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Modeling of Marine Magnetotelluric Response across 85^0E Ridge: A Numerical Simulation

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ABSTRACT
85^0E Ridge in the Bay of Bengal region is one of the most interesting and enigmatic geotectonic features in the Indian off-shore region with its surprisingly low free-air gravity anomalies. As the marine field studies are highly expensive, it is proposed here, to simulate Marine Magneto Telluric (MMT) response across this ridge to estimate the resolvability of layer parameters like thickness and resistivity followed by period band to penetrate the signal to the desired depth using forward modeling. Similar to land MT measurements, the MT data acquired in the marine environment also gets distorted due to coast effect. In order to derive this response, a synthetic initial model has been considered which extends to 800 km on either side of the coast line and down to 600 km depth with a water column of 4 km. A finite element algorithm has been utilized to accommodate inclined continental shelf in the numerical model. In the period range of 40-4000 sec, Ridge response is well reflected in the apparent resistivity, phase, magnetic field components (Hx, Hy), and Tipper in TE and TM modes, whereas electric field components (Ex, Ey) are less pronounced. The present study reveals that the distortion in MMT responses due to coast effect is noticeable up to 200 km from the sea-land boundary for periods between 10 and 4000 sec. As the 85^0E Ridge is located at a distance of 500 km from the coast, the MMT measurements made here are free from coast effect. Data needs to be acquired for a period of at least 8 days to get more than 10 stacks of 4096 sec and therefore for better results.

Key words: 85^0E Ridge, Magnetotellurics, Finite elements, Marine Electromagnetics, Coast-effect, Northeastern Indian Ocean.

INTRODUCTION

The 85^0E Ridge is an enigmatic and aseismic volcanic feature located in the northeastern Indian-Ocean which covers from Mahanadi basin in the north to the Afanacy Nikitin Seamount (ANS) in the south. This North-South oriented ridge extends from 19^0N to 6^0S in a curvilinear shape (Figure 1). The northern part of the ridge is covered by thick pile of Bengal Fan sediments where as in the south it joins the ANS at 5^0S through isolated buried hills raised above sea level (Curray et al., 1982; Liu et al., 1982; Curray and Munasinghe, 1991; Muller et al., 1993; Gopala Rao et al., 1997; Subrahmanyam et al., 1999; Krishna, 2003; Krishna et al., 2014, Shreejith et al., 2011). Two volcanic features in the Bay of Bengal (BOB) are 90^0E Ridge and 85^0E Ridge and the crustal age of BOB is early Cretaceous. From the geological and geophysical data sets it is inferred that 90^0E Ridge is the result of post-outburst phase of Kerguelen hotspot (Duncan and Richards, 1991). But understanding the evolution of 85^0E Ridge is still a complex problem with the abnormal geophysical responses recorded over it.

Therefore additional geophysical evidences like those from Marine Magneto Telluric (MMT) investigations, which are essentially Electromagnetic (EM) induction techniques, can help resolving the problem. Globally MMT technique has been developed and used for delineating resistivity structure in the offshore region (Constable et al., 1998; Key and Constable, 2002; Baba, 2005; Heinson et al., 2005; Kasaya et al., 2005; Constable et al., 2009; Baba et al., 2010). In the Gulf of Kutch region of western India Harinarayana et al., (2008) had conducted MMT investigations and delineated the resistivity structure.

Origin and Evolutionary history of 85^0E Ridge

Curray and Munasinghe (1991) proposed that the trace of Crozet hotspot is the representation of 85^0E Ridge and ANS formed between 117 and 70 Ma but the geochemistry of the ANS and Crozet hotspot do not match together. Later Muller et al., (1993) proposed that another hot spot, which is located underneath the eastern Conrad Rise on the Antarctic plate, is the cause of formation of 85^0E Ridge. On the basis of geophysical studies, it has been inferred that the 85^0E Ridge formed due to the short lived volcanic activity during the late Cretaceous had later joined with the already existing ANS during late Paleocene (Figure 1). Recently, Bastia et al., (2010b) also favored that the ridge formation is due to the hot spot activity, but the source of the volcanism is unknown. According to Krishna (2003), the thick pile of Bengal fan sediments caused the compactness of the underlying material as well as basement rocks and the properties of all the rocks changed. When the

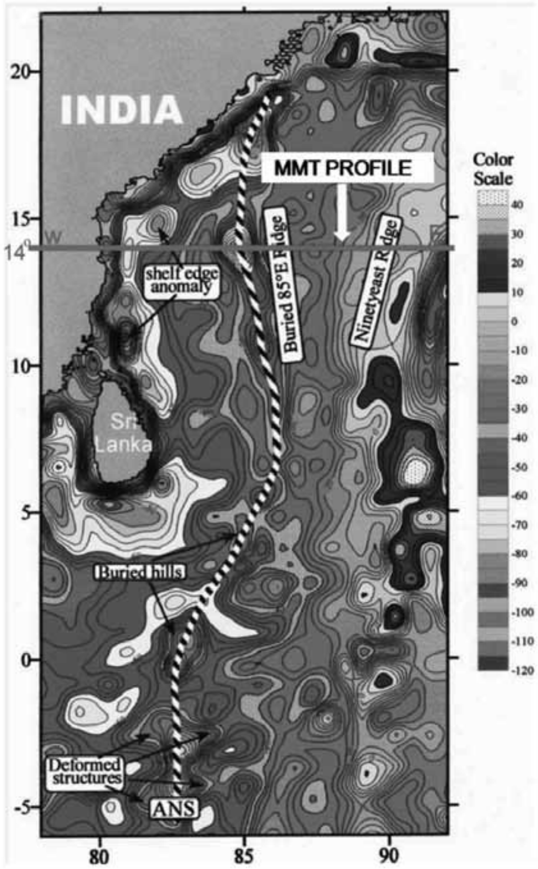

Figure 1. Marine Magnetotelluric (MMT) Profile along 14^0N latitude plotted over free-air gravity anomaly map of the northeastern Indian Ocean across the 85^0E Ridge. Curved line indicates the continuity of the 85^0E Ridge, isolated buried hills and Afanacy Nikitin Seamount (ANS) (after Krishna, 2003).

volcanic activity had taken place, the overlying sediments transformed to metasediments with more compactness than the ridge material which was at higher temperature. Here the situation is that the lower density ridge material is overlaid by higher density metasediments, showing negative free-air anomaly where as in the case of ANS absence of metasedimentary cover might be the cause for the positive free-air anomaly. He also adds that the ridge was formed in the intraplate tectonic system when the lithosphere underneath is about 35 Ma.; the formation of ANS and oceanic lithosphere taken place simultaneously and later on the ANS activated in Paleocene by the hot spot forming the 85^0E Ridge and elevated above sea level. The deformation activity like erosion and subsidence on the ANS caused the northern and southern parts to disappear and buried.

