DEEP SEISMIC SOUNDING STUDIES IN INDIA AND MAJOR DISCOVERIES

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ABSTRACT – *Significant results pertaining to the shallow and deep structural features of the Indian continental crust are achieved by extensive Deep Seismic Sounding (DSS) experiments accomplished by NGRI since 1972 in a variety of geological settings. Seismic refraction and wide-angle reflection data-sets have been acquired along 20 profiles in the southern peninsular shield, Deccan Traps covered regions, across the Narmada-Son lineament, the Himalayas and more recently in the West Bengal basin, covering more than 5000 km of DSS profiling. Interpretation of these datasets brought out for the first time, models of the shallow and deep crustal structure and the Moho configuration delineating fault-controlled crustal blocks (terranes) in various regions. These results provide new insights to a better understanding of the tectonic processes involved in the formation and evolution of the Cuddapah, Dharwar, Vindhyan, Gondwana, and the Cambay basins. The crustal depth sections in the south Indian shield along the Kavali-Udipi profile reveal that the Cuddapah basin on the east and the Dharwar sub-basin on the west were both formed by downfaulting of the Moho. Due to a major thrust movement along a low-angle fault, well delineated by the DSS data, the Eastern Ghats section comprising the Dharwars was thrust up and lies over and in juxtaposition with the upper Cuddapah sediments on the eastern margin of the basin. The large Dharwar sub-basin was subdivided into two parts, the eastern depression and the western depression by an uplifted crustal block where the Closepet granites are now exposed.*

Besides mapping the thickness of the Deccan Trap flows, a large Mesozoic basin, consisting of two grabens separated by an E–W trending fault, the 'Tapti graben' (with maximum sedimentary thickness of 1800 m) and the 'Narmada graben' (with maximum sedimentary thickness of 1000 m), is delineated under a relatively thin cover of the Deccan Traps in the Narmada-Tapti area from the results obtained along six DSS profiles in the region. This hidden Mesozoic basin probably formed part of a larger Mesozoic sea bordering the exposed Vindhyans, Aravallis and the Delhis. Another relatively small Gondwana basin with a maximum sedimentary thickness of 400 m, separated from this large Mesozoic basin is also delineated in the Multai-Pulgaon region, that may be an extension of the Gondwana Godavari graben, under a thin cover of the Deccan Traps. The crustal block bounded by deep East-West faults at Narsinghgarh and Katangi along the Hirapur-Mandla profile across the Narmada-Son lineament, created a graben in the crystalline basement forming the great Vindhyan basin with accumulation of a large thickness of the Vindhyan sediments. The Deccan Traps at the base of a thick sequence of the Tertiary sediments, as well as the subtrappean Mesozoic sediments in the Cambay basin are also well resolved by the DSS datasets. The high velocity lower crustal layer of velocity 7.3–7.4 km/s delineated from Billimora to Tharad throughout the Cambay basin indicates underplating of the crust due to mantle upwelling and rifting with large scale extrusion of the Deccan Traps. The region from Surat to Bombay on the west coast was also characterized by an upwarp of the Moho during the late Cretaceous period, probably representing a transitional crust and a major source for the Deccan Trap flows. The DSS datasets in the wide-angle range also yielded velocity-depth models of the Indian continental crust in various regions, revealing presence of low velocity layers, transitional nature of the Moho and other intracrustal boundaries, providing a unique geophysical framework to understand the rheological structure and intracontinental seismicity, particularly in the Deccan Traps covered Koyna region.

The Moho boundary is delineated with steep dips of about 15°–25° from the Kashmir valley towards the Great Himalayas with its depth reaching 65–67 km in the region of Kunzalwan in the Great Himalayas. The Moho appears to rise to shallower depths further north towards the Nangaparbat due to a local reversal of the dip across a deep fault in the region that might be associated with the uplift of the Nangaparbat massif. It was inferred that the Himalayas were formed possibly due to block uplift against steep-angle faults. The crustal depth section across the Pir Panjal range, besides delineating the Moho, also brought out the Srinagar and Jammu synclines each having a maximum sedimentary thickness of about 18 km. The deep reflection data along the long-range profile Qarrakol-Zorkol-Sopur-Tral revealed presence of two broad zones of reflectors at depths of 150–180 km and 340–365 km that may respectively correspond to the top and bottom of the Asthenosphere layer in the region of the Great Himalayas, Karakoram and Pamir ranges.

Adequate facilities have been recently developed at NGRI for seismic imaging of the continental crust and the subcrustal lithosphere by deep seismic reflection profiling and stacking of near-vertical-incidence reflection data extending to about 20 s two-way-times. Experimental results of reflection profiling and stacking of reflection data in the West Bengal basin revealed promising results consistent with the coincident wide-angle reflection data to the Moho depths.

INTRODUCTION

Deep Seismic Sounding [DSS] studies by controlled source seismic observations constitute the most definitive geophysical technique for exploring structures of the Earth's crust and uppermost mantle. Both shallow as well as deep structures can be resolved by suitable datasets, including narrow-and wide-angle reflection/refraction and converted phases recorded with specially designed acquisition geometery/parameters. Recent advances, both in the areas of seismic data acquisition as well as processing and modeling techniques, offer wide ranging possibilities to explore very complex subsurface structures that may be both heterogeneous and anisotropic. Seismic refraction/wide-angle reflection measurements have undergone progressive changes currently utilizing closely spaced high dynamic range three-component digital recorders on reversed and overlapping profiles, to provide sufficient data redundancy for consistency checks, with a high resolution of subsurface models. On the other hand, modern high resolution reflection profiling experiments utilize multichannel digital recording systems capable of recording vertical-incidence reflection data by a large number of channels to very high recording times, to probe to deep crustal depths, at sufficiently small data sampling rates. Concurrently, methods to process and interpret seismic reflection/refraction datasets have also undergone dramatic development with the possibility to accurately synthesize the wave fields, both in the near-vertical and wide-angle ranges, for the inferred subsurface structures and compare with the observations to successively refine the models. It has also been realized in recent times that coincident reflection/refraction experiments on selected geotraverses provide the most reliable seismic images of the deep crust and uppermost mantle, as the two techniques are complementary to each other together resolving the structural and physical property variations. The deep seismic images of the continental crust, revealed by coincident reflection/refraction profiling across various geological settings, provide necessary clues for understanding the complex geodynamic processes that might be operative during geological evolution in order to shape the presently observed structures. Especially, in tectonically active regions, accurate mapping of the Moho and other intracrustal boundaries with delineation of deep penetrating steep-angle and/or shallow-to-upper crustal low-angle faults and fracture zones by DSS profiling can reveal various crustal blocks (terranes) that are relatively displaced due to movements along the faults. The location of deep faults/fracture zones may have significance due to their possible association with migration and distribution of materials with mineral potential, as well as the brittle failure of crustal rocks causing earthquakes. Further the DSS datasets, especially in the wide-angle range, can provide viable models of the velocity structure of the Earth's crust and uppermost mantle, essentially required to infer the petrological composition and/or grade of metamorphism and material properties such as brittle/ductile regimes that may lead to consistent interpretations of reflectivity structures observed by vertical-incidence reflection data at deep crustal depths. DSS profiling along regional traverses also contributes to a better understanding of major geological features at large depths that are inaccessible for direct mapping, including configuration of various sedimentary layers and the underlying deep basement in regions of large sedimentary basins. These data provide critical constraints for the reconnaissance of poorly known substratum of sedimentary basins and for a better understanding of the geodynamic processes and mechanisms that led to their formation and evolution The results provide new insights to the oil industry, complementing those obtained by the routine industrial shallow seismic reflection surveys for the exploration of hydrocarbon bearing structures.

Deep seismic sounding studies in India were initiated by the National Geophysical Research Institute (NGRI) in 1972, initially as an Indo-Soviet collaboration project for the first three years. Subsequently DSS experiments have extensively been conducted by NGRI in various parts of the country, primarily sponsored by the oil industry (ONGC, OIDB, and OIL). Seismic refraction and wide-angle reflection datasets have been acquired along 20 profiles in a variety of geological settings in the southern peninsular shield, Deccan Traps covered regions, across the Narmada-Son lineament, the Himalayas, and more recently in the West Bengal basin, covering more than 5000 km of DSS profiling (figure 1). Shallow as well as deep crustal seismic data have been obtained by continuous profiling to recording distances of 200–250 km, using explosives as the energy source with shot points spacing of 10 km for shallow and 40 km for deep crustal investigations, and geophones interval of 100–200 m, by deploying two 30-channel POISK analog recording systems of Soviet make with recording frequencies up to 22 Hz. Recently, NGRI has acquired three 60-channel DFS–V digital recording systems and currently DSS profiling is being carried out by the digital systems with 4 ms data sampling and with a more dense coverage of shot points and geophone arrays of 80 m interval, notably in the West Bengal basin. Coincident vertical-incidence reflection profiling

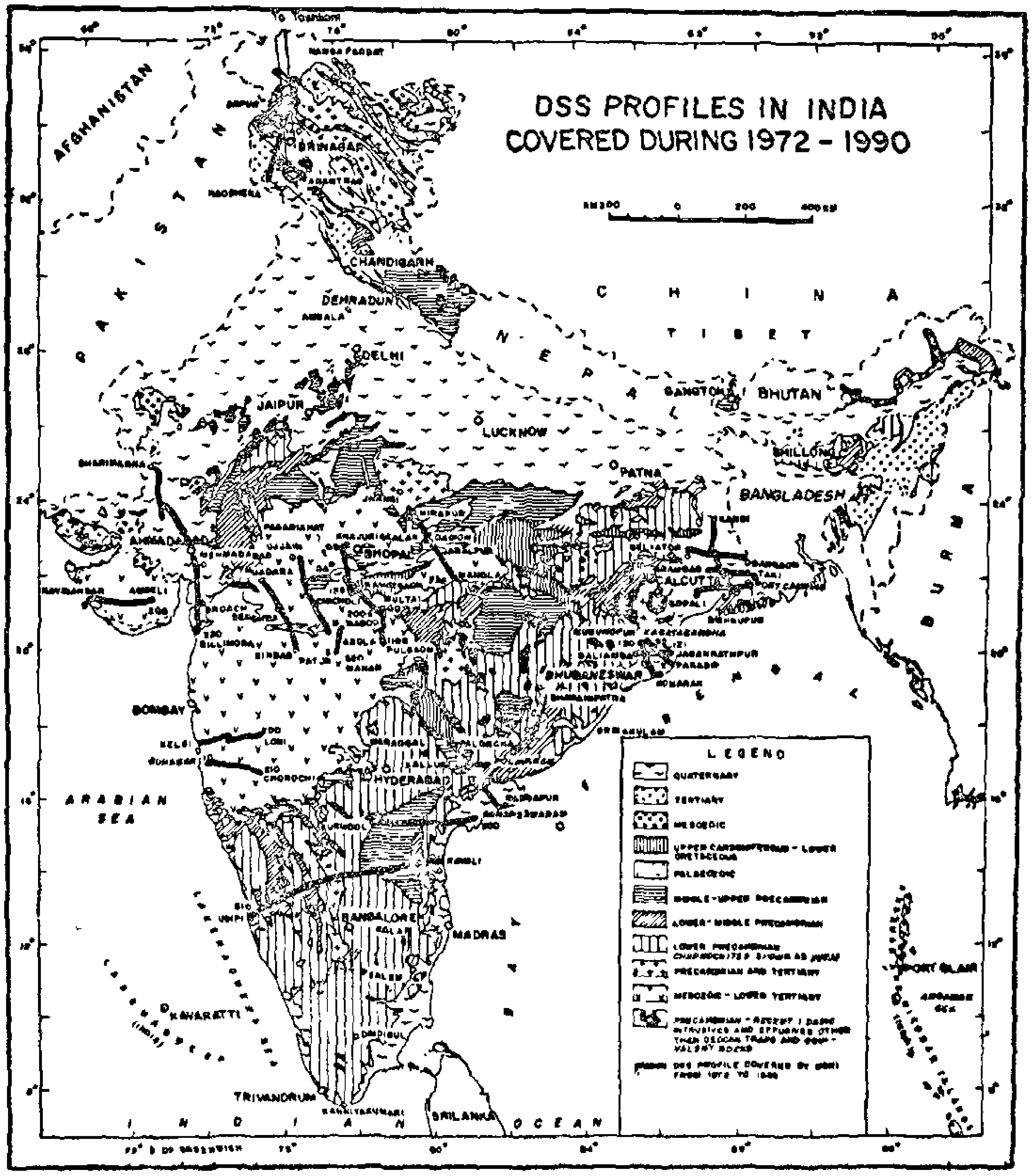

FIGURE 1 Simplified geological map of India showing location of the DSS profiles in various regions covered by NGRI during the period from 1972 to 1990.

has also been carried out over some part of the profiles in this region with recording times extending up to 20 s. Interpretation of DSS data along various profiles brought out for the first time. models of the deep crustal structure including configuration of the Moho in those regions leading to a better understanding of the tectonic processes involved in the formation and evolution of the Cuddapah, Vindhyan, Gondwana, Cambay and West Bengal basins. The Deccan Traps cover a significant part of the Indian land mass, extending over more than 500,000 square kilometers. Conventional shallow seismic reflection surveys could not provide adequate information on the thickness of the Traps or the possible presence of subtrappean sedimentary formations of relatively low velocity. However, from the results of DSS studies cohered over the past few years, it has now been possible to delineate some significant subtrappean structures of sedimentary formations, that may be of interest to the oil industry due to their possible hydrocarbon potential, in addition to mapping the basement configuration which has also been unknown before the DSS work was undertaken in various sedimentary basins. Besides a vast amount of DSS field data acquisition and interpretation, efficient computational methods have also been developed, particularly suitable for wide-angle reflection/refraction data processing.

- To determine velocity-depth functions, by reversed reflection data analysis,
- To construct the deep crustal sections by migration of single-sided wide-angle reflection data,
- To delineate shallow low velocity layers (LVL) and other hidden layers, particularly with a view to investigate the subtrappean structures.

Further, in order to refine the velocity-depth models by synthetic seismograms modeling of DSS field record sections, a viable approach has also been developed to digitize the large volume of analog DSS records along several profiles and present the field record sections with reduction velocities and amplitudes normalization. New models of the crustal and subcrustal velocity structure have been obtained by this modeling approach. In order to develop further the research activities in DSS studies by introduction of vertical-incidence reflection profiling of the continental lithosphere, a modern computer centre has recently been created at NGRI with appropriate hardware systems around a CDC CYBER 180/850A host computer and software packages for seismic reflection data processing, modeling and interpretation. Based on the vast amount of DSS data and results that are now available in various regions, major findings pertinent to site-specific geological problems that are addressed by DSS profiling in India are discussed in this article indicating directions for future research efforts appropriate to this branch of explosion seismology.

DSS STUDIES IN THE INDIAN PENINSULAR SHIELD

DSS studies in the Indian peninsular shield were carried out for the first time during the period from 1972 to 1975 along a 600 km long profile[1,2], extending from Kavali on the east coast up to Udipi on the west coast, in an ENE-WSW direction. This profile cuts across very important geological structures associated with rich mineralized zones of the south Indian shield notably the Nellore schist belt, the Cuddapah basin, and the Chitradurga-Shimoga schist belts of the Dharwar sub-basin. It was also one of the objectives of this first DSS experiment[1,2] to establish the regular relationship between the occurrence of deep faults/fracture zones and their possible association with the already known mineralized zones in this region. A second 300 km long DSS profile, Alampur-Koniki-Ganapeshwaram, was subsequently covered[3] during 1979–80 across the northern part of the Cuddapah basin to investigate in detail the deep tectonic features of the basin.

DSS Results in the Cuddapah basin

The Cuddapah basin, located in the southeastern part of the peninsular shield, is a unique tectonic and orogenic belt of unfossiliferous Precambrian rocks. The geology and tectonics of the Cuddapah basin was studied in great detail[4,5]. Along its eastern margin, the rocks are folded and overthrust, otherwise it mainly consists of an assemblage of a series of low dipping, unmetamorphosed upper Proterozoic sediments of Cuddapah and Kurnool systems (figure 2a). Beyond the eastern margin of the basin, the Cuddapah group of rocks come into contact with the Dharwars [Archaeans]. The 600 km long crustal depth section depicted in detail to a depth of about 50 km, along the Kavali-Udipi DSS profile[1] consists of 17 major crustal blocks besides a few smaller ones. This crustal section from Kavali to Udipi is cut into various blocks by 15 major deep faults and 2 major low-angle faults while 5 other faults/thrusts extend to intermediate crustal depths.

The crustal depth sections delineated from the DSS data along the Kavali-Parnapalle part of the Kavali-Udipi profile[1,2] cutting across the southern part and that along the Alampur-Koniki-Ganapeshwaram profile[3] cutting across the northern part of the Cuddapah basin are shown in figures 2b and 2c respectively. The Cuddapah basin, east of Parnappalle (figure 2b), was formed by downfaulting of the Moho boundary against

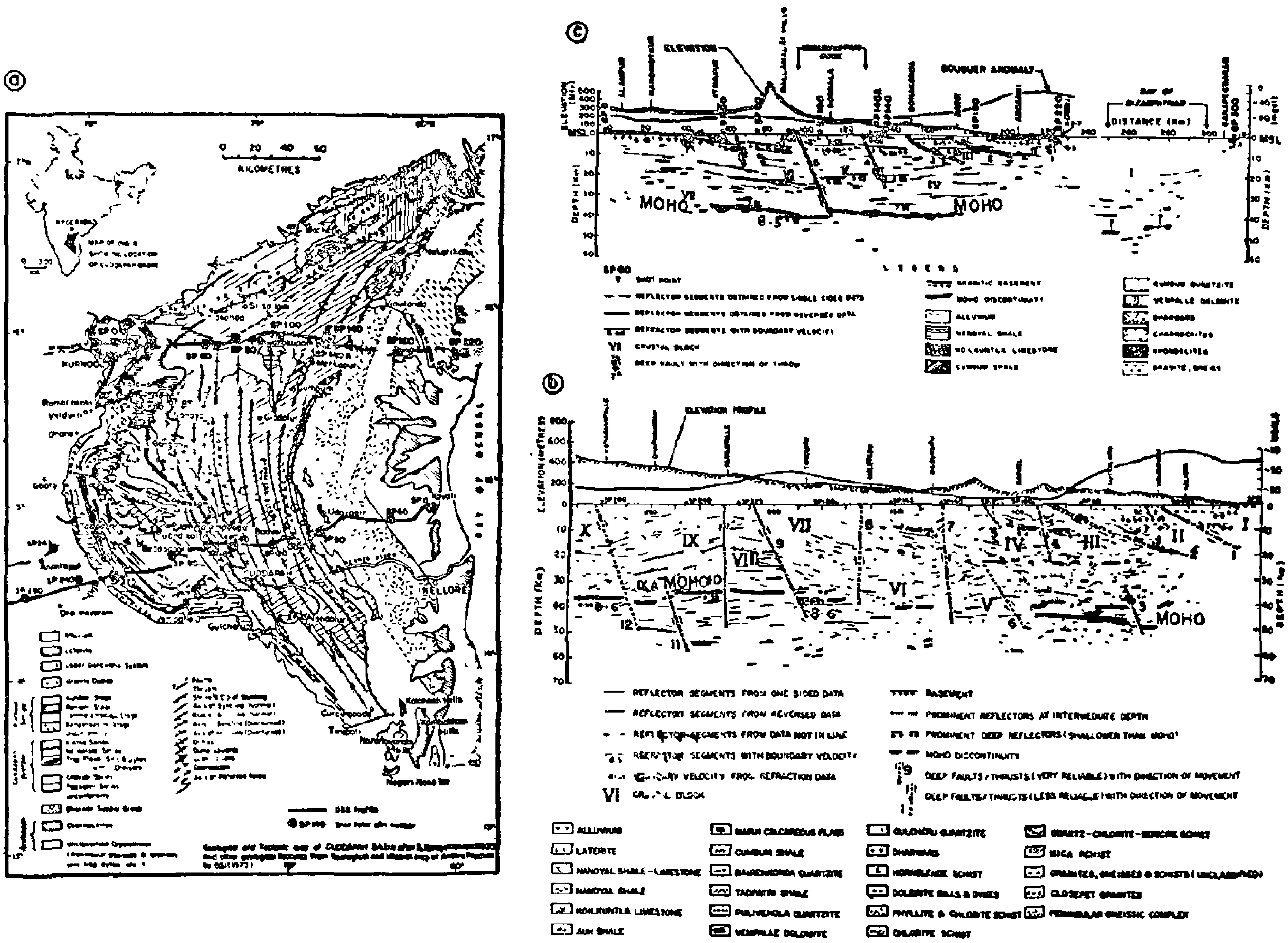

FIGURE 2(a) Geological and tectonic map of the Cuddapah basin (Reproduced from ref. 5) showing location of the two DSS profiles, Kavali-Parnapalle on the eastern part of the Kavali-Udipi profile in the south and the Alampur-Koniki profile in the north of the basin. (b) Crustal depth section along the Kavali-Parnapalle part of the Kavali-Udipi DSS profile across the southern part of the Cuddapah basin, (reproduced from ref. 1) (c) Crustal depth section along the Alampur-Koniki-Ganapeshwaram DSS profile across the northern part of the Cuddapah basin. (Reproduced from ref. 3).

deep faults #9 and #7, the crustal bock #VIII being a stable/rigid block. The Cuddapah basin was first formed on its western part between Maidukuru and Parnapalle where the lower Cuddapah formations were deposited. This part of the basin consists of crustal blocks #VI, VII and VIII where the Moho, with boundary velocity of 8.6 km/s for Pn phase is delineated respectively at depths of 40, 37 and 34 km. There was further downfaulting of the Moho in the area between Maidukuru and Badvel resulting in the formation of the eastern part of the Cuddapah basin where the upper Cuddapah sediments were deposited. Thus it was found that the Cuddapah basin was formed by en-echelon faulting of the Moho boundary, the eastern block consistently downfaulting relative to the adjacent western block. After the deposition of the upper Cuddapah sediments, there was a major thrust movement along the low-angle fault #2, well delineated by the DSS data. Along this low-angle fault, the Eastern Ghats section comprising the Dharwars was thrust up and lies over and in juxtaposition with the upper Cuddapah sediments on the eastern margin of the Cuddapah basin consistent with the geological exposures in this region. The DSS section in this region revealed for the first time a westward lateral movement of about 20 km of the overriding block #II over block #III. Another low-angle fault #1, delineated by DSS refraction data, also reveals an upward movement of block #II relative to the eastern block #I. The two low- angle faults #1 and 2 on the eastern margin of the Cuddapah basin are also well brought out, delineating in detail their geometry by travel times and amplitudes modeling[6] of wide-angle reflection phases in the distance range 30 80 km from the two thrusts. Below the eastern part of Cuddapah basin, the Moho is delineated at a depth of 40 km. It is thus evident that the crustal thickness in this region is quite normal and there is no significant thinning of the crust to explain the observed steep rise in the Bouguer gravity anomaly on the eastern margin of the Cuddapah basin. Modeling of gravity data[7], by utilizing a crustal density model inferred from the two-dimensional velocity-depth section obtained from DSS data in this region, revealed the presence of a high density mass at shallow depths along the low-angle fault, suggesting a massive movement of the high density material from deeper to shallow depths along the eastern margin of the Cuddapah basin. The gravity anomaly pattern with relatively high gradients present along the entire length of the Eastern Ghats region is interpreted[7] as a result of emplacement of high density gabbroic rocks at very shallow depths. The upward movement of this high density mass is likely to be the cause of the Eastern Ghats uplift (orogeny). Travel times and relative amplitudes modeling of digitized DSS record sections[6] in this region further confirmed the presence of high velocity material at relatively shallow depths along the low-angle fault on the eastern margin of the basin. This low-angle fault is also observed from the DSS data along the Alampur-Koniki profile[3].

