JOURNAL GEOLOGICAL SOCIETY OF INDIA
Vol.97, October 2021, pp.1169-1189

Seismic Structure of the Crust and Lithospheric Mantle of the Indian Shield: A Review

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ABSTRACT

The article reviews the history and accomplishments of CSIR-NGRI over the past 60 years, related to elucidating the seismic structure of the crust and lithospheric mantle of the Indian shield. Extensive investigations have been carried out in diverse geological and tectonic provinces of India, employing seismic reflection, refraction/wide-angle reflection and passive seismology to decipher (a) the evolution of the Indian plate through geological time, (b) hazard and its mitigation and (c) accumulation and disposition of natural resources. These endeavours entailed the application and development of state-of-the-art methodologies. Synthesis of the results from active and passive seismology reveals that the thickness of the crust varies between 28 and 65 km in the Kachchh and Aravalli regions respectively, consistent with their evolutionary histories. The thickest crust is observed in the western Dharwar craton (WDC) and the shallowest lies in the west coast. The crust in the shield region is mostly thicker, while it is thin beneath the rift zones. Results from coincident reflection and wide-angle seismic reflection studies broadly suggest a three-layered crust with magmatic underplating. Interestingly, the seismic sections traversing the Aravalli fold belt, central Indian suture zone, Dharwar craton and Southern Granulite Terrain (SGT) depict paleo-collision and subduction environments. The diverse character of the Moho, crustal fabrics and structure in different geological provinces indicate that contrasting tectonic environments might have influenced their evolution and support the hypothesis that plate tectonic processes were operative since Neoarchean.

The thickness of the lithosphere estimated from receiver functions varies from 80 to 140 km. An undulation in the Litho-sphere Asthenosphere Boundary reveals evidence for a flexure on a regional scale, owing to the continental collision of the Indian and Asian plates. However, the lithospheric thickness derived from surface wave dispersion studies is somewhat larger, ranging from 100 to 250 km, with some body wave tomographic studies suggesting it to be ~400 km, in consonance with the concept of Tectosphere. The thickness values derived from both the methods agree at a few locales such as the Eastern Dharwar Craton, SGT, Cambay, Singhbhum and western DVP. However, a broad disagreement prevails in WDC and northern part of the Indian shield where surface wave tomography reveals the thickness of lithosphere to be 140 to 200 km.

INTRODUCTION

In 1909, a Hungarian-Croatian seismologist, Andraija Mohorovicic, first identified the *Moho* by analyzing the recordings of an earthquake in the Alps. He further recognized a change in velocity, which might mark the boundary between the crust and mantle. Subsequent observations on a global scale ascertained that the Moho is one of the most significant boundaries within the Earth (Phinney, 1964; Meissner, 1986). The depth to the Moho varies from place to place, being only about 6-11 km deep beneath the oceans, 30-45 km deep beneath the stable parts of continents and 50-80 km deep below the young orogenic belts. It is argued that the terrestrial crust was created from the underlying mantle by a global differentiation process. Nevertheless, two broad classifications have been advocated for its formation i.e., horizontal accretion of island arcs or vertical accretion due to differentiation of magmatic material above hotspots (e.g., Hoffman, 1988; Percival, 1989). The crustal structure is a key parameter to understand the mechanism of its formation and the tectono-thermal processes underlying it. The knowledge about the crust has a direct relation to the earthquakes and distribution of natural resources within it. Therefore, realizing the tremendous importance of the knowledge crust and its composition, it has become important to interrogate the details of the structure of the crust and uppermost mantle.

Historically, the first information about the crust came from seismological methods. Until 1920s the seismic refraction method was the most popular, after a German Seismologist L. Mintrop demonstrated its commercial applications to explore salt domes in Texas. Witnessing the success of reflection seismology for imaging the sedimentary basins, it was obvious that it should also be adapted for crustal studies. In the 1950s, the refraction methods were refined and got established as a tool for *explosion* or *controlled-source seismology*, sometimes called as *deep seismic sounding*, since it does not require an earthquake to generate seismic energy (Meissner, 2002). The 1970s saw the birth of full-fledged large multinational projects in the Alps and Scandinavia. During the same time, the USSR got a step ahead by detonating underground nuclear explosions and recording the signals along more than 2000 km long profiles. Several mathematical methods were also developed simultaneously to understand the crustal structure and its composition. Soon after, *near-vertical reflection seismology* was initiated to detect the fine scale structure. Consequently, several new discontinuities were detected in the Earth.

In 1975, a mega crustal reflection program COCORP, the first of its kind, was launched in the US. Thereafter, similar programs followed in other countries, e.g. BIRPS in Great Britain (applying marine techniques), DECORP in Germany, ECORS in France and LITHOPROBE in Canada. Apart from the continental regions, other experiments focused over subduction zones (ANCORP Working Group, 1999), the arc-continental collision regions (Lundberg et al., 1997), the convergent plate boundaries (Davey and Stern, 1990), and the orogenic belts (e.g. INDEPTH program; Snyder et al., 1997).

In 1972, India started the Controlled source seismic studies, initially inspired by USSR. However, India soon made drastic changes in the acquisition, processing and interpretation techniques. The CSIR- National Geophysical Research Institute (NGRI) played a vital role in shaping the national program to delineate the velocity and structural configuration of the continental crust in different geological and tectonic settings of the country. It should be noted that prior to

0016-7622/2021-97-10-1169/$ 1.00 © GEOL. SOC. INDIA | DOI: 10.1007/s12594-021-1847-3

this program very little was known about the Indian crust, and this is the first major initiative undertaken in the southeast Asian region. Initially, the recording equipment was analog. However, a paradigm shift occurred when the data acquisition systems were replaced by the digital equipment in 1985. Similar to the global practice, India started acquiring only refraction/post-critical (also known as wide-angle) reflection data. However, in 1992, the acquisition of deep reflection data was initiated, and in 1998, wireless telemetry systems have been introduced (e.g. Tewari et al., 2018; Tewari and Kumar, 2020). This made seismic data acquisition possible even in areas with difficult topography. Further, a hybrid method of data acquisition has been started, where, refraction observations were also incorporated. This way of acquiring the data added advantages of both methods: to study the fine structure through reflection, and estimating the velocities through refraction. In this direction, CSIR-National Geophysical Research Institute carried out a number of DSS experiments, acquiring more than 6000 line-km of data covering the shield, orogenic belts, sedimentary basins, and plume affected areas, that enabled new information of the crustal dynamics, composition and evolution of the Indian plate. The results provided insights into both shallow and deep crustal structures, with unprecedented detail, down to the upper mantle.

Similarly, earthquake seismology was also developing at the same pace. An exemplary shift took place with the advent of the digital era in earthquake seismology, and the enhancement of computational capability. Soon, seismology in India did not limit only to understanding the earthquake sources but also flourished tremendously to image the structure. The real impetus came with the national wide networking program under the umbrella of National Centre for Seismology (NCS). CSIR-NGRI has emerged as a major agency in this endeavor not only for imaging but also for developing a number of new techniques. In order to carry out seismological studies and monitoring of earthquakes, till date, CSIR-NGRI has been operating more than 170 broadband seismological stations as semi-permanent networks in different parts of the country, like in Sikkim Himalaya (e.g. Singh et al., 2010), Andaman-Nicobar Islands (e.g., Srijayanthi et al., 2012), Gujarat (e.g. Mandal et al., 2004), Andhra Pradesh (e.g., Rastogi et al., 1986), Arunachal Himalaya (Saikia et al., 2020), Garwal Himalaya (Kanna and Gupta, 2020), Uttarakhand Network (Srinagesh et al., 2019) and inand in the Dharwar craton in southern India (e.g. Srinagesh et al., 2015). In the Singhbhum craton, CSIR-NGRI has operated 15 broadband seismological stations for crustal and lithospheric mantle studies. Recently, it has launched an important experiment in the hitherto less studied region of Jammu and Kashmir Himalayas, by deploying 40 broadband, 30 strong-motion and 30 GPS stations. Another multidisciplinary project that was recently initiated by CSIR-NGRI is in the Uttarakhand Himalaya region.

