

The 85°E Ridge – Study of Crustal Structure, Isostasy and Negative Gravity Anomaly using Process Oriented Gravity Modeling

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The 85°E Ridge – Study of Crustal Structure, Isostasy and Negative Gravity Anomaly using Process Oriented Gravity Modeling

5.1 Introduction

The 85°E Ridge extends from the Mahanadi Basin in the north to the Afanasy Nikitin seamount (ANS) in the south, is a prominent aseismic ridge in the northeastern Indian Ocean (Figure 5.1). The northern part of the ridge (north of 5°N) is buried under thick Bengal Fan sediments, whereas in the south, its structure occasionally rises above the seafloor (Curry et al., 1982; Liu et al., 1982; Curry and Munasinghe, 1991; Müller et al., 1993; Gopala Rao et al., 1997; Subrahmanyam et al., 1999; Krishna, 2003; Krishna et al., 2011a). At around 5°N, southeast of Sri Lanka, a westward shift of 250 km exists, which is not observed along other major hotspot related tracks in the Indian Ocean such as the Ninetyeast and Chagos-Laccadive ridges .

Origin of the 85°E Ridge is enigmatic due to its characteristic negative gravity anomaly and complex magnetic anomaly signatures. Curry and Munasinghe (1991) were the first researchers to postulate that the Rajmahal Traps in the Bengal Basin, 85°E Ridge and ANS form the trace of the Crozet hotspot. However, geochemical results of lava samples of the ANS do not show affinity to the Crozet hotspot volcanism (Mahoney et al., 1996). Though many subsequent researchers favored the hotspot origin for the emplacement of the ridge (Müller et al., 1993; Gopala Rao et al., 1997; Subrahmanyam et al., 1999; Krishna, 2003), the source of the hotspot volcanism remains speculative. Alternatively, formation of the ridge due to shearing or sagging of crust by horizontal stretching/ compressional forces has also been proposed (Ramana et al, 1997; Anand et al., 2009). Following the analogy of negative gravity signature of the Laxmi Ridge in the Arabian Sea and its continental sliver interpretation (Naini and Talwani 1983; Talwani and Reif 1998; Krishna et al., 2006), it is also possible to think in the direction of continental origin to the 85°E Ridge. This possibility has numerous difficulties for explaining the other aspects: 1. The trend of the 85°E Ridge is not parallel to the configuration of the Eastern Continental Margin of India

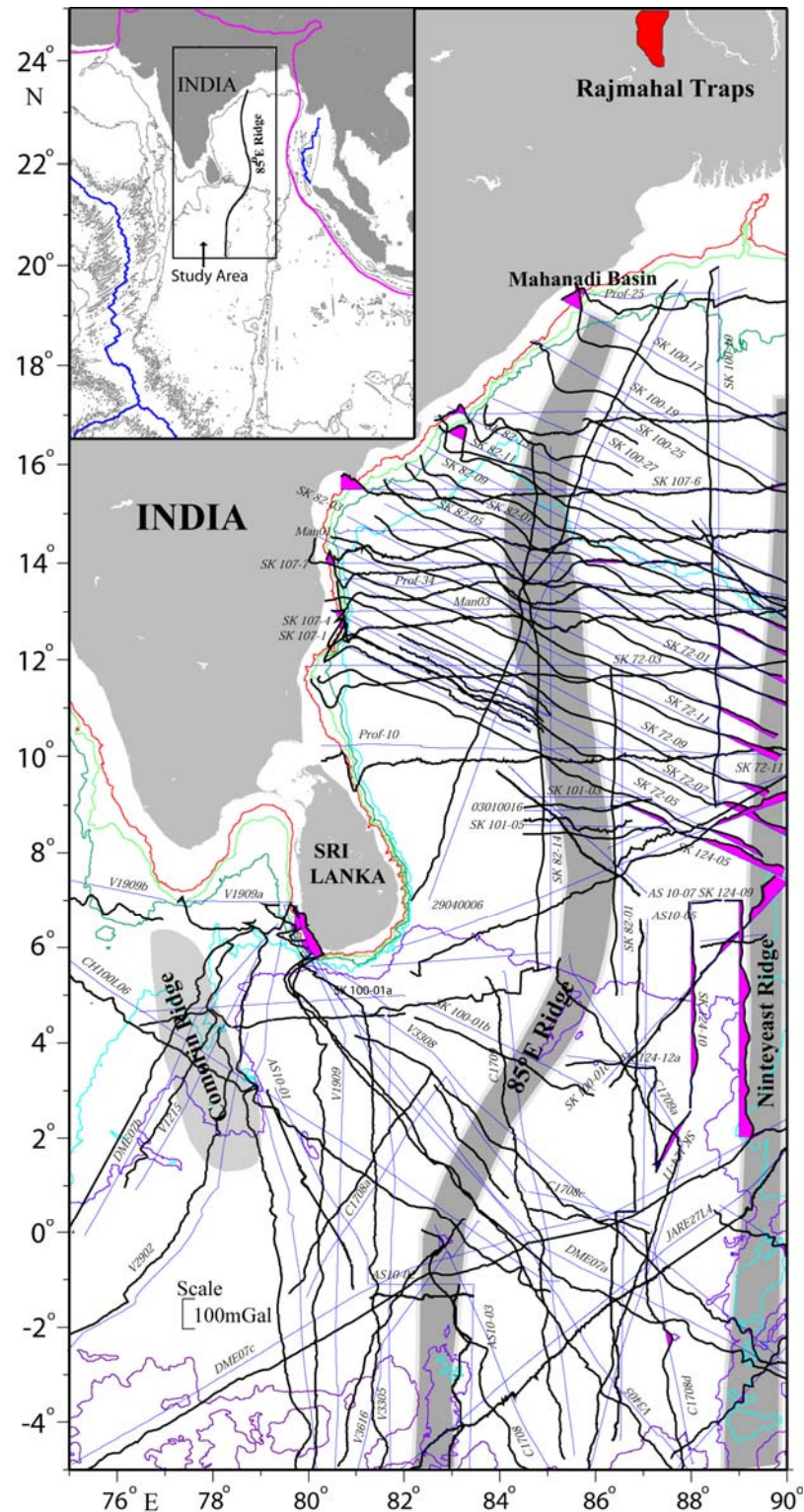


Figure 5.1 Ship-borne gravity profiles in the 85°E ridge and adjoining areas of the NE Indian Ocean. Free-air gravity anomalies (thick black lines) plotted at right angle to the ship tracks. General bathymetry of the Bay of Bengal is from GEBCO.

(ECMI) and to the identified Continent-Ocean Boundary along the ECMI, 2. The oceanic crust in the Western Basin between ECMI and 85°E Ridge does not provide any evidences for the presence of conjugate parts of the ocean floor evolved by the spreading process after so-called breakup of the 85°E Ridge from ECMI, 3. The NW-SE trending oceanic fracture zones identified in the Western Basin obliquely cross the 85°E Ridge, and these fractures zones were earlier have interpreted as conjugate parts of the fracture zones evolved in the Enderby Basin (Krishna et al., 2009a), and 4. The breakup history of the Elan Bank from the north ECMI becomes more complex in case of consideration of the 85°E Ridge as a continental sliver.

Liu et al. (1982) have modeled the negative gravity anomaly of the 85°E Ridge with consideration of two stage loading; initially emplacement of the ridge on a weak lithosphere (5-15 m.y) leading to excess thickening of the crust and subsequently loading of sediments on a stronger lithosphere of 40-80 m.y old. This model infers approximately 180 times increase in the flexural rigidity between emplacement and burial. Later, Krishna (2003) proposed an alternative model, in which he explained the negative gravity anomaly as a result of density contrast between the metasediments and less dense ridge material and a broader Moho depression beneath the ridge. However, the above proposed models lack a clear understanding on the timing of emplacement of the ridge as well as flexural characteristics beneath it. The sources/ mass anomalies that gave rise to the negative gravity anomaly, which otherwise expected to have been positive also needs to be understood and quantified.

The admittance analysis is, in general, used for estimation of flexural rigidity and isostatic response of the geological structures; but in the case of the 85° E Ridge, the technique is unsuccessful because of absence of its topographic expression on the seafloor. Therefore the process-oriented gravity modeling, in which the present-day gravity field of the ridge can be divided into different gravity anomaly components, has been carried out. Thereby, an attempt has been made to determine the elastic plate thickness of the ridge at the time of emplacement and its crustal structure and isostatic compensation mechanism.

5.2 Tectonic Setting

It is widely accepted that the Greater India separated from East Antarctica during the early Cretaceous period and subsequently formed the conjugate oceanic regions, Bay of Bengal and Enderby Basin. The Indian landmass had witnessed two continental breakups in early stages of eastern Gondwana splitting. The first breakup occurred with separation of Greater India from Australia and East Antarctica during the Early Cretaceous (Curry et al., 1982; Royer and Coffin, 1992; Gopala Rao et al., 1997; Müller et al., 2000). In second stage the Elan Bank, a submerged micro-continent lies presently on the western margin of the Kerguelen Plateau in the southern Indian Ocean, sundered from the present-day eastern margin of India at about 120 Ma (Gaina et al., 2003, 2007; Borissova et al., 2003; Krishna et al., 2009a). The breakup events and their timings suggest that most part of the oceanic crust in the Bay of Bengal was evolved during the Cretaceous Magnetic Quiet Period (120-83 Ma).

During the mid-Cretaceous period a major change in the spreading direction occurred from NNW-SSE to N-S, resulted in northward drift of Indian plate followed by collision with Asian plate during the early Eocene. The Indian plate, during the course of its northward movement, recorded the mantle plume expressions on the Indian Ocean seafloor in the form of linear aseismic ridges. The 85°E Ridge is one of the major aseismic ridges formed in this phase in the northeastern Indian Ocean and subsequently buried under the post-collision Bengal Fan sediments.

5.3 Geophysical Data

Multichannel Seismic reflection, gravity and bathymetry data collected on board *MV Sagar Sandhani* (MAN-01 and MAN-03), *ORV Sagar Kanya* (SK107-7) and *RV Issledovatel* (Profile 98791) are used for the model studies. Published seismic refraction results (Naini and Leyden, 1973; Curry, 1994) are used to constrain the densities of various sedimentary layers. Additionally, published seismic reflection data across the ridge (Krishna, 2003; Bastia et al., 2010) are also presented to map the continuity of the 85°E Ridge track.

