GEOPHYSICAL CHARACTERISTICS OF THE NINETYEAST RIDGE – ANDAMAN ISLAND ARC/TRENCH CONVERGENT ZONE

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ABSTRACT

The convergence tectonics of the Ninetyeast ridge (NER), upon the Andaman island arc - trench system is examined through an analysis of ETOPO2 bathymetry, satellite-derived free air gravity and seismic data. Oblique subduction and the buoyancy forces arising from subduction of the NER render the subduction processes near the Andaman arc highly complex. The bathymetric expression of the NER is visible up to Lat. 10°N but seismic reflection data indicate that it extends up to about Lat.17°N. The gravity anomalies are strongly positive over the exposed segment of the ridge but are subdued over the buried portion. There is a prominent break in the continuity of the trench gravity low, where the NER seems to impinge upon the island arc. Further, a strong curvilinear belt of negative anomalies just behind and running parallel to the island arc, associated with the forearc basin, is a dominant feature of the gravity map. An offset in the continuity of this strong negative anomaly occurs at about the same latitude where the NER seems to be converging upon the island arc. Seismic reflection data indicate that the NER is very close to the trench. Flexural modeling of the gravity anomalies for the subducting Indian ocean lithosphere, loaded by sediments and the NER, indicate that the NER is at the starting phase of its collision with the island arc and may not have started affecting the subduction process itself. We infer that the en-echelon block structure of the NER in the proximity of the convergent zone is a consequence of complex strike-slip and subduction related tectonic forces.

Key Words: Ninetyeast ridge, Andaman, gravity, bathymetry, seismic

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1. Introduction and tectonic setting

Basement highs of the ocean floor, such as aseismic ridges, seamount chains and others, when they converge upon subduction zones, significantly modify the subduction zone processes. The convergence of the basement highs on to the island arcs has been well studied for several regions in the Pacific Ocean (e.g.[1]). These studies indicate that the subduction processes in such cases may be affected by way of inhibition of subduction process itself, introducing gaps in volcanism and seismicity, deformation of the forearc and so on [2]. These processes are rendered more complex if the angle of subduction is oblique. Thick buoyant roots underlying the basement highs tend to flatten the subducting plate and thereby inhibit the subducting process. Subduction of such bathymetric highs may also have its own effect in the spreading processes in the back arc basin [3].

In the northern Indian Ocean, aseismic ridges such as the Ninetyeast, Investigator and others converge upon the Andaman, Sumatra and Java subduction zones respectively, but the tectonics involved in these convergence processes has received scant attention. Seismic sections indicate that the Ninetyeast Ridge (NER) lies in the close proximity of the Andaman trench system [4] but the tectonic complexities arising from such convergence process have not yet been examined. In this region, the Indo-Australian plate is underthrusting below the Burmese/(SE Asian) plates in an oblique manner. The nature of convergence varies from continental type in the Burmese arc to oceanic type in the Andaman arc. The Sumatra subduction zone is approximately oriented NW-SE, further north the Andaman subduction zone is oriented N-S, in alignment with the NER and also the direction of spreading in the Central Indian Ocean Basin (CIOB) and the Wharton basin. The obliquity and the speed of subduction also vary from south to north along the arc [5]. The present surface trace of

subduction lies at the western base of the Andaman Nicobar Ridge and the trench is filled with Bengal fan sediments.

The broad morphological features of the study area are Bengal fan sediments, Ninetyeast Ridge, Andaman Nicobar Ridge, a sharp bathymetric depression forming the Nicobar deep east of the Andaman Nicobar Ridge, forearc basin, inner volcanic arc and the Andaman backarc basin (see Fig.1). NER is a major aseismic ridge, which extends from 30°S northwards into the Bay of Bengal where it is buried beneath the Bengal fan sediments. The ridge forms the eastern limit of the Bengal fan against the Andaman arc and separates the Bengal and Nicobar fans.