Consequently, data from both active and passive seismology have been used in conjunction with the state-of-the-art techniques to understand the evolution of the Indian crust and lithospheric mantle.

CRUSTAL STRUCTURE FROM DEEP SEISMIC SOUNDING (DSS) STUDIES

The First DSS Profiling – Kavali-Udipi Profile of the Dharwar Craton

India's first DSS study was carried out along the Kavali –Udipi profile during 1972-75, in collaboration with Soviet Russia, to understand the structure, origin and dynamics of the enigmatic Dharwar craton (Fig.1) (Kaila et al., 1979). The field works were conducted jointly by CSIR-NGRI and Geophysical Institute of the Ukraninian Academy of Sciences, Kiev, USSR. The crustal section revealed many reflection phases in the depth range of 2 to 50 km and a large number of major and minor deep-seated faults. The seismic section revealed that the craton is separated from the Cuddapah basin by an uplifted block (Fig.2). The results explain a number of existing geological conflicts. In the eastern margin of Chitradurga schist belt, two low-angle thrust faults have been delineated, indicating large deformation in that region. However, no deformation is seen under the Shimoga schist belt itself. Another remarkable observation was the variation of crustal thickness from 34 to 41 km along the profile spanning the Archaean and Proterozoic blocks corresponding to the eastern and western Dharwar cratons. A near-surface high-density structure associated with schistose rocks has also been identified in the Chitradurga schist belt region (Kaila and Bhatia, 1981).

The digitized data were further modeled by Sarkar et al (2001) who advocated that the crust along this profile is not akin to the global Archaean type crusts. It is comparatively thicker and the velocity in the lower crust is slightly higher than normal. The seismic results along the profile (Figure 2) show a number of crustal blocks well separated by deep faults. The basement of the schist belt lies at a depth of 4-7 km with a P-wave velocity of 6.4 kms^{-1} (Kaila et al., 1979). The depth to the Moho is 34-41 km in the eastern part of the craton and 38 km in its western part. The velocity in the upper mantle (P_n) is reported to be 8.4 kms^{-1}. A number of researchers re-interpreted the data and presented their views. One view is that the Moho constitutes a thermo-mechanical boundary between a rigid crust and a plastic mantle. The widespread horizontal appearance of the Moho is attributed to ductile shearing and buoyancy driven sharp density contrast (Roy Choudhary and Hargraves, 1981). The recent image of the crust along the Perur-Chikmagalur profile reveals simple structures with a gently dipping reflection fabric below the Chitradurga schist belt in WDC and a subhorizontal Moho to its west (Mandal et al., 2018). In contrast, the EDC exhibits more complex crustal structures. The mafic lower crustal layers of velocity 7-7.1 km/s are also the main features seen in the transect (Vijaya Rao et al., 2015). A pseudo-three-dimensional deep seismic image from the same profile reveals a 10 km thick magmatic underplating, suggestive of the mechanism of epeirogenic uplift in the region due to Marion and Reunion Plume activities during 88 Ma and 65Ma (Mandal et al., 2021).

Cuddapah Basin

The Cuddapah basin is situated in the south-eastern part of the EDC. It is a unique tectonic and orogenic belt that is not fossiliferous, and the largest Proterozoic basin of India. The first order seismic crustal section indicates a three-layered model for the entire Indian peninsula including the Cuddapah basin (Kaila et al., 1979a) (Fig.1). The top layer has a velocity of 5.1 km/s corresponding to Kurnool sediments, 5.85 km/s related to the lower Cuddapah sediments and the bottom one having a velocity of 6.1-6.3 km/s, marks the Archaean basement. The upper mantle P-velocity varies between 7.91 km/s and 8.54 km/s (Kaila et al., 1987). A strong velocity gradient has also been observed to the east of the basin (eastern Ghat region) between 3 and 15 km depth (Tewari and Rao, 1990). The reinterpretation of data by some researchers introduce a layer of velocity 7.2 km/s at the base of the crust in the eastern part of the basin (Kaila and Bhatia, 1981). Some models show a velocity inversion with values in the range of 6.45 to 6.9 km/s, overlying a layer with velocity of 6.7 km/s in the upper crust at a depth of about 10 km (Chekunov et al. 1984; Tewari and Rao, 1987).

The configuration of the basin is controlled by two major fault systems situated in the east and west (Kaila and Tewari, 1985). Re-modeling of the digitized data reveals that these faults extend to deeper levels, there exists a high velocity layer of 6.7-7.2 km/s at lower crustal depths (Krishna et al., 1990) and the thickness of sediments is about 10 km (Mall et al., 2008). Chandrakala et al (2013) modeled the phases and suggested a five-layered model for the basin. Kaila and Tewari (1985) proposed an evolutionary model arguing that the basin was

