The seismic structure of the Saurashtra crust in northwest India and its relationship with the Réunion Plume

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SUMMARY

The Saurashtra Peninsula in northwest India, lying at the northern boundary of the Deccan Volcanic Province, is almost entirely covered by these volcanics. Analogue seismic refraction/wide-angle reflection data along a 160 km long profile, from Navibandar to Amreli, were collected during 1977 to determine the crustal configuration. Reprocessing of these data, after digitization, has yielded a crustal model that is significantly different from the earlier model of Kaila *et al.* The model shows the upper crust down to a depth of 16 km in the west and 13 km in the east and underplating (velocity of 7.20 km s^{-1}) of the lower crust. The Moho is at a depth of ~36 km in the western part and at 32–33 km in the eastern part; the change of depth is quite sharp almost in the middle of the profile. Similar depth changes are seen in other crustal horizons indicating a deep fault that is in line with the extension of the Proterozoic Aravalli trend in to the Saurashtra Peninsula. The crustal structure in the eastern part is similar to that in the Cambay Basin and indicates that the crust to the east of the proposed fault is uplifted. The uplifted region extends as far as another arm of the Aravalli trend that turns eastwards. Crustal underplating in large parts of western India is confined to the corridors affected by the passage of India over the Réunion Plume in the Late Cretaceous. The shallower Moho appears to be confined to the areas close to the axis (trace of the plume) on Earth's surface of the plume.

Key words: crust, Réunion Plume, Saurashtra, seismic structure, velocity, wide-angle reflection.

1 INTRODUCTION

The continental flood basalts, known as the Deccan Volcanics, cover large parts of northwest India. These consist of several flows of mainly tholeiitic lava that extruded from the Réunion Plume during the passage of the Indian Plate over the plume in Cretaceous–Early Tertiary time (Morgan 1981). The Saurashtra Peninsula (Fig. 1) along with the Kutch region is at the northern boundary of these volcanics. It represents a horst-like uplift due perhaps to the Deccan volcanic activity (Krishnan 1982; Valdiya 1984). The geological history in the Saurashtra region is obscure before the volcanic extrusion. A few exposures of Tertiary and Quaternary sediments can be seen in the coastal belt. The geological sequences (Fig. 2) obtained from the deep bore wells at Lodhika and Dhanduka (Singh *et al.* 1997) indicate that the Deccan Volcanics were preceded by Cretaceous/Jurassic sediments, volcanic tuff and possibly another sedimentary layer over a crystalline basement of Precambrian age.

Development of the structural trends, rift basins and different kinds of igneous intrusions over the west coast of India and adjoining regions were affected by three major tectonic events during the Mesozoic period, after the break-up of Gondwanaland (Besse & Courtillot 1988). The first of these was the break-up of Africa from the block consisting of India, Madagascar and the Seychelles during the Middle to Late Jurassic period. The second event was the break-up of Madagascar along the west coast of India, during the Middle to Late Cretaceous, probably under the influence of the Marion Plume (Raval & Veeraswamy 2003). The last event was the break-up of the Seychelles Plateau from the Indian Plate, followed by eruption of the Deccan Volcanics due to interaction between the Réunion hotspot and the overlying lithospheric plate, during the Late Cretaceous (McKenzie & Sclater 1971; Raval & Veeraswamy 2000).

Three major Precambrian orogenic trends (Fig. 3), namely the NNW–SSE Dharwar in the southern part, the NE–SW Aravalli in the northeastern part and ENE–WSW Satpura in the central part, converge in western India (Biswas 1987). The Cambay rift represents the NNW extension of the Dharwar trend. The Delhi–Aravalli system divides itself into three trends. The Delhi trend takes a westward swing to overlap with the Kutch rift. The Aravalli trend crosses the Cambay rift and enters the Saurashtra horst. On its southern side the Aravalli folding takes an acute eastward swing to merge with the Satpura trend.

A number of volcanic plugs in the west (Girnar, Barda, Alech) and in the southeast (Chogat, Chamardi) are reported in this region

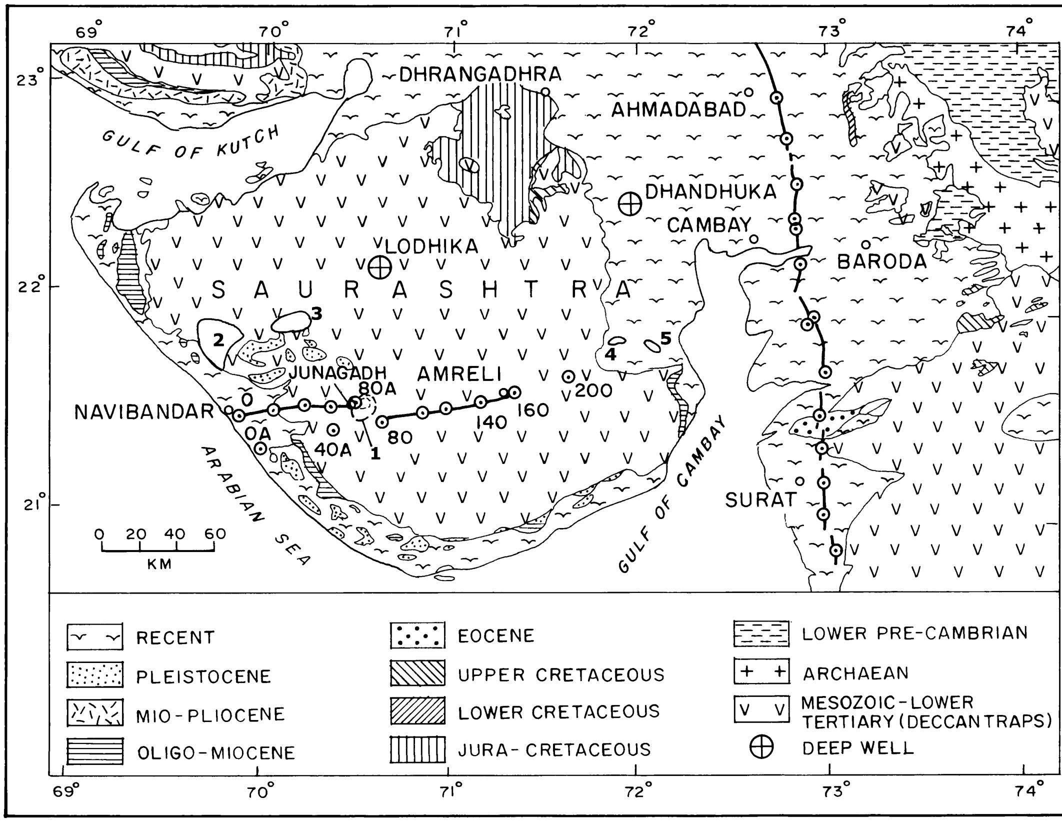


Figure 1. Geological map of Saurashtra and adjoining regions. The Navibandar–Amreli deep seismic sounding (DSS) profile recorded in Saurashtra and a part of the DSS profile of the Cambay Basin are plotted. Some shot point (SP) numbers are indicated for Navibandar–Amreli. SPs 0, 0A, 80A, 80, 160 and 200 have been indicated but the remaining SP numbers are not included due to shortage of space. Volcanic plugs are: 1, Girnar; 2, Barda; 3, Alech; 4, Chogat; 5, Chamardi.

(Fig. 1). The Girnar Massif at Junagadh has acidic and alkaline to mafic/ultramafic rocks (Subba Rao 1968; Chandra 1999). Barda and Alech plugs are predominantly acidic in composition (Merh 1995), while the Chogat and Chamardi plugs are basically alkaline (Karanth & Sant 1995).

Based on ^{40}Ar/^{39}Ar dates the age of the Deccan Volcanics is estimated as 66.5–68.5 Ma (Duncan & Pyle 1988) on the Western Ghats (east of Bombay) and 65.5 ± 2.5 Ma (Vandamme *et al.* 1991) on several samples between Bombay and Nagapur (in central India, not shown in the figures). Allegre *et al.* (1999) give an age of 65.6 ± 0.3 Ma for the samples of Bombay–Nagapur region based on ^{187} Re/^{187}Os dating. Basu *et al.* (1993) give the ^{40}Ar/^{39}Ar age of biotites from igneous complexes to the north of the Deccan Volcanic Province as 68.53 ± 0.16 Ma and 68.57 ± 0.08 Ma at Mundwara and Sarnu-Dandali respectively (not shown in the figures) and from the one which intrudes the flood basalt (Phenaimata, not shown in the figures) as 64.96 ± 0.11 Ma. They conclude that these samples represent early and late magmatism with respect to the main pulse of continental flood basalts at ~65 Ma, the early magmatism shows that 3.5 Myr was the 'incubation period' of a primitive, high-^{3}He mantle plume before the rapid eruptions of the Deccan flood basalts. Karanth & Sant (1995) report that dyke swarms oriented in east–west and northeast–southwest directions, representing the Deccan volcanic activity, are also found in the central and southeast Saurashtra. Mishra *et al.* (2001) hope that the dyke swarms follow dominant structural trends in this region, as their orientation is almost the same as that of igneous intrusions and alkaline complexes of ~65 Ma.

