1900 m. In some sections, however, the Group is up to 3950 m thick. The Dharamsala beds have dips of 30° to 55° towards north-east.

Reconnaissance radiometric surveys around Tileli village during 1996–97 led to the discovery of radioactive zones at about 0.75 km east-north-east of Tileli village (Figure 1 *b*). A radioactive zone of 540 m was traced with its width varying from 5 to 10 m in the sandstones of the basal part of the UDF, near the contact with the LDF. In general, the radioactive zones record radioactivity of 0.03 mR/h to 0.1 mR/h, with several patches showing higher orders of radioactivity up to 0.5 mR/h. Other significant radioactive anomalies were also picked up at Rohin Khad (50 m × 10–15 m) and Garlwar (70 m × 5–8 m). Grab samples from these localities assayed 0.012 to 0.14% eU_3O_8; eU_3O_8 expresses gross radioactivity in terms of equivalent uranium (eU), defined as 'the amount of uranium in equilibrium with its daughter elements, required to give the same counting rate as the sample in a particular type of instrument' and 0.014 to 0.27% U_3O_8 (beta/gamma) (Table 2). During 1997–98, additional significant radioactive anomalies were located at Chah Ka Dora (80 m × 10–25 m), Kalthar (50 m × 3–8 m), Manjkhetar (100 m × 1–2 m) and Mangwana (5 m × 2 m). Grab samples from these localities assayed 0.011 to 0.88% eU_3O_8 and 0.010 to 1.5% U_3O_8 (beta/gamma) (Table 2).

Preliminary petrographic and mineralogical studies indicate that the host rock for uranium mineralization is moderately sorted, subfeldspathic arenite. It shows grain-packed texture and mainly comprises clasts of subrounded quartz (80–85%), rock fragments of phyllite, quartzite, gneisses and negligible feldspar set in an argillaceous matrix (6–7%). Biotite, muscovite, chlorite, rounded zircon, green tourmaline, hematite and ilmenite occur as minor minerals. The organic matter occurs as pore-fillings and veins, and contains tiny framboidal granules of pyrite suggestive of its biogenic origin. Radioactivity is due to uraninite and uranophane, in association with organic matter where radioactive minerals occur as dissemination in the radioactive pockets. These pockets are enclosed within the light-brown coloured thin rim of hydrated iron oxide, at places admixed with clay. These pockets are poorly to moderately sorted, and mainly consist of subrounded to subangular quartz, rock fragments of phyllite and quartzite with negligible plagioclase. Chalcopyrite is present in the rock fragments of phyllite.

Detailed geological and structural work commenced to prove the qualitative and quantitative surface manifestations, and a total of five trenches and four faces were prepared for Shielded Probe (SP) logging. The results of the SP logging have indicated persistency of uranium mineralization over the strike length of 540 m. The SP logging data at cut-off grade of 0.02% eU_3O_8 have indicated average grade 0.039% eU_3O_8 and average exposed width 2.64 m. The channel samples drawn from the above trenches and faces have analysed 0.01–0.27% eU_3O_8, and 0.011–0.076% U_3O_8 (beta/gamma) with negligible ThO_2.

In view of the above data, favourable geological setting, presence of high concentration of uranium in association with organic matter, hydrated iron oxide, at places admixed with clay, the discovery of uranium mineralization in sandstones of Dharamsalas at Tileli has opened up a new environment for survey and exploration of uranium in the Dharamsala basin.

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Structure and tectonics of the Indian peninsular shield – Evidences from seismic velocities

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The Indian shield is an assemblage of cratons and mobile belts. Significant lateral variations in the crustal velocity structure, especially the presence and absence of crustal low/high velocity layers are found to provide an useful input in understanding the structure and evolution of various important tectonic units present in the Indian shield. The subsurface velocity heterogeneities have been shown to provide clues to estimate the stress generation and in understanding to some extent, the seismicity of intraplate regions. Significance and the geophysical aspects of low velocity layers are discussed. Other geophysical anomalies such as gravity, heat flow and seismicity are also discussed with reference to craton and mobile belt.