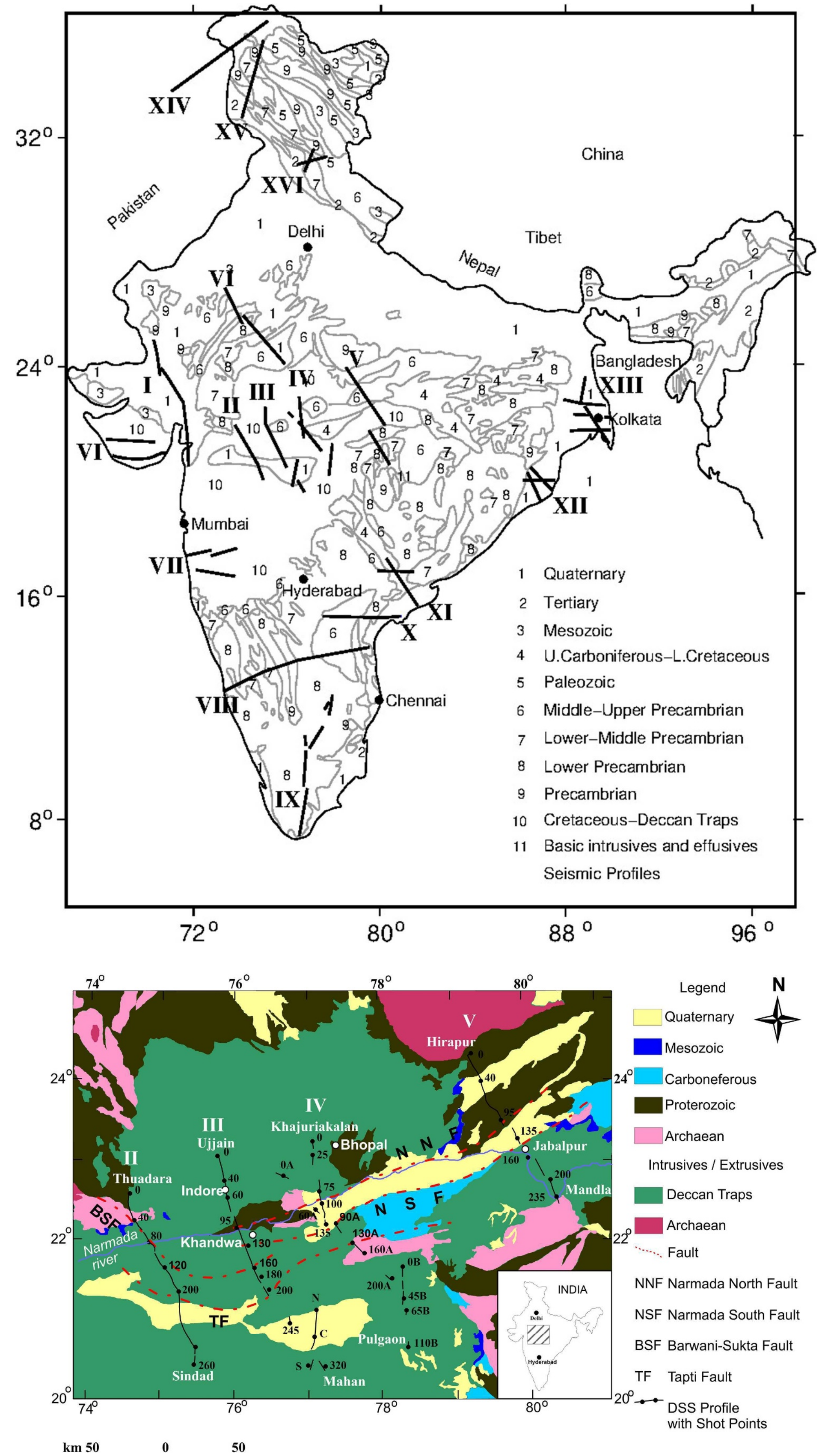

Fig.1. Simplified geological map of India with the location of Deep Seismic profiles **(a)**. The roman letter besides the profile denote different DSS profiles: I: Jakhau-Mandvi, Mandvi-Mundra, Mundra-Adesar, Hamirpur-Halvad. II: Thuadara-Sindad, III: Ujjain-Mahan, IV: Khajuriakalan-Pulgaon, Popatkheda-Patur, V: Hirapur- Mandla. VI: Navibandar-Amreli, VII: Koyna I (Guhaghar –Chirochi), Koyna II (Kelsi- Loni), VIII: Kavali- Udip, IX: Kupam –Palani, Vattalkundu- Kanniyakumari, X: Alampur-Ganapeswaram, XI: Paloncha-Narsapur, Kallur-Polavaram, XII: Baliamba-Jagannathpur, Mukundpur-Konark, Kabatbandha-Paradip, XIII: Beliator-Bangaon Gopali-Portcanning, Taki-Arambagh, Bishnupur-Kandi, XIV: Thanamandi-Nousehra, Kulgam-Pahalgam, Kulgam-Bizbehara, Gulmarg-N of Bandipur, XV: Fersi- Nerchawk, Barsar-Sandhera. **(b)** the central Indian tectonic zone and profiles are shown in enlarged version (modified from Kumar, 2000).

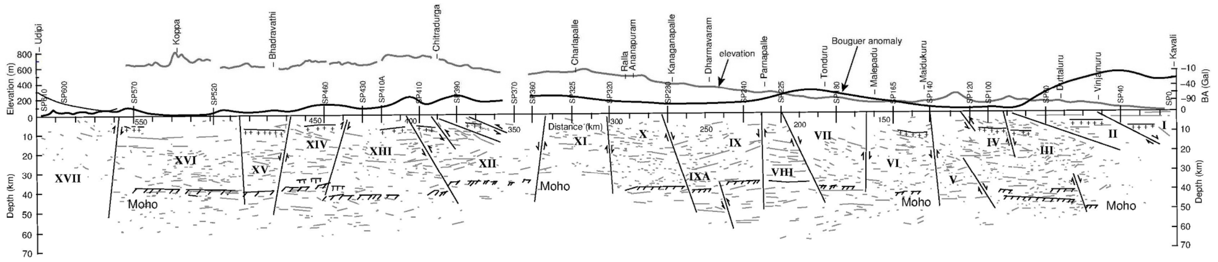

Fig. 2. Crustal depth section along the first seismic profile Kavalli-Udidpi (Profile VIII, as shown in Figure 1) (Kaila et al., 1979a).

created in its western part by down faulting of that crustal block during the Palaeoproterozoic with the deposition of lower Cuddapah sediments. The Moho depths in the Cuddapah basin indicate a horizontal displacement of blocks (Sollogub et al., 1977). The Moho is at a depth of 34 km in the western part and at 38-40 km (Kaila et al., 1987; 1979) in the eastern part of the basin. Another strong reflector is delineated at a depth of 43-48 km and interpreted as a double Moho in the eastern part of the basin.

Central Indian Tectonic Zone

Narmada Son Lineament

The Narmada region in central India bounded by the Narmada North Fault (NNF) and the Narmada South Fault (SSF), essentially consists of the Narmada-Son lineament in the north and the Satpura mobile belt in the south. The region has Bundelkhand craton to its north and the Dharwar and Bastar cratons in the south. A large part is covered by the Deccan Trap volcanics. Some of the opinions expressed about the origin and nature of the Narmada region are (a) swell, (b) zone of persistent weakness, (c) tectonic rift reactivated since the Precambrian time, (d) collision zone and (e) a failed arm. It is a zone of weakness that separates the regions of Meso-Neoproterozoic deposits to the north from the Gondwana (Permo-Carboniferous-lower Cretaceous) deposits to the south. To have a better understanding about the trap thickness and crustal configuration, the Geological Survey of India under the deep geology programme (Project CRUMNSONATA) sponsored Deep Seismic Sounding Studies, which were carried out by the National Geophysical Research Institute.

The crustal structure along the five profiles nearly orthogonal to the NSL has been delineated by DSS studies (Kaila et al., 1989). The profiles are from Mehmabad- Billimora (Profile I), Ujjain- Mahan (Profile-II), Khajuriakalan-Pulgaon (Profile III), Thudara- Sindad (Profile IV) and Hirapur- Mandla (Profile V) (Figure 1). The results reveal a number of new features of the Indian crust and subcrustal lithosphere. Three deep-seated faults at Narsinghagarh, Katangi, and Jabalpur (Kaila et al., 1989) have been delineated. These faults extend from the basement to the lower crust. A wide-angle reflection study along the Hirapur Mandala profile identifies a shallow structure that describes a horst feature in which high velocity (6.5 km/s) lower crustal materials rose up to a depth of ~2 km below the Narmada lineament (Sain et al., 2000). North of this horst feature, ~1.5 km thick Upper Vindhyan (4.5 km/s) and ~4.5 km thick Lower Vindhyan (5.3 km/s) sediments are present. An anomalous high velocity of 6.5-6.7 kms^{-1} is delineated in the upper crust in the entire Narmada zone (Murthy et al., 1998, Kumar, 2000: Kumar et al., 2002; Tewari et al., 2001). A layer with a P-velocity of 6.35-6.40 km/s exists below the high velocity layer which might be related to an intrusion. Based on the DSS results, a unified evolutionary model has been presented (Kumar et al., 2019; Tewari et al., 2018), where it is proposed that the high velocity body has been engulfed within the crust during the time of cratonization in the Archaean. The velocity in the upper mantle is 7.8 km/s and the thickness of the crust varies between 40 and 44 km (Murty et al., 1998). Based on reflectivity modeling, a subcrustal laminar structure with alternate high and low velocity zones has also been inferred, related to partial melt at this depth (Murthy et al., 2005). An interesting hypothesis from these studies is that the Barwani-Sukta and Tapti faults bound the Narmada graben (Sridhar and Tewari, 2001) and play a vital role in shaping the tectonics of the region. The northern limit of sedimentation below the trap across the Narmada region are limited northwest-southeast extending Barwani-Sukta fault (Figure 1b). Further, the upper crustal configuration across this fault is quite distinct. Also, it is noticed that the basement configuration and top of the upper crustal high velocity layer along the Profiles I, II and III are shallower within the Narmada zone and deeper beyond this zone (Kumar et al., 2000; Tewari and Kumar, 2003). An underplated layer of P-velocity 7.2 km/s has been identified at a depth of 28-33 km along Profiles II, III and IV, and is not seen on Profile I, implying that this layer is either very thin or absent there, thus controlled by the disposition of Barwani-Sukta fault. This underplated layer is concurrent with igneous activity related to the extrusion of the Deccan Trap volcanics near the west coast of India, due to rifting above a region of anomalously hot mantle.

