ANNEXURE
The terrace like feature in the mid-continental slope region off Trivandrum and a plausible model for India–Madagascar juxtaposition in immediate pre-drift scenario

V. Yatheesh a,*, G.C. Bhattacharya b, K. Mahender c

a National Centre for Antarctic and Ocean Research, Headland Sada, Vasco-da-Gama, Goa 403 804, India
b Geological Oceanography Division, National Institute of Oceanography, Dona Paula, Goa 403 004, India
c Department of Earth Science, Goa University, Taleigao Plateau, Goa 403 206, India

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Abstract

Bathymetry of the southwestern continental margin of India reveals the presence of an anomalous terrace like feature in the mid-continental slope region off Trivandrum. The genesis of this terrace of large areal extent (~9000 sq. km.) is yet to be established. Based on exercises with several existing paleogeographic reconstruction models and updated compilation of identified offshore tectonic elements, this study attempts to identify a plausible model of India–Madagascar juxtaposition in immediate pre-drift scenario, which provides idea about genesis of this terrace. It is inferred that the terrace off Trivandrum and an anomalous bathymetric notch located in the northern Madagascar Ridge are conjugate features related to India–Madagascar separation and the rifted and sheared segments of the pre-drift plate boundary have shaped their outlines. The drifting of India from Madagascar is suggested to have commenced at about 86.5 Ma.

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1. Introduction

The continental shelf of west coast of India (Fig. 1), limited by the 200 m isobath, has variable width. Towards the north this shelf is relatively wider, being more than 300 km in the areas north off Mumbai coast, whereas towards the south this width gradually narrows down to about 50 km off Trivandrum. As compared to the continental shelf, the continental slope in most of this region is relatively narrow and parallels the trend of the continental shelf edge. However, the continental slope region off Trivandrum (Fig. 1) interestingly depicts the presence of an anomalous broad terrace like feature, which has not drawn much attention of the researchers so far. The western continental margin of India, to which this terrace belongs, is considered to be a passive continental margin (Biswas, 1982, 1987), which evolved during the process of rifting and drifting of Madagascar, Seychelles and India. Even though researchers agree on the concept of a welded Madagascar–Seychelles–India continental block, but opinion differs regarding their immediate pre-drift juxtaposition and consequential early post drift positions. Probably lack of distinct and dependable "piercing points" such as onshore tectonic lineaments, which could have constrained this juxtaposition, is one of the reasons for those varied inferences. The other reason could be the absence of India–Madagascar break-up related magnetic isochrons, which could have allowed arriving at consistent rotation parameters for constraining early India–Madagascar separation, as that break-up took place during Cretaceous long normal superchron.

It was also observed that the outline of this terrace appears in the post anomaly 34 paleogeographic reconstructions of Norton and Sclater (1979) as well as of Besse and Courtillot (1988). However, those studies, apparently due to their emphasis on broader perspective, did not pay specific attention to this terrace or looked for its conjugate feature. Rao and Bhattacharya (1975) analyzed magnetic and seismic data in the northern part (off...
2. The topography of the terrace like feature off Trivandrum

The bathymetry contour map (Fig. 1), shows a conspicuously wide low gradient zone in the mid-continental slope region off Trivandrum. This zone broadly lies between 1000 and 2000 m isobaths and covers an area of about 9000 sq. km. Eight available bathymetric transects (Figs. 2 and 3) across this zone suggest this terrace as a relatively flat zone bounded by a steep ascending (by about 1000 m) seafloor to the adjacent continental shelf on the easterly side and a comparable steep descending seafloor towards the deep sea in the westerly side. This topography appears to be anomalous as compared to the general topography depicted by contours and two bathymetric transects (Fig. 3) across the normal shelf–slope configuration in the north. This wide zone is considered to qualify well as a ‘terrace’ following the definition of Lapides (1978) and for further reference in this study we denote this feature as ‘Terrace off Trivandrum (TOT)’.

3. India–Madagascar juxtaposition at anomaly 34 time — varied inferences

For tracing the India–Madagascar separation one need to start with the India–Madagascar juxtaposition. The aspect of paleogeographic juxtaposition of India and Madagascar has been directly addressed or indirectly depicted in number of studies. The
Fig. 3. Selected bathymetric profiles across the southwestern continental margin of India showing the distinct sectional view of the terrace off Trivandrum as compared to the normal shelf-slope configuration along the northern profiles (SK22-02 and SK22-03). The locations of these profiles are shown in Fig. 2 and the depth levels of 1 and 2 km are labeled on the profiles.