The basement of the Cuddapahs with boundary velocity of 6.4 km/s, along the southern profile (figure 2b), lies at a depth of 10 km in block #III which is downfaulted relative to block #IV where the basement is at a depth of 8.5 km. After the close of the Cuddapah period, there was a downward movement of block #VI between Maidukuru and Malepadu creating a depression in which the Kurnool sediments were deposited. The basement depth in this region is found to be 9–10 km. The crustal depth section along the Alampur-Koniki-Ganapeshwaram profile[3] in the northern part of the Cuddapah basin also reveals block structure (figure 2c). The basement with boundary velocity of about 6.2 km/s in the western part of the Cuddapah basin along this profile is very shallow, and with a gentle dip towards east, it attains a depth of 4.5 km in the deepest part of the Kurnool subbasin. Under the Nallamalai ranges the basement depth varies from 3.5 to 6.5 km again with an easterly dip. Further east in the region of Iswarkuppam dome it is at a depth of 5.0 km and in the eastern part of the Cuddapah basin the basement depth is about 6.8 km. The Moho with boundary velocity of about 8.5 km/s is delineated at depths varying from 35 to 39 km in the inland part of this profile while it is inferred at relatively large depths of 43–45 km in the Nizampatnam bay region. By synthesizing the DSS results along the two profiles across the Cuddapah basin, structural trends at the basement as well as the Moho levels have been brought out in detail and inferences drawn regarding the evolution and tectonics of the basin[8].

DSS Results in the Dharwar Sub-Basin

Several geological classifications and sequences for the Dharwars have been proposed[9–13] in the literature. The Kavali-Udipi DSS profile on its western part cuts across the two important geological structures, the Chitradurga and Shimoga schist belts (figure 3a). In view of gross differences in the character of greenstone belts and type of metamorphism of the high grade schists, the Karnataka craton can be divided into two geotectonic blocks[14,15] the western block and the eastern block. The dividing line between these two blocks approximately coincides with the western margin of the meridional Closepet granite. The crustal depth section delineated from the DSS data[1] across the Closepet granite, Chitradurga and Shimoga schist belts and up to the Western Ghats is shown in figure 3b. The geological evolution of this part of the Indian shield probably began in the early Proterozoic with the formation of the Dharwar sub-basin originated by downfaulting of Moho between Parnapalle [on the western margin of the Cuddapah basin] and Agumbe on the Western Ghats. This large sub-basin was further subdivided into two parts, the eastern depression and the western depression, by the uplifted crustal block #XI near Charlapalle where the Closepet granites are now exposed. The western depression in the area from Jajjur to Agumbe has the thickest section of the Dharwars. On the other hand, the eastern depression from Parnapalle to Rallanantapuram received a relatively thin section of the Dharwars. The Dharwars in the eastern part are now almost eroded, exposing their basement. In this eastern depression the Moho with boundary velocity of 8.6 km/s for Pn phase is delineated in various crustal blocks at average depths of 34 km in block #IX, 38 km in block #IXA and 36 km in block #X. In the western part, where there is a large thickness of the Dharwars, the Moho is delineated with boundary velocity of 8.4 km/s in various crustal blocks at average depths of 34 km in block #XII, 35 km in block #XIV, 39 km in block #XV and 38 km in block #XVI. In the crustal block #XIII, in the region of Holalkere, the Moho is deepest at a depth of 41 km. It is found that the P velocity in the uppermost mantle is significantly high 8.4–8.6 km/s, both in the regions of the Cuddapah basin and the Dharwar sub-basin.

On the eastern margin of the Chitradurga basin two low-angle faults #15 and #16 have been delineated by the DSS data, along which large scale westward thrust movements have been inferred during the intense orogeny towards the close of the lower Proterozoic

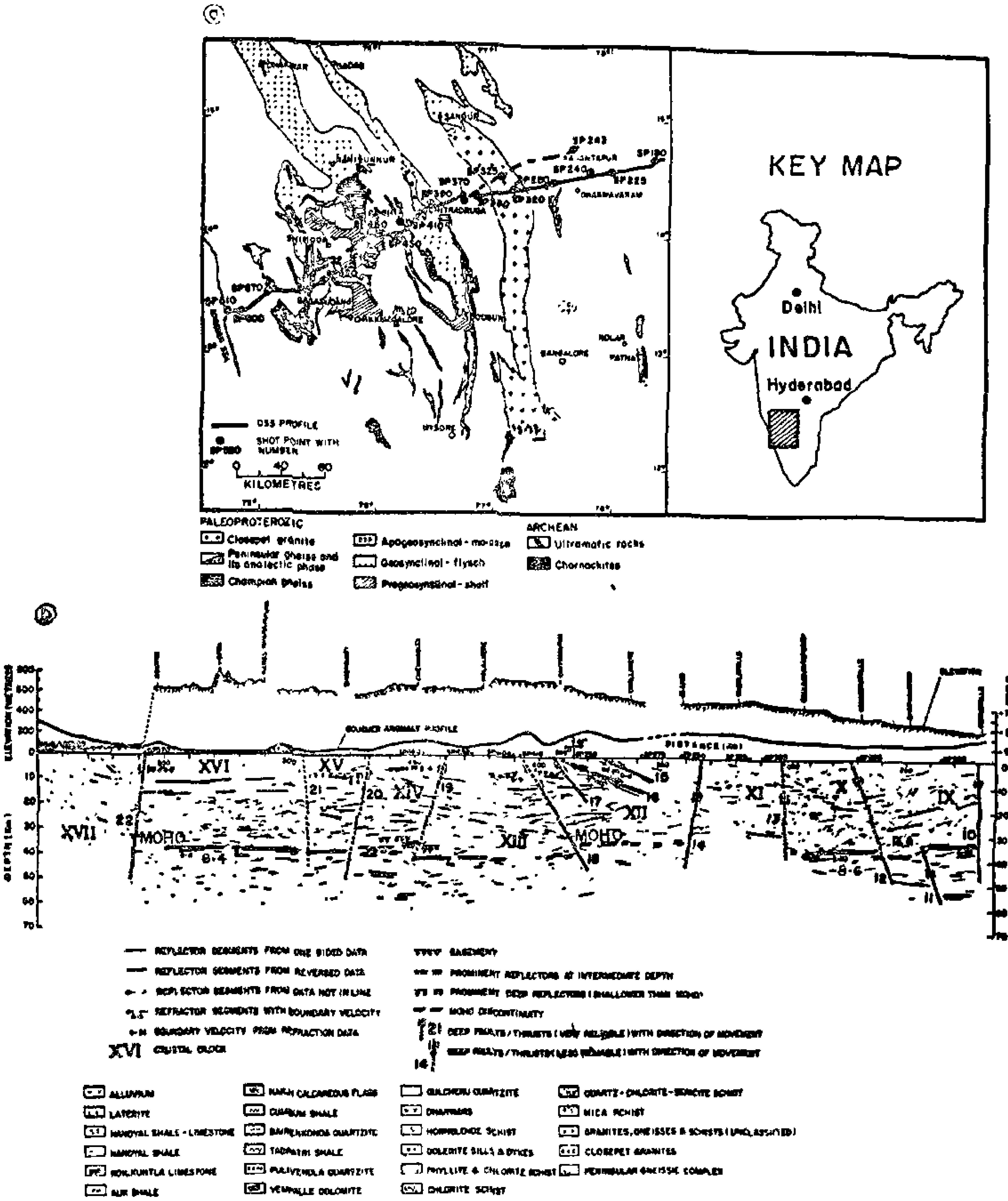

FIGURE 3(a) Geological map of the Chitradurga-Shimoga region (reproduced from ref. 12) showing location of the western part of the Kavali-Udipi DSS profile. (b) Crustal depth section along the western part of the Kavali-Udipi DSS profile across the Dharwar sub-basin (reproduced from ref. 1).

period. The basement of the schist belt has also been delineated with boundary velocity of 6.4 km/s in the depth range of 4–7 km in this region. It is quite evident from the first DSS results obtained along the Kavali-Udipi profile[1] in the Indian peninsular shield across the Cuddapah basin and the Dharwar sub-basins, that detailed crustal cross sections can be interpreted by data from a large number of reflectors delineated from very shallow to about 50 km depth across significant geological structures and these results are extremely valuable for understanding their formation and geological evolution. Most of the deep faults delineated by the DSS data in the Dharwar sub-basin have also been found to correspond well with the major linear features interpreted from the LANDSAT imagery[16].

DSS STUDIES IN THE GODAVARI GRABEN AND GODAVARI (COASTAL) BASIN

DSS investigations have been carried out during the period from 1985 to 1986 in the Godavari graben and

Godavari (coastal) basin along two intersecting profiles, one across the graben from Kallur to Polavaram (95 km long) and the other along the graben from Polancha to Narsapur (160 km long), to study the basement configuration and the deep crustal structure in the region[17]. The general trend of the Archaean basement south and east of Polancha is NE-SW to NNE-SSW [Eastern Ghats trend], while it is NW-SE [Dharwarian trend] towards the northwest of Polancha (figure 4a). The upper Precambrian 'Pakhal series' exposed north of Polancha are not seen in the south. The investigated area also includes the Chintalpudi sub-basin which is covered by the Kamthi sandstone of the lower Gondwana. Shallow and deep crustal sections obtained from DSS data[17] along the Kallur-Polavaram profile are shown in figure 4b and those along the Polancha-Narsapur profile are shown in figure 4c. Two sedimentary basins, the Godavari graben and the Godavari (coastal) basin, separated by a basement ridge, have been delineated by the DSS data. The ridge appears to be the northeastern extension of the Bapatla ridge, separating the two basins. Two other basement ridges on the Polancha-Narsapur profile between SP15 and SP16 (southeast of Polancha) and near Bhimavaram between SP2 and SP3 (Tanuku ridge) are also delineated (figure 4c). The lower Gondwana sediments of P velocity 2.5–3.0 km/s reach a maximum thickness of about 2.8 km near the intersection of the two profiles at Dammapeta. On the basis of velocities obtained along the Polancha-Narsapur profile, the Pakhal basin does not seem to continue southeast of Polancha. It is inferred that in the Godavari (coastal) basin the upper Gondwana sediments with marine incursions continue southeastwards below the Rajahmundry sandstone

(a)

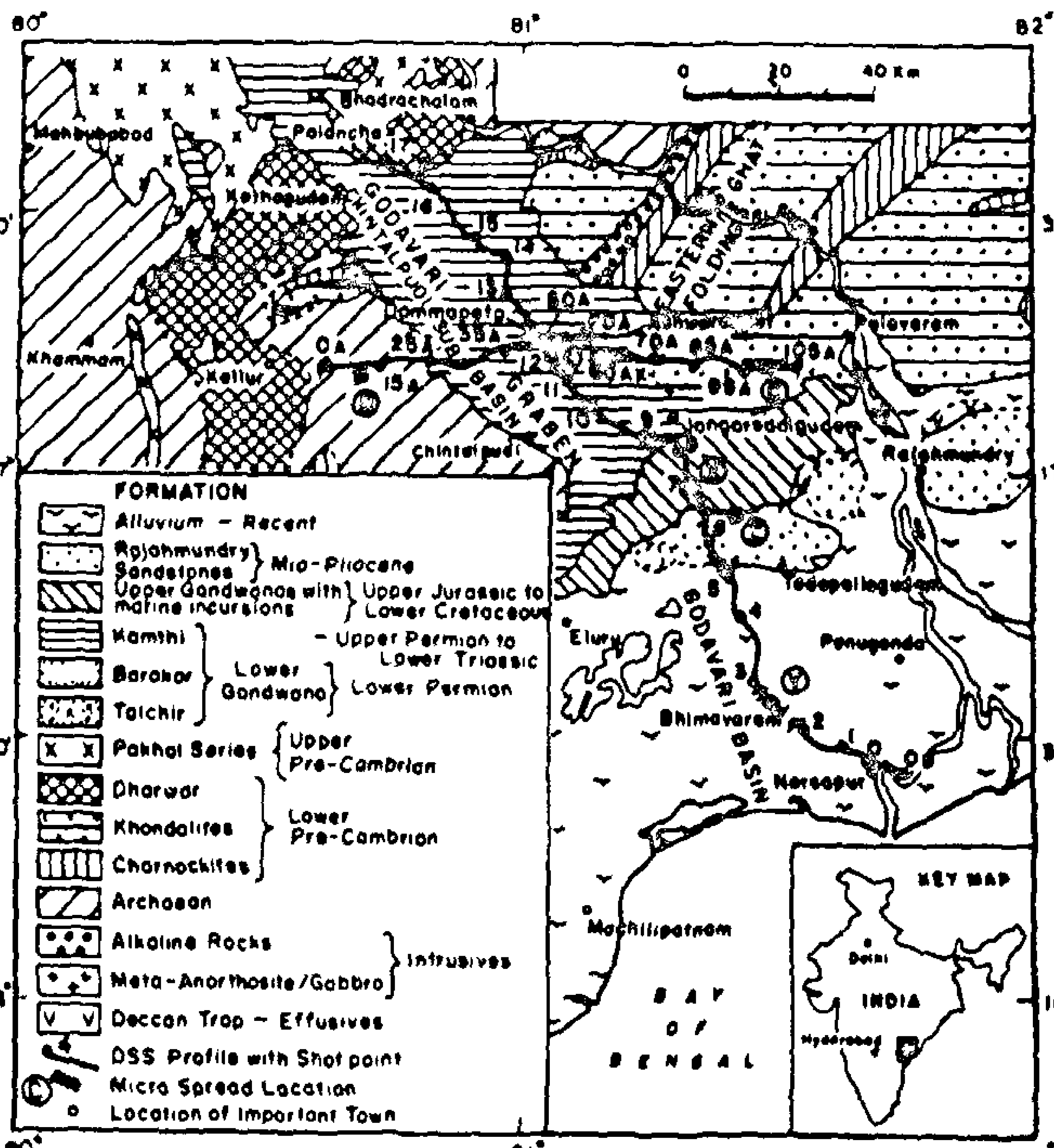

FIGURE 4(a) Geological map of the Godavari graben and the Godavari (coastal) basin showing location of the two DSS profiles, Kallur-Polavaram and Polancha-Narsapur.

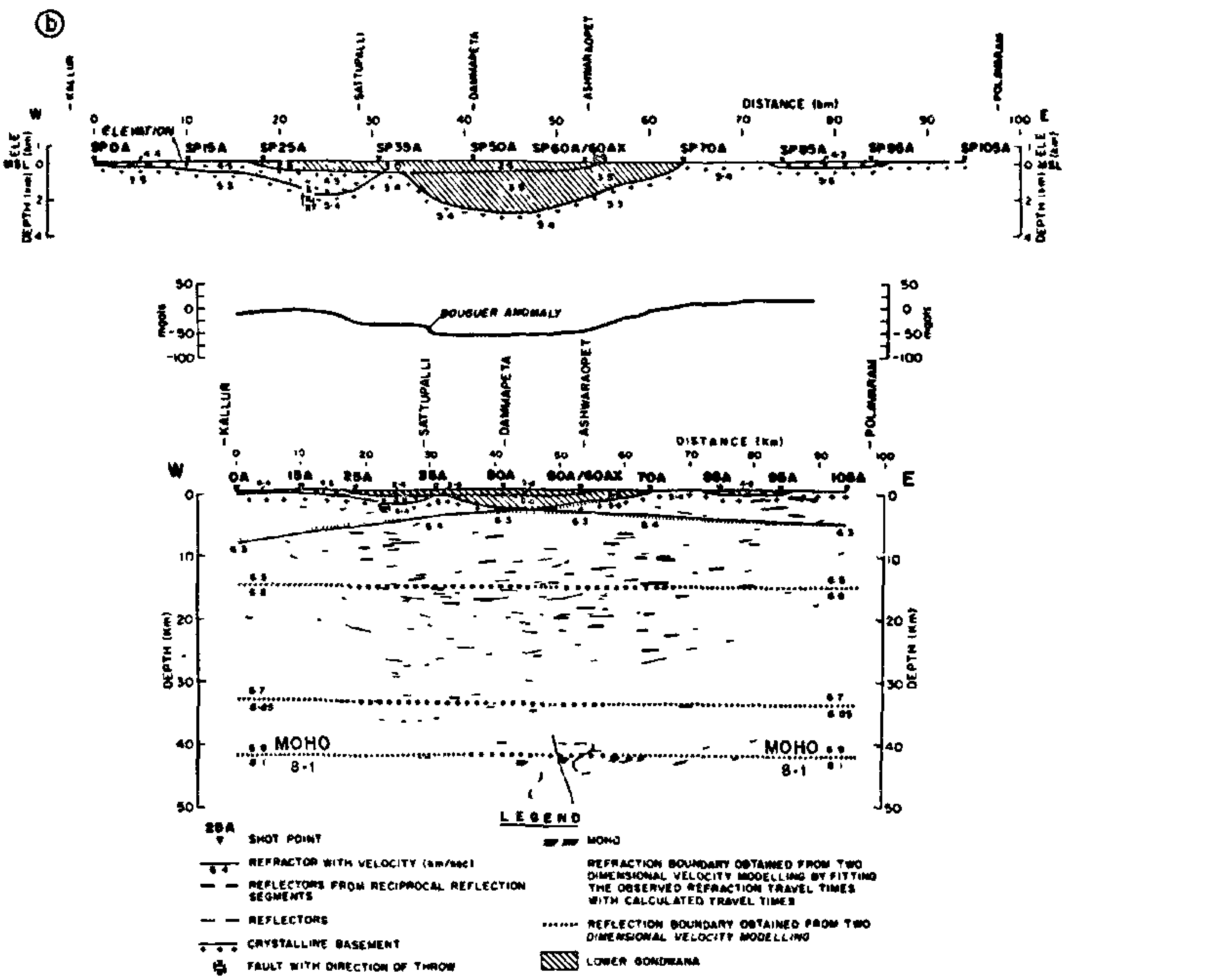

FIGURE 4(b) Shallow and deep crustal depth sections along the Kallur-Polavaram DSS profile across the Godavari graben (reproduced from ref. 17).

between SP5 and SP6 (figure 4c). The P velocity in the crystalline basement is found in the range 5.3–5.6 km/s along the Kallur-Polavaram profile and 5.4–6.0 km/s along the Polancha-Narsapur profile. A prominent interface at 3.5 km depth, with P velocity increasing from 5.3–5.6 km/s to 6.3–6.5 km/s, is delineated in the upper crust. This interface reveals a domal upwarp across the Godavari graben which may be indicative of a NE-SW crustal extension in this region. The P velocity in the lower crust is found in the range 6.6–6.9 km/s along the two profiles. Wide-angle reflection data has yielded a three layer crustal structure below 10 km depth, with the Moho boundary delineated at 41–43 km depth in this region.

DSS STUDIES IN THE MAHANADI DELTA AREA

DSS investigations were carried out in the Mahanadi delta area[18] during 1983 along three profiles:

- Konark-Pratapnagar-Mukundpur (120 km),
- Baliamba-Athgarh-Kendrapara-Jagannathpur (120 km),
- Paradip-Kendrapara-Kabatbandha (90 km).

