Magnetic anomalies over the Andaman Islands and their geological significance

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The Andaman Islands form part of the outer-arc accretionary sedimentary complex belonging to the Andaman–Sumatra active subduction zone. The islands are characterized by thick cover of Neogene sediments along with exposed ophiolite rocks at few places. A regional magnetic survey was carried out for the first time over the Andaman Islands with a view to understand the correlation of anomaly signatures with surface geology of the islands. The residual total field magnetic anomaly maps have revealed distinct magnetic anomalies having intermediate to high amplitude magnetic signatures and correlate with the areas over/close to the exposed ophiolite rocks along the east coast of north, middle and the south Andaman Islands. The 2D modelling of magnetic anomalies along selected E–W profiles across the islands indicate that the ophiolite bodies extend to a depth of about 5–8 km and spatially correlate with the mapped fault/thrust zones.

1. Introduction

The major morpho-tectonic elements (Weeks *et al.* 1967) running N–S along the Andaman arc are the Andaman trench, Andaman–Nicobar ridge (Andaman–Nicobar Islands), Nicobar deep, West Andaman fault (WAF), Andaman Spreading Ridge and the Mergui terrace (figure 1). The Andaman–Nicobar Islands form a major part of the outer-arc sedimentary complex that stretches nearly 1100 km along the Andaman trench-arc system (Curray 2005), and separate the Andaman back-arc basin from the Bay of Bengal. Along the western margin of the islands, the sediments of the Bengal Fan have been deformed below the Andaman trench (Curray *et al.* 1982). The Andaman arc is characterized by the presence of east dipping Benioff zone down to about 200 km depth (Mukhopadhyay 1984). Several earlier investigators have studied the structure and deformation along this active plate boundary zone (e.g., Gahalaut *et al.* 2008; Radhakrishna *et al.* 2008). According to Hamilton (1979), the Andaman arc region forms an important transitional tectonic link between the Burma–Himalayan arc/collision system in the north and the Indonesian arc system in the south. The main rock types occurring over the islands are either of sedimentary or magmatic. The magmatic rocks constitute the ultramafic plutonites and basalt, together with minor radiolarian chert, and this forms the Andaman ophiolite suite (Pal *et al.* 2003a). Owing to strong magnetization contrast between the ophiolites and sedimentary rocks, magnetic method would be an effective tool for investigating the subsurface structure of the ophiolite rocks. However, till date the gravity and

Keywords. Magnetic survey; ophiolites; magnetic anomalies; Andaman Islands; Andaman–Sumatra Arc; northeast Indian Ocean.