Fig. 4a—d presents a reconstruction map of India-Madagascar juxtaposition for anomaly 34ny time (83.0 Ma), which we

qualitative juxtaposition models (Crawford, 1978; Katz and Premoli, 1979; Agrawal et al., 1992; Windley et al., 1994; Menon and Santosh, 1995; Dissanayake and Chandrajith, 1999; Pradeepkumar and Krishnanath, 2000; Torsvik et al., 2000; Anil Kumar et al., 2001) are based on the collinearity of inferred comparable onshore shear zones, geological domains or continental scale MAGSAT and gravity anomalies. On the other hand quantitative models are based on estimated finite rotation parameters. Based on the evaluation of those qualitative models by Yoshida et al. (1999) and other recent studies (Chetty and Bhaskar Rao, 2004; Radhakrishna et al., 2004) it appears that there is a broad agreement about the comparable geological units and shear zones of southern India and Madagascar, however precise conjugate correspondence of these features is still awaited. According to Norton and Scater (1979) the separation of India and Madagascar started shortly before anomaly 34 time. Therefore, in the following paragraph, we briefly discuss some of those quantitative models (Norton and Scater, 1979; Morgan, 1981; Besse and Courtillot, 1988; Muller et al., 1993) with focus on India-Madagascar relative position for the time of this anomaly 34 and show that the relative position of India and Madagascar vary in different models.

The paleogeographic reconstructions (Fig. 4a—d) prepared for this study are for the time of younger bound of anomaly 34 (i.e. anomaly 34ny). These reconstructions have been prepared using finite rotation parameters of different published models (Norton and Scater, 1979; Morgan, 1981; Besse and Courtillot, 1988; Muller et al., 1993). Since the age corresponding to various magnetic isochrons in those studies are based on different geomagnetic timescales, therefore, for using those finite rotation parameters in this study, we have re-assigned the ages according to Cande and Kent’s (1995) geomagnetic time scale. It is generally agreed that the magnetic anomaly 34 identified in the southern Mascarene Basin represents the oldest anomalies formed shortly after the India-Madagascar separation. Therefore, the paleo-ridge positions at anomaly 34ny and paleo-transforms have been marked using the available (Schlich, 1982; Dyment, 1991; Bernard and Munschy, 2000) magnetic anomaly identifications close to Madagascar in the Mascarene Basin and considered them fixed to the African plate while generating reconstruction maps. We considered the 2000 m isobath obtained from recent GEBCO digital data set (Intergovernmental Oceanographic Commission et al., 2003) to define the continent-ocean boundary off India and Madagascar.

In the reconstruction (Fig. 4a) following Norton and Scater’s (1979) model, we observed that the 2000 m isobaths off Indian coast as well off Madagascar coast are symmetric about the anomaly 34ny time ridge position and there is not much offset between the southern tips of India and Madagascar. The reconstruction following Morgan’s (1981) model provides a close fit (Fig. 4b) for India and Madagascar without any intervening gap at 83.0 Ma itself and the paleo-ridge overlaps Indian landmass at places. Further, in this reconstruction, we also observed that the southern tip of Madagascar is much south of the southern tip of India and the 2000 m isobath off the Indian coast overlaps the Madagascar mainland. Reconstructions following model of Besse and Courtillot (1988) depict (Fig. 4c) the 83.0 Ma paleo-ridge positions closer to 2000 m isobath off Madagascar as compared to the same off Indian coast. The reconstruction model (Fig. 4d) following Muller et al. (1993) shows that the 2000 m isobaths off India as well off Madagascar are more or less symmetric about the paleo-ridge position, but towards north Madagascar is much closer to India. It appears that the models of Besse and Courtillot (1988) and Morgan (1981) are not appropriate for the India-Madagascar relative motion as they place the anomaly 34ny time ridge axis asymmetrically with respect to the conjugate 2000 m isobaths. Based on our exercise, we believe that the model of Norton and Scater (1979) provides a better approximation of the India-Madagascar pre-anomaly 34ny time relative motion as it can accommodate the microcontinental fragments in the pre-drift India-Madagascar juxtaposition model.

4. Terrace off Trivandrum in a close fit India-Madagascar configuration

Fig. 5a presents a reconstruction map of India-Madagascar juxtaposition for anomaly 34ny time (83.0 Ma), which we
Various paleogeographic reconstruction models to show the varied juxtaposition of India with Madagascar at anomaly 34 ny (83.0 Ma). Models a, and c are in ed Africa reference frame while models b and d are in fixed hotspot reference frame. Locations of anomaly 34ny time paleo-spreading ridge segments are shown as ck black lines and transform segments by dashed lines. The 200 m and 2000 m isobaths surrounding India and Madagascar are shown by thin lines.