The main objectives of this DSS investigation are: delineation of the sedimentary structures and the basement configuration in the region as well as study of the deep crustal structure. Most of the area under investigation is covered by a thick cover of recent alluvium of Mahanadi delta (figure 5a). Towards the west of the Mahanadi basin, vast tracts of granites, Khondalites, Charnockites and Anorthosites are exposed. These exposures belong to the Eastern Ghats group and are disposed mostly in the form of detached hillocks striking NE-SW or ENE-WSW. Lower Gondwanas are exposed towards the southern part of the iron ore formations lying north of the Eastern Ghats group. Upper Gondwana rocks are exposed between Cuttack and Bhubaneswar. Towards west of Bhubaneswar the strike of the upper Gondwanas is E-W to ENE-WSW with very low dips. Shallow depth sections down to the basement level, obtained from the seismic refraction data[18], along the three profiles are shown in

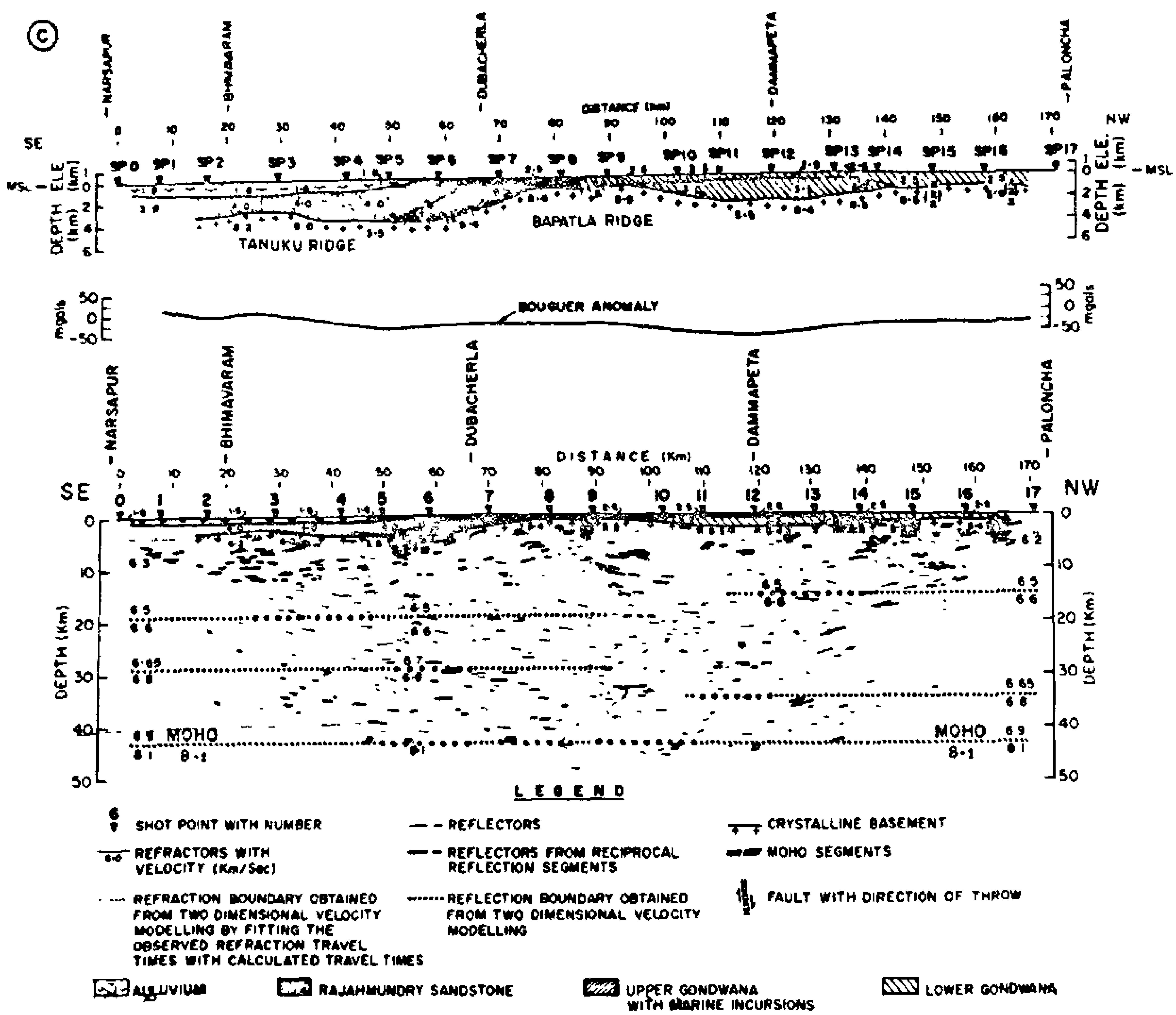

FIGURE 4(c) Shallow and deep crustal depth sections along the Polancha-Narsapur DSS profile along the Godavari graben and the Godavari (coastal) basin (reproduced from ref. 17).

figure 5b. A Gondwana graben with a maximum sedimentary thickness of about 2.8 km has been delineated in the Cuttack-Kendrapara area of the Mahanadi basin. This graben is bounded by faults towards its north and south. The P velocity in the Gondwanas is found to be 3.9 km/s around Cuttack, but changing to 3.2–3.5 km/s towards Kendrapara. South of the Gondwana graben lies the shallow basement area. This basement high probably formed the barrier northwest of which the Gondwana graben was formed. The P velocity in the basement is found in the range 5.6–5.9 km/s. Southeast of this, in the coastal area and in the adjacent offshore region, new basins developed during the Tertiary period. Two coastal depressions, which may also be extending into the Bay of Bengal, have been identified; the Konark depression and the Paradip depression, with in-land maximum sedimentary thickness of 2400 m and 2200 m respectively and of P velocity 2.4 km/s. These depressions are essentially fault-controlled. The deeper crustal sections in this region were mainly delineated by the wide-angle reflection data along the three profiles (figure 5c). From these deeper crustal sections, four reflecting interfaces have been observed at average depths of 6.0, 17.5, 20.5 and 34.5 km, the deepest one representing the Moho boundary in this region. The average crustal thickness in this area is found to be lower than that in the Indian shield region.

DSS STUDIES IN THE DECCAN TRAPS REGION AND ACROSS THE NARMADA-SON LINEAMENT IN CENTRAL INDIA

Extensive DSS profiling has been carried out in the Deccan Traps covered regions, particularly across the

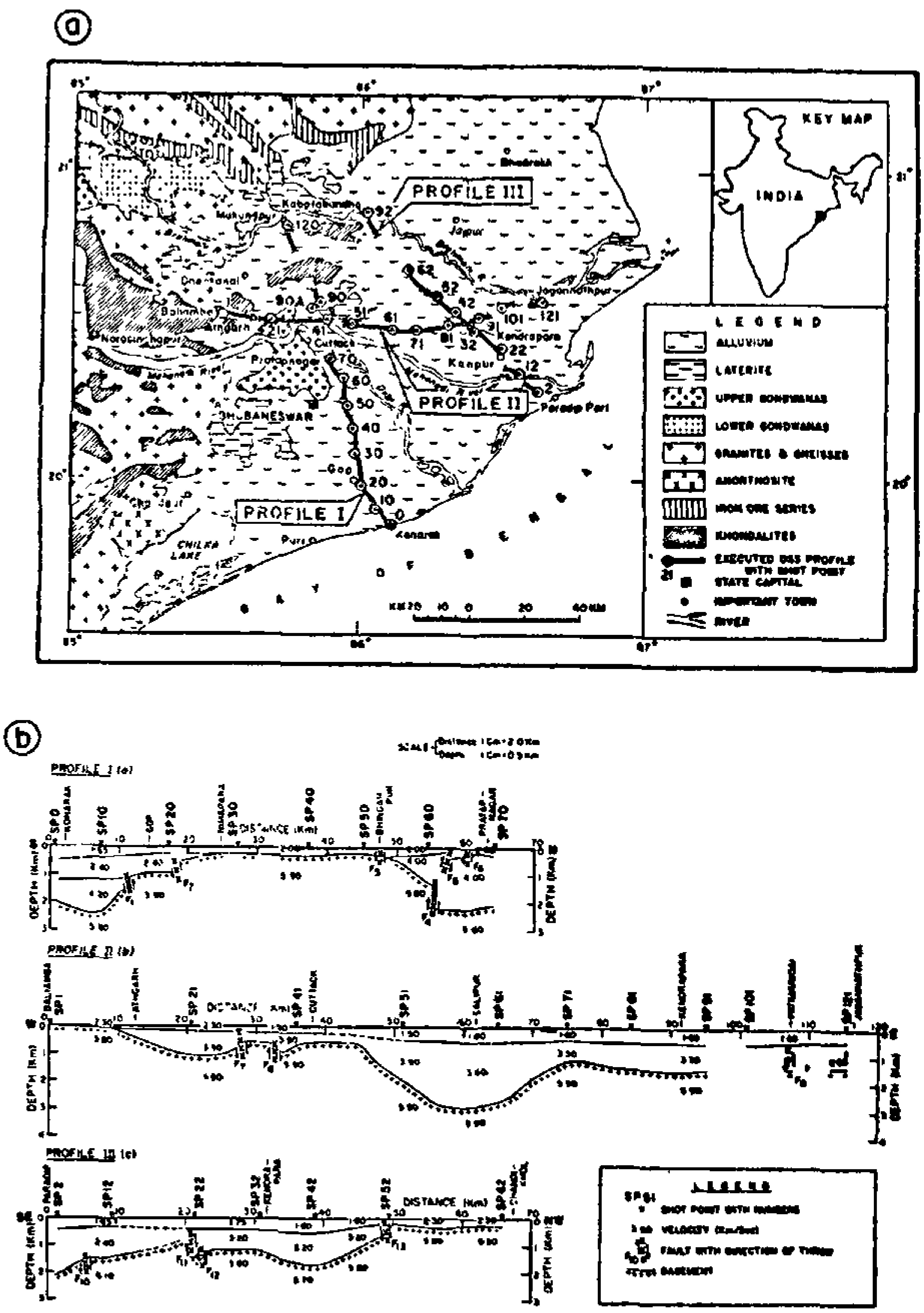

FIGURE 5(a) Geological map of the Mahanadi delta area showing location of the three DSS profiles, Konark-Pratapnagar-Mukundpur, Baliamba-Athgarh-Kendrapara-Jagannathpur, and Paradip-Kendrapara-Kabatbandha. (b) Shallow depth sections to the basement level along the three DSS profiles in the Mahanadi delta area (reproduced from ref. 18).

Narmada-Son lineament. These studies have not only revealed the thickness of the Deccan Traps cover in the regions, they have also brought out for the first time the hidden subtrappean sedimentary structures, the basement configuration as well as the deep crustal structure and the Moho configuration along various profiles..

DSS Results in the Koyna region

DSS studies in the Deccan Traps region were initiated in 1975 in the Koyna region along two profiles at the request of the Koyna Project Authority, Government of Maharashtra. After the occurrence of the Koyna earthquake of 10th December 1967, extensive geoscientific investigations were carried out in this region by many organisations in order to understand the cause of seismicity in the Koyna region. The question whether the major earthquake of December 1967 in the Koyna region was of tectonic origin or a manifestation of the reservoir induced seismicity was highly debated. DSS studies in this region were primarily recommended by the UNESCO experts committee with a view that the

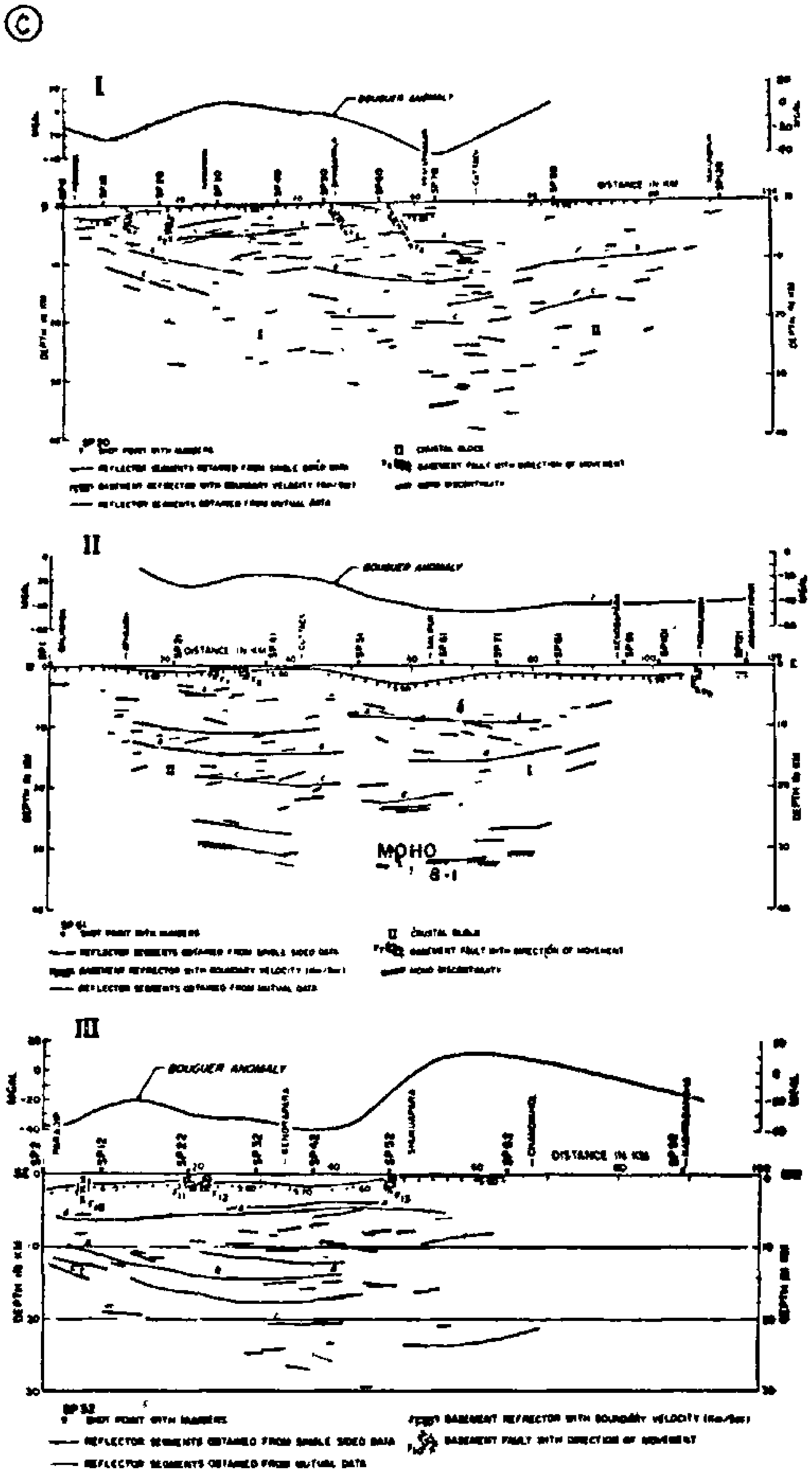

FIGURE 5(c) Crustal depth sections along the three DSS profiles in the Mahanadi delta area (reproduced from ref. 18).

delineation of deep crustal structure and Moho configuration with location and alignment of any deep fault may provide some clues to resolve the question regarding the seismicity in the Koyna region. Further the DSS studies were also expected to provide information on the thickness of the Deccan Traps and the subtrappean structures which were not known earlier in the Koyna region. In order to examine the seismic energy transmission through the Traps cover into the deep crustal depths, preliminary experiments were conducted by recording a few explosions on selected seismic spreads. These preliminary experiments clearly established that the seismic energy transmission through the Deccan Traps is very efficient and waves penentrated into the deep crustal depths can be recorded with significant energy at sufficiently large distances from the source, including the wide-angle reflections and refracted waves from the Moho. Encouraged by these results two DSS profiles, Koyna I (Guhagar-Chorochi)[19] and Koyna II (Kelsi-Loni)[20] each about 200 km long (figure

6a), were covered in the Deccan Traps region of Maharashtra during the period from 1975 to 1978.

Shallow depth section to the basement level delineated from the seismic refraction data, and deep crustal depth section delineated from the wide-angle reflection data are shown in figure 6b for the Koyna II and figure 6c for the Koyna I profile. Along the Koyna I profile the P wave velocity in the Deccan Traps is found in the range 4.7–4.9 km/s while in the Pre-Deccan Trap contact the velocity is found to be 5.9–6.1 km/s. The Traps thickness, essentially controlled by the existing relief of the pre-Trappean topography, is found to vary considerably: 400 m near Chorochi, 600 m near Karad, 1100 m near Koyna, 700 m near

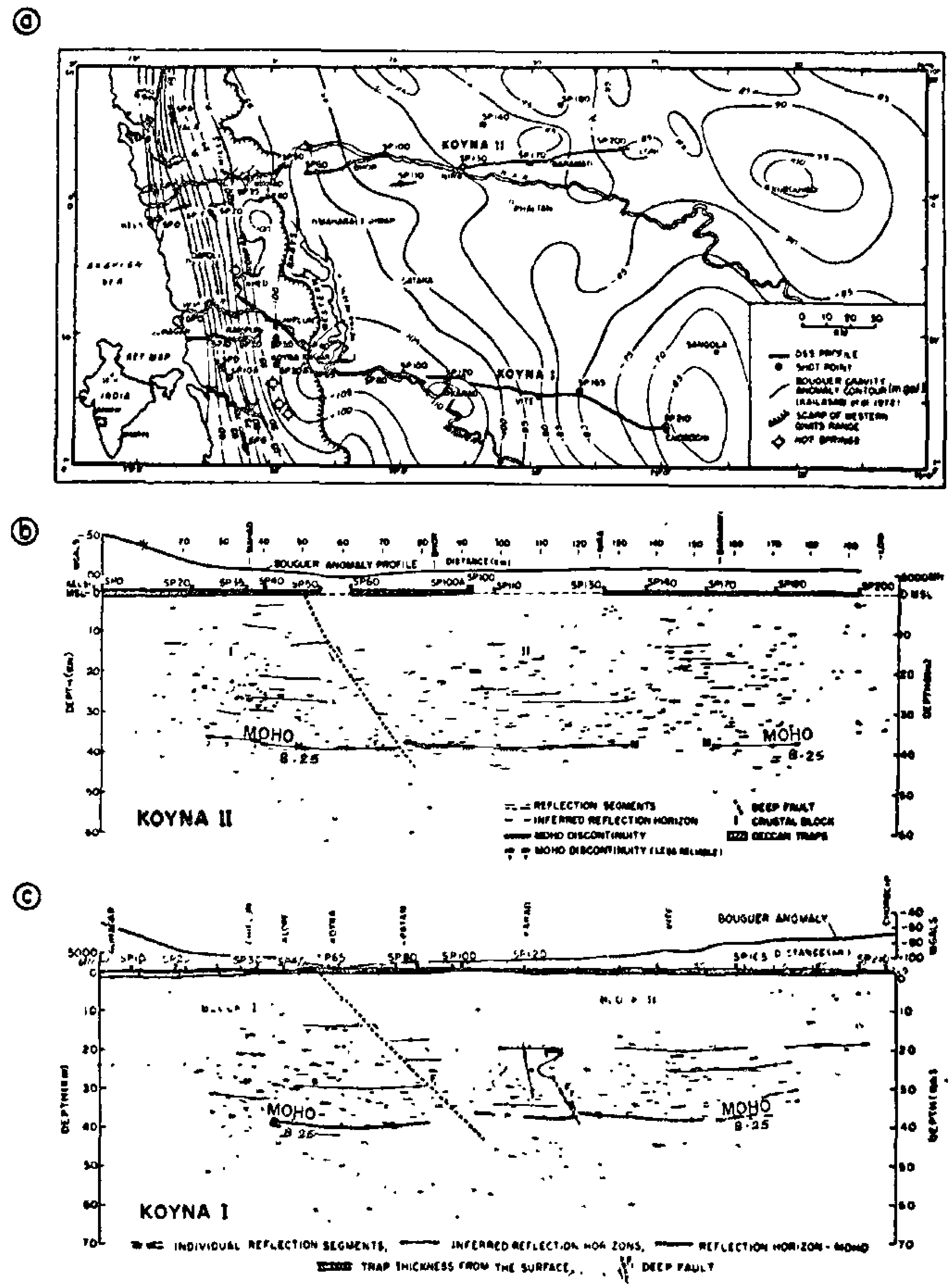

FIGURE 6(a) Map of the Koyna reservoir area showing location of the two DSS profiles, Koyna I (Guhagar-Chorochi) and Koyna II (Kelsi-Loni). The Bouguer gravity anomaly contours (reproduced from ref. 52) are also shown (b) Crustal depth section along the Koyna II DSS profile showing the deep fault displacing the Moho (reproduced from ref. 20) (c) Crustal depth section along the Koyna I DSS profile showing the deep faults displacing the Moho (reproduced from ref. 19).

Chiplun and 1500 m near the west coast. Along the Koyna II profile the Deccan Traps thickness is found to be about 700 m on the eastern part between Nira and Loni and 1500 m near the west coast. The velocity is found to be 4.8–5.0 km/s in the Traps and 6.0–6.15 km/s in the pre-Deccan Trap contact on this profile. On the basis of the observed velocity of 5.9–6.2 km/s in the pre-Deccan Trap contact, it is inferred that the Deccan Traps directly overlie the granites and granitic gneisses and the Bhimas-Kaladgis or the Dharwar schists do not extend under the Traps as far north as the Koyna region. A tentative isopach contour map of the Deccan Traps and a structural contour map of the pre-Deccan Trap contact for the Koyna area were prepared[20] using the information obtained from the shallow depth sections along the two profiles. A flexure aligned in a NNW-SSE direction, is indicated in the pre-Deccan Trap contact which is an expression of the deep fault into the basement. The flexure also coincides with the general orientation of the Deccan Volcanic scarp in the Koyna reservoir area. The deep fault has also been found to extend into the deep crustal depths affecting the Moho boundary along the two profiles. The crustal depth section along the Koyna I as well as the Koyna II profile can be broadly divided into two blocks, separated by the deep fault. Along the Koyna I profile, the depth to the Moho boundary in the western block is about 40 km in the vicinity of the deep fault rising to a depth of about 30 km near the west coast. In the eastern block, the depth to the Moho boundary is found to be 36–38 km. Along the Koyna II profile, the Moho depth is found to be 39 km near the deep fault rising to a depth of 31.5 km near the west coast. The eastern block on this profile is found to have moved up by 1.5 km relative to the western block. A structural contour map of the Moho in the Koyna reservoir area has also been prepared[20] from these results, revealing the deep fault aligned in the NNW–SSE direction in this area. The seismicity observed in the Koyna region is related to the recent movements along this deep fault.

The analog DSS records along the two profiles have been digitized[21] and assembled into trace normalized record sections with a reduction velocity of 6 km/s. Travel times and relative amplitudes modeling[22,23] of these digitized record sections with the aid of synthetic seismograms (figures 7a and 7b) yielded well constrained velocity-depth models for the crustal and subcrustal sections of the lithosphere in the Koyna region. These new velocity-depth models reveal presence of prominent low velocity layers (LVL) in the upper and the lower crust as well as in the subcrustal lithosphere in this region. The Moho is found to be a transitional rather than a sharp boundary with the transition zone thickness of 2–4 km in this region. The uppermost mantle Pn velocity is found to be 8.25 km/s in the Koyna region. The upper crustal LVL with its top at 6–7 km depth is found to be consistent with the observed seismic activity concentration at 4–5 km depth and an appreciable reduction of seismic activity at greater depths (figure 8a). The alternating LVL in the subcrustal lithosphere as well as the LVL in the upper and the lower crust together with the observed depth distribution of seismicity suggest a well defined rheological stratification of the continental lithosphere with varying material properties (figure 8b) in the Koyna region[23]. The earthquakes seem to be occurring in the upper rigid layer of the crust with relatively more strength and temperatures within 200°–300°C. The aseismic lower crust corresponds to a zone of low strength where ductile deformation predominates.

