading centres in the Laxmi and Gop basins (Yatheesh et al., 2009; Bhattacharya and Yatheesh, 2015). The observation of a sharp drop in the spreading rate around chron C28no (~63.63 Ma) appears to be interesting since this sharp drop in the spreading rate is soon after the time of peak of Deccan Flood Basalt volcanism. This timing also nearly coincides with the initiation of a new spreading centre along the palaeo-Carlsberg Ridge, which opened between the Laxmi Ridge and Seychelles (Chaubey et al., 2002; Royer et al., 2002; Eagles and Hoang, 2014; Bhattacharya and Yatheesh, 2015). The spreading directions estimated in the present study suggests that the Mascarene Basin was spreading at an azimuth of ~N85°E during chrons C34ny (83.0 Ma) to C33no (~79.08 Ma) and then experienced a major change in the direction of spreading to an azimuth of ~N60°E, shortly after chron C33no (~79.08 Ma). During the period from a time between chrons C33no (~79.08 Ma) and C33ny (~73.62 Ma) to the timing of extinction (~60.25 Ma) of the spreading in the southern Mascarene Basin, the spreading direction was changing gently from ~N60°E azimuth to ~N40°E, resulting in different trends for magnetic lineations older than and younger to chron C33ny (~73.62 Ma). It is interesting to note that a change in the direction of magnetic lineations corresponding to these periods was also observed (Fig. 3) in the Central Indian Basin, where the lineations older than chron C33ny (~73.62 Ma) trend nearly NW-SE and the lineations younger to chron C33ny (~73.62 Ma) trend nearly E-W (Yatheesh et al., 2008).

4.3 Chain-Kairali Escarpment and Vishnu Fracture Zone - the collinearity examined

Existence of the Chain-Kairali Escarpment as a structural and tectonic feature is a recent finding by Yatheesh et al. (2013b). Several other researchers (Subrahmanyam and Chand, 2006; Bastia et al., 2008; Nathaniel et al., 2008; Das, 2013; Nathaniel, 2013a, b) appear to have noted the existence of a linear gravity low in the region where the Chain-Kairali Escarpment was identified. Interestingly in the gravity anomaly map, this linear gravity low appears collinear with the gravity anomaly trend associated with the Vishnu FZ. This observation might have tempted those researchers to consider the linear gravity low trend in the Chain-Kairali Escarpment region as the landward extension of the Vishnu FZ till ~10°N latitude. It may be mentioned here that the seafloor fabric database (Wessel et al., 2015) suggests the northern extent of the Vishnu FZ is limited at ~1°N latitude. We studied the gravity data in detail to examine the possibility of the Vishnu FZ and the Chain-Kairali Escarpment as a continuous feature. The gravity anomalies plotted as colour-coded image (Fig. 8a) and contours (Fig. 8b) show the characteristic linear gravity lows and the linear gravity anomaly trends associated with the Vishnu FZ and the Chain-Kairali Escarpment. To carry out profile-to-profile correlation of the gravity signatures of these two features, we extracted gravity anomalies along several tracks located nearly orthogonal to the trend of the

Vishnu FZ and the Chain-Kairali Escarpment and plotted as free-air gravity anomaly wiggles (Figs. 8a and 8b). This exercise suggests that the northward extent of the characteristic gravity signature representing the Vishnu FZ can be traced confidently at least up to 4°N latitude (Figs. 8b and 8c). From the gravity anomaly map plotted over the Chain-Kairali Escarpment (Fig. 8d) and the Vishnu FZ (Fig. 8e) in higher resolution, it is observed that the Vishnu FZ is characterized by the existence of a wider gravity low while the Chain-Kairali Escarpment is characterized by the existence of a much narrower gravity low. In between the southernmost end of the Chain-Kairali Escarpment and the northernmost end of the Vishnu FZ, the gravity anomalies do not show apparent continuation of such gravity low signature.

Nathaniel (2013a) analyzed a seismic reflection profile (denoted as DN13-A) over the Alleppey-Trivandrum Terrace Complex region and suggested that the Vishnu FZ is a rift graben with highly deformed structural fabric. Apparently, this opinion of Nathaniel (2013a) stem in the conclusion (Subrahmanyam and Chand, 2006; Bastia et al., 2008; Nathaniel et al., 2008; Das, 2013; Nathaniel, 2013a, b; Unnikrishnan et al., 2018) that the Vishnu FZ extends northwards into the Alleppey-Trivandrum Terrace Complex region. We examined (Figs. 4a-d) the interpretation of seismic profile DN13-A, which was used by Nathaniel (2013a) to characterize the Vishnu FZ. We observed that seismic profile DN13-A does traverse the Alleppey-Trivandrum Terrace Complex region and extends to deeper water across the Chain-Kairali Escarpment. Comparison of this seismic section with another nearby seismic section along profile SST-17 (Yatheesh et al., 2013b), shows that the highly deformed structural fabric, which Nathaniel et al. (2008) used for characterization of the Vishnu FZ, represents the TT - Western Basin (TT-WB) inferred by Yatheesh et al. (2013b). It is also important to note that, while the Vishnu FZ and the Chain-Kairali Escarpment are nearly N-S trending features, the gravity trend coinciding with this block-faulted region trends NNW-SSE (marked as GL-1 in Figs. 8a and 8b), parallel to the trend of the axial basement high, labelled as GH in Figs. 4a and 4b. Therefore, we believe that the block-faulted graben seen from the seismic section DN13-A (km 50 to 125) in Fig. 4c corresponds to the TT-WB observed from the seismic section along SST-17 (km 30 to 70) in Fig. 4d. The Chain-Kairali Escarpment, defined by the sharp drop in the bathymetry and a linear gravity low trend, is located west of this TT-Western Basin. Yatheesh et al. (2013b) identified the Chain-Kairali Escarpment from bathymetry data, but that inference could not be verified using a seismic section since all the available seismic sections terminate slightly east of the Chain-Kairali Escarpment, where the maritime boundary between India and Maldives is defined. However the section DN13-A have crossed this maritime boundary and therefore, DN13-A is the only seismic section that we came across to have crossed the Chain-Kairali Escarpment. This seismic section clearly depicts the sharp drop in the basement signature (at km 47 in Fig. 4c) of the inferred Chain-Kairali Escarpment, which is located west of the block faulted region considered by Nathaniel (2013a) as the Vishnu FZ. Thus it can be seen, that the conclusion of those authors (Subrahmanyam and Chand, 2006; Bastia et al., 2008; Nathaniel et al., 2008; Das, 2013; Nathaniel, 2013a, b; Unnikrishnan et al., 2018) that the Vishnu FZ continues northward into the Alleppey-Trivandrum Terrace Complex region is not tenable. The revised plate tectonic reconstructions for the India-Madagascar separation show that the Chain-Kairali Escarpment was formed during India-Madagascar break-up when the southeast coast of Madagascar moved past India describing a strike-slip motion. As explained in section 4.1, at chron C34ny (83.0 Ma), the Chain-Kairali Escarpment was in close vicinity of a transform fault (TF1), which later developed into the Mahanoro FZ (Fig. 6b). Further, during chrons C34ny (83.0 Ma) to C33no (79.08 Ma), this spreading direction was nearly east-west and the easternmost segment of the Mascarene Basin spreading centre and the westernmost segment of the Central Indian Basin spreading centre were connected directly without any transform fault in between them. The transform fault that eventually gave rise to the Vishnu FZ and its conjugate Mauritius FZ came into existence only around chron C33ny (73.62 Ma), when there was a major change in the spreading direction (Fig. 6d) at the Mascarene Basin spreading centre. Thus it is apparent that the Vishnu FZ is a feature that formed more than 10.0 million years later to the formation of the Chain-Kairali Escarpment. From all the above discussion it can thus be said that the postulations of those researchers that the Vishnu FZ extends northward into the Alleppey-Trivandrum Terrace Complex region is not justifiable.