Deep Crustal Seismic Reflection Study Across the Central India Suture Zone

The Central Indian Suture zone (CSIZ), a mega shear zone, lies in between the Satpura mobile belt and Kotri-Dongargarh mobile belt (Figure 1). It is intriguing to note that the reflectivity pattern along Seoni-Kalimati DSS profile exhibits distinct oppositely dipping patterns on either side of the suture. In the northwest, the reflections dip towards the southeast, while in the southeast the dips are towards northwest (Reddy et al., 1995). The crustal configuration from reflection data shows a sporadically variable thickness ranging between 41 and 46 km (Reddy et al., 2000). Mall et al., (2008) processed the data and presented a tectonic evolution model based on the reflectivity pattern, revealing the presence of a Mesoproterozoic collision between two micro-continents, with the Satpura mobile belt in the north being thrust over the Bastar craton in the south. In recent times, Mandal et al (2014) processed the data using the Common Reflection Surface (CRS) technique, providing an unambiguous picture of the reflectivity patterns. They brought out strong bands of dipping reflectors in the northwestern portion of the profile (between Seoni and Katangi), indicative of a conspicuous dome type structure. A tectonic evolutionary model of the CIS has been proposed, advocating northward subduction of the Bastar craton below the Bundelkhand craton.

Southern Granulite Terrain (SGT)

The southern granulite terrane of India is a classic example of exposed Archaean lower crust, providing a great opportunity to understand and explore the nature of deep continental crust. In 1997, under the aegis of CSIR-NGRI, deep seismic reflection and wide-angle reflection studies have been carried out along a 300 km long Kuppam-Palani profile and about 220 km long Vattalkundu-Kanyakumari profile. The results indicate that the crust along Kuppam-

Palani has four-layers (40-45 km), with a velocity inversion in the mid crust having thickness of 7-15 km and velocity of 6 km/s (Reddy et al., 2003), which is attributed to a low-density mega shear zone of mantle origin. Interestingly, there is another high velocity (6.9-7.1 km/s) layer at the base of the crust, interpreted as magmatic underplating. One of the most important findings from this profile is the deepest Moho (~ 47 km) at about 50 km south of Kuppam, possibly indicative of a crustal root. The reflectivity pattern in the southern part of the profile shows a dipping reflection fabric related to the collision between the Dharwar Craton in the north and a crustal block in the south- a part of the Eastern Ghat Mobile belt (Vijaya Rao et al., 2006). To the south of Bhavani, intriguing features in the seismograms have been interpreted as back-scattered signals (secondary arrivals) with a reverse move out between 3.5 and 6.5 s TWT (10-20 km depth km), which is suggested to be the locale of the shear zones (Vijaya Rao and Rajendra Prasad, 2006).

Along the Vattalkundu-Kanyakumari Profile, two-dimensional tomographic compressional (P) and shear (S) wave velocity images and V_p/V_s ratios, derived from refraction/post-critical reflection data show relatively high V_p (6.3-6.5 kms^{-1}) and V_s (3.5-3.8 kms^{-1}) bodies in the upper crust (Rajendra Prasad et al., 2006). The southern part of this profile shows a strong reflectivity pattern in comparison with the northern part, and interpreted in terms of re-crystallization of the crust due to ultrahigh-temperature metamorphism (Rajendra Prasad et al., 2007). Mandal et al (2021) also reported a subduction zone from the surface to the upper mantle up to 60 km bounded by two shear zones, such as Achankovil Shear Zone(AKSZ) and Tenamalai Shear Zone(TSZ), respectively. Two strike-slip faults, the AKSZ and TSZ are represented as two separate shear zones instead of a single structure.

North-West Indian Shield

Deep Seismic Reflection Profiles across the Aravalli Delhi Fold Belt

The Aravalli Delhi Fold belt (ADFB) in the northwestern part of India imprints evidence for the formation of the earliest day of the earth from the Mesoarchaean to the present time (Sinha-Roy et al., 1995). The region is divided into Marwar Basin, Delhi Fold belt, Sandmata Complex, Mangalwar complex, Hindoli groups, and the Vindhyan basin (Chambal valley). The region has experienced four major regional tectono-magmatic and metamorphic events at about ~3000 Ma (Bhilwara gneissic complex), ~1800 Ma (Aravalli orogeny), ~1100 Ma (Delhi orogeny) and 850-750 Ma (post-Delhi magmatic event). Consequently, the crust has evolved through the successive Proterozoic orogenic belts on an ensialic basement of Archaean age. It is constituted of the Sandmata and Mangalwar complexes and Hindoli group of rocks (Sinha-Roy et al., 1995). In order to understand the crustal architecture and tectonic evolution, a 400 km long reflection profiling was conducted across the Aravalli mountain range and over a 210 km long profile has been recorded along the Nagaur -Ajmer-Kota-Jhalawar transect using two 60 channel DFS V digital systems with 100 m geophone spacing and 4 ms sampling interval.

Refraction and post-critical reflection studies show a crust with P-velocities of 5.75, 6.20, 5.80 and 6.60/7.30 km/s, followed by an upper mantle velocity of 8.40 km/s and a velocity reversal at the base of the crust (Tewari et al., 1997a). Subsequently, Satyavani et al (2001) proposed a velocity model for the Marwar basin. Velocities in the upper and lower Vindhyan sediments are 4.6-4.8 km/s and 5.1-5.3 km/s respectively (Rajendra Prasad and Vijaya Rao, 2006). The Marwar basin (between Nagaur and Ren) exhibits a three-layered velocity model above the basement of velocity 5.9 km/s (Vijaya Rao et al., 2007).

However, significant observations within the crust are derived mostly from the reflectivity pattern based on which the region has been further divided into five sub-blocks i.e., (a) moderate to highly reflective Marwar basin, (b) moderate to poorly reflective Delhi fold belt, (c) poorly reflective Sandmata complex, (d) highly reflective Mangalwar complex and Hindoli group, and (e) moderately reflective Vindhyan basin (Tewari et al., 1997b). Although the Moho could not be imaged in earlier studies, a new processing scheme using Common Reflection Surface stacking, brought out the Moho at about 50 km depth under the Sandmata complex (Mandal et al., 2014). The lower crustal reflectivity pattern beneath the Marwar and Delhi fold belts is more or less similar, implying that the former is an extension of the latter (Rajendra Prasad et al., 1998). Based on the image and reflectivity patterns, operation of plate tectonic processes from Proterozoic to Phanerozoic has also been suggested (Rajendra Prasad et al., 1998, Mandal et al., 2014). Further, several dipping structures have been identified in the migrated near offset reflection images on the western margin of the Delhi fold belt (Krishna and Vijaya Rao, 2011). The image generated by Mandal et al (2014) hypothesized a palaeo-subduction zone during the Mesoproterozoic period, with no major tectono-thermal activity thereafter (Mandal et al., 2018). The Moho topography varies in depth from 38 km to 52 km along the profile, with the highest crustal thickness in ADFB. The Jahazpur thrust extends up to the lower crust, where the Moho is at a depth of 40-46 km (Fig. 3).

