Crustal structure of Peninsular Shield, India from DSS studies

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Deep Seismic Sounding (DSS) investigations have been carried out in the Indian Peninsula, mainly using the refraction and wide-angle reflection techniques. Since 1972, about 22 DSS profiles totalling more than 5000 km in length have been covered. Contours prepared for depth to Moho boundary, show large variations in the depth to the Moho surface emphasizing conspicuous lateral variations of the structure. The Moho boundary is deep (44 km) in the north-western part of the country especially in the region of Aravalli Fold Belt. Similarly, except for the coastal regions, the crust is also thick in the southern parts of the Peninsular Shield (37–45 km). The crust seems to become thinner (24 km) towards the northern parts of the west coast. Compared to the west, the crust towards the east coast seems to be either normal or thicker except for the prominent doming-up at the eastern flank of the West Bengal basin. However, it is relevant to state that absence of deep crustal information of the southern parts of the east and west coasts restricts the above statement to the region north of 15°N latitude. The average crustal thickness in the Dharwar Craton is 35 km, whereas the crustal thickness in the Proterozoic Cuddapah basin is about 40–43 km, with the maximum at its eastern margin. The large thickness of the Tertiary sediments in the Cambay Basin and relatively thin crust in the region suggest further rifting during the Tertiary. The region on the west coast is also characterized by an upwarp in the Moho during the Late Cretaceous period, probably representing a transitional crust and a major source for the Deccan Trap flows. Interpretation of the crustal structure in terms of geological and geochronogical setting and the inferred crustal composition, deep depressions in this prominent boundary associated with faults/fracture zones are presented along with the variations in the velocity structure; an input that can help in better understanding of the structure and tectonics.

SEISMIC refraction/wide-angle experiments are capable of resolving deep continental structures and provide a means of inferring relationships between the surface geology and the underlying crust. Extensive DSS experiments have been conducted by the National Geophysical Research Institute (NGRI), India in various parts of the Indian Peninsular Shield[1].

Peninsular India constitutes one of the prominent dominantly Precambrian Shield areas of the world. The geology and tectonics of India are very complex. It records a history of crustal evolution from an Archaean core to active continent–continent collision. Knowledge of the regional crustal structure is important to address various geodynamic problems as well as to help in better understanding the lateral variations in the seismicity patterns. Since 1972, about 22 DSS profiles totalling more than 5000 km in length have been acquired mainly using refraction and wide-angle reflection techniques (Figure 1). We provide a broad overview of the crustal structure of the Indian continental region, with special reference to the Peninsular Shield, bringing into focus conspicuous structural and evolutionary signatures in different geological settings.

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Through this exercise we wish to arrive at a picture, depicting lateral variations in the Moho configuration – an information of importance from tectonics and geodynamics. Our main aim is to have the knowledge of the crustal thickness and depth to the Moho in different parts of the country which can be taken as an important parameter to have an insight into the crustal dynamics. Coincident seismic reflection/refraction experiments provide complimentary insights into the structure, composition and evolution of the continental lithosphere. However, it is pertinent to point out that nature of the Moho, viz. whether it is a first-order discontinuity or a transition zone could be known only by imaging crust through reflection seismics and this information now being generated in different parts of the shield is not included in this review.

Geology and tectonics of India

For geological considerations, the Indian sub-continent (about 3.2 million sq km in area) is divided into three major units: (1) The Peninsular Shield, (2) Indo-Gangetic Basin (IGB), and (3) The Himalayas. Each of these is characterized by distinctive geomorphic,

