

Structure and Isostasy of the Comorin Ridge

- 4.1 Introduction
- 4.2 Geological Setting of the Region
- 4.3 Geophysical Data
- 4.4 Bathymetry, Gravity and Magnetic Anomalies of the Comorin Ridge
- 4.5 Gravity-Topography Admittance Analysis
 - 4.5.1 Elastic Plate Thickness and Crustal Thickness
 - 4.5.2 T_e and Age of Emplacement of the Comorin Ridge
- 4.6 Crustal Structure of the Comorin Ridge- Two-Dimensional Gravity Forward Modeling
 - 4.6.1 Crustal Structure of the Southern Comorin Ridge
 - 4.6.2 Crustal Structure of the Northern Comorin Ridge
- 4.7 Continent-Ocean Boundary on Western Margin of Sri Lanka and Southern Tip of India
- 4.8 Tectonics and Evolution of the Comorin Ridge

Structure and Isostasy of the Comorin Ridge

4.1 Introduction

The presence of the Comorin Ridge in the north Indian Ocean was first reported by Heezen and Tharp (1964) from the compilation of echo-sounding data acquired during the International Indian Ocean Expedition (IIOE). Using marine geophysical data, Kahle et al., (1981) have suggested that the Comorin Ridge was formed on oceanic crust with Airy type compensation and also opined that the eastern edge of the Comorin Ridge could mark a boundary between oceanic crust and rifted/ altered continental crust. Further they concluded that the ridge seems to act as a barrier to the passage of Ganges sediments to the west. Southeast of the Comorin Ridge, Krishna et al. (2001a) have also mapped steep isolated basement rises in seismic reflection data and attributed that the rises were acting as a barrier for limiting the Bengal Fan sediments in western side. All these structures together have encircled the western margin of Sri Lanka and contributed to the formation of a small basin within the Gulf of Mannar (Figure 4.1). The origin of the Comorin Ridge is not clearly known yet. Using marine magnetic data, Desa et al. (2006) opined that it may be a transform ridge formed during the early phase of opening of the Indian Ocean. Later, Shena et al. (2007) have suggested that the ridge could be a product of large-scale volcanism during the onset of seafloor spreading.

Admittance analysis technique was, in general, earlier performed on various geological features of the Indian Ocean to obtain structure and isostatic compensation mechanisms (Detrick and Watts, 1979; Paul et al., 1990; Ashalatha et al., 1991; Chand et al., 2001; Tiwari et al., 2003; Bansal et al., 2005). However, a detailed study of the isostatic behavior of the Comorin Ridge is not yet attempted. The present study investigates the mode of isostatic compensation and nature of the crust underneath the Comorin Ridge using admittance analysis and forward modeling of ship-borne bathymetry and gravity data sets. Also, an attempt has made to mark the Continent-Ocean Boundary (COB) on west of Sri

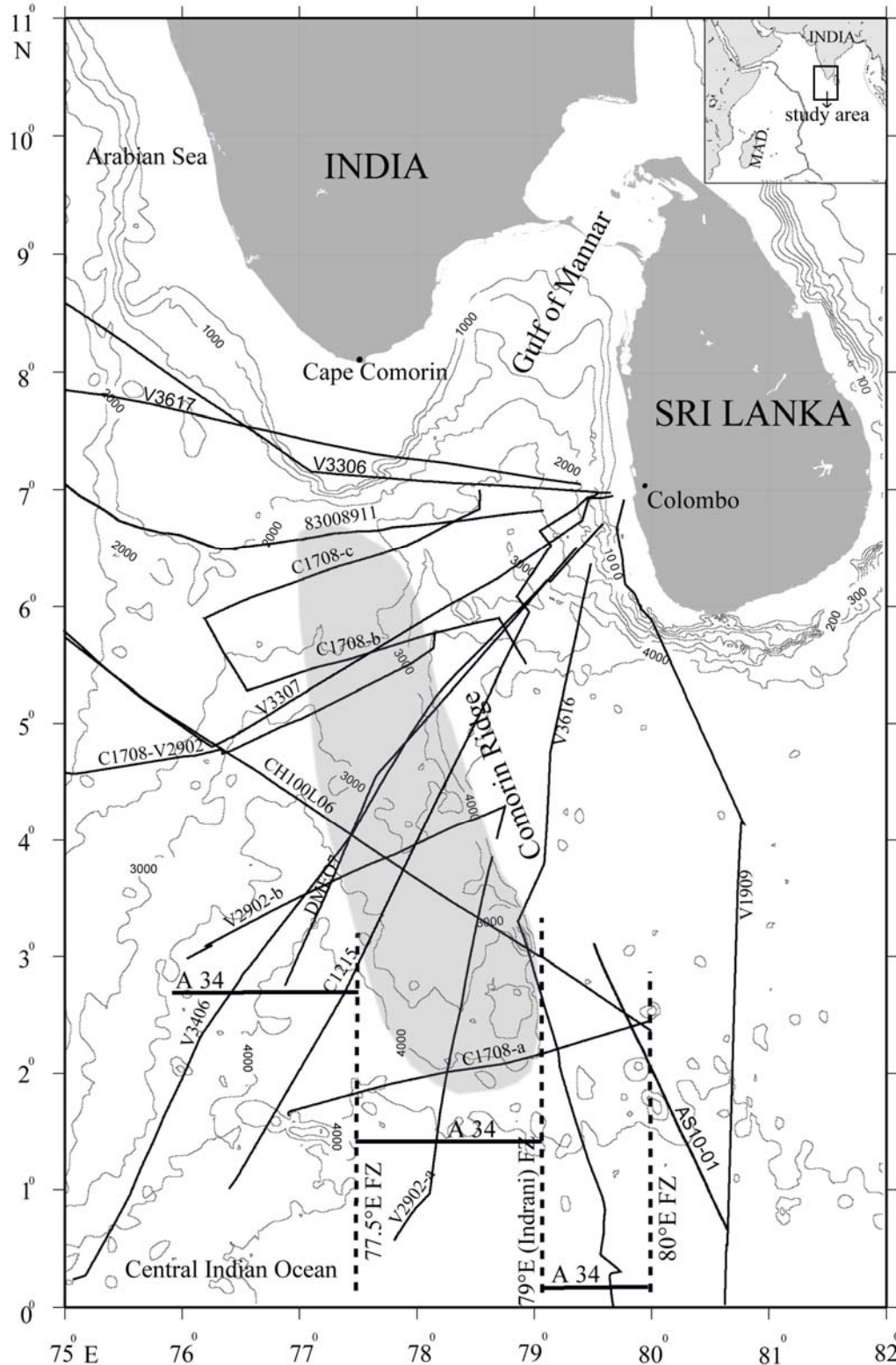


Figure 4.1. General bathymetry of the southern tip of India and south and west margins of Sri Lanka (ETOPO5). Light shaded region shows the location of the Comorin Ridge. Solid lines indicate the geophysical profiles. Magnetic lineation A34 and fracture zones shown in this figure are after Müller et al. (1997) and Krishna and Gopala Rao (2000).

Lanka and southern tip of India. Based on new inferences, a plausible tectonic model for the evolution of the ridge is proposed.

4.2 Geological Setting of the Region

The eastern continental margins of India and Sri Lanka were evolved in the early Cretaceous after their break-up from the Mac.Robertson Land - Enderby Land, east Antarctica (Rotstein et al., 2001; Kent et al., 2002; Giana et al., 2007; Jokat et al., 2010). At a subsequent stage, after 124 Ma, a continental fragment called Elan Bank was detached from the northeastern margin of India (Gaina et al., 2003). The southwest margin of Sri Lanka and southern margin of India seem to have been rifted initially at around 127 Ma from east Gunnerus Ridge, east Antarctica. During the phase, before the commencement of the first major change in spreading direction in the Indian Ocean, there was a probable ridge jump towards India-Sri Lanka region similar to the ridge jump that occurred on the northeastern margin of India. This implies that the earliest oceanic crust formed near the India-Sri Lanka region was transferred to the west Enderby Basin (Nogi et al., 2004). Therefore, most part of the oceanic crust adjacent to the India-Sri Lanka region seems to be evolved during the long Cretaceous normal polarity reversal (120-83 Ma).

It is widely believed that the western margin of India has rifted from the eastern margin of Madagascar during the late Cretaceous period (White and McKenzie 1989; Storey et al., 1995, 1997; Torsvik et al., 1998, 2000; Raval and Veeraswamy, 2003a). Also, it is supposed that the rifting process was associated with the Marion hotspot volcanism, which occurred at Volcan de l'Androy, southeast Madagascar and caused the eruption of widespread basalts and rhyolites in Madagascar and Fe-Ti-enriched tholeiites in southwest India. Hence the hotspot source was attributed to the formation of the Comorin Ridge and some basaltic flows and dykes in the southwestern margin of India (Radhakrishna et al., 1994; Anil Kumar et al., 2001) as well as in Madagascar (Storey et al., 1995; Torsvik et al., 1998) before shifting its activity entirely to the African plate. The Comorin Ridge extends in NNW-SSE direction between latitudes 1.5°N and 6.5°N (Figure 4.1) with an average width of 150 km. The southern part of the ridge lies on the oceanic crust evolved older to the age of seafloor magnetic anomaly A34 and is bounded by the 77.5°E and 79°E

(Indrani) FZs. The nature of the crust beneath the northern part of the ridge is not clearly known.

