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Spatial variations of effective elastic thickness over the Ninetyeast Ridge and implications for its structure and tectonic evolution

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ABSTRACT

We present new data on the strength of oceanic lithosphere along the Ninetyeast Ridge (NER) from two independent methods: spectral analysis (Bouguer coherence) using the fan wavelet transform technique, and spatial analysis (flexure inversion) with the convolution method. The two methods provide effective elastic thickness (T_e) patterns that broadly complement each other, and correlate well with known surface structures and regional-scale features. Furthermore, our study presents a new high resolution database on the Moho configuration, which obeys flexural isostasy, and exhibit regional correlations with the T_e variations. A continuous ridge structure with a much lower T_e value than that of normal oceanic lithosphere provides strong support for the hotspot theory. The derived T_e values vary over the northern (higher T_e ~ 10–20 km), central (anomalously low T_e ~ 0–5 km), and southern (low T_e ~ 5 km) segments of the NER. The lack of correlation of the T_e value with the progressive aging of the lithosphere implies differences in thermo-mechanical setting of the crust and underlying mantle in different parts of the NER, again indicating diversity in their evolution. The anomalously low T_e and deeper Moho (~22 km) estimates of the central NER (between 0.5°N and 17°S) are attributed to the interaction of a hotspot with the Wharton spreading ridge that caused significant thermal rejuvenation and hence weakening of the lithosphere. The higher mechanical strength values in the northern NER (north of 0.5°N) may support the idea of off-ridge emplacement and a relatively large plate motion at the time of volcanism. The low T_e and deeper Moho (~22 km) estimates in the southern part (south of 17°S) suggest that the lithosphere was weak and therefore younger at the time of volcanism, and this supports the idea that the southern NER was emplaced on the edge of the Indian plate.

1. Introduction

Aseismic ridges are prominent bathymetric anomalies in the deep oceans. The origin of many aseismic ridges has been well studied, because they track the long-term history of travel of a tectonic plate over a single or multiple hotspot plume. The Ninetyeast Ridge (NER) in the eastern Indian Ocean is the longest linear bathymetric high in the world (Fig. 1a). It records the northward drift of the Indian plate over a single hotspot from the Late Cretaceous to Early Oligocene. The linear ridge is oriented NNE–SSW, extends along the ninety-east meridian for ~5000 km from 34°S to 18°N (Krishna et al., 1999), and separates the Central Indian basin from the Cocos and West Australian basins. Morphologically there are three distinct domains of the NER: the northern domain (north of 5°S) where the ridge is wide and is formed by discontinuous blocks; the central domain (south of 5°S to Osborn Knoll), where the ridge becomes narrow, linear, and discontinuous; and the southern domain (south of Osborn Knoll), where the ridge becomes significantly wider and slightly less linear (Sclater and Fisher, 1974). It was Sclater and Fisher (1974), who named a broad bathymetric high on the western side of the NER as 'Osborn Knoll', which is situated in a complex terrain composed of northeast-trending ridges and deeps. On the eastern side of the ridge, the prominent east–west Wharton spreading center can be traced from a discontinuity in magnetic anomalies (Liu et al., 1983). The elevation of the ridge ranges from 2 km in the south to 3 km in the north, and north of 10°N it is buried under a thick pile of Bengal Fan sediments (Gopala Rao et al., 1997).

It is widely considered that large parts of the Marion, Kerguelen and Reunion hotspots contributed to the heating of the lithosphere, eventually resulting in the breakup of the center of Gondwana that was incorporated within the Pangea supercontinent at about 140 million years ago (Gaina et al., 2007). The travel of the Indian plate over the hotspots caused large-scale volcanic extrusions of the Ninetyeast Ridge, Rajmahal and Deccan traps. The development of these hotspots was substantiated by Jurdy and Gordon (1984) from their analysis of global plate motions with respect to hotspots. They established that the Indian plate reached an unusually high velocity of 20 cm/yr, enabled by the loss of its lithospheric root. Based on paleomagnetic measurements of samples

