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Lithospheric structure below the eastern Arabian Sea and adjoining West Coast of India based on integrated analysis of gravity and seismic data

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Abstract

Four uniformly spaced regional gravity traverses and the available seismic data across the western continental margin of India, starting from the western Indian shield extending into the deep oceanic areas of the eastern Arabian Sea, have been utilized to delineate the lithospheric structure. The seismically constrained gravity models along these four traverses suggest that the crustal structure below the northern part of the margin within the Deccan Volcanic Province (DVP) is significantly different from the margin outside the DVP. The lithosphere thickness, in general, varies from 110–120 km in the central and southern part of the margin to as much as 85–90 km below the Deccan Plateau and Cambay rift basin in the north. The Eastern basin is characterised by thinned rift stage continental crust which extends as far as Laxmi basin in the north and the Laccadive ridge in the south. At the ocean–continent transition (OCT), crustal density differences between the Laxmi ridge and the Laxmi basin are not sufficient to distinguish continental as against an oceanic crust through gravity modeling. However, 5-6 km thick oceanic crust below the Laxmi basin is a consistent gravity option. Significantly, the models indicate the presence of a high density layer of 3.0 g/cm^3 in the lower crust in almost whole of the northern part of the region between the Laxmi ridge and the pericontinental northwest shield region in the DVP, and also below Laccadive ridge in the southern part. The Laxmi ridge is underlain by continental crust upto a depth of 11 km and a thick high density material (3.0 g/cm^3) between 11–26 km. The Pratap ridge is indicated as a shallow basement high in the upper part of the crust formed during rifting. The 15 –17 km thick oceanic crust below Laccadive ridge is seen further thickened by high density underplated material down to Moho depths of 24–25 km which indicate formation of the ridge along Reunion hotspot trace.

Introduction

The eastern Arabian Sea is the deep oceanic part of the western continental margin of India. The region comprises of several surface/subsurface structural features which include the Chagos–Laccadive ridge (CLR), Laxmi ridge, Pratap ridge and a belt of numerous horst-graben structures in the sediment filled basins bordering the west coast of India (Figure 1). Naini and Talwani (1982) observed that the CLR and Laxmi ridges divide the eastern Arabian sea into two provinces the Western and Eastern basins. While it is widely agreed that the Western basin is underlain by oceanic crust (McKenzie and Sclater, 1971; Whitmarsh, 1974; Naini and Talwani, 1982; Chaubey et al., 1995), the nature of crust below Eastern basin is debated.

Many previous workers suggested that the Eastern basin is characterised by thick transitional rift stage crust extending as far as the Laxmi and Laccadive ridge region (Harbison and Bassinger, 1973; Naini and Talwani, 1982; Kolla and Coumes, 1990; Subba Raju et al., 1990) and extension of Precambrian tectonic trends into deep oceanic areas (Bhattacharya and Subrahmanyam, 1986; Subrahmanyam et al., 1993). However, in the northern part of the Eastern basin, the Laxmi basin, Bhattacharya et al. (1994) and Malod et al. (1997) inferred oceanic crust from magnetic anomaly identifications. The presence of oceanic crust below the Laxmi basin necessitates a clearer understanding of break-up history of Gondwana continents. Recent studies by Miles et al. (1998), Talwani and Reif (1998) and Todal and Eldholm (1998) have brought out considerable information on crustal mass anomalies, volcanism and continental separation below the northern part of the Eastern Basin. The interpretations, however, differ with regard to the continental as against the oceanic character of the crust below the Laxmi basin and plate reconstruction history.

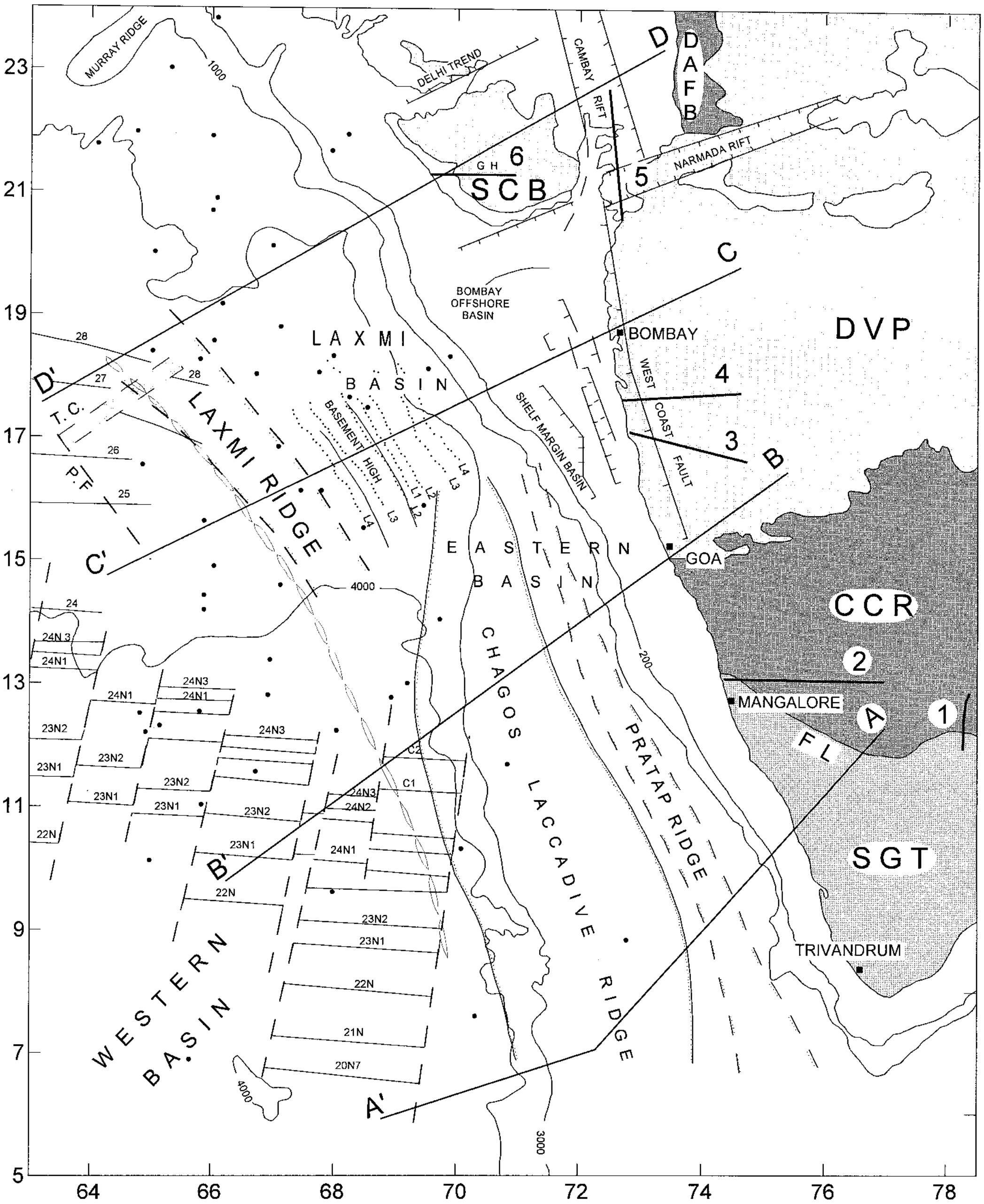


Figure 1. Tectonic and structural trend map of the eastern Arabian Sea and the adjoining West Coast of India. Tectonic and structural details for the western Indian shield and the offshore areas are adopted from Biswas (1982, 1987) and Subrahmanyam et al. (1995). Lines with numbers in the Arabian Sea are magnetic anomaly identifications from Chaubey et al. (1995) and Miles et al. (1998). Dashed lines indicate fracture zones. Filled cirles in the offshore areas show locations of seismic refraction stations from Francis and Shor (1966) and Naini and Talwani (1982). L_1–L_4 are magnetic lineations in Laxmi basin from Bhattacharya et al. (1994). Thick lines with numbers encircled along the West Coast show the location of six Deep Seismic Sounding (DSS) profiles. Lines AA′ through DD′ show the location of regional traverses utilised for structural interpretation. P.F – Pseudo fault; T.C. – Transferred crust; DVP – Deccan Volcanic Province, CCR – Central Cratonic Region; SGT – Southern Granulite Terrain; SCB – Saurashtra Continental Block; GH – Girnar Horst; FL – Fermor Line; DAFB – Delhi Aravalli Fold Belt.