5.4 Seismic Structure and Gravity Anomaly of the 85°E Ridge

The overall trend of the 85°E Ridge is seen in satellite gravity anomaly map shown in Figure 5.2 and also in anomaly wiggles along ship-borne gravity profiles (Figure 5.1). The ridge extends from 19°N to 5°S with variable widths range from 100 to 180 km. The width of the ridge is maximum near 14°N latitude and associated with a deep gravity low of ~80 mGal. Further north, between 15°N and 16.5°N latitudes, the gravity anomaly of the ridge is not significant, but shows its presence again near 17°N latitude and appears to continue up to 19°N in the offshore region of Mahanadi Basin. Using aeromagnetic and marine magnetic data Natyak and Rao (2002) and Subrahmanyam et al. (2008) have traced the continuity of the 85°E Ridge trace in offshore Mahanadi Basin and further to the Chilka Lake. With the use of high-quality seismic reflection data Bastia et al. (2010) have strongly confirmed the presence of ridge structure in the Mahanadi Basin (Figure 5.3a). Northward continuation of the ridge onto the continental slope and shelf tracts of the Eastern Continental Margin is clearly observed in these sections. Towards south between 11°N and 2°N, the ridge track bends in clockwise direction, then appears to continue straight-down to join the Afanasy Nikitin seamount (ANS) (Figures 5.1 and 5.2). Using seismic images of the ridge Krishna (2003) has shown the southward continuity of the 85°E Ridge up to the Afanasy Nikitin seamount (Figure 5.3b). It can be clearly observed that the southern track of the ridge joins with the ANS through isolated buried hills and intervening subsurface structures. Thus, seismic sections and gravity anomaly maps unambiguously shows the continuity of 85°E Ridge from the Mahanadi offshore basin in north to the ANS in south. The prominent negative gravity anomaly associated with the 85°E Ridge in the Bay of Bengal region changes to positive south of 5°N and in further south, the ANS is associated with significant positive gravity anomaly (Figure 5.2).

Four seismic reflection and gravity profiles crossing the 85°E Ridge along 14.7°, 14°, 13° and 4.5°N latitudes (Figures 5.3c and d) are analyzed in detail. The ridge structure in the Bay of Bengal region is completely buried below the Bengal Fan sediments of variable thick. For example, along 14.7°N and 13°N latitudes the ridge is carpeted by about 2.8 and

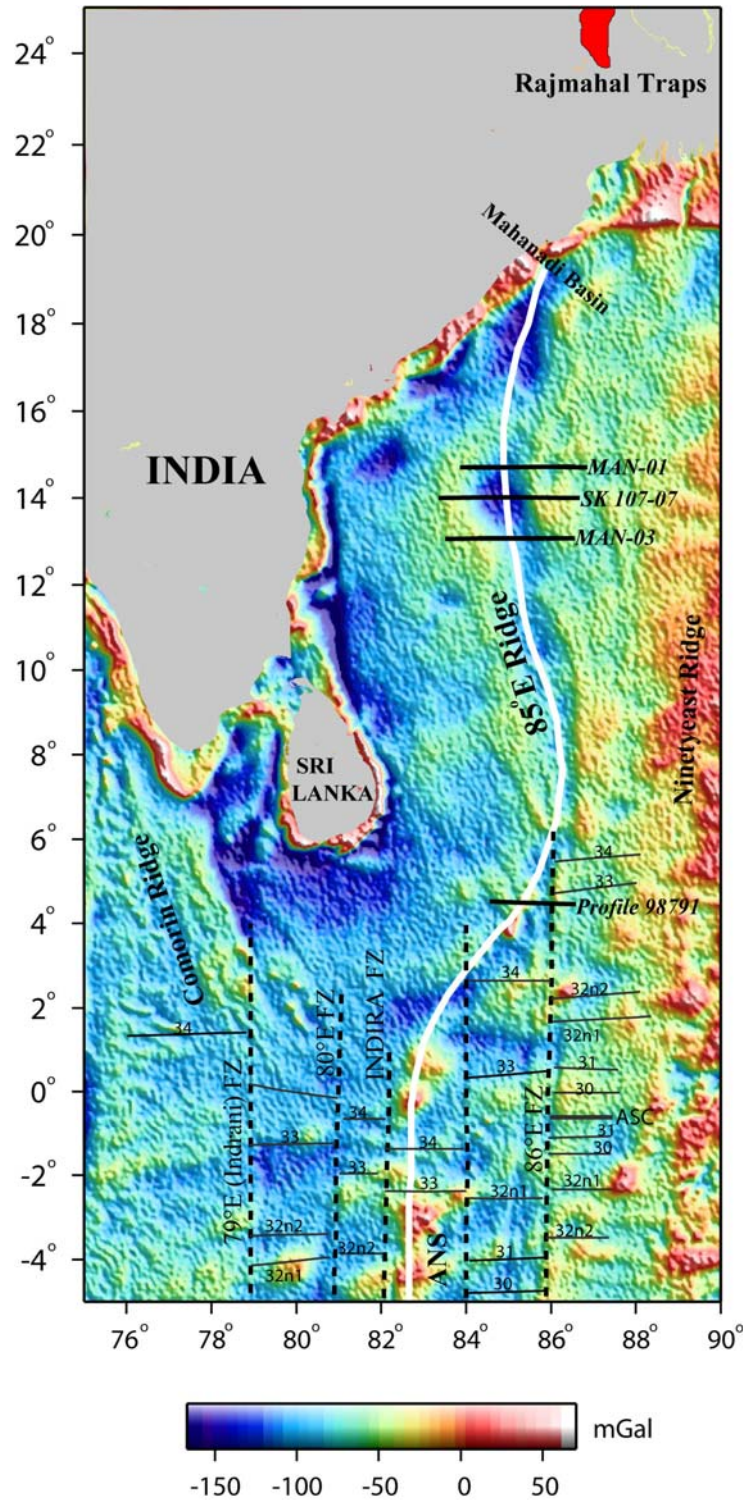


Figure 5.2 Satellite derived free-air gravity anomaly map (Sandwell and Smith, 1997) of the northeastern Indian Ocean. Locations of 85°E (white line), seismic sections (thick line), magnetic lineations (thin line) and fracture zones (dashed line) are superposed on the map. ANS stands for Afanasy Nikitin seamount.

-1.7 s Two-Way Travel Time (TWT) Bengal Fan sediments (Figures 5.3c and d), respectively, whereas along the 14°N latitude about 0.8 s TWT thick sediment strata overlie the ridge crest. Based on seismic results of the Bay of Bengal, Curray et al. (1982) and Gopala Rao et al. (1997) have divided the entire sediment section into two sedimentary packages and interpreted that the lower package was deposited mainly from the rivers of east coast of India, whereas the upper package was deposited by the Ganges and Brahmaputra rivers discharges after establishing the contact of the Indian subcontinent with the Asian continent. Further the packages are classified as pre- and post-collision sediments and are separated by an erosional-type unconformity developed in Paleocene age (Figures 5.3c and d) (Moore et al., 1974). The pre-collision sediment package consists of pelagic and terrigenous sediments deposited prior to the India-Eurasia collision, whereas, the post-collision part mainly consists of Bengal Fan sediments. The 85°E Ridge acts as a structural partition for dividing the thick Bengal Fan into Western and Central basins (Curray et al., 1982).

The subsurface disposition of the ridge is quite variable as can be seen from the seismic sections shown in Figures 5.3c and d. The ridge topography has a steep westward throw and gentle eastward dip along MAN-03 and appears as a double peaked basement rise along SK107-7. Along MAN-01 the relief of the ridge is relatively less and on eastern side the ridge a prominent basement high probably associated with an oceanic fracture zone (Gopala Rao et al., 1997) is observed. Gravity anomaly plots stacked along these sections show that the ridge is associated with a prominent negative gravity anomaly (~50 mGal) flanked by regional gravity highs on either side (Figures 5.3c and d). The wavelength of the negative anomaly is relatively greater than the width of the ridge.

The morphology and gravity signature of the southern part of the ridge structure along profile 98791 at 4.5°N are distinctly different in comparison to the sections of the Bay of Bengal. The ridge structure along the profile 98791 is exposed above seafloor with an elevation of about 0.8 km (Figure 5.3d), but its flanks are buried under 2 to 3 km thick fan sediments. The pre-collision sediments are nearly absent and the thickness of fan sediments are lesser compared to the northern part of the ridge. Along this profile the ridge

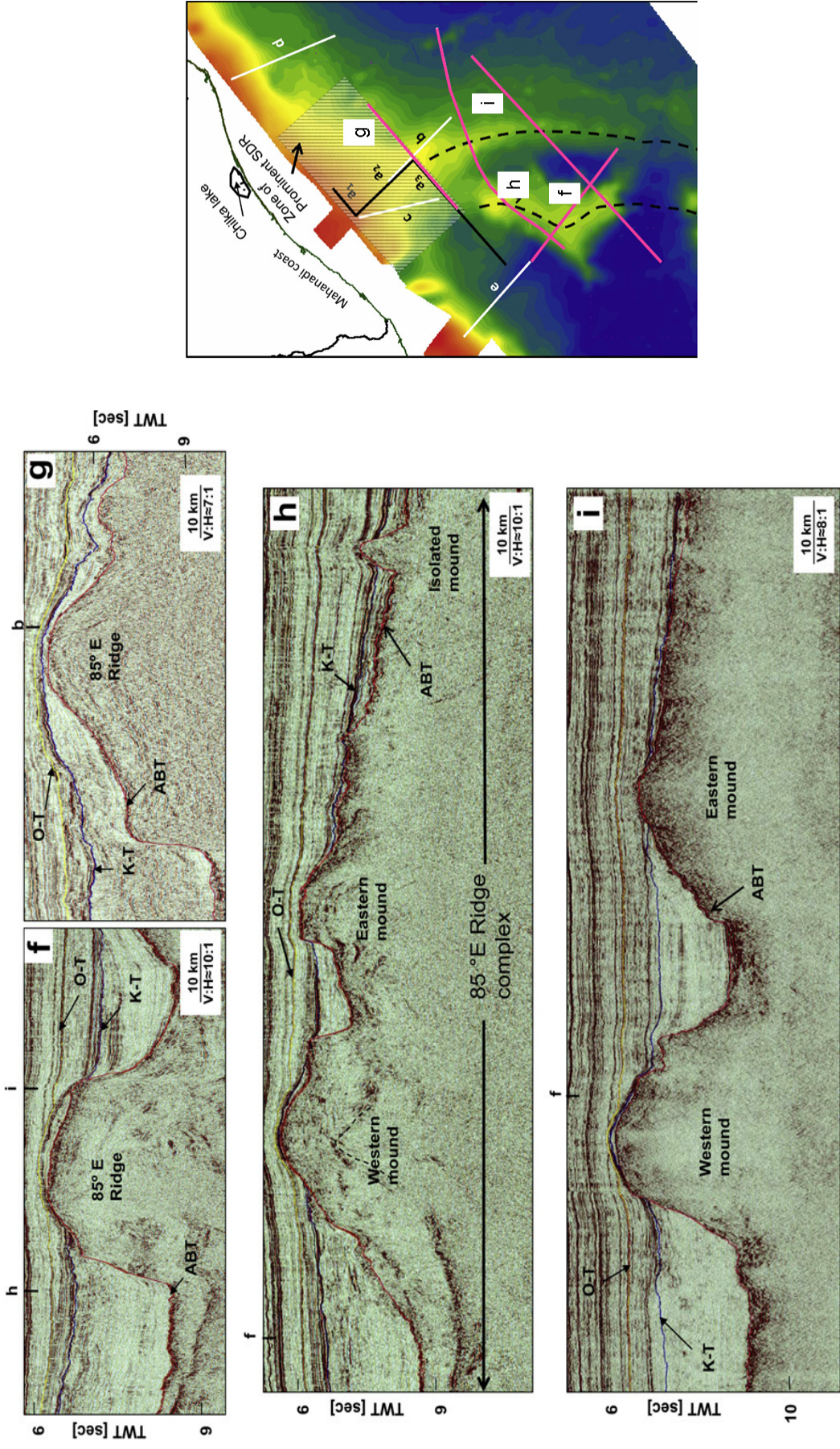


Figure 5.3a Seismic reflection sections depicting structure of 85°E Ridge in Mahanadi Offshore Basin (after Bastia et al., 2010)