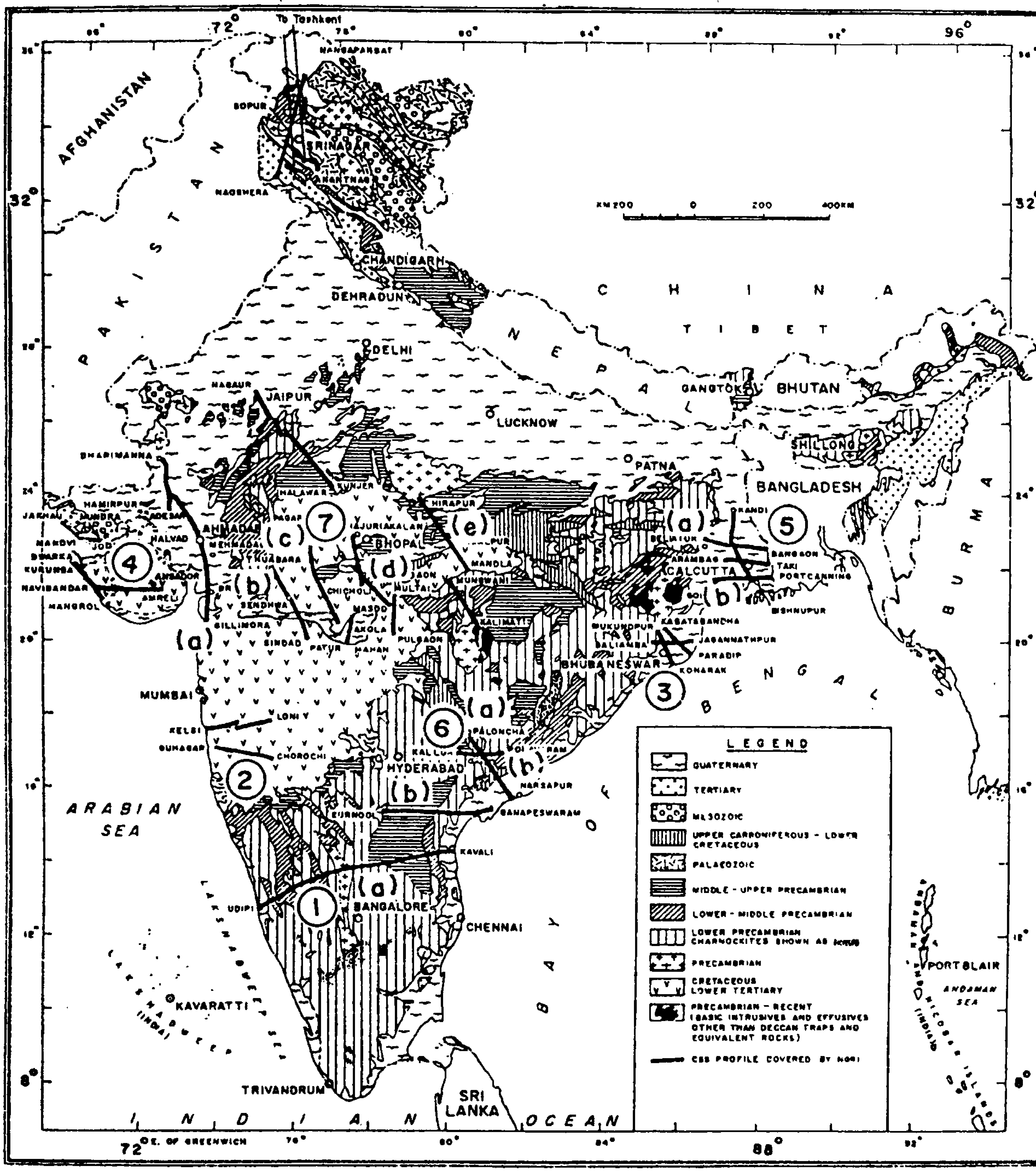


Figure 1. Geological map of India showing location of the DSS profiles.

structural, stratigraphic and deep crustal structures[2]. While the Himalayas is a region of dominant compressional tectonics and IGB is a region of relatively less eventful recent sedimentation, the Peninsular Shield, in contrast, is a region marked by early Archaean cratonization with associated mobile belts. The crustal evolution of the region underlain by the Precambrian formations, which make up nearly two-thirds of the Peninsula, is still shrouded in uncertainties resulting in speculative modelling.

