Geoelectric structure in the Andaman Islands using magnetotelluric studies

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Magnetotelluric studies over the Middle Andaman islands have delineated a NNE-SSW trending suture, along which the Andaman flysch and the underlying Igneous crust subduct eastwards along a high angle thrust with a dip angle of about 60°. The Andaman flysch, which have thickness varying between 4 and 10 km are delineated up to depth of about 17 km along the observed thrust. The crust to the west of the suture has a high resistivity of more than 10000 Ω-m, as against a moderate resistivity of about 1000 Ω-m observed in the eastern part. The complex variations in its thickness and resistivity are indicative of the intense tectonic activity that this juvenile crust has experienced since the Cretaceous. The crust is underlain by a low resistivity, which could be due to the presence of fluids generated by the metamorphosis of the subducting crust and also expelled from the rocks at deeper levels. However the earthquake focal depths, extending up to about 150 km suggest that the lithosphere may be sufficiently solidified to permit strain accumulation at this depth. Thus the extent of the partial melt may be limited to about 1%.

Key words: Magnetotelluric, electrical resistivity, Andaman-Nicobar islands.

1. Introduction

The Andaman Nicobar ridge (ANR) which hosts the Andaman and Nicobar group of islands as well as several sea mounts, is a part of the regional tectonics in the adjoining Bay of Bengal and Andaman sea, resulting from the northward drifting of the Indian plate and its anticlockwise rotation subsequent to the collision with the Eurasian Plate (Curray *et al.*, 1982). This region is the transition zone connecting the Burmese Arc to the north and the Indonesian arc to the south, as shown in Fig. 1. Most of the tectonic evolution in the ANR and surroundings was initiated during the Cretaceous although the uplift of the ANR is known to have occurred much later, during the Eocene (Karunakaran *et al.*, 1968). This region is still tectonically active, as evidenced by the several earthquakes of magnitudes in excess of 8 on the Richter scale and the intense vertical movements of the islands and sea mounts witnessed here over the past about 200 years (Bilham *et al.*, 2005). It is generally accepted now that the Andaman sea is actively spreading along the transform faults with predominantly a strike-slip motion, where as most of the thrusting is observed to occur to the immediate west of the ANR (Curray *et al.*,1982 and Peter *et al.*, 1966). Peter *et al.* (1966) observe from the marine gravity, magnetic and seismic studies that most of the tectonic elements in the Andaman region extend in to the Burmese as well as the Indonesian arcs. The ANR is the outer sedimentary arc, paralleling the inner igneous arc, which passes through the Barren and Narcondam islands in the NE Indian ocean.

Several marine geophysical studies are reported over the

Bay of Bengal and the Andaman sea. However there are no systematic studies aimed at determining the structure beneath the exposed landmass, perhaps due to the poor connectivity to the islands, the inter-island transportation, as well as the dense forest cover. More importantly, the island chain extends parallel to the predominantly NS regional tectonic fabric, with very limited width of about 50 km available in the EW direction, a part of which is covered by dense forests. Thus it is not possible to identify suitable profiles transverse to the tectonic features, which are aligned predominantly along NS direction. These difficulties are further compounded by the submergence of several parts of the islands following the recent Sumatra (2004) earthquake. In view of these difficulties, the 20 km long EW profile in the Middle Andaman island, between Amkunj and the border of the Jharwa reserve forests is one of the few transects available for land based geophysical studies in the ANR region. With an intention of obtaining the geoelectric structure beneath this landmass, which may be useful in constraining the regional tectonic interpretation, magnetotelluric studies were conducted at 6 sites over this profile. Some additional sites were covered in the adjoining islands, which could be useful in the qualitative interpretation of the geophysical structure.