Structural features and Bathymetry in Bay of Bengal

Bay of Bengal (BOB) is the largest in size (Gopala Rao et al., 1993) and one of the largest sedimentary basins in the world which forms the northeastern part of the Indian Ocean. It lies between 22^0N - 7^0S latitudes and 80^0E - 93^0E longitudes. BOB is bordered by India and Sri Lanka in the West, Bangladesh in the North, Myanmar and Andaman Nicobar Islands in the East. The two prominent structural features in the BOB are 85^0E Ridge and 90^0E Ridge. These structural features are covered by thick pile of sediments brought by major rivers (e.g. Godavari, Mahanadi, Ganga, Brahmaputra etc.) and deposited during the pre- and post-collision of India with Asia. The continental margin is characterized by a very narrow (150-200 m) zone (Kader et al., 2013), continental shelf followed by a steep continental slope and deep abyssal plains with smooth topography (Curray et al., 1982). The thickness of the water column in the northern end of BOB is small and depth to sea bed occurs at less than 2000 meters. Bathymetry in the central BOB is relatively flat and having a water column of ~3000 meters (Figure 2). Sea floor gradient increases from north to south (Sarma et al., 2000). The bathymetry along 14^0N latitude and cutting across 85^0E Ridge is also shown in Figure 2.

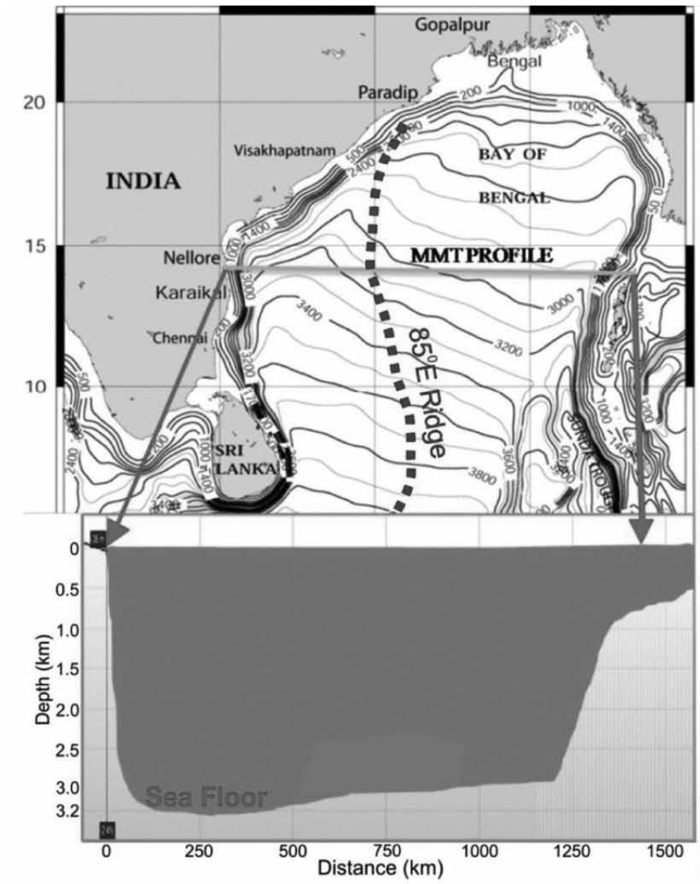

Figure 2. MMT profile across 85^0E Ridge plotted over detailed physiographic map of the Bay of Bengal using bathymetry data. Contour interval is variable up to 3000 m water depth. Bottom panel shows the variation in sea water thickness along the profile.

Earlier Geophysical Investigations

Many geophysical investigations (Bathymetric, Gravity, Magnetic, Seismic reflection etc.) were carried out to estimate the physical parameters of the 85^0E Ridge (Figure 3a-d), which are in turn useful to predict the past geodynamical history of ridge formation and tectonic evolution. From the free-air gravity anomaly map, the 85^0E Ridge appears as a strong curvilinear zone of negative gravity anomaly of about -80mgal surrounded by two small peaks of positive gravity anomalies (Figure 3b). The anomaly is discontinuous in its N-S strike, wider (120km) in the north (of 14^0 N) and narrower (40km) in the south (Choudhuri et al., 2014). Further North (15^0N to 16.5^0N) the ridge is not well pronounced. Again its signature appears from 17^0N and extends up to 19^0N. Presence of the Ridge is identified in Mahanadi basin recently by using high quality seismic reflection data (Bastia et al., 2010a). The southern part of the ridge from 11^0N to 2^0N takes maximum curvature and joins straight with ANS. The negative anomaly becomes positive from south of 5^0N to the ANS (Shreejith et al., 2011; Choudhuri et al., 2014).

The magnetic anomalies are asymmetric over the 85^0E Ridge. Alternative positive and negative magnetic streaks are distributed throughout the ridge (Figure 3a). According to Michael and Krishna (2011), the ridge was formed during the rapid changes in earth's magnetic field. During Cretaceous period, oceanic crust formed under the super long normal polarity phase. But the ridge was formed when the polarity of earth's magnetic field reversed from positive to negative. The cause for the alternative magnetic streaks could be due to the ridge topography and polarity contrast between the oceanic crust and ridge material. From the magnetic dating by Michael and Krishna (2011), the ridge formation is supported by the hotspot volcanism by using the distributed normal and reversed magnetization patterns which resembles changes in the Earth's geomagnetic field polarities related to magnetic chrons; and also that the formation of the ridge started at ~80Ma in the Mahanadi basin and finally ended in the vicinity of the ANS at ~55Ma.