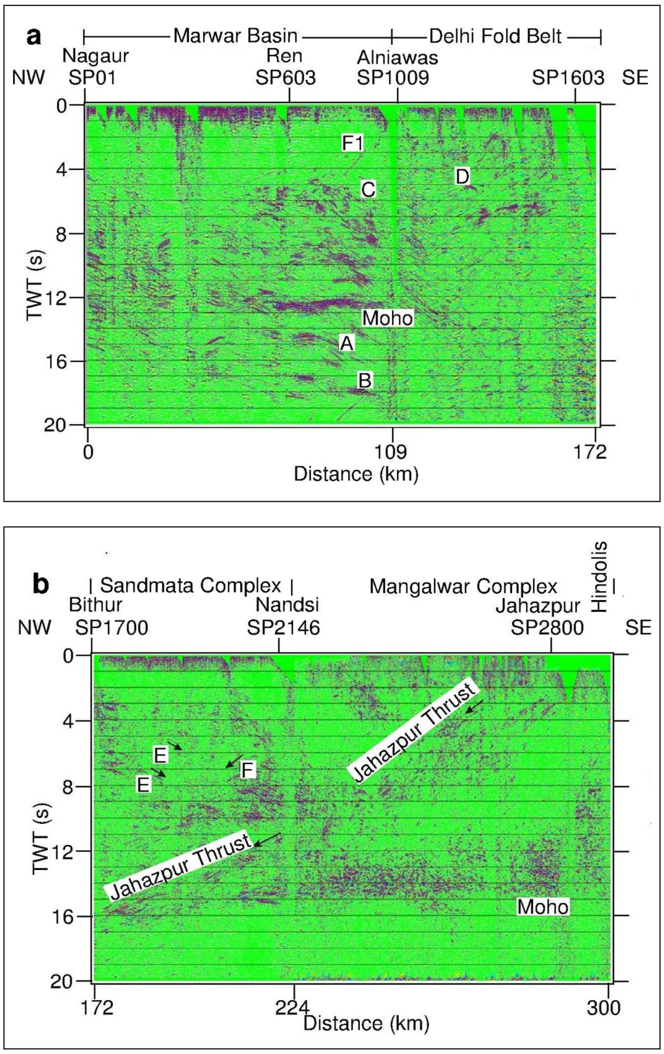

Fig. 3. Examples of true scale of migrated depth section showing the reflectivity pattern in (a) Marwar basin and Delhi fold belt and (b) Jahazpur thrust Fault along Profile VI (Figure 1). The distances are from Nagaur, SP 0 (modified from Mandal et al., 2014).

Deccan Volcanic Province and the West Coast

Koyna Region

The Koyna region is located close to the west coast of the Indian shield and is covered by the Deccan volcanics. The region is known for its reservoir triggered seismicity, where seismicity was first observed just after the impoundment of the reservoir in 1962 (Guha et al., 1968).

During the early eighties, CSIR-NGRI shot two parallel reflection and post-critical reflection profiles in this region in order to delineate the crustal structure and thickness of the Deccan traps, at the request of the Koyna Project Authority, Maharashtra Government. Profile -I runs from Guhagarh to Chorochi (Koyna I) and profile 2 runs from Kelsi to Loni (Koyna II), each ~200 km long and separated by about 70 km (Fig.1). The results reveal, for the first time, a variation in trap thickness from 400 m in the east to 1500 m in the west in Koyna-I and 700 to 1500 m in Koyna-II (Kaila et al., 1979b, 1981a). However, the Moho along the Koyna I profile is at a depth of about 40 km in the western part, and shallows towards east with values between 36 km and 38 km. Along Profile II, the Moho is at a depth of 39 km and 37 km in the western and eastern blocks respectively.

The data were later digitized and reinterpreted utilizing both travel time and amplitude information. A 1D velocity model has been generated till the uppermost mantle depths. The significant features of this model are the presence of two low velocity layers in the upper crust between 6.0 and 11.5 km depth and another at lower crustal depth from 26 to 28 km (Krishna et al., 1989). These two low velocity layers represent zones of lower rigidity and are associated with the hypocentral depths of local earthquakes. Further, the Moho has been found to be a transitional boundary with 2-4 km gradation. An alternate high and low, laminar velocity zones have also been modeled in the uppermost mantle (Krishna et al., 1991) using reflectivity synthetics.

The Cambay Basin

It is speculated that a large thickness of early Mesozoic sediment exists under the Deccan volcanics in some parts of the Cambay rift basin. Also, due to its large hydrocarbon potential, seismic studies have been continued since early fifties. CSIR-NGRI initiated its seismic refraction/post-critical reflection studies along Mehmadabad -Billimora (Profile I in Figure 1) during 1986-87 in the northern part of the basin to image the basement and the velocity-depth configuration of the crust. A number of deep seated faults cutting the basement with some of them reaching to the base of the crust have been identified. The Moho has been mapped at 38 to 40 km depth in the southern side of the profile, with a high-velocity (7.2-7.5 km/s) layer above the Moho. This layer represents magmatic underplating in the region. (Dixit et al., 2010). The granitic basement is identified at a depth of 6-6.5 km. In most of the places, the tertiary sediments are mapped with a thickness of 1-1.5 km (Kaila et al., 1981c). A number of faults are found to dissect the basin. In the Broach area, the basin is the deepest, the depth varying between 350 and 8000 m (Kaila et al 1981b, 1990b). The crustal thickness is shallower in the northern side of the region, in the range of 31-33 km. Dixit et al. (20010) reinterpreted the digitized version of the data after reprocessing, favoring the presence of subtrappean sediments. A maximum sediment thickness of 7.5 km has been delineated between Jambusar and Broach, with the granitic basement at 9.5 km depth.

The Saurashtra Peninsula

In 1977, the CSIR-NGRI launched a deep seismic experiment in Saurashtra Peninsula to delineate the trap thickness, identify intra-trappean sediments and image the crustal section. Acquisition of analog seismic refraction and post-critical reflections data began along Navibandar to Amreli in the western part of the Saurashtra peninsula (Profile VI in Figure 1). Initial results show a trap thickness of 1.3 km and about 400 m thick layer of Quaternary/Tertiary sediments at the western end of the profile (Navibandar). The trap thickness remains constant along the profile till Junagarh, while it thins to about 0.35 km towards Amreli. The basement has been delineated with a P-velocity of 5.85 to 6.0 km/s. A low velocity layer of 2.8 km/s has been inferred, with a maximum thickness of 0.85 km, possibly related to Mesozoic sediments (Kaila et al., 1980).

An underplated layer has also been identified above the Moho whose depth varies from 33 to 36 km (Rao and Tewari, 2005). A number of faults are identified along the profile, creating a horst and graben type of structure.

East-coast Sedimentary Basins of India

There are three prominent deltaic sedimentary basins in the eastern part of the Indian shield i.e., the Bengal, Mahanadi and Pranahita-Godavari basins (Figure 1). These basins are formed due to the break-up of the east Gondwanaland during the upper Carboniferous-lower Cretaceous period. The evolution of the basins is also affected by the complex magmatic and tectonic history of the region. Due to the hydrocarbon prospect, the basins are explored extensively using seismic studies. In order to decipher the sediment thickness and crustal structure, seismic refraction and post-critical reflection data were collected in the Mahanadi and Godavari basins in analog and digital forms in the West Bengal basin.