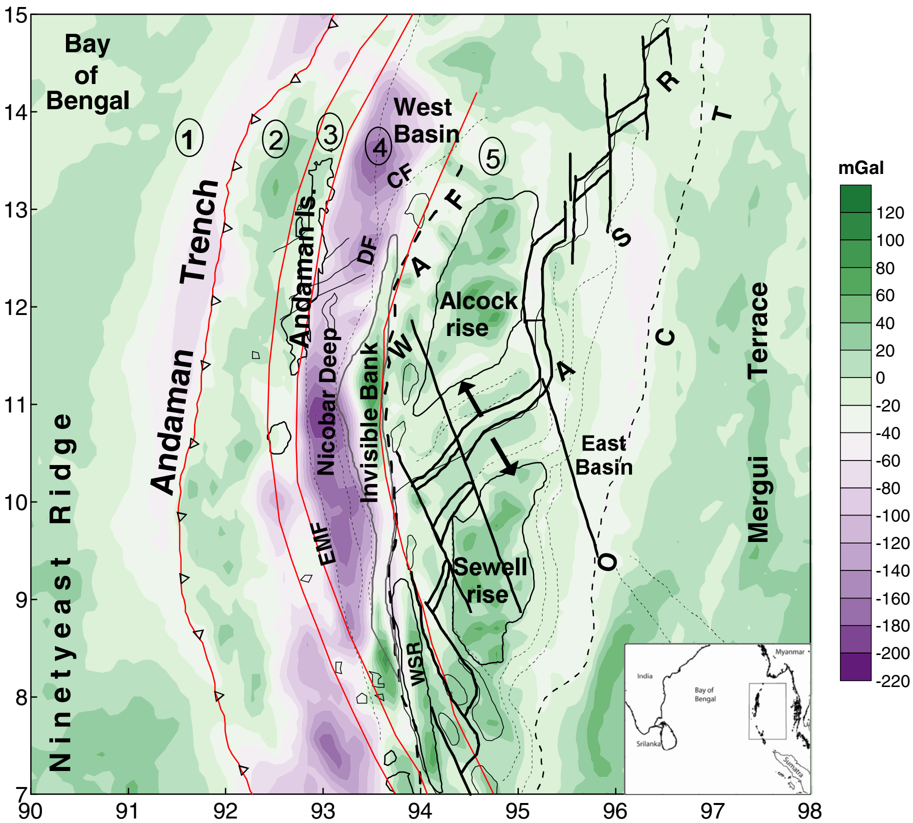

Figure 1. Tectonic map of the Andaman arc and the Andaman Sea region (modified after Curray 2005). The tectonic subdivisions of the region (after Roy and Das Sharma 1993; Kamesh Raju *et al.* 2004) are indicated in 1–5. These are: 1. Outer slope, 2. Inner slope, 3. Trench slope break, 4. Forearc basin, 5. Volcanic arc and the backarc basin, EMF: Eastern Margin Fault, DF: Diligent Fault, CF: Cocos Fault, WAF: West Andaman Fault, WSR: West Sewell Rise, ASR: Andaman Spreading Ridge (after Kamesh Raju *et al.* 2004), OCT: Ocean Continent Transition. Grey shaded area represents the extent of Burma plate (after Curray 2005).

magnetic data was not acquired over the onshore part of the Andaman Islands. So, for the first time, we carried out a detailed magnetic survey over the main Andaman Islands with an objective to understand the geometry of the ophiolite bodies in the subsurface as well as their association with the major fault systems over the islands. Salient results of this investigation are presented in this paper.

2. Geology of the Andaman Islands

The topographic shaded relief map of the Andaman Islands (figure 2a) using the Shuttle Radar Topography Mission (SRTM) database (Jarvis *et al.* 2008) reveals the sub-areal expression of the islands with many geomorphologic features and linear ridges (Narayana 2011). Regional geological mapping of the Andaman Islands was mostly carried out by the GSI and ONGC. The Andaman–Nicobar Islands have formed during the Oligo–Miocene times (Rodolfo 1969). The rock formations can be broadly classified under four major groups in the Andaman Islands (figure 2b), and they are:

(i) Cretaceous to Paleocene Ophiolite suite,
(ii) Lower to Middle Eocene Mithakhari Group,
(iii) Oligocene to Late Eocene Andaman turbidities (Andaman Flysch Group), and
(iv) Mio-Pliocene Archipelago Group (Ray 1985; Ray *et al.* 1988; Pal *et al.* 2003a; Bandopadhyay 2005).

The rock types mainly constitute serpentinites, ophiolites with radiolarian cherts, cherty pelagic limestone and the flysch sediments (Chatterjee 1967; Eremenko and Sastri 1977; Roy 1983). Two prominent N–S trending faults/thrusts have been observed over the Andaman Islands (figure 2c). Among these two, Jarwa thrust is the most significant morpho-tectonic feature (figure 2a) trending N–S all along the main islands (Eremenko and Sastri 1977), and the second important fault is the Eastern Margin Fault (EMF) in the immediate Andaman offshore along its east coast (Roy 1983). The EMF acts as a boundary between the outer-arc ridge and the fore-arc basin (Roy 1983; Cochran 2010).

