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Elastic thickness structure of the Andaman subduction zone: Implications for convergence of the Ninetyeast Ridge

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ABSTRACT

We use the Bouguer coherence (Morlet isostatic response function) technique to compute the spatial variation of effective elastic thickness (T_e) of the Andaman subduction zone. The recovered T_e map resolves regional-scale features that correlate well with known surface structures of the subducting Indian plate and the overriding Burma plate. The major structure on the India plate, the Ninetyeast Ridge (NER), exhibits a weak mechanical strength, which is consistent with the expected signature of an oceanic ridge of hotspot origin. However, a markedly low strength ($0 < T_e < 3$ km) in that region, where the NER is close to the Andaman trench (north of 10°N), receives our main attention in this study. The subduction geometry derived from the Bouguer gravity forward modeling suggests that the NER has indented beneath the Andaman arc. We infer that the bending stresses of the viscous plate, which were reinforced within the subducting oceanic plate as a result of the partial subduction of the NER buoyant load, have reduced the lithospheric strength. The correlation, $T_e < T_s$ (seismogenic thickness) reveals that the upper crust is actively deforming beneath the frontal arc Andaman region. The occurrence of normal-fault earthquakes in the frontal arc, low T_e zone, is indicative of structural heterogeneities within the subducting plate. The fact that the NER along with its buoyant root is subducting under the Andaman region is inhibiting the subduction processes, as suggested by the changes in trench line, interrupted back-arc volcanism, variation in seismicity mechanism, slow subduction, etc. The low T_e and thinned crustal structure of the Andaman back-arc basin are attributed to a thermomechanically weakened lithosphere. The present study reveals that the ongoing back-arc spreading and strike-slip motion along the West Andaman Fault coupled with the ridge subduction exerts an important control on the frequency and magnitude of seismicity in the Andaman region.

1. Introduction

Long, linear, aseismic ridges are prominent bathymetric anomalies in many deep ocean basins of this globe. The origin of aseismic ridges has been much studied worldwide, because they track the long-term history and motion of a tectonic plate over a single or multiple hotspot plume. At present, many of these long, linear mountainous belts occur near subducting plate boundaries at zones of active plate collision (Rosenbaum and Mo, 2011), such as the Iquiqui Ridge (Gutscher et al., 1999b), Nazca Ridge (Pilger, 1981), Carnegie Ridge (Gutscher et al., 1999a), Cocos Ridge (Lonsdale and Klitgord, 1978), Louisville Ridge (von Huene et al., 1997), and Ninetyeast Ridge (Subrahmanyam et al., 2008). On the Indonesian active continental margin the Ninetyeast Ridge (NER) (Fig. 1) is a unique bathymetric high, and the longest linear feature in the oceans. The NER is a prominent marker of the northward drift of the Indian plate over a single hot spot from the Late Cretaceous to Early Oligocene. It is widely considered that large parts of the Marion, Kerguelen and Reunion hot spots contributed to the heating of the lithosphere, eventually resulting in the breakup of Gondwanaland about 167 million years ago (Chatterjee et al., 2013). The Indian plate records one of the most remarkable journeys of all continents, as it drifted about 9000 km in 160 million years (Chatterjee, 1992; Chatterjee and Scotese, 2010; Chatterjee et al., 2013). The Indian plate's traverse over the hot spots caused subsequent large-scale magmatic extrusions giving rise to the Ninetyeast Ridge, and Rajmahal and Deccan traps. The NER has a linear NNE–SSW orientation extending along the Ninety-east meridian from 34°S to 18°N (Krishna et al., 1999). It separates the Central Indian basin from the Cocos and West Australian

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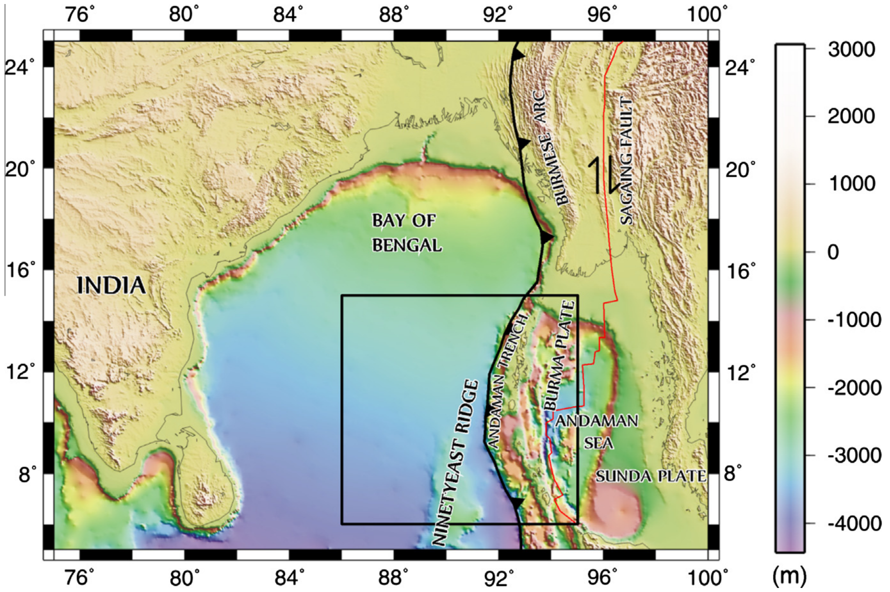

