CHAPTER V

STRUCTURE AND TECTONICS OF THE KERALA BASIN,
SOUTHWEST CONTINENTAL MARGIN OF INDIA
BASED ON GRAVITY DATA
5.1 INTRODUCTION

The Kerala basin is a major onshore-offshore sedimentary basin observed along the western continental margin of India and is located in its southern most part. The basin in the onshore covers mostly the southern and central parts of the Kerala coast between 8.5°N – 10.5°N latitudes bounded by the Western Ghats in the east and the Arabian abyssal plain on the west. The basin is characterized by the presence of major surface / sub-surface structural features such as the Cochin depression, Cape Comorin depression, Pratap ridge and the Alleppey platform which have evolved during the rifting of India and Madagascar and subsequent sea-floor spreading between them (Biswas and Singh, 1988; Singh and Lal, 1993; Storey et al., 1995; Subrahmanyam et al., 1995). Apart from the horsts and grabens, in few places, igneous intrusives and volcanic flows are concealed below the thick sediments in the margin (Subrahmanyam et al., 1995; Chaubey et al., 2002). Many of these structural trends and basement features observed in the offshore areas throughout the western margin were inferred to have been controlled by the Precambrian structural grain of the Indian shield margin (Biswas, 1987; Kolla and Coumes, 1990; Subba Raju et al., 1990). Kolla and Coumes (1990) inferred that the onshore structural trends in the southwest coast extend into the offshore areas as far as the east of Laccadives (Figure 5.1), which suggests that the continental crust extends up to at least east of Laccadive islands. The aim of the present study is to delineate structure of this rifted continental crust and to study rift tectonics of the southwest margin by integrated analysis of both onshore and offshore gravity data.
Figure 5.1 Shaded relief map of the southwestern shield and the adjoining offshore areas. Prominent structural features are marked on the map. The present study area is marked as a square. Major faults continuing into offshore are from Kolla and Coumes (1990), Biswas (1987). T - Tertiary boundary.
5.2 REGIONAL GEOLOGIC AND TECTONIC FRAMEWORK

The western continental margin of India has evolved through a number of phases. The first significant break between Madagascar and India appears to have occurred at about 140 Ma (Agarwal et al., 1992). The imprints of such early extensional tectonism is observed in terms of dyke swarm activity during 120-140 Ma along the southwestern Indian shield margin (Radhakrishna et al., 1994). Radhakrishna et al. (1994) also observed a major dyke in the present study area (near Kottayam) with an emplacement age of 81 Ma and attribute to a precursory gneous episode not related to the Deccan activity.

5.2.1 TECTONIC HISTORY

Although several conflicting evidences exists on the exact time of rifting between India and Madagascar, more precise age determination of felsic magmatic events by Storey et al. (1995) places the time of rifting at 88 Ma. The separation of Seychelles and Mascarene Plateau from India during early Tertiary as shown by the oldest sea-floor spreading anomalies in the eastern Arabian Sea identified by various workers, indicate as during 63-65 Ma (McKenzie and Sclater, 1971; Norton and Sclater, 1979; Miles and Roest, 1993). Consequent upon the rifting of Madagascar and Seychelles from India, the basement tectonics gave rise to the horst-graben morphology and formation of Kutch, Saurashtra, Bombay and Konkan-Kerala sedimentary basins (Katz and Premoli, 1979; Subrahmanyam et al., 1995).
5.2.2 STRUCTURE

5.2.2.1 ONSHORE

In the onshore regions, the Precambrian basement rocks have a general foliation strike in the NNW-SSE trend. Detailed structural analysis of these rocks revealed several phases of deformation. Several major/minor lineaments/faults with varied strike directions such as NW-SE, E-W and NE-SW occur along the Kerala coast from Landsat imageries (Varadarajan and Balakrishnan, 1980; Nair, 1990), of which the Achankovil – Thenmala shear system is the most prominent and major lineament zone in the study area. Narula et al. (2000) presented some of the most prominent and authentic set of lineaments/faults in the region. High-resolution topographic image obtained for the southwest coast (Figure 5.2) suggests that many of these lineaments have a geomorphic expression. Evidences like the displacement of laterites and other geomorphological features indicate that movements have been taking place along some of the lineaments throughout Tertiary and well into the Quaternary period (Soman, 1997). Some of them show considerable seismic activity as evidenced by the epicentral location of earthquakes (Fig. 5.2) in the region (Tilak, 1980; Rajendran and Rajendran, 1995).