The tectonic evolution of the Indian continental crust has been viewed in two main stages, geosynclinal and platformal. Age of folding as a culmination of the geosynclinal stage of evolution, as is widely accepted, is taken as the main criterion in outlining the major tectonic divisions of India. Three major cycles of folding have been distinguished: Archaean, Proterozoic and Cenozoic. The platform stage of evolution begins with the consolidation of the geo-synclinal area with the basement of the platform. The Indian platform is characterized by the folded basement of Archaean and Proterozoic rocks. Major temporal domains in the development of the continental crust in the Indian Peninsular Shield are: the Archaean, Dharwar, Singhbhum, Rajasthan – Bundelkhand and Bastar cratons and the dominantly Proterozoic South Indian, Eastern Ghat, Satpura mobile belts. The great sedimentary basins (Cuddapah, Vindhyan and Pakhal), Gondwana basins, Tertiary basins and Deccan and Rajmahal volcanics[3,4] are largely platformal.

Crustal structure of India

Acquisition and processing

Significant results pertaining to the shallow and deep structural features of the Indian continental crustal structure have been well investigated with DSS profiles, located in different parts of the continent. Table 1 provides a summary of these 22 profiles. Data quality in terms of signal-to-noise ratio is generally good. Before 1985, a travel-time inversion technique was used to process the refraction and wide-angle reflection data. This was mainly due to the availability of seismic data in the form of analog records. With the introduction of digital recording systems, data processing and interpretation involved either one- or two-dimensional modelling of both the seismic travel times and amplitudes. Two-dimensional forward ray tracing modelling was carried out after preliminary one-dimensional modelling[5]. The sensitivity of the model is the highest in the uppermost 10 km, where data on density are generally adequate. More uncertainty exists for the velocity of the lower crust, as this has been mostly inferred from secondary arrivals. In view of the poorly constrained lower crustal structure, the precision of the modelled lower crustal velocity is probably not better than 0.1 to 0.2 km/s. In view of the comparatively greater number of errors in lower crustal velocity coupled with the absence of head waves from the Moho, a maximum of 2 km uncertainty in the Moho depth may be expected. This precision is quite satisfactory for the present data set, although the dipping geometry is unlikely to be affected by this. Even in our case, as suggested by Mooney[6], uncertainties introduced by the interpretive step of phase correlation are usually much larger than the quantifiable uncertainties.

Moho contour map

According to White[7], the nature of the crust–mantle boundary, a fundamental crustal feature, has interested seismologists for a long time. The Moho was originally recognized using wide-angle seismic arrivals from the upper mantle, so the term 'Moho' is preferred for the seismically determined depth to the upper mantle using wide-angle data[8]. The map of crustal thickness or Moho contour map (Figure 2) is the first completed contour map of the crustal thickness of the Peninsular Shield of the Indian continent (especially south of lat. 24°E based on DSS data). A previous crustal thickness map by Mahadevan[2] has been largely based on gravity, magnetic, geoelectrical, teleseismic and few seismic inputs. Kaila[9] prepared a contour map but used data from only eight profiles located in the Koyna region, Saurastra, and across the Narmada–Son lineament (NSL). Qureshy[10] prepared an approximate crustal thickness map based on the relationship between Bouguer anomaly and elevation. The contour map presented in this paper clearly defines lateral depth variations. The velocity–depth details (Figure 3) provide supplementary inputs.