2. Geology and Tectonics

The tectonic processes leading to the formation of the ANR date back to the Cretaceous however, the increase in the elevation and the subsequent formation of the ANR occurred much later after the Indian Plate made its first contact with the Eurasian Plate and commenced its anti clockwise rotation, during the Oligocene-Miocene (Karunakaran *et al.*, 1968). The geology of the Middle and South Andaman islands is shown in Fig. 2, along with the locations
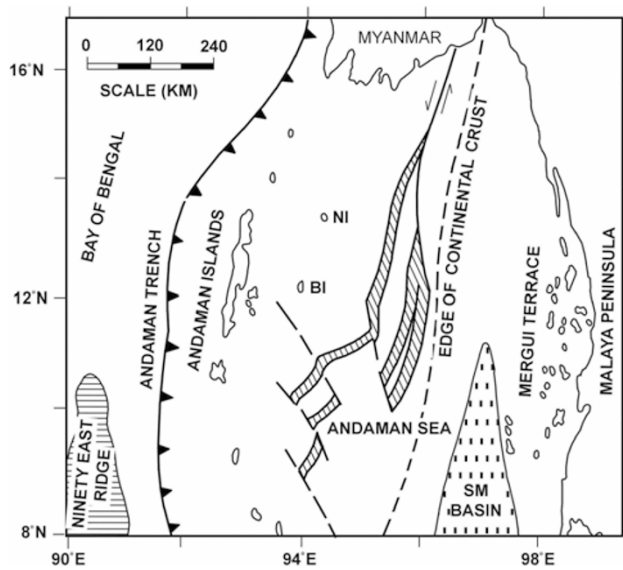
Fig. 1. Tectonic map of the NE Indian ocean (modified from Curray *et al.*, 1982). BI: Barren island, NI: Narcondam island, SM Basin: Sumatra Mergui basin.
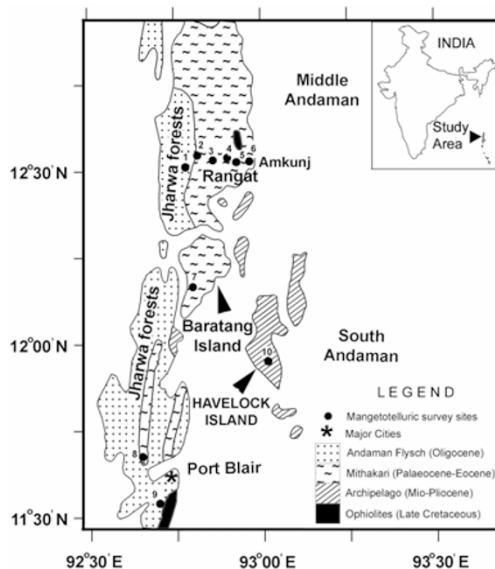

Fig. 2. Geological map of the Andaman islands (GSI, 1998), showing the location of the magnetotelluric survey stations.

of the sites occupied for the magnetotelluric data collection. All the rocks belong to the Late Cretaceous to Tertiary, with the Oligocene Flysch covering the western part and the Paleocene to Eocene sediments of Mithakari covering the eastern part. Some Ophiolites belonging to the Mesozoic–Lower Cenozoic occur in small patches in different places, mostly along the western flank, all over the Andaman and Nicobar islands.

There are no land based geophysical studies in this region. However the results, mostly on the seismic, gravity and magnetic studies are available in the ANR and adjoining region. Bemmelen (1949) suggests two arcs, the inner igneous arc running along the Barren and Narcondam islands (Fig. 1) and the outer sedimentary arc to the west, coinciding with the ANR. The inner volcanic arc connects
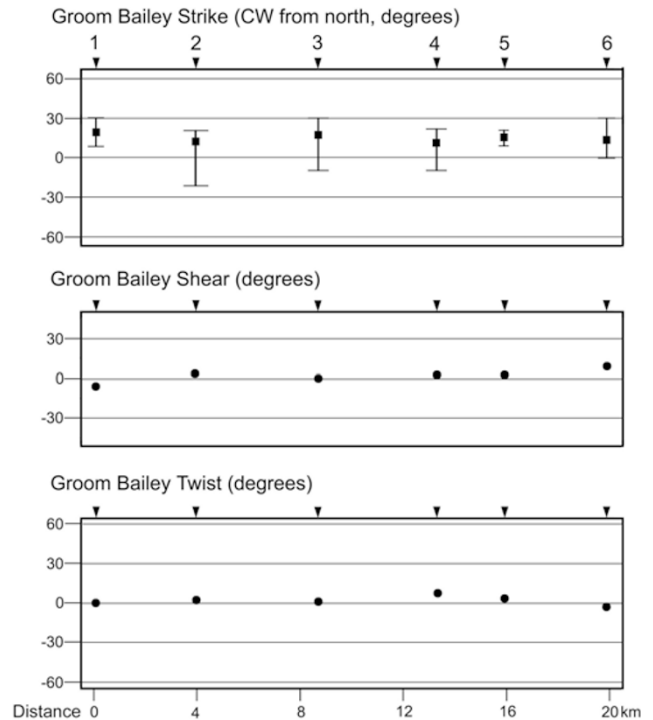