In the present study, a detailed interpretation of gravity anomalies has been carried out to model two-dimensional lithospheric structure along four regional traverses starting from the Western Indian Shield areas and extending into the deep oceanic parts of the eastern Arabian Sea. Such integration of onshore and offshore data along the margin is expected to generate more realistic models on structural styles and processes of crustal rifting along various segments of the margin and deeper mass anomalies which can be interpreted in the overall realm of geodynamics of the region.

Regional geotectonic framework and its evolution

The eastern Arabian Sea and the adjoining West Coast of India contain several structural features which have evolved mostly as a consequence of rifting and seafloor spreading between India, Madagascar and Seychelles (McKenzie and Sclater, 1971; Naini and Talwani, 1982; Biswas, 1987). Biswas (1987) and Kolla and Coumes (1990) suggest that many of the structural trends and basement features in the region have been inherited from the Precambrian structural grain of the western Indian shield. Ghosh and Zutshi (1989) observed that the structural trends seen in the offshore areas were complicated later by shearing movements along the shelf edge. Precise age determination of felsic magmatic events by Storey et al. (1995) indicates the time of rifting between India and Madagascar at 88 Ma. The separation of Seychelles and Mascarene Plateau from India during early Tertiary indicate different times but all within the time during 63–66 Ma (Miles and Roest, 1993; Bhattacharya et al., 1994). Courtillot et al. (1986) proposed that the Deccan Traps, which outcropped the whole northwestern shield margin were formed during initial spreading episodes of 65–68 Ma. Masson (1984) suggests the existence of oceanic crust older to 64 Ma with the opening of an old oceanic domain between Seychelles and India. Malod et al. (1997) inferred that the oceanic crust north of Laxmi ridge has been formed before 64 Ma due to spreading around a triple junction connecting the oceanic Laxmi basin, Narmada Son lineament and the Gop rift. Talwani and Reif (1998) also proposed that the opening of Laxmi basin predate the emplacement of Deccan volcanism and the OCT is located below eastern margin of the Laxmi basin. They further suggested that the seismic velocities greater than 7.0 km/sec in the region represent the initial oceanic crust. On the other hand, Miles et al. (1998) proposed thinned continental crust in the Laxmi basin and noted the existence of underplated crust below the Laxmi ridge and Laxmi basin. They further suggest that the basement features in the Laxmi basin may be due to large scale intrusions. Todal and Eldholm (1998) observed formation of Deccan Continental Flood Basalts (CFB) due to syn-rift-to-break up volcanism during separation of Seychelles from India and suggested a three stage tectonic model comprising of continental extension and fan-shaped spreading between India and Seychelles.

Gravity field over the Eastern Arabian Sea and the adjoining West Coast of India

Various investigators in the past have studied the gravity field of the eastern Arabian Sea (Naini and Talwani, 1982; Subba Raju et al., 1990; Miles and Roest, 1993; Subrahmanyam et al., 1995; Pandey et al., 1995, 1996; Malod et al., 1997; Miles et al., 1998; Talwani and Reif, 1998; Todal and Eldholm, 1998; Singh, 1999) and the adjacent western Indian shield margin (Kailasam et al., 1972; Tewari et al., 1991; Krishna Brahmam, 1993; Balakrishnan, 1997; Singh and Mall, 1998). Though several international agencies have collected shipborne gravity data in the Arabian Sea, the satellite derived gravity anomalies (GEOSAT data) cover the area more completely (Sandwell and Smith, 1997). Also, for the scale of structural features in the region, the satellite gravity data are comparable with the shipborne measurements. Therefore, in order to understand the nature of gravity field, a free-air anomaly map of the eastern Arabian Sea has been utilized using the GEOSAT data as shown in Figure 2. The Bouguer anomalies in the immediate onshore regions of the western Indian shield margin are also included in the map from NGRI (1978).

The map shows that except in the inner shelf region, free-air anomalies are in general negative ranging from -10 to -60 mGal in the whole of eastern Arabian Sea. The bipolar edge effect anomalies i.e. gravity high of $+20$ to $+40$ mGal in the inner shelf region and a low of as much as -60 mGal in the slope can be seen all along the western margin, except between 12°–16° N, the gravity field seems disturbed perhaps due to the presence of several basement ridges and isolated bathymetric features reported by Subba Raju et al. (1990). The subdued and broadly varying gravity field of -20 to -40 mGal in the southwestern

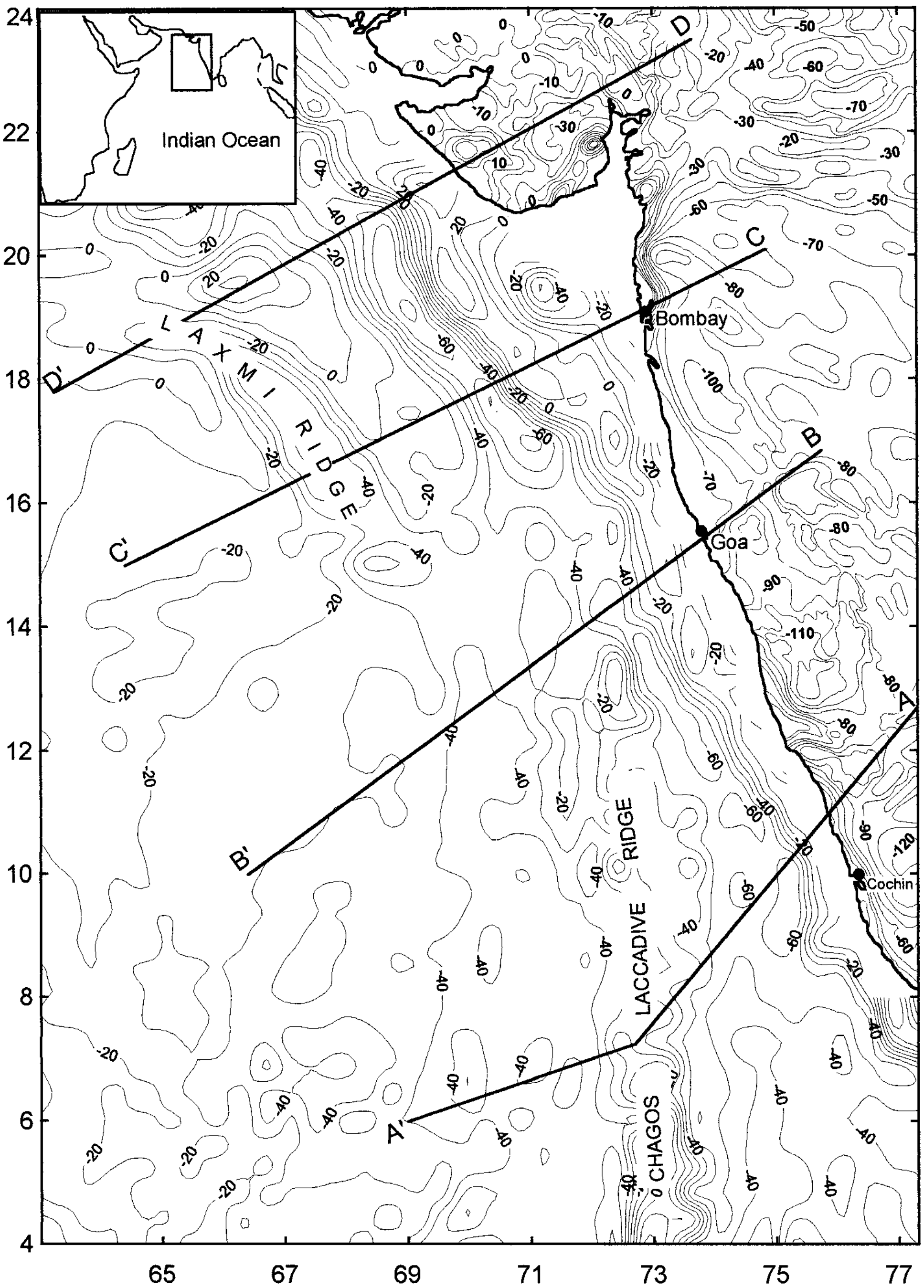


Figure 2. Gravity anomaly map of the eastern Arabian Sea and adjacent western Indian shield region. The contours shown are based on Bouguer anomalies (NGRI, 1978) on land and free-air anomalies (GEOSAT) in offshore areas (contour interval: 10 mGal). Data sources are cited in the text. The gravity traverses AA′ through DD′ shown in Figure 1 follow ship tracks in offshore areas. Wherever necessary, along profiles, ship track data have been extended in both shelf and deep sea areas by GEOSAT and ETOPO5 data. Details are discussed in the text.

part of the map is found to increase sharply on the CLR to as much as $+10$ mGal. In the northwestern part, the deep Arabian Sea region is characterised by positive and negative anomaly belts. A NW-SE trending gravity low of more than -40 mGal correlates well with the Laxmi ridge. North of Laxmi ridge, the gravity high has been inferred by Malod et al. (1997) as due to the presence of a basement high.