The main features of the Bouguer gravity anomaly map of Saurashtra (Fig. 4) are a series of northeast–southwest trending gravity highs (D, E, F) of 40–60 mGal amplitude in the southeastern part and of almost the same amplitude (A, B, C) in the region of the Girnar, Alech and Barda volcanic plugs (Mishra *et al.* 2001). A broad low (H) with a steep gravity gradient (G) to its west, is observed in central Saurashtra (Amreli–Chotila).

It has been proposed that the volcanic eruption from the Réunion Plume at ~65 Ma was mainly responsible for the widespread volcanic activity in western India (White & McKenzie 1989). The centre of the plume at that time was close to the west coast of India. The Saurashtra Peninsula was close to the trace of this plume on the Earth's surface, during the passage of India over it, in the Late Cretaceous. The trace of the plume passed through the Cambay Basin (Campbell & Griffiths 1990; Kaila *et al.* 1990) to the immediate east of the Saurashtra Peninsula.

To understand the crustal configuration, evolution and tectonic history of the western part of India, a few deep seismic sounding (DSS) profiles were recorded in the region (Kaila & Krishna 1992). Under this programme analogue data, in the form of seismic refraction and wide-angle reflections, were also recorded during 1977 along an east–west profile (Navibandar–Amreli) in the western part of the Saurashtra Peninsula. The results of those studies (Kaila *et al.* 1980) provided the first model (Fig. 5) of the Saurashtra crust. Their model was based on conversion of traveltimes to depth. For this conversion an average velocity model was determined for the entire region based on the analysis of mutual shot point data for reflection traveltimes (Kaila & Krishna 1979). This model was translated to a

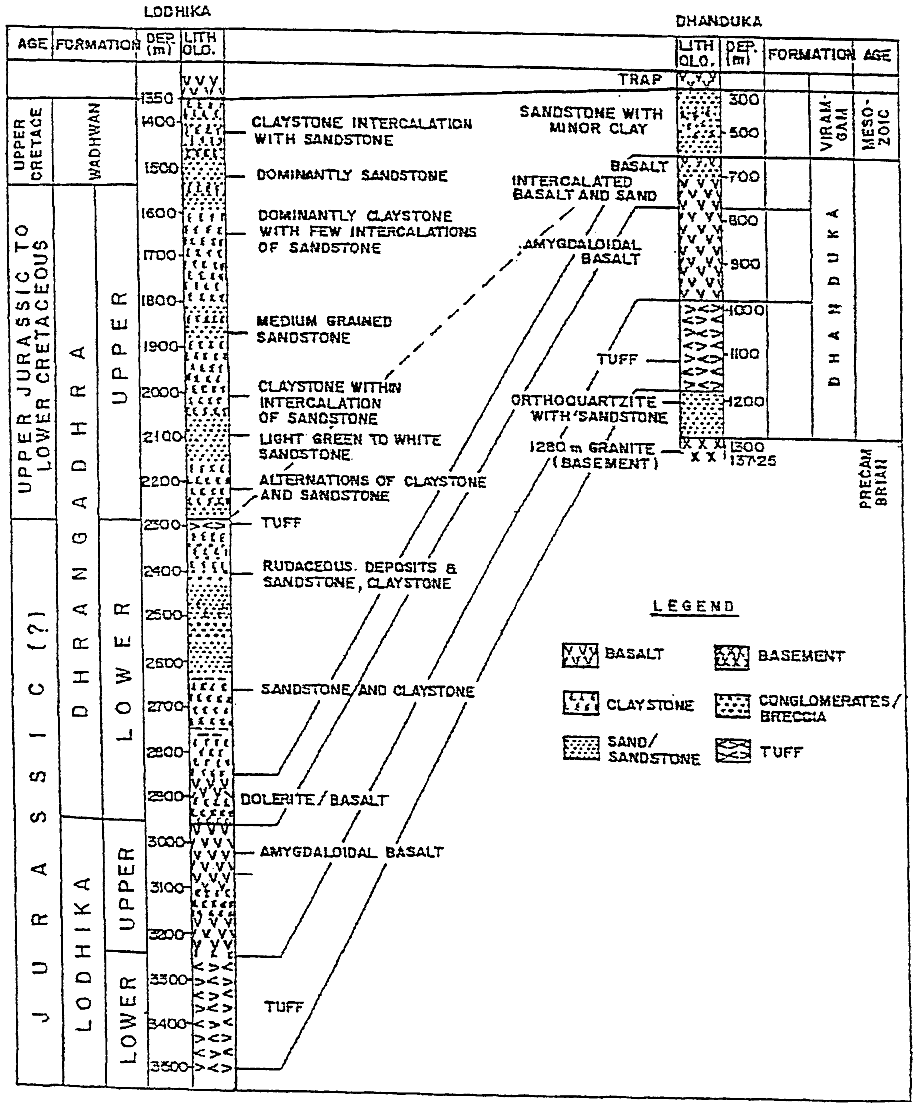


Figure 2. Lithostratigraphic sections of the deep wells drilled in Saurashtra and their correlation (after Singh *et al.* 1997).

1-D interval velocity model to convert the reflection traveltime data to depth and migrated using the approach of Kaila *et al.* (1982). The weak points of this approach were the conversion of average velocity to an interval velocity model, the assumption that this model holds good for the entire region of investigation and the inability to generate synthetic seismograms and compare the same with the observed seismograms.

In view of the new geological and geophysical results, other than the DSS, that have been published over the last 20 yr for the western Indian region and to study the effect of the Réunion Plume on the crust of the region, it became necessary to review the existing interpretation of the DSS data for the Saurashtra. The more sophisticated dynamic forward modelling software that is now available and digitization of analogue traces, to compare them with the computed seismograms, makes the reinterpretation more reliable. Therefore, an attempt was made to obtain a velocity model of the Saurashtra crust based on the kinematic and dynamic characteristics of the observed record sections and to use this model to understand the tectonic development of the region.

2 THE DSS DATA

The DSS data from the Navibandar–Amreli profile (Fig. 1), recorded along two segments Navibandar–Junagadh (SP 0–SP 80A) and Junagadh–Amreli (SP 80–SP 160) in 1977, were in analogue form. These were recorded with two 30-channel instruments in master–slave mode with a high-cut filter of 22 Hz, the low cut being open and controlled by the geophone natural frequency of 10 Hz. Recording was done every 200 m. There were, however, a few gaps due to towns and villages and a profile shift at Junagadh. Twelve shot points (SPs) were operated but only two (SPs 0A, 200) were recorded at long distances. The energy source was dynamite with charge size varying between 50 and 1000 kg depending upon the source–receiver distance. Some of the shots (e.g. 0A, 40A) were recorded only on the Junagadh–Amreli segment. SP 200 was outside the profile and recorded on both segments.

Due to the results obtained by drilling the Lodhika and Dhanduka deep wells (Fig. 2), knowledge of the stratigraphic sequence of the Saurashtra Peninsula is now vastly improved. The former well is