Table 1. Brief description of the profiles

Region/ profile name	Direction	Ref.	Crustal thickness (km)	Pn velocity (km/s)
Cuddapah basin			34–40	
a) Kavali–Udipi	(E–W)	17, 19		8.4–8.6
b) Alampur–Ganapeswaram	(W–E)	28		8.5
Koyna region			36–40	8.25
a) Guhagar–Chorochi	(W–E)	18		
b) Kelsi–Loni	(W–E)	29		
Mahanadi basin		30	34.5	8.1
a) Konark–Mukundpur	(S–N)			
b) Baliamba–Jagannathpur	(W–E)			
c) Paradip–Kabatbandha	(S–N)			
Cambay basin			31–42	
a) Navibandar–Amreli	(W–E)	31		8.05
b) Dharimanna–Degam	(N–S)	16		8.0–8.1
Bengal basin		32		8.1
a) Beliator–Bangaon	(W–E)			
b) Gopali–Port Canning	(W–E)			
c) Taki–Arambagh	(W–E)			
d) Bishnupur–Kandi	(S–N)			
Godavari region		33	41–43	8.1
a) Kallur–Polavaram	(W–E)			
b) Paloncha–Narsapur	(SE–NW)			
Across Narmada–Son Lineament			25–45	
a) Mehmadabad–Billimora	(N–S)	34		8.1–8.2
b) Thuadara–Sindad	(N–S)	35		8.2
c) Ujjain–Mahan	(N–S)	36		7.8–7.9
d) Khajuriakalan–Pulgaon	(N–S)	37		8.05
e) Hirapur–Mandla	(N–S)	38		7.9
Central India		39	38–42	
Mungawani–Kalimati	(NW–SE)			
Himalayan region		40	61–73	
Nangaparbat–Sopur	(NNE–SSW)			