The NER is a complex zone of deformation within the Indian plate and part of the ridge experienced intense seismic activity in the past [6]. The seismicity is concentrated in a zone paralleling the ridge, on its northern segment. Its northern portion (up to 10°S) is seismically more active and undergoing NW-SE compression, wherein both vertical as well as strike slip motions occur. In contrast, in the south, the ridge is far less active seismically. This transition is evident from the change in the pattern of the ridge morphology from the irregular en-echelon blocks in the north to a smooth flat-topped high further south.

The present study aims at the geophysical characterization of the convergence between the Andaman island arc-trench system and the NER. The focus is to address some critical problems such as: 1) is the NER getting subducted at the trench or slipping past the subduction zone along the trench? 2) Significance of the presence of Ninetyeast Fracture Zone (NEFZ) along the eastern flank of the NER and the complexities it can introduce to the overall subduction process and 3) the compensation mechanism of the NER from gravity forward

modeling constrained by seismic data, which will be followed by flexural modeling of the under-thrusting plate with the NER as a top load and its buoyant roots as a negative load.

2. Description of bathymetry and gravity:

The bathymetry of the study area is shown in Fig.2, constructed from the 2' x 2' ETOPO2 bathymetry data set. These are not verified against the ship borne bathymetry. Prominent features are the relief of the NER and the Andaman island arc system. The NER displays en-echelon block structure between 5°S to 10°N. Further north, continuity of the NER is mainly inferred from single and multichannel seismic data as the ridge is buried under the thick pile of Bengal fan sediments (e.g. [4,7]). East of the NER, the Andaman trench looks prominent till about 10°N, but further north, similar to the NER, the trench signature is totally lost as the Bengal fan sediments fill the trench. The Andaman forearc looks prominent in a curvilinear manner extending towards north where it merges with the topographic signature of the Burmese Arc. Along the forearc, there are pockets of isolated deeps and the forearc displays a prominent concavity between 6° - 8°N. Behind the forearc, the bathymetry increases significantly related to the development of the forearc basin. At some places, particularly between 8° – 11°N, the bathymetry is quite deep, exceeding 4000 meters, and is more prominent than the trench signature at the same latitudes. The rise in bathymetry east of this forearc basin is due to the distribution of seamounts in the Andaman sea [3,8]. To the northwest, the Bengal fan sediments display a gently rising bathymetry towards north.

The free air gravity anomaly map (Fig.3), constructed from version 15.2 satellite-derived gravity database [9], shows gravity effects of both exposed and buried structural features of the study area. The en-echelon block structure of the NER is obvious in this map

also, similar to the bathymetry, but one could notice the positive gravity anomaly of the NER extending further north up to Lat. 16°N and possibly beyond. The gravity high, in the northern half of the map, follows the trench and forearc structures, rather than displaying a N-S linearity, expected of a hotspot trace signature. While the overall structural extension as visible in the gravity map, has a N-S strike, the individual blocks of the NER seem to display a NE-SW orientation, which was noted by Petroy and Wiens [6] in bathymetry. The NER gravity trend shows a distinct offset at about 8°N latitude, where the NER gravity high seems to blend with the trench gravity low. From the gravity map, rough estimates indicate that the offset could be by as much as 100 km.

Quite unlike the bathymetry map, the trench gravity signature appears as a well-defined feature on the gravity map, even in locations where the trench seems to have been filled with Bengal fan sediments. The forearc gravity high also displays a distinctive character, but shows a prominent break in its continuity at about $7-8^{\circ}\text{N}$.

The most prominent gravity anomaly over the entire region is the gravity low related to the forearc basin where the anomaly drops below -200 mGal level. The gravity low is reflected as a curvilinear belt of negative gravity contours running close to and just behind the forearc. However, this gravity low seem to fork out with one arm of the fork continuing behind the forearc, while the other veers out and blend with the trench negative gravity anomaly in front of the Sumatra arc. The Sumatra is bounded by the gravity lows reflecting the trench low and the forearc low. Superimposed on this regional gravity feature, several pockets of gravity lows can be visualized which were probably caused by higher degree of subsidence.

