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India–Madagascar paleo-fit based on flexural isostasy of their rifted margins

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ABSTRACT

The present study contributes new constraints on, and definitions of, the reconstructed plate margins of India and Madagascar based on flexural isostasy along the Western Continental Margin of India (WCMI) and the Eastern Continental Margin of Madagascar (ECMM). We have estimated the nature of isostasy and crustal geometry along the two margins, and have examined their possible conjugate structure. Here we utilize elastic thickness (Te) and Moho depth data as the primary basis for the correlation of these passive margins. We employ the flexure inversion technique that operates in spatial domain in order to estimate the spatial variation of effective elastic thickness. Gravity inversion and flexure inversion techniques are used to estimate the configuration of the Moho/Crust–Mantle Interface that reveals regional correlations with the elastic thickness variations. These results correlate well with the continental and oceanic segments of the Indian and African plates. The present study has found a linear zone of anomalously low-Te (1–5 km) along the WCMI (~1680 km), which correlates well with the low-Te patterns obtained all along the ECMM. We suggest that the low-Te zones along the WCMI and ECMM represent paleo-rift inception points of lithosphere thermally and mechanically weakened by the combined effects of the Marion hotspot and lithospheric extension due to rifting. We have produced an India–Madagascar paleo-fit representing the initial phase of separation based on the Te estimates of the rifted conjugate margins, which is confirmed by a close-fit correlation of Moho geometry and bathymetry of the shelf margins. The matching of tectonic lineaments, lithologies and geochronological belts between India and Madagascar provide an additional support for the present plate reconstruction.

1. Introduction

The temporal evolution and spatial configuration of continents can be analyzed through their response to long-term forces, as a function of the elastic property of the lithosphere, which is parameterized as effective elastic thickness (Te). The Te method has been widely used as a key proxy to examine the long-term strength/rigidity structure of the lithosphere. It can be parameterized through flexural rigidity, $D \equiv E \cdot Te^3 / 12(1 - \nu^2)$, which is a measure of the resistance of the lithosphere to flexure in response to loading (Watts, 2001), where Young's modulus, E (10^{11} Pa), and Poisson's ratio, ν (0.25), are the material properties. The elastic thickness in oceanic regions has values between 0 and 65 km that approximately correspond to the depth of the 450 °C isotherm (Watts, 1992). In contrast, the continents exhibit a Te range as high as 80+ km in stable regions (Watts and Burov, 2003), and as low as ~5 km in young and tectonically rejuvenated regions (Watts, 2001). A possible correlation between Te and the age of the lithosphere was studied in Europe (Pérez-Gussinyé and Watts, 2005) and Australia (Simons and van der Hilst, 2002), but most studies concluded that the age of the lithosphere is not the only controlling parameter for determining its mechanical strength. Many studies correlated elastic thickness variations with different factors including "sandwich" deformation (decoupling) when a weak ductile layer in the lower crust does not allow bending stresses to be transferred between strong brittle layers (Burov and Diament, 1995; Ratheesh-Kumar et al., 2014), "frozen" deformation controlled by lattice-preferred orientation of olivine as result of increased melt production within the upper mantle (Simons et al., 2003; Pérez-Gussinyé et al., 2009), localized brittle failure of crustal rocks under deviatoric stress (Lowry and Smith, 1995; Tassara et al., 2007; Ratheesh Kumar et al., 2010; Nair et al., 2011; Ratheesh Kumar et al., 2013), and surface and subsurface loading by large-scale tectonic features such as topographic masses and regional-scale faults (Audet and Mareschal, 2004).

In the present study, we aim to appraise spatial variations of elastic thickness along the conjugate passive margins of India and Madagascar (Fig. 1) (the Western Continental Margin of India (WCMI) and the Eastern Continental Margin of Madagascar (ECMM)). The major objective is to understand how the nature of isostasy varies