5.2.2.2 OFFSHORE

The major morphological regions of the southwest margin are the shelf, shelf margin basin, Alleppey platform in the shelf-slope region, Pratap ridge,
Figure 5.2 Morphotectonic map of the southwestern shield adjacent to the Kerala basin. The major/minor faults shown on the map are from Narula et al. (2000). The location of several moderate earthquakes in the region are shown. Details are discussed in the text.
Laccadive ridge and the western Arabian basin. The margin is characterised by complex bathymetry and presence of numerous topographic highs. The horst-graben complex in the shelf region divides the Kerala basin into Cochin depression and Cape Comorin depression. There is marked variation in the trend of the shelf region between Cochin and Quilon (Fig. 5.1), where a wider shelf with a gentle seaward slope is observed and this feature is called the Alleppey Platform by Singh and Lal (1993). Further south, the Chagos fracture zone, which separates the Chagos Laccadive Ridge from the Chagos basin can be seen. The Pratap ridge, a linear feature between 8° and 17° N latitude is characterised by several basement rises in the deep sea basin area (Naini and Talwani, 1982) and this ridge was considered as the southward extension of the Kori-Comorin ridge by Singh and Lal (1993). The origin of the Pratap ridge is attributed to either volcanic intrusives during the initial phase of rifting (Naini and Talwani, 1982; Subrahmanyam et al., 1995) or volcanic emplacement from the Reunion hotspot when Indian plate moved over it (Krishna et al., 1992). Further west, the Laccadive ridge can be seen as a major topographic feature in the Arabian sea which divides the region into two: the western and the eastern basin. While the eastern basin is believed to be underlain by a transitional rifted crust (Naini and Talwani, 1982), the western basin is underlain by oceanic crust as evidenced by sea-floor spreading anomalies (McKenzie and Sclater, 1971). The origin and emplacement of the Laccadive ridge is still enigmatic.
5.3. GRAVITY DATA ACQUISITION IN THE ONSHORE KERALA BASIN ALONG SOUTH AND CENTRAL KERALA COAST

5.3.1 METHODOLOGY

The geotectonic nature of the southwest margin indicates that several of the observed structural/tectonic elements played a significant role in controlling the Kerala basin formation during pre- to post rift evolutionary history. Keeping this in mind, closely spaced gravity observations have been made in the near coastal areas of central basin area of the Kerala coast. For this purpose, a good network of gravity base stations are essential. The gravity base stations established by Singh et al. (1985) in the Palghat gap region and the bases established by Radha Krishna et al. (1998) in the Bavali shear and adjacent regions of northern Kerala are sufficient enough to conduct the regional gravity surveys north of the Palghat gap. However, in the region south of Palghat, very few stations are available. Many of the base stations setup by Woollard et al. (1969) are located at major railway stations, along the railway track and without any repetitions. Hence their accuracy for using them as reference stations in detailed gravity surveys is doubtful. Therefore, a network of 28 base stations were established by adopting forward looping technique and connected to the nearest available base at Vadakancheri established by Singh et al. (1985).
5.3.2. REFERENCE GRAVITY BASE

In the present study the nearest base station value of Vadakkancheri (observed gravity value – 978.12168 Gals) established by Singh et al. (1985) has been carried by forward looping method. This base was established with respect to Coimbatore airport gravity value of 978.0715 Gals (Qureshy and Krishna Brahman, 1969). The Coimbatore airport base was, in turn, connected to the Bangalore airport value of 978.0386 Gals (Manghnani and Woollard, 1963). The Bangalore base corresponds to a value of 979.0640 Gals of the Indian National Gravity Base at Dehradun, which, in turn, corresponds to the Potsdam gravity value of 981.2740 Gals.