On the basis of seismic reflection surveys, Michael and Krishna (2011) have identified two phases of depositional sedimentary sequences over the 85^0E Ridge, i.e., pre-

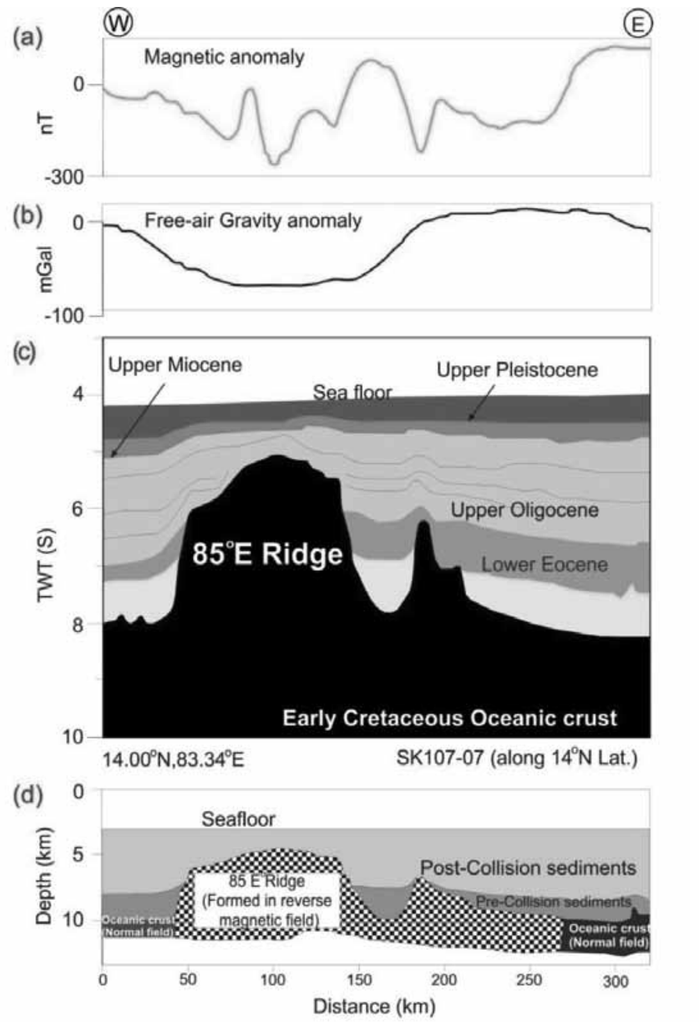

Figure 3. (a) Magnetic anomaly, (b) Free-air gravity anomaly, (c) Interpreted Seismic reflection data along 14^0N Latitude running from Eastern margin of India to Andaman Islands and (d) Crustal section derived from magnetic data (after Michael and Krishna, 2011).

collision and post-collision between India and Asia (Figure 3c,d). During the pre-collision time (end of Cretaceous) the Mahanadi and Godavari rivers deposited the sediments over the ridge. And here the lower Eocene boundary makes the margin between these two. There after collision had taken place and the sediments deposited are from the Ganga and Brahmaputra rivers. The thickness of the sedimentary column decreases from north to south. They recorded the two-way travel time (TWT) of sediments at different latitudes along 15.5^0N, 14.64^0N, 14^0N, 13^0N as 2.4s, 2.8s, 0.8s, 1.7s respectively. The pre-collision metasediments have attained higher velocities and densities due to the greater depth and age than the post-collision sediments. According to Shreejith et al., (2011), the negative free-air gravity anomaly observed over the 85^0E Ridge could be explained by the combination of (i) flexure at the Moho boundary, (ii) high density metasedimentary rocks on either side of the ridge and (iii) thick pile of low density Bengal fan sediments over the ridge.

Origin and evolution of the 85^0E Ridge has been evaluated by different authors on the basis of geophysical and tectonic signatures. Ramana et al., (1997) have proposed two concepts for the evolution of the ridge. They are: i) due to the stretching and compressional forces acted on the lithosphere during the major plate reorganization at the time of K-T superchron, which might have led to shearing of lithosphere, and/or ii) due to horizontal compressional forces acting on the passive continental margin leading to the sagging followed by deformation produced by the buckling instability of the oceanic plate. Krishna (2003) believes that the ridge was formed in the intra-plate setting due to the hotspot activity. Based on the ridge magnetic pattern and the geomagnetic polarity time scale, Michael and Krishna (2011) opined that the

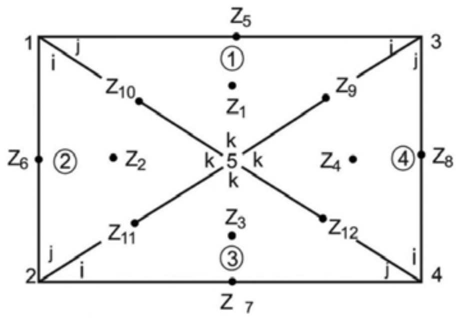

Figure 4. Triangular and rectangular elements, their ordering conventions and evaluation points (after Wannamaker et al., 1987) used for finite element modeling. Z1-Z4 correspond to depths to the centroid of each triangle, Z5 - Z12 represents depth to the boundary midpoint, Nos. 1 – 4 are triangular elements and i, j, k triangular element nodal labels.

ridge was formed in the Mahanadi basin at ~80 Ma by the short lived hotspot activity and continued southwards and ended in the vicinity of the ANS at ~55 Ma. Recently Choudhuri et al., (2014) proposed that the Indian plate moved over the hotspot and the material from mantle rose up to the sea surface and caused the bulge in lithosphere. The eruptions initially took place on the continent and moved to proto oceanic crust and finally to oceanic crust. This causes the development of depocentres which favors the sediment deposition. As the plate motion continues towards north, the volcanic foci moved further south and younger volcanic foci formed in its trail. The negative gravity anomaly observed over the 85^0E ridge, has been attributed to continental origin as in case of Laxmi Ridge in the Arabian Sea (Shreejith et al., 2011). But they also mentioned that there are many limitations in explaining the other aspects like NW-SE oriented oceanic fracture zones delineated in the western basin, which obliquely cut the 85^0E ridge.

The diversity of concepts put forth from earlier studies can be resolved by integrating with MMT data which gives the resistivity variation in the vicinity of the ridge. Prior to taking up highly expensive data acquisition in the marine environment, MMT forward modeling has been initiated over the ridge in the present study to determine the resolvability of different ridge parameters. The modeling is carried out using the finite element solution (Wannamaker et al., 1987) which has some advantages over the usual softwares currently in use.