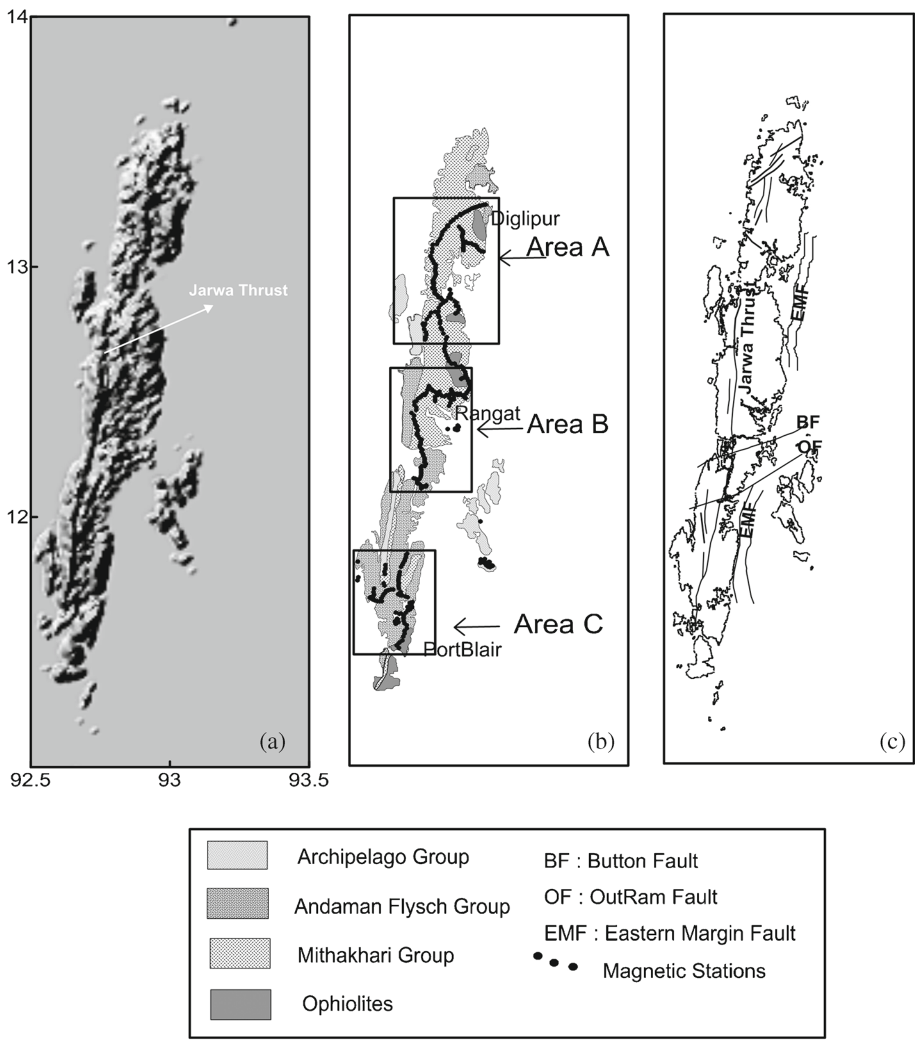

Figure 2. (**a**) Shaded relief map of the Andaman Islands from the SRTM data showing the topographic variations and prominent linear ridges, (**b**) geological map of the Andaman Islands (after Pal *et al.* 2003a) along with locations of magnetic measurement points occupied in three different phases of field surveys. The magnetic anomaly maps prepared for the three areas a–c are indicated on this map, (**c**) tectonic map of the islands and the adjoining Andaman basin region (modified after Pandey *et al.* 1992: Curray 2005).

The ophiolite rocks in the Andaman Islands are interpreted as remnants of oceanic crust and upper mantle that were obducted by complex tectonic processes during the Miocene times, and these are observed along N–S trending linear belts in structurally weak zones (Roy 1983; Acharyya 2007). The ophiolite group of rocks consisting of metamorphic, mélange and ophiolitic rocks with pelagic sediments occur as dismembered bodies (Pal *et al.* 2003a). The eastern part of Andaman Islands is characterized by highly deformed ophiolite rocks from the oceanic floor as well as ultrabasic/volcanic/pelagic sediments along with older metamorphics, whereas, in the western part, sediments belong to the accretionary prism consisting of flysch-sandstone/siltstone with conglomerates and calcareous sediments (Mukhopadhyay *et al.* 2003). Ophiolites are exposed in small isolated patches in the west, whereas, in the east, most ophiolite rocks occur in N–S to NE–SW trending bodies. These ophiolite rocks have contact with underlying sediments and denote thrust-controlled emplacement in an accretionary environment (Pal *et al.* 2003a, b). Petrographically, ophiolites consist of serpentinite, dunite, harzburgite, pyroxenite, olivine gabbro, anorthositic gabbro and gabbroic anorthosite (Dhana Raju and Negi 1984; Jafri *et al.* 2010).

3. Magnetic data acquisition and analysis

3.1 *Magnetic surveys*

As mentioned earlier, for the first time, ground magnetic surveys were carried out over the main Andaman Islands in different field seasons spanning the period February 2007–December 2009.