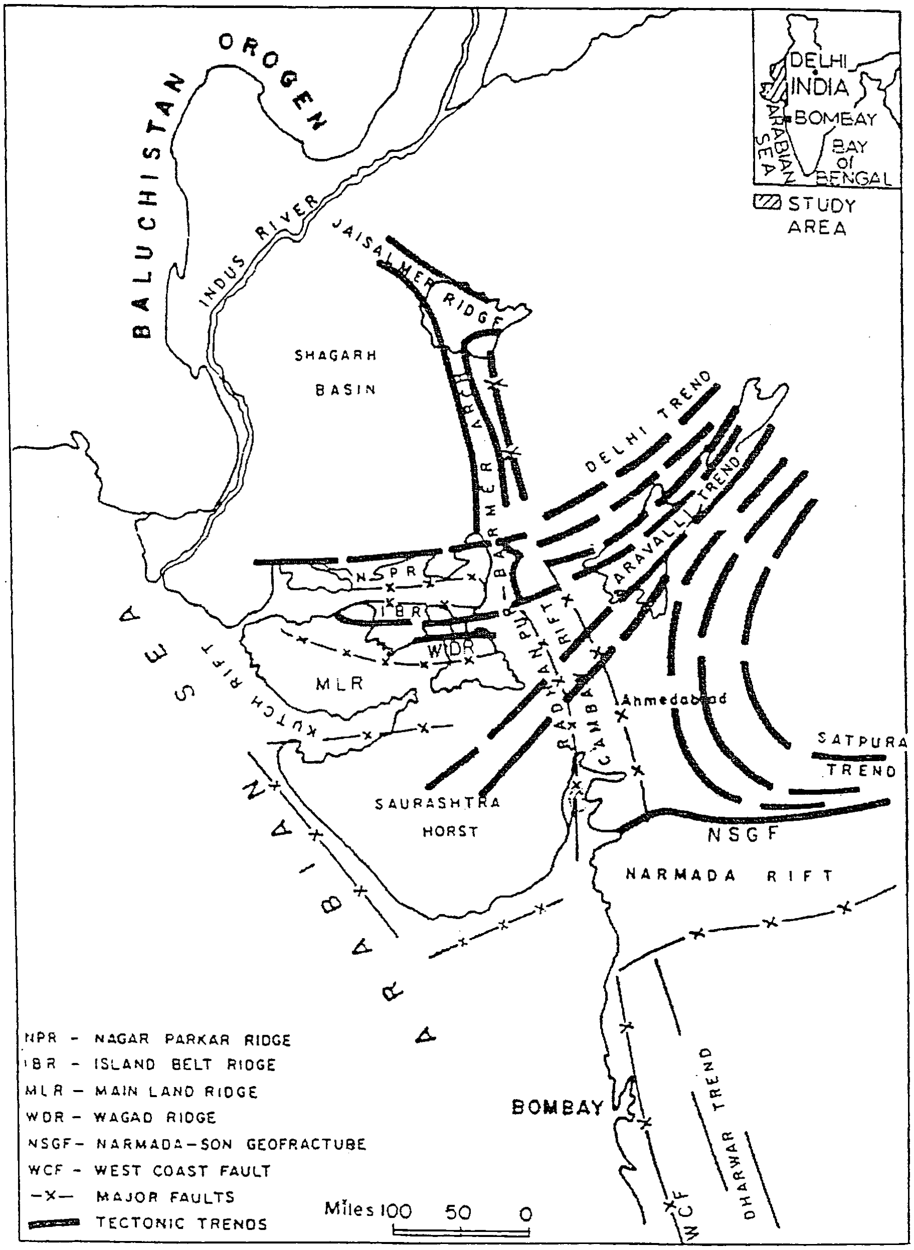


Figure 3. Orogenic trends and major structural lineaments in western India (after Biswas 1987).

situated in the northern part of the peninsula and the latter at its eastern fringe (Fig. 1). Dixit *et al.* (2000) have provided a correlation of seismic velocities with the geological horizons obtained from the well data, down to a depth of about 3.50 km.

In the present analysis, the broad structure down to the base of the volcanics was analysed with the help of refracted first-arrival data every 200 m. These arrivals were identified from the high-gain monitor records as first breaks (Fig. 6). The traveltime error for the first arrivals is of the order of a half cycle (±30 ms), while for the wide-angle reflections it is about one cycle (±70 ms). The amplitudes of later arrivals in most of the monitor records were very high and overlapped with other traces; therefore low-gain play-back records were used for digitization. Due to this, the first arrivals could not be identified in most of the digitized and reassembled records. The base of the Deccan Volcanics was initially modelled with the help of refraction analysis with standard methods available in the literature. It was further improved by kinematic forward modelling of the first-arrival data (Figs 7a and b). The presence of a low-velocity layer below the Deccan Volcanics, though probable, was not considered in this analysis as the secondary arrivals, representing reflections from the top and bottom of the low-velocity zone at near distances, could not be properly identified nor could any shadow zones be seen in the refraction data.

For crustal modelling, the analogue DSS data of lower gain were digitized. In each gather of 30 traces about six to eight traces were digitized, at a 4 ms sampling interval, maintaining a distance of 800–1000 m between the digitized traces. As the field seismic records were generated using different charge sizes, depending on the distance of recording, and with different analogue gain for each record it is not possible to plot the observed seismic record with absolute

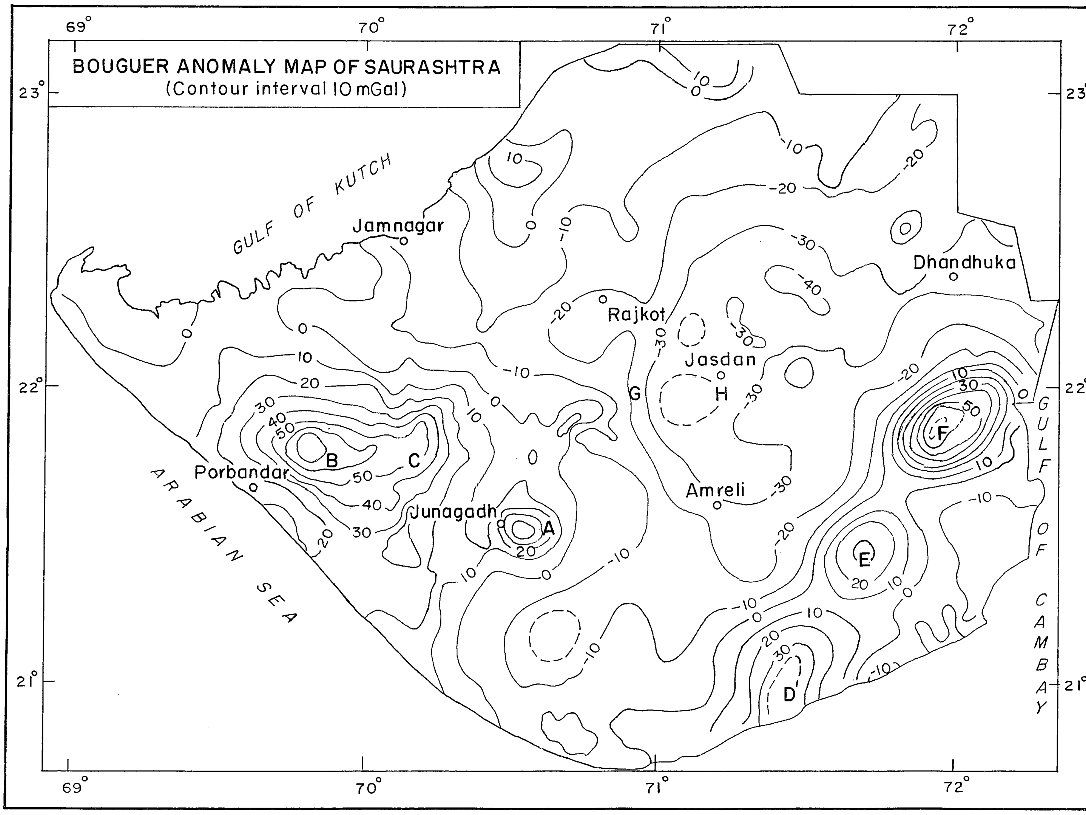


Figure 4. Bouguer gravity anomaly map of the Saurashtra region (after Mishra *et al.* 2001) with the Navibandar–Amreli DSS profile plotted. Note the domination of an east–west Bouguer high gravity trend in the west (B and A) and a northeast–southwest trend in the southeast (D, E, F).

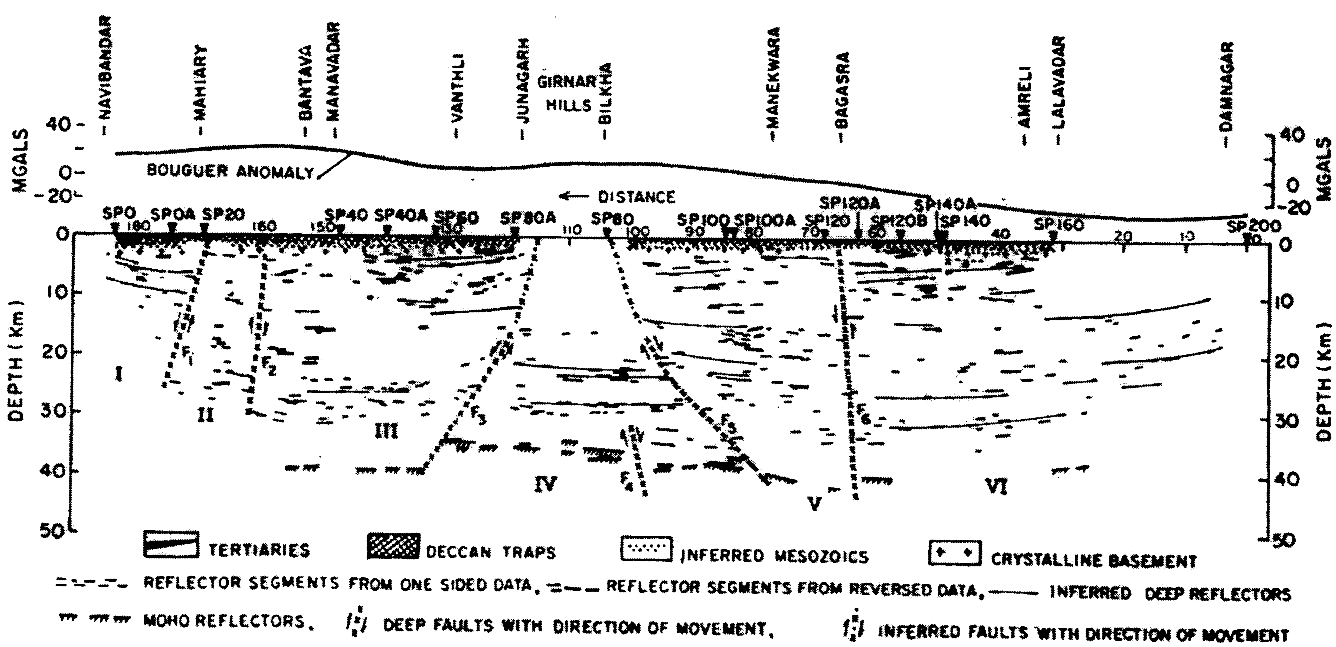


Figure 5. Crustal depth model of Kaila *et al.* (1980).

amplitudes. Therefore the attenuation of energy with distance for the various reflectors cannot be studied. Since the absolute amplitudes could not be studied the digitized data were reassembled in the form of trace-normalized gathers and plotted with a reduction velocity of 6.00 km s^{-1}. In trace normalization all the amplitudes in a trace are scaled with reference to the highest amplitude in that trace, the highest amplitude in different traces being set to a fixed value. The seismic attenuation coefficient therefore does not have any significance.