SHIELD is made up of a cratonic nucleus with a mobile belt at its periphery. A craton is a stable portion of a shield area with low-grade granite–greenstone terrain, which is unaffected by major tectono-thermal events since the end of Precambrian. On the other hand, the mobile

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*For correspondence. (e-mail: postmast@csngri.ren.nic.in) belt is a younger, high-grade granulite facies metamorphic belt surrounding the craton and has suffered from later deformational episodes. In plate tectonic framework, the mobile belt is synonymous with the orogenic belt. Seismic studies help in imaging subsurface crustal structure and understanding the nature and evolution of such diversified areas. A huge volume of seismic refraction/wide angle reflection and near-vertical reflection data has been acquired along a large number of Deep Seismic Sounding (DSS) profiles (Figure 1) covering both cratons and mobile belts. Some of them are across shields, Cenozoic rifts, palaeo-rifts, fold belts, etc. These studies have provided valuable information in the form of velocity–depth models[1], which are used to understand the tectonics of a region.

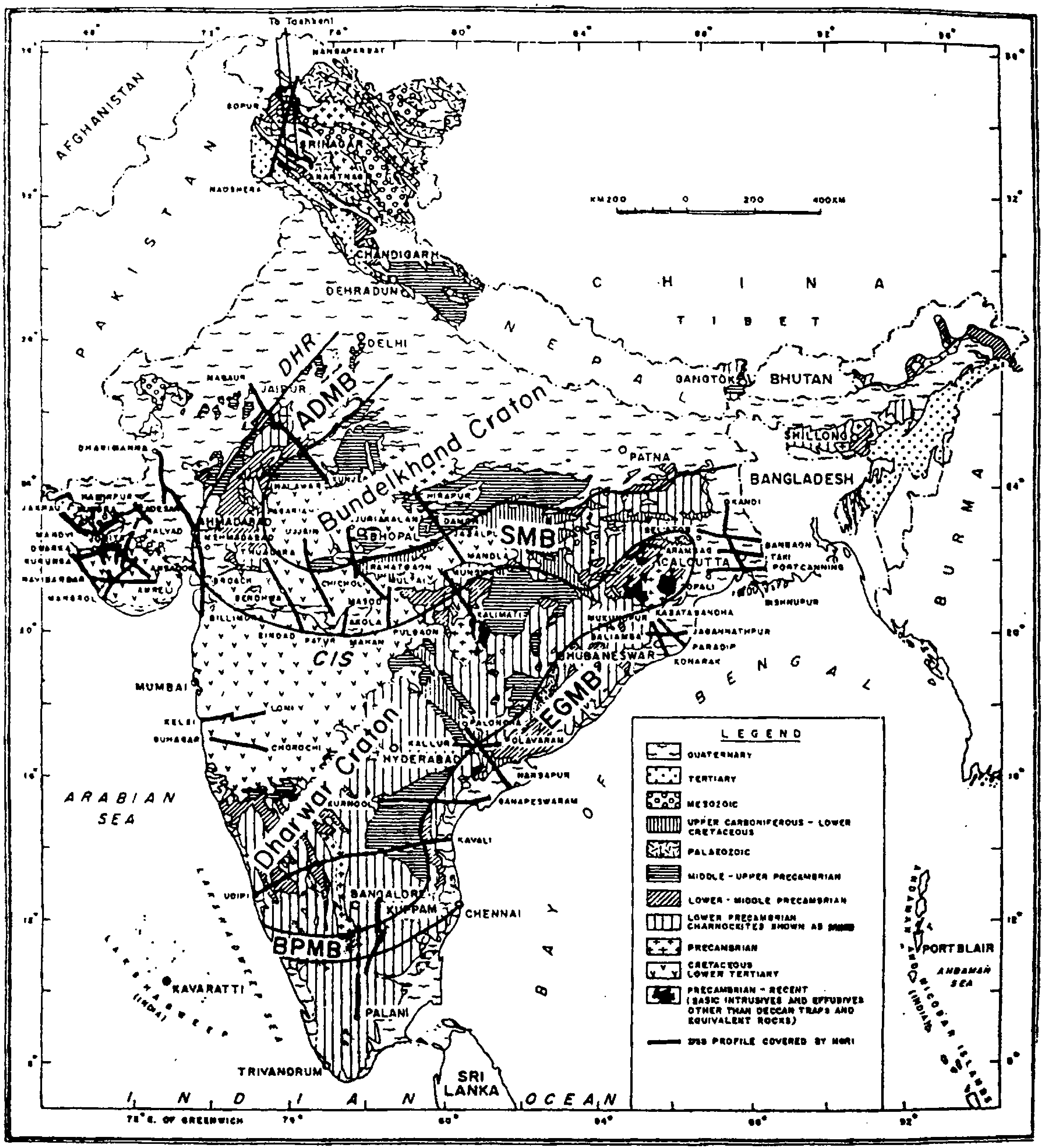

Figure 1. Geological map of India along with various DSS profiles and mobile belts of various periods. ADMB – Aravalli Delhi Mobile Belt; SMB – Satpura Mobile Belt; EGMB – Eastern Ghat Mobile Belt; BPMB – (Bhavani–Palghat) Mobile Belt; (M–B) – Moyar Bhavani Shear Zone; (P–C) – Palghat Cauvery Shear Zone; DHR – Delhi Haridwar Ridge; CIS – Central Indian Suture.

A review of various DSS results is presented by Mahadevan[2]. Kaila and Sain[3] have divided the Indian crust into six zones based on the seismic velocity. In the present study, an effort is made to bring into focus, lateral structural variations of different tectonic units of the Indian peninsular shield by integrating geological, geochemical and seismic results. Such a synthesis would help in developing models that explain the evolutionary history of a geological/tectonic unit.

Deep seismic sounding studies, for crustal studies, were carried out by recording the seismic waves generated by blasting explosives loaded in shot holes, with close detector spacing (80–200 m), all along a profile with a number of shot points. Shot point spacing ranging from 10 to 40 km helps to delineate shallow as well as deep structure of the crust up to Moho. First arrival refractions and later arrival wide angle reflections from various interfaces are used to generate the velocity–depth model of a region. After correlation of mutual times from various reciprocal shot points, reflection phases corresponding to an interface are identified. Critical point, crossover distance and the nature of reflections (amplitude) are also considered in analysing various phases. Wide angle reflections from LVLs generally show high amplitude because of high impedance