DSS Results in the Saurashtra Peninsula

DSS studies were carried out during 1977 along a 160 km long profile from Navibandar to Amreli in the Saurashtra peninsula (figure 9). The Deccan Traps covered Saurashtra region was not explored earlier by seismic methods, thus the Traps thickness, possible extension of the Mesozoic sediments below the Traps, basement configuration and deep crustal structure were not known in this region. Shallow and deep crustal structure delineated by analysis of seismic refraction and wide-angle reflection data[24] along the DSS profile are shown in figures 10a and 10b respectively. The P wave velocity in the Deccan Traps was found in the range 4.9–5.15 km/s, consistent with that found in the Koyna region. The Deccan Traps thickness was found to be relatively large, west of Junagarh, about 1300 m near Navibandar, 900 m between Mahiary and Junagarh Towards east of the Girnar hills the Traps are relatively thin about 400 m, however thickening to about 900 m near Bagasara and again thinning to about 350 m near Amreli. The velocity in the crystalline basement was found in the range 5.9–6.0 km/s in this region. A layer of relatively low velocity of about 4.0 km/s, inferred as the Mesozoic sediments, with a maximum thickness of about 850 m near Amreli was found[24] beneath the Deccan Traps (figure 10a) by a joint interpretation of seismic refraction and wide-angle reflection data from the upper crustal depths. On the basis of this model, it was inferred that a major sedimentary basin during the Mesozoic period probably existed from Bagasara in eastern Saurashtra, extending through the Gulf of Cambay, Broach syncline and ending near Rajpipla where the Mesozoics are now exposed. The deep crustal depth section (figure 10b) in this region down to the Moho, displays a horst and graben structure the various crustal blocks bounded by deep faults. The main horst named the Girnar horst lies in the region of Girnar hills and is flanked by the Manekwara graben

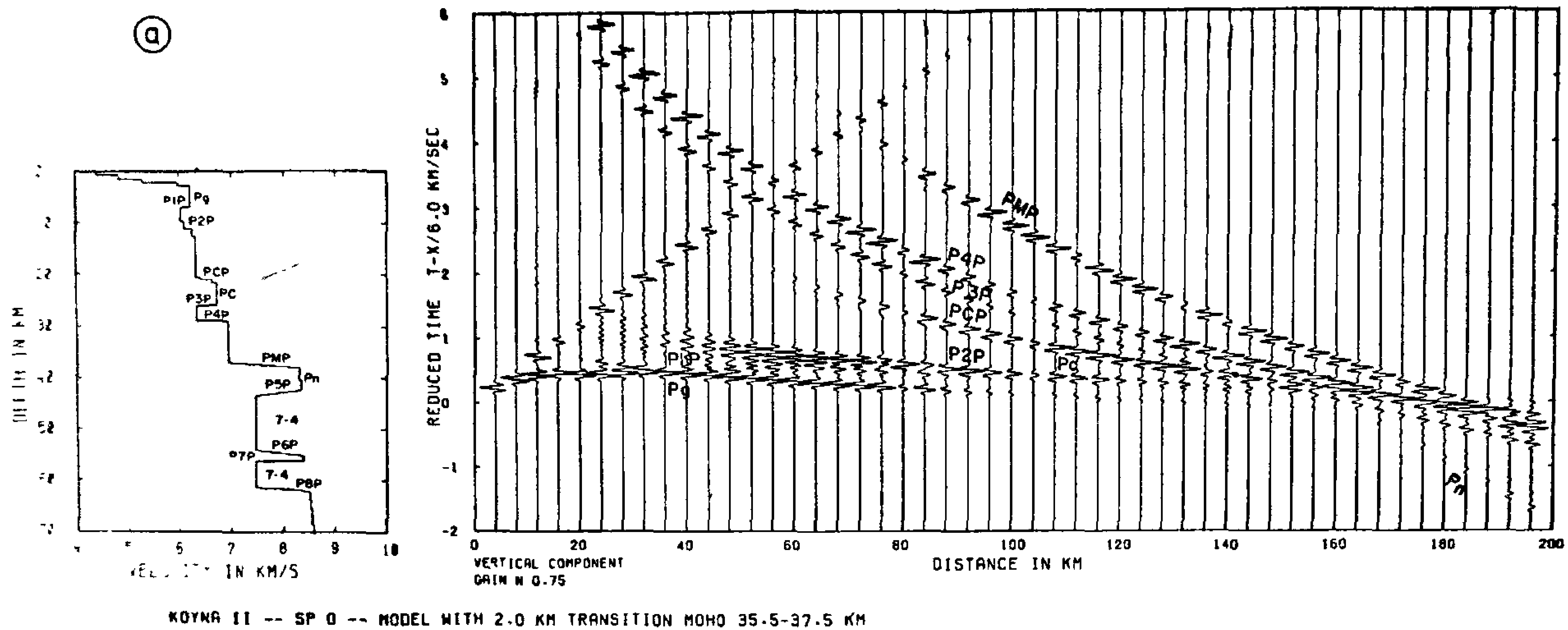

FIGURE 7(a) Normalized record section of ray synthetic seismograms computed by using the velocity-depth model inferred in the Koyna region, revealing low velocity layers in the upper and the lower crust and a 2.0 km thick transitional Moho (reproduced from ref. 22).

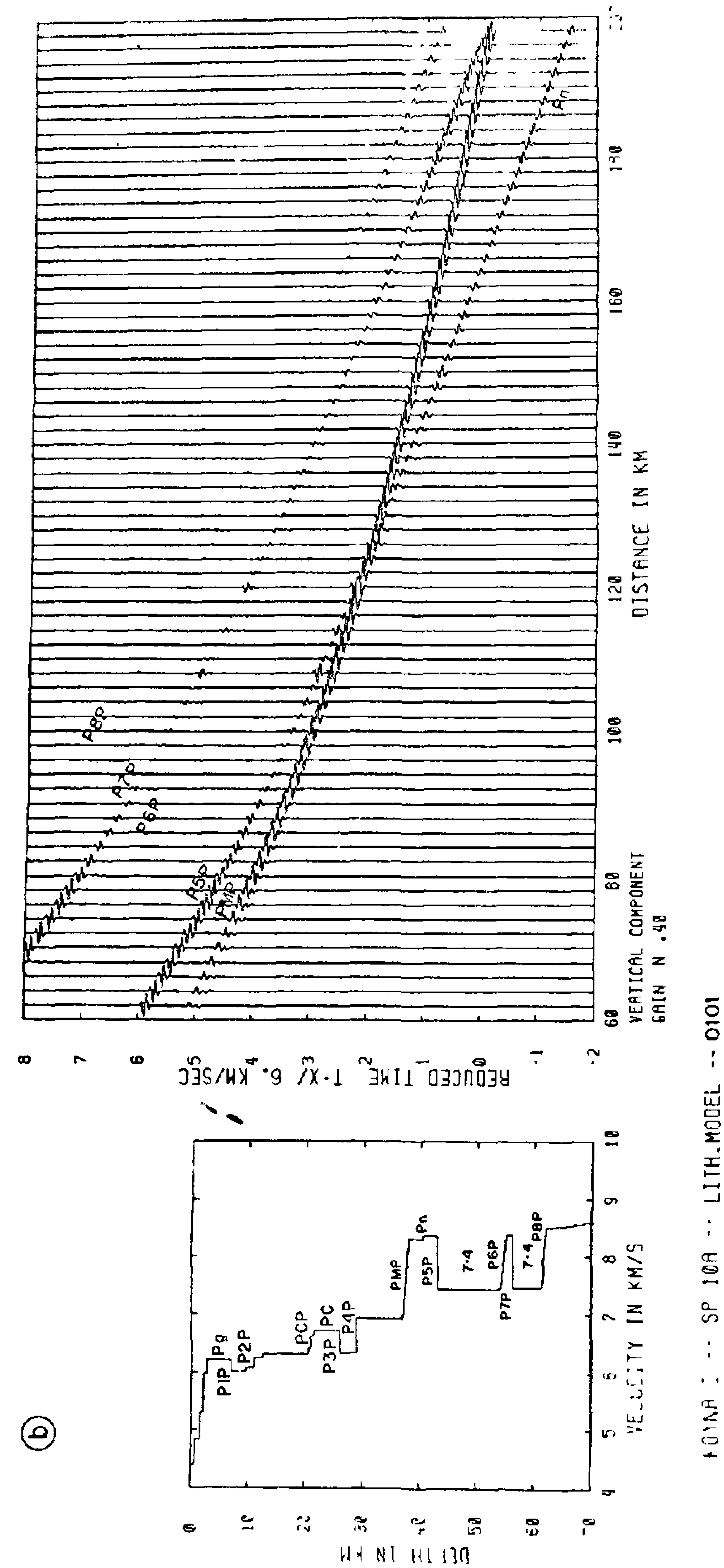

FIGURE 7(b) Normalized record section of ray synthetic seismograms computed by using the velocity-depth model inferred in the Koyna region, revealing low velocity layers in the sub-crustal lithosphere (reproduced from ref. 23).

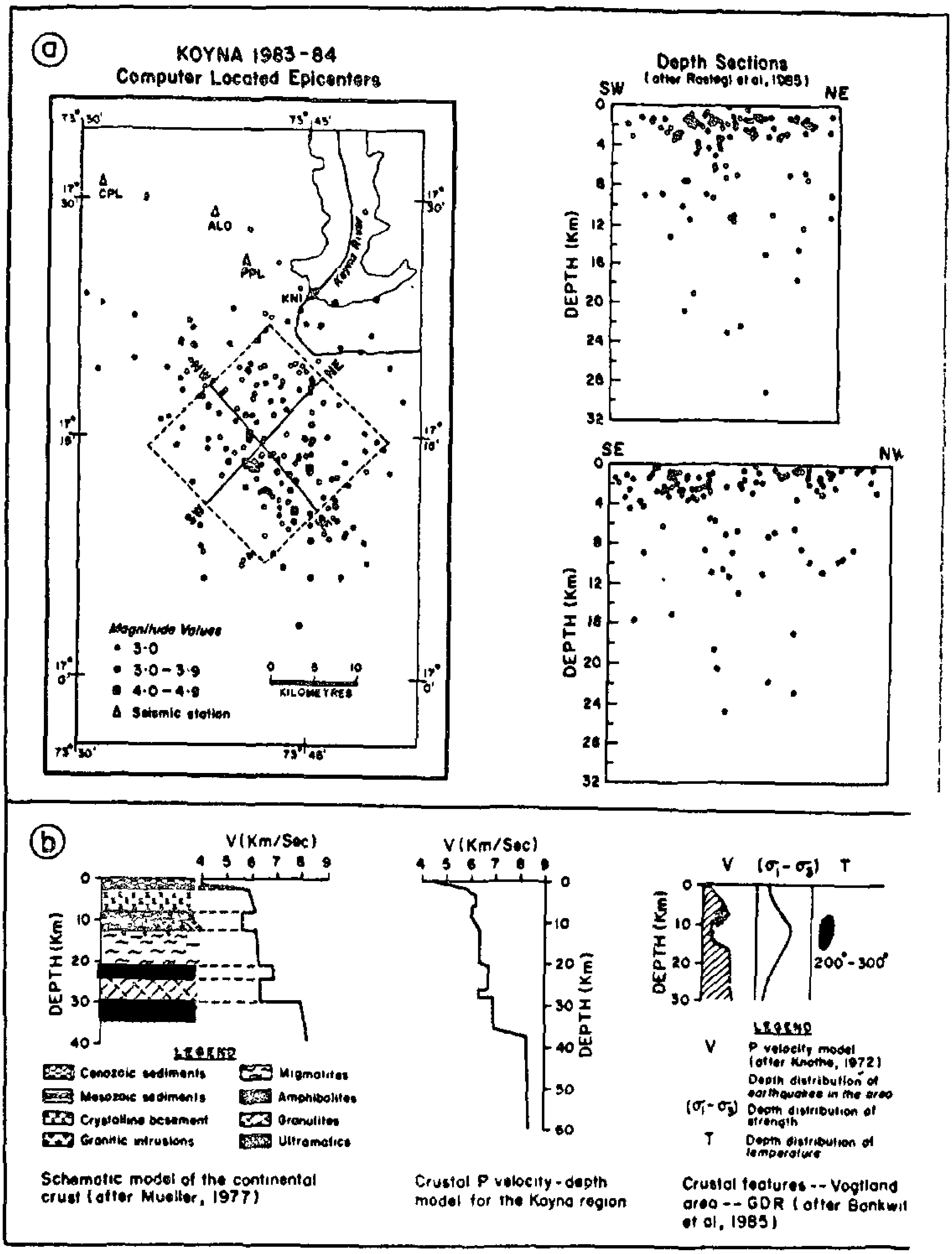

FIGURE 8(a) Spatial and depth distribution of earthquakes in the Koyna region, consistent with the inferred low velocity layers in the upper and the lower crust (reproduced from ref. 22) **(b)** Crustal P velocity-depth models and their relation to the depth distributions of earthquakes, material strength and temperature shown schematically (reproduced from ref. 22).

on the east and the Vanthali graben on the west. Shallow reflectors on either side of the Girnar hills, predominantly updipping towards the hills, indicate an uplift of a plutonic mass from large depths as a mechanism for the formation of the Girnar hills. The Moho boundary is delineated at depths varying from 35 to 42 km in this region.

DSS RESULTS ACROSS THE NARMADA-SON LINEAMENT

The Narmada-Son lineament is a conspicuous linear tectonic feature extending in a ENE-WSW direction in central India, which has played a significant role in the formation of a series of folded structures in the Vindhyan formations. This lineament has been consi-

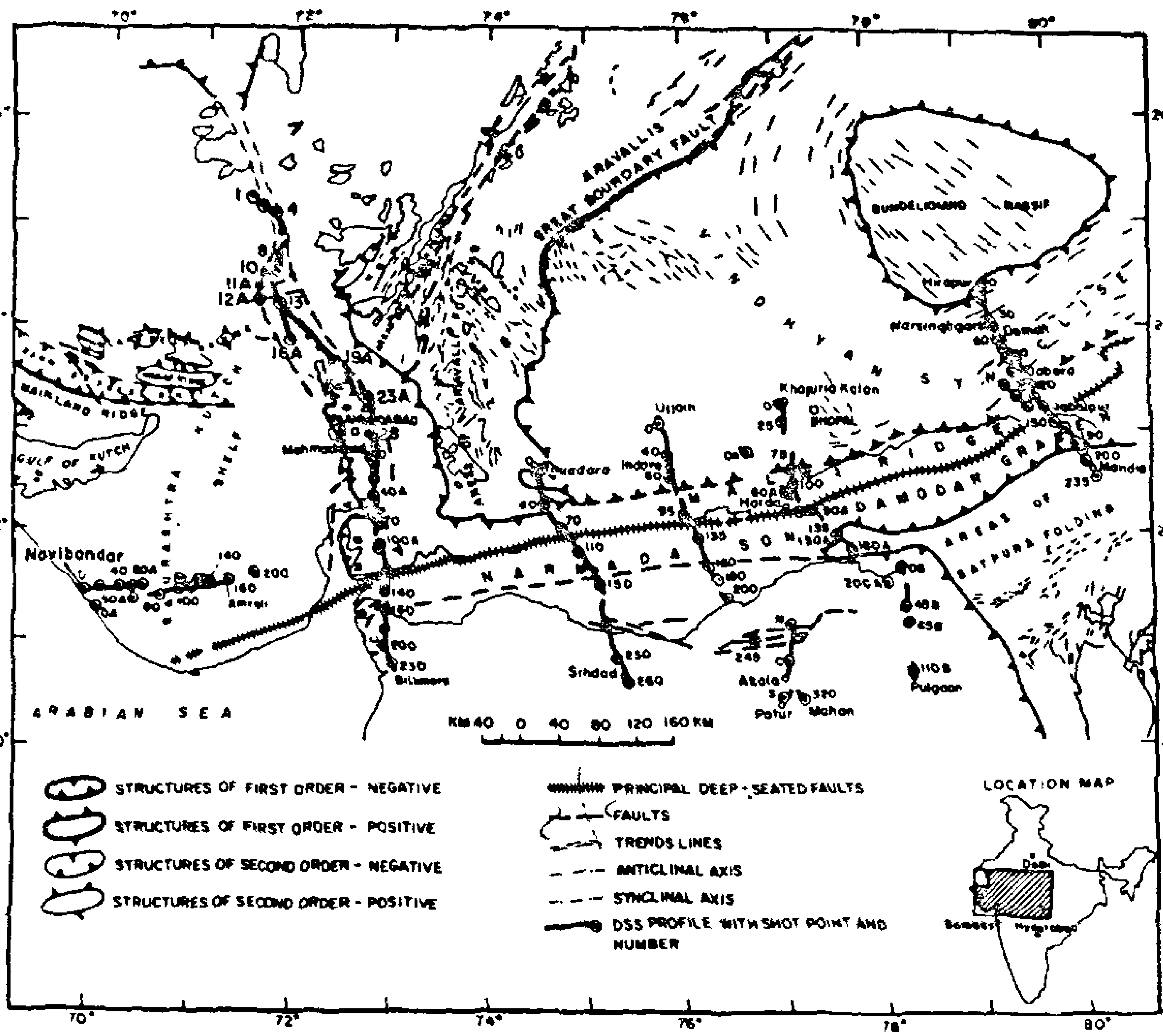

FIGURE 9 *Tectonic map of central India showing location of the DSS profiles across the Narmada-Son lineament.*

dered as an ancient rift or an active fault zone[25]. It is very significant that the Vindhyan sediments were deposited only to the north of this lineament and the Gondwana sediments to the south of it[26]. From various geological studies it has become clear that this lineament is situated close to the fractures of early Precambrian, Cretaceous and post-Deccan Traps period, dating back predominantly to the Deccan Traps period though the movements began significantly earlier. This lineament is also a zone of moderate seismicity[27], and the epicenters of a number of shocks were found to align nearly parallel to the Narmada-Son lineament[28]. The Vindhyan basin is separated towards the northwest from the Aravallis by a great boundary fault trending roughly NE-SW, and in the south the basin is bounded by the Narmada-Son lineament (*figure 9*). The main Aravalli trend continues across the Cambay basin that was formed due to the extension in a northwest direction of the NNW-SSE trend parallel to the west coast of India. The Cambay basin originated during the Mesozoic period but subsided at a greater rate during the Tertiary. The Deccan Traps, which extruded around 67–68 Ma[29], are considered to be the basement of the Tertiary sediments in the Cambay basin. Very little information was available on the thickness of the Deccan Traps both in the Cambay basin, where they underlie the Tertiaries, as well as in the remaining parts of the Narmada-Son lineament zone, where they are exposed on the surface. Further, no reliable information was available on the subtrappean structures, the crystalline basement configuration, the deep crustal structure and the Moho configuration in this region. In order to address some of these problems, five DSS profiles were covered since 1976 in this region, each about 250 km long, cutting across the Narmada-Son lineament:

- Mehmadabad-Billimora profile in the south Cambay basin,

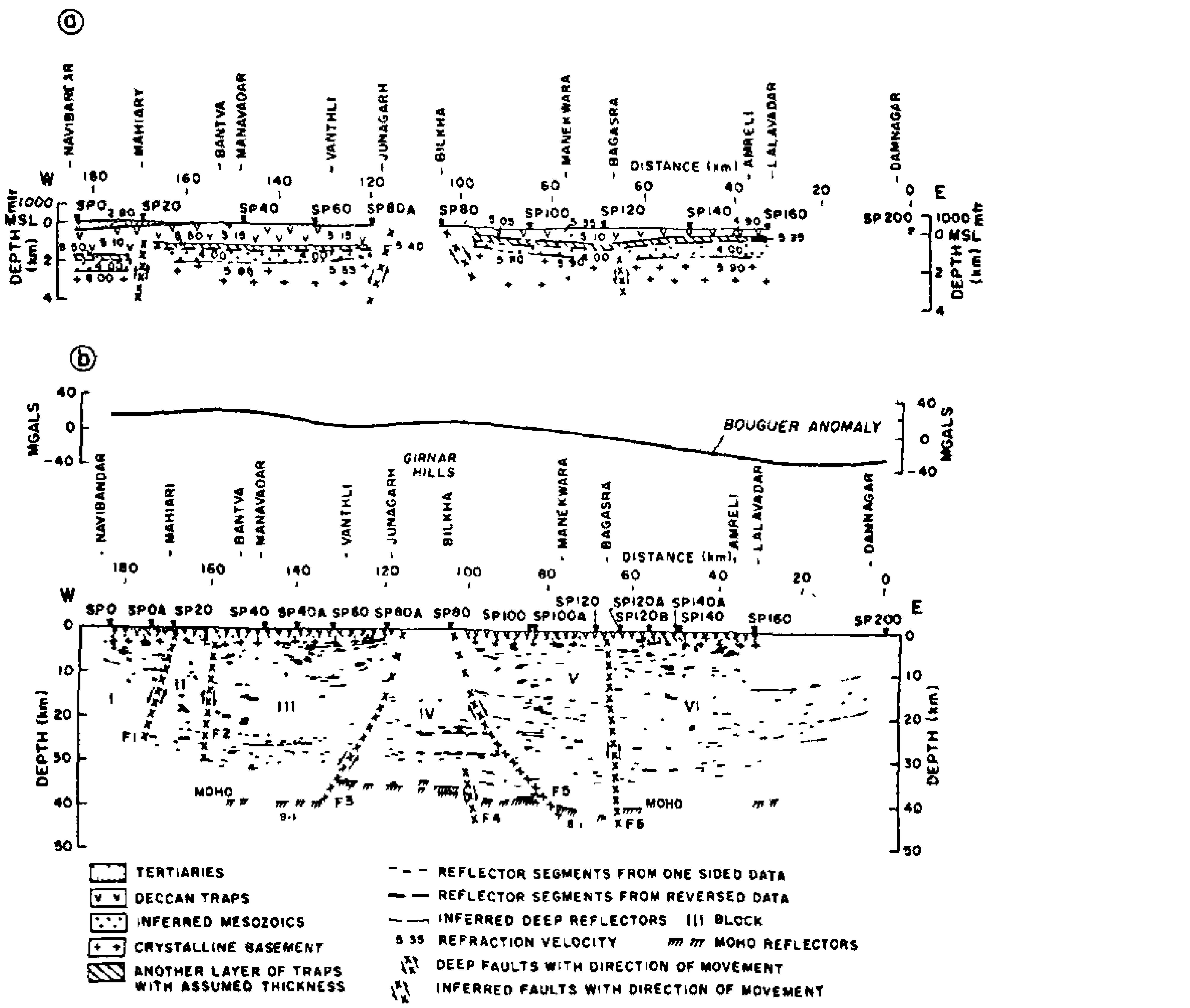

FIGURE 10(a) Shallow depth section to the basement level along the Navibandar-Amreli DSS profile in the Saurashtra peninsula (reproduced from ref. 24). (b) Crustal depth section along the Navibandar-Amreli DSS profile in the Saurashtra peninsula (reproduced from ref. 24).

- Thuadara-Sindad,
- Ujjain-Mahan,
- Khajuria Kalan-Pulgaon
- Hirapur-Mandla profiles (figure 9).

The Cambay basin profile has recently been extended by another 350 km towards north from Mehmadabad to Tharad and also towards the Sanchor basin up to Dharimanna by seismic refraction and wide-angle reflection profiling using a 60 channel DFS-V digital recording system and 4 ms data sampling. All the other DSS profiles across the Narmada-Son lineament were covered by using two 30 channel POISK analog recording systems.