Although we do not agree that the Chain-Kairali Escarpment is the northwards extension of the Vishnu FZ, we note the apparent collinearity of the gravity trends associated with these two features. We therefore attempted to find an explanation for this observation. As discussed earlier, the transform fault TF2, which in due course gave rise to the Vishnu FZ and its conjugate Mauritius FZ, came into existence after a major re-organization of the Mascarene Basin spreading centres around C33ny (~73.62 Ma). Location wise, the weak zones offshore of the Chain-Kairali Escarpment perhaps facilitated initiation of this transform fault TF2. A second episode of gradual re-organization of the spreading centres existed from chron C33ny (73.62 Ma) until the cessation of spreading in the Mascarene Basin at ~60.25 Ma, i.e., shortly after chron C27ny (60.92 Ma). Perhaps sometime around this cessation, the southward propagation of the Carlsberg Ridge halted as it hit the thicker crust of the transform margin of the Alleppey-Trivandrum Terrace Complex at the Chain-Kairali Escarpment. After cessation of spreading in the Mascarene Basin, the Carlsberg Ridge became the Indian – African plate boundary and this boundary was connected with the active spreading axis of the Madagascar Basin through a long transform fault that coincided with the Vishnu FZ. The Chain-Kairali Escarpment transform margin therefore acted as an inhibitor for the lengthening of the Carlsberg Ridge and the weak zones offshore wards of the Chain-Kairali Escarpment perhaps facilitated development of that long offset transform fault, probably as an en-echelon system. In view of these, we suggest that the Chain-Kairali

Escarpment is not a landward extension of the Vishnu FZ. Though these features were formed at different time, they are collinear because at a point of time during their evolution, they became part of a system of a single large-offset transform fault.

5. Conclusions

We constructed high-resolution plate reconstructions to describe the stage-by-stage evolution of the Mascarene and Madagascar basins with particular emphasis on the evolution and relationship of the Mahanoro and Mauritius fracture zones on the Madagascar side with the Vishnu FZ and the Chain-Kairali Escarpment on the Indian side. Our revised reconstruction model suggests an episode of asymmetric crustal accretion due to ridge propagation between India and Madagascar since initiation of spreading around chron C34ny (~83.0 Ma) to a time between chrons C33no (~79.08 Ma) and C33ny (~73.62 Ma). This was followed by a major re-organization of the spreading centres around C33ny (~73.62 Ma), when direction of spreading in the Mascarene Basin changed from ~E-W to ~NE-SW direction. We believe that our study provides important insights into the initiation of the Vishnu FZ and its spatio-temporal relationship with the Chain-Kairali Escarpment off the southwest coast of India. Several researchers considered that the Chain-Kairali Escarpment is the landward extension of the Vishnu Fracture Zone, but their inference is only based on a linear gravity low signature extending towards north of the Vishnu Fracture Zone. In variance to this, our plate reconstructions suggest that the Chain-Kairali Escarpment is an older, India-Madagascar breakup related feature, formed when the southwest coast of India started moving past southeast coast of Madagascar at around 88.0 Ma. The Vishnu FZ is a much younger feature, initiated at around chron C33ny (73.62 Ma). To begin with, the Chain-Kairali Escarpment was closer to the transform fault, which later developed into the

Mahanoro FZ. However, episodes of spreading centre re-organization brought it to the present position, where it appears as nearly collinear with the Vishnu FZ. In view of these, we conclude that the Chain-Kairali Escarpment is not a landward extension of the Vishnu FZ. These features were formed at different time, and during their evolution they became part of a system of a long offset transform fault, which gave rise to their collinear existence.

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Figure Captions

Fig. 1: (a) Generalized map of the Western Indian Ocean depicting the various tectonic elements as described by the isobaths and fracture zones; (b) the satellite-derived free-air gravity anomaly map of the southwestern continental margin of India and the adjoining deep offshore basins, showing gravity anomaly signatures of various tectonic elements. Thin dotted lines are selected (1000 m, 2000 m, and 3000 m) isobaths from GEBCO digital data set (IOC-IHO-BODC, 2003). The brown dashed-dotted lines represent the Rodrigues Triple Junction Trace. The thick grey lines represent present day plate boundaries. The grey dashed lines represent fracture zones obtained from the global seafloor fabric database (Wessel et al., 2015). The fracture zones plotted in the same colour in different plates represent conjugate pairs of fracture zones. The blue labels represent the major plates in the Western Indian Ocean. The region filled with yellow colour represents the extent of deformation zone in the Central Indian Basin (Royer and Gordon, 1997). The region marked with red coloured ellipse represents the straight southeast coast of Madagascar, which is referred in section 4.1.1. IND: Indian Plate; AFR: African Plate; ARB: Arabian Plate; ANT: Antarctic Plate; CAP: Capricorn Plate; ABB: Arabian Basin; ESB: Eastern Somali Basin; MSB: Mascarene Basin; MDB:

Madagascar Basin; CZB: Crozet Basin; CIB: Central Indian Basin; LXB: Laxmi Basin; GPB: Gop Basin; LCB: Laccadive Basin; OFZ: Owen Fracture Zone; LAX: Laxmi Ridge; LCP: Laccadive Plateau; MR: Maldive Ridge; CB: Chagos Bank; AmP: Amirante Plateau; SB: Seychelles Bank; SdM: Saya de Malha; NzB: Nazareth Bank; MI: Mauritius Island; RI: Reunion Island; MDR: Madagascar Ridge; CR: Carlsberg Ridge; CIR: Central Indian Ridge; SEIR: Southeast Indian Ridge; SWIR: Southwest Indian Ridge; SR: Sheba Ridge; VFZ: Vishnu Fracture Zone; CKE: Chain-Kairali Escarpment; MauFZ: Mauritius FZ; MhnFZ: Mahanoro FZ; NBFZ: Northern Boussole FZ; SBFZ: Southern Boussole FZ; NAFZ: Northern Astrolabe FZ; SAFZ: Southern Astrolabe FZ

Fig. 2: Simplified plate tectonic reconstructions of India with Madagascar at (a) chron C22ny (~49.04 Ma) and (b) chron C34ny (83.0 Ma), showing relationship of fracture zones from southeastern continental margin of Madagascar and southwestern continental margin of India. Reconstructions are presented in fixed Madagascar reference frame. (a) and (b) are based on rotation parameters of Norton and Sclater (1979) and Bhattacharya and Yatheesh (2015), respectively. Thick continuous and dashed grey lines represent the ridge segments and the transform segments of the active spreading centre, respectively. Pink and blue coloured dashed lines represent the respective conjugate pairs of fracture zones on the Madagascar and Indian sides. Other details are as in Fig. 1.