Fig. 3. Strike angles along with the constrained values of the shear and twist at the individual sites over the ANR profile.

to the Cretaceous mountain ranges of Burma and Sumatra (Peter *et al.*, 1966). Similarly the outer sedimentary arc extends in to the Simeleu and Nias island in Indonesia.

The ANR and surrounding regions are seat of intense seismic activity, caused by the eastward drifting of the Indian plate beneath the Andaman plate. The epicenters of the earthquakes are clustered predominantly along two NS aligned linear regions (Eguchi *et al.*, 1979; Dasgupta and Mukhopadhyay, 1993), one coinciding with the ANR and the other about 150 km east along the igneous arc. All the epicenters are located to the east of the Andaman trench. Most of the aftershock activity following the Great Sumatra (2004) earthquake was concentrated in the Andaman islands with a sharp cutoff at the 14°N parallel, with all epicenters located to the south of this latitude. The focal depth distribution of the earthquakes that occurred between the latitudes 12°N and 16°N (Sector 1 in Dasgupta and Mukhopadhyay, 1993) during the period, 1964–1984 are shown in Fig. 8. All the foci coincide with the east dipping thrust suggested by Mukhopadhyay and Krishna (1991) and extend to depth of about 150 km.

From the free air, magnetic and seismic studies over four profiles across the ANR and the Andaman sea, Peter *et al.* (1966) have delineated the characteristics of the various tectonic units. The inner igneous arc, passing through the volcanic regions, such as the Barren and Narcondam islands, Cretaceous orogens in Burma and Sumatra is generally associated with a positive free air anomaly and negative magnetization. This is separated from the outer sedimentary arc by a prominent negative free air anomaly. The magnetic field is relatively smooth over the sedimentary arc. All these trends are remarkably continuous over the entire region between the Sumatra arc and the Burmese arc, indicating that
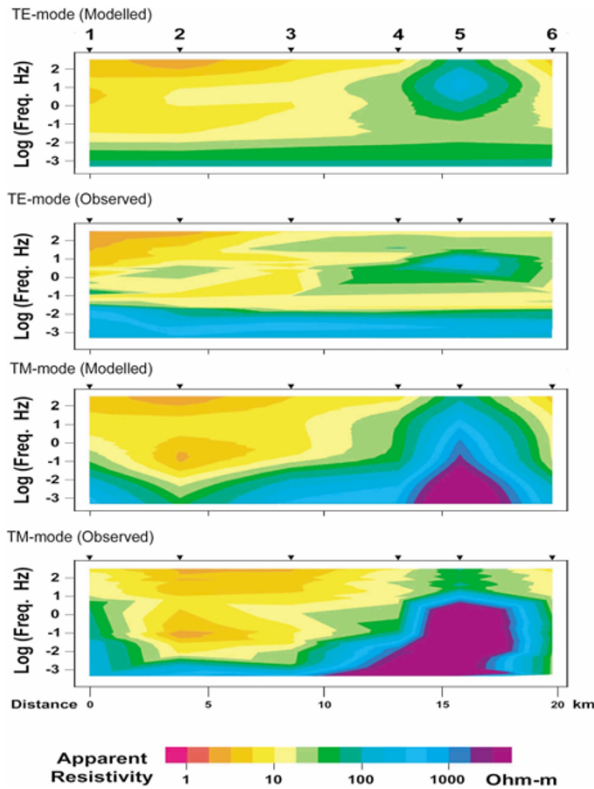
Fig. 4. Groom Bailey decomposed Apparent resistivity pseudo-sections rotated along the regional strike direction.
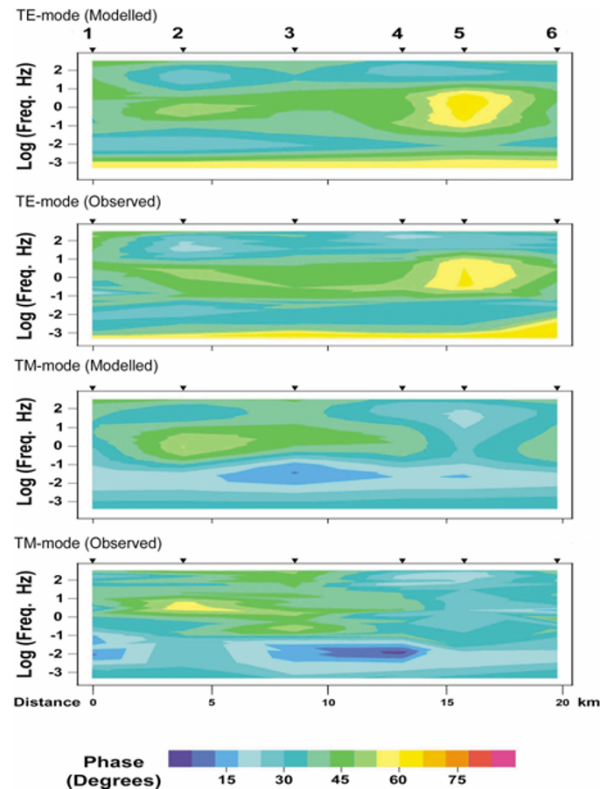