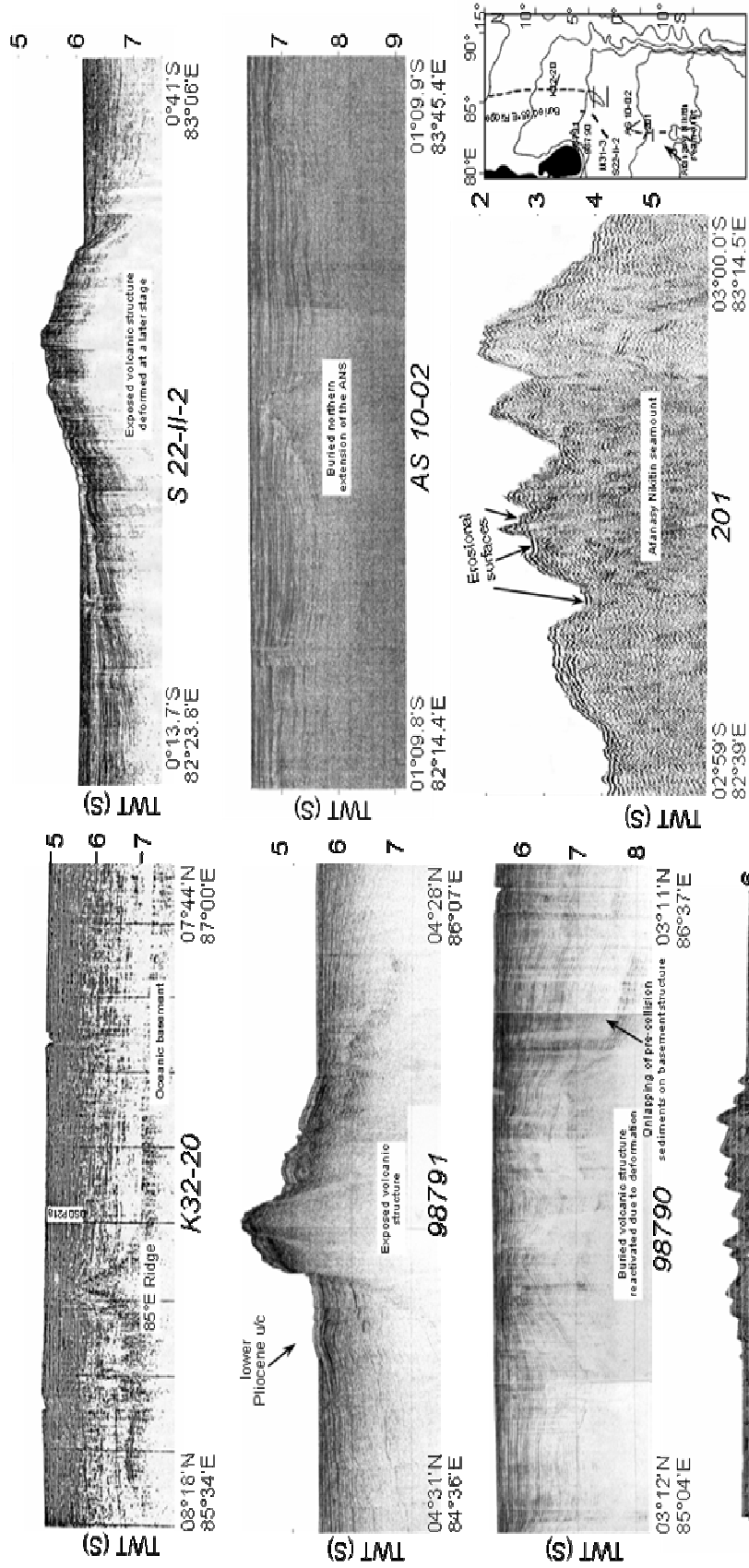


Figure 5.3b Seismic reflections sections depicting the structural continuity of the 85°E Ridge from 8°N (profile K-32-20) to ANS (profile 201) through buried hills (profiles S22-II-2, M31-3 and 98791), subsurface structures (profiles AS 10-02 and 98790) (after Krishna, 2003)

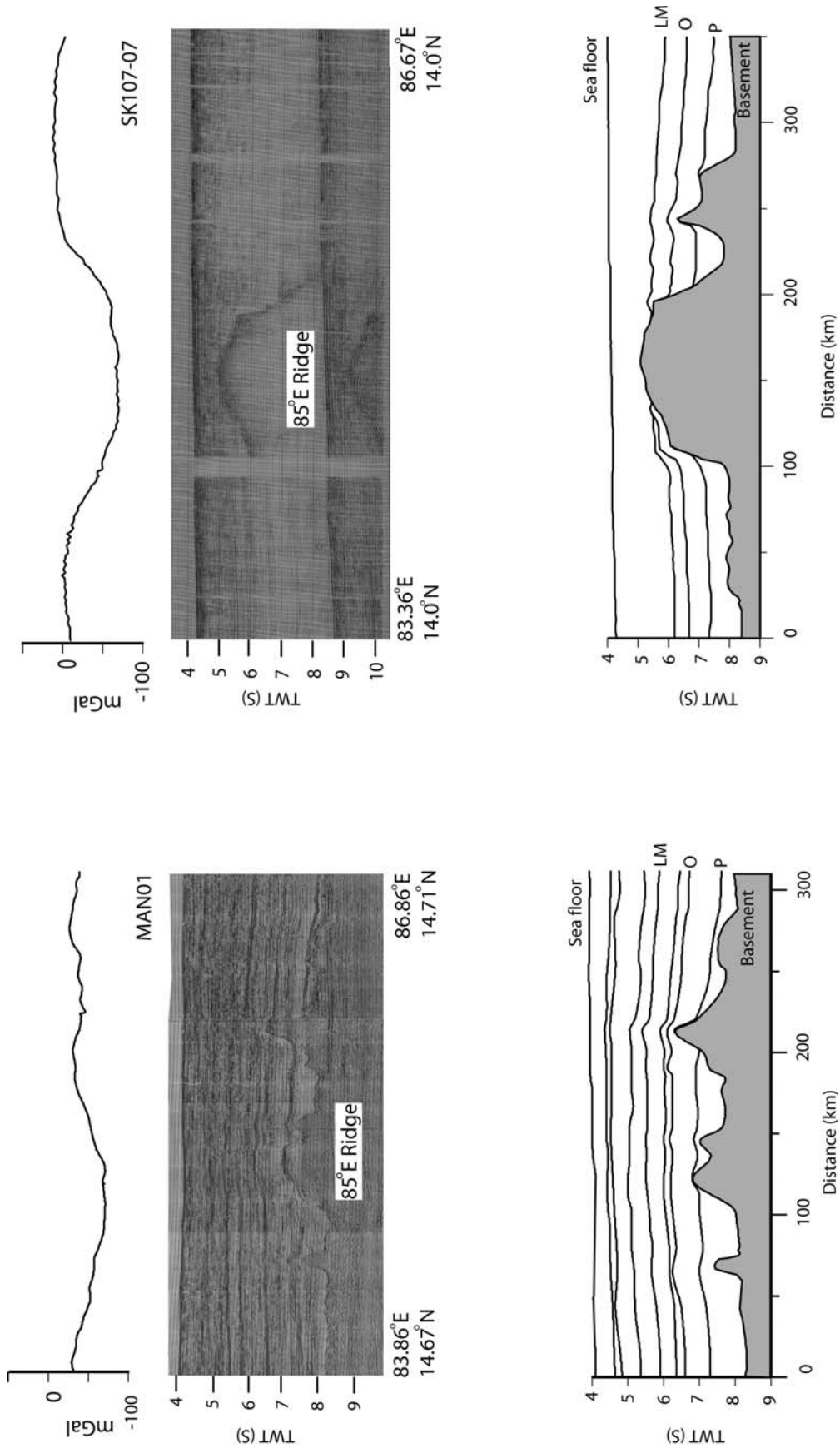


Figure 5.3c MAN-01 and SK107-07 seismic reflection sections and its interpreted line diagrams across 85°E Ridge stacked with gravity anomaly data. The buried 85°E ridge and associated negative gravity anomaly is clearly depicted. Paleocene (P), Oligocene (O) and lower Miocene (LM) boundaries are marked.

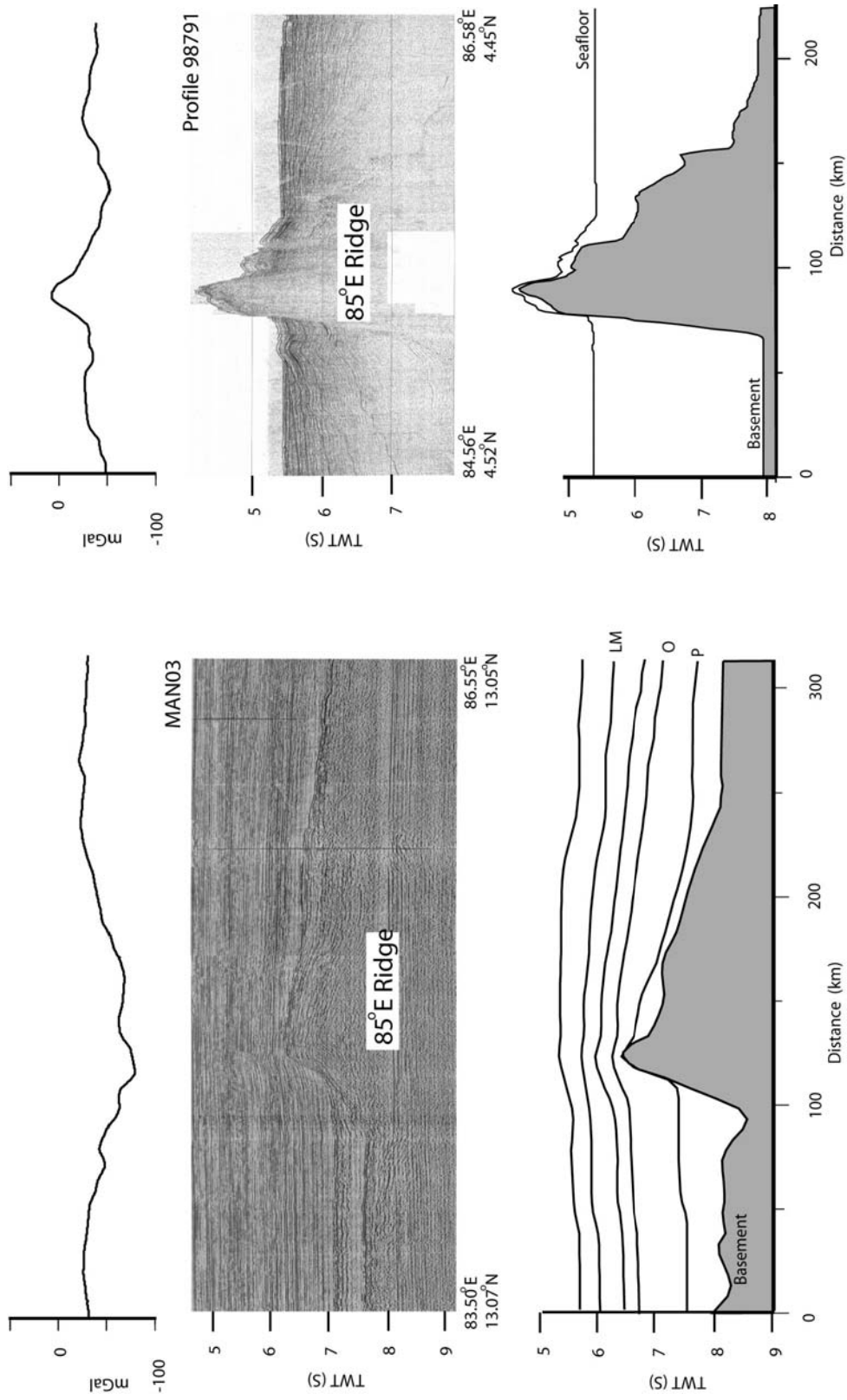


Figure 5.3d MAN-03 and 98791 seismic sections and its interpreted line diagrams across 85°E Ridge stacked with gravity anomaly data. The gravity anomaly along profile 98791 is satellite derived (Sandwell and Smith, 1997). Notations in figure are same as given in Figure 5.3a.

is associated with a prominent positive gravity anomaly with amplitude of about 40 mGal. The wavelength of the gravity anomaly along the profile is comparable with the width of the ridge.