4.3 Geophysical Data

Bathymetry, gravity and magnetic data along 17 profiles totaling to 9200 lkm across the Comorin Ridge and in its adjacent parts, acquired during the cruises of Conrad 17, Vema 29, 33, 34, Chain L06, Jean Charcot 83008911, Dimitry Mendeleev 07 (NGDC 1998) and A. A. Sidorenko (AS 10), are used in the present study. Additionally, ETOPO-5 bathymetric data (3D image) are used to study the morphology of the ridge. Sediment isopachs of this region published by Kahle et al. (1981) are also considered for two-dimensional forward modeling of gravity anomalies in order to constrain the sediment thickness along profiles C1215 and V3307.

4.4 Bathymetry, Gravity and Magnetic Anomalies of the Ridge

A three-dimensional topographic map of the seafloor is presented in Figure 4.2 for better visualization of the Comorin Ridge morphology and its comparison with the adjacent seafloor. Bathymetry, gravity and magnetic profiles have been stacked with reference to the axis of the Comorin Ridge and are shown in Figure 4.3. The depth to the seafloor along the profiles (Figure 4.3) varies from 2 to 4.2 km. The important geomorphic features in the study area are the Comorin Ridge, another ridge-like structure in the northwest quarter of the region, a steep scarp of up to 1.2 km on the eastern flank of the ridge, and 77.5°E and 79°E (Indrani) FZs. In general the water depth adjacent to the Comorin Ridge is decreasing towards north from 4 km to 2.5 km (Figures 4.2 and 4.3). The southern part of the ridge between 1.5°N and 3°N has an elevation of up to 0.5 km compared to that of adjacent seafloor. In the central part between 3°N and 5°N, the ridge has maximum elevation of 1 km from the surrounding water depths, and in the north between 5°N and 6.5°N, the ridge has an elevation generally on eastern side ranging from 0.4 to 0.7 km (Figure 4.3). On the northern part of the ridge, the western flank does not have any distinct bathymetric expression as it probably merges with the continental rise of the southern tip of India

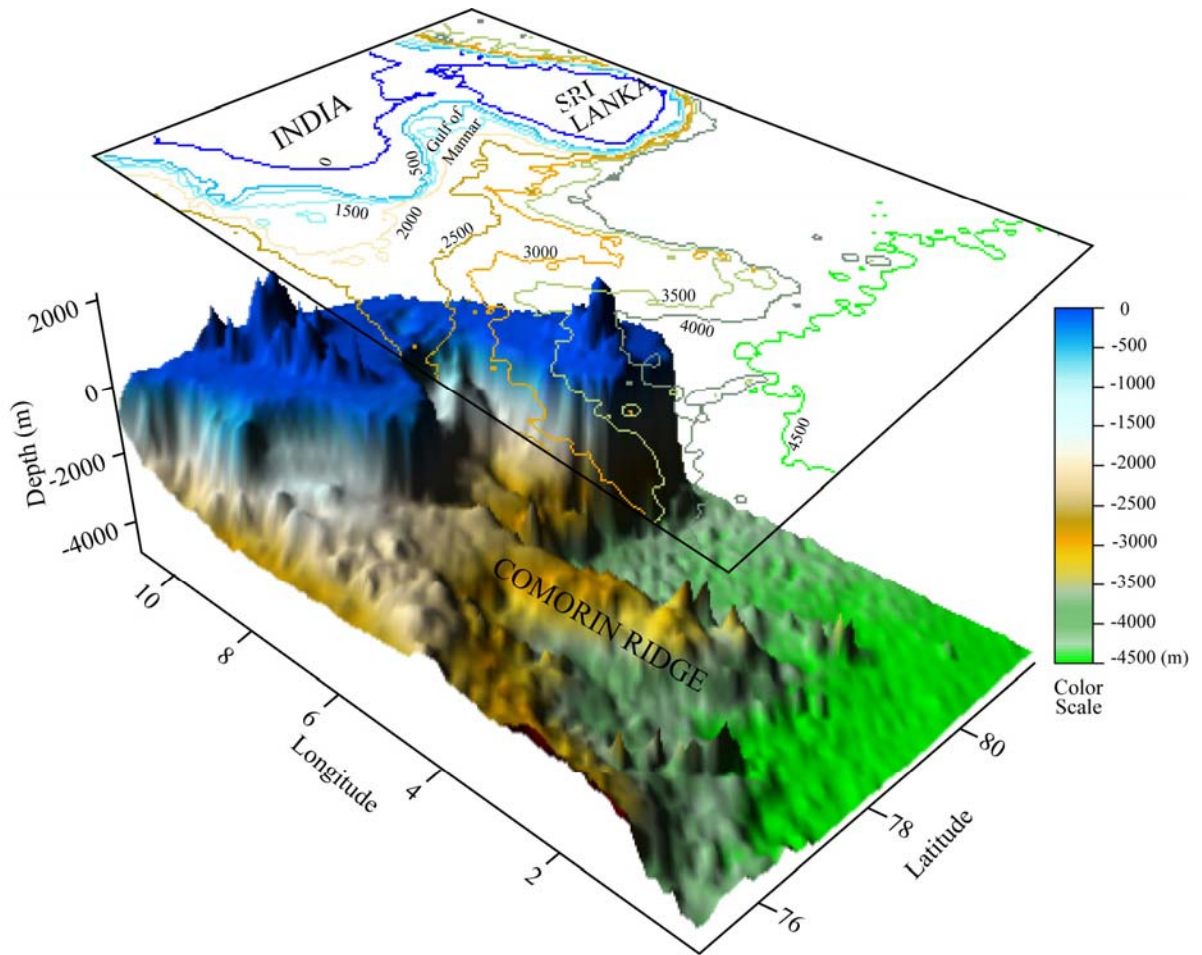


Figure 4.2 Three dimensional view of the Comorin Ridge surface topography generated from ETOPO5 data.

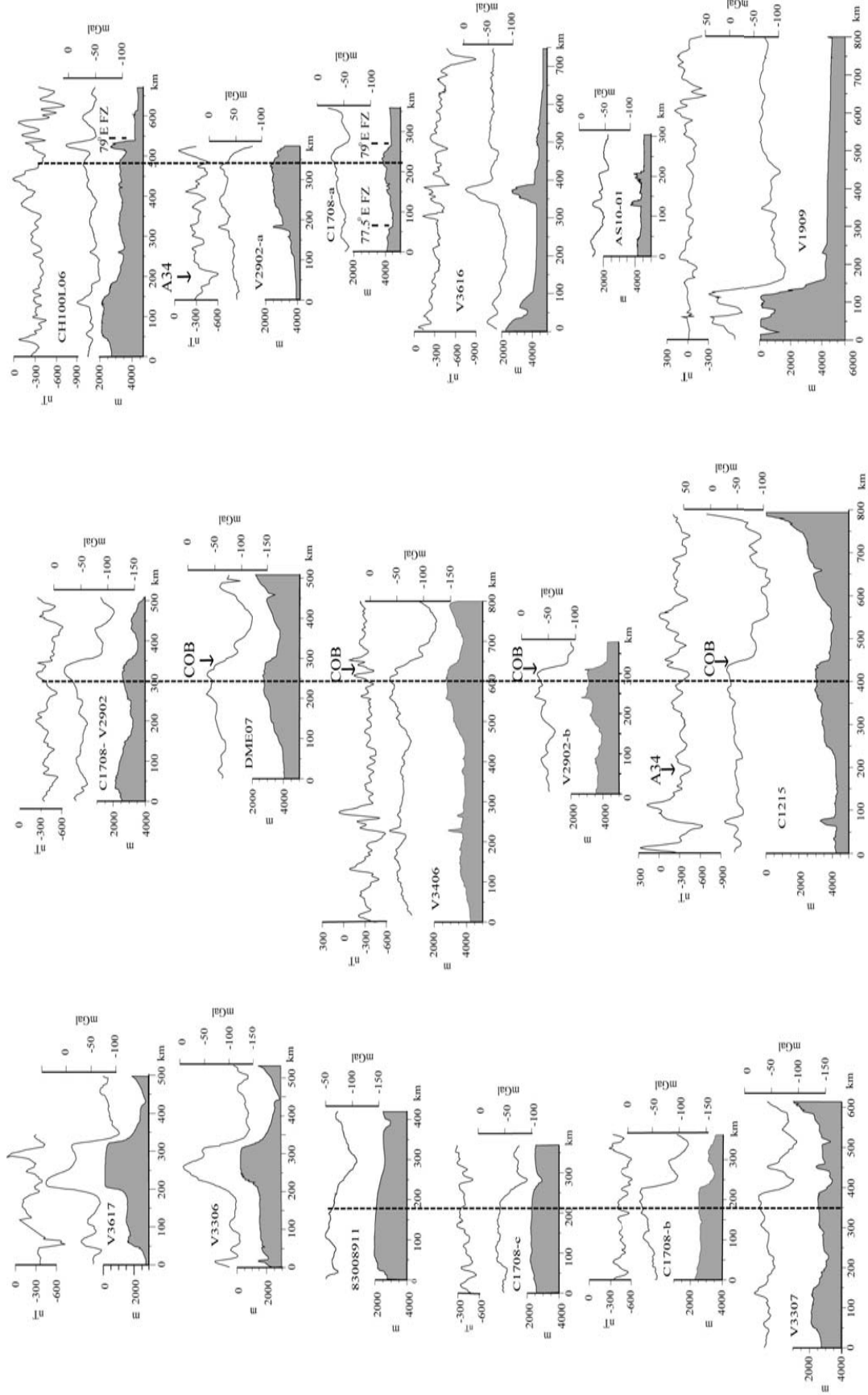


Figure 4.3 Composite plots of bathymetry, gravity and magnetic profile data across the Comorin Ridge and its vicinity. The dashed line marks the axis of the Comorin Ridge

(Figure 4.2). While in the southern part, the western flank extends for more than 100 km with relatively smooth gradient, the eastern flank comes to an end about 50 km distance with a steep scarp of about 1.2 km (Figure 4.3). North of the ridge, north of 5.5°N the eastern steep scarp is not obviously seen.