The main events that could be recognized in these gathers were the wide-angle reflections from various crustal boundaries ($P^{6.10-6.15}$, $P^{6.35-6.40}$, $P^{6.70-6.75}$, $P^{7.10-7.20}$ and $P^{8.10}$). The arrivals are easily

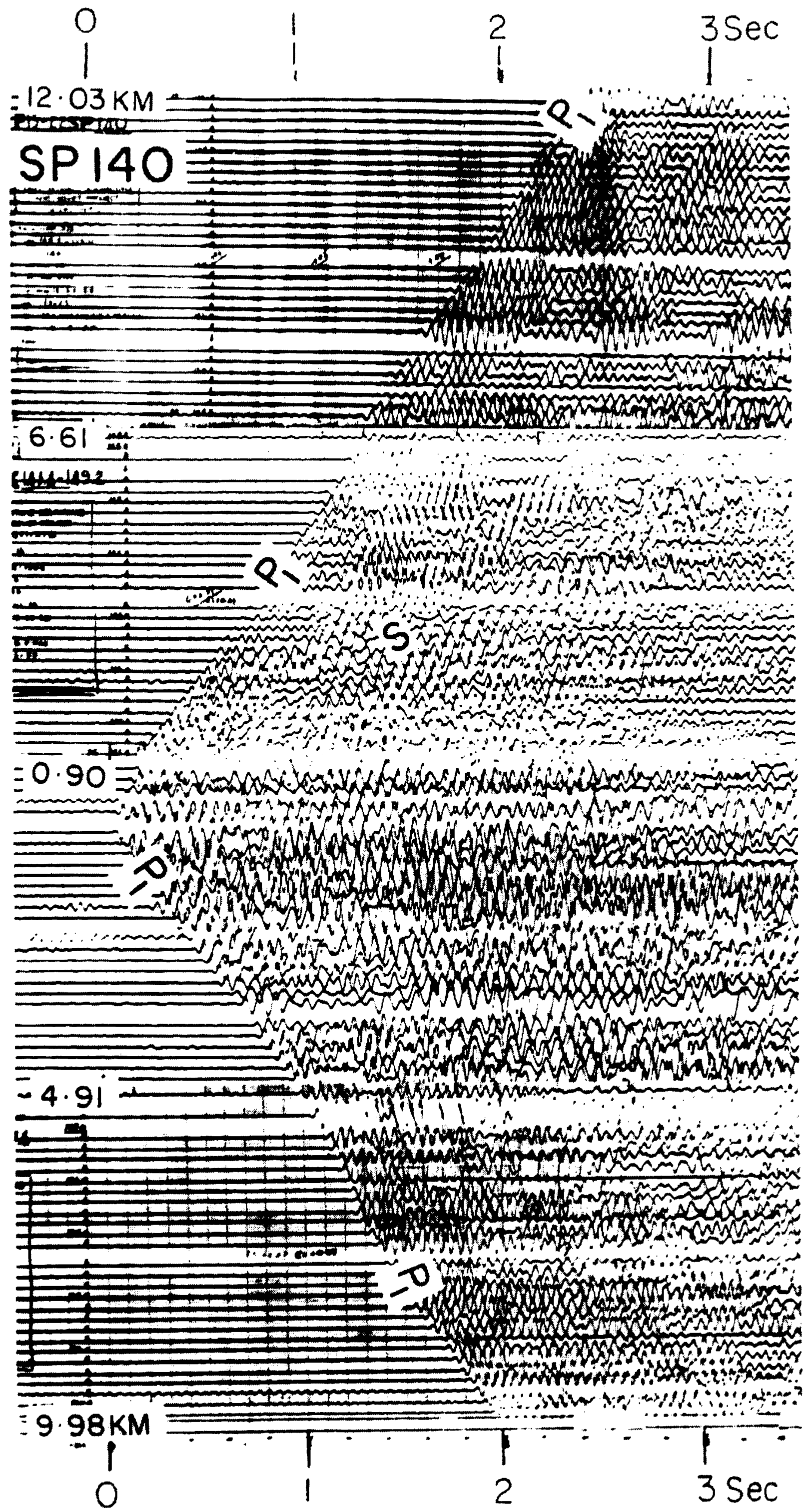


Figure 6. A sample of the analogue monitor record for SP 140. P_1 indicates the first-arrival refraction data.

identified due to their higher amplitude as compared with the coda. Only those arrivals which could be modelled from more than two shot points were used. The velocities on either side of these boundaries were determined on the basis of refracted arrivals ($P^{6.15}$, $P^{6.75}$, $P^{7.10}$) from some of the shot points and trace-normalized amplitude matching of the wide-angle reflections on the observed and synthetic seismograms. The velocities may, however, be in error by ± 0.1 km s^{-1} as it is difficult to observe the change in trace-normalized amplitude for such a small variation.

To constrain the deep crustal structure down to the Moho, a starting pseudo 2-D earth model was constructed, on the basis of modelling of wide-angle reflection traveltimes for each shot point. The same model was further improved through the amplitude modelling of various phases using the RAYAMP-PC (1987) program for 2-D