Fig. 5. Groom Bailey decomposed Phase pseudo-sections rotated along the regional strike direction.

they were formed as a result of the same set of crustal evolutionary processes.

Mukhopadhyay and Krishna (1991) from the studies of the marine gravity field over three approximately EW trending profiles in the ANR, Burma and Bay of Bengal propose a crustal cross section across the ninety east ridge and the ANR. Here, the densities of different rocks are constrained from the seismic wave velocities. The profile across the sea between North and Middle Andaman islands is in close vicinity of the MT profile discussed here and hence the relevant part of the density model over this profile is shown in Fig. 7. These authors suggest a thrust zone along the strike of the ANR along which the Igneous crust and the overlying sediments subduct eastwards to depth of about 16 km.

The ANR region was the seat of the aftershock activity following the Sumatra (2004) earthquake. In view of this fact, land based broadband magnetotelluric studies were conducted in the Midde Andaman along an EW profile between Amkunj and the eastern border of the Jharwa reserve forests. Due to the logistic difficulties caused by the dense forests as well as the inhabitation of the not so friendly tribals further west, the profile could not be extended in this region.

3. Field Data Collection

Broadband magnetotelluric data were collected at 10 sites shown in the Fig. 2, using the MTU-5A magnetotelluric system procured from M/s Phoenix Geophysics, Canada. The data collected at six sites between Amkunj and Jharwa forest (sites 1–6), located over a 20 km long EW trending profile are used here for the analysis and interpreta-

tion purpose. The impedance tensors were decomposed using the tensor decomposition scheme proposed by Groom and Bailey (1989) using the step-by-step approach advocated by Groom *et al*. (1993), where in the unconstrained values of the strike, shear and twist were obtained at each site for all frequencies. This process was then followed by constraining the twist and shear to suitable frequency invariant values by trial and error method, so as to obtain a stable, frequency invariant strike angle at each site. The shear, twist and the unconstrained strikes thus obtained are shown in Fig. 3. Here the bars on the strike indicate the distribution of the strike angles and the solid rectangles indicate the modal value at the individual sites. Most of the strike angles are along N 20°E direction within an error of about 5° and thus this was assumed to be the regional strike angle. This is consistent with the NNE-SSW strike of the ANR and alignment of the tectonic features in its vicinity (Figs. 1 and 2). The impedance tensors were then obtained along this regional strike value and the shear and twists constrained at the values shown in the Fig. 3 and a fully constrained GB decomposition was performed. The response functions (apparent resistivity and phase of impedance) with the electric field measured parallel to the strike (N 20°E) were assumed to be the TE mode values and those perpendicular to it, the TM mode values. The TE and TM responses thus obtained are shown in Figs. 4 and 5.