Two dimensional modeling

Wannamaker et al., (1987) program is a stable finite element algorithm for 2-D Magnetotelluric modeling which solves directly for secondary variations in electrical and magnetic fields. In general, while computing for total fields, the finite element programs produce erroneous numerical results at low frequencies. However, this inaccuracy is more severe for transverse magnetic results (TM) as compared to Transverse electric (TE). The present program overcomes such a difficulty with numerical accuracy at lower frequencies as it computes the secondary field variations. The equations are solved using the approximation that there is no change in the primary field within each triangular area (depths Z1 - Z4), as shown in Figure 4. Once again, the primary field has been considered as constant along the boundary of each triangular element and is calculated at mid-points of the boundary (depths Z5 – Z12) as shown in Figure 4.

Mesh Design

In the present study, a finite element mesh has been utilized to calculate the secondary field variations (Coggon, 1971) at low frequencies as it gives better values as compared to total field (Wannamaker et al., 1987). The mesh design is comprised of rectangular elements, with constant column width and row heights in a given rectangular cell (Figure 4). Again the rectangular element is divided into four triangular elements within each of which the impedivity and admittivity are constant. Such a construction through triangular elements, allows us to consider the sloping boundaries, like continental shelf, in the simulating model. The unknown secondary fields parallel to strike are calculated by piecewise linear functions defined over each triangular sub region. The field is specified using three linear shape functions whose amplitudes are unity at one node and zero at other two nodes. The primary field is constant within each triangular element and it is evaluated at the centroid of each triangular area. The evaluations of triangular cells are in anti-clock wise direction in which Z1 is the first and Z4 is the fourth triangular cell.

In general, Dirichlet's boundary conditions are applied at all mesh boundaries for solving the magnetotelluric problems. By convention, on the left hand side earth layering has been considered as the host layering for the remaining anomalous conductivity medium. Zero boundary conditions have been applied for the left side as its edges are located at large distances from the anomalous zone. In

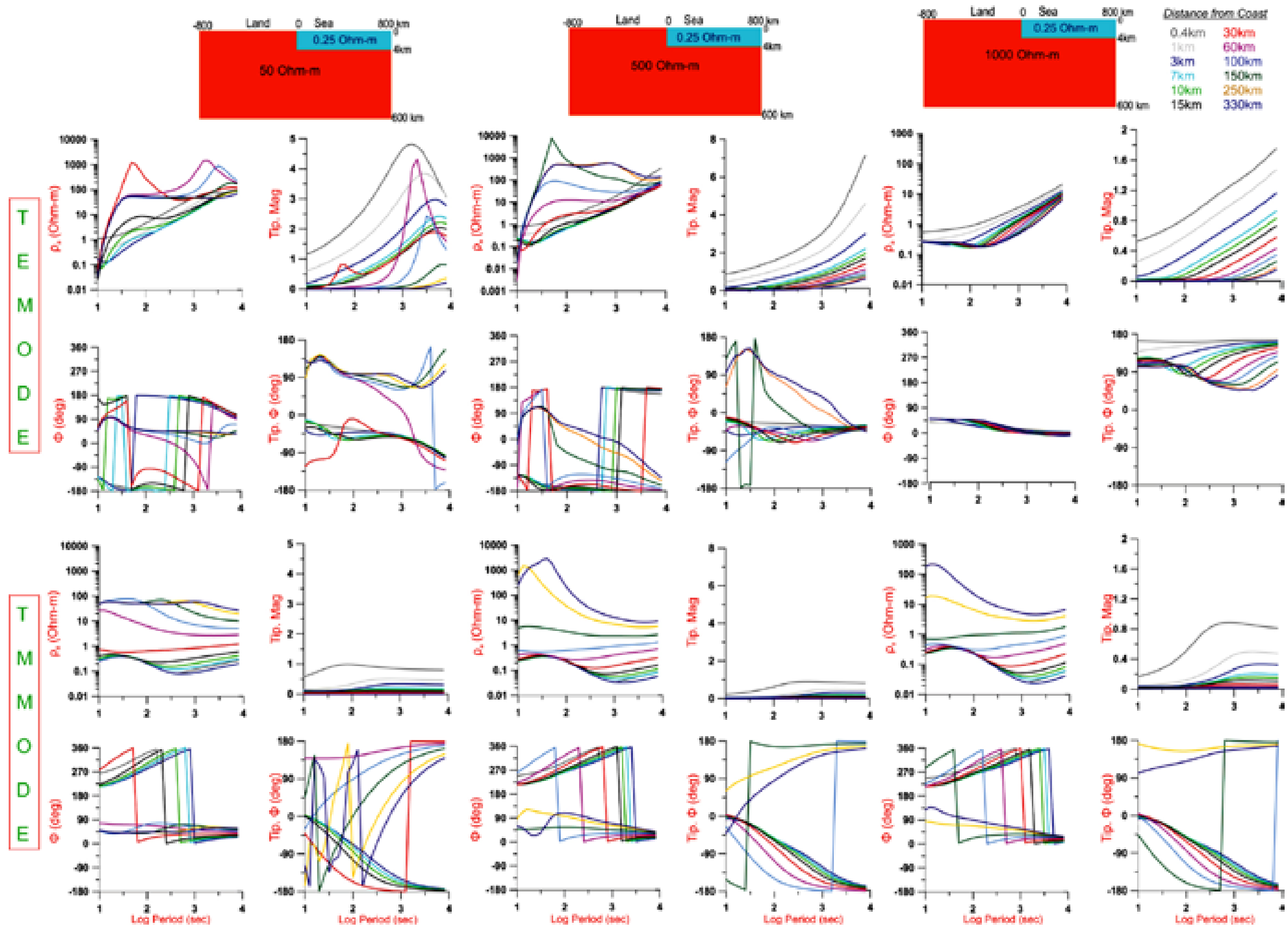

Figure 5. Synthetic modeling of the MMT response which includes only two bodies, i.e., sea water and single host with different resistivities to calculate the extent to which the MMT data is affected by coast. Coast effect is observed in the period range of 10-4000 sec and the extent of the data distortion limited up to 200 km. As the distance and period increases coast effect decreases in TE mode, where as in TM mode coast effect is increasing at longer periods and decreasing with increase in distance.

case, the right layering differs from the left layering, then conductivity inhomogeneity layering can be considered to extend indefinitely towards right hand side to infinite distance. Therefore, non-zero boundary conditions apply at right side at infinite distance. This program has been used to accommodate the inclined boundaries like continental slope and bathymetry in the BOB to simulate MMT response (like Ex, Ey, Hx, Hy, Rho-a, Phase etc.). The results, when plotted along the profile for various MMT parameters, show the ridge resolvability under thick pile of sediments.