5.5 Magnetic Response of the 85°E Ridge

The 85°E Ridge is, in general, associated with significant magnetic anomalies compared to the anomalies of the oceanic crust in the Bay of Bengal (Liu et al., 1983; Ramana et al., 1997; Gopala Rao et al., 1997). The overall strength of the magnetization of the 85°E Ridge suggests that the ridge is made of highly magnetized rocks. The asymmetry in the magnetic anomaly is attributed to the phase shift produced by the northward drift of the Indian plate (Liu et al., 1983). Recent compilation of geophysical data over the northeastern Indian Ocean (Krishna et al., 2009a; Michael and Krishna, 2011) revealed alternative stripes of high amplitude positive and negative magnetic anomalies along the 85°E Ridge track in the Bay of Bengal region. Michael and Krishna (2011) have correlated these magnetization patterns to geomagnetic time scale of Cande and Kent (1995) and assigned approximate ages to the ridge track.

5.6 Process Oriented Gravity Anomaly Modeling

The process oriented gravity modeling technique is highly regarded for the studies of crustal structure and tectonic evolution of geologically complex regions, like rifted continent margins (Watts, 1988; Watts and Fairhead, 1999). The modeling technique was developed based on the concept that the observed gravity anomaly is considered as sum of gravity effects of several processes, those were involved during the evolution of continental margins such as rifting, underplating, sediment loading, flexure, erosion, etc. This approach has been followed in the present study to model the gravity field and its spatial variation along the 85°E Ridge. However, the geological processes involved in the evolution of the 85°E Ridge and a rifted continent margin are different. For modeling, it is assumed that the 85°E Ridge was emplaced in an oceanic setting by a volcanic activity and the structure was eventually buried under the thick Bengal Fan sediments. The first step in the modeling is to reconstruct initial ridge topography by flexurally unloading each sedimentary layer. This is carried out by computing the flexure caused by distributed load on elastic plate and removing this effect from the

basement. Theoretical basis for the flexural computations is discussed in detail in Chapter-3. The oldest sedimentary sequence immediately above the basement in the Bay of Bengal region was deposited from early Cretaceous to Paleocene. This means that thin cover of sediments were present by the time of ridge emplacement at about ~85 Ma (Krishna, 2003; Michael and Krishna, 2011). All the sedimentary layers except a thin basal sediment layer have been backstripped for different elastic plate thickness (T_e) values. The backstripped section represents the initial morphology of the ridge covered with a thin layer of sediments overlain by water. The ridge emplacement is modeled as a load on thin elastic plate and as a load on a plate with no strength (Airy), resulting in flexural and Airy type compensations, respectively at the Moho boundary. The gravity anomalies are calculated with the consideration of ridge material on both flexure and Airy Moho configurations, which gave rise to 'Ridge Anomaly'. In second stage the sedimentary layers are brought back over the ridge structure, thereby the deflections created at basement and Moho levels are considered for gravity anomaly computations. The positive contribution of the sediment load and negative effect of flexure at the Moho boundary, when added will give rise to 'Sedimentation Anomaly'. The combined gravity effect of ridge anomaly and sedimentation anomaly is compared with the observed gravity anomaly of the ridge for a specific T_e value. Entire process is repeated for different T_e values range from 0 to 25 km, until a good fit is obtained between the observed and calculated gravity anomalies, considering RMS error as well as amplitude and wavelength of the anomalies as the goodness of fit. A simplified flow chart diagram of the process oriented modeling is given in Figure (5.4). The model parameters used in the computations are given in Table 5.1.

5.7 Elastic Plate Thickness and Crustal Structure of the 85°E Ridge

Following the approach described above, individual gravity anomalies contributed by ridge structure and overlying sediments are computed for three profiles (MAN-01, SK107-07 and MAN-03) in the Bay of Bengal region and one profile (98971) in the distal Bengal Fan and shown in Figure 5.5. The ridge anomalies of the Bay of Bengal profiles are, in general, positive with variable amplitudes and wavelengths for different T_e values, while the sediment anomaly is negative due to less thickness of sediments on top of the ridge compared to its flanks. The sum anomaly is calculated by adding both ridge and sediment anomalies for different T_e values and compared with the observed

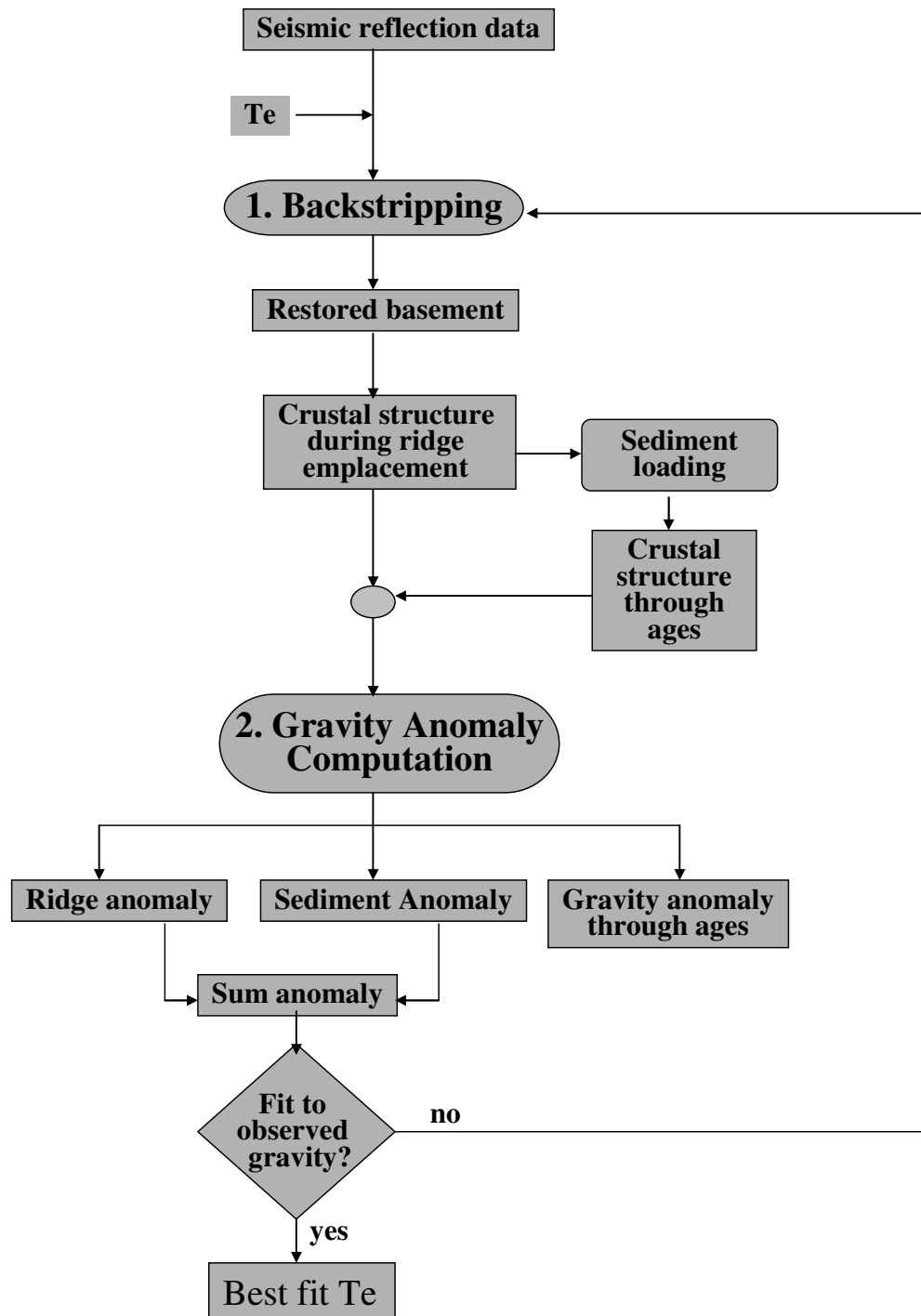


Figure 5.4 Simplified flow diagram of process oriented modeling depicting the two major steps - 1. Backstripping and 2. Gravity anomaly computation. Crustal structure and gravity anomalies through ages (right panels) are computed with the best-fit T_e (section 5.7).

Table 5.1 Model parameters used for the flexural calculations and gravity modeling

| <i>Parameter</i> | <i>Value</i> |
|--|--|
| Density of Sea-Water (ρ_w) | 1.03 gm/cc |
| Density of oceanic crust (ρ_c) | 2.90 gm/cc |
| Density of load (ρ_l) | 2.65 gm/cc |
| Density of mantle(ρ_m) | 3.30 gm/cc |
| Density of sedimentary layer1(ρ_1) | 2.3 gm/cc |
| Density of sedimentary layer 2(ρ_2) | 2.6 gm/cc |
| Density of metasediments (ρ_3) | 2.8 gm/cc |
| Average crustal thickness (t) | 6 km |
| Young's modulus (E) | 100 Gpa |
| Poisson's ratio (σ) | 0.25 |
| Universal gravitational constant (G) | $6.67 \cdot 10^{-11} \text{ Nm}^2\text{kg}^{-2}$ |
| Acceleration due to gravity (g) | 9.8 ms^{-2} |

gravity anomalies (Figure 5.5). It is observed that $T_e=15$ km provides a better match for profiles MAN-03 and MAN-01, both in terms of amplitude and wavelength, though the RMS errors correspond to $T_e = 15$ and 25 km are almost same. Whereas, for other profile SK107-07, $T_e=10$ km gives a better fit with the observed anomaly. On the other hand, anomalies computed for the Airy model ($T_e=0$ km) matches poorly with the observed anomalies and shows much smaller wavelength than the width of the ridge and more negative than the observed anomaly. The model results along the southern profile (98791) provide a best-fit for T_e value 10 km (Figure 5.5) by comparing the sum anomaly with the observed anomaly. Thus, the analysis supports flexural isostatic compensation model with T_e ranging from 10 to 15 km for both northern and southern parts of the 85°E Ridge.