contrast. Travel times of various phases identified from the seismograms are picked up and plotted. Apparent velocities and time-intercepts of main refractors are calculated. Then, an initial velocity–depth model is prepared by slope–intercept, delay time or any other inversion method[4] using refraction data for shallow depths. The Kaila and Krishna method[5] is used in processing wide angle reflection travel time data for obtaining middle and lower crustal details. From this initial model, theoretical travel times are calculated and compared with the observed ones. Subsequently, the velocity model is modified in an iterative manner so as to give a reasonable agreement between observed and theoretical travel times. The velocity model obtained from travel time modelling is further refined by amplitude modelling, by generating synthetic seismograms.

Low velocity layer present at shallow depths, specially above the basement are also identified using travel time delay or skip (shadow zone) observed in the refracted first arrivals.

Crustal seismic studies carried out by the DSS group of the National Geophysical Research Institute (NGRI), along various geological terrains of India, have provided useful velocity structure for different segments of the Indian shield. Velocity–depth models of various DSS profiles[6–11] covering different geological/tectonic provinces are presented in Figure 2. The studies have revealed upper crustal low velocity layers in the Koyna region, western flank of Narmada–Son Lineament, North Cambay, West Bengal, Mahanadi and Krishna–Godavari basins[1]. Presence of mid/lower crustal, low velocity layers has also been noticed in Koyna, Central India and the Aravalli–Delhi fold belt region. Preliminary results from the coincident deep seismic reflection and refraction studies, along Kuppam–Palani Geotransect, in the southern granulite terrain[12] also indicate the presence of a thick mid-crustal low velocity layer in the entire Moyar–Bhavani shear zone region. Differences in seismic velocity structure in the form of these LVLs (Figure 2) and their relative distribution are used to understand tectonically discrete terranes of the Indian shield.

Some of these models (Figure 2 *b* and *f*) show LVLs/HVLs, which were identified prior to the synthetic seismogram modelling exercise using analogue seismic data. This clearly suggests that delineation of these zones neither depend much on instrumental limitations nor on synthetic seismogram modelling. The broad features are identified even with the correlation of travel times of various wide angle reflection phases considering their reciprocal times from various shot points, relative amplitude, critical distance, etc. Initially, a similar procedure was adopted to identify LVLs in different parts of the world[13]. However, the digital data and synthetic seismogram modelling provide considerable improvements in developing the crustal velocity model.