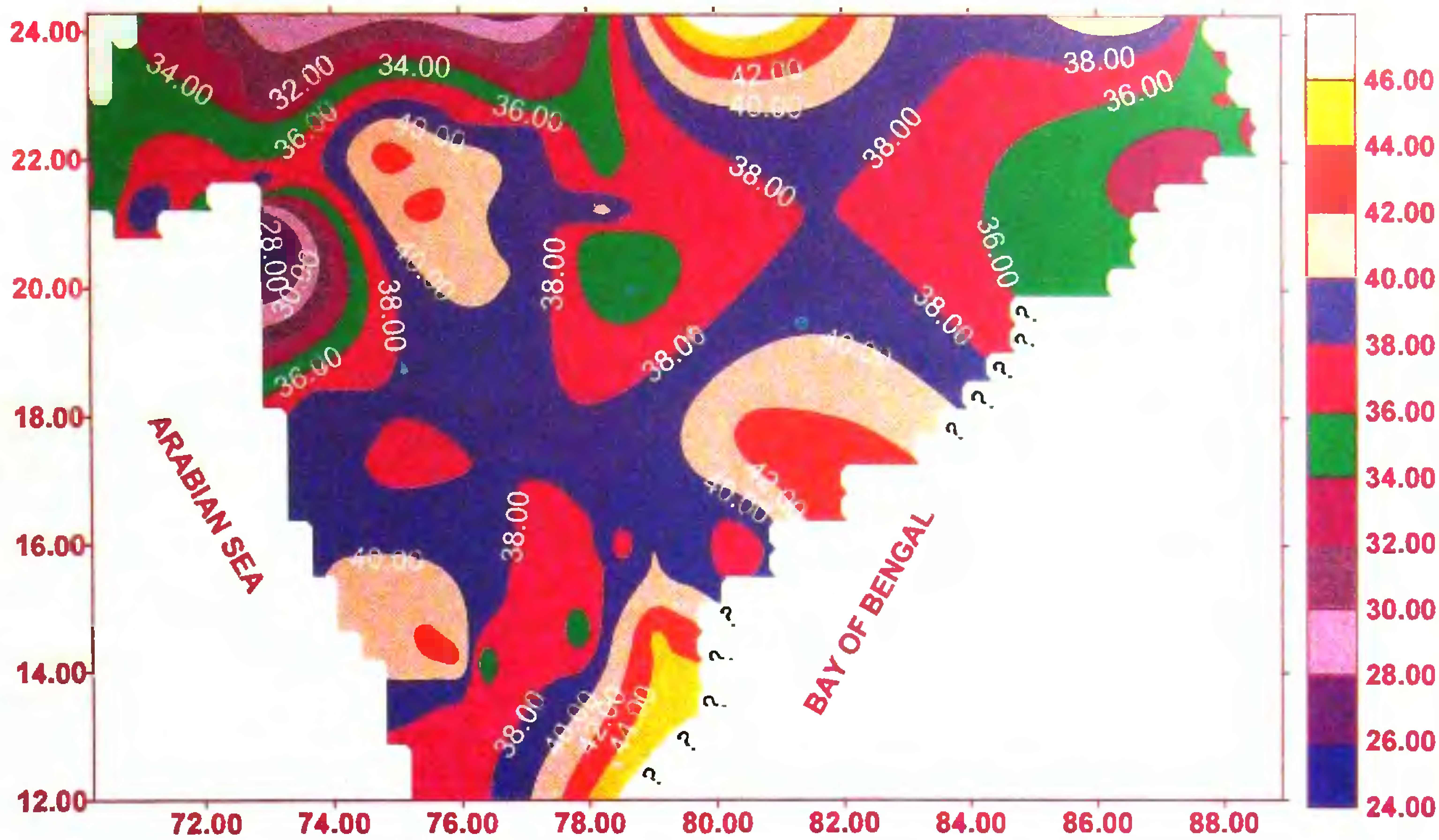
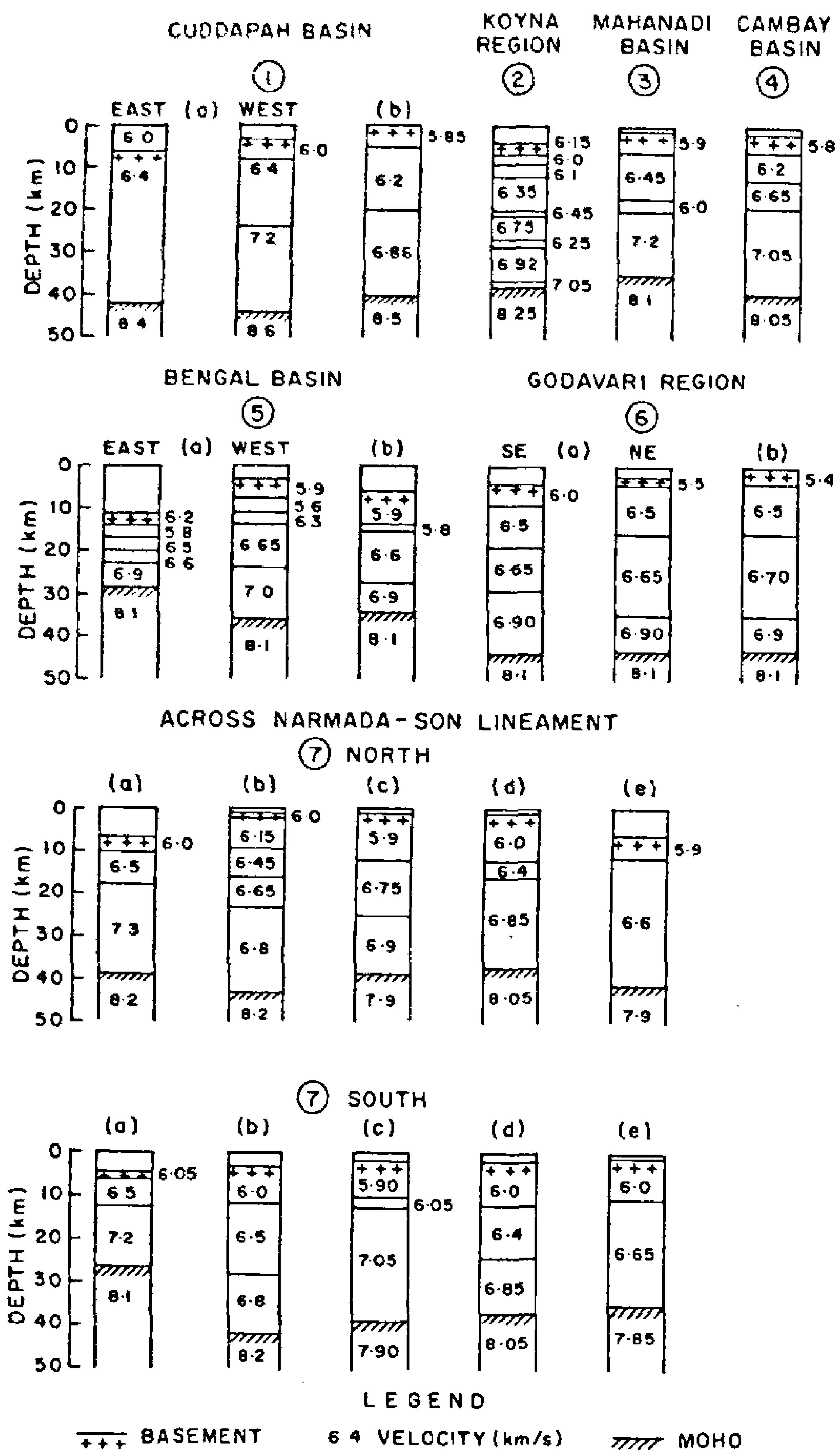