For computations, different densities corresponding to various lithological units are used following the published seismic refraction results of the Bay of Bengal. Naini and Leyden (1973) identified a total of nine reflecting layers with velocities ranging from 2.0 to 5.78 km/s with oceanic basement having velocity of 6.2 km/s. Subsequently using seismic reflection and refraction data Curray et al. (1982) have determined velocities ranging from 1.7 to 4.85 km/s for different lithological units. Later, Curray (1991) mapped high velocity ($6.0 - 6.4$ km/s) pre-collision sedimentary section

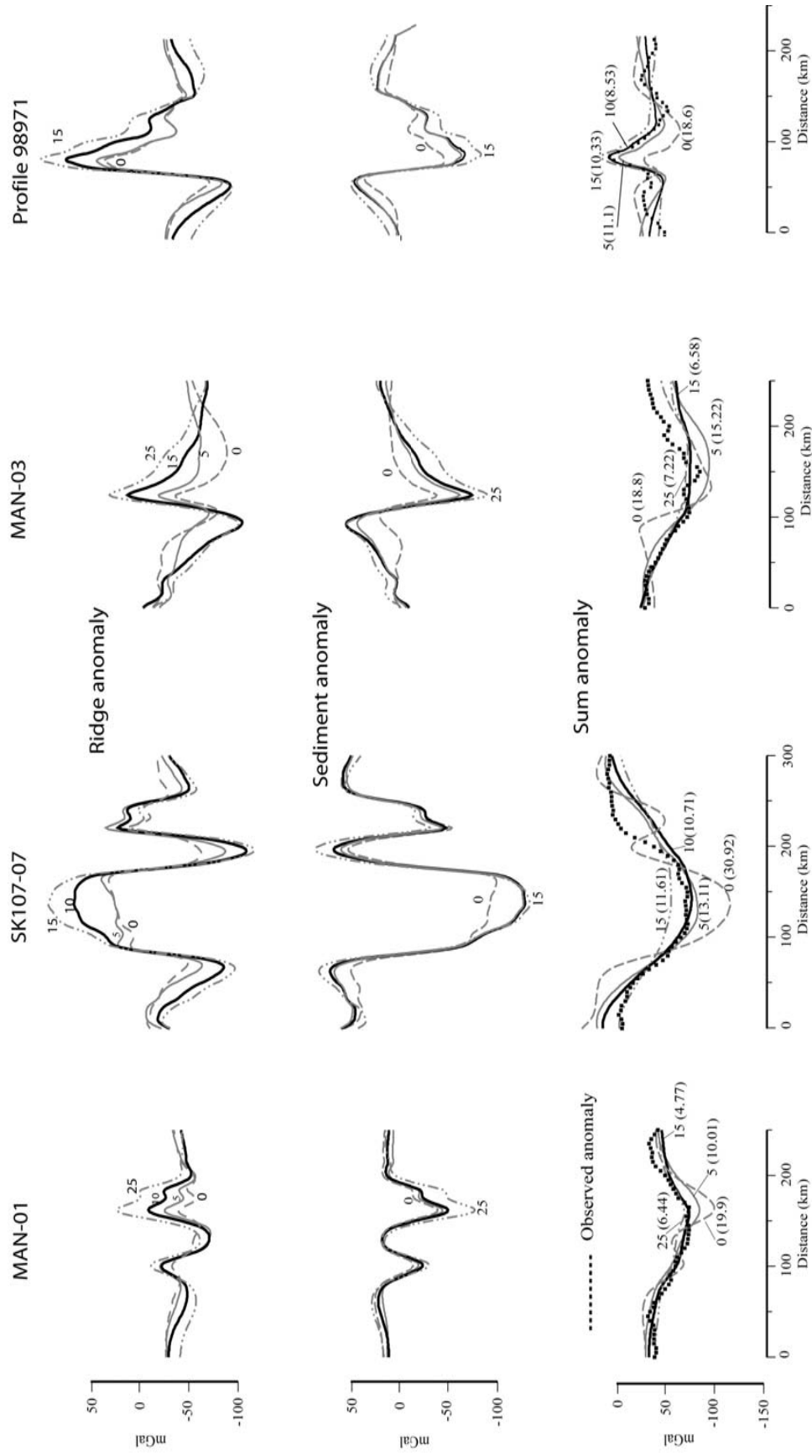


Figure 5.5 The ridge and sedimentation anomalies computed for different T_e values through process oriented gravity modeling for profiles MAN-03, MAN-01, SK107-07 and 98791. The sum anomaly of these two is compared with observed gravity anomaly with degree of fitness shown as RMS error (bracket).

(metasedimentary rocks) below the Paleocene unconformity. Velocity-depth relation of Bay of Bengal sediments derived from compilation of seismic refraction data (Radhakrishna et al., 2010) also shows high seismic velocities for deeper sediments of northern Bay of Bengal compared to the southern sediments (Figure 5.6). The observed seismic velocities were converted to density values and broadly grouped into three density distributions for consideration of gravity model studies. Density values of 2.3 and 2.6 gm/cc are considered for the upper and intermediate sedimentary layers (layer-1 and layer-2 in Table 5.1), whereas higher density of 2.8 gm/cc is considered for the metasedimentary rocks (layer-3 in Table 1), which is slightly higher than the density considered for the volcanic ridge (2.65 gm/cc). Density value 2.8 gm/cc considered for metasediments is not unusual as sediments undergo more compactness due to the overburden deposits than the basalts undergo.

The sediment loaded crustal structures derived for the best-fit T_e values along all four profiles are presented in Figures 5.7a, b, c and d. The crustal model along the Bay of Bengal profiles suggests a broad flexure at Moho boundary with a wavelength more than the width of the ridge. For profiles MAN-01 and MAN-03 the isostatic compensation is achieved by a flexure of Moho up to 2-3 km (Figure 5.7a, c), whereas along profile SK107-07 the flexure is about 5.5 km (Figures 5.7b). The relief and width of ridge along SK107-07 quite high and lead to higher surface load, which resulted in deeper flexure at Moho boundary for isostatic compensation.

The crustal model derived along profile-98791 (Figure 5.7d) is similar to that along the northern profiles with deflection of the Moho (about 3 km) due to the loading of ridge and sediments. However, a single sediment layer with an average density of 2.3 gm/cc is only used in the modeling, as the thickness of the Bengal Fan sediments in this area is relatively less to consider the compaction effects (Figure 5.6).

5.7.1 Crustal Structure of the 85°E Ridge- Two-dimensional Gravity Forward Modeling

Process oriented gravity modeling of gravity profiles running across the 85°E Ridge suggests flexural isostatic compensation with an approximate crustal structure beneath the ridge. The crustal models (Figures 5.7a, b, c and d) derived so are further improved using two-dimensional gravity forward modeling in order explain the observed gravity

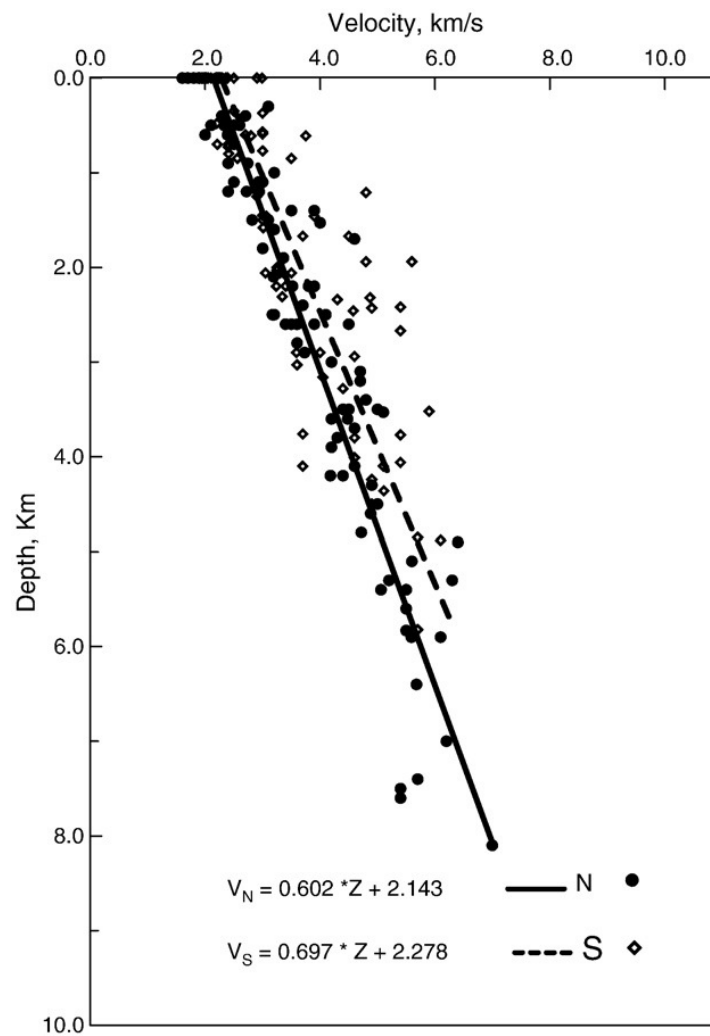


Figure 5.6 Velocity–depth relation for sediments in the Bay of Bengal based on compilation of available seismic refraction measurements (after Radhakrishna et al., 2010). Note different burial effect for northern (N) and southern (S) Bay of Bengal sediments.

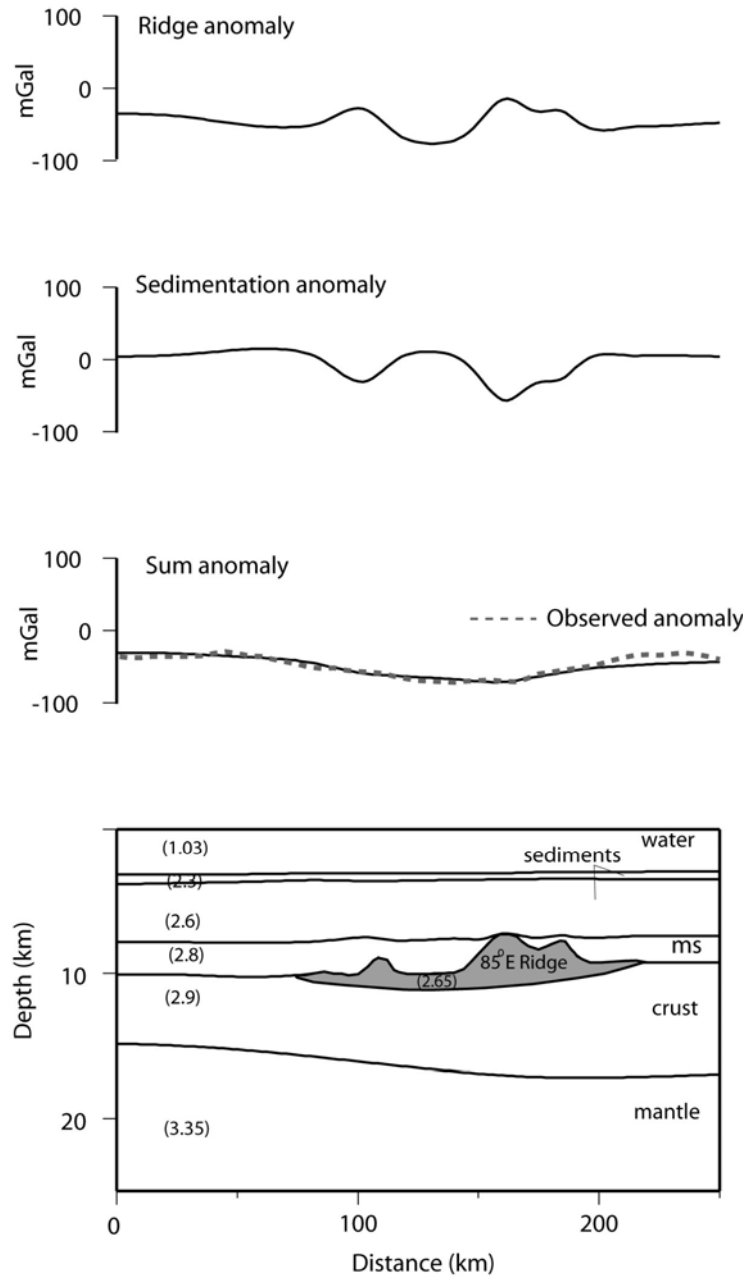


Figure 5.7a Crustal structure of the 85°E Ridge along profile MAN-01 along with different anomaly components (see details in text) obtained from process oriented gravity modeling. The values in bracket represent density for corresponding layer in gm/cc. The sum anomaly computed for best fitting T_e (15 km) is shown along with the observed gravity anomaly. ms in Figure indicates metasediments.