The gravity field over the western Indian shield margin ranges between -20 to -120 mGal and is characterised by a westward gravity high gradient zone striking N-S all along the coast, a gravity high in the Cambay rift basin and several isolated gravity highs hugging the coast at many places. The isolated coastal gravity highs have been inferred either due to large basic intrusives at depth or localised thinning of the crust (Chandrasekharam, 1985). Balakrishnan (1997) has attributed the westward gravity gradient along the coast to the alignment of the West Coast fault. Widdowson (1997) observed the location of this fault much westward. Since the gravity gradient zone is almost 50 km wide covering the entire coast, it could be explained by a crustal upwarp or lithospheric thinning (Qureshy, 1981; Mishra, 1989). The gravity high observed over the Cambay rift basin has been interpreted by several workers as due to large thickness of volcanic intrusives (Kailasam and Qureshy, 1964), shallowing of Moho (Sen Gupta, 1967), upper crustal intrusives (Verma et al., 1968), crustal thinning and high density underplated crust (Tewari et al., 1991). Singh and Mall (1998) observed high density underplated crust in the Koyna region based on gravity modeling.

Seismic velocity data and inferences on density values

The seismic data along the western continental margin and deep oceanic parts of the Arabian Sea include the wide angle reflection and seismic refraction surveys carried out by Francis and Shor(1966), Rao (1967), Naini and Talwani (1982) and Naini and Kolla (1982). Along the West Coast of India, deeper information on crust / mantle structure is available from six refraction Deep Seismic Sounding (DSS) profiles collected by National Geophysical Research Institute along Kavali–Udipi profile (Reddy et al., 2000; Sarkar et al., 2001), Guhagar-Chorochi (KOYNA-I) and Kelsi-Loni (KOYNA-II) profiles in Koyna region (Kaila et al., 1981; Krishna et al., 1991), Cambay basin (Kaila et al., 1990), Amreli–Navibandar profile in Saurashtra (Kaila et al., 1988) and Kuppam–Palni transect in the Southern Granulite Terrain(SGT) (Reddy et al., 2001). Mahadevan (1994) reviewed these profiles in terms of crustal models for the western Indian shield. The locations of available refraction stations in the eastern Arabian Sea and the DSS profiles in the western Indian shield are shown in Figure 1.

Naini and Talwani (1982) presented the crustal structure variations below the western basin, Laxmi ridge and the Laxmi basin from seismic data. Their refraction results are illustrated as velocity-depth profiles in Figure 3. These data have been plotted considering seafloor at zero depth. The data indicate that in sedimentary layers the velocities in general vary from 1.7 km/sec for top unlithified sediments to 4.9 km/sec for deeper layers above the acoustic basement. The velocities in the range of 4.0–4.9 km/sec observed mainly in the Eastern basin and Laxmi ridge region (Naini and Talwani, 1982) have been inferred as due to basal sedimentary layers related to early rifting. The acoustic basement can be inferred at a velocity of 5.0 km/sec. The crustal layers show a range of velocities between 5.2–7.3 km/sec (with predominantly 6.2–6.4 km/sec values). At few refraction stations in the Laxmi basin and Laxmi ridge, velocities >7.0 km/sec are observed in the lower crust. Moho velocities of 7.9–8.3 km/sec have been observed at several locations in the region at an average Moho depth of 11.5 km. The seismic data (Figure 3) clearly indicate that the western basin is underlain by oceanic crust with Moho at 11–13 km depth. Velocities observed along the Laxmi ridge indicate the continental affinity of the ridge, but, the nature of crust below the Laxmi basin is ambiguous from velocity data. The observed crustal velocities as low as 6.3 km/sec in the Laxmi basin were interpreted as representing continental crust by Miles et al. (1998), while Talwani and Reif (1998) ascribe these velocities to the presence of initial oceanic crust.

The DSS investigations in the western Indian shield bring out a clear picture regarding unstretched continental crust and the later rifting features. Figure 4(a) shows the derived velocity-depth models for different DSS sections along the west coast of India. The inferences from DSS studies are: (i) Deccan traps having velocities of 4.5–5.5 km/sec with a maximum thickness of 2.0 km underlain by Mesozoic sediments (velocities 4.0 km/sec) in Saurashtra; (ii) a two layered continental crust with a variable upper crustal thickness of about 10–20 km characterised by velocities

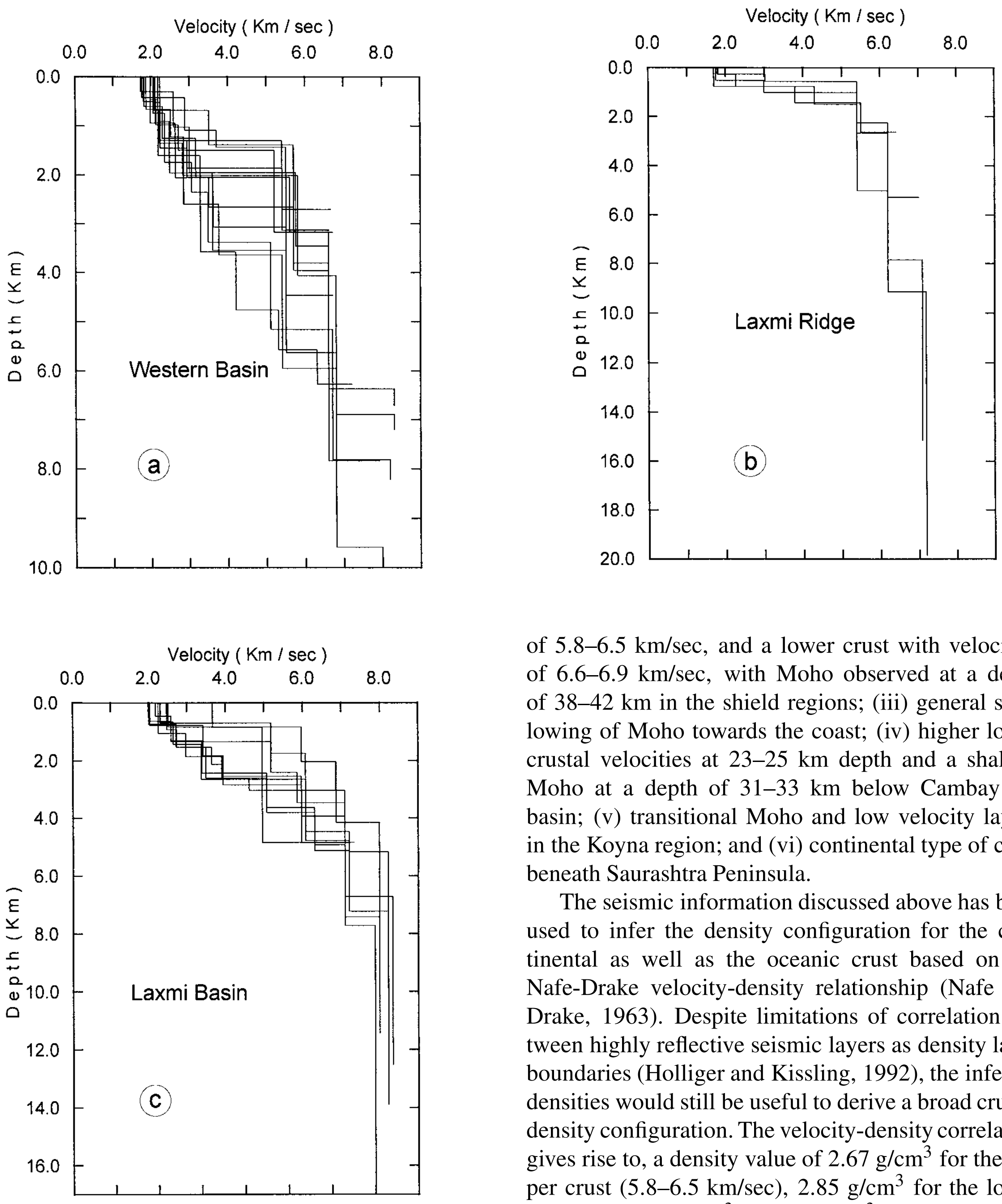
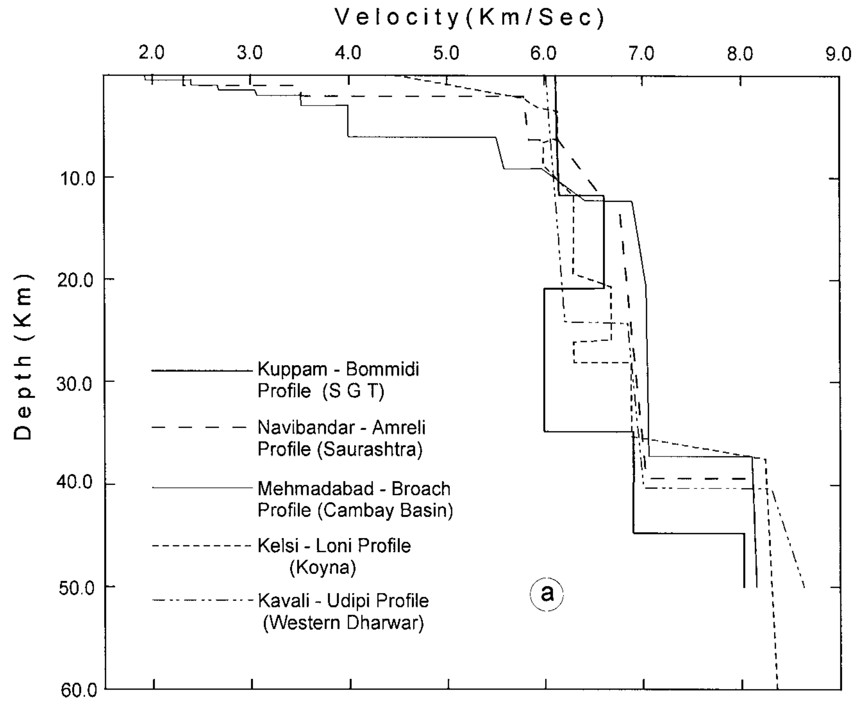