Figure 2. Crustal thickness obtained primarily from seismic refraction/wide-angle reflection experiments. ????? indicate regions where data control is lacking.

The Moho is deeper along the middle parts of the east coast than along the west coast. However, thinning of the crust, probably due to its transition from continental to oceanic, is noticed at the eastern and south-eastern flanks of the Mahanadi and Bengal basins, respectively. The sharp rise in the Moho from west to east clearly points to the presence of a significantly thinned crust in the eastern and south-eastern parts of the Bengal basin. The recent findings of Brune and Singh[11] and Brune and Priestly[12] from earthquake surface wave data indicating evidence for anomalous continental-like crustal structure beneath the Bay of Bengal is also consistent with the above studies. Contrary to this, presence of reasonably thick crust in western and middle parts of the basins is noticed, suggesting close to normal continental type crust in this region. This has considerable significance in understanding the evolution of these basins and the interaction between the continental and oceanic structures.

NSL is the most conspicuous linear geologic feature in India after the Himalaya, which has played a significant role in the formation of a series of folded structures in the Vindhyan formation. This lineament cuts across the whole of Central India in NNE–SSW direction and has been periodically reactivated since Pre-Cambrian times[13,14]. Due to compressional tectonism, north-south trending ridges have formed at an average interval of 5° (ref. 15). A close examination of the present contour map clearly shows such a trend, if not in other places at least along NSL. Results from the five DSS profiles across NSL have thrown much light on many of the upper and lower crustal features and emphasize the major role they played in the geological and tectonic setting of the region. The crustal thickness varies from 38 to 43 km along NSL. The most outstanding feature of the Moho is its shallowing up from 35 to 25 km near Billimora along Mehmabad–Billimora profile. The Moho configuration reveals a ENE–WSW trending depression in the central part coinciding with Narmada–Tapti region where the Moho depth is about 41 km. The sagging of the Moho in this region initiated the formation of a Mesozoic basin and Deccan syneclise[9]. The region from Billimora 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 as a major source of the Deccan Trap flows that spread across to large distances towards the east, west and north. The middle part of NSL is characterized by normal continental type of structure. It is relevant to state that but for the region in and around Surat/Cambay the crustal thickness all along NSL is thick, viz. approximately 40 km. Evidence for high velocity layers along the Cambay, Ujjain–Mahan, Hirapur–Mandla profiles suggest the significant influence of underplating and compressional tectonism. Crustal thinning along these three profiles could be attributed to various phases



'igure 3. Seismic velocity–depth columns of various regions Average crustal and upper mentle velocities along different DSS profiles).