4. Inversion of the Data

The GB decomposed apparent resistivity and phase data shown in Figs. 4 and 5 were inverted using the two-dimensional inversion scheme (Rodi and Mackie, 2001).
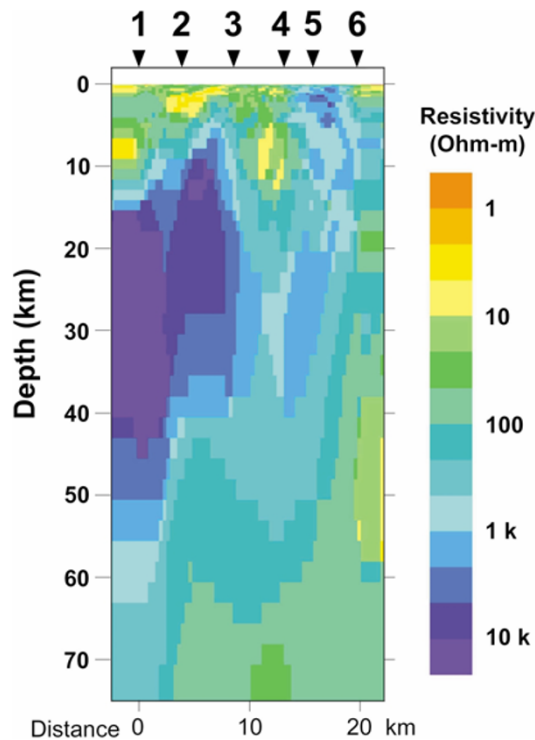
Fig. 6. Geoelectric cross section over the Middle Andaman region.

The initial model was a uniform half space with a resistivity of 100 Ω-m, which was inverted with about 200 iterations for arriving at the final model. Even after the GB decomposition, the static shift distortion caused by the shallow surface inhomogenieties, which leads to the frequency invariant up or down shift of the apparent resistivity, remains to be corrected. The phase data are not influenced by the near surface inhomogenieties. In order to eliminate the static shift in the apparent resistivity the weight of this parameter in the inversion process was decreased by increasing the errors on it by a factor of 100 at all frequencies and sites. Thus the phase data have a stronger control over the resultant geoelectric cross-section. These do not have the information on the absolute resistivity levels, which is adequately provided by the apparent resistivities even with decreased weight.

The study area is located over a long narrow ridge, (about 600 km long and 50 km wide) with the geological and tectonic strike parallel to the geoelectric strike of N 20°E obtained here. In order to study the contribution of the sea to the geoelectric model, the TE and TM data were modeled separately and compared with the model obtained using both the TE and TM mode responses, without invoking the sea. The entire exercise was repeated with a sea invoked conforming to the bathymetry available from the geology and topography map published by the Geological Survey of India (GSI, 1998). The geoelectric section obtained from the TM responses, and the sea modeled as explained earlier, was accepted as the final model and is shown in Fig. 6, with no vertical exaggeration. The choice was governed by the fact that the TM mode responses sense the vertical contrasts better than the TE mode data. Further more, the responses in the TE mode were uniformly affected at all sites by the sea parallel to the strike direction, where as, the

responses in the TM mode showed some variation albeit weak, with the distance of the measurement site from the sea. A quantitative assessment of the coast effect is made in Gokarn *et al*. (2004).