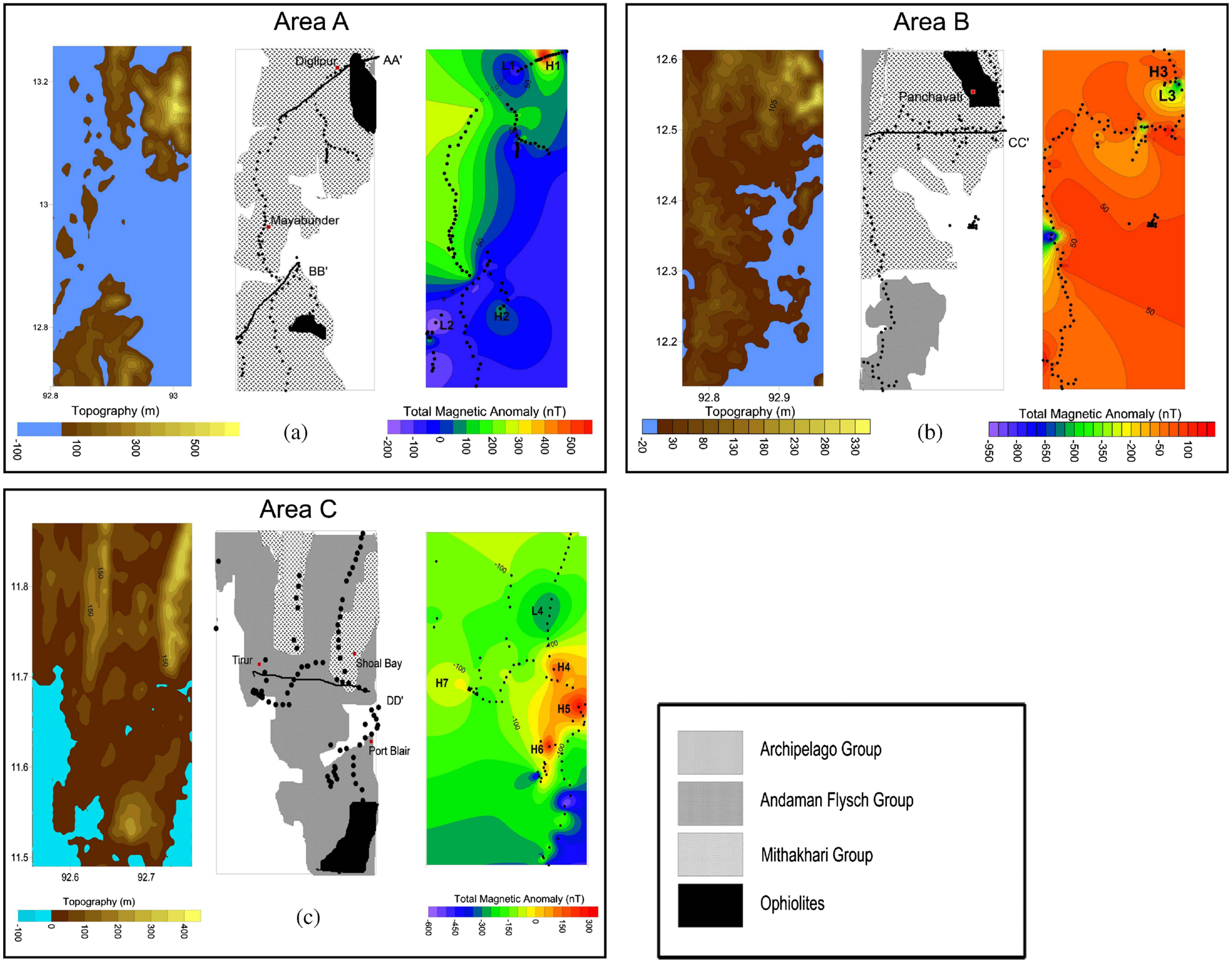

Figure 3. Topography (left panel), geology (middle panel) and the magnetic anomaly (right panel) maps prepared for (**a**) north Andaman Islands (Area A), (**b**) middle Andaman Islands (Area B), and (**c**) south Andaman Islands (Area C). Details are discussed in the text.

The total magnetic intensity measurements were made with a portable proton precession magnetometer of GEM System, Canada with a sensor height of 1.6 m from the ground. We have placed the observation points at intervals of 1000 m, and in some places, where we found bare rock outcrops of the ophiolite; the points were picked up at 500 m interval. The total field magnetic anomaly was obtained at each observation point by subtracting the International Geomagnetic Reference Field (IGRF) 2005 model (Rukstales and Love 2007) from the observed data. Diurnal variation of the geomagnetic field was corrected by using total geomagnetic intensity data computed using the Magson fluxgate magnetometer that measures north–south (X), east–west (Y) and vertically downward (Z) components at a sampling interval of 1 min. The temporary base station was established at the Department of Science and Technology (DST), Port Blair, Andaman–Nicobar Division during the survey period. A total of 418 magnetic measurements were made and the data coverage is shown in figure 2(b). Though the coverage is mainly along the N–S oriented Grand Trunk Road covering the entire island, wherever possible we have collected data along many E–W profiles as well as other minor roads. We could not collect the magnetic data in certain inaccessible areas such as the reserved Jarwa forest of the middle-south Andaman Islands.