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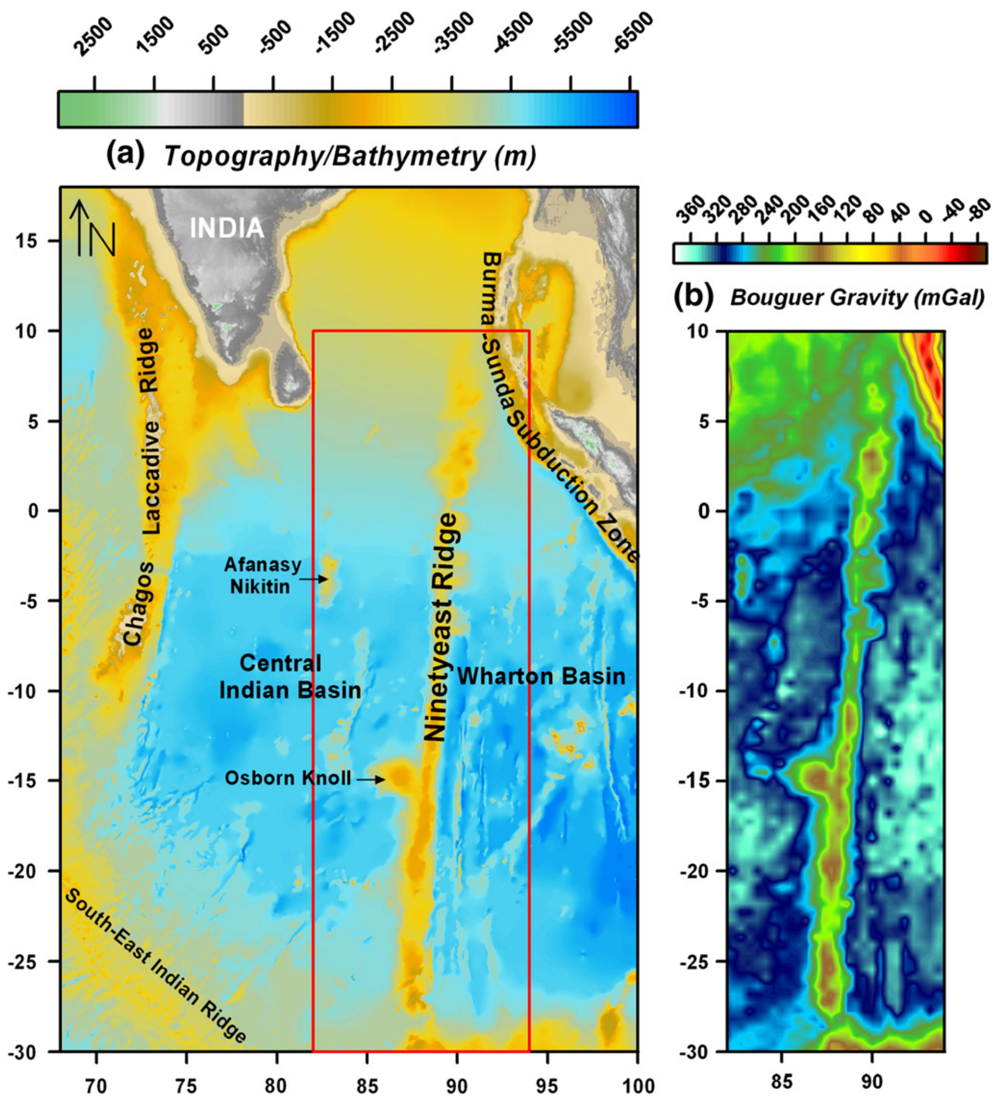

Fig. 1. (a) Location of the Ninetyeast Ridge and surrounding eastern Indian Ocean (red window, used for T_e and Moho depth estimates). The map shows the major geotectonic features superimposed on bathymetric data (GEBCO 1 × 1 minute grid). (b) Bouguer gravity anomaly map of the equivalent area.

from DSDP sites 213 through 217, Peirce (1978) suggested that the NER was attached to the Indian plate and that both drifted northward rapidly since the Late Cretaceous. Sager et al. (2010) correlated the prevailing EW-trending gravity lineaments in the seismic and bathymetric data with horsts and graben, and suggested that these transverse faults formed from the spreading ridge near the hotspot and led to separation of the Indian and Antarctic plates.

Several geological and geophysical investigations have been carried out to understand the crustal and the tectonic evolution of the NER; however, to date no unanimous theory has evolved. By analyzing the magnetic and bathymetric data in the Central Indian Basin and the Wharton basin, Royer et al. (1991) proposed that the northern part of the NER (north of 2.5°S) evolved from intra-plate volcanism within the Indian plate, that the middle segment (2.5°S to 15°S) formed at the edge of the Antarctic plate or was a short-lived platelet, and that the southern part (south of 15°S) erupted on the edge of the Indian plate. Krishna et al. (1999) investigated the emplacement history of the NER by examining bathymetric, magnetic and seismic reflection data. They suggested that the ridge north of 2.5°S was created during intraplate volcanism on the Indian plate, the segment between 2.5°S and 11°S was most likely emplaced on the edge of the Indian plate, the portion between 11°S and 17°S resulted from hotspot volcanism on-axis, and that the ridge south of 14°S formed on the edge of the Indian plate. Tiwari et al. (2003) used effective elastic thickness (T_e) to parameterize the inherent mechanical strength of the lithosphere, and suggested an evolutionary model for the NER. They obtained variable T_e results in different parts of the NER; comparatively high T_e values in the north (T_e ~ 17 km) and south (T_e ~ 22 km), and zero strength (T_e ~ 0 km) in the center. They assumed that the high T_e regions were emplaced on relatively older lithosphere through off-ridge intraplate volcanism. According to their evolutionary model, the southern segment was emplaced along a fracture zone on the Antarctic/Australian plate, and from the low T_e values in the central segment they inferred that thick underplated crust resulted from the interaction of a hotspot with the extinct Wharton spreading ridge. As apparent from the evolutionary models of Royer et al. (1991), Krishna et al. (1999) and Tiwari et al. (2003), the origin of the NER remains elusive, and thus a major reassessment of the ideas is required using better techniques available today.

Here we present high resolution maps of the lithosphere's effective elastic thickness over the exposed section (between 10°N and 30°S) of the Ninetyeast Ridge (NER), in order to understand its temporal evolution based on variations in the thermo-mechanically- and compositionally-controlled strength of the lithosphere. The effective elastic thickness (T_e) has been broadly used as a key proxy for the