Figure 3. Shows velocity-depth profiles plotted for (a) western basin (b) Laxmi Ridge (c) Laxmi basin in the eastern Arabian Sea. The seismic refraction data given by Naini and Talwani (1982) have been utilised for this purpose.

of 5.8–6.5 km/sec, and a lower crust with velocities of 6.6–6.9 km/sec, with Moho observed at a depth of 38–42 km in the shield regions; (iii) general shallowing of Moho towards the coast; (iv) higher lower crustal velocities at 23–25 km depth and a shallow Moho at a depth of 31–33 km below Cambay rift basin; (v) transitional Moho and low velocity layers in the Koyna region; and (vi) continental type of crust beneath Saurashtra Peninsula.

The seismic information discussed above has been used to infer the density configuration for the continental as well as the oceanic crust based on the Nafe-Drake velocity-density relationship (Nafe and Drake, 1963). Despite limitations of correlation between highly reflective seismic layers as density layer boundaries (Holliger and Kissling, 1992), the inferred densities would still be useful to derive a broad crustal density configuration. The velocity-density correlation gives rise to, a density value of 2.67 g/cm^3 for the upper crust (5.8–6.5 km/sec), 2.85 g/cm^3 for the lower crust (6.6–6.9 g/cm^3), 2.80 g/cm^3 for the Deccan traps, 2.40 g/cm^3 for sediments in the Cambay basin and the Mesozoic sediments lying below the Deccan traps. A density of 3.0 g/cm^3 has been assumed for the high velocity layer (7.1–7.4 km/sec) in the lower crust. However, the crust in the western Indian Shield south of 13° N is characterised by exhumed lower to middle crustal rocks which would imply that top crustal layers in this region have higher densities than the rest



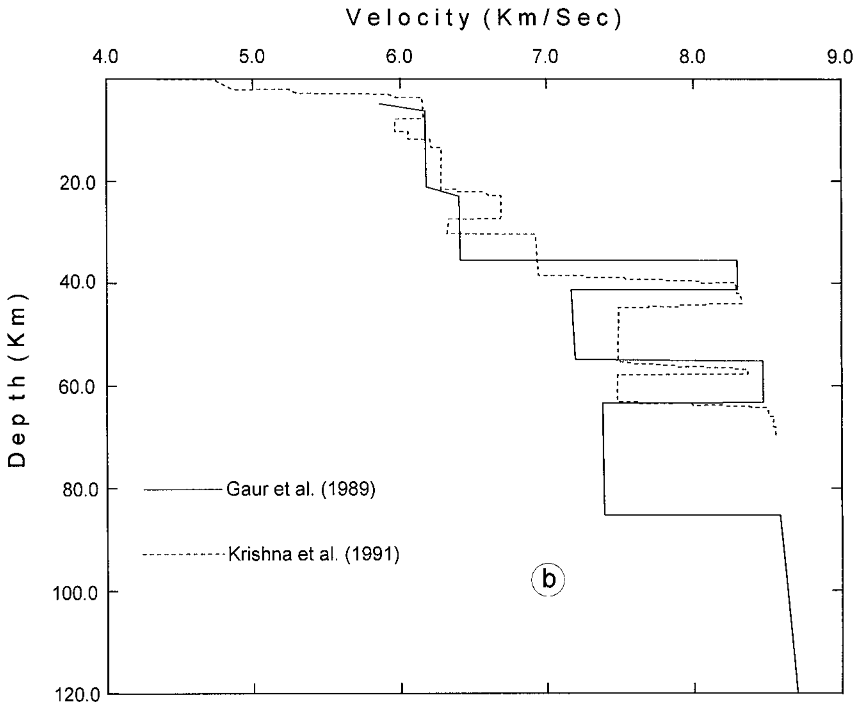


Figure 4. (a) shows the crustal p-wave velocity models for different DSS profiles along the western Indian shield region considered in the present study. (b) p-wave velocity models for lithosphere below the West Coast in the DVP.

of the shield. This is further confirmed by the density estimates of dominant surface rocks given by Kurian et al. (1999). Therefore, an average density value of 2.75 g/cm^3 for the exhumed mid-lower crustal layer in the SGT has been inferred.

In the oceanic areas, the 1.7–2.8 km/sec (density of 2.1 g/cm^3) and 2.9–5.0 km/sec (density of 2.3 g/cm^3) for shallow and deeper sediments were assigned a uniform value of 2.2 g/cm^3 for the sedimentary layer. A two layered oceanic crust of 2.66 g/cm^3 for the top part (5.1–6.3 km/sec velocities) and 2.90 g/cm^3 for the bottom layer (6.4–7.0 km/sec velocities) has been assigned. A uniform value of 3.3 g/cm^3 for the lithospheric mantle and 3.2 g/cm^3 for the Asthenosphere have been assumed. Table 1 shows the seismic velocities and estimated densities for the eastern Arabian Sea and the Indian shield crust. The density configuration for the oceanic crust considered here is in agreement with the values inferred by Miles et al. (1998) and Todal and Eldholm (1998).

The lithosphere thickness of 70 km in the Arabian Sea obtained by Singh(1990) from surface wave attenuation studies has been considered. For the west coast of India, velocity information on subcrustal lithosphere in the DVP is given by Gaur et al. (1989) and Krishna et al. (1991). The velocity-depth model obtained by them is shown in Figure 4b. The presence of two subcrustal low-velocity layers (LVL) in the Koyna region along the West Coast is noteworthy from the figure.

Gravity modeling

In the present study, four regional gravity traverses AA′ through DD′ uniformly located along the western continental margin of India (Figure 1) have been considered to interpret 2D-lithosphere structure. The profiles are selected on the basis of availability of ship track gravity, bathymetry and seismic data. Wherever necessary, the ship track data have been complimented with GEOSAT and ETOPO5 data to fill the data gaps in the shelf region as well as in deep oceanic areas. In the onshore regions, the Bouguer anomalies have been considered along the traverses. All seismic refraction data points within half degree on either side of these profiles have been projected. The sediment thickness map compiled by Balakrishnan (1997) and basement depths inferred from magnetic anomalies by Subrahmanyam et al. (1993) along with the refraction data are used to obtain thickness of sediments along the

Table 1. Crustal seismic velocities and inferred densities utilised for gravity modeling in the region. * indicates the density value for the exhumed mid-to-lower crustal rocks in the SGT.