The free-air gravity anomalies of the Comorin Ridge region, in general, follow the topography of the seafloor with variable amplitudes (Figure 4.3). From satellite gravity data of the central Indian Ocean, Gopala Rao et al. (2004) found NW trending elongated gravity high closures associated with the Comorin Ridge. From the profile data, it is evident that the ridge is associated with relatively low-amplitude gravity anomalies of about 25 mGal in southern part (1.5°N – 5°N) and 30 mGal in northern part (5°N – 6.5°N) corresponding to its variable elevations (Figure 4.3). The less elevated northern part of the ridge is associated with relatively high-amplitude 30 mGal gravity anomaly, suggesting that this part of the ridge is relatively less compensated in comparison to its southern part. Along the profiles C1215, V2902-b, V3406, DME07, C1708-V2902, V3307 and C1708-b a significant regional gravity anomaly of more than 50 mGal is observed on the eastern flank of the Comorin Ridge (Figure 4.3). Such significant anomaly is absent on other profiles, CH100L06 and C1708-a, in spite of sharp increase in depths to the seafloor (about 500 m) on eastern side of the ridge. Northern most profiles, V3306 and V3617 show bathymetric rise and associated high gravity anomalies (Figures 4.1 and 4.3), which are related to the southern tip of continental margin of India and not associated with the Comorin Ridge.

Most of the present study area is underlined by oceanic crust and was evolved during the period from post-anomaly 34 to younger part of the long Cretaceous magnetic quiet period. The seafloor magnetic anomaly 34 is identified with confidence on profiles V2902-a and C1215 (Figure 4.3). The rest of the anomalies having short-wavelength and low-amplitude are in general non-coherent and may have been formed during the Cretaceous Magnetic Quiet Period. The anomaly identifications (A34) are reasonably acceptable as they are found to be compatible with the earlier anomaly identifications of adjacent region (Krishna

and Gopala Rao, 2000). It is further observed that the Comorin Ridge as one is not associated with any specific magnetic anomaly signatures.

4.5 Gravity-Topography Admittance Analysis

The theoretical basis and methodology for admittance analysis are described in detail in Chapter 3. Out of 12 bathymetry and gravity profiles (Figures 4.1 and 4.3), 9 profiles crossing the Comorin Ridge were selected for the admittance analysis. These profiles were projected perpendicular to the strike of the ridge and their length is limited to 300 km keeping the apex of the ridge in the centre. Each profile has been sampled at an interval of 1.172 km representing a spatial wave-number range of $0.0105 < k < 2.6805 \text{ km}^{-1}$ ($600 > \lambda > 2.344 \text{ km}$). The mean including linear trend in the data were removed and the ends of the profiles were tapered using a cosine window of 10% profile length prior to the spectral estimation. The Welch's averaged periodogram method was used to compute cross spectrum and power spectrum because of its improvement over the conventional Fast Fourier Transform (FFT) method (Welch 1967). The method has advantage of having less variance, hence it produces smooth admittance. In this method, bathymetry and gravity data are divided into overlapping segments and each of them is detrended, windowed using Hanning window and discrete Fourier transformed. MATLAB codes are developed for admittance analysis. The inputs to the program are gravity-bathymetry data and model parameters for theoretical admittance computation as listed in Table 4.1. These codes can processes the data sets, generates admittance values, compute theoretical admittance curves, plot them together and finally select the best fit by computing the RMS difference between the two.

4.5.1 Elastic Plate Thickness and Crustal Thickness

In admittance analysis, the admittance values generally computed along individual ship-tracks crossing the aseismic ridge, are smoothed by averaging. Thus, the smoothed admittance exclusively represents the overall isostatic state of the ridge structure. In order to examine the variation of the isostasy along the Comorin Ridge, individual admittance estimates are computed and then compared with the Airy and flexure theoretical models

for a wavenumber range of $0.0105 < k < 0.15$, where the isostatic compensation effect is prominent (Figures 4.4a and b). Though the admittance values along the profiles show considerable scatter, the southern profiles show low amplitude admittance compared to the

Table 4.1 Model parameters used for the calculation of theoretical admittance.

<i>Parameter</i>	<i>Notation</i>	<i>Value</i>
Density of Sea-Water	ρ_w	1.03 gm/cc
Density of oceanic layer 2	ρ_2	2.70 gm/cc
Density of oceanic layer 3	ρ_3	2.90 gm/cc
Density of mantle	ρ_m	3.35 gm/cc
Thickness of oceanic layer 2	t_2	2 km
Thickness of oceanic layer 3	t_3	5 km
Young's modulus	E	100 Gpa
Poissons ratio	σ	0.25

northern profiles. A rough estimate of T_e and t values along the profiles were made by visual match and presented in Table-4.2. Following the T_e and t value ranges, the profiles are combined into two groups: southern profiles (T_e range 1-5 km, t range 15-20 km) and northern profiles (T_e range 9-20 km and t more than 30 km) and calculated smoothed admittance by averaging individual spectra.

The \log_{10} of the amplitude of admittance, coherence and phase for southern and northern profiles of the Comorin Ridge are presented in Figures 4.5a and b. High coherence ($\gamma_{(k)}^2 > 0.5$), low phase (θ) and smooth admittance values are observed for $k < 0.314$ ($\lambda > 20.01$ km). For this same waveband the coherent gravitational energy caused by topography is dominant over incoherent energy (Figures 4.6a and b). This clearly indicates that for $k < 0.314$ ($\lambda > 20.01$ km) the admittance computation is most reliable and can be used to compare with the theoretical models. The amplitude of the admittance decreases at lower wave-numbers indicating isostatic compensation at deeper depths. At higher wave-numbers the admittance flattens, probably because of instrument noise in the shipboard gravity data. The part of the admittance not caused by isostasy and instrument noise

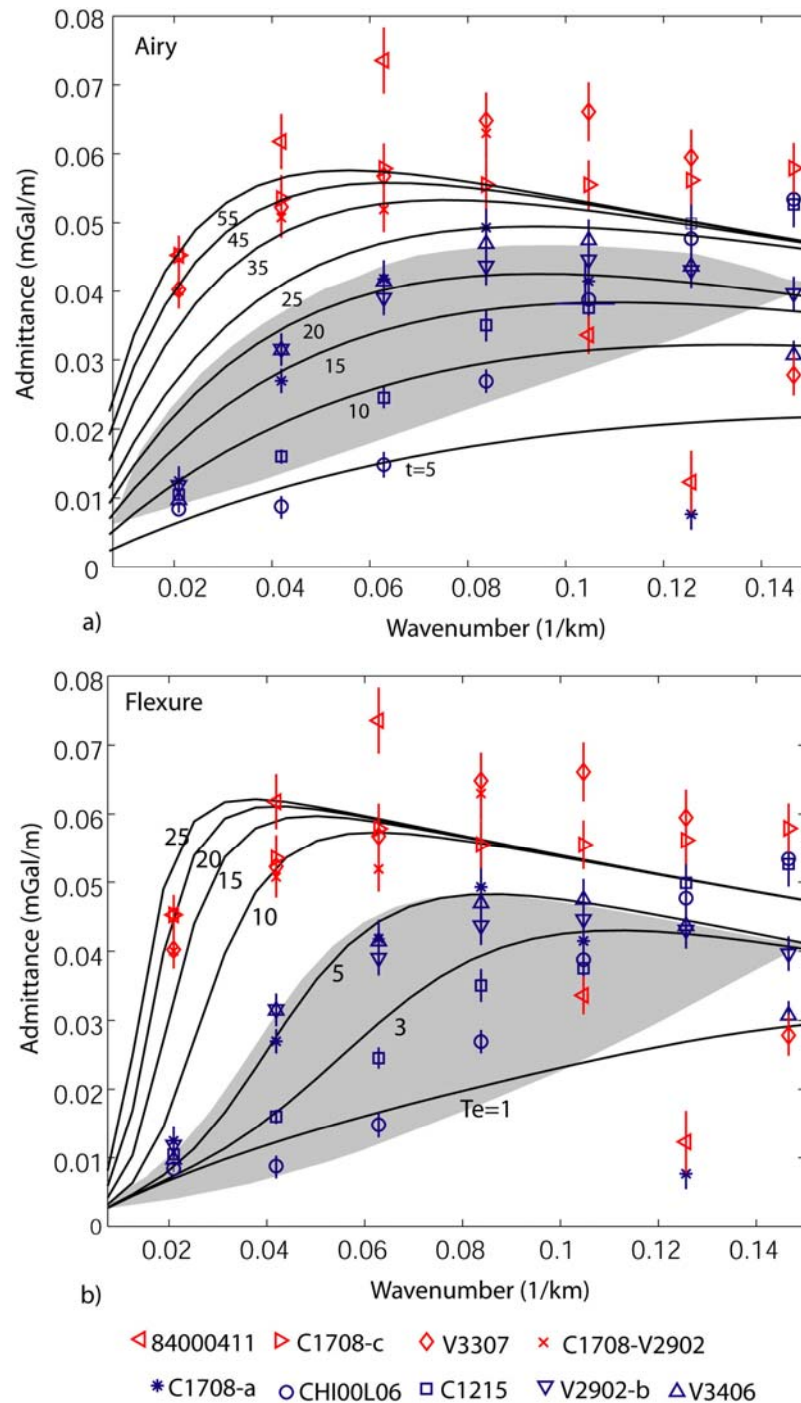


Figure 4.4a and b Admittance values computed for individual profiles plotted with theoretical curves for Airy and Flexure models. Southern profiles (blue) matches with $T_e \sim 1-5$ and $t \sim 10-20$ (shaded region). Northern profiles (red) matches with $T_e \sim 10-20$ and $t \sim 30-50$. The T_e and t values for each profiles are listed in Table 4.2.