Fig. 3: Updated tectonic fabric map of the southwestern continental margin of India and its adjoining deep offshore regions showing the magnetic lineations, fracture zones and the other offshore tectonic elements. The magnetic lineations in the Central Indian Basin have been created based on the magnetic anomaly picks and rotation parameters adopted from Yatheesh et al. (2008). The magnetic lineations and the associated

tectonic fabric of fracture zones and pseudofaults in the Arabian Basin were adopted from Chaubey et al. (2002). AT: Alleppey Terrace; TT: Trivandrum Terrace; RFZ: Rudra Fracture Zone; WCIB: Western Central Indian Basin; ECIB: Eastern Central Indian Basin. Other details are as in Fig. 1.

Fig. 4: Geophysical signatures of the Alleppey-Trivandrum Terrace Complex and the Chain-Kairali Escarpment as depicted by (a) bathymetric contours of 100 m interval (after Yatheesh et al. (2013b)); (b) satellite-derived free-air gravity anomalies of Sandwell et al. (2014); (c) and (d) are the multi-channel seismic reflection sections along profile DN13-A (modified after Nathaniel (2013a)) and profile SST-17 (after Yatheesh et al. (2013b)), respectively. The thick pink lines in (a) and (b) represent the extent of the TT-Western Basin (TT-WB) along the seismic sections. Dashed blue line represents the extent of the Chain-Kairali Escarpment (CKE) and grey shaded region labeled as GH is the gravity high zone in the central part of the Trivandrum Terrace. Labels with green fonts are the interpretation of Nathaniel (2013a), N1: oceanic / transition; N-2: Vishnu FZ; N-3: Inverted graben; N-4: Mesozoics N-5: KT Boundary. The highly faulted region interpreted by Nathaniel (2013a) as the Vishnu FZ, labelled as N2, represents the TT-Western Basin identified by Yatheesh et al. (2013b). TT-EB: TT-Eastern Basin. Other details are as in Figs. 1 and 3.

Fig. 5: Updated tectonic fabric map of the southeastern continental margin of Madagascar and the adjacent Mascarene and Madagascar basins, showing the magnetic lineations, fracture zones and the other offshore tectonic elements. The magnetic lineations in the Mascarene and Madagascar basins were created based on the magnetic anomaly picks from Eagles and Wibisono (2013) and Yatheesh et al. (2008), respectively. The magnetic lineations and the associated tectonic fabric of fracture zones and pseudofaults in the Eastern Somali Basin were adopted from Chaubey et al. (2002).

The thick black line represents the extinct spreading axis. The compartments from A to D fall in the Southern Mascarene Basin and the compartment E falls within the Northern Mascarene Basin. NMR: Northern Madagascar Ridge. Other details are as in Fig. 1.

Fig. 6: Simplified plate tectonic reconstruction maps (in fixed Madagascar frame) for the evolution of the Western and Central Indian Ocean regions based on an up-to-date compilation (Chaubey et al., 2002; Royer et al., 2002; Yatheesh et al., 2008; IFCPAR, 2010; Eagles and Wibisono, 2013; Bhattacharya and Yatheesh, 2015) of magnetic anomaly picks and the rotation parameters that describe relative motion of India and Madagascar along with the intervening continental slivers of the Seychelles Plateau, Laxmi Ridge, Laccadive Plateau and the anomalous Alleppey-Trivandrum Terrace Complex and its conjugate Northern Madagascar Ridge. (a) Reconstruction for a pre-drift juxtaposition of continental blocks at 88.0 Ma (Late Cretaceous). (b) Reconstruction for chron C34ny (~83.0 Ma, Late Cretaceous). (c) Reconstruction for chron C33no (79.08 Ma, Late Cretaceous). (d) Reconstruction for chron C33ny (73.62 Ma, Late Cretaceous). (e) Reconstruction for chron C30ny (65.58 Ma, Early Paleocene). (f) Reconstruction for chron C28ny (62.5 Ma, Early Paleocene). (g) Reconstruction for chron C27ny (60.92 Ma, Middle Paleocene). (h) Reconstruction for chron C26no (57.90 Ma, Early Eocene). The rotation parameters used for these reconstructions are given in Supplementary Table ST-1 (modified after Bhattacharya and Yatheesh (2015)). The extent of the major continental blocks and the microcontinents were adopted from Bhattacharya and Yatheesh (2015). ATTC: Alleppey-Trivandrum Terrace Complex; MAD: Madagascar; NIP: Northern Indian Protocontinent; SIP: Southern Indian Protocontinent; SLK: Sri Lanka; SEY:

Seychelles Plateau; SVP: Saurashtra Volcanic Platform; DT: Deccan Trap. Other details are as in Figs. 1 and 3.

Fig. 7: (a) Flow line and (b) estimated half spreading rates and spreading directions computed for the India-Madagascar relative motion during the evolution of the Mascarene Basin, based on the rotation parameters used in the present study. Computations were done for a seed point (shown as blue open circle) at the extinct spreading centre, from compartment B (18.520°S, 54.760°E). The flow line (shown as red line) is computed for 83.0 Ma to 60.25 Ma, at 2 m.y. interval. The computed locations of the points are shown as black thick dots in a reconstruction map at 60.25 Ma, the timing of extinction of spreading in the Mascarene Basin. Thick black lines in the Mascarene Basin represent the extinct spreading centre. Thin dotted lines represent the fracture zones. Other details are as in Fig. 1.

Fig. 8: Maps showing the characteristic gravity signatures of the Vishnu FZ and the Chain-Kairali Escarpment. (a) colour-coded image of the satellite-derived free-air gravity anomalies (Sandwell et al., 2014); (b) satellite-derived free-air gravity anomalies presented as contours with 10 mGal interval (c) the location and extent of the Vishnu FZ and the Chain-Kairali Escarpment superimposed on updated (Yatheesh et al., 2013b) bathymetric map (IOC-IHO-BODC, 2003). The satellite derived free-air gravity anomalies over the Chain-Kairali Escarpment and the Vishnu FZ are shown in smaller scale in (d) and (e), respectively. Free-air gravity anomalies extracted from the satellite-derived free-air gravity anomaly grid are plotted as wiggles (in grey colour in (a), blue colour in (b) and white colour in (d) and (e)), to trace the gravity signature corresponding to the Vishnu FZ and CKE. The pink coloured dotted lines and shades, labeled as GL-1, represents the extent of the characteristic gravity low corresponding to the location of the Vishnu FZ (labeled as N-2 in Fig. 3c), as inferred

by Nathaniel (2013a). The red dotted line represents possible northward extension of the Vishnu FZ by tracing its gravity signature. Other details are as in Figs. 1 and 6.

Table captions

Table 1: Ages of the magnetic chrons (after Cande and Kent (1995)). The old (o) and young (y) edges of magnetic chrons represents the beginning and end of normal polarity.