2.1 NER – trench – topography and gravity profiles:

To visualize clearly the gross variations in topography and gravity as the NER converges upon the subduction zone from its deep sea setting, we have constructed a series of profiles at every half degree latitude from 5°N to 14°N as shown in Fig.4. The burial of the NER and adjacent trench under the Bengal Fan sediments becomes more visible as we progress from south to north. The pronounced topography of the NER diminishes rapidly towards north and is totally absent north of Track 10°. The pronounced positive gravity signature of the NER can however be seen almost up to Track 12° beyond which it becomes subdued. The trench topography and gravity anomalies also follow a similar trend and start losing their characteristic signatures towards north. However, the trench gravity low is visible on all the profiles, even on Track 14° where the trench topography is completely masked by the fan sediments. The forearc displays its characteristic topography and gravity highs all through from Track 5° to Track 14°. But, the forearc basin signature remains the dominant feature right through on all the profiles.

Quite unlike the Middle Americas Trench [10], we do not find any substantial shift of the gravity minima with respect to the trench axis, which indicates that the younger and more recent sedimentation processes have not significantly altered the trench axis and the associated gravity anomaly.

2.2 NER – Andaman forearc indentation signatures:

On the bathymetry map, the indentation of the NER over the forearc can be clearly seen at 7°N in the form of concavity of both the trench and the forearc topographies. On the forearc this is marked by a zone of sudden depression, with bathymetry dropping to nearly 2250 m. In

perfect alignment with this is the nosing of the NER topography contours in a NE direction, oblique to the general N-S trend of the NER. On the gravity map, the bathymetric depression on the forearc is matched by a prominent gravity low of less than -150 mGal. Surprisingly the NE-SW trend of the NER topography observed in the bathymetry map does not find a similar representation in the gravity map. Here the gravity contours display a general N-S trend but the localized peaks in gravity, particularly between $6-7^{\circ}\text{N}$, show a tendency to trend ENE-WSW.

Significantly the indentation of the NER-Andaman forearc seems to be marked by absence of volcanism (Fig.1) as well as very minor seismic activity compared to the arc segments towards north and south. The Benioff zone beneath the Andaman subduction zones at 9°N , where the NER converges upon the trench, the maximum depth of occurrence of earthquake epicenters is limited to 150 km while to its north it is 200 to 100 km and in the south they vary between 250 to 200 km [11, 12]. Incidentally, the western extreme of the Andaman backarc spreading center (ABSC) behind the forearc is situated at about these latitudes. Absence of volcanism between 6 and 9.5° is attributed to opening of the Andaman Sea [4].

2.3 En-echelon block structure of the NER:

The topography map clearly shows the en-echelon block structure of the NER north of the equator. Two distinct blocks can be visualized, one from equator to Lat. 5°N and the other, between $5^{\circ} - 9^{\circ}\text{N}$, probably separated by northeast trending faults. However, a relative eastward displacement of the topographic peaks by about 50 km can be seen. This is better reflected in the gravity map, where we can visualize an eastward shift of the axes of individual peaks of the NER in a dextral manner by about 50 km or more, as we move from south to north

(see Fig.3). These dextral shifts could be due to the combined forces of plate rotation and variable spreading/ridge push forces from the Central Indian spreading ridge, which has a similar pattern of high en-echelon faulting [13]. In fact, some of the NE trending faults defining the en-echelon blocks of the NER can be correlated to the transform faults on the Central Indian Ridge. It is also possible that the apparent increase in the width of the NER may possibly due to its spread-out as a consequence of transform motion along the en-echelon faults.

3. Seismic images of the buried NER and trench:

In northern latitudes of the study area, both the NER and the trench topographies are buried under thick Bengal Fan sediments. To get a clear picture of the relief of the NER and its proximity to the trench and also some indication of the sediments over and adjacent to the NER, we have examined six multichannel and single channel seismic reflection sections available from the northern part of the study area (location shown in Fig.3). Curray et al [4] and Gopala Rao et al [7] presented the details of the seismic sections.