Radhakrishna and Naqvi[14] have proposed a mobile belt surrounding the cratonic parts of the Indian shield. Subsequently, Radhakrishna[15] has suggested that the Indian sub-

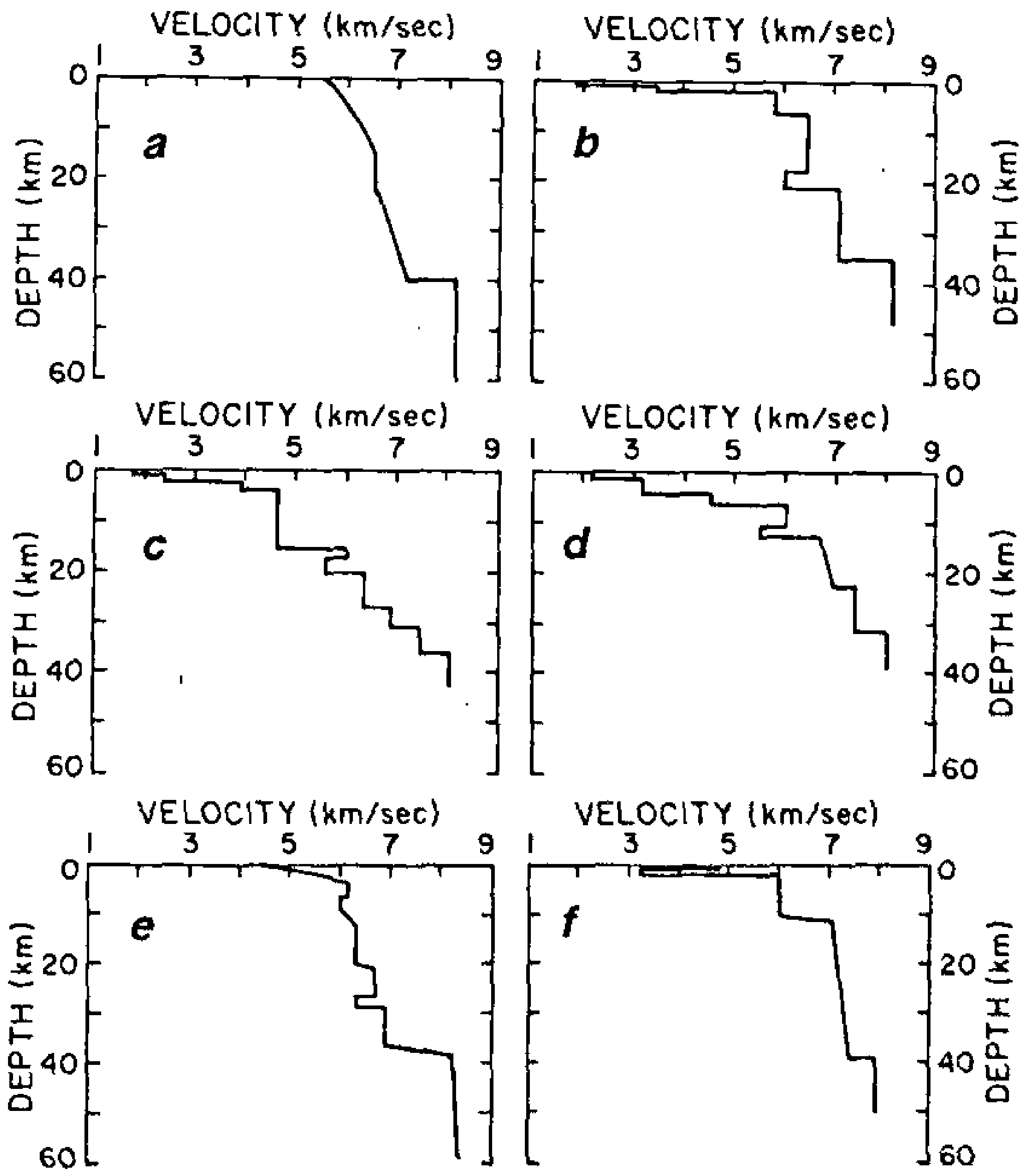

Figure 2. Interval velocity–depth models for various parts of the Indian shield (after Kaila *et al.*[6] as mentioned in the text). *a*, Dharwar Craton; *b*, Mahanadi Basin; *c*, West Bengal Basin; *d*, North Cambay Basin; *e*, Koyna (western flank of Dharwar craton) Region; *f*, Narmada–Son Lineament.

continent is a mosaic of crustal blocks, unrelated to each other, juxtaposed and sutured together in different periods of the earth's history. Some of these blocks have resulted due to the collision of different cratonic blocks with the generation of mobile belts, where the major crustal growth took place in the continental regions. The nature of the continental crust of the Indian shield can be understood better by studying the characteristics of its basic units, the cratons and mobile belts. Accordingly, the cratonic blocks and mobile belts of the Indian shield (based on Radhakrishna and Naqvi[14], Radhakrishna[15], Raval[16] and Ramalingeswar Rao[17]) are shown in Figure 1 along with geology and DSS profiles. Velocity structure of these DSS profiles is used to understand the nature of cratons and mobile belts.