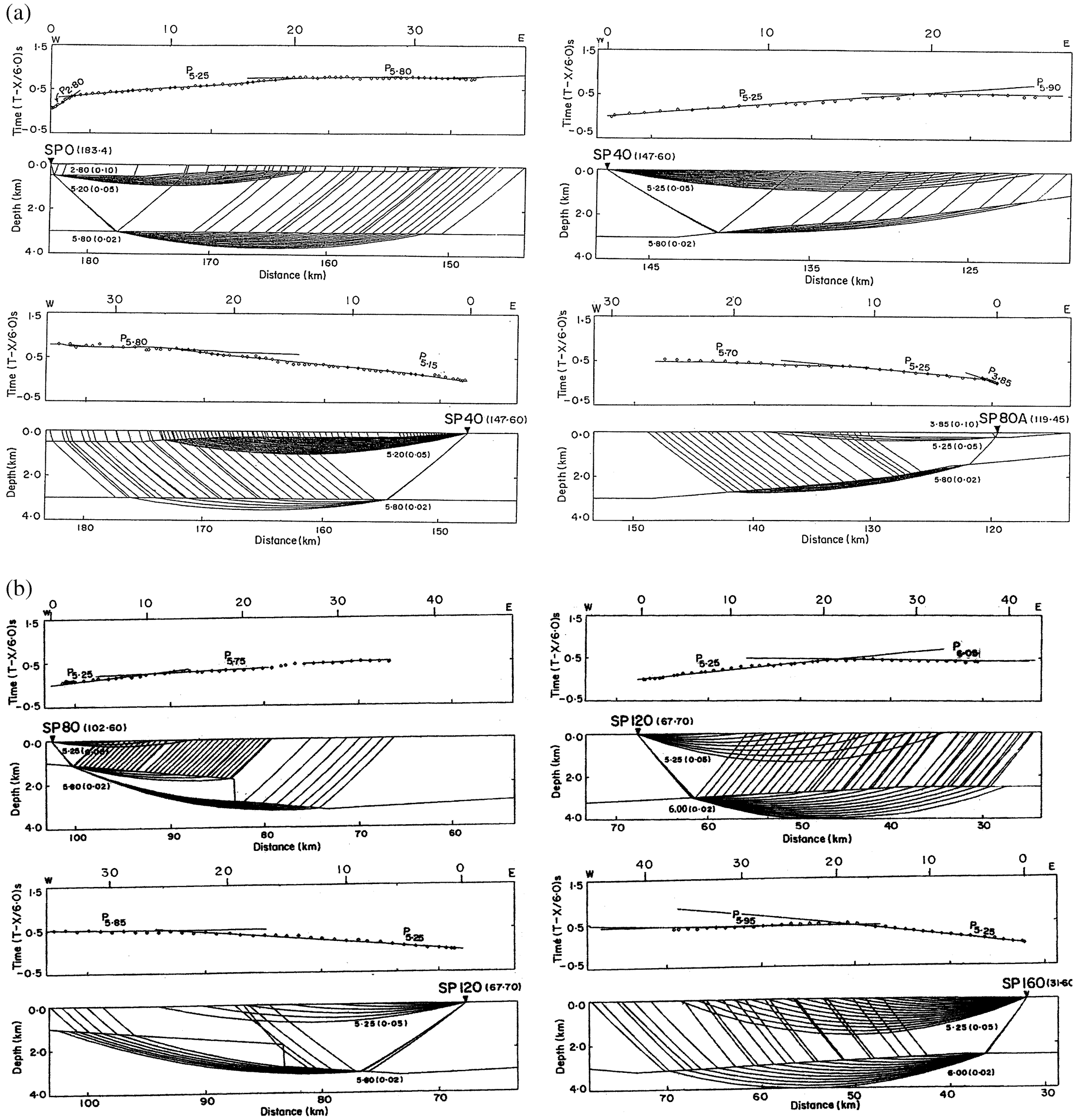
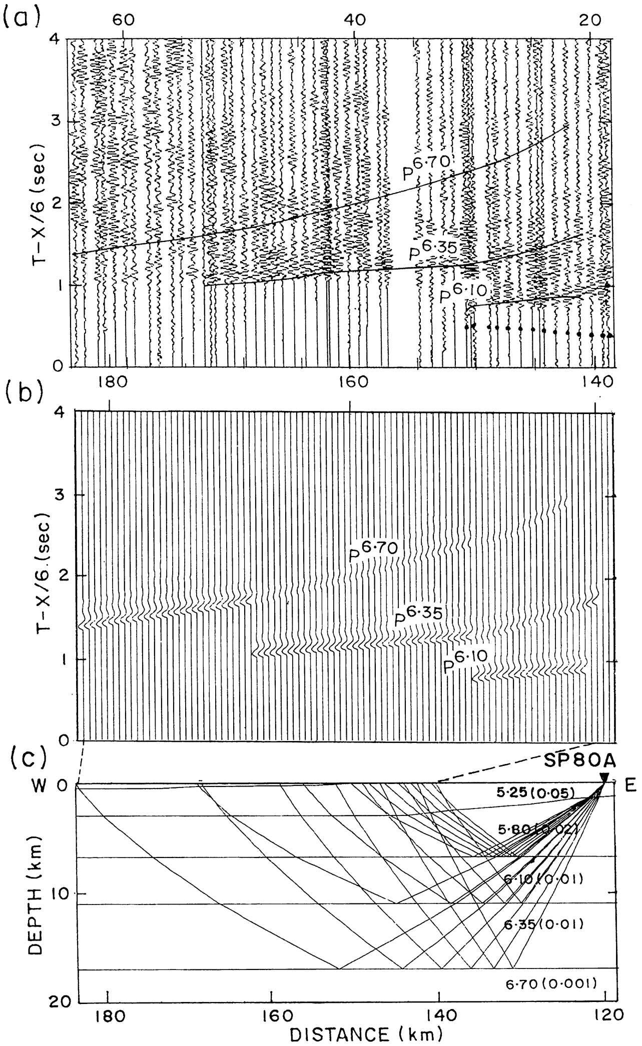


Figure 7. (a) The first-arrival refraction data, ray trace diagram and depth model up to the base of the Deccan Volcanics between SP 0 and 80A. In addition to the shot points shown, refraction data from intermediate shot points 20 and 60 were also used to constrain the model. The velocity on the traveltime is apparent while that on the depth section is actual. For the sake of clarity of figures traveltimes are plotted approximately 800 m apart and not every 200 m. For each shot point the shot–receiver offset is marked at the top with SP located at 0 distance. (b) Same as above between SP 80 and 160. Data from shot points 100 and 140 were also used.

asymptotic ray tracing. To fill in the gaps and also to explain the broad gravity features, a 2-D gravity model based on seismic data was also constructed.

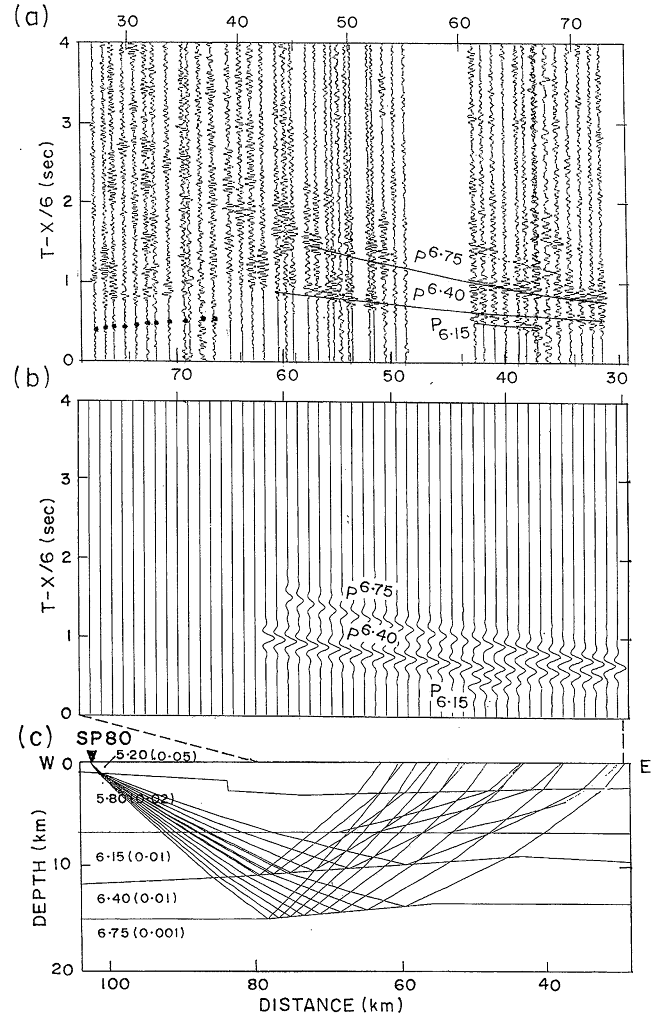
3 THE DEPTH MODEL

The shallow depth section was computed segment wise for both the segments. Segment I (Fig. 7a) shows a layer of 2.80 km s^{-1} velocity with a thickness of 0.4 km at the western end (SP 0, Navibandar). This velocity is attributed to the Quaternary/Tertiary sediments that are exposed in this part. Another layer with a thickness of about 0.2 km and velocity of 3.85 km s^{-1}, is identified in a patch of about 10 km to the west of the SP 80A near Junagadh. This layer is likely to belong to the Tertiary exposures near SP 80A. Except for these low-velocity exposures a layer with a velocity varying between 5.20 and 5.25 km s^{-1}, attributed to the exposed Deccan Volcanics, covers the entire segment. This layer also underlies the layers of velocity 2.80 and 3.85 km s^{-1} and overlies a layer of velocity 5.80–6.00 km s^{-1}. Segment II (Fig. 7b) is covered by Deccan Volcanics of velocity 5.25 km s^{-1} that overlie a layer of velocity 5.80–5.90 km s^{-1}, the depth to which varies between 1.4 km and 2.6 km below the surface level. The data (Fig. 7b) require a steep increase in depth for this layer between SPs 80 and 120. Though it is difficult to distinguish in the first arrival refraction data between a steep dip of 20°–30° and a fault, we have preferred to put it as an east-dipping fault as the kinematic model gives a better fit with a fault as compared with a steep dip. The increase in depth may partly be due to the existence of subvolcanic Mesozoic sediments around Amreli, the presence of which is supported by the gravity low to the north of Amreli (H of Fig. 4) as well as the drilling results for the Lodhika and Dhandhuka wells. We have, however, not indicated these sediments in our depth section, as in the absence of reflections



▼ Shot point 5.80 Velocity km s^{-1} (0.02) Velocity gradient s^{-1}

Figure 8. (a) Observed and (b) synthetic seismograms and (c) ray diagrams for the presented velocity–depth model for SP 80A. The offset for the start of the digitized record section is 20 km from the SP. The distance marked in Figs 8 to 12 is from SP 200. The first arrival times picked from high-gain monitor records for refraction analysis are not seen in the digitized seismogram and are marked as (•). For each shot point the shot–receiver offset is marked at the top with SP located at 0 distance.



▼ Shot point 5.80 Velocity km s^{-1} (0.02) Velocity gradient s^{-1}

Figure 9. Same as Fig. 8 for SP 80. The offset distance for the start of the digitized records is 24 km from the SP.

from the volcanic–Mesozoic boundary our data are insufficient to confirm (or deny) their presence.