3.2 *Magnetic anomaly maps*

The distribution of measured magnetic stations described above gave rise to three areas of Andaman Islands (see figure 2b), one in the north (Area A), second in the middle (Area B) and the third in south (Area C) having reasonable spatial coverage to prepare the magnetic anomaly maps. For these three areas, magnetic anomaly maps have been prepared along with the topography and surface geology maps (figure 3a–c). The topography of the islands vary between zero and 600 m and most of the elevated areas lie in the eastern part of Andaman Islands and correlate with ophiolite rocks. The magnetic data acquired over the islands reveal that the anomalies range between –600 and +600 nT. Details of these anomalies for the three selected areas are discussed below:

(i) *Area A: North Andaman surrounding Diglipur*

The magnetic anomalies in this area (figure 3a) reveal two magnetic anomaly highs, one over the saddle peak (H1) and the other intermediate high (H2) in the eastern part, and two magnetic anomaly lows L1 and L2 over the Mithakhari group of rocks. While, the anomaly H1 is observed over the exposed ophiolite bodies, the anomaly H2 could be related to mafic/ultramafic rocks surrounded by the obducted sediments. The topography map shows that height of saddle peak varies between 600 and 800 m.

(ii) *Area B: Middle Andaman surrounding Rangat*

The magnetic anomaly map (figure 3b) covers the middle Andaman Islands from Bartang to Panchavati area. The magnetic anomaly high (H3) is located near Panchavati over the ophiolite bodies as observed from the surface exposure. Intermediate magnetic highs in this region could be related to mafic/ultra mafic rocks within the sediments. L3 is observed in the sedimentary region.

(iii) *Area C: South Andaman surrounding Port Blair*

The magnetic anomaly map (figure 3c) in this area shows prominent magnetic low (L4) located near Shoal Bay region. The magnetic highs (H4, H5 and H6) are located over the ophiolite/mafic intrusive bodies near Chidiyatapu. Another high (H7) is located near Tirur within the sedimentary region and may be due to the localized emplacement of ophiolite body in the subsurface.

3.3 *Magnetic profiles*

Four magnetic profiles (AA' through DD') oriented in ∼NE–SW direction were selected across the islands from the anomaly maps based on the availability of dense coverage of magnetic stations and are presented in figure 4. The surface geology is also shown along these profiles for correlation with magnetic anomalies. As can be seen, the profile AA' is located in north Andaman region and passes through Mithakhari group of rocks and ophiolites. While, the magnetic signature is broader and devoid of significant anomaly variation within the sedimentary formations, towards east, over the ophiolite rocks known as the Saddle peak ophiolite hill; a distinct magnetic high is observed. The profiles BB' and CC' pass through the sedimentary region of Mithakhari group of rocks. The magnetic anomalies are broader all along the profile BB' except for minor low observed in the eastern margin. Whereas, along profile CC' which is located in middle Andaman Islands, a sharp magnetic high and low anomaly signature can be correlated with the contact between the ophiolite bodies and the sedimentary rocks. It can be seen from the surface geological map (figure 3b) that the eastern part of the profile is in close proximity to the exposed ophiolite rocks near Panchavati. On the other hand, profile DD' located in the south Andaman Islands passes through