SUMMARY AND DISCUSSION OF RESULTS

Variation in MMT response due to Coast effect

The MT data acquired on the land side will be affected by the marine environment in TE and TM mode responses (Veeraswamy, 1993; Singh et al., 1995; Rodriguez et al., 2001; Malleswari and Veeraswamy, 2014) due to large conductivity contrast between the ocean (0.25 Ohm-m) and continent (1000 Ohm-m). For 2-D model this coast effect is considerable for marine Magnetotelluric data (Key and Constable, 2011) and geo magnetic response derived from the induced currents flowing parallel to the coast. The maximum distortion in amplitude and phase response in general occurs at a definite range of period at a specific distance from the coast. Based on the model considered, it is possible to identify the characteristic period and distance with the host resistivity and the ocean depth. The coast effect does not mask the subsurface conductivity anomalies but it is sensitive to the sea floor. When the sloping coast is considered, the distortion in data may shift according to the volume of water displaced. The characteristic period is defined as the product of host resistivity and square of ocean depth where as characteristic distance is the product of host resistivity and ocean depth (Worzewski et al., 2012). Electrical conductivity structures in the offshore region

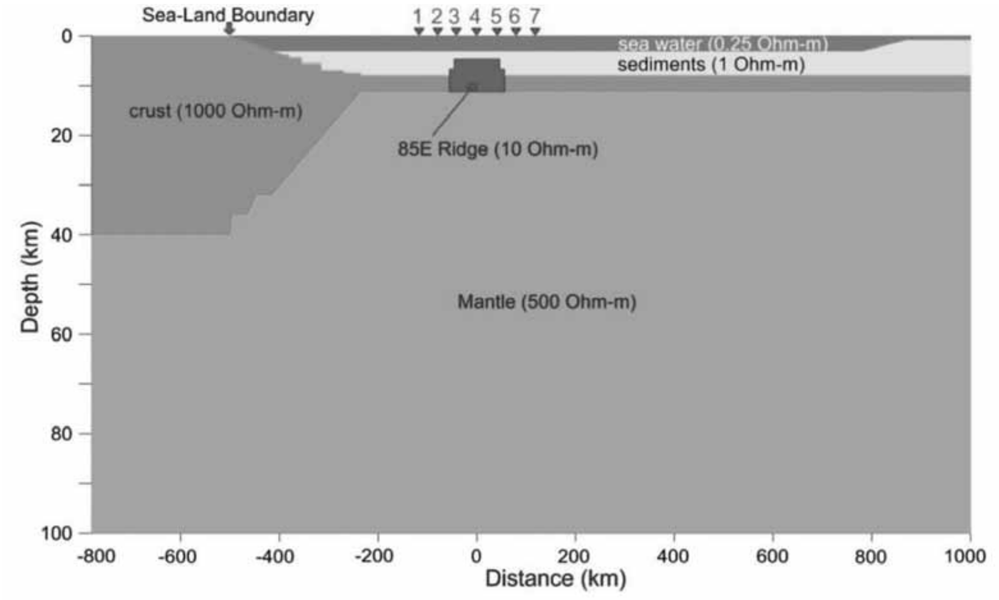

Figure 6. Two dimensional model utilized to compute MMT response across the 85^{0}E Ridge embedded in thick pile of sediments under ocean environment with corresponding resistivities.

were earlier delineated by using magneto variational (Arora et al., 2003; Baba, 2005) and magnetotelluric (Constable et al., 1998; Key and Constable, 2002, 2011; Baba and Chave, 2005; Kapinos and Brasse, 2009; Baba et al., 2010) investigations.

In the present study, the resolution analysis has been carried out for the coast effect with the half space and vertical water column with uniform thickness. The considered initial model (Figure 5 & 6) extends to 800 km on either side of the coastline and down to 600 km depth with sea water thickness as 4 km. Near the coastline the grid width is as small as 25 m in the offshore region and it increases to 1.3 times for the subsequent grids. Three different land resistivities (50 Ohm-m, 500 Ohm-m and 1000 Ohm-m) have been considered to estimate the effect of coast on MMT measurements. In all models the resistivity and thickness of sea water are taken as 0.25 Ohm-m and 4 km respectively. Figure 5 shows the variation in different MMT responses with period. Various curves correspond to response at different distances from the coast for both TE and TM modes. As shown in Figure 5, the MMT response is affected more by the coast for the models with host resistivities 50 Ohm-m and 500 Ohm-m as compared to 1000 Ohm-m. Key and Constable (2011) earlier did similar modeling while interpreting the data collected in the offshore of northeastern Japan. They observed single narrow positive peak in TE mode apparent resistivity at 100 sec period when the site is located at more than 100 km from the coast. In the present numerical study also a single narrow positive peak is seen for the same distance and period mentioned. However, this peak is migrated to 1000 sec when the site is moved to 200 km. The coast effect produces maximum variation in apparent resistivities for TE mode when the site is located between 30 km and 60 km, while for TM mode such variation is not evident. A fluctuation in apparent resistivity can be noticed when the land resistivity is 50 Ohm-m and an increasing apparent resistivity with period can be seen when the land resistivity is 1000 Ohm-m. The apparent resistivity is distorted when the station is located at less than 100 km from the coast, afterwards the effect is reduced and Tipper attains maximum between 300 and 3000 sec while Phase gets distorted when the station is located at <100 km. Tipper phase is positive when the station is at >100 km and it is negative when station is at <60 km. Phases show large negative response at maximum coast effect i.e. at <100 km. Tipper component is decreasing towards the ocean but there is a high magnitude at longer periods from 100 sec to 10000 sec and the distances from 30 km to 100 km from coast. From this analysis, it can be concluded that the MMT measurements shall be distorted when the site is located at less than 200 km from the coast and thereafter the coast effect is negligible.