DSS Results in the Cambay Basin

Shallow and deep crustal depth sections delineated from seismic refraction and wide-angle reflection data in the south Cambay[30] and the north Cambay and Sanchor basins[31] are shown in figures 11a and 11b respectively. The crustal depth section along the Mehmadabad-Billimora profile in the south Cambay basin (figure 11a) reveals that the basin which is well known to be bounded by step faults on the eastern and western margins, is also dissected in the north-south direction into seven major crustal blocks. The crustal blocks #I to VII are bounded by deep faults, some of them extending down to the Moho. The seismic activity observed in this region, during historical to modern times, suggests that these deep faults may be currently active. A horst and graben structure is also quite evident in the north-south direction within the south Cambay basin. The Jambusar-Broach block #IV, which is well known from the shallow seismic surveys in the region as a broad regional syncline with the maximum thickness of the Cenezoic sediments, has been brought out in the DSS section as a major graben with the deepest depths of the granitic basement at 6.0–

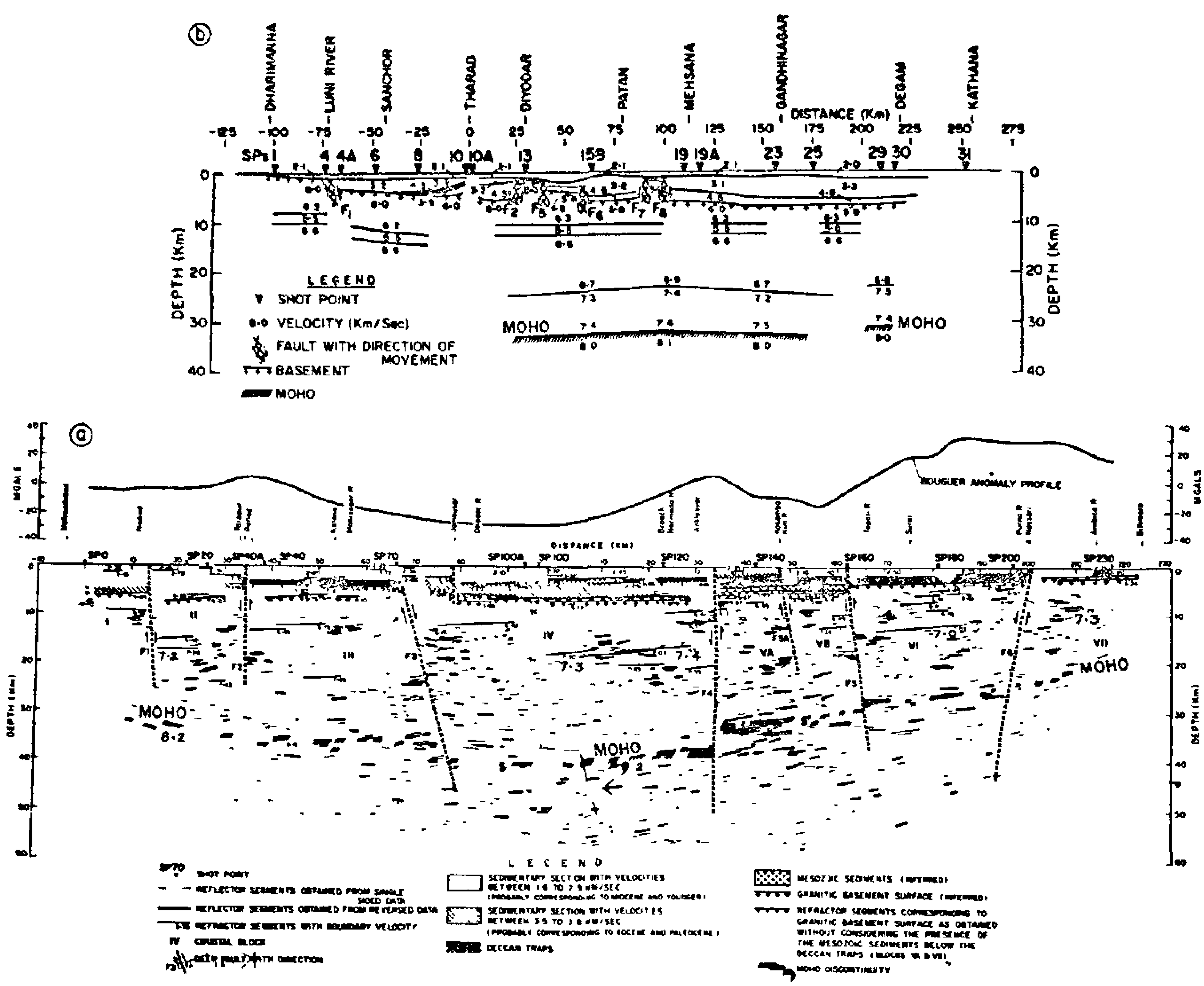

FIGURE 11(a) Crustal depth section along the Mehmadabad-Billimora DSS profile in the south Cambay basin (reproduced from ref. 30) (b) Crustal depth section along the Dharimanna-Degam DSS profile in the north Cambay and Sanchor basins (reproduced from ref. 31).

6.5 km and the Moho at 38–40 km within this block. To the north and south of this graben, the Moho is relatively shallow in various crustal blocks: 32–35 km in blocks #I, II and III towards north, 31–34 km in block #V, 25–29 km in block #VI and only about 20 km in block #VII thus rising rapidly towards south. The deep fracture corresponding to the Narmada-Son lineament is delineated on the southern margin of the Jambusar-Broach block #IV, by the deep fault F4 south of Ankleswar. The uppermost mantle Pn velocity in this region is found to be 8.1–8.2 km/s. The P velocity in the granitic basement reveals lateral variations in the range 5.7–6.3 km/s along this profile. Two deeper interfaces were also delineated in the deep crust with boundary velocities of 6.5–6.8 km/s and 7.0–7.5 km/s. Especially in the region south of the Narmada river, the interface with the boundary velocity of 7.0–7.3 km/s rises to very shallow depths similar to the Moho configuration in this region. The shallow structural features delineated by the DSS section consist of at least two prominent layers of P velocity 1.6–2.9 km/s (Miocene and younger formations) and 3.5–3.8 km/s (Eocene and Paleocene) of the Tertiary sediments. A layer of velocity 4.8–5.2 km/s has been delineated at varying depths below the Tertiary sedimentary layers in the Petlad-Katana block #III and south of the Narmada river up to Billimora, which is interpreted as the Deccan Traps layer. The thickness of the Deccan Traps layer varies from 1.0–1.6 km in block #III, 1.1 km in block #V, 1.4–1.8 km in block #VI and about 1.0 km in block #VII. It is also found likely that the Mesozoic sediments may be present beneath the Deccan Traps in this region.

By extensive modeling[31] as shown in figure 12, of the digital DSS record sections acquired along the profile in

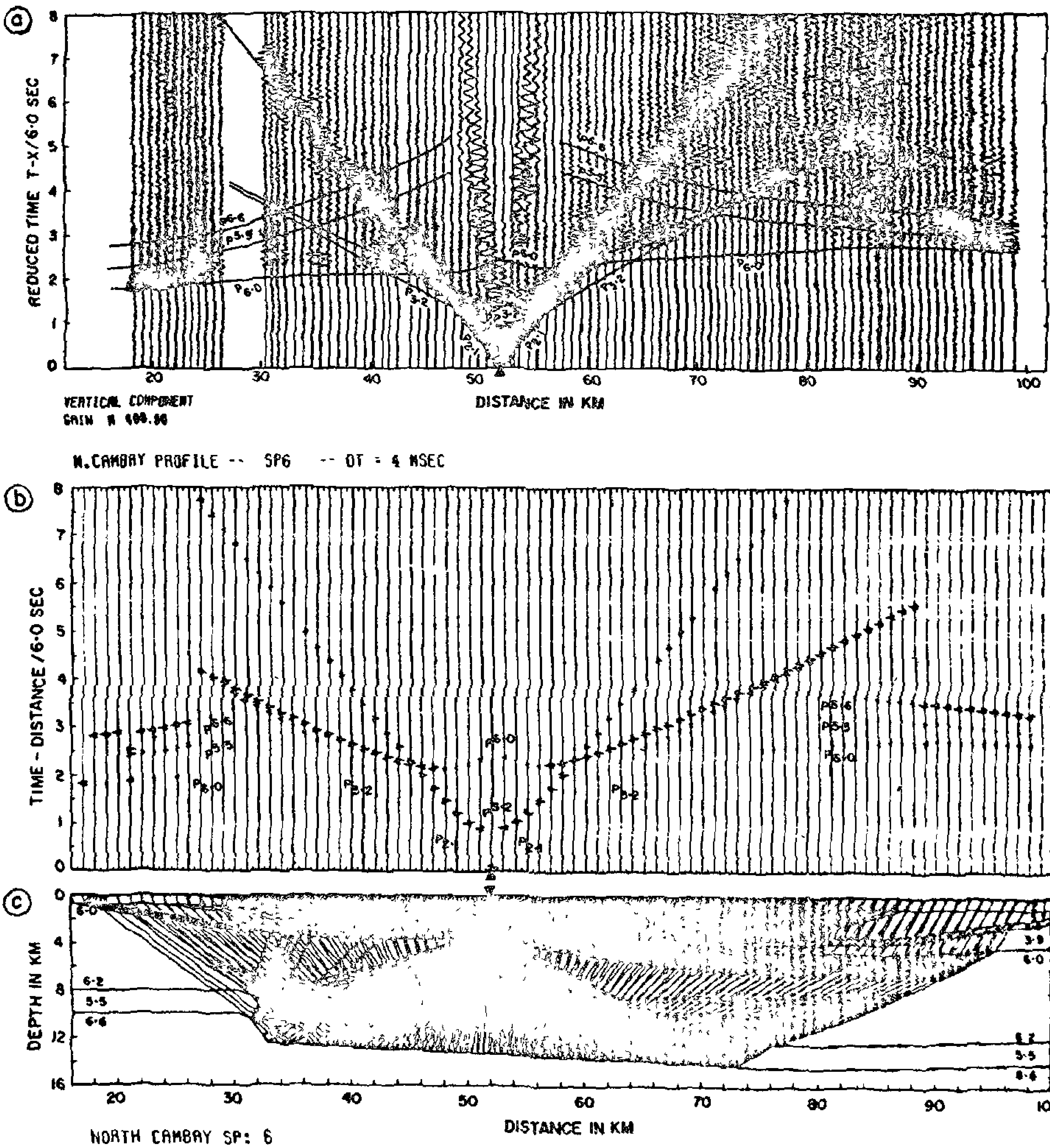

FIGURE 12(a) Normalized record section of field seismograms from SP6 in the Sanchor basin acquired by the DFS–V digital recording system with 4 ms data sampling (b) Normalized record section of ray synthetic seismograms computed by using the 2D-model of the upper crust inferred in the Sanchor basin (reproduced from ref. 31) (c) Ray path diagram for reflected and refracted phases and the 2D-model of the upper crust inferred in the Sanchor basin (reproduced from ref. 31).

the north Cambay and Sanchor basins, shallow and deeper crustal structural features have been delineated. Four sedimentary sub-basins are delineated (figure 11b) in this region: the north and south Sanchor basins, the Patan basin and the Gandhinagar basin. Within the sedimentary basin, two horst features the Diyodar ridge and the Unhawa ridge are also brought out. The Deccan Traps of P velocity 4.3–4.8 km/s form the base of the Tertiary sediments in this region also except in the extreme northern part of the Sanchor basin. There is also some indication of the presence of subtrappean Mesozoic sediments along the north Cambay profile. Maximum depth to the granitic/proterozoic basement [P velocity 5.9–6.0 km/s] is about 5000 m in the north Sanchor and the Patan sub-basins, about 5600 m in the south Sanchor subbasin, and is deepest about 7700 m in the Gandhinagar subbasin. The velocity in the upper crust varies from 5.8 to 6.3 km/s, with presence of a prominent low velocity layer of velocity 5.5 km/s in this region. The lower crust consists of two layers of velocities 6.6–6.9 km/s and 7.3–7.4 km/s. The Moho [Pn velocity 8.0–8.1 km/s] is delineated at a depth of 31–33 km in the north Cambay basin (figure 11b). The large thickness of the Tertiary sediments in the Cambay basin and a relatively thin crust in the region suggest further rifting during the Tertiary. The high velocity lower crustal layer of velocity 7.3–7.4 km/s delineated from Billimora in the south to Tharad in the north throughout the Cambay basin (figures 11a and 11b) indicates underplating of the crust due to mantle upwelling and rifting with large scale extrusion of the Deccan Traps.

DSS Results along the Thuadara-Sindad Profile

DSS results, obtained by iterative two-dimensional ray tracing and travel times modeling, along the Thuadara-Sindad profile[32] are shown in figures 13a and 13b respectively for the shallow and deeper parts of the crustal depth section. Along this profile, the P velocity is found in the range 4.7–5.0 km/s in the Deccan Traps layer and 5.7–6.0 km/s in the granitic basement. In the region north of the Narmada river the Deccan Traps layer is 500–900 m thick and directly overlies the basement. A prominent low velocity layer inferred as the Mesozoic sediments of velocity 3.2–4.0 km/s with a maximum thickness of 1900 m, is delineated below the 900 m thick Deccan Traps layer towards south of the Narmada river (figure 13a). The Narmada-Son lineament is delineated as a basement fault in this region. The P

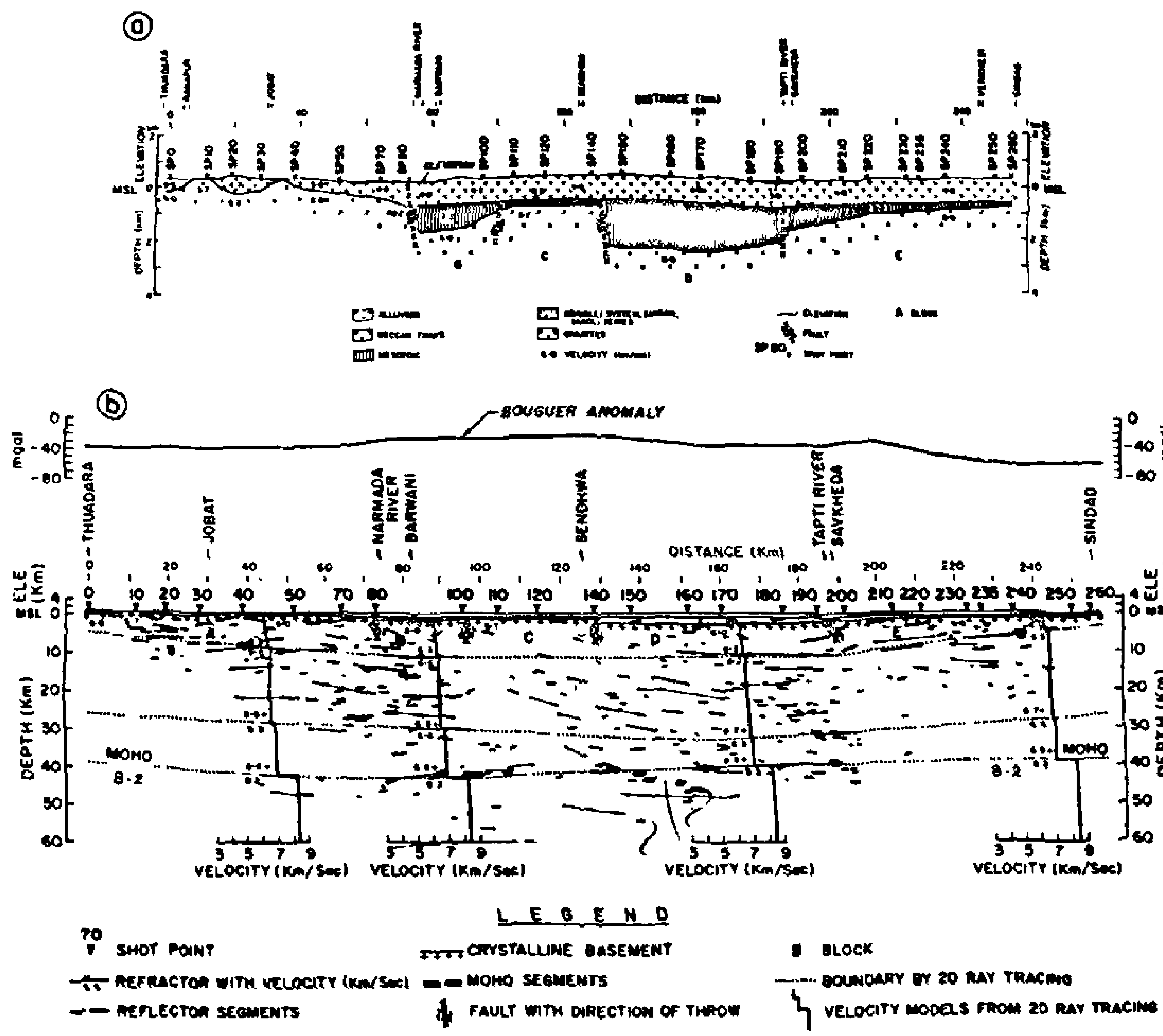

FIGURE 13(a) Shallow depth section to the basement level along the Thuadara-Sindad DSS profile across the Narmada-Son lineament (reproduced from ref. 32) (b) Crustal depth section along the Thuadara-Sindad DSS profile across the Narmada-Son lineament (reproduced from ref. 32).

velocity in the lower crust, above the Moho, is found to be 6.8–6.9 km/s. The Moho boundary is delineated with Pn velocity of 8.2 km/s in the depth range 38–43 km along this profile (figure 13b) with a gentle upwarp of about 2 km relief between the Narmada and Tapti, coinciding with the location of the upper crustal graben [above the granitic basement] consisting of the Mesozoic sediments. These structural features are *indicative of continental rifting in this region.*

DSS Results along the Ujjain-Mahan Profile

The DSS results along the Ujjain-Mahan profile[33] are shown in the form of a shallow depth section down to the granitic basement and the deep crustal depth section down to the Moho in figures 14a and 14b respectively. In the northern part of the profile from Ujjain to Dorwa, a 600 m thick low velocity sedimentary section comprising of the Cretaceous lametas, Vindhyan quartzites and Bijawars of average velocity 3.7 km/s has been inferred underlying a relatively thin *cover of 100 m of the Deccan Traps* of velocity 4.7–5.1 km/s. In the southern part of this profile, south of the Narmada-Son lineament, between Dorwa and Mahan a maximum thickness of 1.7 km of low velocity Gondwana/Mesozoic sediments of velocity 3.2 km/s, underlying a 400 m thick Deccan Traps layer (figure 14a) has been inferred. The velocity in the granitic basement is found in the range 5.8–6.1 km/s along the Ujjain-Mahan profile. An interface with boundary velocity 6.9–7.0 km/s has been found at relatively shallow depths of 8–10 km along this profile. In the deeper section four crustal blocks are recognized in this region (figure 14b). The Moho boundary is delineated in the depth range 37–42 km along this profile, and the uppermost mantle Pn velocity is found to be 7.8–7.9 km/s. The Narmada Son-lineament is brought out as a deep fault delineated near Dorwa.

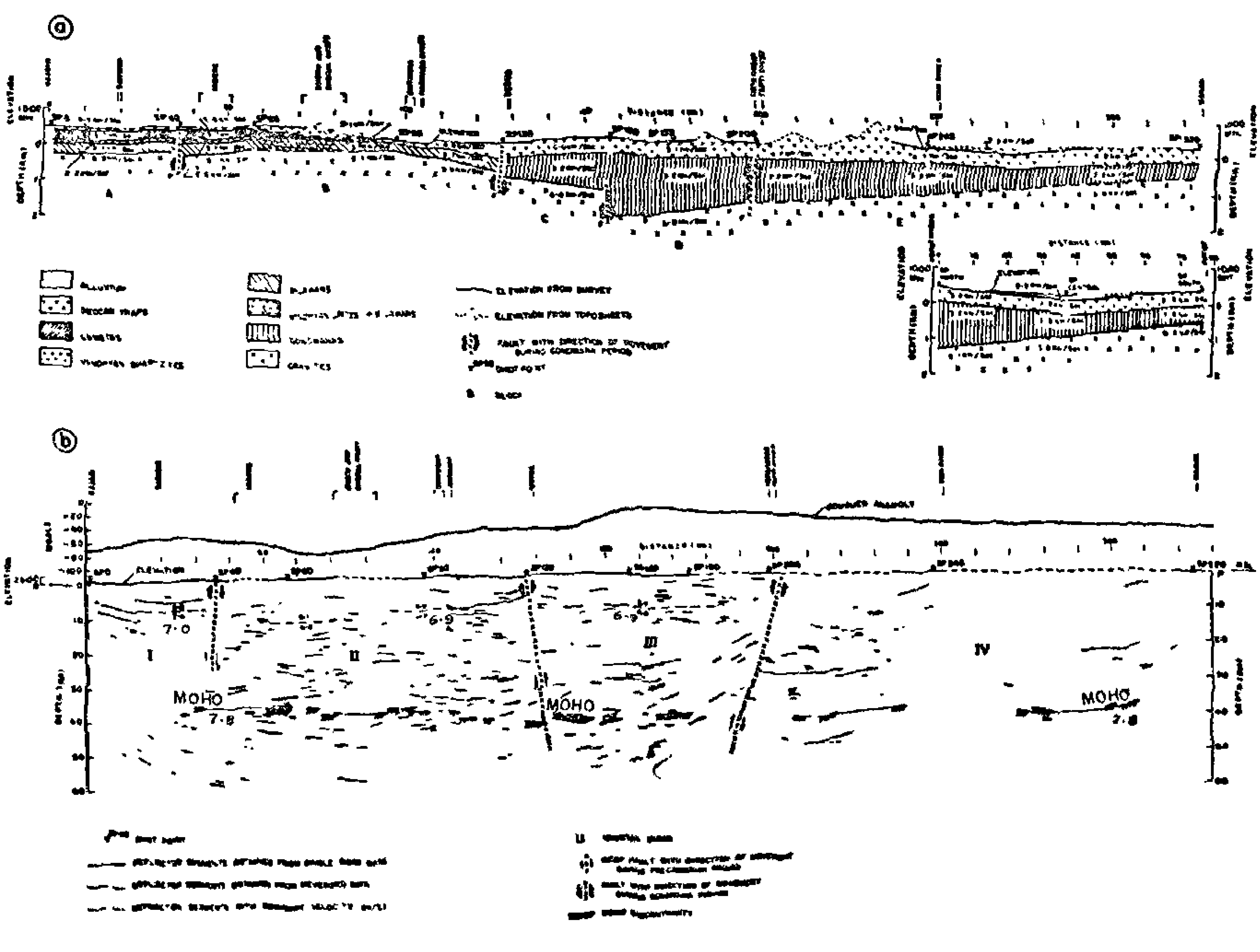

FIGURE 14(a) Shallow depth section to the basement level along the Ujjain-Mahan DSS profile across the Narmada-Son lineament (reproduced from ref. 33) (b) Crustal depth section along the Ujjain-Mahan DSS profile across the Narmada-Son lineament (reproduced from ref. 33).