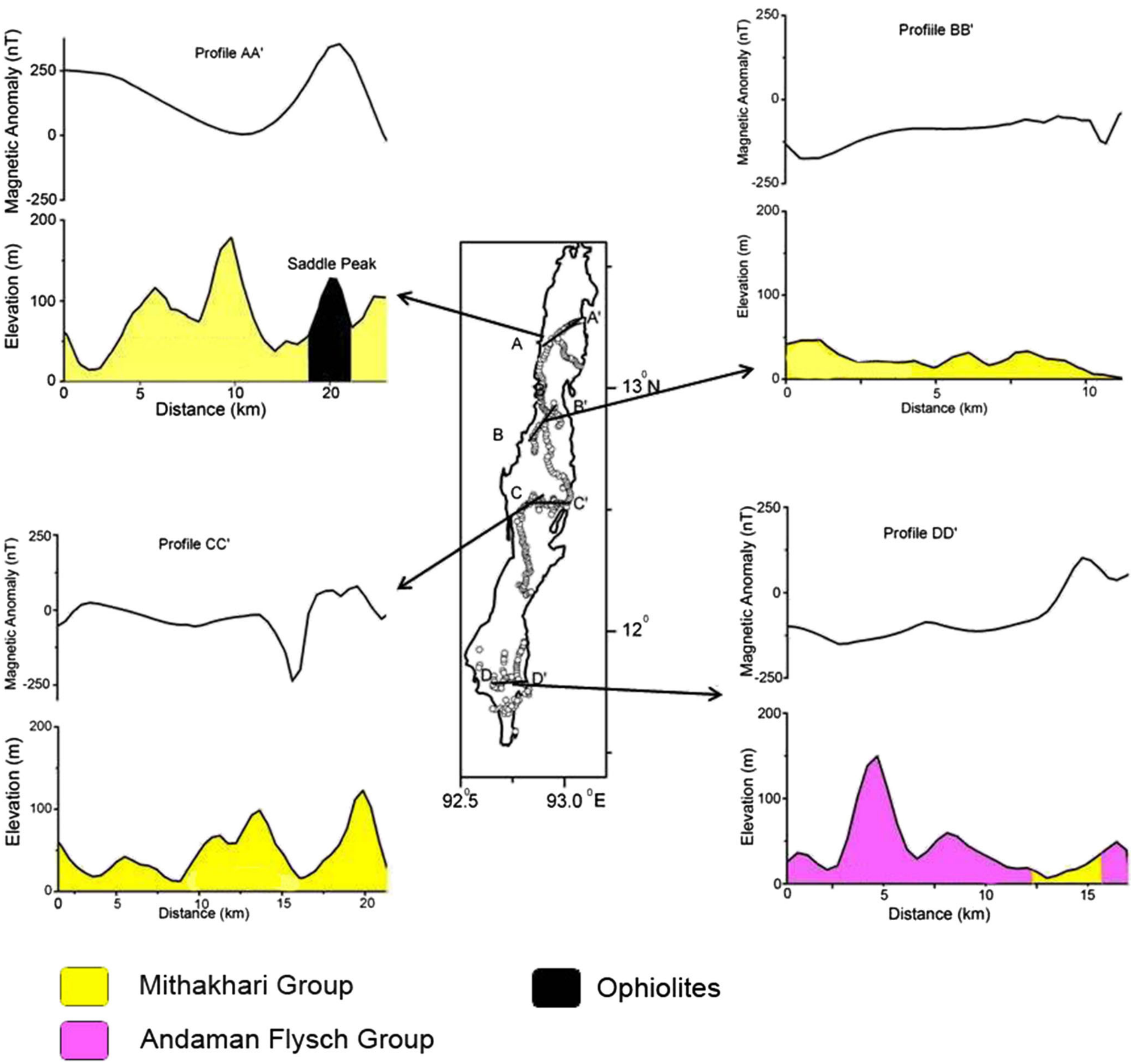

Figure 4. Magnetic anomalies plotted along four selected profiles (AA' through DD') across the Andaman Islands. Surface geology along these profiles is presented along with the topography in the bottom panel for each profile.

Andaman flysch and Mithakhari group of rocks. In the eastern part of this profile, a similar magnetic anomaly high could be related to ophiolite bodies as surface exposures are observed in and around Chidiyatapu.

3.4 *2D magnetic modelling*

From the foregoing description of magnetic anomaly maps and profiles, a clear correlation of strong magnetic anomalies can be seen associated with the emplaced ophiolite rocks over the islands. In order to delineate their subsurface geometry and magnetic characteristics, we have chosen three profiles, AA' in the north, CC' in the middle and DD' in the south Andaman Islands (figure 4) for the purpose of modelling as these three profiles show distinct anomaly correlation with the emplaced ophiolites. Profile BB' do not reveal any distinct magnetic anomaly variation, hence not considered for modelling. The magnetic anomalies along each of these profiles were modelled using the GM-SYS software, which is based on the 2D polygon method of Talwani (1965). For the purpose of modelling, the sedimentary strata and the basement structure known from Roy (1983, 1992) have been used. Based on the seismic and well correlations, two E–W seismo-geologic sections were prepared by these workers across the Andaman

Table 1. *Magnetic parameters used in the 2D magnetic modelling for the oceanic crust and the emplaced ophiolites. Details are discussed in the text.*

	Oceanic crust				Ophiolites			
Profile	Susceptibility (cgs)	Remanent magnetization (emu/cc)	Magnetic inclination	Magnetic declination	Susceptibility (cgs)	Remanent magnetization (emu/cc)	Magnetic inclination	Magnetic declination
AA'	0.004	0.005	−57	310	0.014	0.002	−61	300
CC'	0.004	0.008	−58	310	0.016	0.0065	−62	319
DD'	0.004	0.006	−57	310	0.014	0.008	−63	319