Oceanic crust: Eastern Arabian Sea				Laxmi Ridge				Indian shield: West Coast							
									DVP and CCR			SGT			
Layer	Velocity range	Average velocity km/s	Density g/cc	Layer	Velocity range	Average velocity km/s	Density g/cc	Layer	Velocity range	Average velocity km/s	Density g/cc	Velocity range	Average velocity km/s	Density g/cc
Sediments	1.7–5.0	3.0	2.20	Upper crustal layer	5.2–6.3	5.8	2.67	Upper crustal layer	5.8–6.5	6.1	2.67	6.1–6.5	6.3	2.75*
Oceanic layer 1	5.1–6.3	5.5	2.66											
Oceanic layer 2	6.4–7.0	6.7	2.90	Lower crustal layer	6.4–7.0	6.6	2.84	Lower crustal layer	6.6–7.0	6.7	2.85	6.6–7.0	6.7	2.85
High velocity layer	7.1–7.4	7.2	3.00	High velocity layer	7.1–7.4	7.2	3.00	High velocity layer	7.1–7.4	7.2	3.00			
Upper mantle	7.9–8.2		3.30					Upper mantle	8.0–8.4		3.30		8.3	3.30

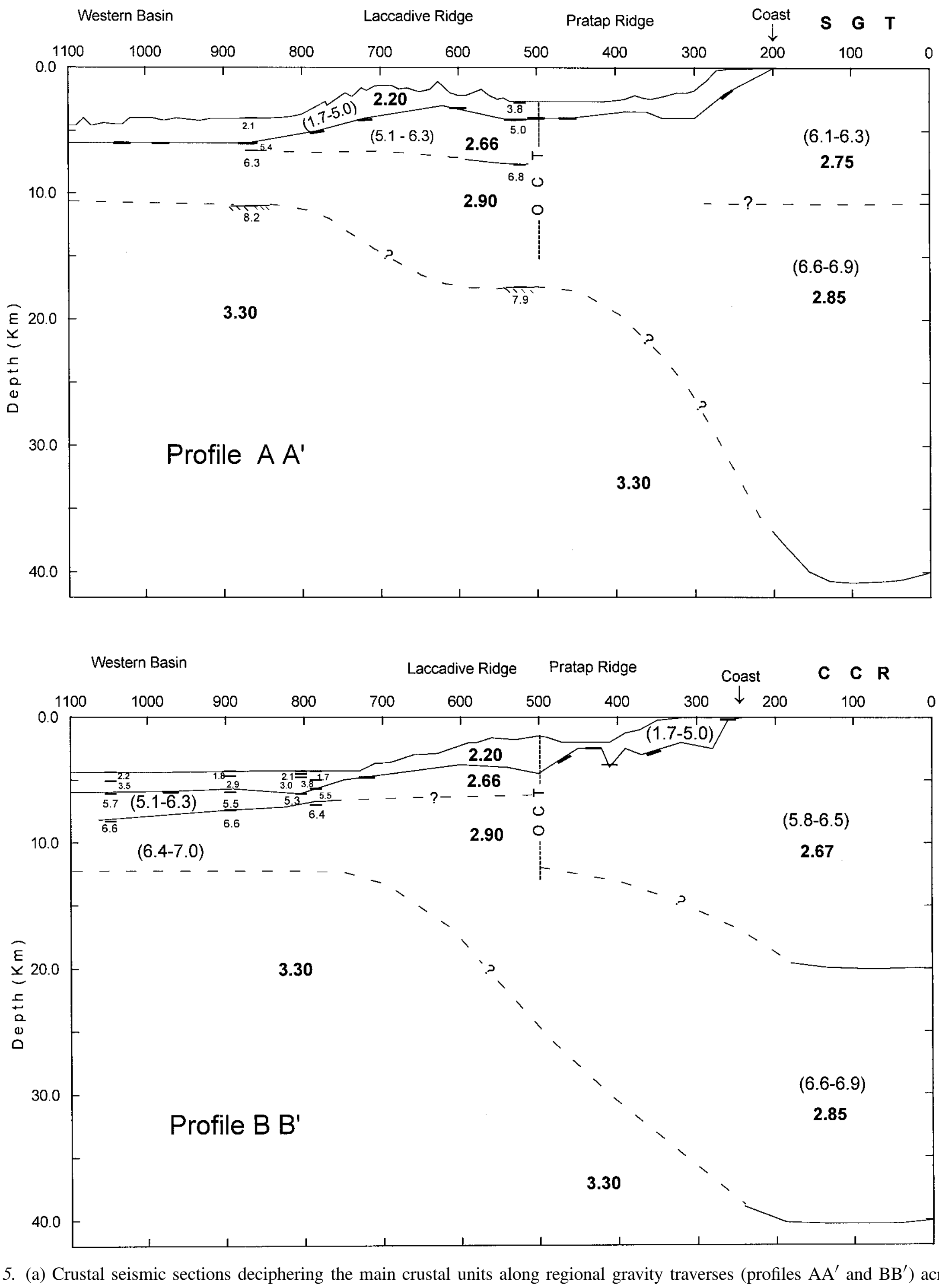


Figure 5. (a) Crustal seismic sections deciphering the main crustal units along regional gravity traverses (profiles AA′ and BB′) across the western margin considered in the present study. All available seismic information on crustal velocities, sediment and trap thickness and Moho information have been projected onto these sections. The continuous lines denote actual seismic information, while dashed lines indicate gaps in the seismic data. Thick hyphens on basement layer indicate control points obtained from published basement maps. Details are discussed in the text.

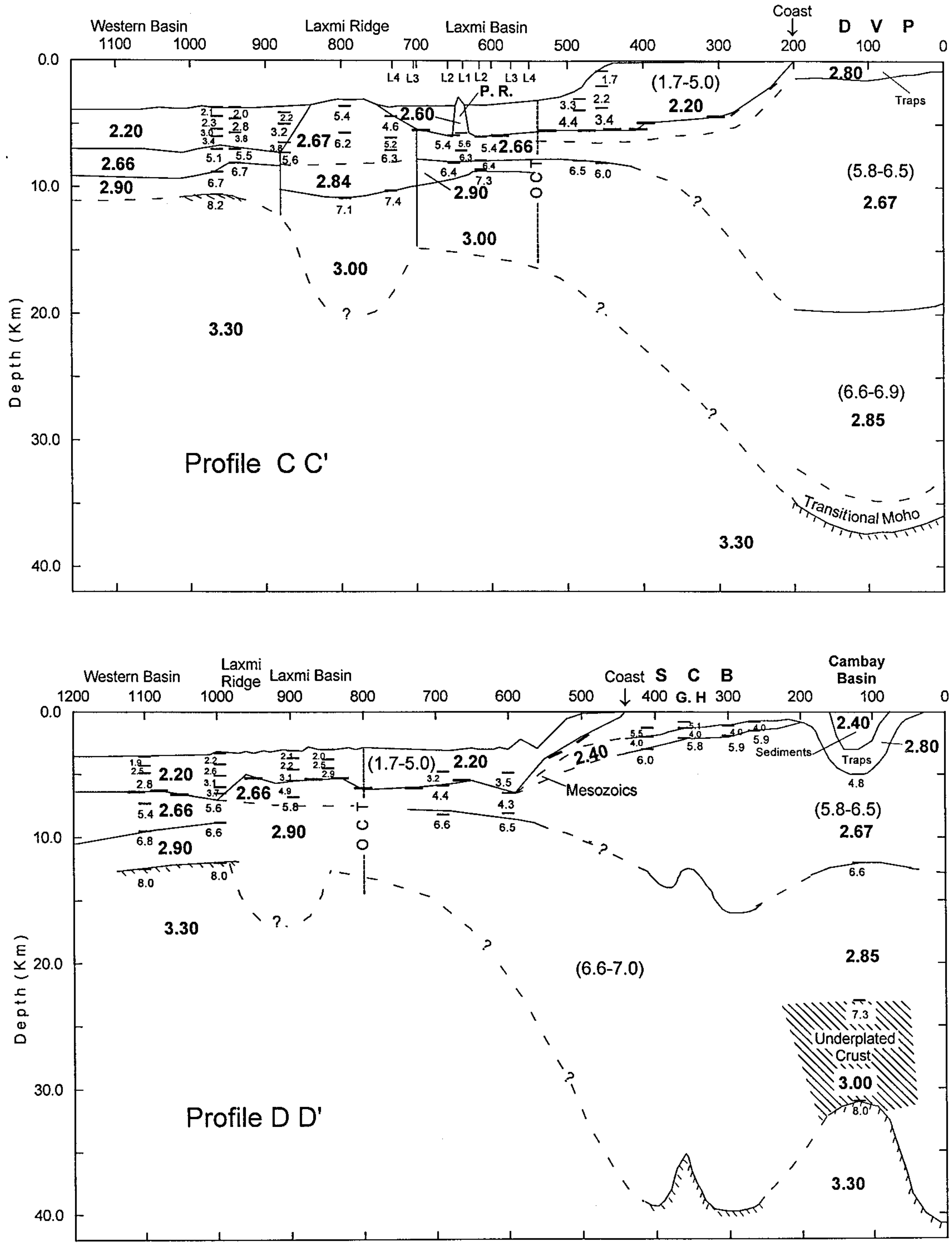


Figure 5. (b) Crustal seismic sections deciphering main crustal units along regional gravity traverses (profiles CC′ and DD′) across the western margin. Other details as given in Figure 5a.

profiles. The upper and lower crustal boundary as well as the Moho variations known from the DSS sections in the West Coast are projected onto the profiles. This gives information on stretched as well as unstretched continental crust below the West Coast.