Variation in MMT response across 85^{0}E Ridge

The two dimensional model used to compute the MMT response, should consider the environment of the ridge which includes sediments, water column, crust (land and marine) and mantle with the respective resistivities and thicknesses. Variations in crustal thickness are also considered all along the profile (i.e. on land and offshore). The numerical model considered here, starts from land and passes through continental shelf, continental slope,

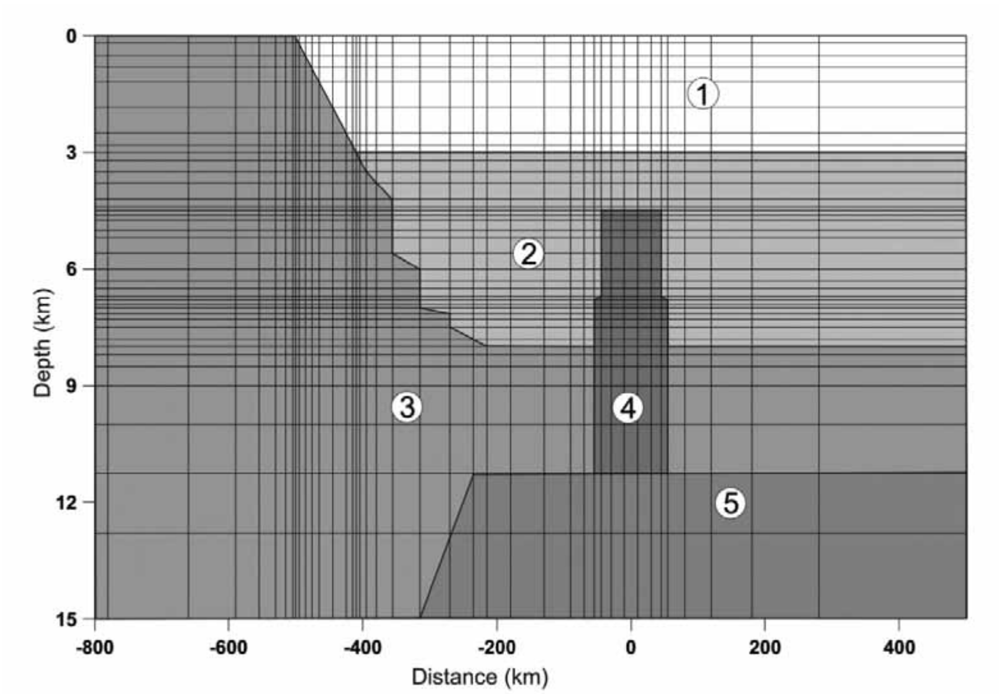

Figure 7. A section of the mesh used to generate marine MT data. The mesh geometry utilized here allows triangular sub-elements which tolerates elements with large aspect ratios. Nos. 1, 2, 3, 4, 5 represents Sea, Marine Sediments, Crust, Ridge and Mantle respectively.

Table 1. Resistivity and thickness parameters used for different formations in 2-D modeling during simulation.

Formation	Resistivity (Ohm-m)	Thickness (km)	Remarks/Reference
Sea water	0.25	0 – 3.0	As per bathymetry
Sediments	1	5.0	Constable (1990)
Ridge (variable)	10, 100, 1000	6.5	To accommodate both conductive and resistive ridge material
Crust	1000	11.5 - 40	Joseph et al., (2000) Matsuno et al., (2010)
Mantle	500	- - -	Baba et al., (2010)

continental rise and finally ends after 85^0E Ridge (Figure 6). The resistivities and thicknesses considered for different zones of the model are given in Table-1. As shown in Figure 6 the water column thickness varies towards ocean side. The numerical model was developed using the information across the 85^0E Ridge i.e., width and thickness of the ridge, pre- and post-collision sediments, crustal thickness etc. (Michael and Krishna, 2011) and passing through 14^0N latitude.

Numerical forward modeling has been carried out for 2D model (Figure 6) of the coastline and seafloor along the profile in order to study the nature of the distortion in the MT responses. Sea floor topography along a 1000 km long profile was discretized into different cells with variable widths of 5 to 20 km in the anomalous region (Figure 7). The entire model mesh was considered for more than 5000 km wide to make sure distortions from the sea floor topography in the central portion did not corrupt the 1D boundary conditions assumed along the sides of the model. The model has been divided into six regions viz. air, ocean, marine sediments, crust, ridge and mantle (or underlying half space) and the corresponding grid used for numerical modeling is shown in Figure 7.

Figure 8 shows the apparent resistivity and phase responses along the MMT profile for both TE and TM modes showing the coast effect and ridge effect at different periods. The coast effect is clearly visible when the sites are located in the continental shelf region. The TE mode parameters are more sensitive to larger distances as compared to TM mode. The distortion in TE and TM modes is maximum when the sites are located at <200 km from the vertical coast. This effect is defined here as

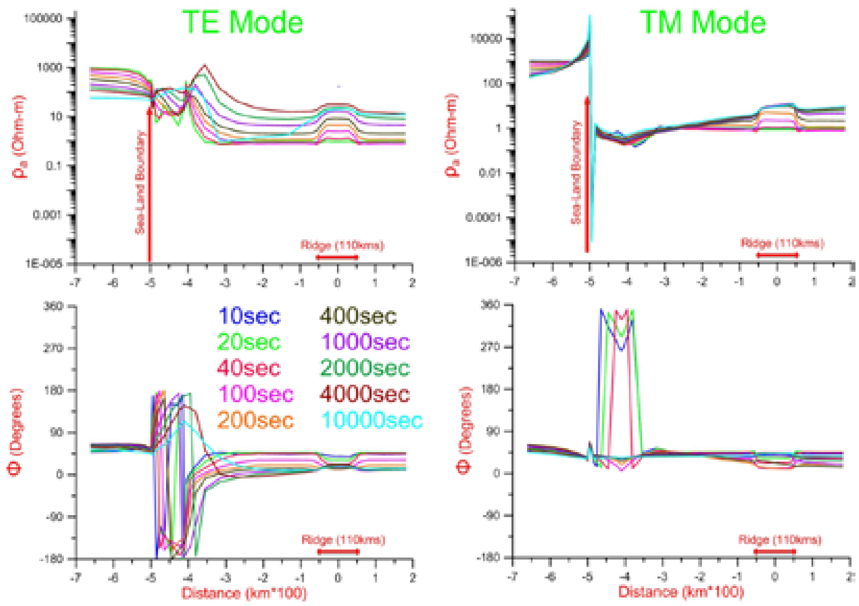

Figure 8. Apparent resistivity and phase variations along the MMT profile for both TE and TM mode showing the coast effect and the ridge effect at different period bands. TE mode data is strongly affected by the coast. The coast effect is limited to 200 km from the coastline. It is evident from this figure that the coast effect is negligible in the region of 85^{0}E Ridge.