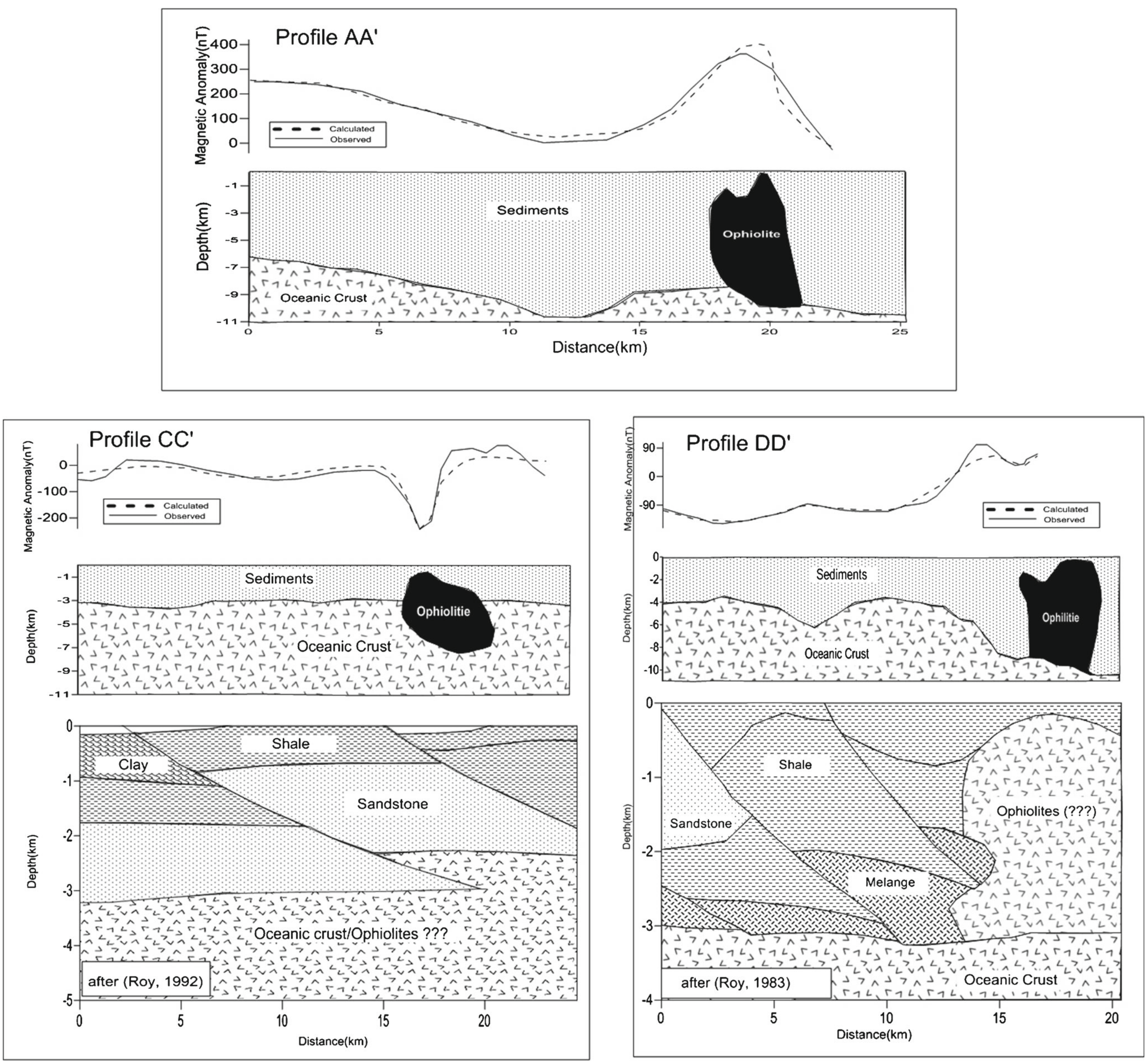

Figure 5. 2D modelling of magnetic anomalies along the profiles located in the north Andaman (profile AA'), middle Andaman (profile CC'), and south Andaman (profile DD') Islands region. The models reveal the presence of highly magnetized bodies related to ophiolites and ultramafic rocks along the east coast of Islands.