5.3.3. PLAN OF SURVEY

The base establishment was done initially for 22 stations with a Lacoste and Romberg gravimeter (model G-1042) having a world wide range of 7000mGals. For setting up additional 6 stations (Nos.23 to 28) in the far south, near around Trivandrum, a W.Sodin Gravimeter of scale value 0.24 mGal and 240 mGal range was employed. The base stations were established using the well known method of forward looping, the procedure being, to carry forward the gravity value from an already established base A to a new base B, by making a loop A-B-A. Well defined and permanent land marks such as verandhas of Rest House (RH), Guest Houses (GH), Inspection Bungalows (IB), Railway Stations (RS), Post Offices (PO) and other easily accessible locations were selected for locating the base stations. Elevation data was collected from spot heights, SOI
toposheets and by using an American Paulin Altimeter. The locations of 28 gravity base stations established in the present study as shown in Figure 5.3.

5.3.4. DESCRIPTION OF BASES

Description of gravity bases along with basic details such as the SOI toposheet number, height, latitude, longitude and observed value of the bases are given in the sketches of gravity base stations in Figures 5.4 – 5.9.

5.3.5. DYNAMIC DRIFT AND ACCURACY OF THE BASE VALUES

Drift rate in the individual base ties during the course of base establishment was calculated in order to ascertain the errors in the base values. The histogram of the dynamic drift rate for the total number of base ties is shown in Figure 5.10. The dynamic drift was assumed to be linear during the survey and care was taken to close the individual base loops in 2-3hrs within the tidal cycle. As can be seen in Figure 5.10, most of the drift values fall within the range 0-0.002 mGal/min.

As mentioned earlier, in order to compare and check the accuracy of HIG base stations established in the central and south Kerala region by Woollard et al. (1969), we have reoccupied nearly 6 of their stations. The base values for these stations are given in Table 5.1. For comparison, the base values established in the present study are also shown in the Table. Though sketches for bases at Ettumannur and Chengannur Railway Stations are available but their
Figure 5.3  Map showing the distribution of 28 gravity base stations established in central and south Kerala region in the present study.
Figure 5.4. Sketches showing location of five permanent base stations (nos. 1–5).
Figure 5.5. Sketches showing location of five permanent base stations. (nos. 6-10).
Figure 5.6. Sketches showing location of five permanent base stations. (Nos. 11-15).
Figure 5.7. Sketches showing location of five permanent base stations (nos. 16-20).
Figure 5.8. Sketches showing location of five permanent base stations. (Nos. 21-25).
Figure 5.9. Sketches showing location of three permanent base stations (nos. 26-28). The legend describing the above base station data is given.
value were not reported in the volume of Woollard et al. (1969). Table 5.1 shows that the HIG values in general are higher and the difference between HIG and CUSAT values range approximately from 0.1-1.5 mGal. In view of this wide range in the HIG values, we conclude that the use of these base stations as reference base stations must be done with care in the detailed gravity surveys. The gravity bases presently reported here can be of help for routine gravity mapping of the region.

5.3.6. GRAVITY DATA

Utilizing this base network, a total of 600 gravity measurements were made using the Lacoste and Romberg gravimeter having a world wide range of 7000 mGal (model G1042) and W. Sodin gravimeter having 240 mGal range. The gravity data collected in this region by the National Geophysical Research Institute (NGRI, 1981) were also considered. The distribution of gravity measurement points are shown in Figure 5.11. Location of gravity stations were chosen in such a way that the topographic effects of undulating terrain and hills would be minimum and negligible. An American paulin altimeter was used along with benchmarks, spot heights and topographic contours from the Survey of India toposheets for obtaining elevation at each measuring point. The data has been reduced using 2.67 gm/cc as the average density of crustal rocks in order to calculate the Bouguer anomalies. The overall accuracy of the presently obtained Bouguer gravity anomalies is of the order of ± 1 mGal making them suitable for analysing along with the marine gravity data for deep crust and tectonics. In the
<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Location</th>
<th>HIG value mGal</th>
<th>CUSAT value mGal</th>
<th>Difference mGal</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>Pudukkad R.S.</td>
<td>978138.13</td>
<td>978138.07</td>
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</tr>
<tr>
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<td>978134.65</td>
<td>978134.69</td>
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<td>978142.38</td>
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<td>4</td>
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<td>-</td>
<td>978139.25</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>Kottayam T.B.</td>
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<td>6</td>
<td>Chengannur R.S</td>
<td>-</td>
<td>978143.31</td>
<td>-</td>
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</table>