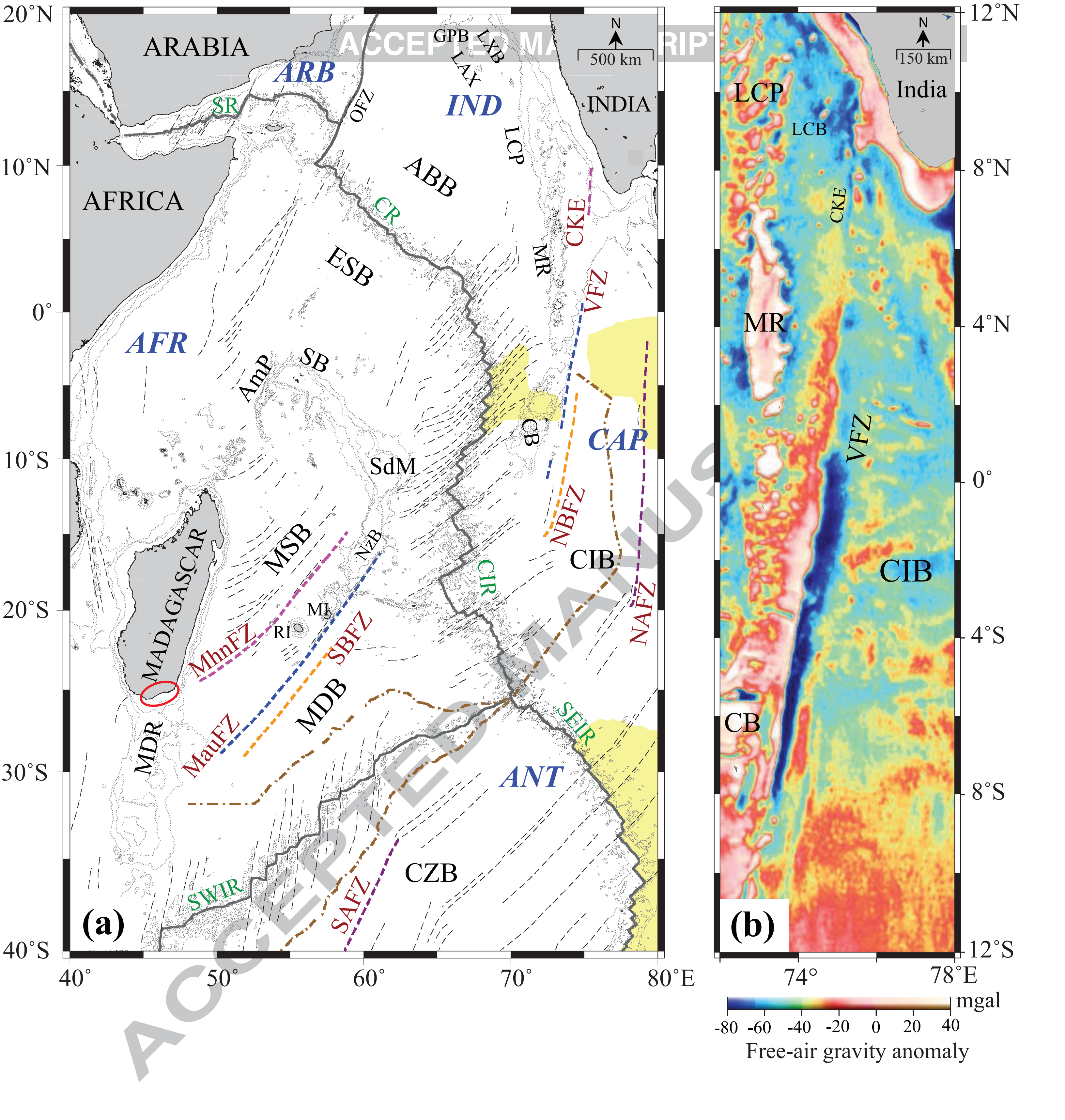

Figure 1

2-column fitting image

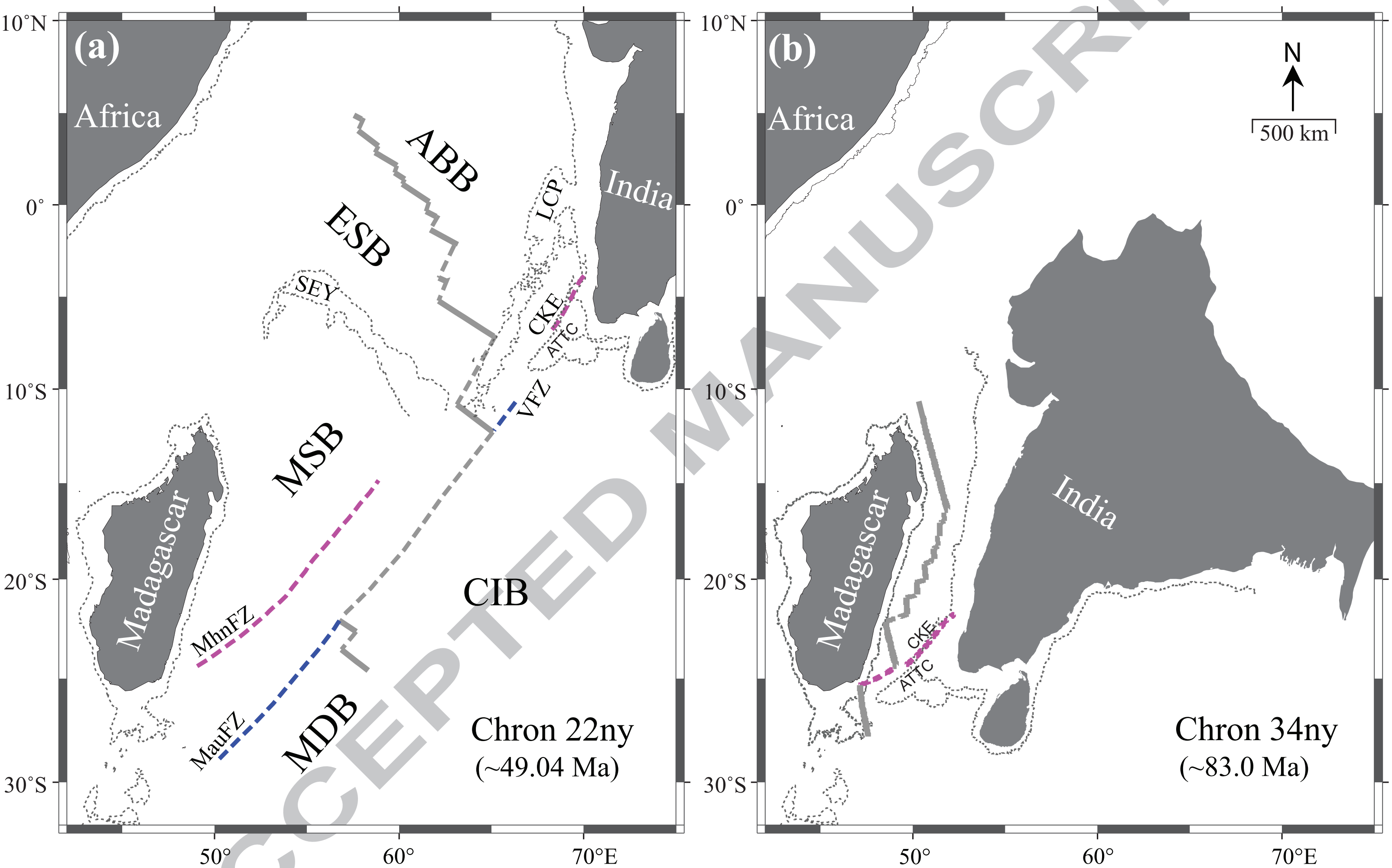

Figure 2