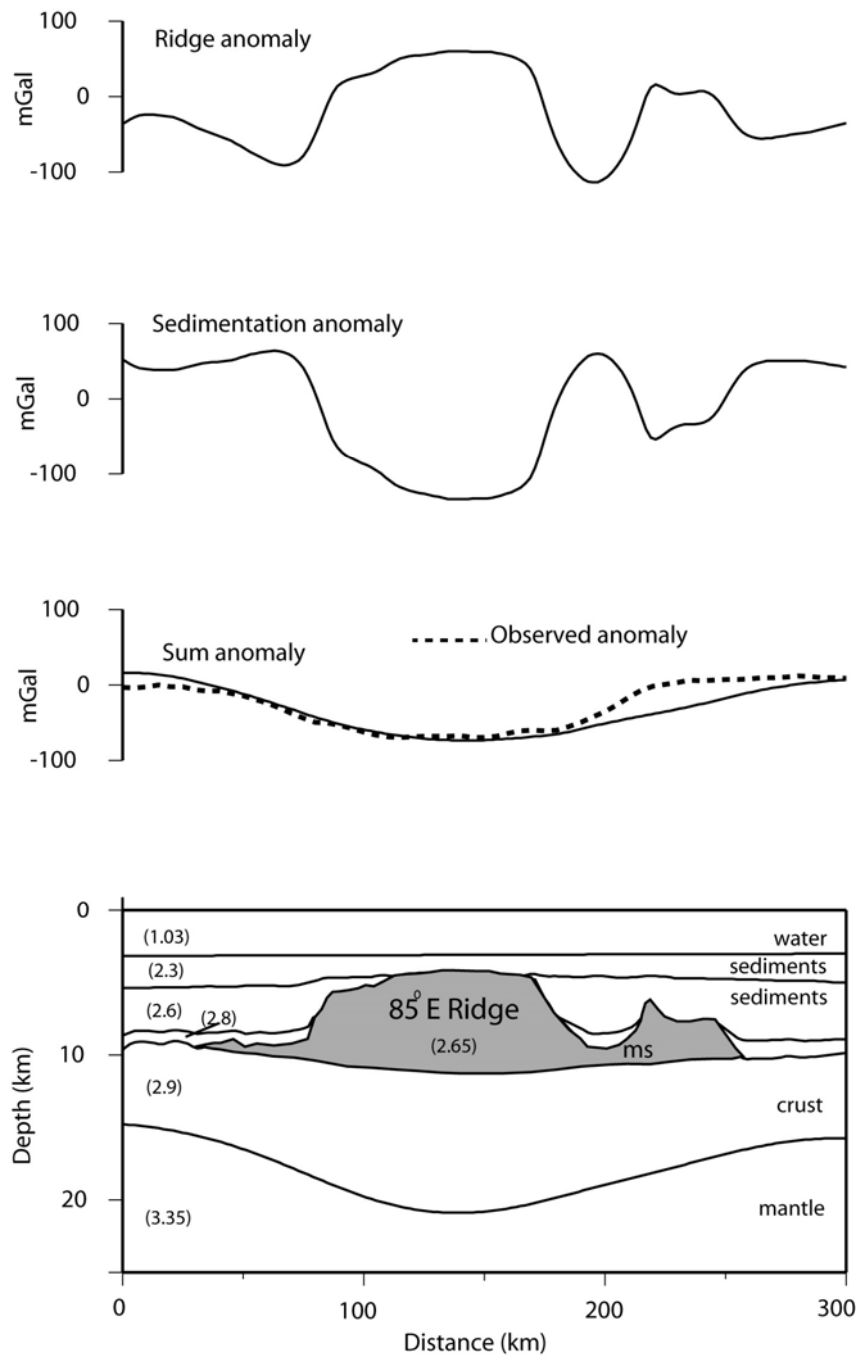


Figure 5.7b Crustal structure of the 85°E Ridge along profile SK107-07 along with different anomaly components obtained from process oriented gravity modeling. The sum anomaly computed for best fitting T_e (10 km) is shown along with the observed gravity anomaly. Notations are same as given in Figure 5.6a.

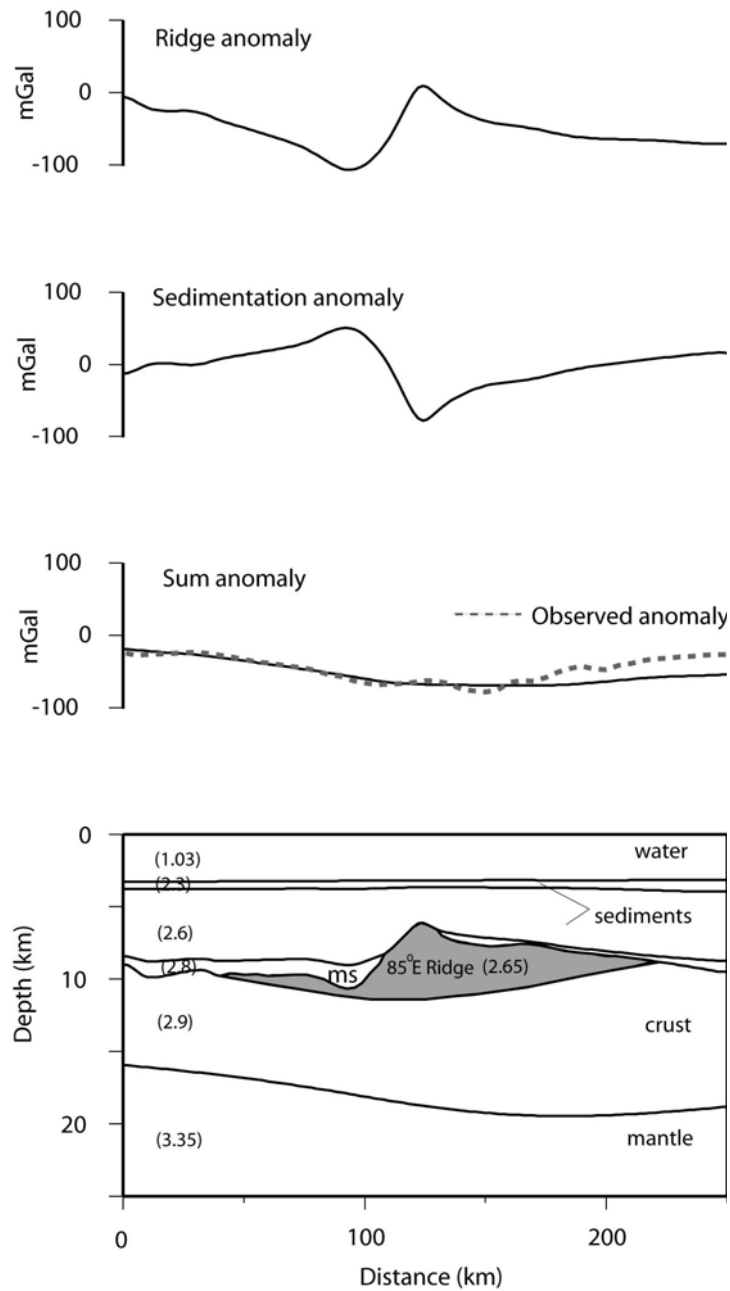


Figure 5.7c Crustal structure of the 85°E Ridge along profile MAN-03 along with different anomaly components obtained from process oriented gravity modeling. The sum anomaly computed for best fitting T_e (15 km) is shown along with the observed gravity anomaly. Notations are same as given in Figure 5.6a.

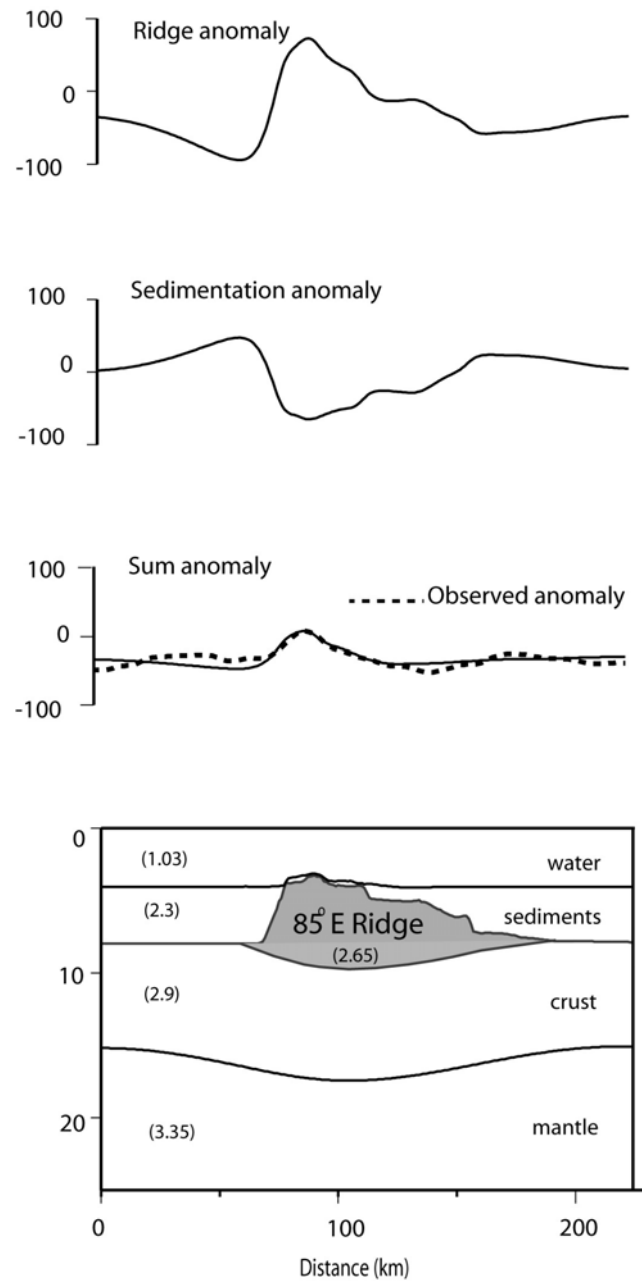


Figure 5.7d Crustal structure of the 85°E Ridge along profile 98791 along with different anomaly components obtained from process oriented gravity modeling. The sum anomaly computed for best fitting T_e (10 km) is shown along with the observed gravity anomaly. Notations are same as given in Figure 5.6a.

field of the ridge. The forward modeling has been carried out along two profiles, MAN-03 and 98971, chosen from northern and southern parts of the ridge, respectively (Figure 5.8a and b). Oceanic crustal layers (2 and 3) with typical densities (2.7 gm/cc and 2.95 gm/cc) and thicknesses (2 km and 4 km) and mantle with density 3.35 gm/cc were considered for the model. The details of densities of sediments used in the model studies are discussed earlier in the previous section. The Moho geometry suggested by process oriented modeling is considered as initial constraints and depths to the Moho and the crustal interfaces were varied iteratively until to get a good match between observed and computed gravity anomalies.