Table 4.2 Elastic plate thickness (T_e) and crustal thickness (t) are determined from admittance analysis and approximate age of lithosphere at the time of ridge emplacement is determined for each profile following the relationship of Calmant and Cazenave (1987).

<i>S. No.</i>	<i>Profile Id</i>	<i>T_e (km)</i>	<i>t (km)</i>	<i>Approximate Age (Myr)</i>	<i>Remarks</i>
1	C1708-a	4-5	15	2.2-3.5	Low T_e and high t values
2	CH100L06	1-3	No match	0.13-1.2	Low T_e value
3	C1215	2-3	10-15	0.6-1.2	Low T_e and high t values
4	V2902-b	3-4	20	1.2-2.2	Same as above
5	V3406	3-4	20	1.2-2.2	Same as above
6	C1708-V2902	9-15	30-40	11-31	High T_e and exceptionally high t values
7	V3307	10-15	40	14-31	Same as above
8	C1708-c	10-15	>40	14-31	Same as above
9	84000411	15-20	>50	31-55	Same as above

reflects the uncompensated topography ($0.11 < k < 0.8167$ and $0.04 < k < 0.44$ for the southern and northern parts respectively). This part of the spectrum carries the information on the mean water depth and density of the topography. As discussed in Chapter 3, the uncompensated admittance can be expressed as

$$Z(k)_{uncomp} = 2\pi G(\rho_c - \rho_w)e^{-kd}$$

Taking logs on both sides yields

$$\log_{10} Z(k)_{uncomp} = -kd \log_{10} e + \log_{10} (2\pi G(\rho_c - \rho_w))$$

The slope and intercept of the log linear plot of $Z(k)$ against k is $d0.4335$ and $\log_{10} (2\pi G(\rho_c - \rho_w))$, respectively. Average water depth and density of the crust are calculated from slope and intercept of the linear least square fit to the log10 admittance for $0.11 < k < 0.8167$ and $0.04 < k < 0.44$ for the southern and northern parts of the ridge (Figures 4.5a and b). For the southern part the mean calculated water depth, 3.52 km is in agreement with observed water depth of 3.5 km and the estimated density of 2.5 gm/cc is less than the density of normal oceanic crust. Estimated water depth (2.7 km) and density (2.75 gm/cc) for the northern part are comparable with the observed water depth of 2.6 km and density of normal oceanic crust.

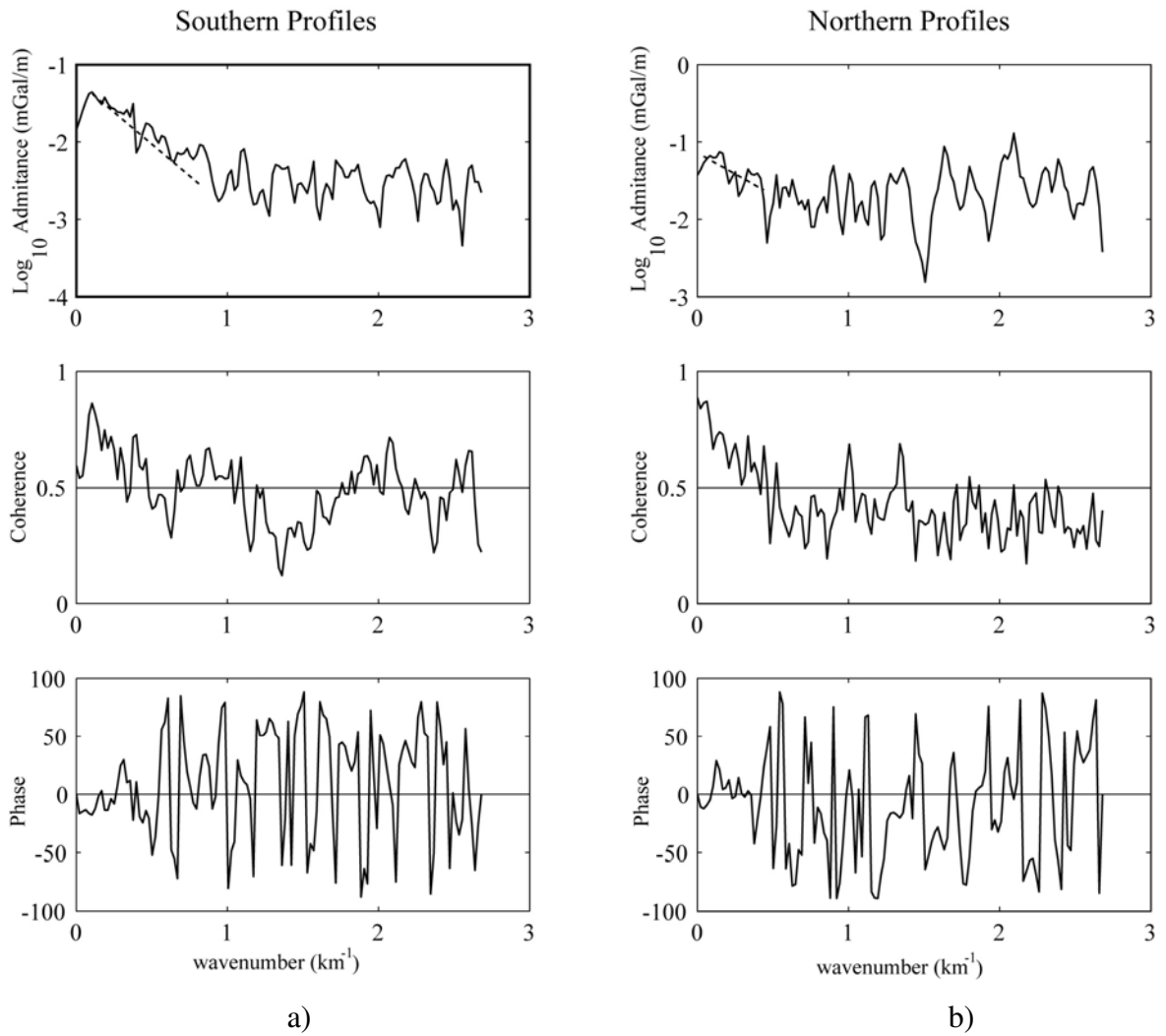


Figure 4.5a and b Admittance, coherence and phase in degree generated from a) southern and b) northern set profiles. The dashed line represents the best fit to the observed admittance

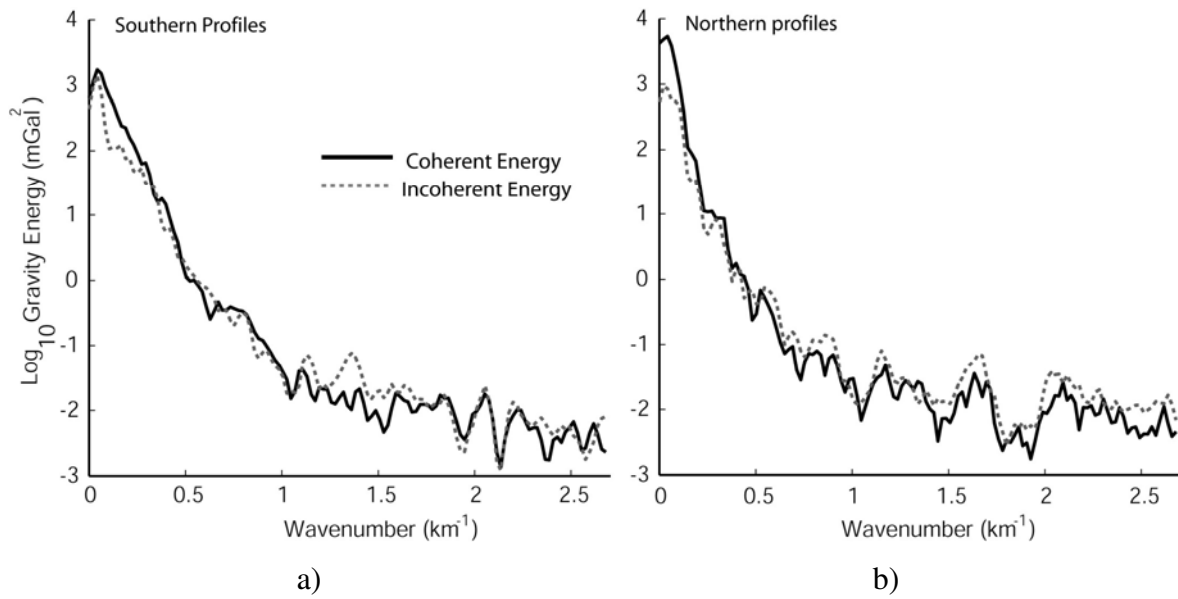


Figure 4.6a and b The gravity energy generated from a) southern and b) northern profiles.

Theoretical admittance values and observed admittance values with standard error bars are shown in Figures 4.7a and b. Root Mean Square (RMS) errors between the observed and theoretical admittance for different t and T_e values are also presented (Figures 4.7a and b). Both RMS error and error bounds in the admittance calculation are considered as the criteria for choosing the best fit T_e and t . Admittance values calculated for southern part of the ridge (Figure 4.7a) are suitable for Airy model of isostatic compensation with a crustal thickness (t) of 15-20 km and for flexural model with T_e value of ~3 km. The observed admittance for the northern part of the ridge is too high to be explained by the Airy model compensation. Crustal thickness of about 40 km is required for explaining the observed admittance, which is very unlikely to be beneath the ridge. On the other hand a simple flexural model with T_e value of ~15 km is reasonably in agreement with the observed admittance (Figure 4.7b). Earlier, Shena et al., 2007 have estimated T_e value of 10 km beneath the Comorin Ridge with the consideration of whole Comorin Ridge and a part of the continental shelf of the southern continental margin of the India as a single block.