2-column fitting image

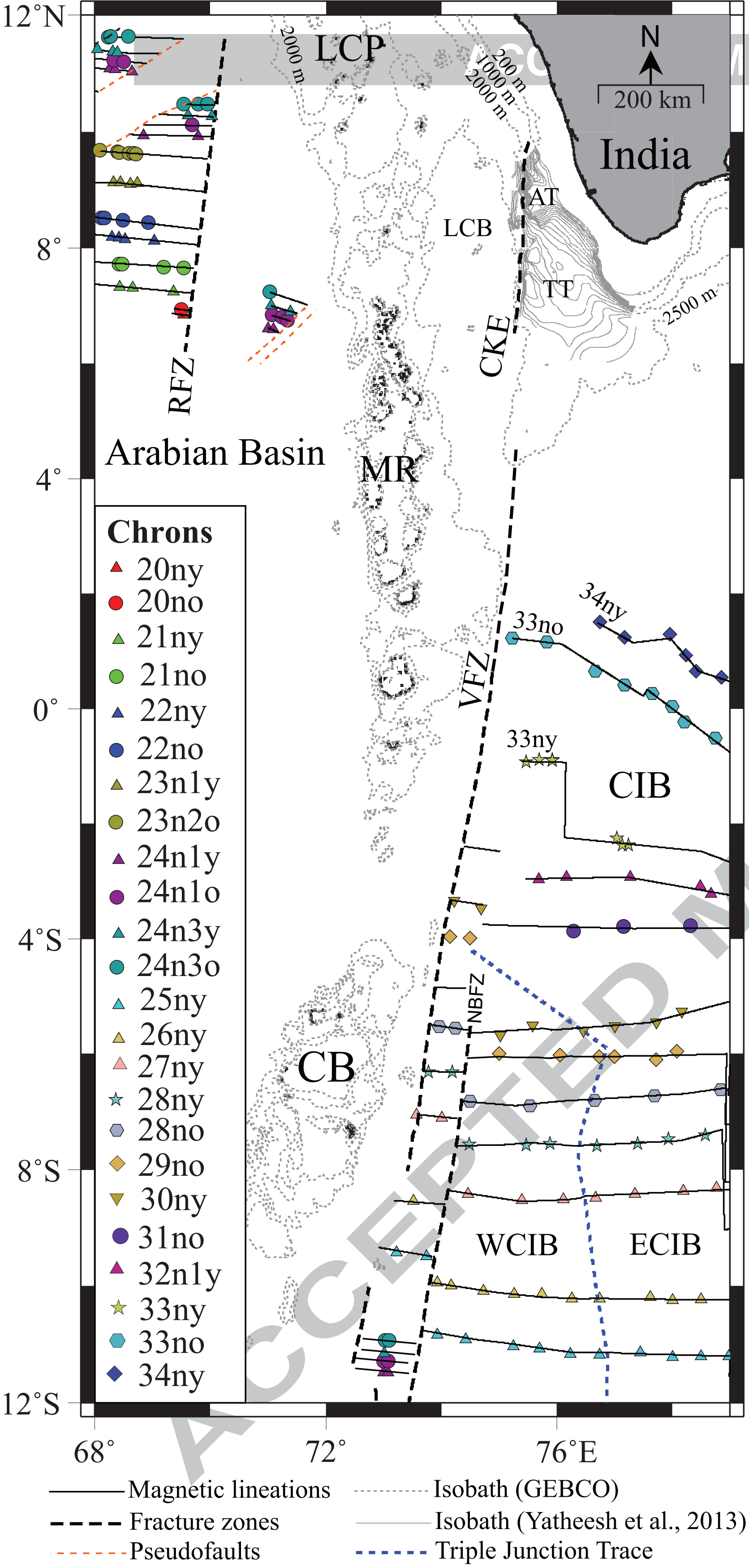

Figure 3

Single -column fitting image

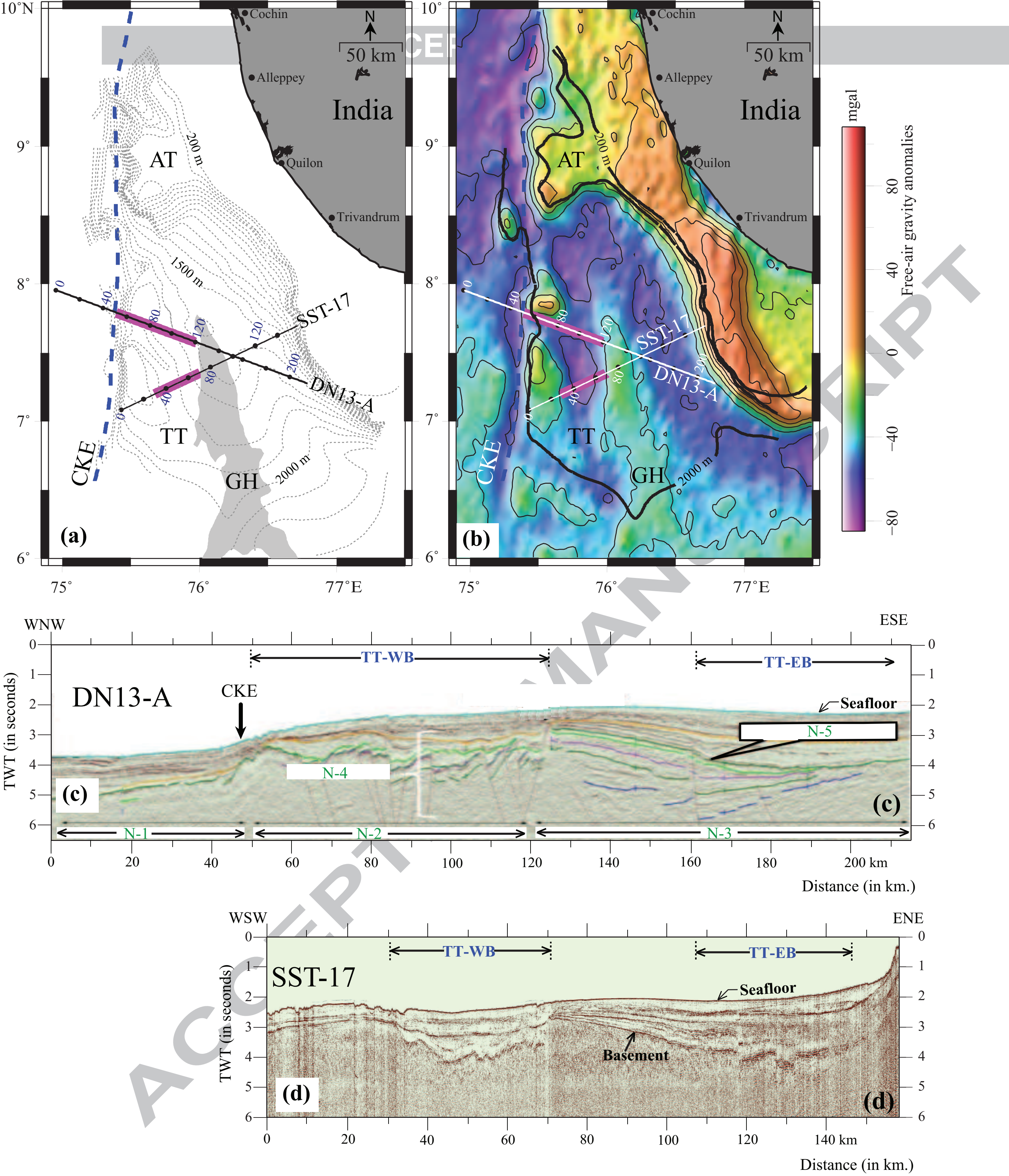