Table 5.1. Comparison of the gravity base values established by Hawaii Institute of Geophysics and reoccupied by CUSAT. Note that base values for Ettumannur R.S and Chengannur R.S. were not given in HIG volume by Woollard et al. (1969)
Figure 5.10  Histogram showing the number of base ties against dynamic drift during base establishment
Figure 5.11  Map showing the distribution of gravity stations in the coastal Kerala and the adjoining shield area collected in the present study and also from NGRI (1981). Geology of the area is also shown.
offshore areas, the available GEOSAT gravity data (Sandwell and Smith, 1997) has been considered along with the ETOPOS bathymetry.

5.4. **GRAVITY ANOMALY MAP**

Based on the data discussed above, a gravity anomaly map of the area (both onshore and offshore) has been prepared as shown in Figure 5.12. The map reveals several important structural correlations. The Bouguer anomalies in the onshore areas in general ranges from +20 to −100 mGal. The anomalies in general are gradually increasing towards the coast. A gravity high with a maximum of +20 mGal is observed at the coast between Alleppey and Quilon. The free air anomalies in the offshore show good correlation with the bathymetric features. The characteristic bipolar gravity edge effect anomaly is observed with +10 to +20 mGal positive values in the shelf and decreasing to −60 mGal with a strong gradient following the continental slope. A gravity high of 20 mGal is seen correlating with the Alleppey Platform. The Pratap ridge in this region does not appear very strongly on the gravity anomaly map. However, just east of the ridge several isolated bathymetric (circular to semicircular) features give rise to strong +ve gravity anomalies. Whether these isolated anomalies form a part of the Pratap ridge complex or not is not very clear from this study. The Chagos fracture zone is characterised by a gravity high of 20 to 40 mGal with a gravity low characterised by −50 mGal contour on either side. The anomalies in the Arabian basin, in general, vary from −40 to −50 mGal.
Figure 5.12 Gravity anomaly map of the Kerala basin and the surrounding area. Bouger anomalies (contour interval : 5mGal) in the onshore and free air anomalies (contour interval : 5 mGal) in the offshore are shown. The thick lines indicate the location of four profiles (1-4) considered in the present study for gravity modeling. Tvm - Trivandrum. The present day shelf and the Miocene shelf edge has been indicated as dashed line in the offshore.
5.5. GRAVITY MODELING

In the present study, gravity anomalies along four profiles (1-4) across the southwest continental margin of India covering the Kerala basin have been considered for interpreting 2-D crustal structure. The profiles have been extended oceanward up to the location of the Pratap ridge. As the region between the continental slope and the Laccadive ridge within the Eastern basin of the western continental margin of India is believed to be either transitional crust or thinned rift stage continental crust (Naini and Talwani, 1982; Chaubey et al., 2002), the modeled structure would therefore be expected to give information on rifting style and associated tectonism during margin evolution.

The Southern Granulite Terrain (SGT) contains granulite facies rocks that represent an exhumed lower to middle crustal section with exhumation levels of 10 to 15 km (Harris et al., 1982; Mahadevan, 1994). The southwestern shield margin within the present study area is a part of the SGT. The rock density estimates made by Kurian (2000) show overall higher densities for granulite facies rocks and their retrogressed products. The dominantly higher densities above 2.73 gm/cc with values not lower than 2.65 gm/cc and other geological constrains such as P-T and geochronological information suggests a highly exhumed crust. For the south Indian shield, Kaila and Bhatia (1981) generated a density profile along Kavali-Udipi DSS profile, where the deep lower crustal layer is of 2.85 gm/cc and the upper mantle has 3.3 gm/cc density. Considering the higher densities for granulite facies surface rocks in the region and the mid-to-
lower crustal exhumation in the SGT, a generalized two-layer crustal density model for the SGT can be adopted as follows: an upper crustal layer having a density of 2.75 gm/cc (around 10 km), a lower crustal layer with a density of 2.85 gm/cc and the upper mantle with a density of 3.3 gm/cc. This two-layer density model for the crust is consistent with the simplified two-layer density model proposed for the SGT by Ramachandran (1992) based on velocity-density relations of major rock types.