Islands, and relevant parts of these sections were projected along profile CC' (after Roy 1992) and profile DD' (after Roy 1983). The modelling is carried out along CC' and DD' by partly constraining these sections with minor modifications in order to fit the observed magnetic anomalies. Below the Andaman Islands, the basement is composed of oceanic crust (Curray 2005) with ophiolite suite of rocks emplaced along the faults or thrust sheets within the outer-arc accretionary prism. It is known that the ophiolites were emplaced as a result of scrapping of oceanic crust during late Cretaceous–Paleocene time (Roy *et al.* 1988; Pal 2011). This tectonic scenario is used for structural delineation through magnetic anomalies. For this purpose, we considered present-day age of the oceanic crust below the Andaman Islands as ∼85–90 Ma, and the age of oceanic crust (ophiolites) at the time of emplacement as ∼120 Ma. For these two ages, we obtained paleo-latitude of India (Klootwijk *et al.* 1991; Radhakrishna 2003; Radhakrishna and Mathew 2012) which then provided us the remnant magnetization (paleo inclination and declination) required for magnetic modelling. The parameters used for the modelling that include magnetization, inclination and declination are given in table 1. Magnetic anomaly highs having amplitude of about 100–300 nT have been interpreted as ophiolite/mafic rocks that are constrained to be at the ground surface/subsurface and extend to a depth of about 5–8 km. Magnetization intensities were adjusted to match the observed magnetic anomaly. High magnetization is observed in the middle Andaman Island region that could be related to mafic/ultramafic intrusions in this region. The resultant models are shown in figure 5.

4. Results and discussion

The present study clearly brought out strong magnetic anomaly signatures over the ophiolite bodies along the eastern margin of Andaman Islands and modelling of these anomalies revealed their extension to depths of about 5–8 km. The seismo-geologic sections across middle and south Andaman Islands prepared by Roy (1983, 1992) revealed an accretionary prism (outer-arc ridge) structure formed by imbricate thrusting of east-dipping fault slices (along with ophiolites intrusions); linked to westward shifting of the subduction zone. The electromagnetic induction (magnetotelluric and geomagnetic depth sounding) studies over the islands also brought out anomalous conductivity zones in the eastern part of Andaman Islands and were related to emplacement of N–S trending ophiolites (Gokarn *et al.* 2006; Subba Rao 2011).

Previous geological mapping of the Andaman Ophiolites revealed that they occur as rootless, subhorizontal bodies with overlying Eocene–Oligocene flysch sedimentary rocks uplifted and emplaced by a series of east dipping thrusts (Sengupta *et al.* 1990; Pal *et al.* 2003a; Srivastava *et al.* 2004; Ghosh *et al.* 2013). These ophiolite slices show thrust contacts with the surrounding sediments (Roy 1992). While, the ophiolites are exposed as small patches in the western part of Andaman Islands, in the east, they occur as N–S to NE–SW-trending discontinuous slices having tectonic contacts with underlying sediments indicating thrust-controlled emplacement in an accretionary environment (Pal *et al.* 2003a; Pal 2011). It is suggested that these ophiolites were emplaced as a result of subduction; ocean crust (ophiolite) of the subducting slab was scraped off and emplaced as a thrust slice. Our modelled profiles in this study support such emplacement. With continuous subduction from the Cretaceous onwards, the ophiolites were emplaced along a series of thrust slices (Sengupta *et al.* 1990; Pal *et al.* 2003a). The convergence of India and Burma during late Eocene possibly enhanced upliftment of ophiolite and metamorphic rocks and caused extensive deformation in the accreted sediments (Pal *et al.* 2003a). However, SHRIMP age data of the plagiogranites in the Andaman ophiolites gave rise to 93.6 Ma (Sarma *et al.* 2010), which suggest that arc magmatism was initiated much earlier than the Eocene accretion of the ophiolites (Sengupta *et al.* 1990). These ophiolites preserve the mantle sequence, layered ultramafic–mafic rocks, intrusive and extrusive rocks (Pal 2011). Geochemical studies indicate that the ophiolite bodies show interplay of mantle-crustal processes and were derived from a boninitic parental melt (Jafri and Sheikh 2013; Pal *et al.* 2003b). This melt represents the crystallization of ophiolites through differentiation and assimilation reactions of andesitic rich magma containing iron rich material and derived from multiple parental magmas. Thus magnetic highs are observed over ophiolite bodies. High magnetization observed in the middle Andaman region along Profile CC' may be due to highly magnetized thick mafic/ultra mafic rocks (volcanic sediments) present in this region. Dhana Raju and Negi (1984) opined that these ophiolite rocks might have been emplaced through the EMF.

5. Conclusions

Total magnetic field measurements carried out for the first time over the Andaman Islands revealed the following geological information:

(i) Magnetic anomalies are, in general, smooth in the sedimentary region, however, along the east coast of north, middle and south Andaman Islands, significantly high amplitude magnetic anomalies occur over the mafic/ultramafic cumulates of ophiolite bodies.

(ii) 2D modelling of magnetic anomalies along selected profiles across the islands indicate that the ophiolite bodies extend to a depth of about 5–8 km and spatially correlate with the mapped fault/thrust zones.

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