The crustal sections prepared along these profiles are shown in Figure 5. For profile AA′, no DSS data for SGT is available in the coastal areas. The gross velocity structure obtained by Reddy et al. (2001) along nearby Kuppam-Bommidi profile in the interior of SGT together with regional crustal thickness estimates given by Rai et al. (1993) and Moho depth map of South India by Subba Rao (1987) have been considered. Profile BB′ passes just outside the fringe of Central Cratonic Region (CCR), where small thickness of trap flows overlie the Dharwar crust. As the crustal structure along BB′ is more characteristic of the CCR than the DVP, the crustal structure from the Kavali-Udipi DSS profile has been considered for profile BB′ in preference to the Guhagar-Chorochi DSS profile (Koyna I) further north which presents a structure more characteristic of the DVP. For profile CC′, the structure along the Kelsi-Loni DSS profile (Koyna II) has been considered. It may be noted that the shipborne gravity data available for profile CC′ was earlier modelled by Miles et al. (1998). Their derived crustal model confining only to the offshore areas indicates the presence of high density underplated crust below Laxmi ridge and Laxmi basin. For better understanding of the spatial extent of the underplated crust and also in view of additional seismic data available in the present study, we attempt to remodel by extending the profile onto the rifted collar of the continental crust further east in the DVP. The subcrustal LVL in the Koyna region of DVP (Figure 4b) has been extended westward into the offshore areas below the Eastern basin by Pandey et al. (1996) for gravity modeling. Except in the Koyna region, the spatial extent of these LVL's along the West Coast and the adjoining oceanic areas is not known. So, incorporating such layers in the gravity modeling leads to more ambiguity and hence not considered here. But, if present, it would only enhance the modelled thickness and/or density of the underplated crust in the region. Profile DD′ passes across the Cambay basin and Saurashtra Continental Block (SCB) in the West Coast where detailed velocity structure is known from Mehmadabad-Billimora and Navibandar-Amreli DSS sections. For both CC′ and DD′ profiles, the thickness of traps is considered from Kaila(1988) in the DVP region and in the offshore areas from Gopala Rao (1990) and Dessai and Bertrand (1995). For all profiles, the lithosphere thickness of 70 km below the Arabian Sea (Singh, 1990) has been assumed.

Utilising the crustal seismic profiles shown in Figure 5, the gravity modeling has been carried out. Wherever seismic control is very high along these profiles, model parameters in that region are held fixed to infer the structure in the surrounding areas. The modeling is carried out by minimizing the misfit between observed and computed anomalies and the models presented here bring an r.m.s error of around 5–8 mGal for all four profiles which is sufficient for regional gravity interpretation. The models are shown in Figures 6–9.

Interpreted models and implications

The seismically constrained gravity models along profiles AA′ through DD′ throw some light on the probable lithospheric thickness variations in the region; extent of underplating influenced by episodic rifting and accompanying magmatism; rifting styles across the margin; and also partially helps to reconcile some of the existing models in the Arabian Sea. Some of the salient observations in the context of overall geodynamics of the region are presented below.

Lithosphere thickness

The lithosphere fixed uniformly at a depth of 70 km in the oceanic areas has been modelled here below the West Coast to fit the gravity anomalies. The models show considerable variation in lithospheric thickness along the western Indian shield margin.The thickness varies from 110–120 km observed in the southern and central part (profiles AA′ and BB′) to as much as 85–90 km in the northern part below Deccan plateau and Cambay rift basin (profile CC′ and DD′). The shallowest part of the lithosphere is 85 km below the Cambay rift basin (profile DD′) which sharply increases on either side to 120 km below the Aravallis and 90–110 km below the SCB.

Crustal structure below West Coast and the Eastern Basin

The SCB is underlain by typical continental crust which appears to be highly faulted and fractured (profile DD′). The Girnar horst within the SCB seems to be due to localized crustal uplift deep from the Moho. The highly faulted nature of the crust might have resulted from successive rifting episodes and block movements beginning with the evolution of surrounding Mesozoic rift basins. The Cambay basin region

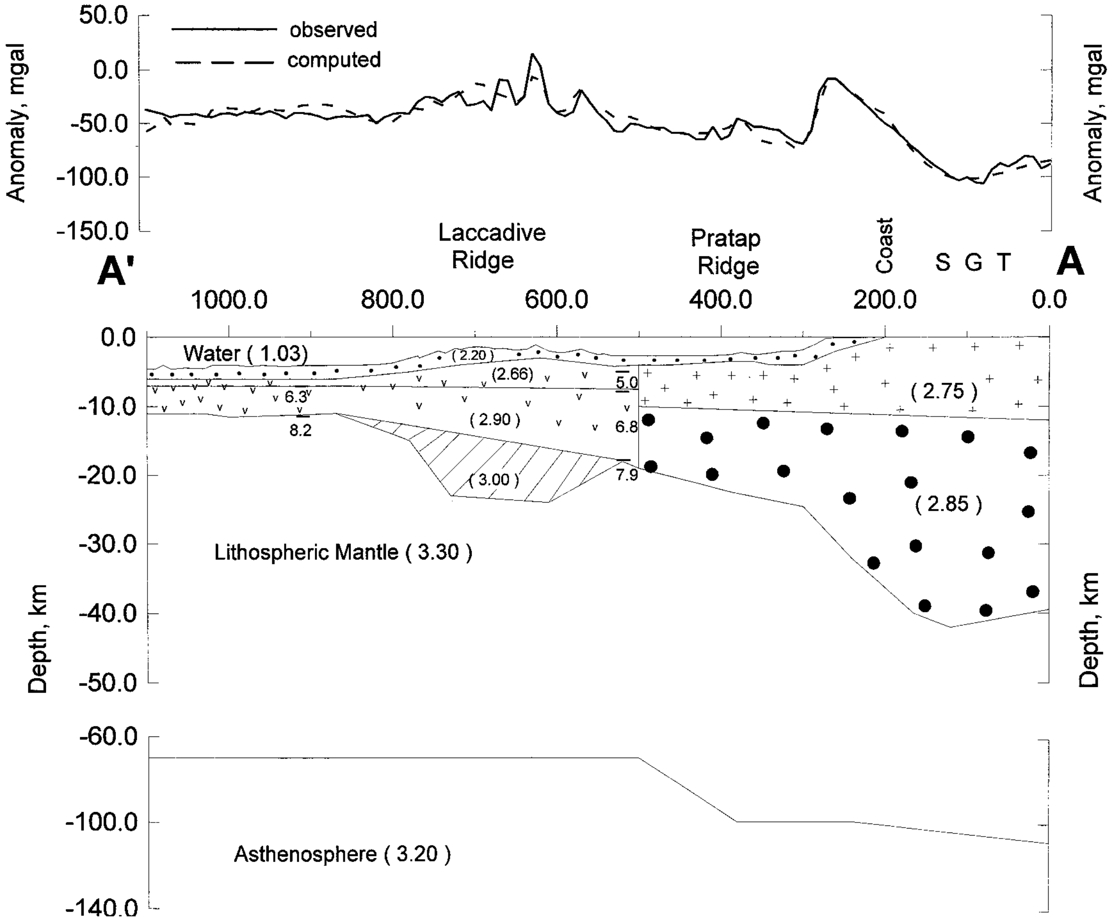


Figure 6. Profile AA′ and the two-dimensional gravity model across the SW continental margin of India. The numbers with short bars refer to seismic velocities from refraction stations and the values in bracket refer to inferred densities as discussed in the text. Hatched region indicate underplated material of density 3.0 g/cm^3 below the Laccadive ridge. SGT-Southern Granulite Terrain

further east is characterized by crustal thinning with the Moho shallowing to a depth of 31 km and presence of high density material (3.0 g/cm^3) between 22–31 km. The observed Moho depths of nearly 35–39 km below SCB (profile DD′) and the region east of Bombay (profiles CC′) require high density material at depth in order to explain the gravity anomalies. The continental crust varying in thickness between 38–42 km below the western Indian shield is thinning towards deep oceanic areas and can be seen to extend up to the eastern edge of Laccadive ridge in south (profiles AA′ and BB′), whereas in north, thinned rift stage continental crust extends definitely up to east of Laxmi basin (profiles CC′ and DD′). In the Laxmi basin, a large basement high feature can be seen in profile CC′ which was identified by Gopala Rao et al. (1992) as Panikkar ridge. As mentioned earlier, there is considerable ambiguity regarding the nature of crust in the Laxmi basin region that has implications on the location of OCT as well as reconstruction history of the margin. An oceanic crust in this region has been proposed by Bhattacharya et al. (1994) and Malod et al. (1997) based on magnetic anomaly identifications. Talwani and Reif (1998) further support their idea stating that the region underlies the initial oceanic crust. This observation places the location of OCT below east of Eastern basin. Contrary to this, Miles et al. (1998) and Todal and Eldholm (1998) favour the presence of thinned continental crust in the Laxmi basin and OCT location south of the Laxmi ridge. While post- anomaly 28 sea floor spreading history proposed by Miles and Roest (1993) and Chaubey et al. (1998) in terms of complex propagating ridge sequences is generally accepted, the spreading anomalies older to