Figure 4

2-column fitting image

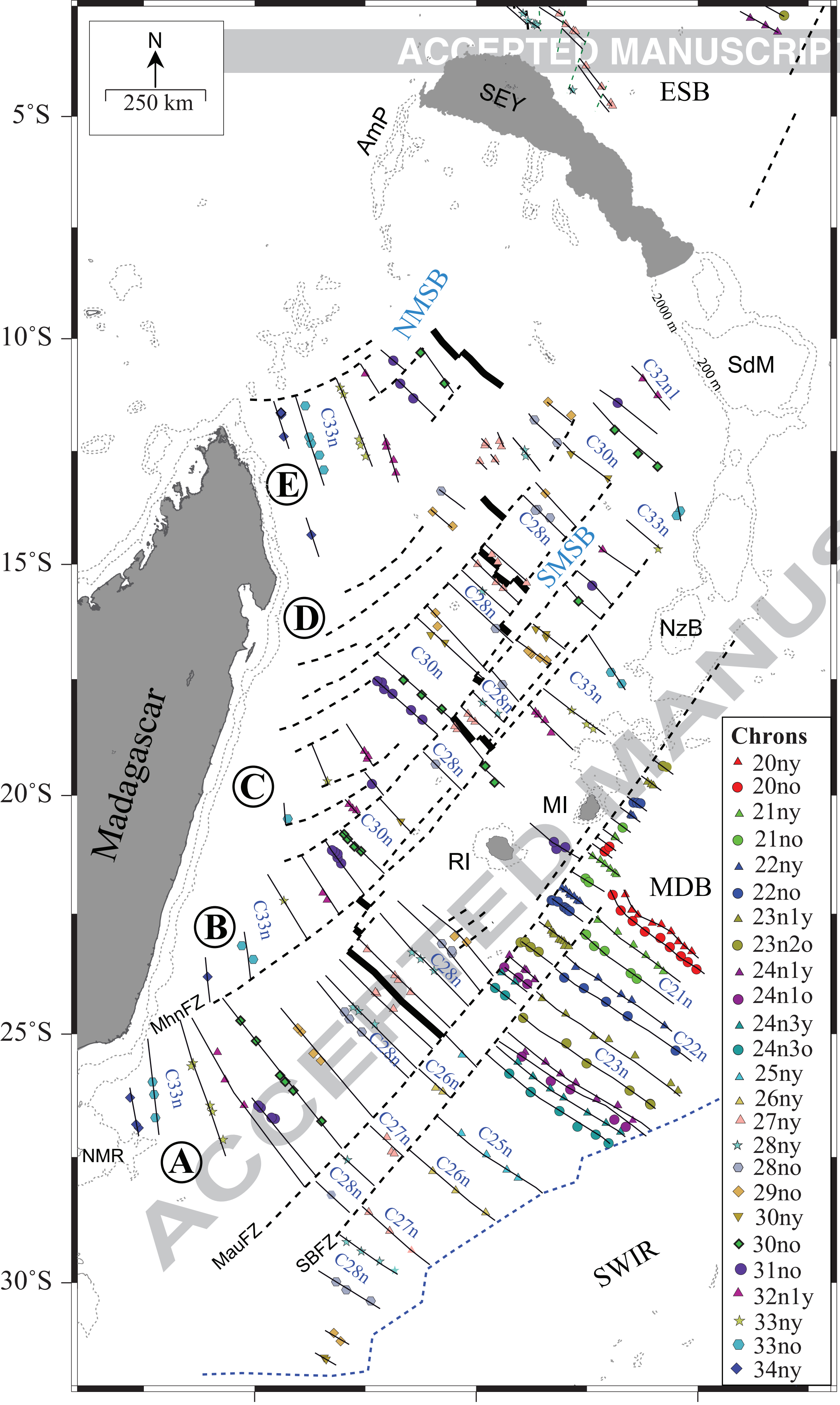

Figure 5

1.5-column fitting image