Crustal velocity structure is used to differentiate various segments of the Indian shield. Velocity structure associated with the western Dharwar craton and adjoining regions provides a diversified picture from the surrounding regions. Kaila *et al.*[6] have indicated a thick western Dharwar craton flanked by relatively thinner crustal column at its eastern flank. The Kavali–Udipi analogue seismic refraction data[18] suggests that the thick but relatively lower velocity western Dharwarian cratonic crust is flanked at the east by a thin but relatively higher velocity crust. The study has also indicated absence of crustal low velocity zones within this area. Gokaran, Rao and Gupta[19] have suggested absence of high conductive layer in the entire crustal column of the western Dharwarian crust. Velocity model of the Archean Dharwar craton obtained from Kavali–Udipi profile[6] is presented in Figure 2 *a*. It shows 5.9–6.4 km/s and 6.8–7.0 km/s velocities corresponding to upper and lower crusts extending to a depth of ~ 22 and ~ 38 km, respectively. The upper mantle velocity of the region is found to be 8.1 km/s. This velocity structure is considered as the typical crustal velocity model of the Indian shield.

The 1-D interval velocity–depth models (Figure 2 *b–d*) from Baliamba–Jagannathpur and other profiles of Mahanadi basin[8], Dharimanna–Degam profile of North Cambay basin[9] and Beliator–Bangaon and other profiles of West Bengal[10] basin (Figure 1), show a low velocity layer in the upper/middle crust and a high velocity layer of varying thickness in the lower crust just above Moho. The velocity model (Figure 2 *e*) from Guhagar–Chorochi profile of Koyna region[11], situated on the western flank of Dharwar craton also shows low velocity layers in the upper as well as in the lower crust at a depth of 6–11 km and 26–28 km. A 2–3 km thick high velocity layer (7.26 km/s) is also noticed at the base of the crust, representing the transitional Moho at 35–37 km depth. These regions are affected with rifting due to hotspot activities, Kerguelen in the east[20] and Reunion in the west[16] with the separation of Antarctica and Seychelles from India, during 115 Ma and 66 Ma, respectively. The related volcanic activity is exhibited as Rajmahal and Deccan traps. The western margin of the Indian shield is also affected with the separation of Madagascar from India during 88 Ma. These major tectonic episodes with mantle upwelling have moulded the present-day deep crustal velocity configuration of these regions. All these regions exhibit high heat flow[21,22] values. Thermal perturbations might have resulted from hotspot activities experienced in this region. The high heat flow could be due to shallow lithospheric thickness[23–25] at these rift basins/rifted margins. Generally, it is observed that rifts and rifted margins show shallow lithosphere and high heat flow[26]. Some of the thermal anomalies can as well be due to continuous reactivation of old faults and rifts.

Crustal low velocity zones can arise due to various reasons. They can be due to high temperature, transition from α to β quartz, increased pore pressure/presence of fluids, change in composition and even due to partial melts. The reduced heat flow (40 mW/m^2) for the entire region from the Godavari graben towards the north is much higher than the global average[27]. But, still the existing geothermal gradients[21,22] cannot give rise to melts at depths of the LVLs (Figure 2) mentioned in various parts of the Indian shield. So, melts cannot be responsible for the presence of LVLs in these regions. Similarly, α to β transition of quartz cannot be responsible for the presence of LVL, as the conversion takes place around 550°C at one atmospheric pressure. The transition temperature increases further with pressure. Shallow LVL at Koyna region is attributed to the presence of fluids[28].