The line drawings of the six interpreted seismic sections are shown in Fig.5. A notable feature of all these sections is the gentle gradient of the western flank of the NER compared to the steep slope of its eastern flank. With the exception of section Seis5, the NER has great widths of 300 km and over. The ridge rises by at least 2 to 3 km above the adjoining oceanic volcanic layer 2 reflecting its strong topographic relief. Thickness of the sediments overlying the NER shows considerable variation but is in the general range of 1.5 – 2.0 km. Similarly, the trench sediments are in the range of 2 to 6 km

Two representative seismic sections, Seis2 and Seis5, are shown in the top panels of Figs.6a and 7a. In general, the sections reveal: 1) seismic sequences and structure of sediments

of 1.5 to 2.0 km overlying the NER, 5.6 to 6.6 km on the western flank of the NER and 3.4 to 6.0 km of the eastern flank close to the trench and; and 2) morphology of the NER and the adjoining sea floor and in some cases, the relief of the forearc also. Irregular edifices and deeps characterize the NER topography. The velocity structure of the sedimentary sequences comprises, from top to bottom: 1.6 to 1.9, 2.4 to 2.7, 3.2 to 3.4, 4.5 to 4.6 and 5.2 to 5.7 km/s layers along the western flank, 1.7 to 2.0, 2.3 to 3.2 and 4.5 to 5.7 km/s of the Quaternary, Pre-Miocene and Pre-Paleocene sediments respectively over the crest of the ridge and 2.3, 2.9 and 4.8 km/s velocity along the eastern flank of the ridge underlain by basement with 6.4 km/s velocity (Fig. 7a, [4]).

The reflectors of the basal sequence in the Central Basin abutting the western flank of the ridge and the upper sequence reflectors draping the NER have helped to mark the ridge relief varying from 1.8 km to 3.0 km and its near anticline shape along its entire length. The crest of the NER consists of numerous peaks and in between sediment-filled basin. The shape and structure of the NER is affected by the flexural response of the subduction zone in addition to ridge-push forces, thus there are two effects that are summing to give basement high. The ridge dimensions and sediment thickness decrease to the south in the study area. The ridge adjoins the northern boundary of the intraplate deformation area of the Central Indian Ocean Basin in the south and has subdued relief of 1.8 km.

4. Modeling the gravity data

The availability of seismic reflection sections, good number of seismic refraction sounding points over the NER and the adjoining trench up to the basement [4], provide the necessary constraints for forward modeling of gravity data of the NER near the subduction zone and the adjoining sediment-filled trench. Seismic sections are digitized along these

profiles to obtain the relief of the NER and the thickness of the sedimentary layers and water column. Thickness of the sedimentary layer is estimated using average velocities taken from Curray et al [4], Section 1 for Seis5 and Section 2 for Seis2. We have carried out forward modeling and flexural analysis of the gravity data constrained by seismic information for these two sections.

4.1. Slab residual gravity anomaly:

In order to limit the modeling to crustal depths only, we have first removed the long-wavelength gravity effect due to the Indian Ocean lithosphere subducting below the Andaman arc, following Furuse and Kono [14]. The subducting plate geometry for these profiles is taken from Dasgupta et al [15]. An average crustal thickness of 22 km is adopted from Kumar [16]. The thickness of the subducting plate is assumed to be 75 km [15] and situated at a depth of 22 km below the crustal levels. A density contrast of 0.05 gm/cc is assumed for the lithosphere-asthenosphere transition. The computed gravity effect due to the descending lithosphere is greatest over the deepest part of the Benioff zone and decreases towards the trench and further west. The subducting plate geometry and its gravity effect along Seis2 and Seis5 are shown in the middle panels of Figs. 6a and 7a. The observed free air values are corrected for the descending lithosphere effect and the remaining anomalies are interpreted for the crustal structures.

4.2. Forward modeling of gravity data:

Forward modeling of slab residual gravity anomaly along the six profiles is carried out, using the USGS Potential Field Saki subroutine and the GMSYS software package, under seismic constraints on water/sediment thickness and NER relief.