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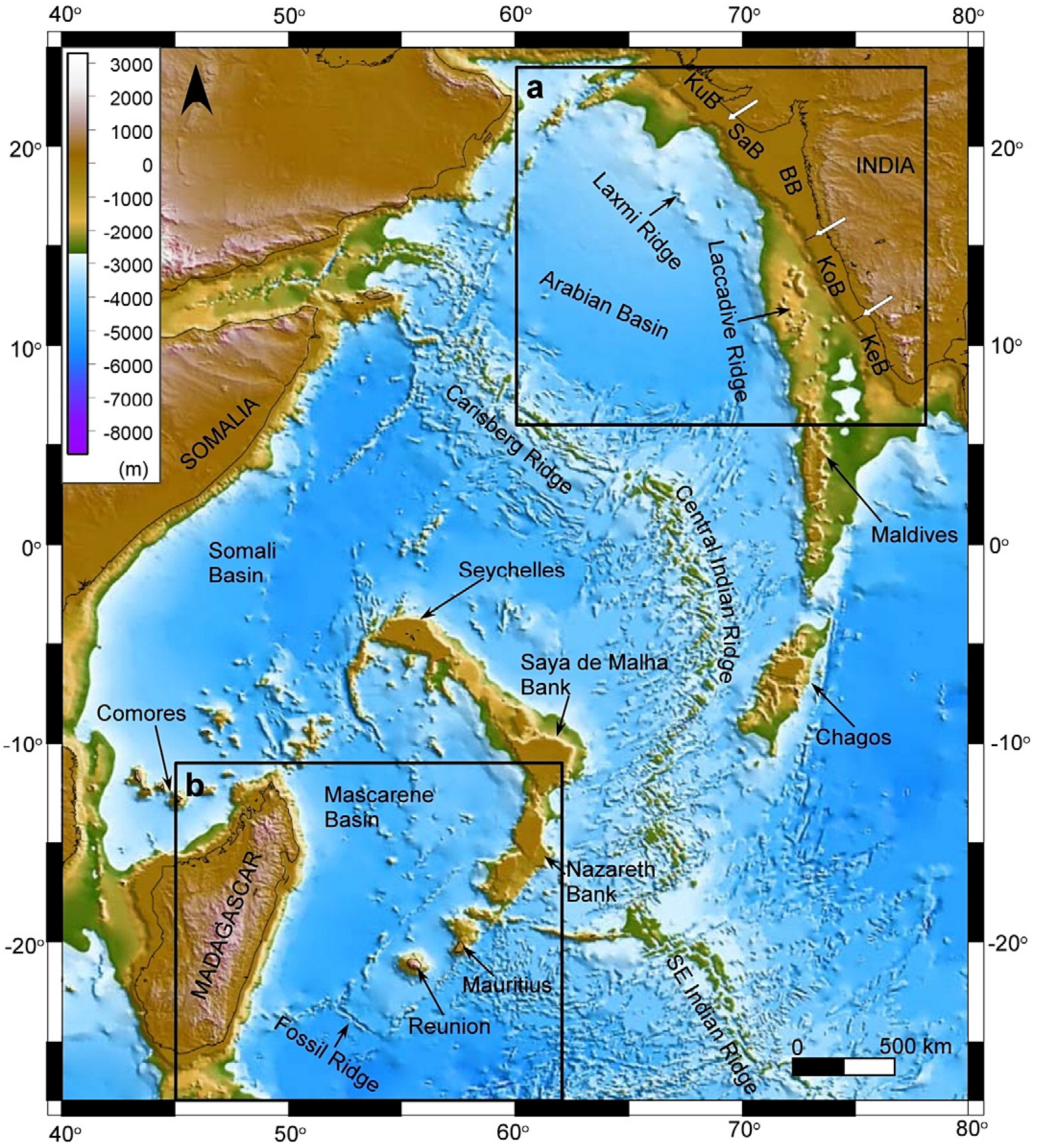

Fig. 1. Tectonic setting of the western Indian Ocean superimposed on a GEBCO (1 × 1 min grid) bathymetry map. The windows (a) and (b) represent the selected areas over the Western Continental Margin of India and Eastern Continental Margin of Madagascar respectively. Acronyms: KuB — Kutch Basin, SaB — Saurashtra Basin, BB — Bombay Basin, KoB — Konkan Basin, KeB — Kerala Basin.

along these margins, and to find any possible conjugate correlation between them. The present study can be regarded as a significant upgrade of the previous approach of Chand and Subrahmanyam (2003), which used Te estimates to examine the conjugate nature of India–Madagascar passive margins. The significance of our study relies on the fact that for the first time it brings together the spatial variations of elastic thickness and the Moho configuration in the WCMI and the ECMM. In contrast to other geophysical investigations that used seismic, gravity and bathymetry data to constrain the geometry/structure of the passive margins, by using Te variations the present study effectively maps the lithospheric deformations in the major tectonic structures along the WCMI and ECMM.

Previous studies of Te of passive margins in the world have shown variable results. Stern and Brink (1989) estimated a Te of ~19 km in the Ross Sea where rifting occurred at about 60 Ma, whereas in the Valencia trough where there is a comparatively young rift age of 20 Ma, elastic thickness estimates are ~5 km (Watts and Torné, 1992). Daly et al. (2004) computed the elastic thickness of the Irish Atlantic margin using a multitaper coherence method between scaled bathymetry and Bouguer gravity and obtained Te values of ~6–18 km. Wyer and Watts (2006) applied flexural back-stripping and gravity modeling techniques to calculate the gravity anomaly associated with rifting and sedimentation along the eastern continental margin of the USA. They iteratively compared the calculated gravity anomaly to the observed free-air gravity anomaly to derive a best-fit Te structure that shows a significant variation of $0 < Te < 40$ km, which they attributed to strength variation in the rifted lithosphere. Several studies revealed crustal thinning and depth of necking as appropriate parameters to predict the flexural response of lithospheric stretching (Braun and Beaumont, 1989; Fourno and Roussel, 1994; Ratheesh Kumar et al., 2011). Ratheesh Kumar et al. (2011) used the orthonormalized Hermite multitaper method to estimate Te along the northeastern passive margin of North America, and suggested that low-Te values were indicative of the passive nature of the margin when loads were emplaced during the continental break-up process at high-temperature gradients. Chand et al. (2001) examined the cross-spectral correlation between gravity and bathymetry along 1D profiles across the Eastern Continental Margin of India (ECMI) and its conjugate East Antarctica margin. They obtained Te ~ 10–25 km and Te < 5 km over the northern and southern segments of the ECMI, and suggested their possible match with the Te data of the corresponding congruent