Some of the causes for LVLs are interdependent. Increase of temperature increases porosity, thereby increasing the fluid content and pore pressure, thus decreasing the velocity. The existing velocity models are analysed to identify a unified process, which might be responsible for the presence of LVLs in the region. The high velocity layers observed in the velocity models (Figure 2 *b–d*) at the base of the crust are due to the magmatic underplating by the hotspot/rift-related activity, which has injected the mantle material into the crust. The intrusion of hot basaltic material at the base of the crust (magmatic underplating) during rifting process results in prograde metamorphism and releases water. These fluids move up until reduced temperature and pressure would result in substantial amounts of silica precipitation along grain boundaries that sharply reduces permeability. This forms an impermeable layer that traps the fluid horizon below[29]. These fluids present at midcrustal levels increase pore pressure, thus reduce velocity. Evidence for such a process has been reported by Hyndman and Shearer[30] for the Phanerozoic areas. In favourable environments these fluids help in undergoing retrograde metamorphism and the subsequent compositional variations such as serpentinization exhibit as a LVL. Such a process might be responsible for the observed LVLs in the above-mentioned rifts. Mid-crustal LVLs in different parts of the world are correlated with high conductive zones[28] observed at similar depths. They correspond to the brittle–ductile transition zones at many places. So, the presence of LVL is related to geological processes and is not an artifact of modelling. The geological age and the time of the last thermo-tectonic event are very important for the presence of LVL. The marked deviation of velocity structure of these regions from that of Dharwar craton (Figure 2 *a*) is due to the differences in the evolutionary process and tectonic activities experienced by them.

The velocity model (Figure 2 *f*) from Ujjain–Mahan and some other profiles (Figure 1) of Central India[7] across Narmada–Son rift zone, exhibits a very high velocity of the order of 6.9 km/s at a shallow depth of ~ 10 km. This suggests a thin upper crust and a thicker lower crust. Such a high velocity layer at a shallow depth is not present in the Dharwar craton or any other cratonic regions of the world. This part of the mobile belt (Satpura Mobile Belt, SMB) with subsurface crustal velocity heterogeneities is sandwiched between Bundelkhand and Dharwar cratons. Deep seismic reflection studies[31] have indicated the operation of collision tectonics during the Proterozoic period between these two cratons. The collision process might be responsible for the presence of the high velocity layer found in this mobile belt region. The anomalous velocity feature coupled with high heat flow generates considerable amount of stress, as the differential isothermal rise and large lateral temperature differences on a regional scale are responsible for seismic activity of a region[32]. Stress is released along the pre-existing faults. This must be one of the reasons for more seismicity in the Narmada–Son Lineament (SMB) region. Mandal[33] has calculated the amount of stress generated due to crustal density/velocity heterogeneities (subsurface loads) in various parts of the Indian shield and demonstrated its significance in the seismicity of a region. Reddy[34] also indicated the importance of crustal thickness and velocity distribution in stress generation with reference to the Indian shield.

Prominent features to the south of the Dharwar craton are the Moyar–Bhavani and Palghat–Cauvery shear zones. They extend in the NE direction and finally merge with the Eastern Ghat mobile belt (Figure 1). The region covering these shear zones has been interpreted as collision zone, mobile belt, dislocation zone, suture zone, etc. It is referred to as the Bhavani–Palghat Mobile Belt (BPMB) in the present study. Geological, geochemical and geochronological studies have suggested that the crustal blocks situated to the north and south of this mobile belt are different[35,36]. The southern Madurai block is affected by the global Pan-African, tectono-thermal event at the end of the Precambrian period (550 Ma). A similar feature is also observed in other Gondwana continents to a large extent. In contrast, the Dharwar craton situated to its north is completely devoid of such an event. Presence of the regionally extending mid-crustal low velocity layer[12] and the thrust faults[37] of the mobile belt region indicate that these regions are structurally different. Regional palaeomagnetic studies[38] also suggest divergent structures north and south of the mobile belt. These geoscientific evidences suggest that the BPMB (Figure 1) separates two entirely different crustal domains, the Dharwar craton in the north and the remobilized, juvenile Madurai block in the south. Presence of seismic activity[39] in this region indicates its mobility. The above evidences indicate that the Bhavani–Palghat shear zone region be regarded as a mobile belt rather than the entire eastern coastal belt or the entire region south of Bhavani shear zone. This is in agreement with suspect terranes of India proposed by Radhakrishna[15] and Ramalingeshwar Rao[17].

Deep seismic reflection studies in the NW Indian shield[40,41] suggest that the Aravalli–Delhi Mobile (Fold) Belt has evolved due to the collision of two cratons generating the Jahazpur Thrust. Valdiya[42] has suggested the extension of this fold belt into the Himalayas. Two prominent features of this region, namely the Delhi–Haridwar ridge and Muradabad fault, are situated on the boundary of craton and mobile belt (Figure 3). They are characterized by high seismicity and heat flow. This demarcates the northern extension of the mobile belt.