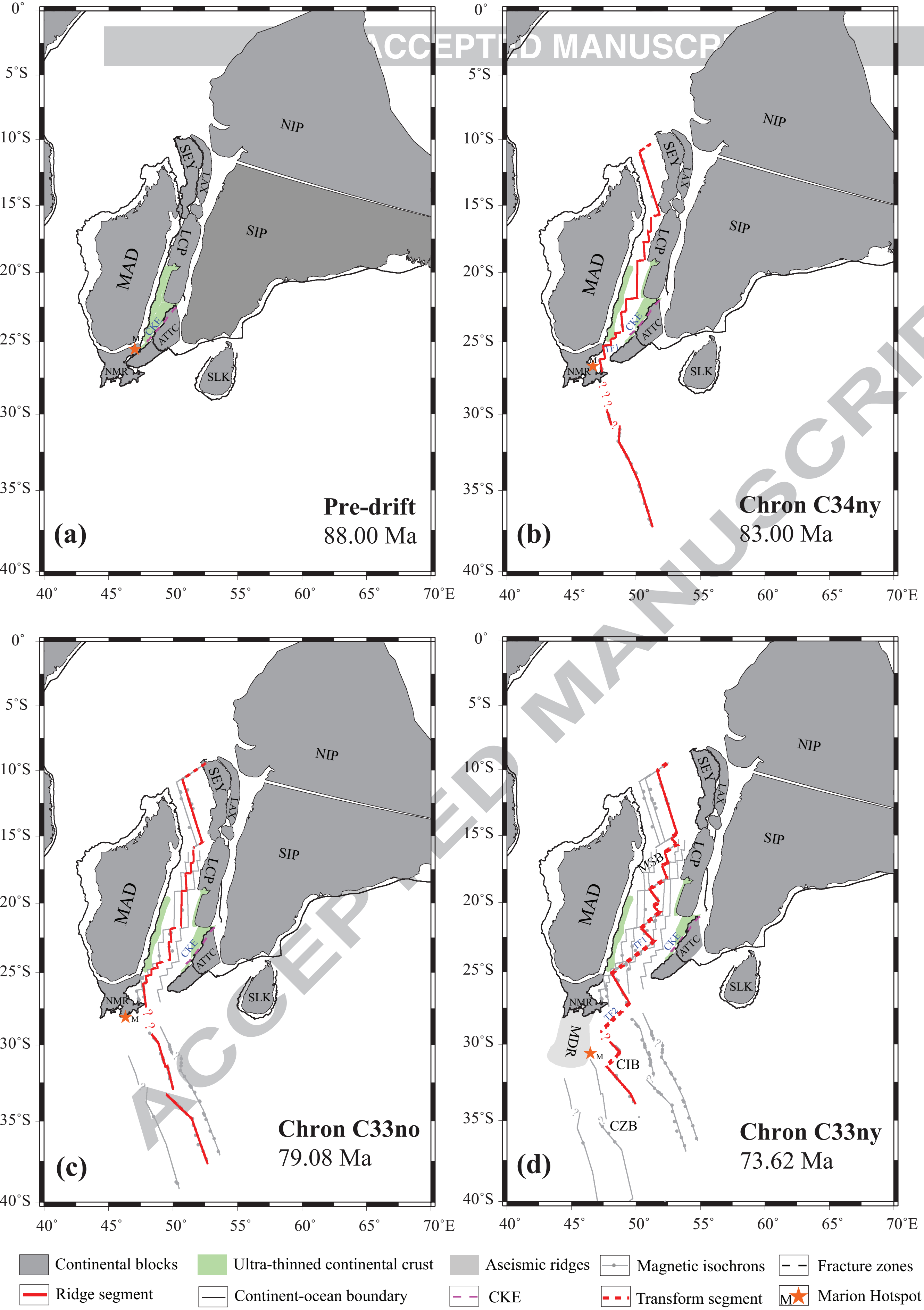

Figure 6

2-column fitting image

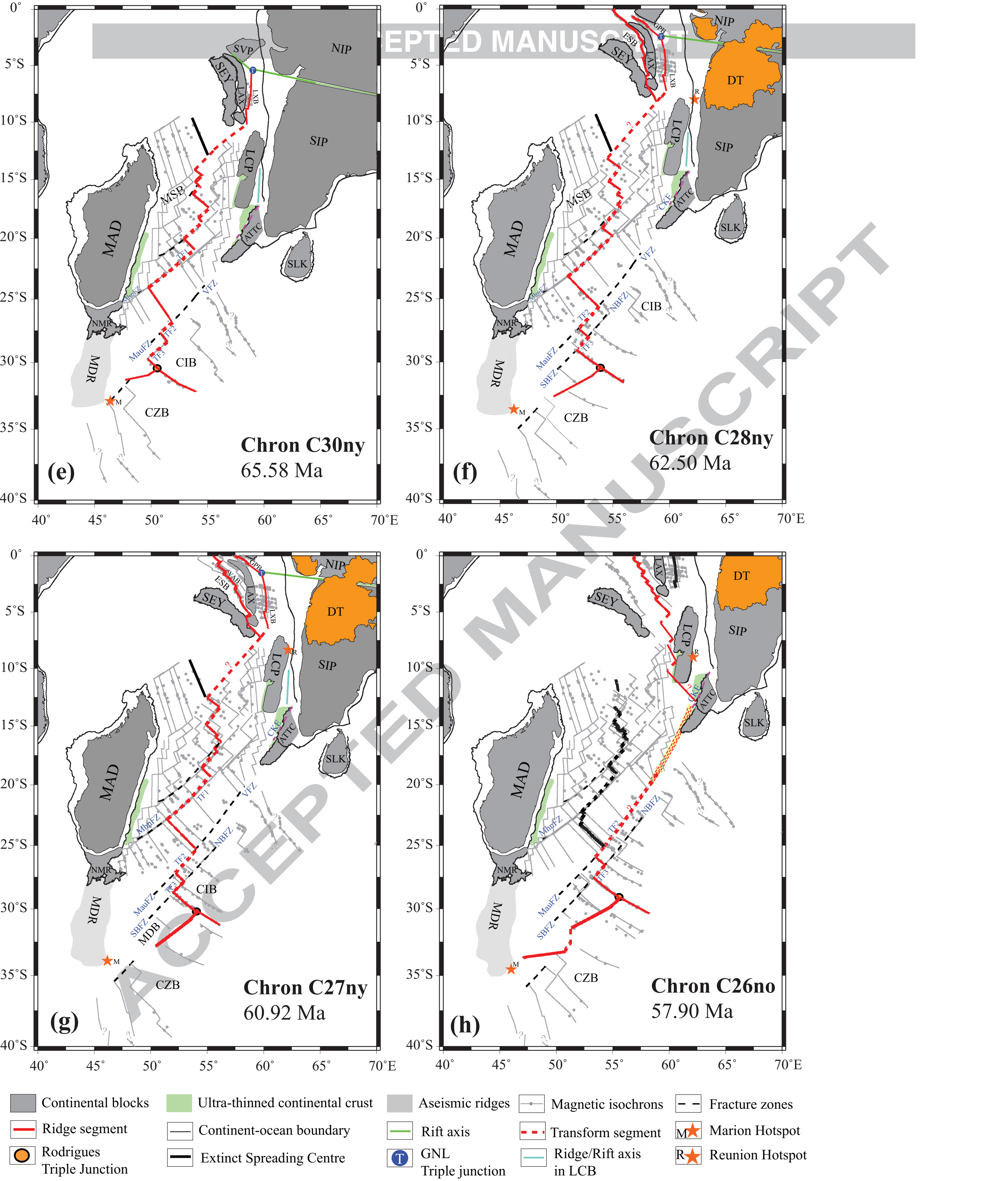

Figure 6 (contd.)