The derived models for Seis2 and Seis5 are shown in the bottom panels of Figs.6a and 7a. The densities used for various crustal layers are shown in the models. In this modeling we have used an average oceanic crustal thickness of 7km [17]. From earlier investigations it is known that a thick crust underlies the NER by (e.g. [17,18,19]). In the present gravity interpretation we have assumed that thick crustal roots following airy isostatic compensation compensate the NER topography. The relief of the NER rising above the adjoining oceanic basement of the Bay of Bengal to the west is used in calculating the airy root thickness, adopting a density contrast of 0.4 gm/cc across the Moho. The NER topography is assumed to have a lesser density of 2.6 gm/cc relative to the crustal (2.8 gm/cc) and root density (2.9 gm/cc). The trench gravity low is accounted for by taking less dense accreted sediments filling the trench.

4.3. Flexural modeling of the subducting Indian Ocean lithosphere

A two dimensional flexural isostatic model is considered to study the effects of sediment and ridge loading of an oceanic lithosphere and its deformation under such loads in front of the subduction zone along Seis2 and Seis5. Figs.6b and 7b (top panels) show the seismo-geologic section on which the flexural modeling is carried out. In particular, we model the elastic lithosphere using the plate subduction model of Turcotte and Schubert [20].

We modeled the mechanical deformation of the subducting Indian Ocean lithosphere through different phases such as, NER loading, sediment loading and that of the overriding plate. We considered the region comprising NER and the NEFZ, which are located close to the Andaman subduction zone (Fig.1). From the interpreted seismic sections (Fig.5), we can observe that the NER and NEFZ have not reached the region of the overriding plate but lie buried under the sediments. Hence, we assume that the NER-loaded subducting plate is yet to

reach the region where the process of basal erosion of the overriding plate is taking place. In such a framework, we assume that the main factors influencing the subduction zone geometry arise from flexural rigidity of the subducting and overriding lithospheric plates, the sediment and ridge loads, and the length of the subducted slab. The subducting slab is assumed to support the overriding plate flexurally. The emplacement of the NER is analyzed for its isostatic compensation. Simple forward gravity modeling of Seis2 and Seis5 considered above shows that a root deeper than the Airy local compensation model (bottom panels of Figs. 6a, 7a) best explains the gravity anomaly. Hence, we modeled the deformation of the lithospheric plate through a step- by-step process.

This involved backstripping of sediments, layer by layer, assuming an exponential increase in flexural strength of the lithosphere [20, 21]. We assume that the Bay of Bengal is underlain by a lithosphere having a T_e of 35 km considering the average age of the lithosphere as 80Ma (A32) [17]. The sediments are backstripped assuming an exponential increase of T_e from 0 to 35 km. The two profiles considered here are separated by a distance of ~400 km. Since the region is under the influence of fan sedimentation, the sediment load is not exactly cylindrical but decreases in thickness from Seis2 to Seis5 (see Fig. 5). Since the trend is linear we assume that the effects will cancel each other and backstripping along a line represents the true unloading. The sediment-backstripped water-loaded basement (Figs. 6b, 7b) gives the configuration of the Bengal basin in the absence of any sedimentation.

The second process to be modeled is the emplacement of NER. Since the ridge could have been emplaced through fissures on a continuous plate or along a fracture zone as a broken plate, we analyzed both cases. The two morphologies of the plate considered here are only different by a factor of two if the T_e assumed is the same [20]. Since neither the exact age of