Prepared using the rotation parameters of Norton and Sclater (1979). As evidenced from this reconstruction map, we believe the shape of the 2000 m bathymetry contours off the southwest Indian coast and southeast Madagascar coast strongly suggest the conjugate nature of the terrace off Trivandrum and bathymetry notch in the northern Madagascar Ridge. As mentioned earlier, it is generally believed that the separation of India and Madagascar started shortly before anomaly 34 ny time based on dated onshore volcanics this separation is considered to have been initiated around 88-91 Ma (Storey et al., 1995; Torsvik et al., 2000; Pande et al., 2001; Anil Kumar et al., 2001). If that is the case, then India and Madagascar were much closer as compared to their position in the anomaly 34ny reconstruction (Fig. 5a). In view of this we tried to construct Madagascar and India for a pre-anomaly 34ny time close fit configuration. Since the finite rotation parameters to describe this motion are not readily available in the Norton and Sclater (1979) model, so we tried to bring a closer fit of India and Madagascar by extrapolation, considering the same pole and rate of rotation as of anomaly 34ny time. This exercise provided a closer fit of India and Madagascar at 86.5 Ma and interestingly depicted a near fit (with slight overlap) of the terrace off Trivandrum with the bathymetric notch of the northern Madagascar Ridge. We tried to improve this fit by trial and error and believed to have obtained a reasonably good fit (Fig. 5b) of those terrace and notch for the same 86.5 Ma using a slightly modified Euler pole (Table 1) of Norton and Sclater (1979). In view of this, we are tempted to believe that this terrace off Trivandrum (TOT) and the bathymetric notch (BN) of northern Madagascar Ridge are the conjugate features
Fig. 5. Paleogeographic reconstruction of India and Madagascar in fixed Africa reference frame; (a) at 83.0 Ma following Norton and Sclater (1979) rotation parameters, (b) a plausible close fit at 86.5 Ma following the additional rotation parameters suggested in this study (Table 1). Madagascar is in its present position. Land portions of India and Madagascar are shaded, surrounding 200 m isobaths are shown by thin lines and 2000 m isobaths are shown by thick lines. Locations of onshore shear zones simplified after Mcissner et al. (2002) and Windley et al. (1994). TOT: Terrace off Trivandrum, BN: Bathymetric notch; NMR: Northern Madagascar Ridge, ASZ: Achankovil Shear Zone, PCSZ: Palghat—Cauvery Shear Zone, MSZ: Moyar Shear Zone, KSZ: Ranotsara Shear Zone, AXSZ: Axial Shear Zone.

published maps do suggest the existence of traces of several fracture zones. Considering the disposition of this terrace (TOT) and bathymetric notch (BN) with respect to the trends of paleo-ridge and paleo-transform segments in the reconstruction map (Fig. 4a) it may not be unreasonable to believe that the shape of those conjugate features were controlled by the ridge and transform segments of the paleo-ridge which existed at 86.5 Ma.

According to Storey et al. (1995) the Madagascar Ridge is believed to be a volcanic emplacement related to the motion of the African plate over the Marion hotspot since 90 Ma. However, based on the difference in the nature of the crust, the Madagascar Ridge is considered to be divided, roughly by a transition zone along 32°S latitude, into a northern domain and a southern domain (Goslin et al., 1980; Schlich, 1982; Bhat- tacharya and Chaubey, 2001). The velocity—depth distribution of the southern domain is closely related to that of a mean oceanic crust, but the crust underlying the northern domain is considered to be anomalous as it is neither purely continental nor of oceanic affinity. Perhaps the terrace off Trivandrum also has a similar nature of crust as the conjugate areas of the northern Madagascar Ridge and probably represents areas of inferred by Dyment (1991). It may be mentioned here that so far not enough anomaly 34ny magnetic isochrons have been mapped in the vicinity of the northern Madagascar Ridge but

Fig. 6. A schematic model showing possibility of accommodating Seychelles Bank [SEY] and other probable microcontinental slivers (Laccadive Plateau [LP], Laysan Ridge [LR], Saya de Malha Bank [SMD]) in the gap between the 2000 m bathymetry contours in a close fit India—Madagascar configuration at 86.5 Ma. BH: Bombay High. Other details are as in Fig. 5.