The crustal model is based mainly on the analysis of seismic wide-angle reflection data and a few refracted arrivals (Figs 8 to 12 show the examples from a few shot points). This model (Fig. 13) shows that the upper crust consists of three layers of velocities 5.80–6.00, 6.10–6.15 and 6.35–6.40 km s^{-1}. The base of the upper crust is at about 16 km in the western part (below SP 40A) of the profile and at about 13 km near the eastern end, below SP 140. The lower crust consists of two parts. The trace-normalized amplitude modelling indicates a velocity of 6.70–6.75 km s^{-1} for the upper part. This conforms with the velocity of 6.75 km s^{-1} determined for this layer from the refracted arrivals of SP 200 (Fig. 11). The lowermost part of the lower crust indicates a velocity between 7.10 and 7.20 km s^{-1}. The velocity of 7.10 km s^{-1} is also determined from the first-arrival data of SP 0A (Fig. 10). The depth to this layer varies between 24 and 22 km from west to east. The reflection from this layer is followed by another reflection that is reasonably strong in SP 200 (Figs 11 and 12) and very strong in SP 0A (Fig. 10). Head waves have not been recorded from this reflector due to limitations in profile length. To determine the velocity of this layer, synthetic seismograms were computed by attributing various velocities to this layer for the data of SP 0A. The comparison of trace-normalized amplitudes (Fig. 14) shows that 8.1 km s^{-1} can be taken as a compromise velocity for this layer even though it is possible that this velocity may be in error by $\pm$0.20 km s^{-1}.

The depth to the top of this layer is about 36 km below SP 40A and 32 km below SP140. Since this layer follows the layer of velocity 7.10–7.20 km s^{-1} and a velocity of about 8.10 $\pm$ 0.20 km s^{-1} produces suitable amplitudes in SP 0A, this interface has been identified as the Moho. A steep updip brings it from a depth of 36 km below SP 80A to a depth of about 33 km below SP 120 (Fig. 13). From there the updip is gentle to about 32 km near SP 160.

The model obtained through the present study differs from that of Kaila *et al.* (1980) (Fig. 5) in many respects. The main differences are: the Moho configuration given by Kaila *et al.* (1980) was shown to be changing in an irregular pattern between 35 and 42 km depth

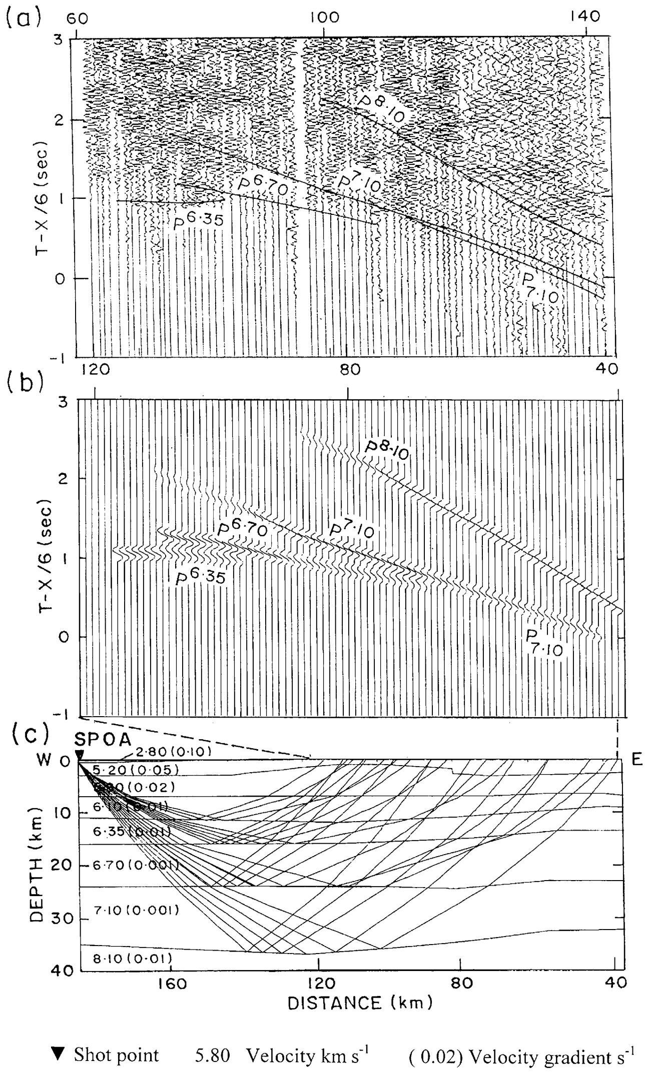


Figure 10. Same as Fig. 8 for SP 0A. The offset distance for the start of the digitized record is 60 km from the SP. The first arrivals are not marked.

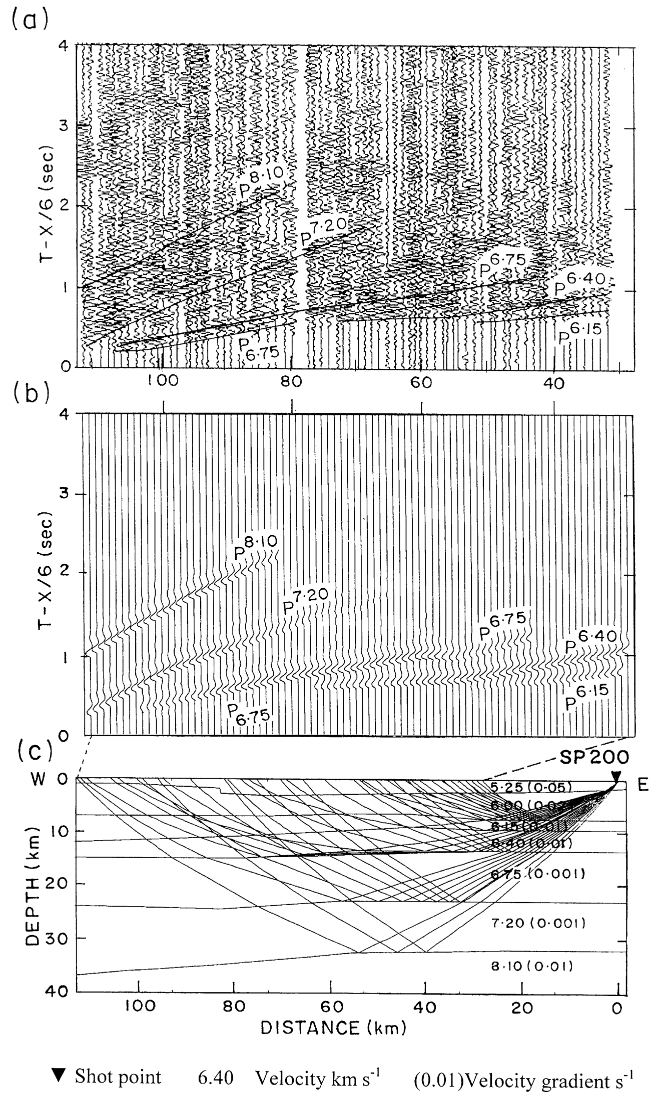


Figure 11. Same as Fig. 8 for SP 200 (distance range 35–110 km). The offset distance for the start of the digitized record is 30 km.

and its coming up towards the east was not identified. Also they did not identify the 7.20 km s^{-1} velocity in the lower crust. Use of digitized data followed by dynamic forward modelling, the consistency and accuracy of which is much better than the technique used by Kaila *et al.* (1980) with analogue data, has provided a velocity–depth model which is more consistent with the available data.

4 THE GRAVITY MODEL

To understand the Bouguer gravity picture along the DSS profile *vis-à-vis* the seismic structure and also to fill the gaps, particularly at the ends of the profile, a 2-D density model based on the crustal seismic structure was computed using the algorithm of Talwani *et al.* (1959). The observed gravity values along the profile, taken from the Bouguer anomaly map of Mishra *et al.* (2001), show a large high in the western part of the profile (Fig. 15).

The Deccan Volcanics are known to have a higher density than the granites, even though their velocity is lower than the granite velocity. In the Saurashtra region the Deccan Volcanics' velocity is 5.20–5.25 km s^{-1}. Their density, based on the laboratory measurement, is reported as 2740 kg m^{-3} (Mishra *et al.* 2001) and the same value was used for the present model. The model was computed mainly in three steps. In the first step the density of the base of the Deccan Traps was considered as 2670 kg m^{-3} and the crustal interfaces were horizontally extended on both sides. This, however, resulted in a set of computed values that did not match with the observed ones (curve 1, Fig. 15). The high gravity values to the west could mainly be due to two reasons: (a) a decrease in the depth of deep crustal interfaces, including the Moho, towards the sea coast (near SP 0A) and (b) higher densities at the shallow depth probably due to volcanic plugs. From the seismic data there is no control on the depth to the Moho and other crustal interfaces at the sea coast (SP 0A), the last control for the Moho being at a distance of about 40 km, where the depth is 36 km. However, it is well known that the depth to crustal interfaces, including the Moho, decreases towards the sea. Therefore in the second step we assumed a depth of 29 km for the Moho at the sea coast (SP 0A). Similar adjustments were also made for other crustal layers. Despite these adjustments the computed gravity values did not match with the observed ones (curve 2, Fig. 15).