5.   Results and Discussion

The geoelectric section (Fig. 6) shows a top conducting layer to the west of Rangat (site 4) with a conductance ranging between 200 and 1000 Siemens corresponding to the Andaman Flysch. This is underlain by a 40–50 km thick crust with a resistivity in excess of 10000 Ω-m. The irregular shape of the crustal block in this region is indicative of the intense tectonic compression that this juvenile crust may have experienced since its formation during the Cretaceous, which has resulted in the eastward thrusting of this crust and the overlying Andaman Flysch at Rangat (site 4). The low resistivity feature traced up to depth of about 17 km and beyond beneath this site may thus be due to the subducting Andaman Flysch. Further east, the crust is moderately resistive (1000–2000 Ω-m) and has a depth extent of about 15 km, beyond which it is intercepted by the underthrusting western crustal block. The geology of this region shows the presence of the Mithakari sediments belonging to the Paleocene-Eocene, but these studies could not detect any sedimentary layer over the east crust. Perhaps these sediments may not have sufficient resistivity contrast with the underlying crust. The presence of the Ophiolites in patches (Fig. 2), scattered over the eastern part of the Andaman islands suggest that the oceanic crust may be exposed here with a thin sedimentary cover.

At deeper levels, the crust is underlain by a low resistivity of about 500 Ω-m. The top of this low resistivity layer is rather irregular in shape and is delineated at a depth of about 50 km at the site 1 to the west. This depth decreases to about 20 km at the site 6, which is in close proximity of about 1 km from the eastern sea. The resistivity of this layer also shows a decrease towards the east as well as at deeper levels. This layer has a high conductance of about 10000 Siemens beneath the site 6. In order to ascertain that the low resistivity is not caused by the spill over from the high conductance of the adjoining sea, the responses were remodeled with a high conductance of 10000 Siemens, which represent a 4000 m deep sea with a resistivity of 0.25 Ω-m, as against the reported bathymetry of 2500 m of the Andaman sea to the east. Even with the overcompensated sea, the resistivity structure at the deeper levels did not show any appreciable variation. It is thus reasonable to assume that the crust in the east Andaman is underlain by a low resistivity at depths as shallow as 20 km.

Several mechanisms for the occurance of low resistivity in the deep crust are discussed by Jones (1992). The deep crustal low resistivity in this region of thrusting and active subduction is likely to be related to the generation of fluids, which are expelled from the pores of the deeper rocks. The fluids generated in course of the metamorphosis of the subducting sediments could also contribute to the low resistivity (Peacock, 1990). The saline nature of these fluids leads to ionic conductivity at these depths and thus leading to the low resistivity. The ANR is in close vicinity of the igneous arc (Fig. 1), which has recently witnessed a few
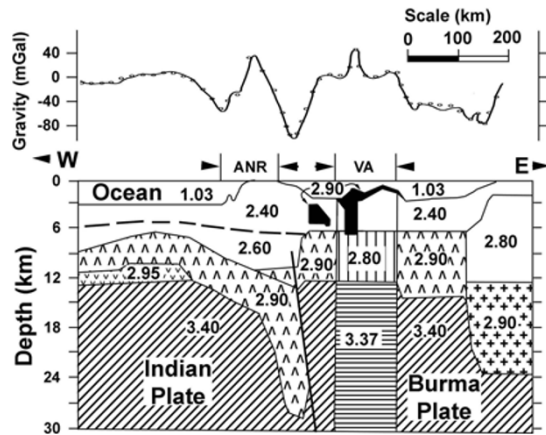
Fig. 7. Crustal section across the Andaman ridge mapped from the marine gravity studies, with densities constrained from the seismic velocities, between the Middle and North Andaman islands.
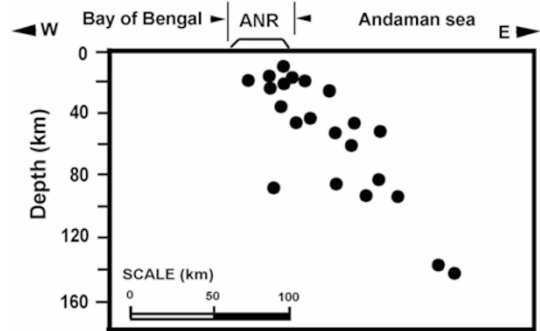