emplacement of NER nor its mode of emplacement is known, we modeled these two parameters as variables. Also, earlier studies suggest an increase of T_e during emplacement from south to north along NER [22]. But, before modeling the NER, we have to remove the subduction- related forebulge from the NER configuration. To implement this, we modeled the subducting plate assuming different configurations and found the best fit explaining the forebulge as well as the subducted portion assuming a T_e of 35 km for the total length of the Indian Ocean plate. The model predicts a maximum forebulge of 250 m at a distance of 100 km from the subduction zone (Figs. 6b, 7b). We subtracted this deflection from the backstripped crustal configuration to get the unbent/unsubducted Indian Ocean lithosphere configuration showing the actual topography of NER. Since island chain volcanism has lower density than normal oceanic crust we assumed a density of 2.6 gm/cc for the NER. Using this new basement configuration, we estimated the moho configuration for each of the models (Figs.6b, 7b). It can be observed that the flexural models with higher T_e only predict very small moho deflections that are too low to explain the gravity model. The only feasible model for the observed gravity anomaly is very low T_e during emplacement of the NER implying a weak lithosphere. Hence, we can infer that the NER is emplaced along a fracture zone near a spreading ridge. We calculated an Airy-compensated crust for the backstripped basement and added the contributions of the deflections due to NER (Figs.6b, 7b). It can be observed that the new model can explain the deepened root observed along the eastern flank of the NER which otherwise would have been seen as over compensation. The deflection plots in Figs.6b and 7b indicate that the Indian ocean lithosphere seems to respond to the loads, particularly the fan sediment load, in a normal manner, with an increase in the deflection from south to north in accordance with the increasing load towards the north which supports our acceptance of a

continuous plate model with no significant variations across the convergent zone progressing along the island arc/trench. Forearc and trench deformation seems to be centered further south between 6°-8° N.

Thus, the process-oriented modeling explains the physical phenomena and the relation to the age and effective elastic thickness of the oceanic lithospheric plate in a more realistic way. We have only considered the vertical forces acting since the horizontal forces acting on the plate are reported to be minimal. The subducting lithosphere is older compared to the southern segment along the Sumatra region and is of same age along the Java region. The Benioff zone reported for the present segment is around 200 km deep [15] and lithospheric thickness is around 75 km. Assuming 1330°C as the boundary for the lithosphere at 80 km, the secondary effects of subduction coming from phase transition (spinel to eclogite) and resistance from negative buoyancy could be only beginning to act at the end of the plate. In fact, they could be canceling each other giving an effective length of plate as 180 km. Since the ridge is still away from the overriding plate, the buckling of the two plates due to positive topography and other related secondary effects have not yet started to influence the stress pattern and subduction process under the Andaman subduction zone.

5. Discussion

The seismic records presented here establish the proximity of the NER to the Andaman trench. In some sections the eastern flank of the NER is seen buried under the trench sediments. The gravity models derived in the present study as well as those by earlier workers (e.g., [23]) indicate that thick and buoyant roots underlie the ridge. In this tectonic setting two possible scenarios can be envisaged. The first one implies that the entire NER along with its buoyant root is getting subducted along with the Indian Ocean lithosphere. In such an

eventuality, the buoyancy of the root would tend to flatten the subducting plate, inhibiting the subduction process itself and the associated back arc volcanism and seismicity. We do find from Fig.1 that volcanism is indeed absent between 6°N and 11°N. However, it should be noted that the backarc spreading center in the Andaman sea [3] is also located between these latitudes and whether the lack of volcanism is due to the spreading processes operating along the spreading center or due to the subducting process of a basement high (NER) or both, needs to be resolved. Another possibility is that the upper part of the NER (its topography) is getting obducted or accreted to the forearc while the lower part (the root material) along with the oceanic lithosphere is getting subducted. Miura et al [24] demonstrate from a seismic reflection-refraction experiment near the Solomon arc - Ontong Java Plateau (OJP) that the upper part of the OJP is getting accreted to the arc while its lower part is getting subducted. The disposition of the NER with respect to the trench as seen in the seismic sections (Fig.6), indicates that the NER is yet to reach a stage where such detachments between its upper and lower parts could be taking place. Flexural modeling of the gravity anomalies also suggests that the NER topography and its compensating roots still remain locked. Seismic data on the deep crustal structure of the NER near the subduction zone is required to resolve this issue more clearly.