4.5.2 T_e and Age of Emplacement of the Comorin Ridge

Watts (1978) proposed that the elastic plate thickness of seamount chains depends on age and temperature gradient of the lithosphere at the time of loading. Further, he has postulated that the elastic plate thickness roughly corresponds to $450 \pm 150^\circ\text{C}$ isotherm of the cooling plate model. Therefore, seamounts with low T_e values are considered to be emplaced on younger oceanic crust and those with higher T_e values on relatively older oceanic crust. Calmant and Cazenave (1987) estimated T_e values over the Pacific, Atlantic and Indian Oceans and proposed a simple empirical relationship between T_e and age of the oceanic crust (million years) at the time of loading is given as

$$T_e = (2.7 \pm 0.15)\sqrt{\Delta t} \quad \dots (4.1)$$

The results derived from the above empirical relation suggest that the southern part of the Comorin Ridge ($T_e = 3$ km) was emplaced on young oceanic crust of 2 to 3 Myr old, whereas the northern part of the ridge ($T_e = 15$ km) might have emplaced on an oceanic

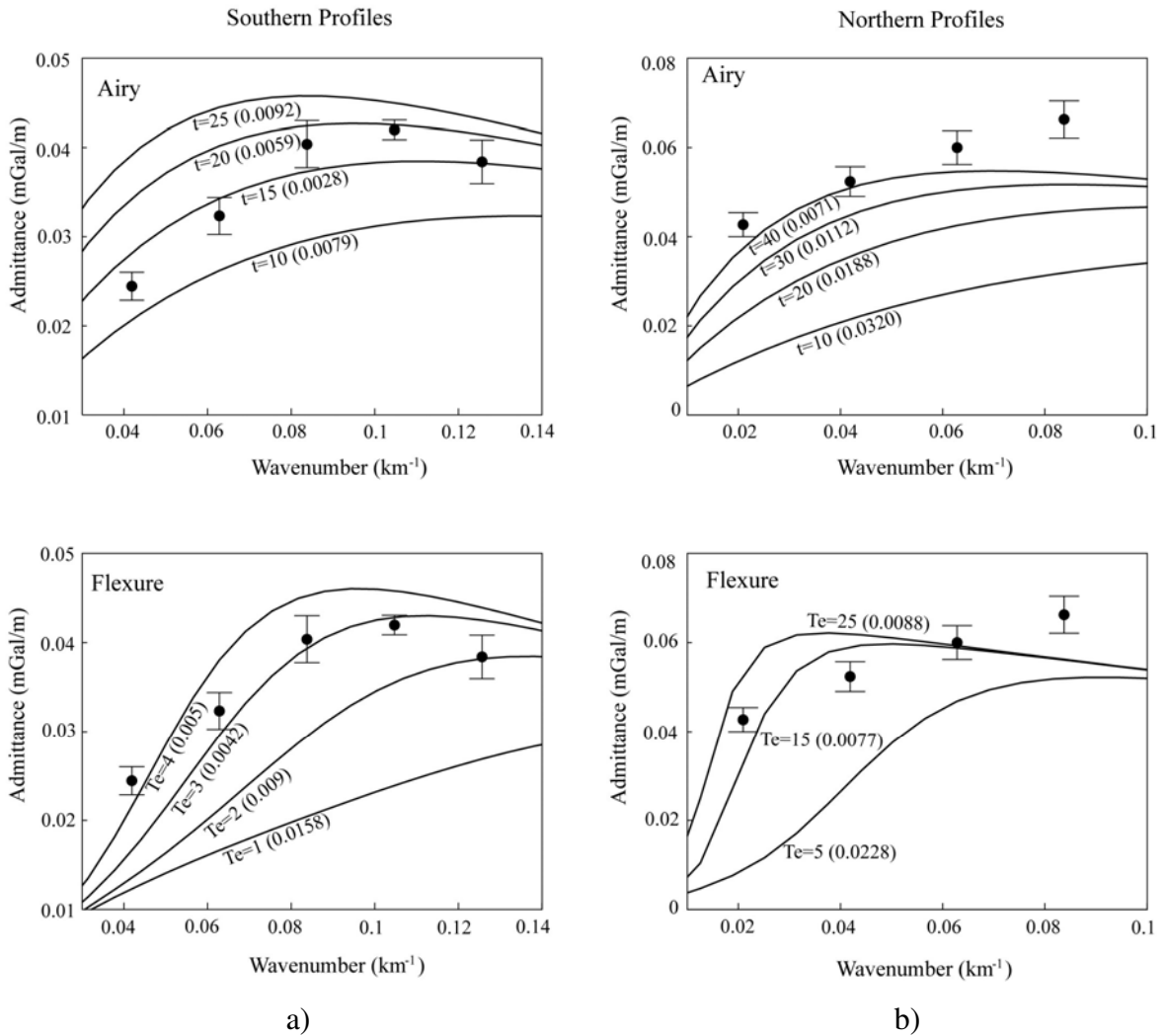


Figure 4.7a and b Observed admittance (solid dots) with standard error bars generated from a) southern and b) northern set profiles plotted with theoretical models based on Airy and Flexure models. The RMS error in mGal/m between the observed and theoretical admittance for various t and T_e values are shown in bracket.

crust of ~30 Myr. To explain this age difference, extremely slow spreading rates during the emplacement of the ridge are required to be considered. Alternatively, the higher T_e value for the northern part of the ridge could be explained by emplacement on altered/ stretched continental crust. Two-dimensional gravity forward modeling is also carried out to obtain the crustal architecture of the Comorin Ridge, and the results are described in the following section.

4.6 Crustal structure of the Comorin Ridge- Two-Dimensional Gravity Forward Modeling

Two gravity anomaly profiles, C1215 from southern part and V3307 from northern part of the Comorin Ridge (Figure 4.1) have been chosen to determine the crustal structure using two-dimensional forward modeling technique. These profiles were selected as the admittance results broadly suggested that the ridge was emplaced in two geological settings: southern part of the ridge was formed on weak oceanic crust and the northern part was formed either on old oceanic crust or altered/ stretched continental crust. Sediment layer and oceanic crust layers (2 and 3) thicknesses are considered from sediment isopach map of Kahle et al. (1981) and seismic refraction results of equatorial region published by Bull and Scrutton (1990) and Neprochnov and Gopala Rao et al. (1998), respectively as initial model parameters. The crustal layers are refined moderately to determine the crustal structure of the Comorin Ridge. Seismic velocities obtained from the refraction studies of the equatorial region, 1°S - 2°N (Bull and Scrutton, 1990; Neprochnov and Gopala Rao et al., 1998) were utilized to determine the densities for oceanic crustal layers, whereas for densities of continental crust, seismic velocity results of western continental margin of India (Naini and Talwani, 1983) were considered. Then these velocities were converted to densities following the velocity-density relationship of Christensen (1977).

4.6.1 Crustal Structure of the Southern Comorin Ridge

The gravity model results along profile C1215 reveal that the crust beneath the southern part of the Comorin Ridge is ~17 km thick, consisting of 2 km thick volcanic rocks, 6 km thick oceanic crust and 9 km thick underplated magmatic rocks (Figure 4.8). The crust

beneath the ridge is comparatively thicker than average oceanic crust thickness (7-8 km) lying west of the ridge and nearly equals the thickness of continental crust extending from the southwest of Sri Lanka. The continental crust off southwest of Sri Lanka terminates at eastern flank of the Comorin Ridge, revealing that the ridge was basically emplaced on the oceanic crust lying adjacent to the continental crust. A small flexure to the magnitude of up to 1 km is observed at interfaces within the crust. Beneath other geological features of the Indian Ocean such as Ninetyeast Ridge and Afanasy Nikitin seamount, thick anomalous crustal structures including volcanic and magmatic rocks were determined (Krishna et al., 2001b; Krishna, 2003) and they are comparable with the results of crustal structure of the southern part of the Comorin Ridge.

4.6.2 Crustal Structure of the Northern Comorin Ridge

An attempt has been made to model the gravity anomalies of the profile V3307 running across the northern part of the Comorin Ridge, with two types of crust (continental or old oceanic) to determine the nature of crust beneath the ridge (Figures 4.9 and 4.10). In the first computation the underneath crust was assumed as continental and could achieve a reasonably good fit between observed and computed gravity anomalies (Figure 4.9). The crustal structure indicates that the northern part of the ridge was emplaced on continental crust with a crustal thickness of about 18 km. About 3 km thick volcanic rocks are determined on top of the crust, which had eventually contributed to flexure the crustal layers and Moho boundary with a magnitude of about 3 km (Figure 4.9).