2-column fitting image

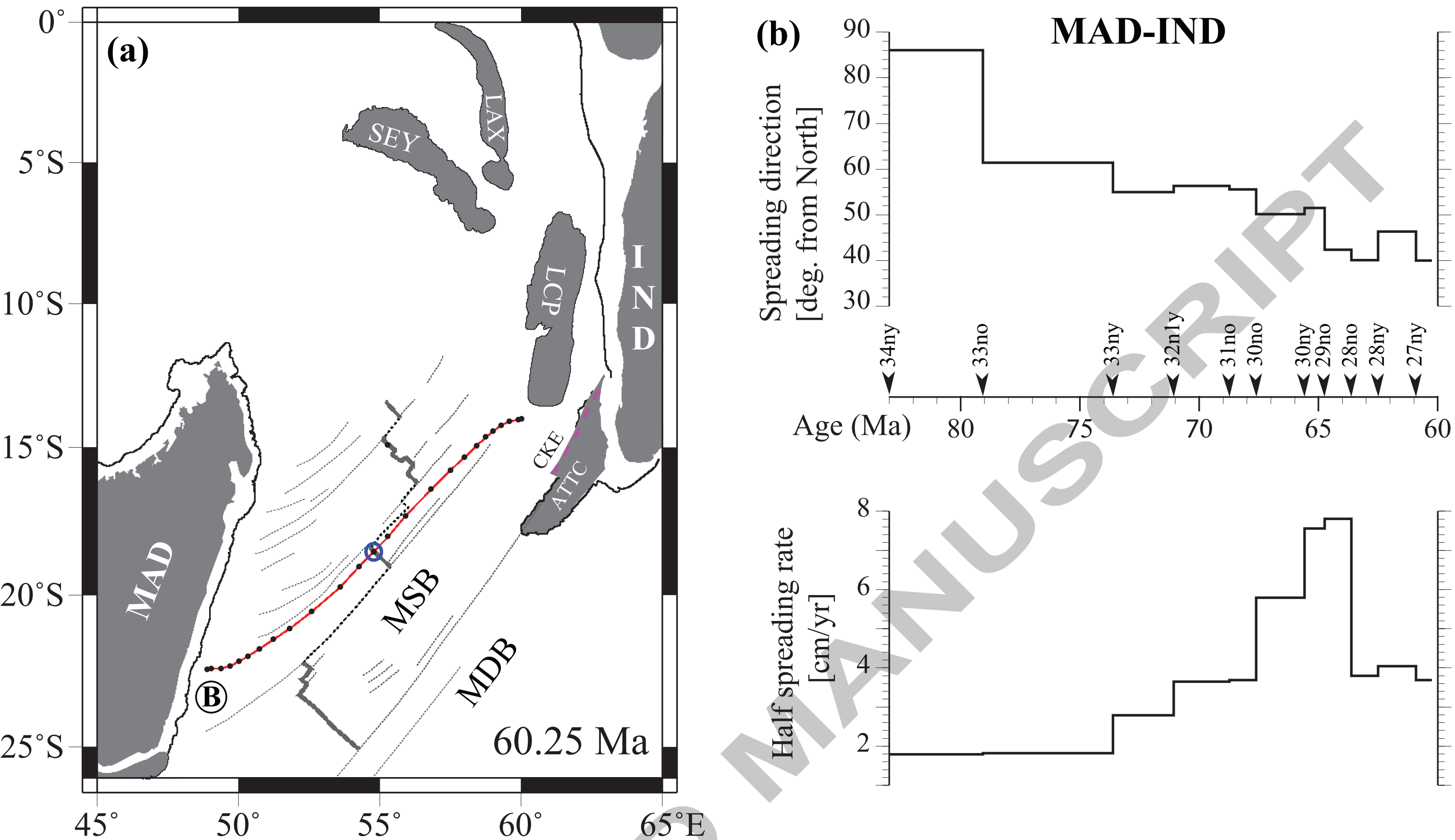

Figure 7

2-column fitting image

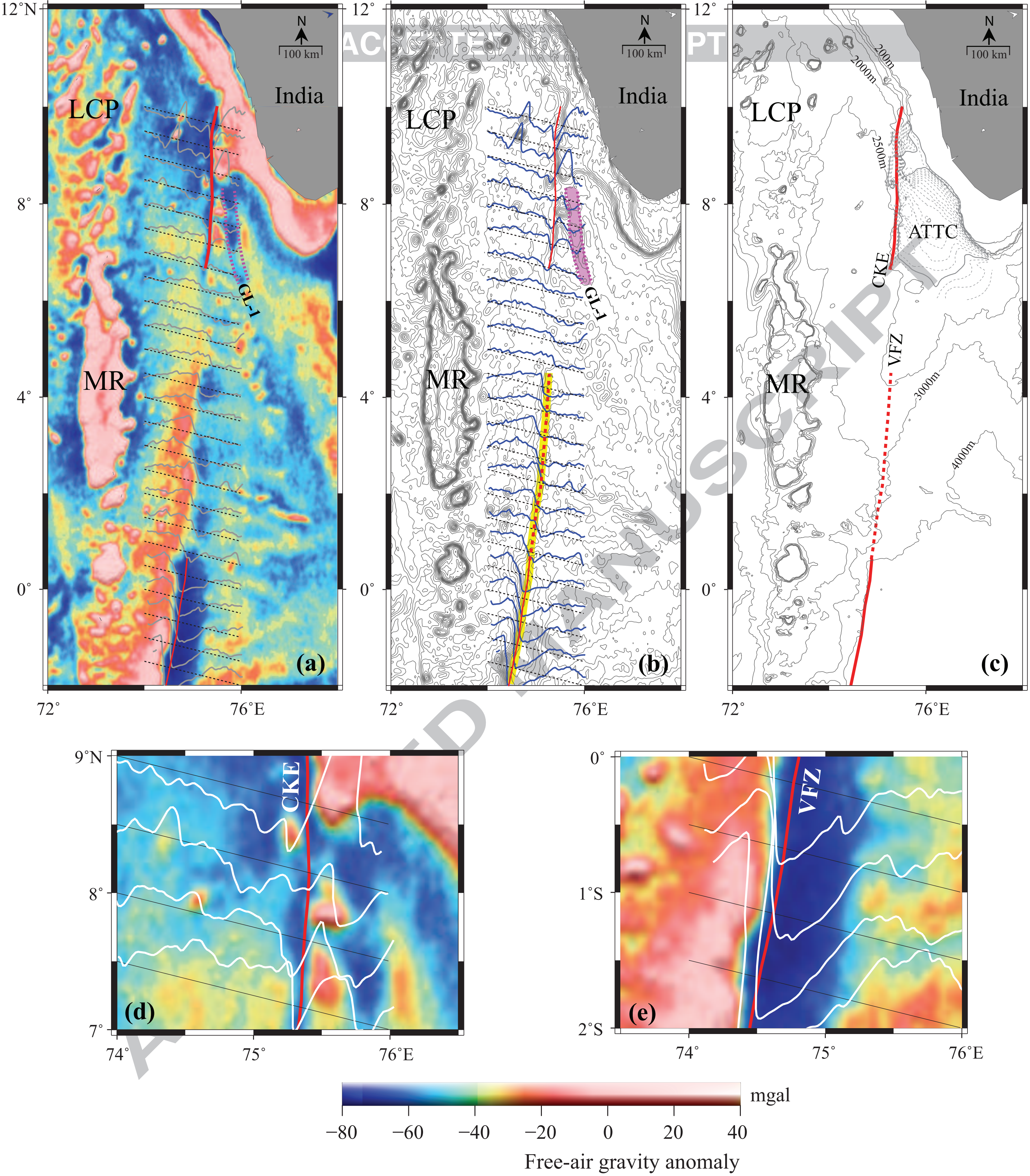

Figure 8

2-column fitting image

Research highlights

- Evolution of conjugate plate kinematic traces related to India-Madagascar separation
- Proposed nearly contemporaneous divergence in the Laccadive and Mascarene basins
- The Chain-Kairali Escarpment is not landward extension of the Vishnu Fracture Zone

Table 1

Chron	Young edge (Ma)	Old edge (Ma)
25n	55.904	56.391
26n	57.554	57.911
27n	60.920	61.276
28n	62.499	63.634
29n	63.976	64.745
30n	65.578	67.610
31n	67.735	68.737
32n.1n	71.071	71.338
32n.2n	71.587	73.004
33n	73.619	79.075
34n	83.000	118.000