The crustal thickness estimates were presented for the peninsular shield crust by Subba Rao (1987) based on gravity and Rai et al. (1993) based on seismic tomography. The thickness of the crust estimated by them along the southwest coast in the study area give rise to Moho depths of 35 – 37 km. A generalized thinning of the Moho towards the coast has been observed by both the workers. For the purpose of gravity modeling in the present study, Moho depth in the onshore regions has been adopted from the above data. Sediment thickness is also an important constraint in any gravity modeling of sedimentary basins. Bose et al. (1980) presented sediment thickness map of the coastal belt of Kerala based on detailed seismic refraction and electrical resistivity data. Their study reveal that the onshore part of the Kerala basin contains more than 600m of thick sediments in the deeper parts of the basin south of Alleppey. Based on the sediment facies distribution, Nair and Rao (1980) observed that the basin is divided into a southern and northern block by a NW trending line in the vicinity of Alleppey. In the offshore areas, sediment thickness information is available in the form of several published maps from (Naini and Kolla, 1982; Zutshi et al., 1995;
Balakrishnan, 1997). The generalised stratigraphy of sedimentary formations as revealed from the well data is presented in Table 5.2. These available information have been compiled to arrive at a composite basement configuration as shown in Figure 5.13. The basement data along the gravity profiles has been selected for modeling. Sediment thickness in general varies 3-5 km in the shelf region and 1-2 km in the deeper areas of the Kerala basin. Profile 1 covers northern part of the of the basin off Cochin, Profiles 2 and 3 in the central deep sedimentary part and Profile 4 passes through southern most part of the basin.

Apart form the effect of shallow sedimentaries, the gravity anomalies in the coastal and offshore areas are generated by deeper mass anomalies which include undulations in the crust-mantle boundary and the boundary separating upper part of the crust (2.75 gm/cc) from the lower part of the crust (2.85 gm/cc). However, both these boundaries cannot be arbitrarily changed unless and until the models are constrained by other geophysical data. In the absence of such data, in the present study, we adopted the following procedure. First, the crust-mantle boundary is modeled to fit the long wavelength anomalies and the remaining anomalies (shorter wavelength) have been explained by varying the density boundary within the crust.

5.6. GRAVITY MODELS AND IMPLICATIONS

The gravity derived crustal models have been presented along the four profiles (1-4) across the Kerala basin as shown in Figure 5.14. Since the basement along these profiles is seismically controlled, modeling mainly involved
Figure 5.13  Contours showing sediment thickness in the Kerala basin region. Details are discussed in the text. Contour values are in kilometers.
Figure 5.14 Gravity derived crustal models along four profiles (1-4) across the southwestern margin of India in the Kerala basin region. A. P - Alleppey platform; P. R - Pratap ridge; CFZ - Chagos Fracture Zone. Details are discussed in the text.
<table>
<thead>
<tr>
<th>Age</th>
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<th>Offshore</th>
<th>K-1-1</th>
<th>CH-1-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neogene</td>
<td>Continental</td>
<td>Dominantly Coarse Sandstone</td>
<td>Dominantly fine to medium grained Sandstone</td>
<td>Clay/Claystone</td>
</tr>
<tr>
<td></td>
<td>Alluvial Clay, Black to Lateritic towards Bottom</td>
<td>Shallow Marginal Marine</td>
<td>Coarse grained, pebbly Sandstone, clayey in lower part</td>
<td>Limestone</td>
</tr>
<tr>
<td></td>
<td>Warkalli Formation Arcose Sands, Kaolinitic Clay, Conglomeratic Sands, Shaly with LSt bands towards top</td>
<td>Shallow Marine</td>
<td>Clay/Sst alternations with occasional carbonaceous bands</td>
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</tr>
<tr>
<td></td>
<td>Quilon Formation Limestone with calcareous Sand and Clay</td>
<td>Shallow Marine</td>
<td>Carbonates with thin Sandstone and sandy Clay bands</td>
<td>Limestone</td>
</tr>
<tr>
<td></td>
<td>Mayanad Formation Sandstone, Sand/Clay and Peat</td>
<td>Shallow Marine</td>
<td>Sandstone with Clay bands and carbonaceous band in lower part</td>
<td>Limestone</td>
</tr>
<tr>
<td></td>
<td>Continental</td>
<td>Sandstone/Clay alternations with Lignitic Coal bands</td>
<td>Limestone with Claystone</td>
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</tr>
<tr>
<td></td>
<td>Shallow Marine</td>
<td>Sandy Clays with thin carbonate bands</td>
<td>Limestone with Claystone</td>
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<td>Crystalline basement</td>
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<td></td>
<td>Garnetiferous Gneisses and Charnockites</td>
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</table>