Major gravity high trends of Bouguer anomaly of the Indian shield[43] are presented in Figure 3. A good correspondence is observed between the craton–mobile belt and the broad Bouguer trends (Figures 1 and 3). The gravity low–high pair for the craton and mobile belt has very clearly brought out the suture zones of the Indian shield. Such a bipolar gravity anomaly is interpreted as a suture[44] for the Canadian shield. The Bouguer gravity high (Figure 3) demarcates the boundary of a craton/mobile belt. Gravity highs H-2 and H-1a represent the boundary of the Dharwar craton and the Madurai block, respectively. The intermediate region represents the BPMB as inferred earlier in the text.

A closer look at Figures 1 and 2 indicates that the locations of the zones that contain crustal low velocity layers belong to the regions that either contain mobile belts, rift zones or suture zones. However, in some parts of the mobile belt, presence of high velocity layers are noticed, at shallower depths, viz. in some parts of the Narmada–Son Lineament[7] and the Cuddapah basin[3]. In these crustal columns, presence of low velocity layers at any depth has not been reported. Presence of low or high velocity layers in the mobile belt depends on the latest tectonic activity experienced in this region and also on its period. It can be due to rifting, collision, underplating, plume-related activity or even continental breakup. This in turn suggests that the crust of mobile belts with low or high velocity zones, with significant differences in the thickness of various other crustal layers (velocity heterogeneities), and high heat flow, is different from that of the stable western or eastern Dharwar cratons. The smooth velocity structure (Figure 2 *a*), along with low heat flow values suggests that the cold normal crust of the Dharwar craton is rigid and strong. Crustal structures of the Archean Superior

Province of the Canadian shield and cratons of the African shield, with a crustal thickness of 36–40 km and absence of high velocity basal layer[45], are similar to that of Dharwar craton. The low–high gravity pair observed over the craton and mobile belt of the Indian shield is also observed in different parts of the world. Heat flow in the Kaapval, Limpopo and Zimbabwe cratons of the African shield, and Superior Province of the Canadian shield is low and high over the Proterozoic mobile belts[46]. This is similar to that of Indian shield.