West Bengal Basin

The Bengal delta is known to be the largest delta in the world, that evolved due to the break-up of the east Gondwanaland and subsequent drift of the Indian plate from Antarctica and Australia (Curray et al., 1982). Most of the early Gondwana sediments are concealed under the Rajmahal volcanic traps that resulted from the Kerguelen hot spot activity. Deep seismic sounding studies (refraction and post-critical reflection) were carried out by CSIR-NGRI in the Bengal basin during 1987-88, along four profiles (Figure 1) - three in the east-west direction; Gopali-Port Canning (Profile P1), Arambagh-Taki (Profile P2), Beliatore-Bangaon (Profile P3); and one in the north-south direction - Bishnupur-Kandi (Profile P4) (Kaila et al., 1992; 1996). The basin was mapped well in the entire zone with a south-easterly dipping nature of the basement having a maximum depth of about 14 km at the eastern end of the profiles, close to the Bangladesh border. Interestingly, a Hinge Zone has been identified in Profile-P1, a sharp flexure in Profile-P2 and a basement up warp on Profile III (Kaila et al., 1992). The intriguing feature of the Bengal basin data is the presence of high energy multiple phases - parallel to the first arrival phases. Sarkar et al. (1995) analysed these phases and remodeled the sedimentary basin configuration. Tomographic modeling shows a variation of seismic velocity within the basin and an extension of the Hinge Zone, which is correlated with thinning of the crust. The depth to the Moho varies between 36 and 26 km along Profile P3 and is about 33 km along Profile P1, while, it is at a depth of 35 km along Profile P4 (Profile XIII in Figure 1) (Kaila et al., 1996; Rao et al., 1999).

The data along all the four profiles were later reinterpreted and a strong reflector of high P-velocity (7.5 kms^{-1}) is identified at the base of the crust (Mall et al., 1999). An underplated layer provides evidence for the trace of a mantle plume in the continental region with an up-warp in the Moho depth. Interestingly, the model proposed by Mall et al., shows a rift-pillow, which should be normally associated with the rift structure at the base of the crust (Tewari et al., 2018). Based on modelling, Krishna and Vijay Rao (2005) show two low velocity layers in the basin, one in the upper crust (10 to 12 km depth) and the other in the lower crust (30 to 32 km depth).

Damodar et al. (2017) also present a pseudo three-dimensional

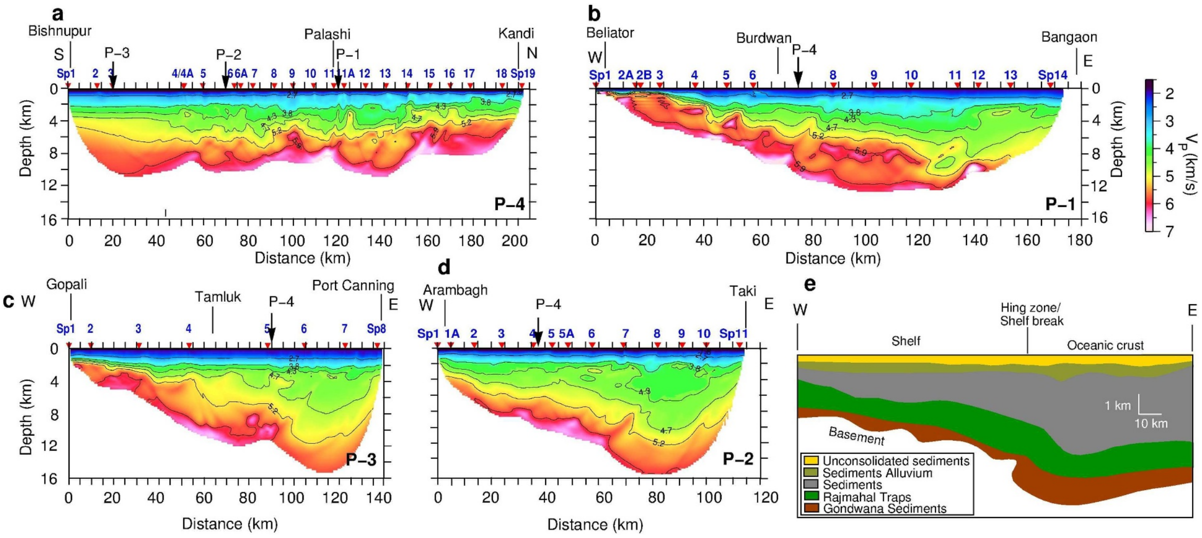

Fig. 4. The tomographic model of sedimentary thickness along the four seismic profiles in Bengal basin (Profile XIII as shown in Figure 1). **(a to d).** The subplot in **(e)** depicts the cartoon diagram showing the hinge zone and deepening of the basement (modified after Damodar et al., 2017).

basement picture of the west Bengal basin (Figure 4). Their results show an extension of the Hinge Zone in the northeast direction up to a distance of 150 km, that coincides with magmatic underplating above the Moho.

Mahanadi Basin

The Mahanadi delta located around the convergence of the river Mahanadi with the Bay of Bengal, is a classic example of an arcuate delta. The geology of the region is mainly controlled by the eastern Ghat orogeny that is limited in extent towards the west by a number of faults of the Jurassic period. The basin is also associated with widespread volcanic activity due to the separation of India from Antarctica and Australia during the early Cretaceous (Burke and Dewey, 1973). A number of faults in the basin are associated with the creation of horst and graben structures such as Cuttack, Puri-Konark and Paradip depressions. These grabens mostly host Gondwana coals of upper Carboniferous and early Cretaceous. Since the basin is known for its hydrocarbon potential, a number of geophysical studies have been conducted. However, to elucidate the evolution of the basin and to decipher the basement configuration, CSIR-NGRI gathered long-range seismic refraction and post-critical reflection data during January-May 1983, along three profiles (Profile XII in Figure 1). Profiles I (Konark-Mukundpur) and III (Paradip-Kabatabandha) traverse the Cuttack depression while Profile II (Ballamba-Jagannathpur) is along it. Profile I also cuts the Konark depression and Profile III the Paradip depression. The data were recorded in analog form along a short length of the profiles. Therefore, the coverage of the crust-mantle boundary is very limited.

Results reveal a four-layer crustal model of the region with a good demarcation of the Precambrian basement configuration (Kaila et al., 1987b). The maximum depth to the basement is reported to be about 2400 m in the Konark depression and 2100 m in the Paradip depression. The model shows presence of a low velocity layer at 17.5 km depth with crustal thickness varying between 30 and 34 km (Kaila et al., 1987b). The Konark depression consists of three sedimentary layers with velocities of 1.7, 2.4, and 4 km/s. Based on the first arrival travel time skip phenomena, a 1.75 km thick low-velocity layer, belonging to the Gondwana period (4 km/s), having a basinal shape, has been identified. However, based on drilling results, the earlier model of this depression was modified to show the presence of two thin high velocity volcanic layers (Tewari, 1998).

Subsequently, the analog wide-angle data were digitized and reinterpreted based on results from inversion (Behera et al., 2002). The Konark depression has been identified as a series of alternate Graben and Horst structures. The crustal thickness (35–37 km) has been found lesser compared to the adjacent areas (including Indian shield and Godavari graben) where the average thickness is ~42 km. Behera et al. (2004), further suggested the presence of an underplated crust in the Mahanadi region related to the Kerguelen hot spot activity.

Pranahita-Godavari Rift Basin

The Godavari rift basin (Profile XI in Figure 1) is an intra-continental rift, extending along northwest to southeast. Major sedimentation in this basin took place during the Proterozoic and Gondwana (Permian-Jurassic) periods. The graben is filled with 2.8 km thick Gondwana sediments. As a part of the hydrocarbon exploration activity, ONGC sponsored the seismic work to CSIR-NGRI, to map the basement configuration. However, CSIR-NGRI has utilized this opportunity also to study the crustal structure down to the Moho. The data were recorded in analog form along two profiles from Paloncha to Narsapur, and Kallur to Polavaram (Kaila et al., 1990a). 2D modeling of the data shows three layers, with the Moho at about 41 to 43 km depth. The data were later reprocessed using the first arrivals and the model has been modified along the Paloncha-Narsapur profile (Tewari et al., 1996). The important result was that the basement velocity (5.4 km/s) has been found to be a little lower than that normally found in the Archaean rocks. It is inferred that the basement beneath the Gondwana group possibly belongs to the Proterozoic or eastern Ghat suite of rocks.