Fig. 1. Map of the northeastern India plate showing the location of the study area (inset window of size 990 × 990 km^2) and the major tectonic zones. GEBCO 1 × 1 min grid bathymetry map.

basins. The ridge is buried under a thick pile of Bengal Fan sediments north of 10°N, and the continuity of the ridge is mainly inferred from single and multichannel seismic data (Curray et al., 1982; GopalaRao et al., 1997; Subrahmanyam et al., 2008), and its elevation ranges from 2 km in the south to 3 km in the north. The northern part of the NER, where it lies close to the Andaman trench, is a complex zone of deformation within the Indian plate as indicated by a zone of seismicity paralleling the ridge (Curray et al., 1982; Subrahmanyam et al., 2008). The deformation of the Indian plate in its stable interior part is very slow (<1–2 mm/year) and behaves as a single plate (Mahesh et al., 2012). In a stark contrast, in the leading edges of the Indian plate where active subduction is taking place, the spatial variation of deformation is reasonably high as a result of discrepancy in convergence tectonics. We investigate the convergence tectonics of the NER upon the Andaman island arc-trench system with an analysis of the flexural isostatic response of the region using a square window of size 990 × 990 km (Fig. 1).

Flexural rigidity, $D \equiv E \cdot T_e^3/12(1-v^2)$, is a measure of the resistance of the lithosphere to flexure in response to loading, and it parameterizes the mechanical strength (effective elastic thickness) of the lithosphere (Watts 2001). The constants, Young's modulus, E (10^{11} Pa) and Poisson's ratio, ν (0.25) are the material properties. Effective elastic thickness (T_e) represents the integral strength of the lithosphere within limits imposed by the brittle–elastic–ductile rheology of the lithosphere (Burov and Diament, 1995). Hence, T_e can be used as a proxy to understand the factors that influence lithospheric dynamics such as thermal state, composition, geometry, and deviatoric forces (Burov and Diament, 1995; Lowry and Smith, 1995; Lowry et al., 2000). We use the Bouguer coherence (morlet wavelet) technique using satellite-derived gravity and bathymetry data to derive the spatial variation of T_e in the Andaman region. Our approach is similar to the flexural analysis in South America by Tassara et al. (2007), who used satellite-derived gravity and bathymetry/topography to estimate the elastic thickness along the continent-ocean transition over the seismically active subduction zone of the western Andean margin using a wavelet formulation (Bouguer coherence) technique. They obtained a good correlation between the pattern of crustal seismicity and the along-strike variation of T_e and the geotectonic segmentation of the active margin.

The first attempts to estimate T_e in the Indian plate were by Lyon-Caen and Molnar (1985) and Karner and Watts (1983). Using forward modeling between Bouguer anomaly and topography they obtained T_e values of 80–110 km in the Ganges basin. Free air admittance by McKenzie and Fairhead (1997) yielded low T_e values of 24 km. Using multitaper spectral analysis, Rajesh et al. (2003) characterized the relative variations of T_e in India–Eurasia collision zones, and by using transitional coherence wavelengths Rajesh and Mishra (2004) characterized the tectonic provinces. Jordan and Watts (2005) used both forward and inverse flexural and gravity modeling techniques and obtained spatially variable T_e structures of 0–125 km in India–Eurasia collision zones. Earlier investigations of flexural analysis in the NER and adjacent regions, which were carried out in spectral domain along a 1D profile or across some discrete blocks (Tiwari et al., 2003; Subrahmanyam et al., 2008), could not obtain the spatial variations of the effective elastic thickness. Furthermore, those studies were mainly confined to the exposed segment of the NER (~10°N). Tiwari et al. (2003) used free-air admittance function and obtained variable T_e results over the different parts of the NER: e.g. comparatively high T_e values in the north ($T_e \sim 17$ km) and south ($T_e \sim 22$ km), but zero strength ($T_e \sim 0$ km) in the center. They assumed that the high T_e regions were emplaced on relatively old lithosphere by an off-ridge intraplate volcanism, and suggested that the southern part was emplaced over the Antarctic/Australian plate along a fracture zone. The low T_e values over the central blocks led them to infer that thick underplated crust in the center might have resulted from the interaction of a hot spot with the extinct Wharton spreading ridge. Subrahmanyam et al. (2008) used a process-oriented approach involving back-stripping of the sediments constrained by two seismic profiles across the NER; they obtained T_e values of 1 km, 4 km, 9 km, 16 km, and 25 km for the continuous ridge model as well as the broken model. They interpreted these T_e results as evidence for emplacement of the NER onto young oceanic lithosphere close to a mid-oceanic ridge aligned along a fracture zone. Using the multitaper coherence technique Nair et al. (2011) derived uniformly low T_e values over the subducting oceanic plate in the Indonesian continental margin. Their results reveal varying flexural anisotropy that correlates with maximum horizontal stress orientation, which they attributed to the coherent and incoherent deformation of a truly anisotropic plate margin.