DSS Results along the Khajuria Kalān-Pulgaon Profile

DSS data has been acquired along three lines on this profile:

- 140 km long N-S line Khajuria Kalan-Rahatgaon,
- 200 km long NW-SE line Pagariahat-Masod,
- 120 km long N-S line Multai-Pulgaon.

Interpretation[34] of shallow refraction and deep reflection data along the three lines delineated the Deccan Traps thickness, subtrappean low velocity layers and the granitic basement configuration (figure 15a) as well as the deep crustal structure (figure 15b) in this region. It was found that the Deccan Traps cover is very thin 100–200 m, along a major part of this profile. Below this thin Traps cover of velocity 4.7–5.1 km/s, a 200–350 m thick layer of the Vindhyan and Bijawar sediments (upper Precambrian-lower Palaeozoic) of relatively low velocity of 3.7 km/s has been found in the northern part of the profile from Khajuria Kalan to Pagariahat, north of the Narmada river. On the southern part of the profile, especially on the Multai-Pulgaon line, a 300–400 m thick layer of the Gondwana sediments (upper Carboniferous-lower Cretaceous) of velocity 3.2 km/s has been found to underlie the thin cover of the Deccan Traps (figure 15a). This Gondwana basin is probably the northwestern extension of the Godavari graben under the Deccan Traps cover. The Narmada-Son lineament is brought out as a deep fault delineated near SP 90A on the Pagariahat-Masod deep crustal section (figure 15b). The Moho boundary is delineated in some parts of this profile in the depth range 34–40 km.

DSS Results along the Hirapur-Mandla Profile and the Evolution of the Vindhyan Basin

With a view to understand the nature of the Narmada-Son lineament at depth and evolution of the Vindhyan basin, a DSS profile was covered from Hirapur (close to the boundary of the Bundelkhand massif) to Mandla cutting across the Precambrian sedimentary sequences of the Vindhyan basin (figure 9). The Bundelkhand group forms the Archaean basement in the area consisting of migmatites, granites and subordinate quartzites. The Bijawar sediments lie directly on the basement and outcrop at the border of the Bundelkhand complex and on the southern borders of the Vindhyans along the Narmada-Son lineament. The crustal depth section along this profile has been computed in two steps from the DSS data[35,36]. The shallow section to the crystalline basement (figure 16a) is derived by inverting first arrival refraction travel times. The shallow section reveals a simple two layer model from Hirapur to Narsinghgarh with P velocities of 4.2–4.8 km/s and 5.8–6.2 km/s in the two layers. The second layer is considered to be the basement that outcrops in the Bundelkhand complex. In the region from Damoh to Jabera there are three layers to the basement level, with P velocities of 4.5–4.8 km/s, 5.4 km/s and 6.5 km/s. The velocity in the range 5.8–6.2 km/s, corresponding to the basement complex in the northern section, is not found in this part of the profile. The relatively thick layer of velocity 5.4 km/s directly overlies the higher velocity layer of 6.5 km/s. In the first layer, the P velocity varies across the basin in the range 4.0–4.8 km/s. This range of velocity corresponds to different formations of the upper Vindhyan group. The second layer of velocity 5.3–5.4 km/s which is relatively thick, is only confined to the Vindhyan graben bounded by deep faults at Narsinghgarh and Katangi. This layer corresponds to the lower Vindhyan sequence. The deeper layer of velocity 6.5 km/s in this graben region, represents the crystalline basement. Further south between Katangi and Jabalpur the first layer is of 5.9 km/s velocity representing the crystalline basement. The velocity in the underlying layer is 6.7–6.9 km/s occurring just at 2 km depth. In the southernmost part between Jabalpur and Mandla the profile covers the exposed Deccan Traps. The first layer of the Deccan Traps is delineated with a velocity of 4.5–4.8 km/s, while in the second layer the velocity is found to be 5.9 km/s representing the crystalline basement. Although a possibility of the Satpura Gondwana rocks continuing beneath the Deccan Traps in this region was suggested[37], however, no indications were found from the DSS data for the presence of a low velocity layer of the Gondwanas below the Deccan Traps layer of relatively high velocity.

To construct the deeper crustal section, by migration of wide-angle reflection data, two velocity-depth functions were used separately for the Vindhyan basin region and the Deccan Traps covered region. The crustal depth section was also further refined by an iterative two-dimensional ray tracing technique. From the deep crustal section in this region (figure 16b) obtained from wide-angle reflection data, three deep faults are inferred at Narsinghgarh, Katangi and Jabalpur. Block tectonics appear to have been active in this area throughout the geological history. The crustal section is divided into four major blocks. The crustal block between Narsinghgarh and Katangi has given rise to a graben in the crystalline basement, forming the great Vindhyan basin[36]. The continuous sinking of the cystalline basement at Katangi resulted in the accumulation of a large thickness [about 5.5 km] of the Precambrian Vindhyan sediments. The crustal block between Katangi and Jabalpur is a horst block. The Narmada-Son lineament appears to be a horst crustal block bounded by deep faults at Katangi and Jabalpur. The normal crystalline basement of velocity 5.9–6.2 km/s is either absent or very thin in the Vindhyan graben as

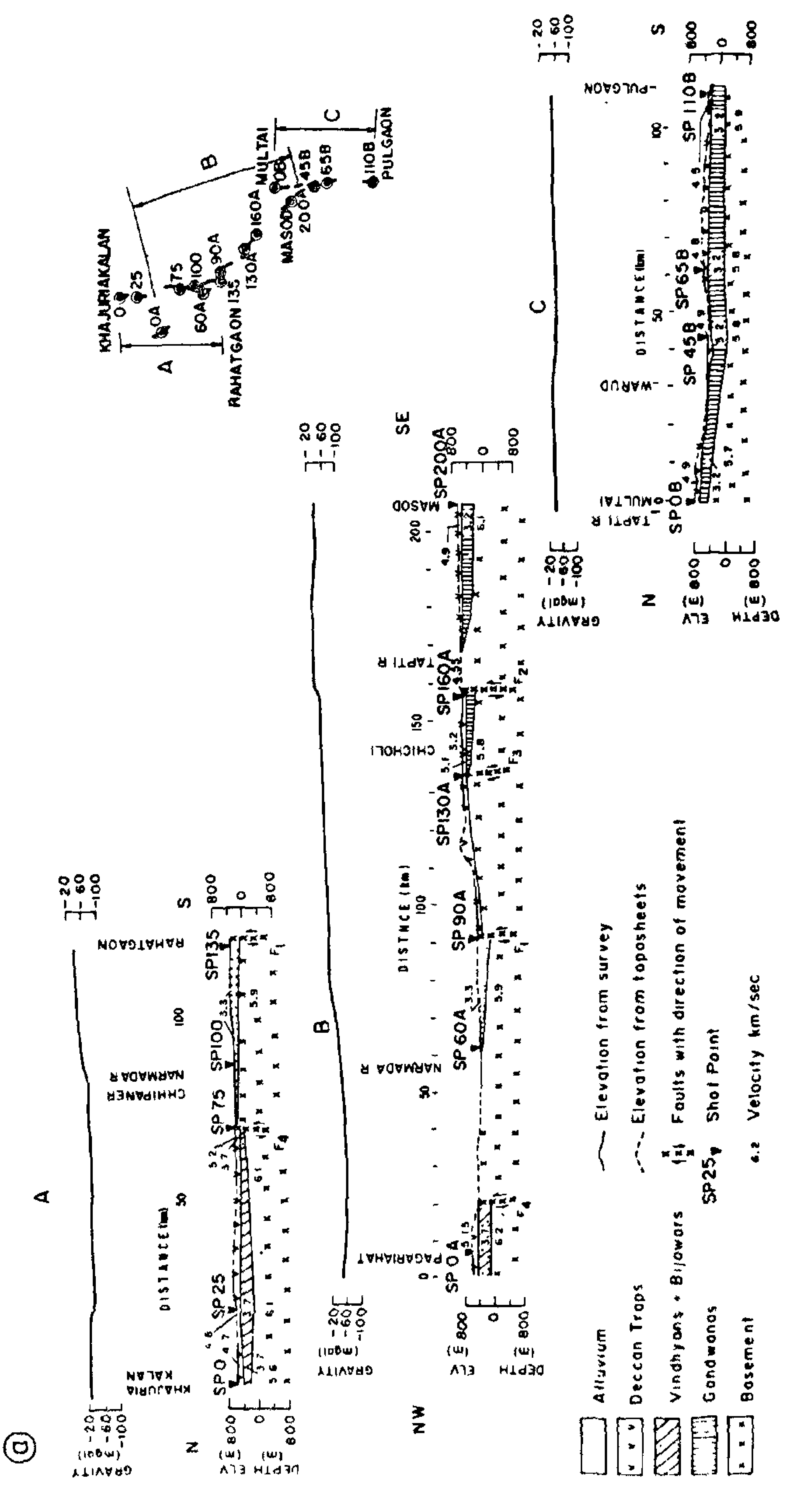

FIGURE 15(a) *Shallow depth sections to the basement level along the three DSS profiles, Khajuria Kalan-Rahatgaon, Pagariahat-Masod, and Multai-Pulgaon, across the Narmada-Son lineament (reproduced from ref. 34).*

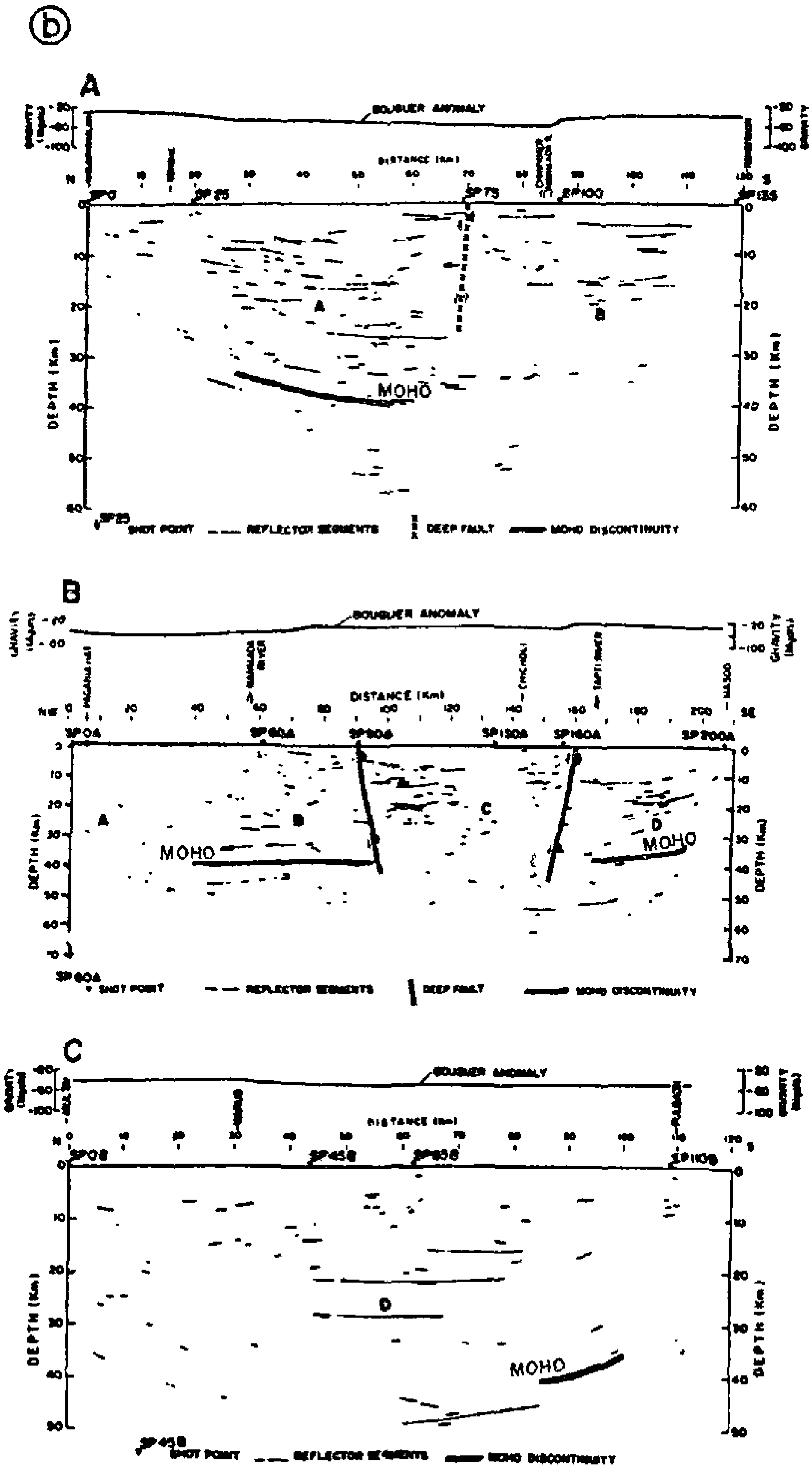

FIGURE 15(b) Crustal depth sections along the three DSS profiles, Khajuria Kalan-Rahatgaon, Pagariahat-Masod, and Multai-Pulgaon, across the Narmada-Son lineament (reproduced from ref. 34).

compared to the normal crust between Jabalpur and Mandla. This suggests 'uplift and erosion' of old basement prior to the deposition of the Vindhyan sediments, indicating that the deep faults are as old as the early Precambrian period. Subsequently, the sediments have been deposited directly on the 6.5 km/s velocity layer, that may correspond to higher grade metamorphic rocks. The Moho boundary is delineated with a velocity of 8.0 km/s in the depth range 39.5–45 km in this region.

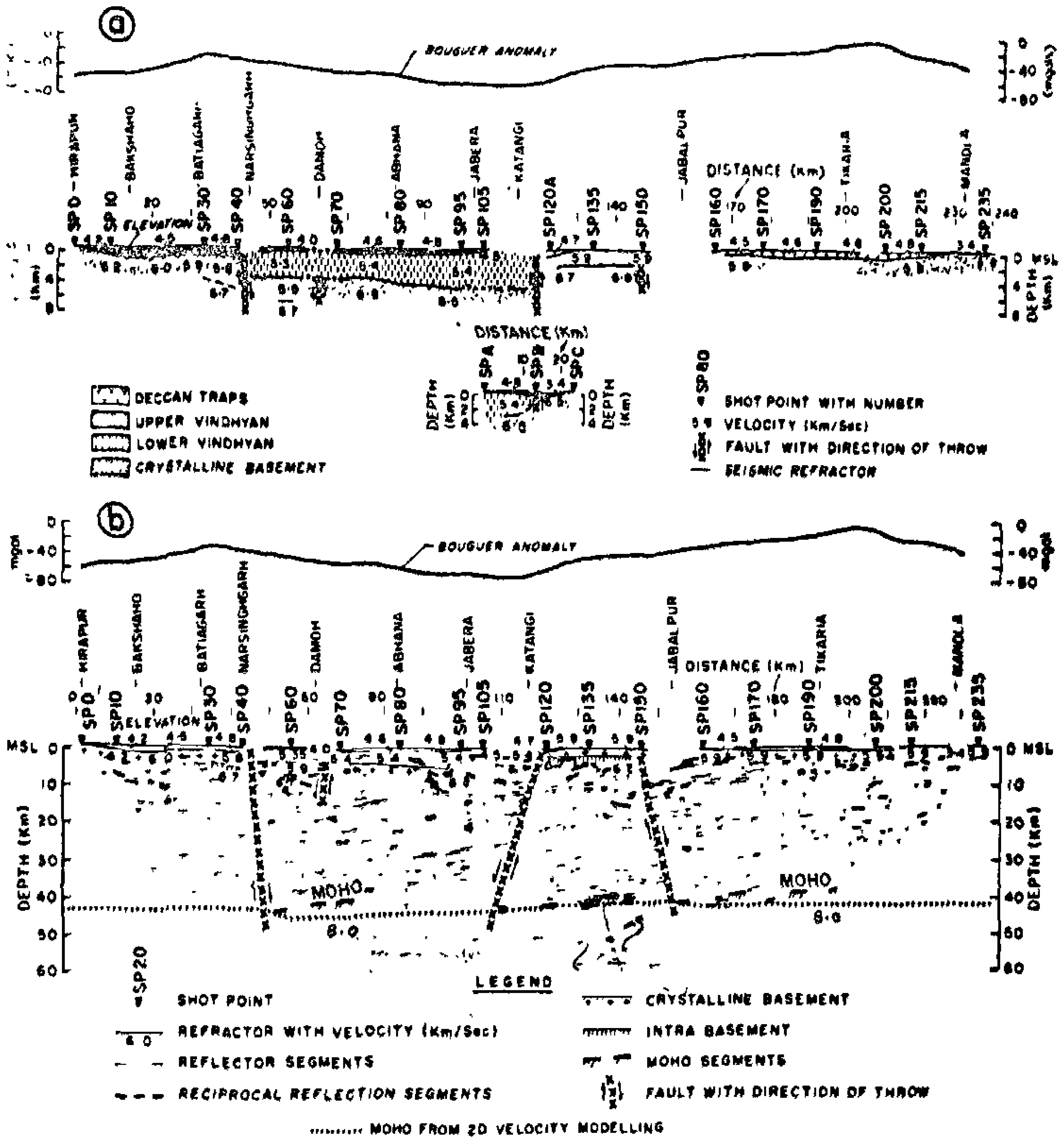

FIGURE 16(a) Shallow depth section to the basement level along the Hirapur-Mandla DSS profile across the Narmada-Son lineament (reproduced from ref. 36). (b) Crustal depth section along the Hirapur-Mandla DSS profile across the Narmada-Son lineament (reproduced from ref. 36).

MAPPING THE THICKNESS OF THE DECCAN TRAP FLOWS AND INFERENCE OF A HIDDEN MESOZOIC BASIN IN THE NARMADA-TAPTI REGION

On the basis of the DSS results obtained along the three profiles: Mehmadabad-Billimora, Ujjain-Mahan and Khajuria Kalan-Pulgaon, a large [200 km × 100 km] WNW-ESE trending 'Tapti graben' consisting of the low velocity [3.2 km/s] Mesozoic sediments, with a maximum thickness of about 1700 m was inferred[38] under a thin Deccan Traps cover [about 400 m, of velocity 5.0 km/s]. Quite separated from the Tapti graben a small Gondwana graben [100 km × 100 km] in the Multai-Pulgaon region consisting of the low velocity [3.2 km/s] Gondwana sediments, with a maximum thickness of about 400 m was also inferred[38] under a thin Deccan Traps cover [about 100 m]. Recently the results pertinent to the shallow and deep crustal structure obtained along eight DSS profiles in the Deccan Traps regions of Koyna, Saurashtra and across the Narmada-Son lineament have been synthesized[39] to map the thickness of the Deccan Traps and infer the extent of the hidden Mesozoic basin beneath the traps. These results are presented in the form of three maps:

- Isopach contour map of the Deccan Traps (figure 17).

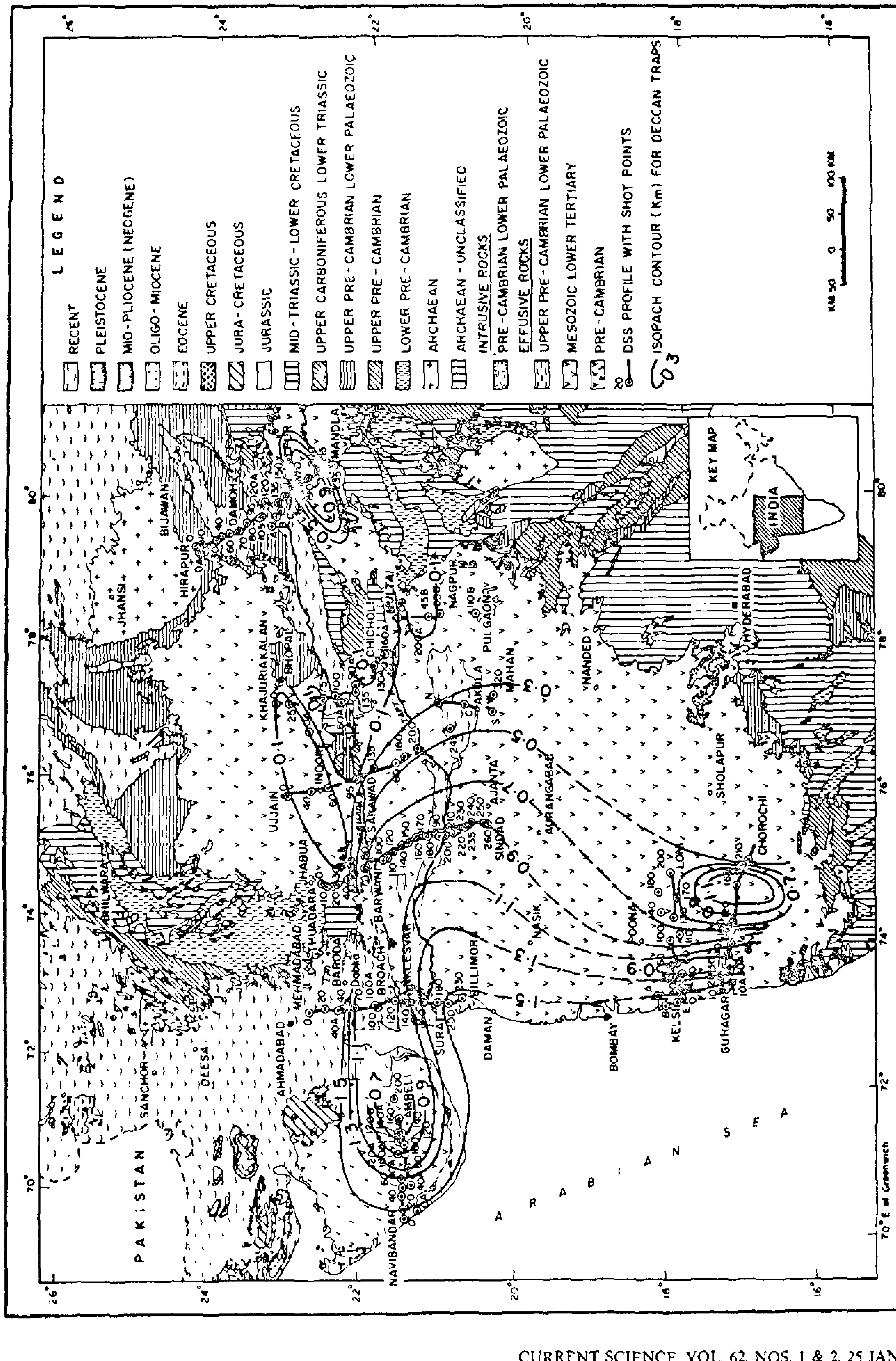

FIGURE 17 Geological map of westcentral India showing *isopach contours for the* Deccan Traps (thickness in km) based on results obtained from the eight DSS profiles in the region (reproduced from ref. 39).