DEVELOPMENT OF NEW METHODOLOGIES FOR DEEP CRUSTAL SEISMIC STUDIES

Tremendous efforts towards the development of efficient methodologies were made by the researchers of CSIR-NGRI in the past 6 decades. A few significant theoretical developments are listed below.

A statistical method akin to an inversion scheme has been developed to interpret the refraction data to estimate the thicknesses and velocities of different layers. The method effectively solves the hidden layer problem, a fundamental one in seismic interpretation (Kaila and Narain, 1970). They further provided an approach (Green's method) to resolve a multilayer overburden. Its practical application has been demonstrated using real data from the Hoshiarpur-Tanda profile acquired by ONGC.

A computer program was written for carrying out the migration of seismic reflection data, when the usage of computer was in its infancy. The method utilized a pair of direct and reverse reflection travel time curves from two reciprocal shot points for finding the effective velocity. The method yields more accurate results in various theoretical and field cases than the conventional graphical wave front methods which are widely used for crustal reflection work (Kaila and Krishna, 1979). Another indirect method has been proposed to solve the low velocity layer problem in seismic prospecting. The method enables determination of the thickness of a low-velocity layer (LVL) underlying a high- velocity layer (HVL) (Kaila et al., 1981). The method employs the comparison of two average velocity-depth functions, one derived from first arrival refraction data and the other from reflection data in the same region below the LVL. It was proposed that it is possible to identify the LVL and estimate its thickness. The applicability has been demonstrated to field data.

An analytical migration method has been developed for wide angle seismic reflection travel time data using the concept of effective vertical inhomogeneous earth. The migration process was rapid and improved as it replaces the curved path by equivalent straight line paths (Kaila et al., 1982).

An attempt has been made by CSIR-NGRI to carryout damped least square inversion of wide-angle seismic reflection data (Sain and Kaila, 1994). A fast and simple method for inversion of non-hyperbolic travel time data to estimate the interval velocities for a multilayer earth model has been proposed by calculating the forward response, retaining the higher order terms of the reflection series of the Taner Keohler series, through Chebychev (orthogonal) polynomial approximations. (Sain and Kaila, 1994).

In a multi-layered earth system, a solution to low-velocity layer problem has been discussed and solved using traveltimes of first arrivals alone. The method is based on layer-stripping applied to the post-critical reflection times from the bottom of the low velocity layer (Sain et al., 1995).

A theoretical approach has been provided for joint inversion of travel time data from refraction and wide-angle reflections data to calculate the thickness of the overlying layer and low-speed layer (Sain and Kaila, 1996b).

The acquisition of wide-angle reflections data is a routine to decipher the crustal structure. However, using the hyperbolic approximation to the travel times at far offset may lead to the error estimation of crustal parameters. An approach to estimate the interval velocities and layer thicknesses in a vertically heterogeneous earth using layer stripping method has been proposed, unlike Dix's hyperbolic approximation (Sain and Kaila, 1996a, 1996b).

Sain and Kaila (1996c), further discussed about the necessary condition for the seismic refraction data to be detected as first arrivals for a multilayered earth. Again, a stripping method has been employed to fit the first arrivals in a least-square sense to avoid subjective judgment.

In geophysical prospecting, a common problem encountered is the scenario of velocity inversion with high velocity layers (HVL) alternating with low velocity layers (LVL). In models where the relative thickness of the LVL is larger than that of the HVL, a skip in refraction travel time is observed. This can be modeled to determine the thicknesses of the HVL and LVL. An example of this phenomenon is visible in the alluvium-covered Cuttack depression of the on-shore Mahanadi basin, where travel-time shifts can be correlated with thin volcanic layers in the well data (Tewari, 1998).

Ghosh and Kumar (2002) analytically and numerically established that the time-offset Taner-Koehler power series employed in reflection seismics are in fact divergent and asymptotic in nature. The divergence becomes prominent when larger number of terms are included in it. The work further suggests the optimal strategy to use this series to represent the reflection travel time curves.

An approach to estimate the thickness and average velocity of the layers has been proposed using the travel times of wide-angle reflection data without the knowledge of any velocity information of the overlying structure (Kumar et al., 2003).

SEISMIC STRUCTURE OF THE CRUST AND LITHOSPHERIC MANTLE OF THE INDIAN SHIELD FROM SEISMOLOGY – SIGNIFICANT RESULTS

Crustal structure of the Indian shield is largely known from the results of active-source deep seismic programs primarily conducted by CSIR-NGRI in various geological provinces. Although the seismic refraction/wide angle reflection data provides fine scale and accurate determination of the depths and velocities of the crustal layers, however due to its expensive nature and logistic requirements, it is not always possible to acquire data everywhere. Consequently, a large part of the Indian shield remained unexplored. The gaps have been filled by relatively low-resolution methods using earthquake sources. The widely used methods to effectively image the gross structure of the crust employ converted waves (Receiver Function Analysis) and surface wave dispersion. Due to their large penetration depth and low frequencies, these methods also provide a good deal of information from the upper mantle and thus became standard tools for seismologists.

In the sixties, Indian researchers initiated surface wave dispersion studies by measuring the group velocity (Tandon, 1964) from arrival times of peaks and troughs. Gupta and Narain (1967) were the first to estimate the crustal thickness in the Himalaya and Tibetan Plateau regions using surface wave dispersion data. Almost a decade later, based on the Rayleigh and Love wave data due to an earthquake in the New Hebrides Islands (9 July, 1964) recorded at the WWSSN stations CHG in Thailand and New Delhi (NDI), India, Gupta et al. (1977) reported an interesting observation that the velocity structure beneath the Indo-Gangetic plain is akin to that in the shield. Apart from the dispersion studies, some researchers also used travel time curves from regional, teleseismic and nuclear explosions to decipher the structure. One such observation suggests three prominent discontinuities at depths of 400, 650, 950, 1350 and 1900 km (Kaila et al., 1968). They further estimated the range in upper mantle P and S wave velocities to be 8.2-8.4 km/s and 4.6-4.8 km/s respectively. A similar work using the statistical analysis of travel times of shallow local earthquakes revealed a Pg-velocity of 5.6 km/s and a Pn velocity of 8.1 km/s in the shield area with a crustal thickness of 37 km (Narain et al.,1968, Kaila and Reddy, 1969).

There is a paradigm shift in our understanding of the Indian lithosphere due to the digital era in seismology, enabled by the establishment of permanent and temporary networks in the shield region. During this period, numerous imaging techniques have been developed. Other than the India Meteorological Department, the CSIR-NGRI pioneered in establishing national networks of seismological stations, since 1970. Under a collaborative research program between IPG, Paris and CSIR-NGRI, Hyderabad, a wide band digital seismograph was installed at CSIR-NGRI campus, Hyderabad. Using the data from this station the transfer function has been derived to obtain crustal structure below HYB (Singh et al., 1978). The thickness of crust was found to be 33 km. It is to be noted that the transfer function method first proposed by Phinney (1964) involves the spectral ratio method, where the radial and vertical components are used for the estimation of the crustal structure below the receiver. Subsequently, this method took the form of Receiver function analysis (Burdick and Langston, 1977; Vinnik, 1977) which enables the identification of weak converted phases from the Moho and upper mantle discontinuities. The first receiver functions were computed for

Hyderabad station by Gaur and Priestley (1997). Subsequently, Saul et al. (2000) estimated the RFs for HYB in a much improved way with large amounts of data and reported the crust to be about 33 km thick with a Poisson's ratio of 0.25.