The crustal model along the profile MAN-03 reveals that about 5 km thick volcanic material is emplaced on oceanic crust (Figure 5.8a). The crust responds to the load of the ridge and the overlying sediments by down flexing the crustal layers and Moho boundary to about 2.8 km. This is comparable to the 3 km flexure derived in process oriented model studies (Figure 5.7b). In addition, gravity forward model reveals more detailed geometry of crustal layers and Moho boundary beneath the ridge (Figure 5.8a). The gravity models derived by both the techniques conclusively suggests that the negative gravity anomaly of the 85°E Ridge could be explained by a combination of sources: the flexure at Moho boundary, presence of high density metasedimentary rocks on either side of the ridge and thick Bengal Fan sediments over the ridge

The crustal model derived along the profile 98971 is shown in Figure 5.8b. The ridge appears to be composed of volcanic material of about 6 km thick. Along this profile also, the ridge load is compensated by flexure of crustal layers as well as Moho boundary by about 3.2 km. The model is in good agreement with the model obtained by process oriented technique (Figure 5.78). The positive gravity over the ridge could be explained due to the exposition of the ridge structure above the seafloor and the absence of high-density deeper sedimentary rocks.

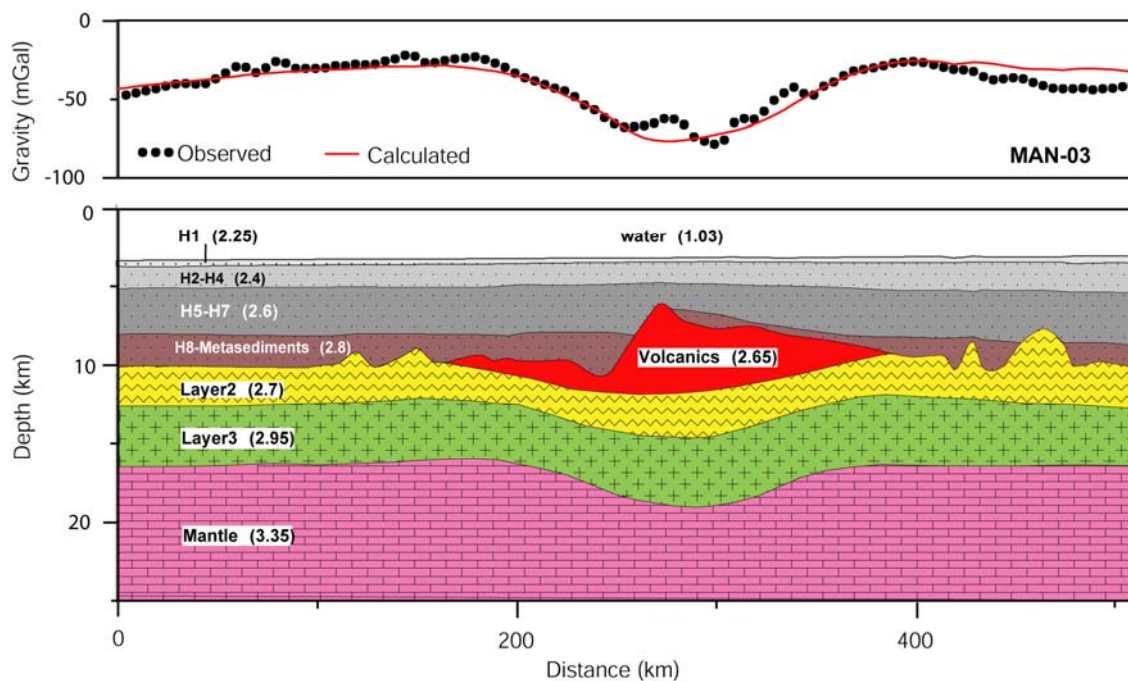


Figure 5.8a Two-dimensional gravity model and crustal structure along profile MAN-03. Values in bracket represent densities in gm/cc. H1, H2-H4, H5-H7 and H8 are sedimentary layers derived from the seismic sequences (H1-H8) identified along the section by Gopala Rao et al., 1997.

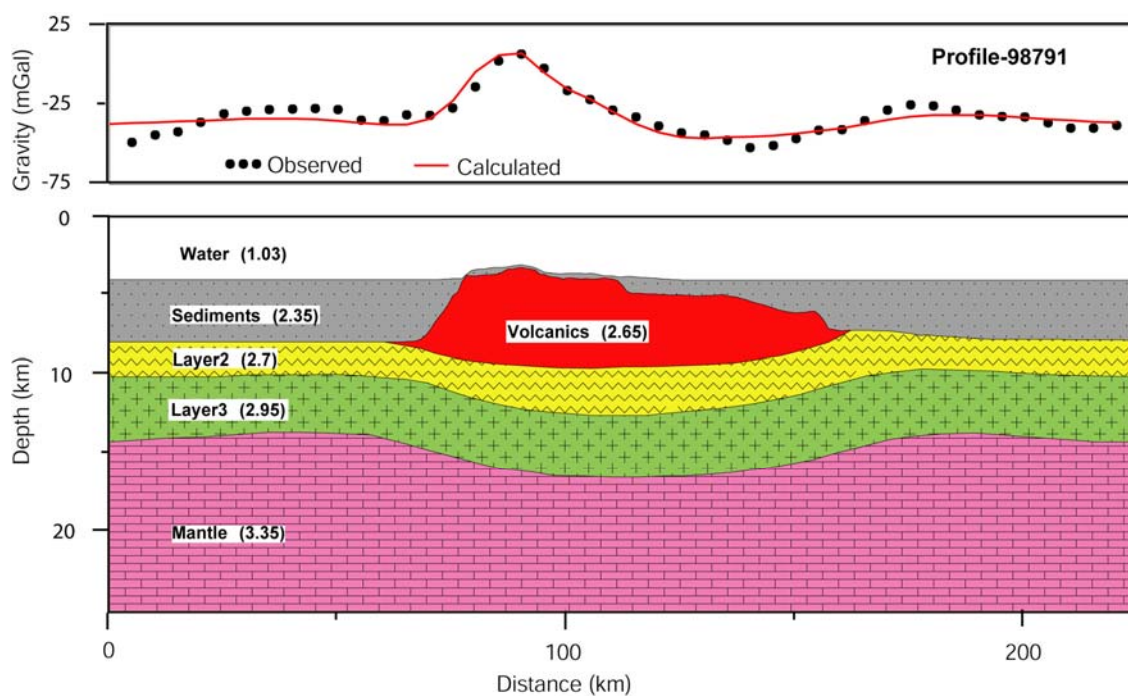


Figure 5.8b Two-dimensional gravity model and crustal structure along profile-98791. Values in bracket represent densities in gm/cc. A single sedimentary layer identified along the section is considered for modeling.

5.8 Different Stages of the 85°E Ridge – Simulation of Gravity Anomalies

As discussed in earlier sections, the initial flexural rigidity and the subsequent sediment deposition explain well the present-day negative gravity anomaly of the 85°E Ridge. Curray et al. (1982) and Gopala Rao et al. (1997) have identified several seismic horizons and unconformities within the sediments of the Bay of Bengal and discussed the sedimentation history in detail since the early Cretaceous. Keeping these results in view an attempt has been made to understand how the gravity field of the 85°E Ridge had changed through time, particularly in response to the sediments of the Bay of Bengal. In other words, gravity anomalies have been simulated at three different geologic ages since the formation of the ridge: late Cretaceous, early Miocene and Present. A simple procedure is followed- flexurally load the sediment layers phase by phase to the backstripped section and compute the gravity anomalies for each phase, particularly for the periods, late Cretaceous, early Miocene and Present. Best-fit T_e value derived for each profile is used for anomaly computations. These steps are briefly described in the flow diagram of process oriented modeling (Figure 5.4). The simulated gravity anomaly and corresponding crustal model derived for three profiles of the Bay of Bengal at three different ages are presented in Figures 5.9a, b and c.

Along profiles MAN-03 and SK107-07, during the late Cretaceous the ridge structure was existing above the seafloor and associated with positive gravity anomaly due to the density contrast existed between the ridge material and water (Figure 5.9b and c). The second panel shows the crustal structure of the ridge and corresponding gravity anomaly determined for the early Miocene period, when the ridge had completely buried under the sediments. The anomaly shows a substantial reduction in amplitude, but it was still positive signature and follows the trend of the ridge topography. However, along MAN-01, by late Cretaceous the ridge structure was overlain by thin layer of sediments and hence associated with comparatively low amplitude gravity anomaly and by early Miocene the ridge got deeply buried under the sediments (Figure 5.9a). The amplitude of gravity anomaly has reduced substantially, but still remains positive over the ridge crest. After loading thick Miocene and post-Miocene sediments, the basal sediments deposited before the continental