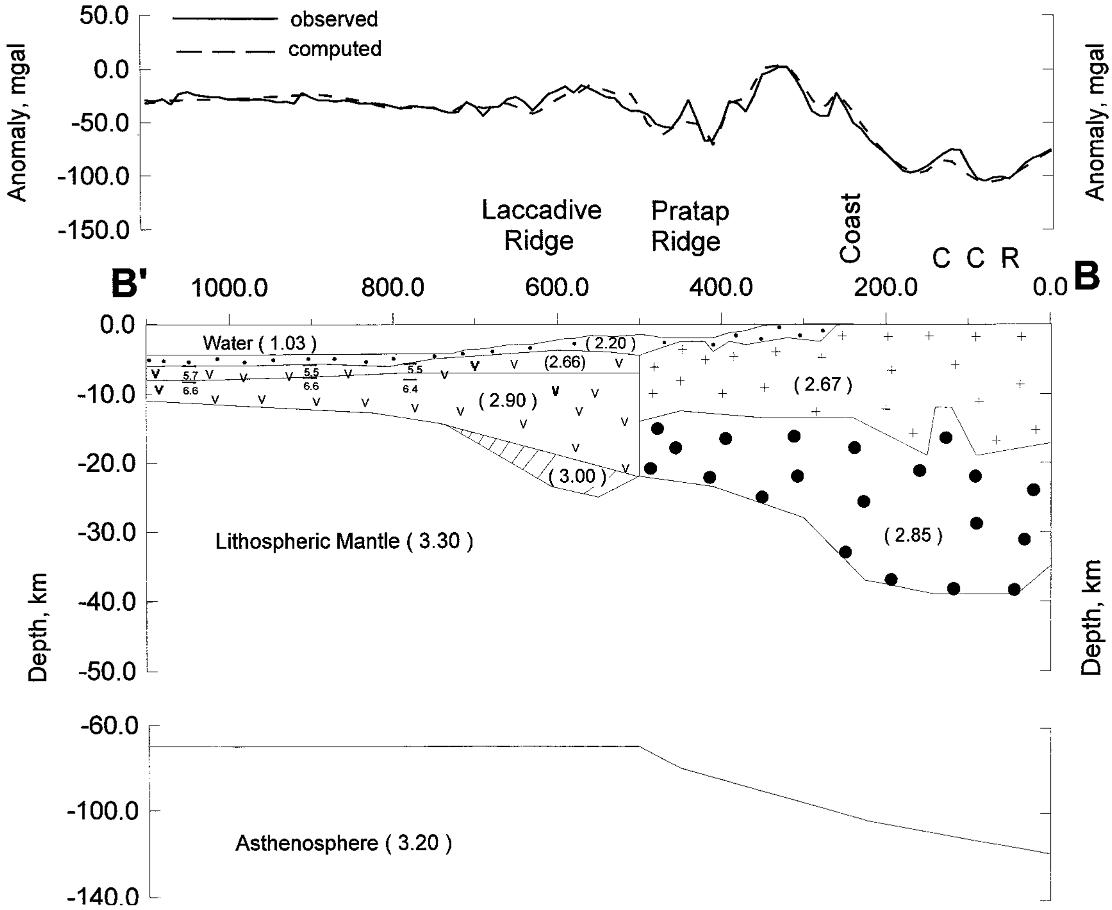


Figure 7. Profile BB′ and the two-dimensional gravity model across the central West Coast of India. CCR-Central Cratonic Region The notations are the same as in Figure 6.

anomaly 28 in the Laxmi basin proposed by Bhattacharya et al. (1994) and Malod et al. (1997) have been questioned by Miles et al. (1998) stating that the magnetic anomalies in this region could be explained as large scale intrusions into the thinned continental crust. Todal and Eldholm (1998) suggest the occurrence of massive Deccan volcanism under the late syn-rift tectonic setting and defined the region as part of Deccan Large Igneous Province. The gravity models in the present study neither resolve this issue nor can unequivocally identify the location of OCT as the density differences in the crust below Laxmi ridge and Laxmi basin are not sufficient to clearly distinguish the two through gravity modeling. However, it may be pointed out that the modelled thickness of underplated crust would be more if the Laxmi basin is underlain by continental crust in comparison to an oceanic crust. In order to obtain a lower bound on the thickness of the underplated crust, we invoke an oceanic crust in the modeling (profiles CC′ and DD′).

Structure below Laxmi, Laccadive and Pratap ridges

Based on seismic velocity structure, Naini and Talwani (1982) inferred a thick continental type of crust below the Laxmi ridge. The continental nature of this ridge has also been widely accepted by many later workers though the nature and extent of underplated material below the ridge is debated (e.g., Miles and Roest, 1993; Bhattacharya et al., 1994; Malod et al., 1997; Miles et al., 1998; Talwani and Reif, 1998; Singh, 1999). Pandey et al. (1995) explained the low gravity anomaly due to thickened oceanic crust in terms of underplating while Todal and Eldholm (1998) described the ridge as a marginal high comprised of both continental and oceanic crust. The gravity models for Laxmi ridge in the present study (profiles CC′ and

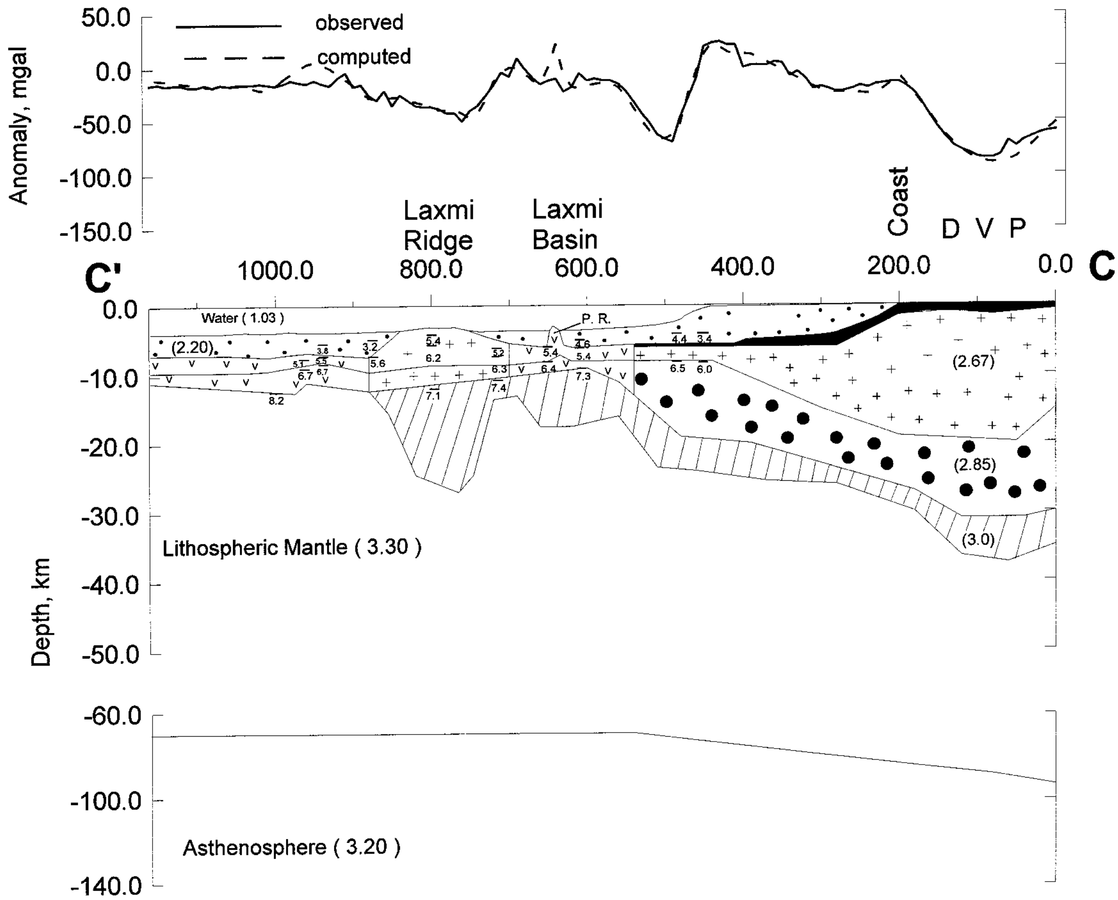


Figure 8. Profile CC′ and the two-dimensional gravity model across the northwest coast of India within the Deccan Volcanic Province. Note the dark shaded region for the Deccan traps. The hatched region indicates the high density material in the lower crust and is seen between West Coast and the Laxmi ridge. See text for more details. DVP – Deccan Volcanic Province. PR-Panikkar Ridge.