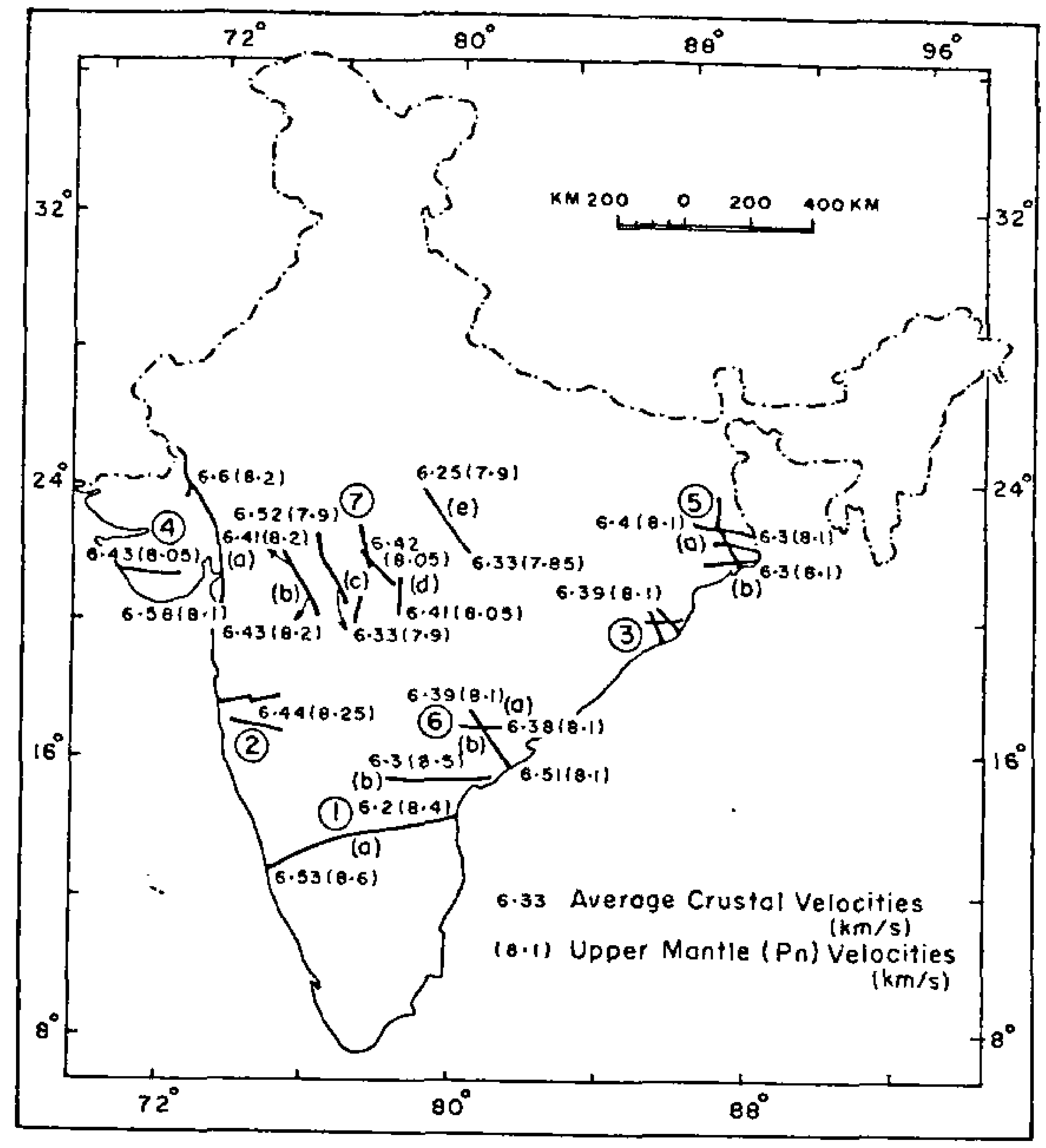


Figure 4. Average crustal and upper mantle (Pn) velocities along different DSS profiles in the Peninsular Shield of India.