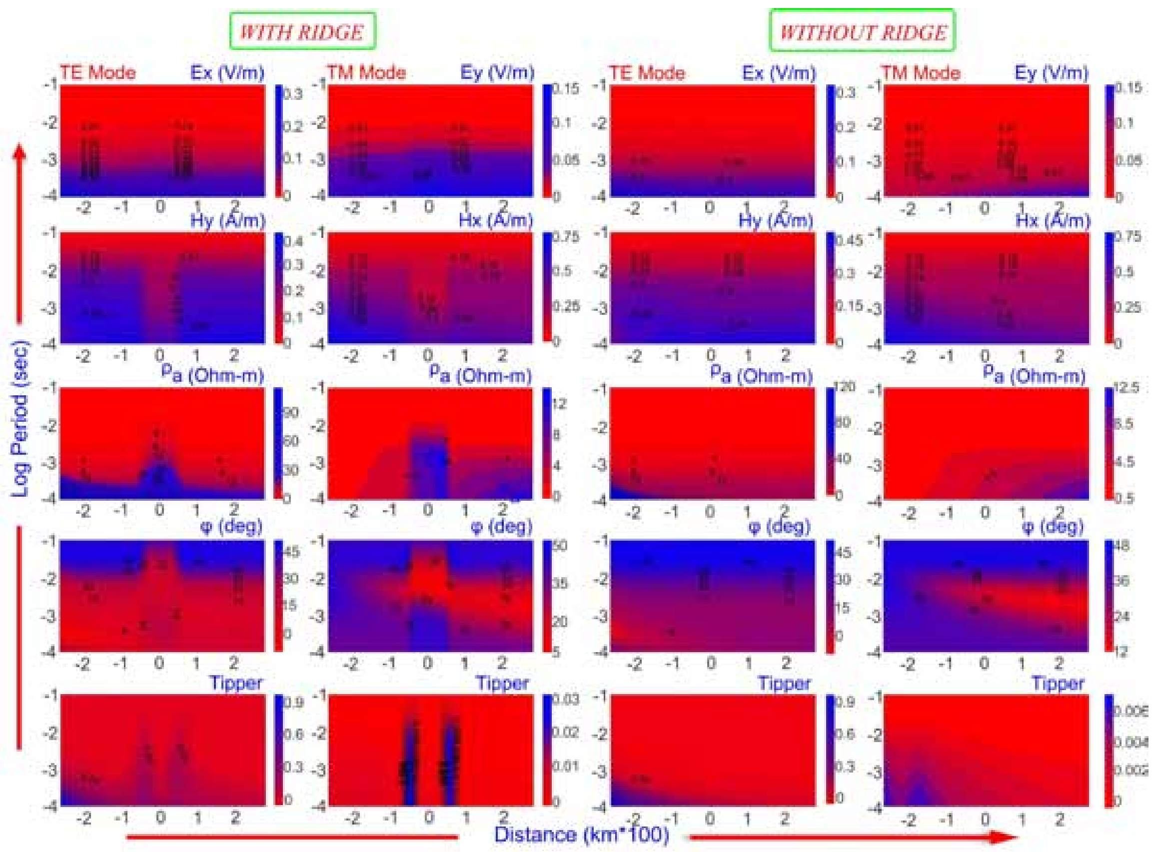

Figure 9. MMT parameters of TE and TM mode showing the variation in response due to the ridge. For the sake of comparison, response without ridge is also shown. Parameters like Horizontal magnetic field components (Hx, Hy), apparent resistivity (ρ_a), phase (ϕ) and Tipper showing the clear response when the ridge is present where as Horizontal electrical field components (Ex, Ey) are less affected in both TE and TM modes. Vertical resolution of the ridge is well pronounced in TM mode parameters as compared to TE mode.