The indentation signature of the NER on the Andaman forearc is clearly visible in the bathymetry and gravity maps (Figs.2 and 3). The forearc is concave towards the open sea just west of the Nicobar group of islands and clearly demarcates the forearc deformation zone. Interestingly, in this region, the two en-echelon blocks of the NER seem to veer away from the general N-S trend of the ridge and align themselves in NE-SW orientation pointing towards the deforming zone of the forearc, as earlier pointed out by Petroy and Wiens [6]. It is observed

that the present day trench axis has prominent indentation signatures at few places along the Andaman-Sumatra-Java sectors of the subduction zone. These are at 3° S (near Sunda strait); at 2° N off Sumatra; at 8°N and 15° N in the Andaman Sector. It is noteworthy that the Andaman backarc spreading center is located immediately behind this deforming zone.

This forearc deformation zone is about 200 km south of a region of large gap in the aftershock distribution of the Dec.2004 tsunami event identified by Lay et al [25]. However, CMT solutions plotted by them show a combination of both thrust and strike-slip mechanisms in the NER-Andaman forearc convergent zone of the present study.

Gahalaut et al [26] showed the simulated displacements obtained from GPS-derived coseismic slip estimates. It is rather interesting to note that stations between Lat.7°-9°N display the highest degree of displacement towards southwest, which is coincident with the NER-trench convergent zone of the present study. They note that this region of maximum slip of 15.1 m is coincident with the bend in the subduction zone, but we maintain that it is coincident with the forearc deformation zone (concave towards the open sea), which is the NER-trench convergent zone. Incidentally, this deformation zone is identified as a transverse seismic zone across the Andaman trench where the CMT solutions indicate strike-slip mechanisms [27]. Guzman-Speziale and Ni [11] noted a lack of intermediate-depth seismicity at 8°N attributable to the subduction of the buoyant NER crust forcing the slab upward. The Wadati-Benioff zone is not clearly visible and focal depths extend to depths of only 60 km beneath the sedimentary forearc [11].

General views on the NER indicate that the transform associated with its eastern flank has long since ceased to be an active plate boundary and the NER itself does not demarcate any distinct boundary between the lithospheres of the Central Indian Ocean Basin (CIOB) to its

west and the Wharton Basin to the east. In fact, Petroy and Wiens [6] argued that the seismicity patterns across the NER, both in the CIOB and the Wharton basin are similar, resulting from regional compressive stresses and that the Indo-Australia diffuse plate boundary zone encounters the Sumatra trench rather than a discrete transform zone. They argue that the NER has a very slow rate of motion of less than 3 mm/yr and that the slip on the NEFZ is just a fraction of the total convergence in the diffuse plate boundary zone of the CIOB. However, recent investigations infer that the NER represents a zone with a very high strain rate and the zone where the NER meets the trench, the predicted strain is high [e.g. [28]]. This zone seems to experience a combination of both thrust and strike-slip deformation. Deplus et al [29], from multidisciplinary geophysical investigations, argue that the NER may possibly represent a mechanical boundary zone between the two deforming ocean lithospheres of the CIOB and the Wharton basin. This may lead to the important question whether the CIOB and Wharton basin lithospheres are advancing towards the Sumatra-Andaman subduction zone as two distinct entities, which in turn may control the nature of coupling between the subducting plates and the overriding Burmese plate. Multi-wave speed seismic tomography indicates that there is a possible contrast in physical properties of the lithosphere entering the subduction zone at about 6.5°N possibly affected by the hotspot associated with the NER [30]. Socquet et al [31] state that the NER itself demarcates a diffuse boundary between the India and Australia plates and near the NER-Andaman trench intersection may comprise the India, Australia and Capricorn plates.

Focal mechanisms of earthquakes along the NER indicate strike-slip mechanisms particularly between the equator and Lat.10°N [6]. However, there is a shift from western flank in the south to the eastern flank in the north, over the en-echelon blocks of the NER [6].

The close spatial occurrence of both strike-slip and thrust solutions for earthquakes along the eastern flank of NER and the proximal trench-forearc regions [25, 27] indicates that complex tectonic forces characterize the NER-Andaman arc/trench convergent zone.