DD′) indicate that the ridge comprises of continental crust and a thick high density layer of 3.0 g/cm^3 extends from 11–12 km down to a maximum depth of 26 km.

It has been debated whether the formation of the Pratap ridge is related to the impact of Reunion hotspot along with the CLR (Krishna et al., 1992) or whether its evolution is influenced by a Precambrian fabric during the process of rifting (Subrahmanyam et al., 1995). From the gravity models (profiles AA′ and BB′), it can be seen that the Pratap ridge is a shallow uncompensated basement high over thinned rifted continental crust which gives rise to the observed gravity high. So, the models are not consistent with a relation to the Reunion hotspot in its formation. Such basement highs could be related either to the formation of outer highs skirting the rifted crust at the OCT (Schuepbach and Vail, 1980) or to horst-graben tectonics within the upper crust during rifting (Curray, 1980).

The gravity models (profiles AA′ and BB′) across the CLR indicate a thick oceanic crust below the ridge which juxtaposes the continental crust along its eastern margin. The ridge is further characterized by thickening of the crust to as much as 24–25 km by the presence of a high density material of 3.0 g/cm^3 below the ridge. Ashalatha et al. (1991) observed thick crustal roots beneath the ridge on the basis of admittance analysis. The presence of such thick high density material is consistent with the processes of underplating beneath the oceanic ridges along volcanic hotspot traces due to massive intrusions related to hotspot volcanism (Caress et al., 1995). Therefore, the models indicate the formation of the CLR due to Reunion hotspot at the edge of continental crust to the east.

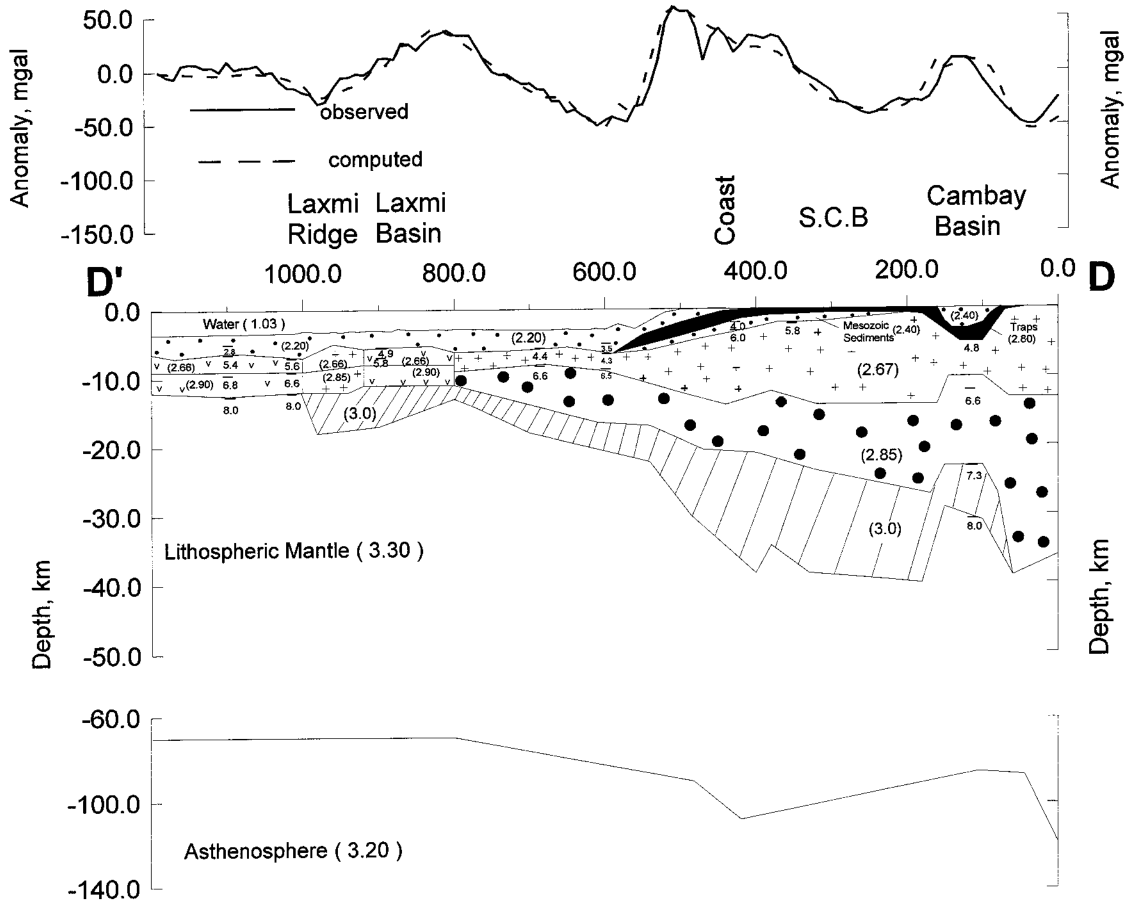


Figure 9. Profile DD′ and the two dimensional gravity model across the northwest coast of India within the Deccan Volcanic Province. The dark shaded region represent the trap below which Mesozoic sediments are present. The notations and other details are as given in Figure 6 and 8. SCB – Saurashtra Continental Block.

Underplated crust

The modeling requires that in order to explain the gravity anomalies, a high density material of 3.0 g/cm^3 is required to be present at the base of the crust in the northern part of the study area covering the West Coast in the DVP and the adjoining oceanic areas as far as the Laxmi ridge (profiles CC′ and DD′) . The underplated crust seems to be enveloping the entire crust in the region. It is relevant to note here that the conjugate Seychelles margin has no evidence of crustal underplating (Francis and Shor, 1966; Mathews and Davies, 1966) which suggest that the underplated material present below the DVP and adjoining offshore areas is not completely due to rift related magmatism. The variation in the structure in terms of faulting of the crust, lithosphere thinning and widespread underplating between the northern part of the margin within DVP (profiles CC′ and DD′) and southern part outside the DVP (profile AA′ and BB′) can be clearly seen from the models. This difference could be due to the fact that the lithosphere experienced multiple rifting episodes and massive Deccan volcanism in the north. Though the layer appears to be underplating the whole region, its formation could be temporally related to processes such as rift related volcanism, oceanic crust generated in the initial break up and also large scale magmatism during the Deccan Volcanic episode.

Conclusions

Gravity modeling along the four regional traverses across the western continental margin of India highlights the large variation in crustal configuration between northern part of the margin within the DVP and the southern part outside the DVP. The lithosphere thickness below the West Coast in general varies from

110–120 km in the southern and central part (within SGT and CCR) to as much as 85–90 km in the Deccan plateau and Cambay rift basin. The crust below the SCB and Cambay rift appears to be highly faulted and the Girnar horst in the SCB is seen as a localised crustal uplift deep from the Moho. The Eastern basin is characterised by thinned continental crust which extends as far as Laxmi basin in the north and the CLR in the south. The modeling could not definitely identify the location of OCT in the Eastern basin. However, the models indicate a high density underplated crust of 3.0 g/cm^3 in the northern part of western margin covering the West Coast in the DVP and the adjoining oceanic areas as far as the Laxmi ridge. The models indicate the Pratap ridge as a shallow basement high over continental crust formed during rifting and formation of CLR due to Reunion hotspot at the edge of continental crust. The variation in lithospheric structure in terms of faulting of the crust, lithospheric thinning and widespread underplating observed in the northern part of the western margin within DVP can be attributed to multiple rifting episodes and massive Deccan volcanism in the region.

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