Fig. 8. Distribution of the foci of the earthquakes occurred in and around the Andaman Nicobar ridge during 1964–1984 between the latitudes, 10°N and 16°N (redrawn from Dasgupta and Mukhopadhyay, 1993).

volcanic eruptions. There are no reports on the heat flow in the ANR region. The studies (Burns *et al*., 1964) in the adjoining Andaman sea are indicative of high heat flows of 80–200 mWm^{-2}, suggestive of possible partial melt in this region. However these studies also show that the heat flow values are high only in the close vicinity of the island arc and drop to lower values sharply within short distance from it. Thus the heat flow expected in the ANR region may not be sufficiently high to warrant the partial melt.

The focal depths of the earthquakes of Richter magnitude 5 and more experienced during the period, 1964–1984, in and around ANR are shown in Fig. 8 (Dasgupta and Mukhopadhyay, 1993). These corroborate reasonably with the thrust zone proposed here. It is also observed here that some of the focal depths extend up to about 140 km, indicating that the rock masses are in sufficiently solid state to permit the strain accumulation. The possible fluid generation leading to the low resistivity zone at comparatively shallow depth of 25 km apparently contradicts this observation, because, such fluids may render the crustal rocks slippery and may not permit the strain accumulation, indicated from the seismic data. It is thus suggested that the extent of the fluids leading to the low resistivity may be limited to less than 1%, which may adequately accommodate the expected strains (personal communications, M. Unsworth and S. S. Rai, Oct, 2004). Another possibility is that the serpentinites as the possible mechanism for the low resistivity. However additional studies may be necessary before concluding the exact causes of the low resistivity in the ANR region.

The gravity studies (Mukhopadhyay and Krishna, 1991 and Peter *et al*., 1966) in the sea surrounding this region show a positive Bouguer anomaly on the eastern part of the continental shelf to the north as well as south of this NS trending island chain, which may be attributed to the thinner cover of Mithakari sediments to the east, compared to the 4–10 km thick layer of the Andaman Flysch to the west. Mukhopadhyay and Krishna (1991) have used the marine gravity data and the rock densities estimated from the available seismic velocities, for modeling the crust and mantle in the ANR and surrounding region over three different EW trending profiles in the Bay of Bengal and the Andaman sea.

The profile A-A′ of these authors passes through the sea between Middle and North Andaman islands, which is in close proximity of the MT study area. Further more, the orientation of the tectonic features is similar in the two regions and hence the relevant part of the gravity/seismic model is shown here (Fig. 7). These results are corroborated well by the present studies.

6. Conclusions

Magnetotelluric studies conducted in the Andaman Nicobar islands are perhaps the first ever geophysical studies aimed at deciphering the deep crustal structure beneath the exposed land mass in this region. The availability of sufficiently long profiles transverse to the tectonic features make this region rather unattractive for any systematic geophysical studies. However the geophysical controls available in the available land area may be of importance in understanding the crustal evolutionary processes in the NE Indian ocean region, as well as the tectonics of the Indian plate, leading to the Himalayan and Indo-Burman orogeny.

These studies have delineated a major thrust zone striking approximately NNE-SSW and dipping at more than 60° to the east, beneath Rangat in the Middle Andaman, which may be the line of suture and eastward subduction of the Indian plate beneath the Andaman Plate. The Andaman Flysch, which form the cover sequences in the western part subduct along the thrust to depth of about 17 km. The earthquake foci show a wide distribution over almost about 50 km in the EW direction, with several foci spread far in to the Andaman sea to the east, indicative of several parallel to subparallel thrust zones. This is also indicated in the lower resistivity observed in the eastern crustal block at shallow depth, which may be due to the fracturing of the crust due to the tectonic compression. It is interesting to note that despite being young formed only in the Cretaceous as a part of a fast moving Indian plate, the lithosphere in Andaman Nicobar region has solidified sufficiently to accumulate such large tectonic strains up to depths as great as 150 km as is evident from the focal depths of the earthquakes.

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