- Isopach contour map of the Mesozoic sediments inferred below the Traps (figure 18),
- a structural contour map of the Moho (figure 19) in the region.

It is found from this study that the Deccan Traps are relatively thin, about 100 m in the northeastern part, and gradually thicken to 1500 m near the west coast. The same thickness is obtained in the southern and western coasts of Saurashtra and in its northern part (figure 17). The presence of a hidden Mesozoic basin is also inferred from this study[39] below the Deccan Traps cover in the Narmada-Tapti region. This basin consists of two grabens separated by a smaller horst (figure 18). The major basin is formed in the southern graben in the Tapti river area which is bounded in the north by an E-W fault. This graben is referred here as the 'Tapti graben' in which the low velocity Mesozoic sediments with a maximum thickness of 1800 m are deposited. The northern graben referred here as the 'Narmada graben' has a maximum sedimentary thickness of about 1000 m. The Mesozoic basin in the Narmada-Tapti area appears to have formed part of a larger Mesozoic sea that extended in an arcuate shape from Sanawad-Mahan through Barwani-Sindad, Ankleswar-Surat, Navibandar-Amreli, Kutch, Rajasthan, Sind and up to Salt range. This Mesozoic sea must have bordered the exposed Vindhyans, Aravallis and the Delhis almost girdling around them in the south, west, and northwest in the form of a horse shoe.

The sediments found to be present beneath the Deccan Traps in the region east of Pulgaon and west of Nagpur are considered to be representing an extension of the Gondwana Godavari graben. This small Gondwana basin in the Multai-Pulgaon region with a maximum sedimentary thickness of 400 m is separated by a hypothetical fault from the large Mesozoic basin towards the west. In the Deccan Traps covered region, the Moho configuration reveals a ENE-WSW trending depression in the central part coinciding with the Narmada-Tapti region (figure 19) where the Moho depth is about 43 km. The sagging of the Moho in this region probably initiated at the time of formation of the Mesozoic basin as well as the Deccan syneclise. The region from Surat to Bombay on the west coast, was characterized by an upwarp of the Moho during the late Cretaceous period probably representing a transition type crust acting as a major source of the Deccan Trap flows that spread across to large distances towards the east, west and south[39]

DSS studies across the Himalaya

An international Pamir-Himalaya project was formulated in 1973 for carrying out detailed geological and geophysical investigations in the Pamir-Himalayan region. As a part of this international geoscientific programme a long-range DSS profile Toktogul-Qarrakol (Karakul)-Zorkol-Nangaparbat (Sangosar)-Srinagar across the Great Pamirs, the Great Karakoram and the Great Himalayas, was selected for studying deep seismic structure in the region. The shot points Qarrakol and Zorkol in the Pamirs were operated by the Soviet scientists and the shot point Nangaparbat in the Himalaya was operated by the Italian and Pakistani scientists. First experimental shots in the Qarrakol lake, USSR, were successfully recorded by the DSS group of NGRI near Srinagar, Kashmir, in 1974. Further recordings followed in 1975 and 1978. Due to limitations of logistics and large source-receiver distances involved in these experiments, the scheme of recordings consisted of only isolated but suitably selected spreads for successful recording of various shots from Qarrakol (5 tons), Zorkol (10 tons) and Nangaparbat (2–3 tons). While continuous and overlapping coverage of the subsurface was not available, the data was however treated along three profiles (figure 20) based on the orientation of lines joining the shot points and the recording spreads near Manasbal lake, Sopur and Tral areas of Kashmir providing discontinuous travel time curves. The NNE-SSW trending profile 1 (Nangaparbat-Sopur) starts near Wular lake and cuts across the Panjal Traps, Dogra slates, black slates and Phyllites with marble intercalations and then traverses the exposed granites, a thick section of basic lava and an alternating exposure of granite and gneiss-migmatites before ending up on the eastern flank of the Nangaparbat massif. The travel times data on the profile 1 is available from the shot point Nangaparbat in the distance range 97–143 km. Subsequently this profile was also extended towards SSW up to Naoshera cutting across the Srinagar and Jammu valleys of Kashmir. The profile from Wular lake to Gulmarg, as well as from Thanamandi to Naoshera was covered by reversed continuous profiling in order to obtain the deeper crustal coverage across the Pir Panjal range. The shallow section to the basement level was however covered both in the Srinagar and the Jammu valleys. The NNW-SSE trending profile 2 (Nangaparbat-Tral) starts near Tral and cuts across the Panjal Traps, black slates and Phyllites, exposed granites, basic lava and reaches the Nangaparbat massif passing through Indus Ophiolites and the Mesozoics. The travel times data on the profile 2 is also available from the shot point Nangaparbat in the distance range 152-188 km. The profile 3 (Qarrakol-Zorkol-Sopur-Tral) has the general alignment of profile 2 and extends in the north up to the Qarrakol lake in the Pamirs. The travel times data on the profile 3 is available from the shot points Qarrakol and Zorkol in the distance ranges 363–388 km, 430–440 km, 529–539 km and 585–596 km.

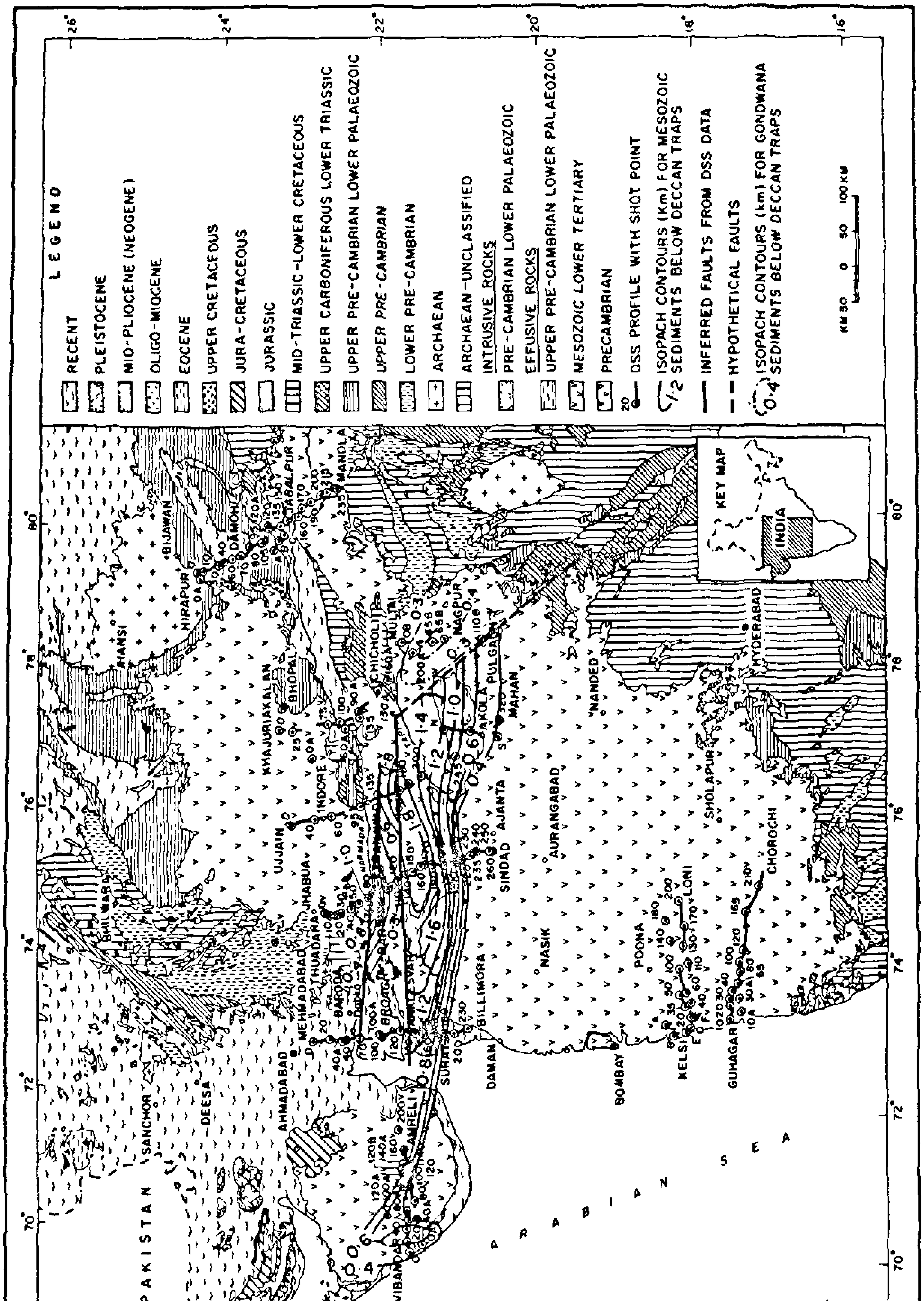

FIGURE 18 Geological map of westcentral India showing isopach contours for the inferred Mesozoics (thickness in km) below the Deccan Traps based on results obtained from the six DSS profiles in the Narmada-Son lineament region (reproduced from ref. 39).

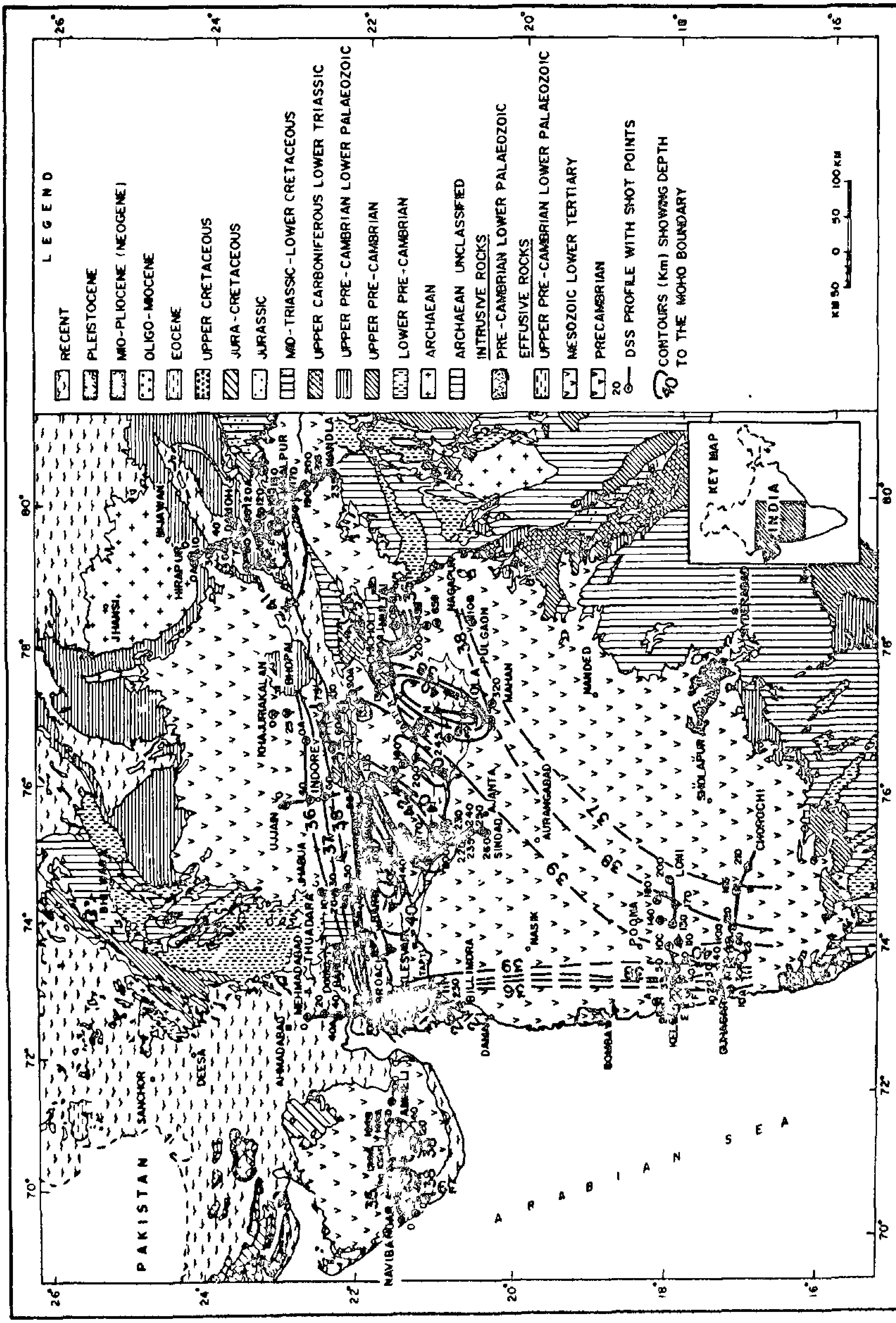

FIGURE 19 Geological map of westcentral India showing structural contour map for the Moho (depth in km) based on results obtained from the eight DSS profiles in the region (reproduced from ref. 39).

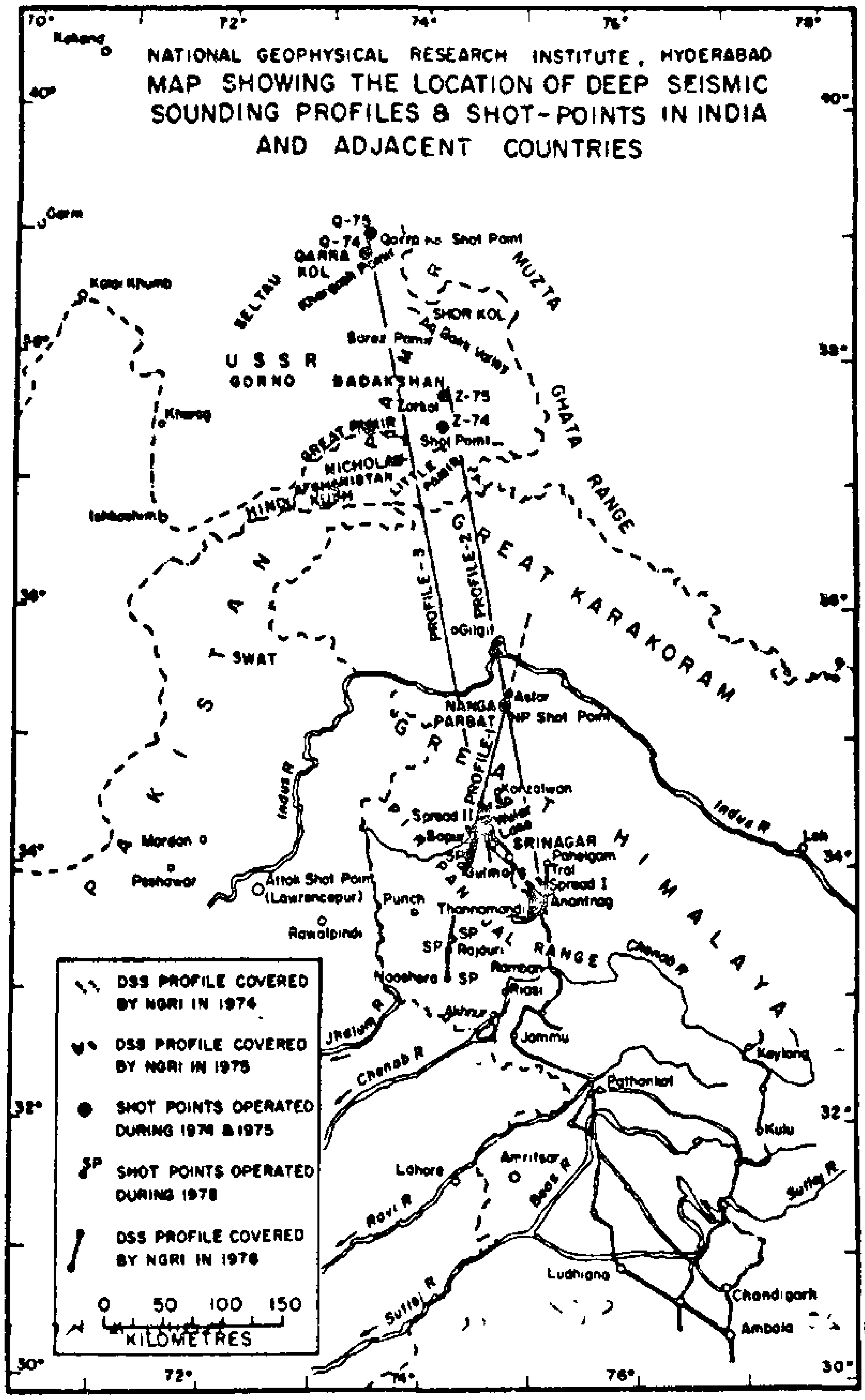

FIGURE 20 Map showing locations of the DSS profiles across the Great Himalayas and shot points operated during 1974, 1975 and 1978 in India, Pakistan and the USSR under the International Pamir-Himalaya project.

The wide-angle reflection data obtained from the shot point Nangaparbat along the profiles 1 and 2 were used[40,41] to derive the velocity-depth function applicable for the Nangaparbat region of the Himalaya. An average depth of about 60 km for the Moho in this region is indicated by the velocity model compared to the average Moho depth of about 40 km in the Indian shield region[1]. The velocity model obtained for the Nangaparbat region was used to invert the wide-angle reflection travel times data into depth sections. The deep crustal depth sections obtained[40,41] along profile 1 (Nangaparbat-Sopur) and profile 2 (Nangaparbat-Tral) are shown in figures 21a and 21b respectively. Along profile 1, between Sopur and Kanzalwan all the reflection boundaries including the Moho show steep dips of 15°–25° towards Kanzalwan in the NNE direction. The Moho rapidly reaches a depth of about 65 km in the region of Kanzalwan. Two intermediate reflection boundaries are also indicated in this section. The sudden steepening of all the reflectors to 25°–35°

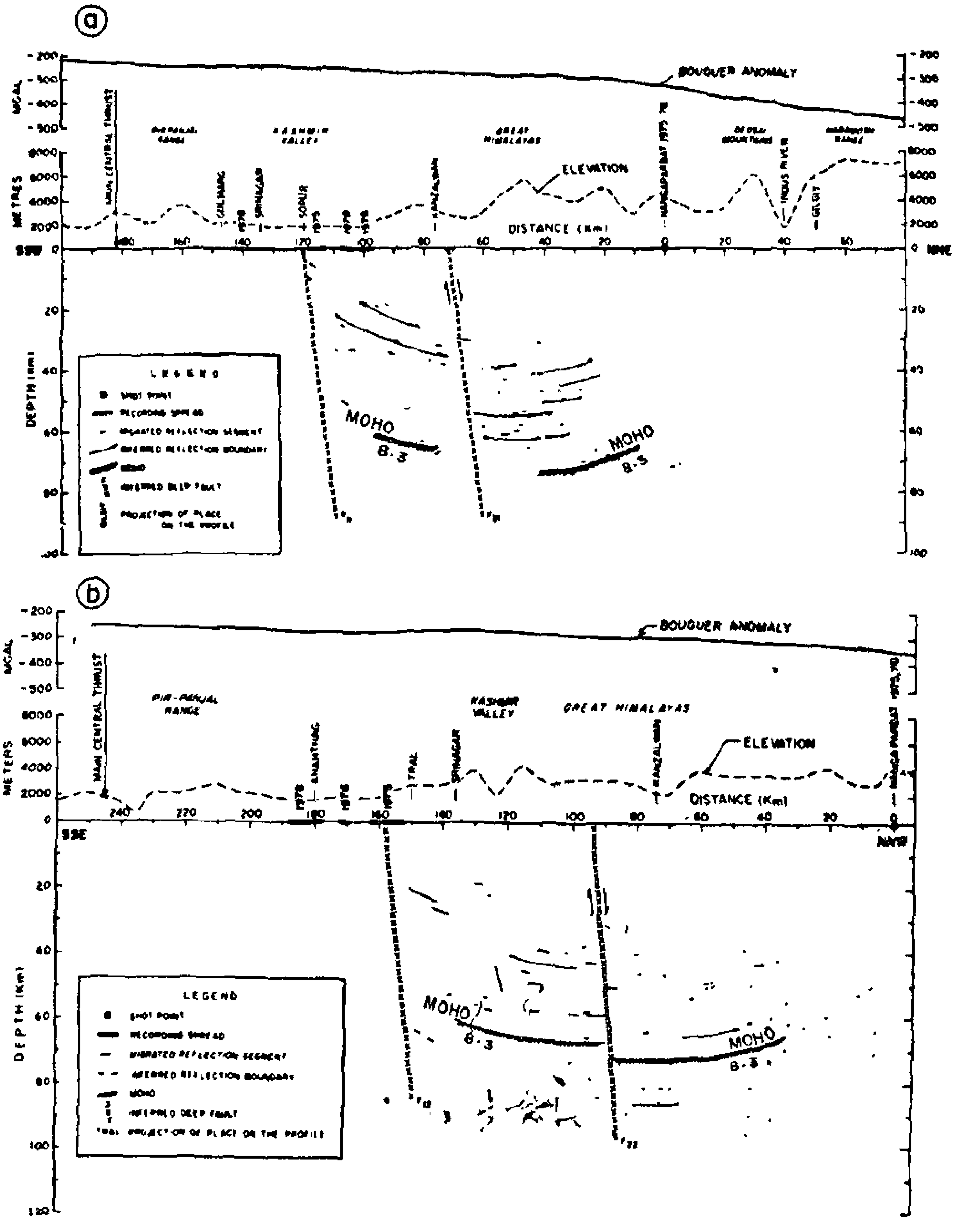

FIGURE 21(a) Deep crustal cross section along the Nangaparbat-Sopur profile across the Great Himalayas based on seismic reflection data from the Nangaparbat shots (reproduced from refs. 40, 41) (b) Deep crustal cross section along the Nangaparbat-Tral profile across the Great Himalayas based on seismic reflection data from the Nangaparbat shots (reproduced from refs. 40, 41).

on the Sopur side indicates a possible faulting (F_{11}). Towards NNE from Kanzalwan the reflection boundaries show a general updip of 10°–20° towards the Nangaparbat massif. The Moho appears to have been displaced due to faulting (F_{21}) by about 6 km, from about 67 km in the SSW block to about 73 km in the NNE block. The Moho rises to about 60 km depth below the Nangaparbat massif due to reversal of the dip in the NNE block (figure 21a). The deep crustal section along profile 2 also reveals similar structural features. At Tral the crustal section reveals an apparent dip towards NNW but appears to be relatively flattened south of Kanzalwan. The relatively large dips of about 25° of various reflection segments near Tral are indicative of a possible faulting (F_{12}). Beyond Kanzalwan towards the Nangaparbat massif in the NNW there appears to be again a reversal of the dip of the Moho and other shallower reflection segments. The

Moho appears to have been displaced due to faulting (F_{22}) by about 5 km along this profile (figure 21b). The Moho which is at a depth of about 60 km north of Srinagar reaches a depth of about 67 km in the flattened region near Kanzalwan. The Moho rises towards the Nangaparbat massif due to a reversal of its dip in the NNW block. The rise of the Moho consistently found on the two profiles, Nangaparbat-Sopur and Nangaparbat-Tral, appears to be related to the uplift of the Nangaparbat massif. The crustal block enclosed by the two profiles seems to be cut up by two almost vertical deep faults running WNW-ESE, and the southern fault may be associated with the intrusive contact of the Panjal Traps in the Srinagar area. The northern fault has displaced the Moho by 5–6 km.