A higher density at shallower depths was required to bring the computed gravity values close to the observed ones. Chandrasekhar *et al.* (2002) has given a bulk density of 2850–2900 kg m^{-3} for the

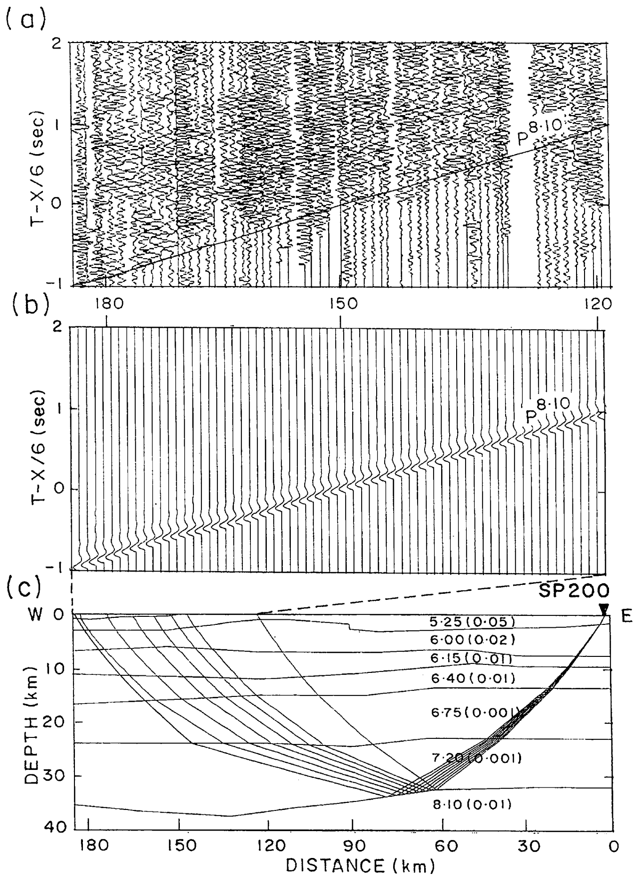


Figure 12. Same as Fig. 8 for SP 200 (distance range 120–180 km).

plugs in western Saurashtra and Mishra *et al.* (2001) indicate that these plugs have deep roots. Therefore, in the third step a density of 2850 kg m^{-3} was given to the layer below the Deccan Volcanics. In the western part of the profile this density continues down to depths of about 10 km. To the east of Girnar a density of 2670 kg m^{-3} is required above this high density until the lower density replaces it. To the east of Amreli a high density (2820 kg m^{-3}) is again required below the density of 2670 kg m^{-3}, probably due to the effect of volcanic plugs of southeast Saurashtra. According to Chandrasekhar *et al.* (2002) these plugs have a deeper source than those in the west. With the above assumptions, taking the seismic boundaries as control and without disturbing the basic nature of the seismic section, a gravity model that fits with the observed gravity values could be obtained (curve 3, Fig. 15).

The 2-D gravity model based on seismic data thus indicates that the base of the volcanics in the western part may not be granitic and is likely to be volcanic, due to the presence of a series of high-density volcanic plugs. Mishra *et al.* (2001) infer that the Girnar and other volcanic plugs to its west (Barda, Alech, etc.) show large gravity highs due to felsic composition at Barda and more mafic/ultramafic (high-density) components at Girnar. Our 2-D model, for a gravity picture that shows major variation in the third dimension (Fig. 4), does have certain limitations and some errors in density and depth values are likely. For example, in a 3-D approach either the density (2850 kg m^{-3}) or the thickness of the layer at the base of volcanics may be different than that given in Fig. 15. Since seismic control in the third dimension is not available, we did not try a 3-D model of gravity.

5 DISCUSSION AND CONCLUSIONS

The subsidence of Saurashtra Peninsula along the eastern margin fault of the Cambay Basin during the Early Cretaceous (Biswas 1987), its uplift and faulted boundaries indicate several phases of

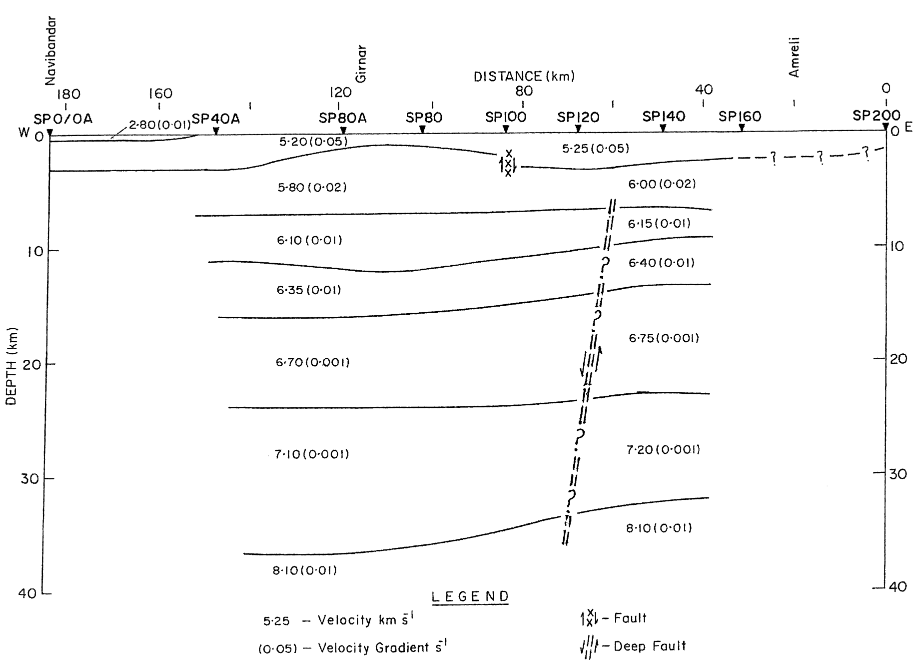


Figure 13. Crustal velocity–depth model, based on refraction and trace-normalized amplitude synthetic seismogram modelling along the Navibandar–Amreli profile in Saurashtra. The faults are interpreted and not actually observed on the record gathers.

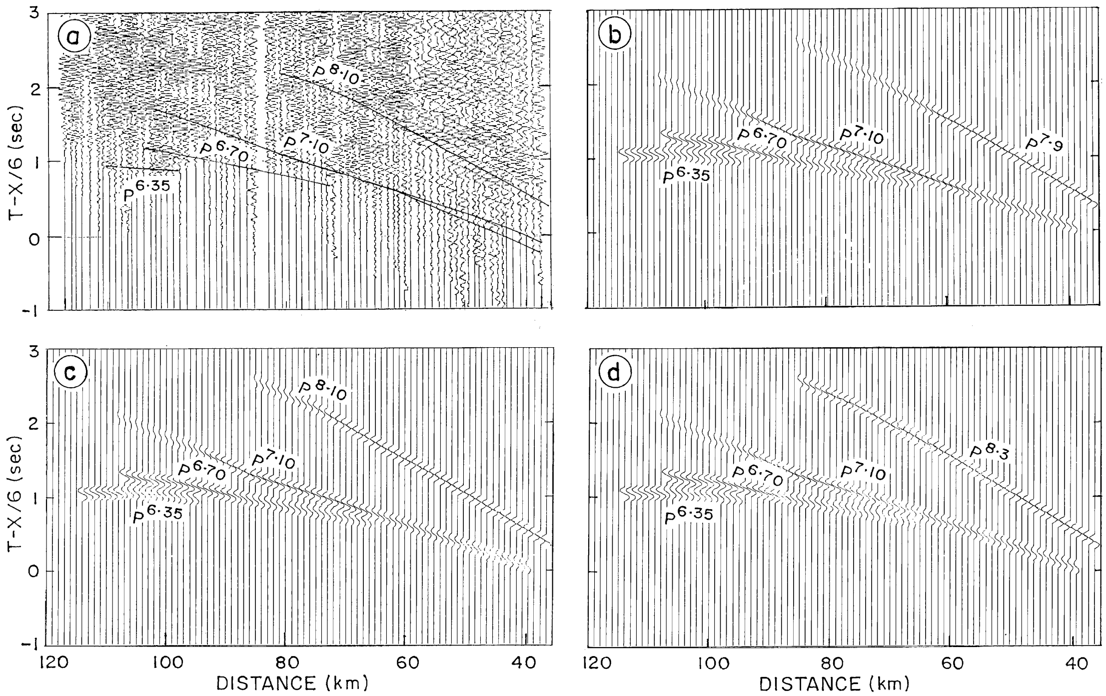


Figure 14. Comparison of observed (a) with synthetic (b, c, d) trace-normalized amplitudes for Moho velocities of 7.90, 8.10 and 8.30 km s^{-1} respectively for SP 0A. Part (a) shows high amplitudes for the Moho boundary between distances of about 70 and 40 km and relatively lower amplitudes for the 7.10 km s^{-1} velocity layer between 40 and 60 km distance. Part (b), however, shows larger amplitude for the 7.10 km s^{-1} velocity in this range and part (d) shows a larger amplitude for the Moho boundary even between 85 and 70 km distance. Part (c), where the Moho velocity is taken as 8.10 km s^{-1}, is therefore a good compromise.