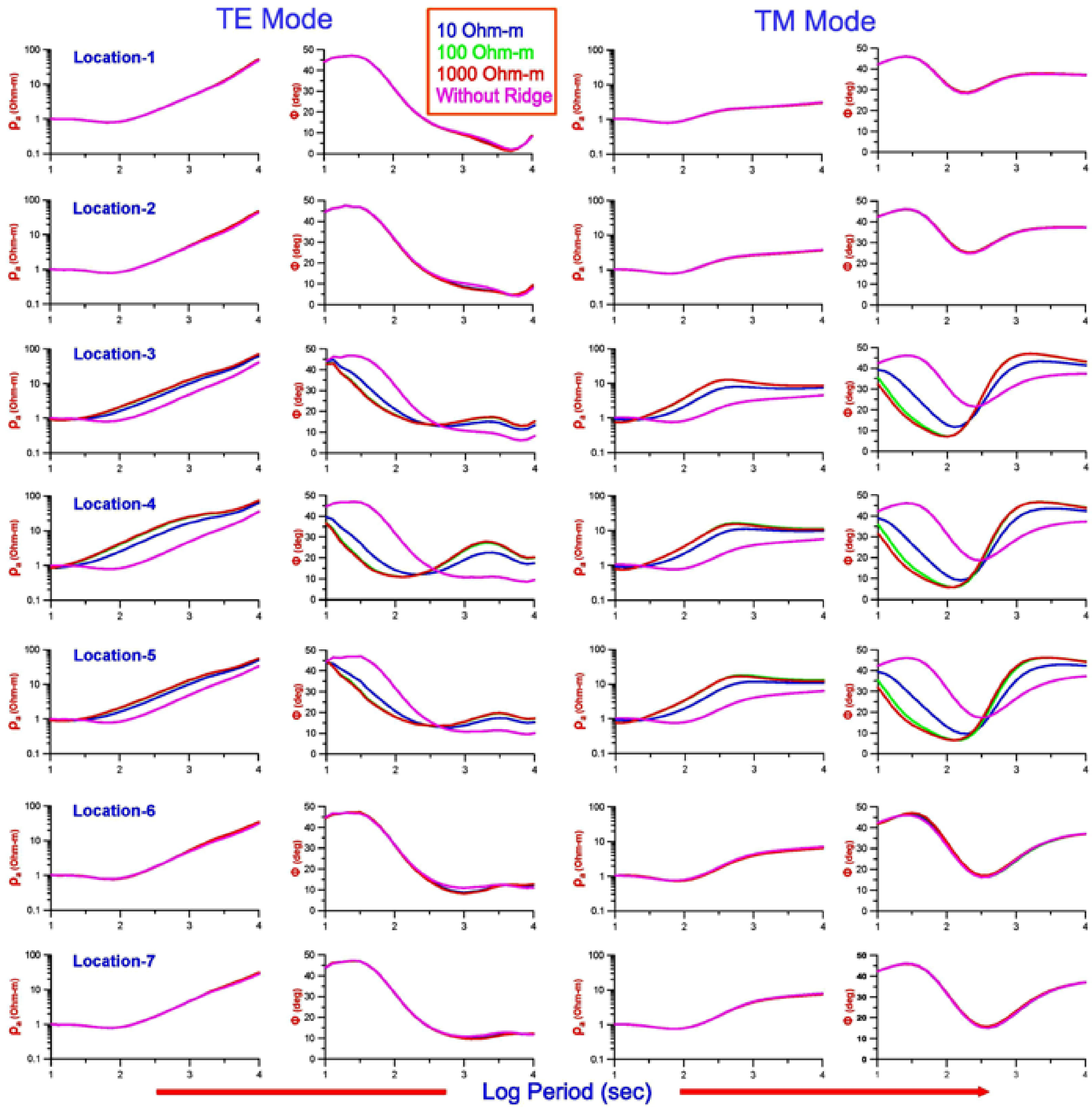

Figure 10. MMT response (apparent resistivity and phase) at different locations across the ridge with different ridge resistivities. The ridge effect is clearly seen in phase response of the TM mode as compared to TE mode. As the resistivity of the ridge increases the variation in apparent resistivity and phase response attains maximum towards centre of the ridge.

the maximum coast effect and extending up to 200 km. As the ridge is lying at 500 km from the coast, there is no coast effect on the ridge. In the same figure the ridge is well resolved in the period band of 40-4000 sec.

The data recording duration is another important factor that needs to be analyzed. Generally LF3 band has to be chosen to acquire data, wherein the sampling interval is 0.5 sec. So, after 4096 sec there are 8192 samples. During the processing the LF3 data has to be filtered with 32x filter to transform the data in to LF4 band (Friedrichs, 2007). Then one will have 256 samples with 16 sec sampling rate which is not enough for Fast Fourier Transform (FFT) computations. As a prerequisite, for a standard FFT with 4096 points, it is necessary to have 16 times of that data. Therefore, 18.2 hours (16 * 4096) recording time is essential to get one stack of 4096 sec. Hence, it is necessary to acquire data for a period of 8 days to get 10 stacks which is the minimum requirement in relatively less noisy areas. On the basis of the present numerical study, it can be surmised that the MMT surveys carried out for Hydrocarbon exploration within the EEZ (0-370 km away from the coast), it is necessary to consider the effect of coast up to 200 km from the sea-land boundary.

In order to view the two dimensional response of the ridge, the MMT parameters are plotted as pseudo sections and are shown in Figure 9. For the sake of comparison models with and without ridge are plotted. The model with ridge shows the ridge response in an excellent way; where as the model without ridge is clear from the response of the ridge. In each model, transverse electric and transverse magnetic modes are shown to estimate the parameters to what extent they are responding to the ridge presence. Parameters like Horizontal magnetic field components (Hx, Hy), apparent resistivity (ρa), phase (ϕ) and Tipper showing the clear variation in the response when the ridge is present, where as Horizontal electrical field components (Ex, Ey) are less distorted in both TE and TM modes. Vertical resolution of the ridge is well pronounced in TM mode parameters as compared to TE mode. Vertical flanks of the ridge are well resolved in the TM mode tipper response.

The MMT response at different stations across the ridge is shown in Figure 10. Results are plotted for seven stations with a station spacing of 35 km, out of which three of them are lying directly above the ridge and remaining four placed on either side of the ridge. Variation in apparent resistivity against period is plotted with four curves in which three curves are representing the ridge resistivity of 10 Ohm-m, 100 Ohm-m and 1000 Ohm-m and another curve is without ridge. The three resistivity values considered here are representative of ridge material when it is made up of mantle (or) oceanic crustal (or) continental crustal material. On the basis of numerical simulation, it can be surmised that the ridge response is prominent in the TM mode phase as compared to TE mode phase. As the resistivity of the ridge increases the variation in apparent resistivity and phase response rises towards center of the ridge.

CONCLUSIONS

Marine Magnetotelluric measurements are relatively more expensive and it is advisable to estimate through modeling, the resolvability of different parameters of tectonic features like ridges before conducting the field measurements. Keeping this in view, the MMT response at different locations across the 85^0E Ridge has been generated by numerical simulation. Interestingly, the computed results reveal that (i) the coast effect on MMT measurements can be seen in the entire continental shelf and continental slope regions, (ii) the coast effect is negligible on the MMT measurements made over the 85^0E Ridge as it is located at ~500 km east of coast line in the Bay of Bengal, (iii) the 85^0E Ridge is more visible in TM mode response as compared to TE mode in the period range of 40-4000 sec, (iv) horizontal magnetic field components (Hx, Hy) are more sensitive as compared to electric field components (Ex, Ey), and (v) MMT data needs to be acquired for a period of at least 8 days to get more than 10 stacks of 4096 sec.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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A Map of Earth`s Viscous Crust-- Recent Scientific Achievement

On long scales of length and time, Earth`s crust and upper mantle flow like stiff liquid. To understand how the rocks deform under geologic stresses, one needs to know their viscosity—a property that depends on the rock temperature, strain rate and composition. Among those features variations in composition, specifically trace amounts of water and magma, are the most difficult to determine but exert a strong influence on the rock`s behaviour (Marc Hirschmann and David Kohistedt, Physics Today, March, 2012, page 40). The hotter, wetter, or more molten a rock the weaker it is. Fortuitously, the same factors that weaken a rock and lower its viscosity also make it more electrically conductive. Since the last 6 decades, researchers have been able to infer resistivity profiles as a function of depth in crustal and mantle rocks from variations in magnetic and electric fields measured Earth`s surface using magnetotelluric (MT) imaging. Recently an US and an Australian scientist jointly have derived an empirical conversion factor to determine viscosity variations from two-dimensional variations in electrical resistivity obtained from an MT survey across the western US. The researchers calibrated the magnitudes of the viscosity variations with geodynamic flow models to produce a viscosity map. The map predicts the region`s rough surface topography, crustal deformation and mantle upwelling more accurately than do standard geological models. The upwelling identifies spots of potential earthquakes or volcanism. (**Citation**: L.Liu, D.Hasterok, Science 353, 1515, 2016).