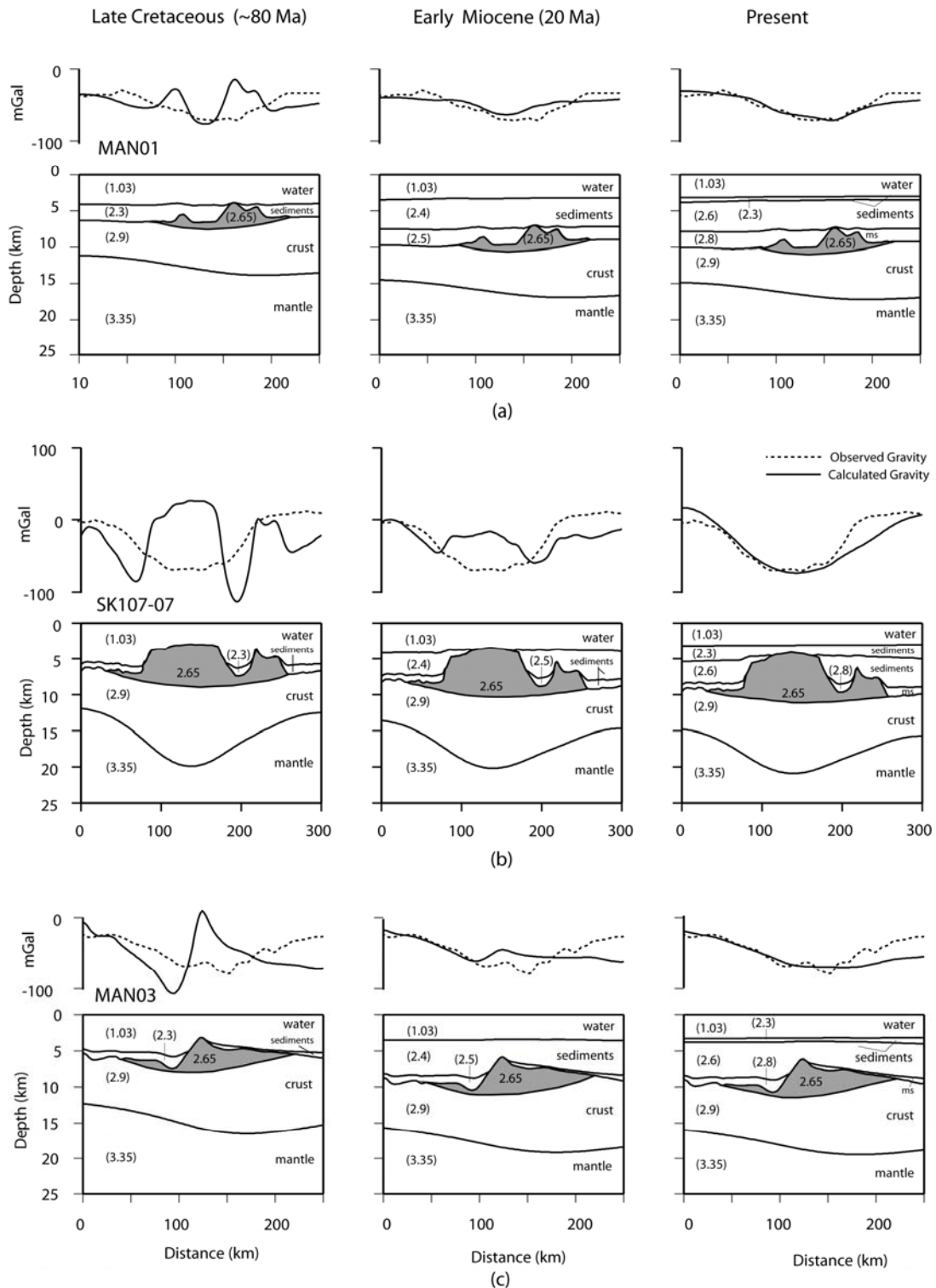


Figure 5.9 Reconstruction of the gravity anomalies over the 85°E Ridge through geological ages for profiles a) MAN-01, b) SK 107-07, c) MAN-03. The bottom panels represent the crustal structures for the respective periods. Note the change of gravity anomaly from positive to negative. ms in figure indicates metasediments.

collision have attained higher densities equivalent to the density of metasediments (2.8 gm/cc) (third panel in Figures 5.9a, b and c). It can be observed that the gravity high over the ridge structure remains till the early Miocene age, subsequently the anomaly signature switches to negative field.

Another interesting aspect is the response of the ridge and adjacent oceanic crust to the sediment loads since the ridge emplacement. The Moho deflection produced by the ridge load during the late Cretaceous has progressively broadened with the addition of sediment material. As the thicknesses of sediments are less over the ridge crest and increases on either side of it, the sediment load flattens the flanks of the Moho deflection. The wavelength of computed gravity anomaly matches with that of the sediment loaded Moho deflection. This suggests that the sediment layers mask the gravity effect of the ridge, and the negative anomaly could be attributed to the deflection created by the ridge load and sediments on adjacent crust. These effects are more clearly visible along the profile SK107-07 as the flexure is more prominent compared to the flexure observed along other profiles (Figures 5.9)

5.9 Structure and Tectonics of the 85°E Ridge

Process oriented modeling of seismic and gravity data of the 85°E Ridge determines the elastic plate thickness range from 10 to 15 km for both northern and southern parts of the ridge, suggesting that the ridge emplacement was in an intraplate (off-ridge) setting. When the hotspot volcanism takes place on relatively older lithosphere, the emplaced volcanic construct would be compensated regionally. Subsequent sediment deposition led to the deeper burial of the ridge structure and adjacent oceanic basement, as a result pre-collision basal sediments have turned into metasedimentary rocks. The crustal models (Figures 5.7a, b and c, 5.8a and b, 5.9) further suggest that the 85°E Ridge and overlaying sediment load are compensated by the regional flexure of the Moho boundary. This inference is not in agreement with the earlier interpretations of the ridge structure (Liu et al., 1982; Mukhopadhyay and Krishna, 1991; Ramana et al., 1997; Subrahmanyam et al., 1999; Anand et al., 2008), wherein they favored the Airy model of isostatic compensation for the 85°E Ridge. Subrahmanyam et al. (1999) have considered underplated magmatic material

within the deep crust beneath the ridge in order to explain the negative gravity field satisfactorily; this led to believe that the 85°E Ridge was formed by a hotspot on young oceanic crust similar to the emplacement process of the Ninetyeast and Chagos-Laccadive ridges. As no deep seismic reflection or seismic refraction data are available to examine the presence of underplating or subsurface loading beneath the ridge, a simple tectonic model considered, in which the ridge includes only a surface load emplaced on a thin elastic plate. Consideration of a complex model with subsurface loading may add ambiguities in Te estimation and crustal structure as well. Also, it should be noted that plume related ridge emplacement can occur in different tectonic settings on the plate, so the structural complexities and mode of isostasy along its path (aseismic ridges) must be understood in detail, particularly in the case of deeply buried 85°E Ridge.

The results obtained in this work are combined with the earlier geophysical results of the 85°E Ridge and Conrad Rise, and with the geochronology of the rocks recovered from the ANS (Sborshchikov et al., 1995) in order to understand the evolution of the ridge and ANS in a broader perspective. Recent understanding on evolution of the conjugate oceanic regions of the Bay of Bengal and Enderby Basin (Gaina et al., 2007; Krishna et al., 2009a) enlighten that most part of the oceanic crust in the Bay of Bengal was accreted during the Cretaceous super long normal polarity phase. Hence, it is obvious that no coherent magnetic anomalies related to the Earth's magnetic reversals are probable in the Bay of Bengal. In spite of this, the 85°E Ridge is associated with alternate stripes of strong positive and negative magnetization patterns distributed for asymmetrical extents (Michael and Krishna, 2011). Following the magnetic model studies and correlations of the ridge magnetization patterns with Geomagnetic Polarity Timescale, Michael and Krishna (2011) found that the ridge was formed from 85 Ma onwards and recorded the changes of the Earth's magnetic fields, earlier to that, the underlying Bay of Bengal crust was created during the Cretaceous super-long normal polarity phase. The intermediate elastic plate thickness (10-15 km) derived from the present study strongly support the emplacement of the ridge on already evolved oceanic crust. These results when combined with the age constraint (~120 Ma) of the Bay of Bengal oceanic crust (Gopala Rao et al., 1977; Krishna

et al., 2009a) would conclusively suggest the emplacement of the ridge on an oceanic crust of about 35 m.y old.

From the recent geophysical investigations, Krishna et al. (2011a) have suggested that the ANS includes two components of volcanic materials, the main plateau and seamount highs. The main plateau was constructed along with the formation of the oceanic crust during 79-73 Ma, and seamount highs were formed subsequently in an intraplate setting. The low elastic plate thickness up to 5 km determined beneath the ANS (Paul et al., 1990), is much lower than the T_e values calculated for the 85°E Ridge and is attributed to the initial on-ridge volcanism. Following the above results and discussions it is believed that the 85°E Ridge volcanism started approximately 85 Ma ago in Mahanadi Basin by a short-lived hotspot. Around this time the Conrad Rise hotspot has emplaced the main plateau of the ANS and Marion Dufresene seamount together close to the India-Antarctica Ridge (Diament and Goslin, 1986), thereafter the hotspot has moved to the Antarctica plate leaving the main plateau of the ANS as an isolated feature on the Indian plate (Figure 5.10). At other end in the Bay of Bengal the hotspot, which initiated the emplacement of the 85°E Ridge in the Mahanadi Basin, has continued its activity towards south and probably ended at ~55 Ma in the vicinity of the ANS.

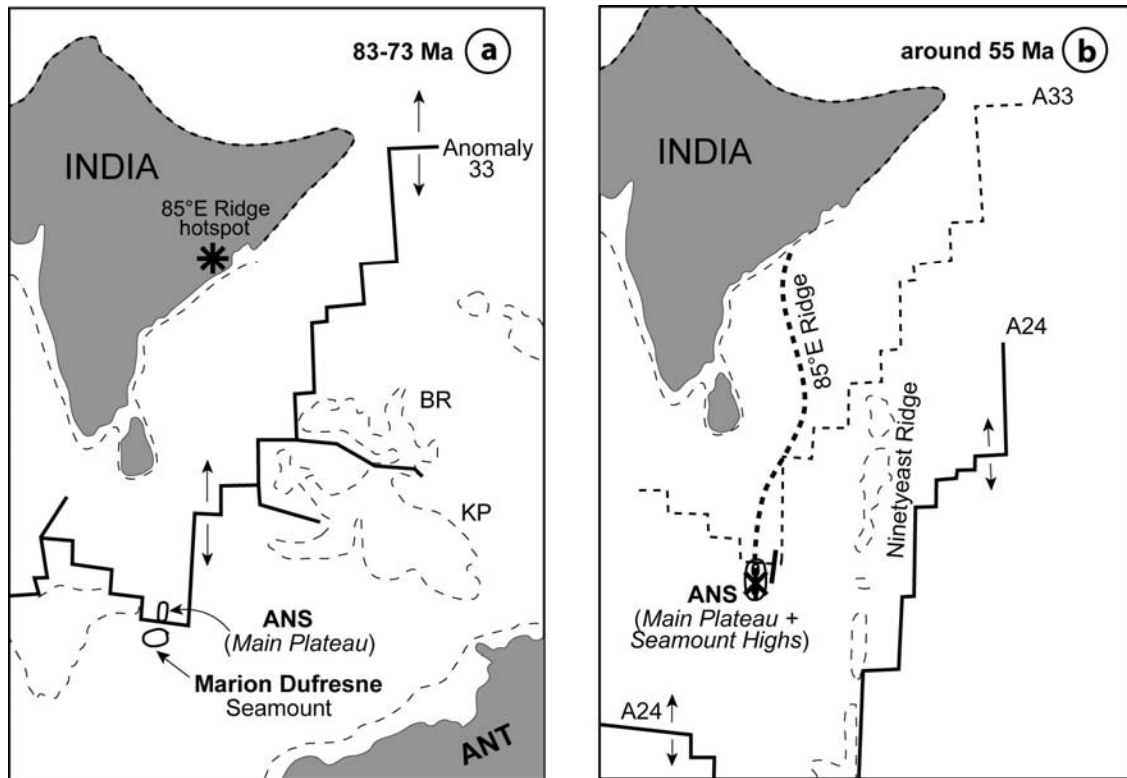


Figure 5.10 Late Cretaceous (Left) and Paleocene (Right) reconstruction of northeastern Indian Ocean (Krishna et al, 2011a). The emplacement the main plateau of ANS and initiation of 85°E Ridge emplacement at Mahanadi Basin during ~85 Ma is shown in the left panel. By ~55Ma 85°E Ridge emplaced and the causative hotspot reactivated ANS (Right). The concurrent evolution of Ninetyeast Ridge by Kerguelen hotspot activity is also shown (Right). BR and KP stands for Broken Ridge and Kerguelen Plateau respectively.