tectonic activity during and after the Cretaceous period. The depth to the crust–mantle boundary (Moho) in the western part of Saurashtra is close to that in the Indian Shield, while the eastern part appears to be uplifted due to a sharp reduction in the depth of Moho and other crustal layers, between SP 80 and SP 120. This unusually large reduction in the Moho depth is also accompanied by a reduction in depths to all the crustal boundaries towards the east. This can probably be interpreted as a zone of deep fault, thrown up towards the east, which may come close to the surface near SP 140. Mishra *et al.* (2001) have also interpreted this deep fault west of SP 160, based on the gravity gradient (G of Fig. 4) and a pair of long north–south lineaments in the satellite data. The deep fault could also have acted as a lava feeder from the lower crust/upper mantle to the near surface. A large number of dykes and volcanic plugs in the Saurashtra and the high density in the upper crust (Fig. 15) are consistent with this possibility.

The proposed fault is in line with the extension of the Aravalli trend in the Saurashtra and appears to divide the Saurashtra lower crust into two distinct parts. The crustal thickness to the east of this fault is between 32 and 33 km. The Cambay Basin, to the east of Saurashtra, shows an upper crust at 13 km depth, the Moho at 32 km depth and an 8–10 km thick layer of velocity 7.10–7.20 km s^{-1} at 23–25 km depth (Kaila *et al.* 1990). This structure is more or less similar to that in the eastern Saurashtra. However, there are a few differences in the details of upper crustal configuration of the two regions. In the Cambay Basin the base of the sedimentary column and the Deccan Volcanic shows only one velocity that varies between 5.90 and 6.00 km s^{-1} and is underlain by a low-velocity layer (5.50 km s^{-1}), while in Saurashtra the low-velocity layer is not seen.

The crustal thickness in eastern Saurashtra, the Cambay Basin and even in the region of the Vindhyan exposure to the immediate east of Aravalli (Rajendra Prasad *et al.* 1998) is of the order of 32–35 km. This region lies between two tectonic trends of Aravalli, one crossing the Cambay Basin and the Saurashtra and the other turning eastwards and merging with the Satpura trend. It thus appears that the crust in the eastern Saurashtra, Cambay and adjoining regions between the above two trends is uplifted by as much as 6 to 8 km as compared with the regions out side these trends. This region was close to the central part of the rising Réunion Plume during the Late Cretaceous. It thus appears likely that the rise of the Réunion Plume was accompanied by a phase of tectonic activity in western India during the Late Cretaceous and caused uplift of the crust in a large region including the eastern part of Saurashtra and the Cambay Basin. The main subsidence of the Cambay Basin occurred later, in the Early Tertiary, after the eruption of the Deccan Volcanics (Tewari *et al.* 1995). The upper crustal structure of the Cambay Basin might have been modified during this period.

The high-velocity (7.20 km s^{-1}) layer at the base of the crust is a common feature in the western part of India. Kaila *et al.* (1990) show the presence of a similar layer in the Cambay Basin. Deep seismic studies across the Narmada zone (to the east of the Cambay Basin) have shown the presence of a similar, 10–15 km thick, layer up to at least 600 km east of the Cambay Basin (Sridhar & Tewari 2001; Tewari *et al.* 2001). Singh & Meissner (1995) have shown a high-density layer at the base of crust in the same region. It is generally accepted that a large part of the Deccan volcanic extrusion was from the Réunion Plume which was close to the west coast of India at ~65 Ma (Raval 1989; Richards & Duncan 1989; White & McKenzie 1989). The passage of the western part of India over the Réunion Plume resulted in partial melting, initiated by the arrival of a hot plume that thinned and conductively heated up the lithosphere. Further rise of the plume through the lithosphere caused rapid eruption of the continental flood basalts (Duncan & Pyle 1988; Renne

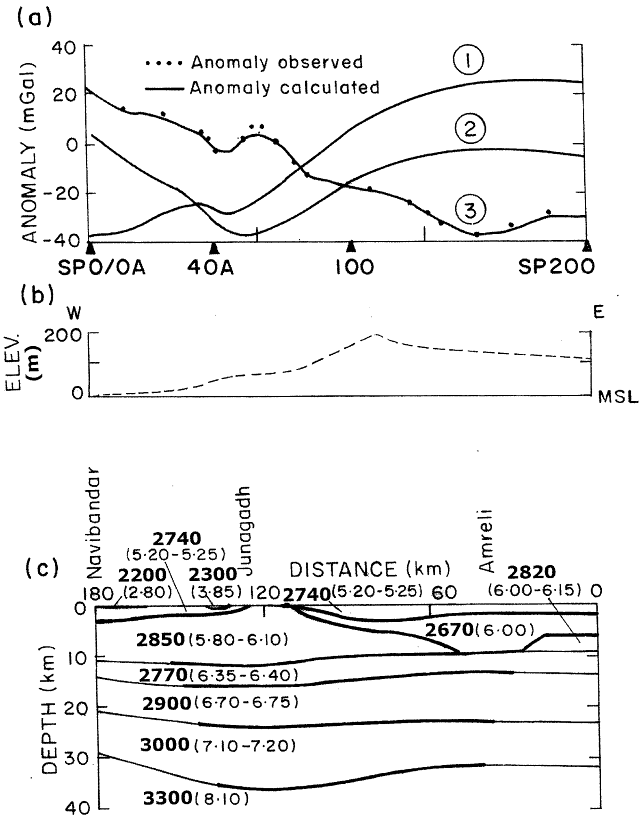


Figure 15. Part (c) shows the crustal density (in kg m^{-3}) model, based on the seismic model, along the Navibandar–Amreli profile in Saurashtra. The elevation along the profile is plotted in (b). The dots in (a) are the observed Bouguer anomaly values. Curve (1) shows the computed 2-D Bouguer anomaly values by horizontally extending the depth of Moho (36 km) and other crustal layers up to SP 0A at the sea coast, and the base of the volcanic layer having a density of 2670 kg m^{-3} . Curve (2) is similar to curve (1) with the Moho and other crustal layers uplifted towards the sea coast according to the given model. In curve (3), which shows a good match with the observed values, the base of the volcanic layer has a density of 2850 kg m^{-3} in most parts in the west and 2820 kg m^{-3} in the east. The values in brackets are the *P*-wave velocities (in km s^{-1}) for various layers. The interfaces that are constrained by the seismic observations are thickened in part (c).

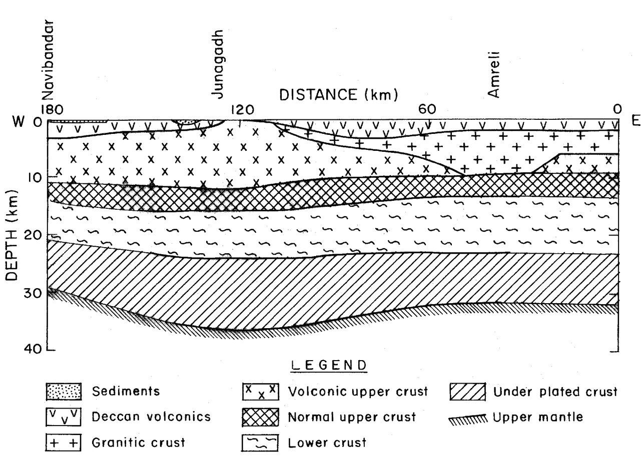


Figure 16. Geological section of the crust along the Navibandar–Amreli profile in the Saurashtra Peninsula by seismic/gravity modelling.

& Basu 1991). As the head of the plume had a diameter of 1000–2000 km (White & McKenzie 1989), consequent intrusion of the magmatic material at the base of the crust led to underplating in a large part of the crust in western India, including Saurashtra.

The following conclusions can be made on the basis of the present study:

(1) The 7.10–7.20 km s^{-1} velocity layer at the base of the crust in Saurashtra and other parts of western India represents underplating of the crust due to the passage of India over the Réunion Plume in the Late Cretaceous.

(2) The eastern part of Saurashtra and the Cambay Basin represent an uplifted crust close to the central part of the Réunion Plume.

(3) From seismic/gravity modelling, obtained geological section of the crust, along the Navibandar–Amreli profile in the Saurashtra peninsula is shown in Fig. 16.

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