Table 5.2. Generalized stratigraphy of the Kerala basin as obtained from well data. Stratigraphy in the onshore adopted from Soman (1997) and in the offshore from Singh and Lal (1993)
variations in the upper crustal layer and the Moho. The models show that the crust, which is 35-36 km below the crystallines along the SW coast of India thins down to as much as 16 km in the deeper oceanic parts of the basin. Further, a steep rise in the Moho by 10 – 15 km is observed below the coast and shelf region. This rapid rise of the Moho is also associated with thinning of the upper crust seaward. Such characteristic crustal geometry across the rifted continental crust may possibly be an expression of the initial rift related faulting along the West Coast. The modeled Moho geometry based on the broad gravity anomalies in the four profiles studied here could be explained by invoking the southward extension of the West Coast fault (WCF) noticed by Balakrishnan (1977) based on gravity trends further north of the study area. However, possibilities of shearing movements through a system of transform faults in the NNE-SSW direction offsetting the primary faults oriented in NNW-SSE trend (cf. Ghosh and Zutshi, 1989; Dirghangi et al., 2000) render the picture of faulting more complex in the region. Therefore, more detailed and closer gravity data with better seismic constraints will be necessary before attempting to trace the primary rift related fault pattern in the region. In Profile-1, a gravity high of 30 mGal is observed right over the coast near Cochin. Similar gravity highs hugging the coast have been observed all along the western margin and interpreted either due to basic intrusions at depth (Takin, 1966) or due to the thinning of the crust (Chandrasekharam, 1985). In the deep oceanic areas, just east of the Pratap ridge, several minor topographic highs are associated with a gravity high of ~25 mGal. The models indicate that this could be due to local variations in the
thickness of upper/lower crustal layers. As mentioned previously, whether these highs form part of the Pratap ridge complex or not is not clear. The gravity high observed over Alleppey platform, a distinct platformal feature in the outer shelf-slope region (Profiles 2 and 3) is explained as a minor basement high with variation in thickness of lower crustal layer characterized by a Moho rise below the platform. The Chagos Fracture Zone (CFZ) which separates the Chagos Laccadive Ridge from the Chagos basin is seen as a high at both upper crustal as well as Moho level with a steep Moho gradient (Profile 4) on its western flank. It is interesting to note that the Alleppey platform which appear as a northern continuation of the CFZ at the margin also displays similar crustal geometry (Profile 3). It has been suggested that northward motion of India has mainly taken up along the CFZ in the west and ninety east fracture zone in the east (Mckenzie and Sclater, 1971). The counterclockwise rotation of the Indian subcontinent during the early Tertiary period might have terminated the CFZ at the margin near Alleppey Platform (Singh and Lal, 1993). Subsequently, the motion along the CFZ also slowed down rapidly after the collision of Indian plate with Eurasian plate (McKenzie and Sclater, 1971) which might have resulted in extensive deposition of carbonate sequences over the Alleppey platform, causing the present day crustal geometry of this platformal structural feature.