In second computation the underneath crust is assumed as old oceanic crust with the consideration of similar geometry for upper/ lower crust and Moho interfaces obtained in the earlier model, but with greater densities and reduced thickness of crustal layers (Figure 4.10). Even with this consideration, a reasonable fit with a crustal thickness of about 13 km beneath the ridge is obtained, but towards east, crust thickness increases up to 20 km (Figure 4.10). This crustal model has two difficulties for acceptance: 1. it is difficult to consider such over thick oceanic crust beneath the northern part of the ridge against usual thickness of 7 km oceanic crust, and 2. high T_e value of about 15 km and oceanic crust age of about 30 m.y. (determined from T_e value) at the time of volcanic emplacement are not

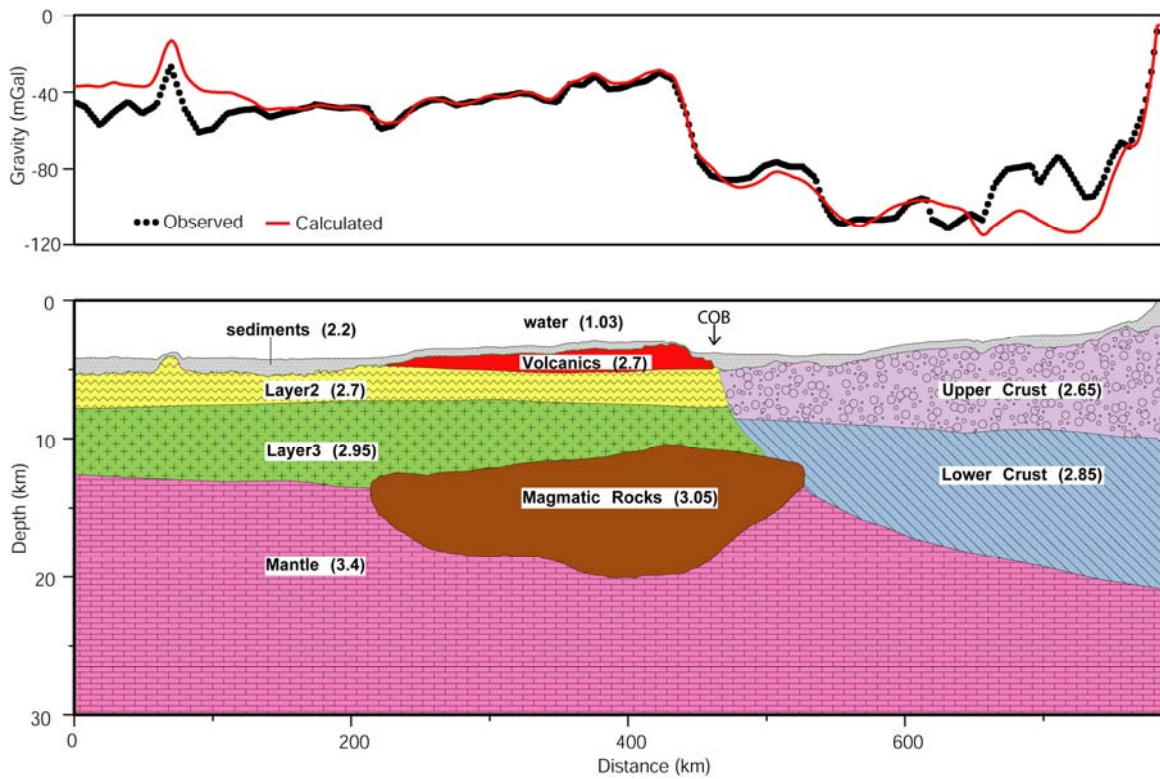


Figure 4.8 Two-dimensional gravity model with interpreted crustal structure along profile C1215. Numerical values within brackets indicate the densities (gm/cc) of different strata.

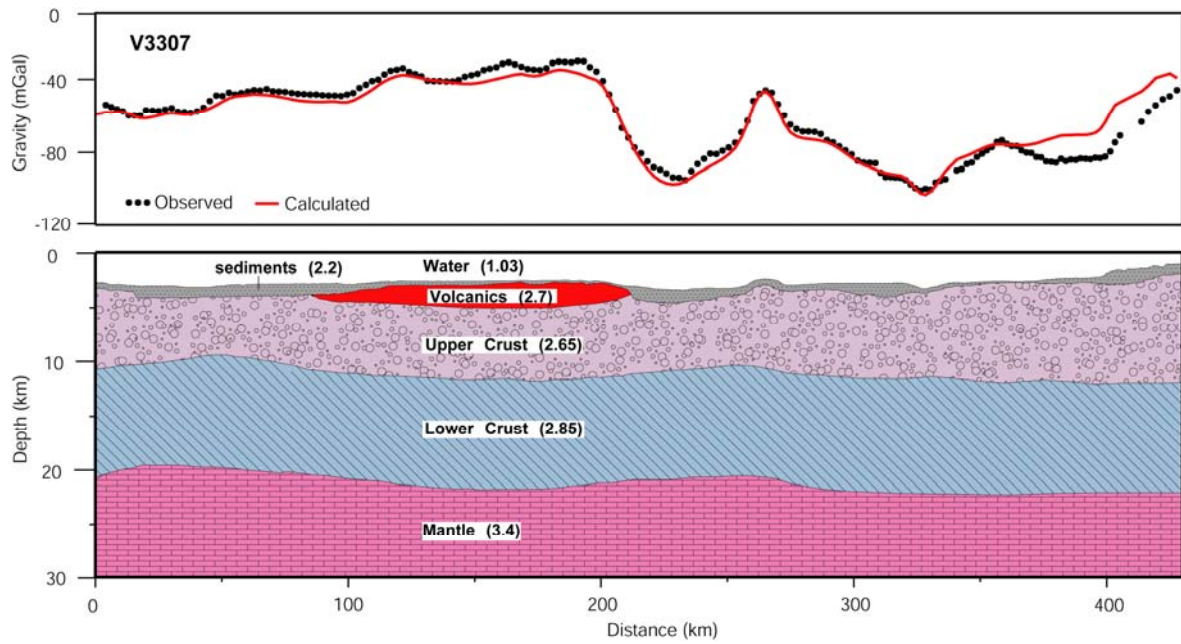


Figure 4.9 Two-dimensional gravity model with interpreted crustal structure along profile V3307 considering that the underneath crust is continental.

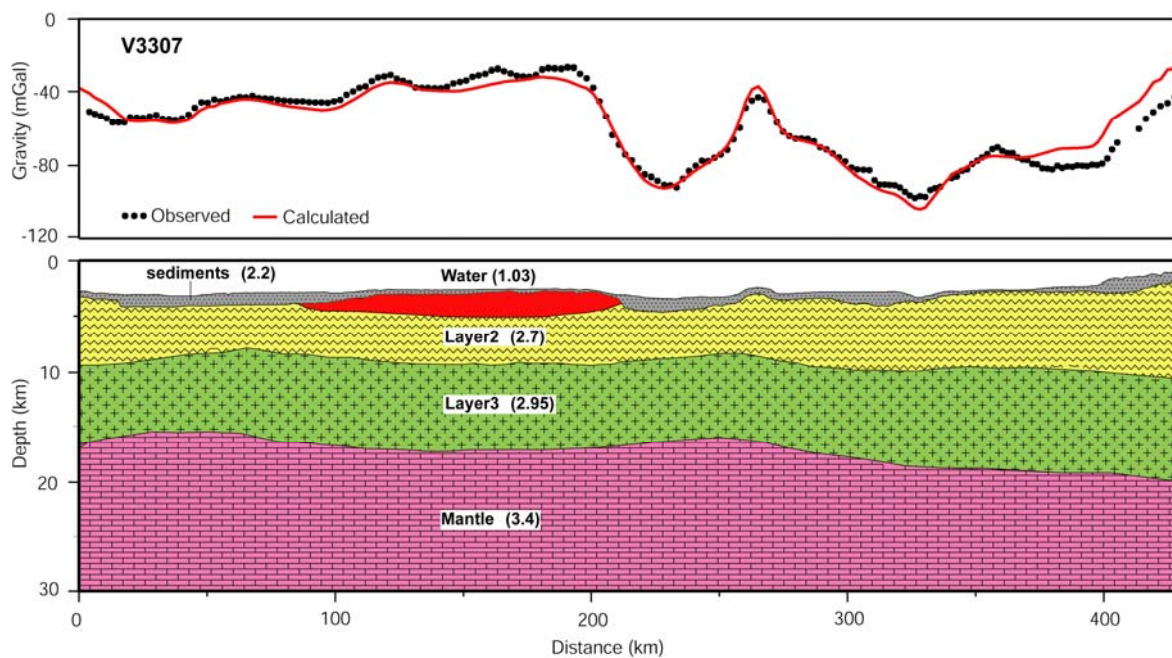


Figure 4.10 Two-dimensional gravity model with interpreted crustal structure along profile V3307 considering that the underneath crust is oceanic.

in accordance with the plate motion data particularly with reference to the evolution of the southern part of the ridge.