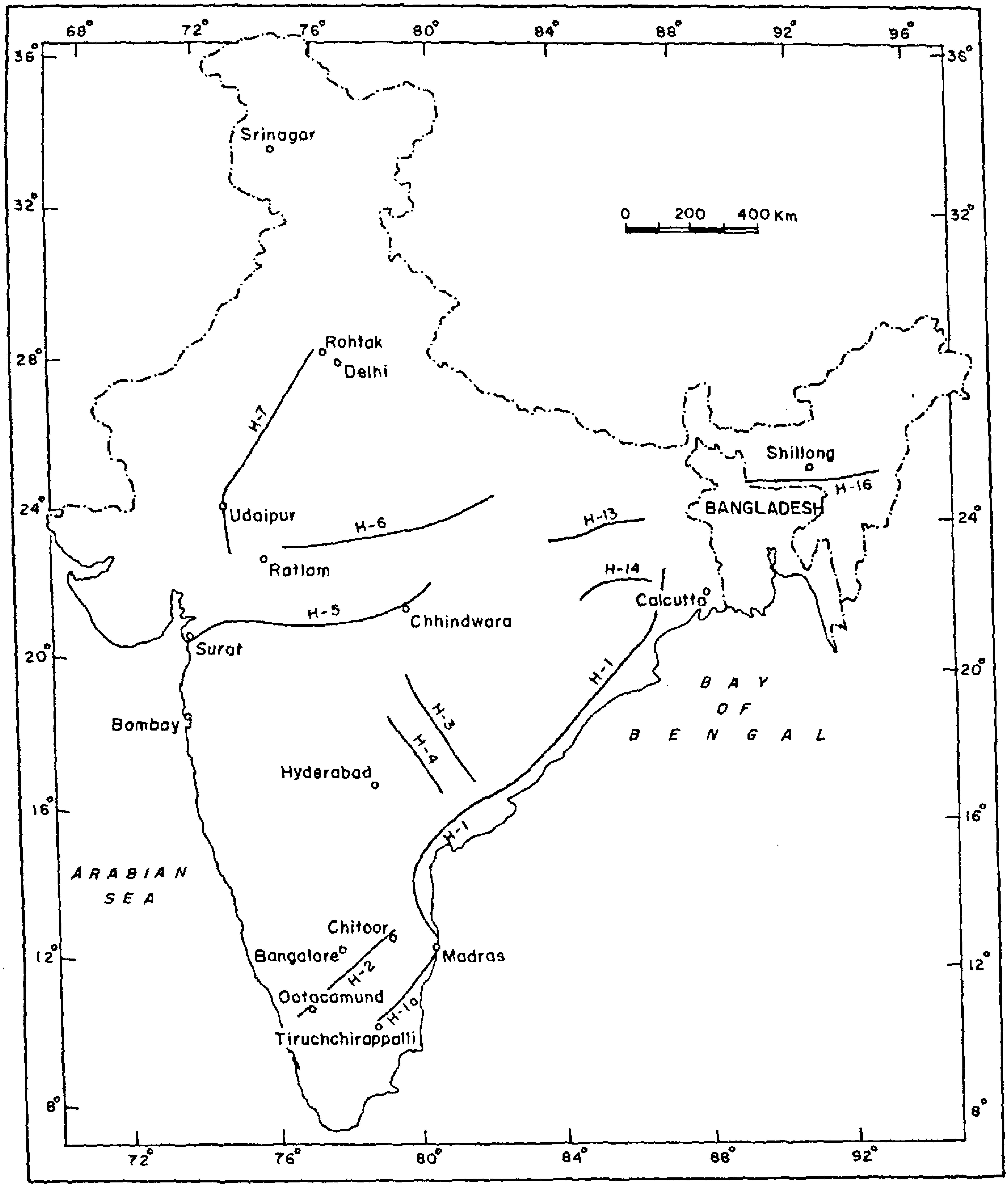

Figure 3. Major gravity high trends of Bouguer anomaly (after Verma[43]) of the Indian shield.

The mobile belts are juxtaposed between cratons, with the involvement of compressional and extensional tectonics, at different stages of their evolution. Presence of thrust faults and their deep-seated nature along all the mobile belts of the Indian shield indicate that collision tectonics must be responsible for their evolution. All these mobile belts have also undergone granulite facies metamorphism during different times of the Proterozoic period indicating their different evolutionary periods. Some of them have been repeatedly rejuvenated from Proterozoic to the present times. They are also intruded by anorthosites, alkaline complexes, granites, etc. Such heterogeneous mobile belts are naturally more prone to later tectonic activities than the stable cratonic part due to the differences in the thermo-mechanical properties.

A mobile belt in one period may become part of a craton in a subsequent period, when the tectono-thermal activity characteristic of the mobile belt has ceased after stabilization. But, presence of such activity along all the Precambrian mobile belts of the Indian shield (Figure 1) indicates that subsequent tectonic activities with some periodicity may affect only the earlier mobile belts, without disturbing much, the relatively stable cratonic part. This could be due to the large lithosphere thickness of the Dharwar craton[25], which may be acting as a barrier for hotspot and other deeper tectonic activities, diverting the heat to the relatively thinner lithosphere[47] of the mobile belts. Global lithospheric studies by Durheim and Mooney[46] have also suggested a relatively thicker lithosphere for the Archean cratons and thinner ones for Proterozoic provinces.

From the above discussions, it is clear that the bipolar gravity anomaly, high seismicity and heat flow are confined to the tectonic boundaries of cratons and mobile belts, old sutures, and deep-seated basin marginal faults. Some of them are palaeo-plate boundaries[34,48,49]. Presence of major seismo-tectonic activities at these boundaries situated in the intraplate regions resembles the present-day plate boundary scenario to a lesser extent.

The crustal velocity structure of the stable cratons is relatively smooth, whereas it is heterogeneous in the mobile belts. The differences in the crustal velocity models are due to the different geological/tectonic processes which the regions have undergone during different periods. The remnants of those processes are manifested in the crustal velocity structure.

Most of the geophysical anomalies, viz. seismic velocity, gravity, heat flow and seismicity are more pronounced in the mobile belts. This suggests that the geological processes that have formed the continental crust are complex and are found to be different for the Archean cratons and subsequent mobile belts. The crustal velocity structure and Moho configuration are the important parameters to understand the tectonic process and evolution of any region. It can be used to calculate the stress generation and to understand the seismicity of intraplate regions.

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