Table 1
Suggested addition to the finite rotation parameters of Norton and Sclater (1979) to obtain a closer fit India and Madagascar in fixed Africa reference frame

<table>
<thead>
<tr>
<th>Anomaly</th>
<th>Age (Ma)</th>
<th>Finite rotation parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>34ny</td>
<td>83.0</td>
<td>18.7 25.8 —56.00</td>
</tr>
<tr>
<td>Close fit</td>
<td>86.5</td>
<td>18.7 26.4 —58.36</td>
</tr>
</tbody>
</table>

CCW: Counter Clock-Wise.
tinided continental crust on which at places Marion hotspot
lated volcanics might have been emplaced.
Several authors (Barron, 1987; Lawyer et al., 1999)
onsidered the unusual steep and straight edge of eastern Mad-
ascarc as an evidence of transform motion between India and
agadagascar, which was believed to have taken place between
0 and 105 Ma. It is therefore necessary to examine the com-
tuatility of our proposed model of juxtaposed conjugate TOT
and BN and the transform motion between India and Mada-
ascarc, because a locked-in TOT and BN would have prevented
ch a transform motion. It may be noted that the inferred
nsform motion between India and Madagascar had taken
ace about 18 m.y. prior to the locked-in TOT and BN model
ich we have proposed for an India-Madagascar immediate
r-end scenario at about 86.5 Ma. The region which later
eveloped into TOT and BN might have existed simply as
lignant crusts across the transform boundary subsequent to the
nsform motion. Later, this area probably thinned when it came
nder the influence of Marion hotspot, and the bathymetric
trusion (TOT) and notch (BN) were formed by the initial
metry of the spreading axis when spreading was initiated
etween India and Madagascar. Assumption of such an initial
reading geometry in this region appears to be reasonable based
 disposition of the TOT with respect to the reconstructed
ahanoro and Mauritius Fracture zones along with their inter-
niing magnetic anomaly 34 (Fig. 4a).
Our proposed close fit (Fig. 5b) depicts the existence of a
e gap between the conjugate 2000 m isobaths in the areas
th of TOT. On the other hand we have not shown the dis-
sition of Seychelles microcontinent in this model and we also
ed to provide space for accommodation of Laxmi Ridge, Saya
: Malha Bank, and Laccadive Plateau, in case they are
icrocontinental slivers as believed by some authors (Krishnan,
8, Naini and Talwani, 1982; Plummer and Belle, 1995; Todd
 Eldhom, 1998; Talwani and Reif, 1998; Bhattacharya and
abey, 2001; Collier et al., 2004; Lane et al., 2005), which
isted between India and Madagascar in pre-drift scenario. We
elaccommodation of these features is possible in our 86.5 Ma
adia-Madagascar close fit model and to depict that possibility
: presented a schematic map (Fig. 6) where major portion of
ese features (outlined by the simplified surrounding present
 0 m isobath) have been accommodated in the gap available
tween the conjugate reconstructed 2000 m bathymetric con-
s. Since these features are inferred as thinned continental
ist, therefore, their present extents perhaps are much larger in
ir original pre-thinning state. Therefore, we feel they
uld be more conveniently accommodated in the gap in their
-thinning dimension. As mentioned earlier, perhaps there was
ne crustal extension in the regions of the TOT and BN before
spreading event, and therefore, the unstretched TOT and BN
uld have fitted slightly better and closer, but the overall
ario would have remained the same.

Summary and conclusions
We believe to have presented a better constrained model for a
se fit juxtaposition of India and Madagascar in the immediate
pre-drift tectonic scenario. This model suggests that the bathy-
metric protrusion of the terrace like feature off Trivandrum
(TOT) fits well in shape and size with the bathymetric notch
(BN) located in the northern Madagascar Ridge and they lock
well in a close fit India-Madagascar configuration. This fit can
be obtained for an 86.5 Ma reconstruction using a slightly
modified finite rotation parameters of Norton and Scalter (1979)
for relative motion of India with Africa. This model also appears
to accommodate Seychelles, Laxmi Ridge, Saya de Malha Bank
and Laccadive Plateau as intervening microcontinental slivers.
In view of these, it is inferred that the terrace off Trivandrum
and the bathymetric notch of the northern Madagascar Ridge
represent scars related to the India-Madagascar break-up, the
outlines of which were shaped by the rifted and transforms
segments of the initial spreading geometry and the drifting of
India from Madagascar was initiated around 86.5 Ma.

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