The crustal depth section across the Pir Panjal range of the Himalaya along the Wular lake-Naoshera profile[42], which is a southwestern extension of the Nangaparbat-Sopur profile (profile 1), is shown in figure 21c. The shallow section to the basement level delineated the Srinagar and Jammu synclines each having a maximum sedimentary thickness of about 18 km. In the Srinagar syncline, the thickness of the exposed Karewas of P velocity 2.8 km/s is found in the range 500–1100 m. Under this thin cover of the Karewas, a relatively thick (2.0–3.6 km) section of the Triassic limestones of velocity 4.50–4.65 km/s is found in the Srinagar syncline which may have some hydrocarbons potential like those in the North Sea. The third layer of velocity 5.8 km/s with a thickness of 2.5–3.0 km is inferred to be the Panjal Traps, the observed velocity being also found to be consistent with the laboratory measurements of velocity on samples of the Panjal Traps (5.94 km/s). In the Jammu syncline, the exposed Murrees and middle and lower Siwaliks of velocity 3.8–4.6 km/s seem to have a total thickness of about 3 km near Naoshera overlying the Waishnodevi limestones of velocity 5.5–5.8 km/s. The velocity of 5.8 km/s also corresponds to that in the Panjal Traps in the Srinagar valley. However, in the Jammu valley region huge exposures of the Waishnodevi limestones are extensively found which may as well occur at depths. In the region between Rajauri and the Murree thrust, below the lower Murrees of velocity 3.9 km/s, a 700 m thick layer of Subathus [Nummulites] is inferred that may also have some hydrocarbon potential. The huge thickness of about 18 km of sediments found in the Srinagar and Jammu synclines may imply that the Panjal Traps in the Srinagar valley and the Waishnodevi limestones in the Jammu valley may be underlain by older Palaeozoic sediments like the Dogras and Salkhalas. The deeper crustal section is divided into three major blocks bounded by deep faults. In the southern block the Moho is at a depth of 44 km near the Main Boundary Fault, 57 km under the Pir Panjal range, 51 km near Babarishi and 63–69 km in the region north of Muquam. Under the Great Himalaya, the Moho rises from its deepest depth of 78 km to 67 km below the Nangaparbat massif (figure 21c).

The deep structure of the upper mantle delineated across the international profile Qarrakol-Zorkol-Sopur-Tral is shown in figure 21d. Along this profile the primary reflection data from the Moho boundary could not be recorded due to the relatively large source-receiver distances involved for recording the Qarrakol and Zorkol shots. This is also consistent with the findings that the velocity model determined for the Himalaya region theoretically predicts the Moho reflections to a maximum distance of only about 370 km. The strong arrivals identified on these long distance records along this profile possibly correspond to reflections from prominent interfaces in the upper mantle. The deep reflection data on this profile thus reveal presence of two broad zones of reflector segments at depth ranges of 150–180 km and 340–365 km, extending laterally over 200–300 km distance across the Great Himalayas, Karakoram and Pamir ranges. The shallow reflector in the upper mantle at 150–180 km depth may represent the top while the deeper reflector at 340–365 km depth may be associated with the bottom of the Asthenosphere layer in this region[40,41].

Based on the deep seismic sounding results and the seismotectonic studies in the Himalaya it was postulated[43] that the Himalayas were formed due to block uplift against steep angle faults rather than due to a widely believed continental collision mechanism that envisages underthrusting of the Indian shield under Tibet to build up a large crustal thickness found in the region. The large crustal thickness in the Trans Himalaya-Tibet region may possibly be due to normal processes of crustal formation and the excess overloading might be the cause of structural failure in the Himalayas which were eventually uplifted[43]. It was also further postulated[43,44], on the basis of the DSS and seismotectonic studies in this region, that the northern boundary of the Indian plate falls very much to the north of the Main Central Thrust in the Himalaya, the Indus Suture line and even the combined Indo-Tibetan block, coinciding with the southern margin of the Tien Shan-Nan Shan mobile fold belt, passing south of the Ordos and Shanshi blocks finally turning northeastwards.

DSS STUDIES IN THE WEST BENGAL BASIN

Recently during the period from 1987 to 1990, detailed DSS profiling experiments have been conducted in the West Bengal basin along three E-W profiles:

- Beliator-Bangaon,

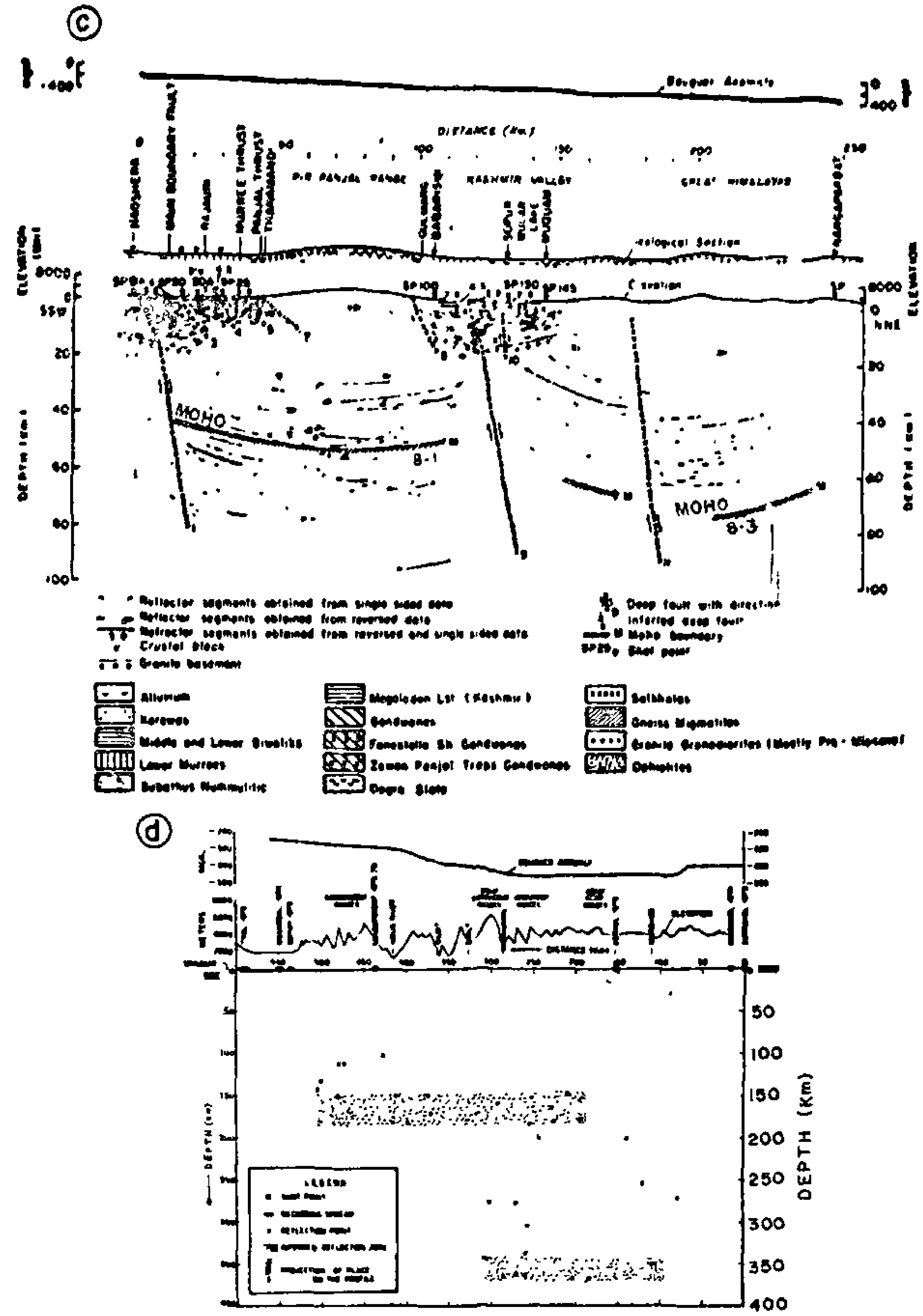

FIGURE 21(c) Crustal depth section along the Wular lake-Gulmarg-Thanamandi-Naoshera DSS profile revealing the Srinagar and Jammu synclines and the deep crustal structure across the Pir Panjal range and the Great Himalayas (reproduced from ref. 42). ☐ (d) Upper mantle depth cross section along the International profile Qarrakol-Zorkol-Sopur-Tral across the Pamir-Himalaya region revealing deep reflector zones at depths of 150–180 km and 340–365 km inferred as the top and bottom of the Asthenospheric layer in the region (reproduced from ref. 41).

- Gopali-Port Canning,
- Arambag-Taki,

and an intersecting N-S profile Bishnupur-Kandi (figure 1). Seismic refraction and wide-angle reflection data have been acquired with two 60 channel DFS-V systems at 4 ms sampling using explosives source with shot points spacing of about 10 km and geophone interval of 80 m. The large number of closely spaced shot points with reversed and overlapping coverage of the profiles provide sufficient data redundancy to map the sedimentary basin structure and the relatively deep (8–10 km) basement configuration as well as the deep crustal structure and the Moho configuration in the region[45,46]. The inference of a relatively low velocity layer (3.8–4.0 km/s) of Gondwana sediments underlying the higher velocity layer (4.6–4.7 km/s) of the Rajmahal Traps is of particular interest to the ONGC who have sponsored the DSS studies in this region. The deep crustal structure and the Moho configuration inferred by the DSS studies suggest the 'continental' type of crust in the West Bengal basin. Coincident deep seismic reflection profiling along a 30 km line on the N-S profile resolved the sedimentary section, underlying basement and the Moho remarkably well, consistent with the wide-angle reflection data, besides revealing for the first time the deep crustal reflectivity structure in this region.

Research and Development Activity

Concurrent with the extensive DSS profiling experiments in a variety of geologically significant regions in India, efficient computational methods and software are developed particularly suitable for seismic wide-angle reflection/refraction data processing, modeling and interpretation. A computerized method is developed[47] for finding effective velocity at the depth of common reflection point, the reflector dip and its migrated position from the analysis of a pair of direct and reversed reflection travel time curves. The significant property of convergence of perpendicular distance of a dipping reflector to the shot point for any assumed reflector dip, makes it possible to scan through a wide range of dips by an iterative process until the velocities computed by the direct and reversed travel times data agree within the required tolerance limit which then yields the appropriate effective velocity to the depth of the common reflection point. The corresponding dip also determines an optimum migrated reflector position consistent with the reversed travel times data. This method has extensively been used for obtaining velocity-depth functions for most of the regions covered by DSS profiling in India. Based on this concept of effective velocity an analytical method is further developed[48] to construct the deep crustal sections by migration of single-sided wide-angle reflection data. The migration process is found to be extremely rapid by this method as the curved ray paths are successfully replaced by equivalent straight ray paths. However, a post-migration sliding correction is found to be necessary that arises due to non-collinearity of the recording point, reflection point and the image point of the source. Migration of wide-angle reflection data along most of the DSS profiles has efficiently been carried out on high speed computers by this method yielding interpretable depth sections of deep crustal structures.

In order to delineate the shallow low velocity layers (LVL), particularly the subtrappean sedimentary layers discovered along several DSS profiles an indirect seismic method based on statistical criteria is developed[49] by a joint analysis of seismic reflection and refraction data. The thicknesses of both overlying high velocity and underlying low velocity layers can be estimated reliably in regions where the velocity in the LVL is accurately known from nearby exposures or the drill holes. In the absence of reliable velocity estimates of the LVL, however, upper limits of both the velocity and the thickness of the LVL can be inferred by this method. The subtrappean sedimentary structures in various regions have been inferred by application of this indirect method. Approaches to solution of the hidden layer problems in seismic refraction prospecting have also been proposed[50,51] based on interpretations of later arriving refraction and wide-angle reflection phases. Forward modeling of large amplitude wide-angle reflection data corresponding to the hidden layers contributes to reliable interpretation of seismic refraction data by providing hidden layer parameters, as demonstrated by delineation of the hidden Deccan Traps layer underlying the Tertiary sedimentary section in parts of the Cambay basin[31,51]. In order to refine the velocity-depth models of the crust and the subcrustal lithosphere by application of modern data processing techniques and synthetic seismogram modeling, a viable approach has successfully been developed[21] to digitize the analog DSS field records and display the record sections with reduction velocity and amplitudes normalization. New models of the crustal and subcrustal velocity structure have been obtained[22,23] in the Koyna region by digitization and synthetic seismogram modeling of the record sections. Efficient software packages have also been developed for processing digital wide-angle reflection data acquired by the DFS-V systems, as well as for modeling of crustal seismic record sections.

Concluding Remarks

Extensive DSS profiling experiments have been conducted by acquiring seismic refraction and wide-angle reflection data in a variety of geological settings in India. A wide range of geologically significant problems have been addressed by these datasets: notably delineation of subtrappean sedimentary structures and basement configuration, formation and evolution of sedimentary basins, deep crustal structure and tectonic framework depicting fault controlled crustal blocks (terranes) extending down to the Moho, in the south Indian shield, across the Narmada-Son lineament and the Great Himalaya. The DSS datasets in the wide-angle range have also yielded velocity-depth models of the Indian continental crust in various regions, revealing presence of low velocity layers, transitional nature of the Moho and other intracrustal boundaries, providing a unique geophysical framework to understand the rheological structure and intracontinental seismicity particularly in the Koyna region. Further insight to the brittle/ductile regimes of the continental crust and the subcrustal lithosphere can be obtained by seismic imaging of the reflectivity structure by deep seismic reflection profiling and common depth point (CDP) stacking of near-vertical incidence reflection data extending to 15–20 s two way times. Experimental reflection profiling and CDP stacking in the West Bengal basin, conducted for the first time in the Indian region, revealed encouraging results of the deep seismic image of the crustal lithosphere, consistent with the coincident wide-angle reflection data to the Moho depths. In order to study the complex structure and evolution of the Proterozoic basins, the underlying Archaean basement and the deep structure in the region, a 400 km long profile from Nagaur-Ajmer-Kota-Jhalawar across the Aravallis is planned to be covered essentially by CDP reflection profiling. Coincident wide-angle reflection/refraction profiling on selected parts of this CDP reflection profile will also be covered for consistent interpretation of the datasets. Long-range refraction profiling experiments should be conducted out to about 1000 km range by deploying high dynamic range three-component digital stand-alone recording systems to study the seismic anisotropy and fine structure of the Indian continental crust and the subcrustal lithosphere.

REFERENCES

1. Kaila, K. L. *et al.*, *J. Geol. Soc. India*, 1979, **20**, 307.
2. Kaila, K. L. *et al.*, in *Developments in Solid Earth Geophysics and Geodynamics*, 25th Int. Geol. Cong., Sydney, 1976, **2**, 368.
3. Kaila, K. L. *et al.*, *Tectonophysics*, 1987, **140**, 1.
4. King, W., *Mem. Geol. Surv. India*, 1872, **8**, 1.
5. Narayanaswami, S., *J. Geol. Soc. India*, 1966, **7**, 33.
6. Krishna, V. G., Kaila, K. L., Rao, G. S. P. and Reddy, P. R., in *Fourth International Symposium on Deep Seismic Reflection Profiling of the Continental Lithosphere, Bayreuth, FRG, TERRA Abstracts*, **2**, 50.
7. Kaila, K. L. and Bhatia, S. C., *Tectonophysics*, 1981, **79**, 129.
8. Kaila, K. L. and Tewari, H. C., *Tectonophysics*, 1985, **115**, 69.
9. Pichamuthu, C. S., *Curr. Sci.*, 1951, **20**, 117.
10. Nautiyal, S. P., Presidential Address, Geol. and Geogr. Sec., Indian Science Congress, 1966, Session 53, 107.
11. Radhakrishna, B. P., *J. Geol. Soc. India*, 1968, **8**, 102.
12. Srinivasan, R. and Sreenivas, B. L., *J. Geol. Soc. India*, 1972, **13**, 75.
13. Radhakrishna, B. P. and Vasudev, V. N., *J. Geol. Soc. India*, 1977, **18**, 525.
14. Swaminath, J., Ramakrishnan, M. and Viswanatha, M. N., *Rec. Geol. Surv. India*, 1976, **107**, 149.
15. Ramakrishnan, M., Viswanatha, M. N. and Swaminath, J., *J. Geol. Soc. India*, 1976, **17**, 97.
16. Srinivasan, R. and Sreenivas, B. L., *J. Geol. Soc. India*, 1977, **18**, 589.
17. Kaila, K. L., Murty, P. R. K., Rao, V. K. and Venkateswarlu, N., *Tectonophysics*, 1990, **173**, 307.
18. Kaila, K. L., Tewari, H. C. and Mall, D. M., *J. Geol. Soc. India*, 1987, **29**, 293.
19. Kaila, K. L., Reddy, P. R., Dixit, M. M. and Lazarenko, M. A., *J. Geol. Soc. India*, 1981, **22**, 1.
20. Kaila, K. L., Murty, P. R. K., Rao, V. K. and Kharetchko, G. E., *Tectonophysics*, 1981, **73**, 365.
21. Krishna, V. G. and Kaila, K. L., in *Deep Seismic Soundings and Crustal Tectonics*, 1986, *AEG*, 99.
22. Krishna, V. G., Kaila, K. L. and Reddy, P. R., in *Properties and Processes of the Earth's lower crust*, AGU Geophys. Monogr. **51**, IUGG 6, 1989, 143.
23. Krishna, V. G., Kaila, K. L. and Reddy, P. R., *Phys. Earth and Planet Inter.*, 1991, **67**, 288.
24. Kaila, K. L., Tewari, H. C. and Sarma, P. L. N., *Mem. Geol. Soc. India*, 1980, **3**, 218.
25. Auden, J. B., *Natl. Inst. Sci. India*, 1949, **15**, 315.
26. West, W. D., *Curr. Sci.*, 1962, **31**, 143.
27. Kaila, K. L., Gaur, V. K. and Narain, H., *Bull. Seismol. Soc. Am.*, 1972, **62**, 1119.
28. Tandon, A. N. and Chowdhury, H. M., *Indian J. Power River Val. Dev.*, Symposium on Koyna earthquake.
29. Duncan, R. A. and Pyle, D. G., in *Deccan Flood Basalts, Mem. Geol. Soc. India*, 1988, **10**, 1.
30. Kaila, K. L., Krishna, V. G. and Mall, D. M., *Tectonophysics*, 1981, **76**, 99.
31. Kaila, K. L. *et al*, *Geophys. J. Int.*, 1990, **103**, 621.
32. Kaila, K. L., Rao, I. B. P., Rao, P. K., Madhava Rao, N., Krishna, V. G. and Sridhar, A. R., in *Properties and processes of the Earth's Lower Crust*, 1989, AGU Geophys. Monogr. **51**, IUGG **6**, 127.
33. Kaila, K. L., Reddy, P. R., Dixit, M. M. and Rao, P. K., *J. Geol. Soc. India*, 1985, **26**, 465.
34. Kaila, K. L. and Rao, P. K., in *Deep Seismic Soundings and Crustal Tectonics*, 1986, AEG, 43.
35. Kaila, K. L., Murty, P. R. K., Mall, D. M., Dixit, M. M. and Sarkar, D., *Geophys. J. R. Astron. Soc.*, 1987, **89**, 399.
36. Kaila, K. L., Murthy, P. R. K. and Mall, D. M., *Tectonophysics*, 1989, **162**, 277.
37. Pascoe, E. H., *Manual of Geology of India and Burma II*, Govt. of India Publ., Calcutta, 1959.
38. Kaila, K. L., in *Reflection Seismology: A Global Perspective*, AGU Geodynamics Series, 1986, **13**, 133.
39. Kaila, K. L., *Mem. Geol. Soc. India*, 1988, **10**, 91.
40. Kaila, K. L., Krishna, V. G., Roy Chowdhury, K. and Narain H., *J. Geol. Soc. India*, 1978, **19**, 1.
41. Kaila, K. L., Roy Chowdhury, K., Krishna, V. G., Dixit, M. M. and Narain H., *Boll. Geofis. Teor. Appl.*, 1983, **XXV**, 221.
42. Kaila, K. L., Tripathi, K. M. and Dixit, M. M., *J. Geol. Soc. India*, 1984, **25**, 706.
43. Kaila, K. L. and Narain, H., in *Himalayan Geology Seminar: Structure, Tectonics, Seismicity and Evolution*, 1976, **Sec. II**, 1.
44. Kaila, K. L., in *Zagros, Hindukush, Himalaya Geodynamic Evolution*, AGU Geodynamics Series, 1981 **3**, 272.
45. Kaila, K. L. *et al.*, in *Fourth International Symposium on Deep Seismic Reflection Profiling of the Continental Lithosphere, Bayreuth, FRG, TERRA Abstracts*, **2**, 17.
46. Kaila, K. L. *et al.*, in *XX General Assembly*, IUGG, Vienna, 1991.
47. Kaila, K. L. and Krishna, V. G., *Geophysics*, 1979, **44**, 1064.
48. Kaila, K. L., Roy Chowdhury, K. and Krishna, V. G., *Stud. Geophys. Geod.*, 1982, **26**, 254.
49. Kaila, K. L., Tewari, H. C. and Krishna, V. G., *Geophysics*, 1981, **46**, 1003.
50. Kaila, K. L. and Narain, H., *Geophysics*, 1970, **35**, 613.

51. Sarkar, D., Tewari, H. C., Dixit, M. M. and Kaila, K. L., *Geophysics*, 1991, **56**, 302.
52. Kailasam, L. N., Murty, B. G. K. and Chayanulu, A. Y. S. R., *Curr. Sci.*, 1972, **41**, 403.
53. Rastogi, B. K., Sarma, C. S. P., Chadha, R. K. and Kumar, N., *NGRI Tech. Rept.*, 1985.
54. Mueller, S., in *The Earth's Crust*, AGU Geophys. Monogr., 1977, **20**, 289.
55. Bankwitz, P., Bankwitz, E. and Grunthal, *Gerlands Beitr. Geophys.*, 1985, **94**, 294.
56. Knothe, D. H., Deutsche Demokratische Republik, *NKGG Geodat. Geophys. Veroff.*, 1972, **27**, 59.

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