4.7 Continent-Ocean Boundary on Western Margin of Sri Lanka and Southern Tip of India

Demarcation of Continent-Ocean Boundary (COB) along the continental margins, in general, provides useful geological information for understanding the evolution of basins, ridges, etc., lying in the vicinity of margins or seaward. The boundary and associated geophysical signatures may further useful for the better understanding of how continental margin segments split from its conjugate margin segments, whether those were in transform motion before they drifted away or in rift phase for longer periods. A steep scarp on seafloor topography and rapid decrease in gravity anomaly are, in general, observed with variable amplitudes on eastern edge of the Comorin Ridge (Figure 4.3). The 79°E FZ in the central Indian Ocean, south of the present study area possess a distinct step-like structure with rapid increase in water depths by about 0.3 km and sudden fall in gravity anomalies by about 20 mGal on east side of the FZ (Kamesh Raju et al., 1993). Keeping these signatures in view, the northward continuity of the 79°E FZ on profiles C1708-a and CH100L06 (Figures 4.1 and 4.3) are mapped. Further north along profiles C1215, V2902-b, V3406 and DME07 steep scarp of about 1.2 km on east side of the ridge is seen associated with lateral shift of ~50 mGal in regional gravity field. But no significant magnetic anomaly is seen coinciding with the steep scarp of the seafloor topography and lateral shift of the gravity field as the oceanic crust of the study area may have evolved during the long interval of Cretaceous Magnetic Quiet Period. The shift in regional gravity field may be interpreted due to the presence of high-density oceanic rocks beneath the volcanic rocks of the Comorin Ridge (Figure 4.8) between latitudes 3.5°N and 5°N. Earlier, following the same criterion of lateral shift in gravity field, Chaubey et al. (2002) and Krishna et al. (2006) have demarcated the COB on west of the Laccadive Ridge and Laxmi Ridge, respectively. On close observation, it is observed that the amplitude of the gravity anomaly along the eastern edge of the Comorin Ridge varies from ~55 mGal in the central part between 3.5°N and 5°N to ~65 mGal in the northern part between 5°N to 6°N, although the depth to the seafloor is nearly constant (~0.9 km). The gravity anomaly on

northern part is independently controlled by the undulations of seafloor topography, whereas in the central part the anomaly is contributed by multiple sources such as seafloor undulation and geometry between the Moho, lower crust and magmatic body at deeper depth. In other words the northern part of the ridge was emplaced on rigid continental lithosphere and the central part was evolved nearly in the vicinity of continent-ocean adjoining region, hence the gravity anomaly of the central part of the ridge is isostatically compensated.

From Admittance and gravity forward modeling studies it is found that continental crust lies below the northern part of the Comorin Ridge (north of 5°N latitude), allowing COB to run across the strike of the ridge. The boundary permits the northern part of the ridge on continent and southern part on oceanic crust. Earlier Kahle et al. (1981) have related the eastern edge of the Comorin Ridge to the place of significant change in crustal structure, which they have cautiously attributed to the boundary between oceanic crust on the seaward side and rifted or altered continental crust on the landward side.

The COB and associated magnetic and gravity anomalies of the present study area are compared with that of eastern and western margins of India (Gopala Rao et al., 1997; Krishna et al., 2006) (Figure 4.11), with a view to discussing the possible geological processes associated with COB evolution (Figure 4.11). On eastern margin of India the COB was located at about 70-80 km seaward of the shelf edge, whereas on western margin of India the COB was placed along the west of the Laxmi Ridge about 400 km away from the shelf edge. In the present study area, it is inferred that the COB lies about 250 km off southwest of Sri Lanka and about 300 km off southern tip of India (Figure 4.11). The gravity signature having a lateral shift in regional field is seen associated with the COB on both western margins of India and Sri Lanka, while on the eastern margin of India the COB associates with a different gravity signature of high-amplitude, short-wavelength negative gravity anomaly that rapidly changes to low-amplitude broad regional anomaly (Gopala Rao et al., 1997; Subrahmanyam et al., 2001; Krishna et al., 2009a). South of Sri Lanka, the COB has been placed about 250 km away from the coastline following the changes in regional trend of the gravity field on profiles (V3616 and V1909 in Figure 4.3)

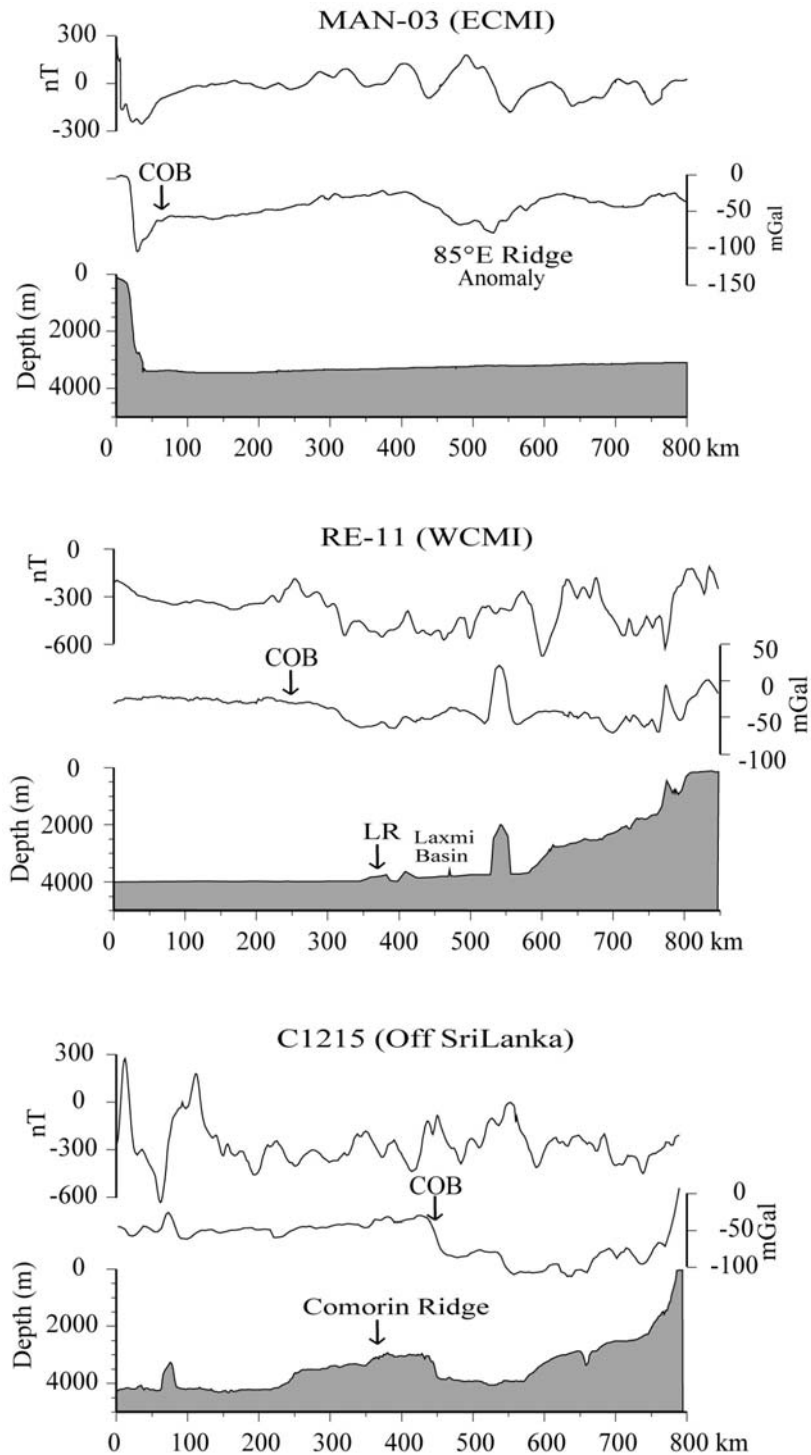


Figure 4.11 A comparison of bathymetry, gravity and magnetic profile data from western continental margin of India (WCMI), eastern continental margin of India (ECMI) and western margin of Sri Lanka. The diagnostic character of regional shift in gravity anomaly for demarcation of COB is observed in western margin of Sri Lanka and WCMI

as well as in satellite gravity image (Figure 4.12). The boundary is tentatively indicated, but needs to be confirmed by other geophysical results. Off Kron Prinz Olav Kyst and Gunnerus Ridge region, east Antarctica (believed to be conjugate part of Sri Lanka), Stagg et al., (2004) have marked the COB within the Enderby Basin, which is about 250 km away from the coastline and lying in water depths of around 4000 m. Thus the COB on southwest and southern parts of Sri Lanka and their conjugate region, off east Antarctica has evolved approximately in similar geological processes.

4.8 Tectonics and Evolution of the Comorin Ridge

The geophysical results obtained from admittance analysis and gravity modeling are explained in light of the tectonic history of the Indian Ocean in order to put forward a plausible geological mechanism for the evolution of the Comorin Ridge. Airy isostatic model beneath the southern part of the ridge, proximity of seafloor spreading anomaly 34 between 77.5°E FZ and 79°E FZ and plate kinematic models suggest that the ridge was formed during the late Cretaceous period. Volcanic rocks, erupted during the late Cretaceous were found on the southwest coast of India (Radhakrishna et al., 1994; Anil Kumar et al., 2001) and southeast of Madagascar (Storey et al., 1995; Torsvik et al. 1998 and 2000) and the rocks were considered as products of the Marion hotspot formed during the rift stage of western margin of India from Madagascar. Earlier investigations: plate motions relative to the Indian Ocean hotspots (Müller et al., 1993), plate reconstructions (Storey et al., 1995; Torsvik et al., 2000) and sub-marine morphological structures of India and Madagascar (Yatheesh et al., 2006) suggest that the breakup between Madagascar and India has occurred at around 90 Ma. The probable location of the Marion hotspot with reference to the continental masses of India, Madagascar, Seychelles and Africa for the late Cretaceous period, just prior to the emplacement of the Comorin Ridge is shown in Figure 4.13 (Torsvik et al., 2000). Keeping these inferences and present geophysical results in view, it is proposed that the Comorin Ridge may have been emplaced by the Marion hotspot volcanic activity in a span of about 6 m.y. from north (88-90 Ma) to south (82-84 Ma).