›f mantle upwarping from Late Cretaceous to the ·ertiary[16]. The average crustal thickness in these areas s found to be lower than that of the Indian Shield areas[17–19].

The average crustal thickness in the Dharwar craton is ›5 km, whereas the crustal thickness at the eastern flank ›f the Cuddapah basin is considerably higher approximately 43 km) due to probable underplating.

'elocity structure

'igure 4 shows velocity particulars including P_n. Aver-ge crustal velocity, a parameter well determined from)SS data is important as it is directly related to bulk crustal composition. A low average crustal velocity (6.0–6.3 km/s) is indicative of a dominantly felsic composition, and a higher average velocity (6.5–6.8 km/s) indicates a significantly more mafic crustal composition[20–22]. A close look into the average crustal velocities (Figure 4) suggests that the values in the continental part except for West Bengal, Mahanadi and Godavari basins are more or less equal to the global average of 6.44 km/s (ref. 20). This suggests a typical platform/shield crust.

The crustal columns (Figure 4) for the middle and eastern flanks of NSL, Cambay basin, Cuddapah basin and Dharwar geo-syncline show thick crust. It is significant that even Aravalli Fold Belt[23] has thick crust, averaging to about 40 km. In some of these areas one can notice the presence of a high velocity (more than 7.0 km/s) lower crustal layer. When viewing the structure along different segments of NSL, the above findings with regard to high lower crustal velocity have definite significance. White and Mckenzie[24] suggested that the presence of a high velocity lower crustal layer in the rift zone and its absence in the adjacent areas can be attributed to the igneous accretion. The intensive volcanism at the time of crustal extension and continental rifting resulted in the formation of the Deccan flood basalts and the concurrent igneous activity. Deitz and Holden[25] opined that the Deccan lava poured out following episodes of intense igneous intrusion that accompanied tectonic activities on the western margin of India when it crossed the mantle hotspot near the equator.

Presence of upper and mid crustal low velocity layers in Central India in the region of Koyna and Latur and also in the West Bengal basin suggests that in these regions, a fluid-like layer may be present at the inferred depth levels. Presence of the upper crustal low velocity layers plays an important role in understanding the regional tectonics and crustal configuration. Raval[26] and many other workers suggested that large distance migration of fluids and thermal energy may take place. It is possible that large amounts of aqueous fluids that might have been generated during subduction, collision processes and the consequent great Himalaya uplift might have migrated to large distances. The fluid mobilization in the Himalayan event may involve a fluid mass similar to ice-caps[27]. This suggests that large quantities of fluids might have percolated down, since long resulting in a probable fluid chamber/chambers covering the western flank of NSL, Cambay and Koyna on one side and West Bengal basin on the other. In addition to the above, especially in the western Deccan Trap covered region, viz. Koyna, Cambay and surrounding regions the impact of Deccan Volcanism might have played a significant role in developing fluid-filled upper and middle crustal columns.

Worldwide, P_n velocities for continental mantle range from 7.6 to 8.4 km/s. However, we have noticed high velocities ranging between 8.4 and 8.6 km/s both in the Cuddapah basin, below Gauribidanuar and Chitradurga–Shimoga Schist belt regions. The high P_n velocities could be correlated with thicker crust (more than 40 km) with low heat flow (i.e. stable continental interiors)[20–22].

The above velocity–depth details act as primary inputs not only for understanding geodynamics of the Indian sub-continent but also help in better synthesis of geological, geochronological and other geophysical results.

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