6. Conclusions

From an examination of the bathymetry and gravity maps, we conclude that the NER is probably at the initial stages of indentation on the Andaman forearc. Seismic data confirm the proximity of the NER close to the trench. The NER may be partially going down the trench and at the same time slipping northward. Flexural studies indicate that the NER and NEFZ are still some distance away from the overriding the Burmese plate causing little hindrance to the subduction process itself. Estimation of T_e values indicates that the NER is emplaced on a young oceanic lithosphere close to MOR along a fracture zone. The role of the NER in the subduction process, particularly the coupling of the subducting and overriding plate needs critical examination. The combination of strike-slip and normal thrust mechanisms for earthquakes in the convergent zone suggests partial subduction and partial shearing of the NER near the Andaman arc-trench system. The en-echelon block structure of the NER may owe its existence due to these complex tectonic forces.

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Captions for Figures:

- Fig.1. Tectonic scheme of the study area, superimposed on GEBCO bathymetry. Outline of Andaman arc-trench system, Andaman back arc spreading center (ABSC) and West Andaman Fault (WAF) are also shown [4, 32]. Short E-W lines are magnetic lineations and numbers indicate corresponding magnetic anomalies. N-S dashed lines are fracture zones identified from displacements in magnetic lineations [22]. DSDP and ODP sites with corresponding ages are also shown with open circle. Black arrow denotes plate velocity [26]. Black triangles are Quaternary volcanoes [11]. Black filled circles are Narcondam (NI) and Barren (BI) island volcanoes. Note their absence between Lat.6°-11°N. Blue star is the December 2004 tsunami event and red star is March 2005 event [25]. Earthquake epicenters and focal mechanism solutions for selected events are from NEIC, USGS and Harvard-CMT solution catalogue respectively.
- Fig.2. Bathymetry map of the NE-Andaman convergent zone from ETOPO2 database. E-W trending white lines indicate the location of profiles of gravity and topography at one-degree latitude interval (see Fig.4). Thick dashed line indicates NE-SW trending faults controlling the en-echelon block structure (encircled with black outline) of the NEA.
- Fig.3. Gravity map of the NE-Andaman convergent zone from Sandwell and Smith (1997) database. Seis1 to Seis6 are the seismic reflection sections, line drawings of Seis2 and Seis5 are shown in Figs.6a and 7a. Note the prominent negative gravity anomaly characterizing the forearc basin.
- Fig.4. Stacked E - W profiles of bathymetry and gravity. Location is shown in Fig.2. Track 6° to Track 14° denote the latitude along which these profiles are plotted. Location of the NEA, Andaman trench, forearc ridge and forearc basin are shown.
- Fig.5. Line sections of Seis1 to Seis6. Location is shown in Fig.3. Note the gentle western and steep eastern flanks of the NEA. Disposition of various tectonic elements like the NEA, trench and forearc ridge are also shown.
- Fig.6a. Forward modeling of the gravity anomalies constrained by seismic data along Seis2. Top panel shows the seismic section with seismic sequences H1 to H8 (Gopala Rao et al (1997) and the velocities in km/sec for Quaternary, Pre-Miocene, Pre-Paleocene respectively are shown. Middle panel shows the slab geometry from Dasgupta et al (2003) and its gravity effect. Bottom panel shows the derived model. Numbers indicate density in gm/cc.
- Fig.6b. Backstripping analysis along Seis2. Top two panels show the gravity anomaly and the seismo-geologic section and Q to P and Pre P are the various stratigraphic sequences from Curray et al (1982) and Gopala Rao et al (1997). The thickness of different layers are scaled corresponding to thicknesses observed in other interpreted seismic sections
- Fig.7a. Same as in 6a for Seis5; Q (Quaternary), M (Miocene), P (Paleocene) and others are the unconformities identified by Curray et al (1982).
- Fig.7b. Same as in 7a for Seis5.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6a

Figure 6b

Figure 7a

Figure 7b