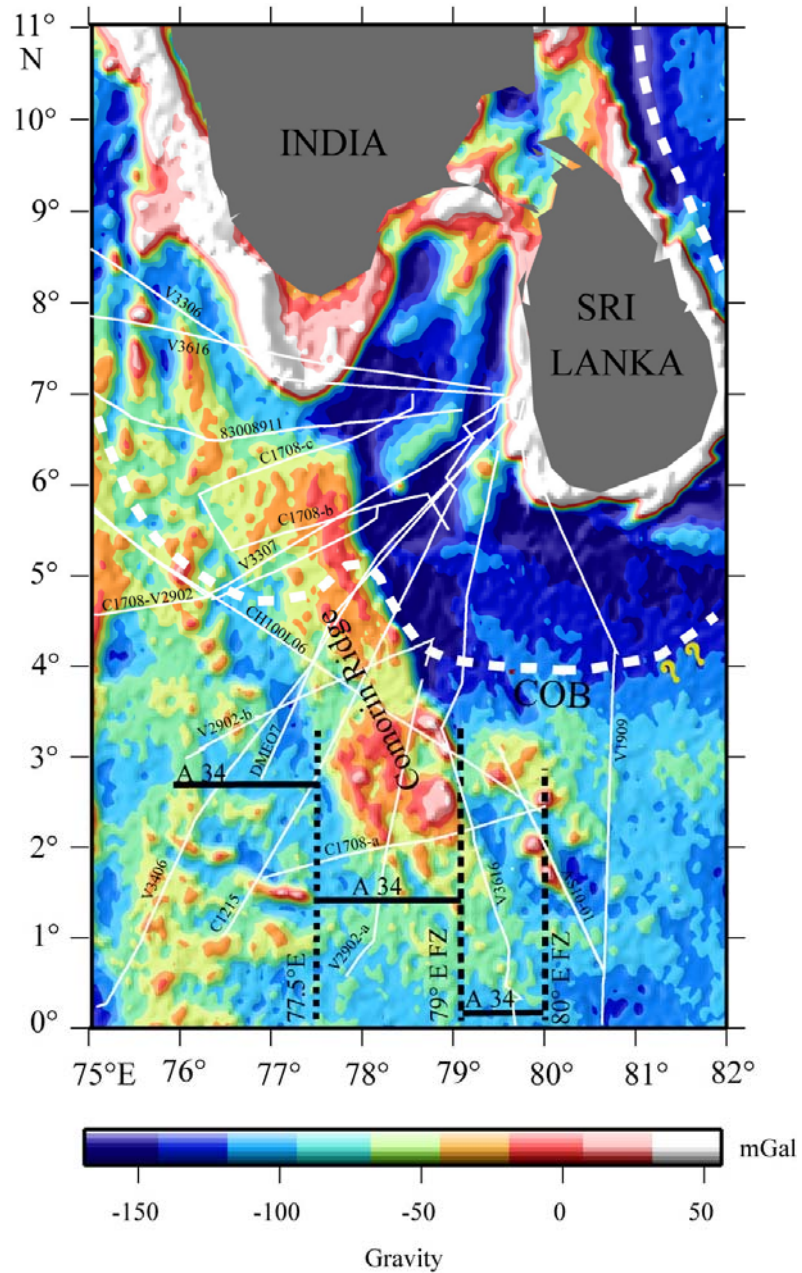


Figure 4.12 Interpreted COB on western margin of Sri Lanka and southern tip of India, geophysical profiles used in this study, fracture zones and magnetic lineation A34 are superimposed on satellite gravity field (Sandwell and Smith, 1997). Eastern margin of Comorin Ridge is bounded by different tectonic elements.

T_e value (about 15 km) beneath the northern part of the Comorin Ridge suggests that the ridge was emplaced either on approximately 30 m.y. old oceanic crust or on rifted/ altered continental crust, whereas the southern part of the ridge was emplaced on 2-3 m.y. old oceanic crust ($T_e=3$ km). It is difficult to reconcile the presence of old oceanic crust beneath the northern part of the ridge as the age spans for the formation of the oceanic crust from north to south beneath the ridge (about 28 m.y.) and for emplacement of the ridge by the Marion hotspot (about 6 m.y.) are not in accordance with the plate motion data with reference to Indian the Ocean hotspots. Therefore, probably the northern part of the Comorin Ridge was emplaced on rifted continental crust. The gravity model studies across the northern part of the ridge (along profile V3307) also suggest the continental nature of the crust beneath this part of the ridge (Figure 4.9).

Geophysical profiles: C1215, V292b, V3406 and DME 07, across the Comorin Ridge show a distinct character of steep downward-scarp on eastern flank of the ridge. The geophysical signatures such as steep seafloor topography and lateral shift in regional gravity field (Figures 4.3 and 4.8) allow to place the Continent-Ocean Boundary on east side of the central part of the ridge (Figure 4.12). The east side of the ridge (entire) is controlled by different tectonic elements, southernmost part (up to 3.5°N) by the 79°E FZ, central part (3.5°N to 5°N) by the COB and northernmost part by the termination of the Gulf of Mannar Basin (Figure 4.12). From geophysical signatures it can be interpreted that continental crust extends on western margin of Sri Lanka up to east side of the ridge and off the southern tip of India up to 5°N latitude, which includes northernmost part of the ridge (Figure 4.12). Model studies of gravity anomalies suggest that about 21 km thick continental crust lies on the western margin of Sri Lanka that is relatively thinner than the normal continental crust. This thin continental crust may have evolved due to the crustal stretching during the rift processes that took place between Sri Lanka and the Gunnerus Ridge part of east Antarctica (Rotstein et al., 2001; Kent et al., 2002) and between India and Madagascar (Storey et al., 1995; Torsvik et al., 2000). Demarcation of the COB on the western margin of Sri Lanka (Figure 4.12) may provide new constraints on the nature of the crust beneath the Gulf of Mannar Basin. Western part of the Greater India (India-Madagascar-Seychelles) had experienced continental rifts several times in the geological

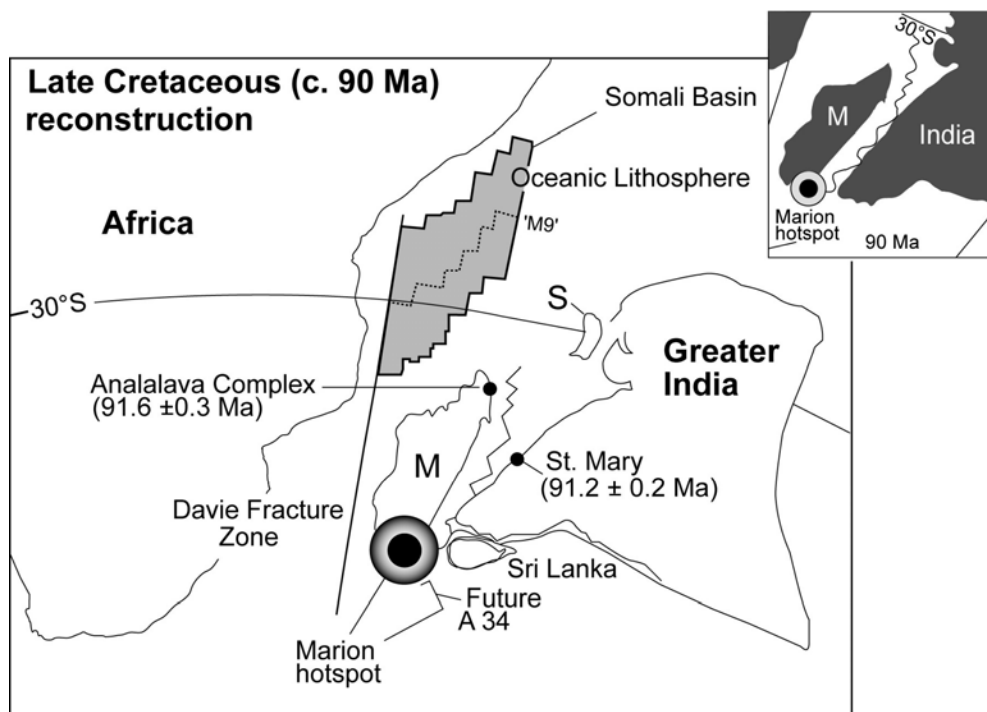


Figure 4.13 Late Cretaceous reconstruction of India, Madagascar (M), Seychelles (S) and Africa with reference to the Marion hot spot position before emplacement of the Comorin Ridge, reproduced from Torsvik et al. (2000).

past; thereby new basins have formed on continent as well as in offshore regions of western India (Krishna et al., 2006). The stretching process that eventually led to continental splitting contributed to the evolution of rifted basins both on western and eastern margins of India. The basins underlain by thin continental crust did not extend further for continental break-ups. For example Cambay and Kutch rifts on western India (Raval and Veeraswamy, 2003b) and Laxmi Basin on western margin of India (Krishna et al., 2006) have remained as failed rifts due to some changes in geological settings. On the basis of subsidence rates, particularly higher rates during the Neogene, in the Gulf of Mannar Basin and folded and uplifted Bengal Deep-Sea Fan sediments off the SSE continental margin of Sri Lanka, Curray (1984) has suggested a possible continuation of continental stretching in the basin. The stretching process between India and Sri Lanka may have contributed to the initiation of basin in Gulf of Mannar and the basin appears to be widening due to the continuing process of stretching. Hence, probably the basin in the Gulf of Mannar had evolved by extensional tectonics, but underlain by relatively thin continental crust.

On comparison of geophysical signatures of COB obtained from the present study area with those from western margin of India (Krishna et al., 2006) and eastern margin of India (Gopala Rao et al., 1997), it appears that western margins of India and Sri Lanka have rifted margin character and eastern margin of India, south of 15°N latitude has transform-rift character. These observations are supported by earlier results obtained from admittance analysis of bathymetry and gravity data of conjugate margins of southeastern margin of India and Enderby Land of Antarctica (low elastic plate thickness of less than 5 km) (Chand et al., 2001; Subrahmanyam and Chand 2006) and conjugate margins of India and Madagascar (Te values ranging from 8-15 km) (Chand and Subrahmanyam 2003).