Crustal Structure using Seismological Data

South India – Dharwar Craton and SGT

Under the aegis of CSIR-NGRI, a number of temporary seismic stations were installed in different parts of the country. The southern Indian shield is the most studied part. Mohan and Rai (1992) used coda waveforms from regional and teleseismic events recorded at the 20- station L-shaped GBA seismic array and indicated a zone of dominant scattering encompassing the crust in the region west of GBA, coinciding with a large N–S elongated intrusion, called the Closepet granite. The teleseismic S-P converted phase travel time and travel time residuals at 10 stations in southern India indicate an anomalously thick (4-5 km thicker) low velocity (-3%) crust beneath Kodaikanal (KOD). The granulitic crust here is also characterized by an oriented inhomogeneity (FPA of N60 °E), that could be due to the presence of Mylonites, while the crust beneath the adjoining Precambrian granite-gneiss terrain is devoid of it. This analysis lends support to the hypothesis of a continent-continent collision origin for the granulites in this region (Ramesh et al., 1992). The tau-p extremal inversion of P-wave travel times from 2 quarry blasts recorded by a network of 11 seismographs in the distance range of 30-250 km revealed an anomalous crust of thickness 53 km. Such a thick crust has been interpreted due to magmatic underplating at the base of the crust, that took place in the process of cratonization of the eastern Dharwar craton during the late Archaean (Rai et al., 1996). The P-wave teleseismic travel time measurements over the granulite terrain show an anomalous pattern of delayed arrivals in contrast to fast arrivals on the Dharwar craton. The study was conducted using data from a sparse network of 11 vertical component portable seismic stations. The P-wave velocity tomography using teleseismic rays indicates that the crust (0-40km) in the western Dharwar craton and the granulite terrain has a lower velocity (up to -3%) compared with the higher velocity (1-3%) observed over the eastern Dharwar craton. In the upper mantle (40-177km), the velocity beneath the granulite terrain is 2-3% lower compared to the western Dharwar craton. It is interpreted that since the late Archaean times, thick and chemically distinct lithospheres that did not participate in mantle convection are preserved in these regions (Srinagesh and Rai, 1996). In another work, Mohan et al (1997), inverted Rayleigh wave group velocities in a period range of 15-60s, along 54 paths across the Indian lithosphere. Their results reveal that the Indian shield has a high-velocity (4.4-4.6 km/s) upper mantle which, however, is slower than other shields in the world. A similar work has been attempted by Singh (1999) but for the period range of 5 to 60s for more than eighty propagation paths across the Indian subcontinent. High values of Rayleigh wave group velocities are concentrated at periods of 30 to 60s near the region of the Precambrian shield of central India, suggesting a continuation of shield type structure beneath the Himalaya. Further, a two-layer model for the Indian crust has been proposed based on the Rayleigh- and Love-wave group velocity dispersion curves. The upper crust is 14-km (Vs, 3.55 km/sec) and the lower layer is 25 km (3.85 km/sec) thick. The upper mantle velocity is 4.65 km/sec (Singh et al., 1999). A 3-D P-velocity map of the crust and upper mantle beneath the southeastern part of India has been reconstructed through inversion of 1161 teleseismic travel times measured at 24 stations of a temporary network (Prakasam and Rai, 1998). Across the array, velocity variations of 7–10 per cent in the crust (0–40 km) and 3–5 per cent in the uppermost mantle (40–120 km) are observed (Prakasam and Rai, 1998).

Another imaging tool which became a routine is the converted wave technique, or receiver function analysis. Using data from 10 broadband stations spread over the Indian shield, Kumar et al. (2000) presented a detailed crustal picture beneath the Indian shield. The results show a remarkably simple crust in the south Indian shield having thickness between 33 and 39 km, with an average Poisson's ratio close to 0.25. They found that the Archaean crust is devoid of any prominent intra-crustal discontinuities, while the Proterozoic crust in the northern part of the shield exhibits a complex character, due to the presence of additional seismic discontinuities, with a 40 km thick crust. This appears to follow the global trend reported by Durrheim and Mooney (1994) that the Archaean crust is thinner than the Proterozoic crust (Kumar et. al., 2000). Further, receiver function data also revealed a present day crustal thickness of 43-52 km beneath the 3.4-3.0 Ga mid-Archean segment of the western Dharwar craton (WDC), that is undisturbed by the Proterozoic events (Gupta et al., 2003). In contrast, the adjoining late-Archean (2.7-2.5 Ga) eastern Dharwar craton (EDC) has a 33-40 km crustal thickness similar to the global Archean average. Based on a detailed analysis, it was also argued that terrain accretion in the Dharwar craton during 3.4 to 2.5 Ga transpired through subduction related process. The crustal composition of the Deccan Volcanic Province and the Cuddapah basin are found to be similar to that of the southern India shield. The most unanticipated outcome of the receiver function analysis from the western Dharwar craton is an anomalous thick crust of 42–51 km beneath the mid-Archaean (3.4 – 3.0 Ga) segment. Srinagesh and Rai (1996), Gupta et al. (1991), and Gupta et al. (2003) have demonstrated the presence of a thick, cool lithospheric root beneath this region. In summary, the crustal thickness beneath the exhumed granulite terrain in southernmost India varies between 42 km beneath the central part and 60 km beneath the Nilgiri Hills with Poisson's ratios ranging between 0.24 –0.28. These observations of a thickened crust suggest significant crustal shortening in South India during the Archaean. However, Ramesh (2004) opined that the majority of the stations on WDC and SGT in particular, suffer severely from poor quality of multiples and consequently result in large errors in parameter estimates.

In order to reduce the uncertainties in crustal structure, one study by Rai et al (2003) performed joint inversion of surface wave dispersion and receiver functions using data along a 600 km long north-south corridor from Nanded to Bangalore. Inversion results show that on an average, the crust along the transect is two layered, with the top layer having a thickness of 12 km (Vs=3.81 km/s) and the lower crust is 23 km (3.66 km/s) thick. The average crustal thickness is 35 km. No evidence for a high velocity basal layer has been found in the central Dharwar craton, suggesting that there is no seismically distinct layer of mafic cumulates overlying the Moho (Rai et al., 2003).

A similar type of exercise has been attempted by Julia et al (2009) utilizing joint inversion of P wave receiver functions and Rayleigh wave group velocities at 38 broadband stations in the subcontinent. The results provide a comprehensive seismological perspective of the Indian crust. The inferences made were that the crust under the Archean Western Dharwar craton and Southern Granulite Terrain is 45 to 50 km thick with lower crustal velocities around 4.1 km/s. Whereas, the crust beneath the Archean Eastern Dharwar and Bundelkhand cratons is 32–35 km thick with lower crustal velocities around 3.8–3.9 km/s. The crust is 50–65 km thick under the Proterozoic Bhandara craton, with lower crustal velocities around 4.2–4.3 km/s; and 55 km thick under the Proterozoic Aravalli-Delhi belt, with lower crustal velocities around 4.2 km/s. Finally, the study concluded that the deep crust in India can be attributed to mafic lithologies, with no secular change in the Precambrian evolution of the south Indian shield.

Under the *Indian Deep Earth Imaging Experiment* (INDEX) program, CSIR-NGRI deployed 70 broadband seismometers in the southern Indian shield to explore the crust and mantle structure. In order to study the crust, the converted wave technique has been applied.

The results revealed two types of crusts, one thin (32–38 km) in the EDC, CB and Madurai/Kerela Khondalite Block and the other, a thick crust (38–54 km) underneath the Western Dharwar Craton (WDC) and northern part of Southern Granulite Terrain. Compositionally, most of the crustal domains are felsic to intermediate (Vp/Vs <1.69–1.75) except the mid Archean block in the southern WDC where it is mafic (Vp/Vs > 1.81) (Rai et al., 2013). Results from inversion of surface waves derived from ambient noise are more or less similar to the earlier findings. However, a significant lateral variability in shear wave velocity and Moho depth in the Archean crust, beneath the Dharwar craton have been seen. Borah et al (2014) suggest that the preserved mafic crustal root beneath the middle Archean terrain in the WDC has remained inert since its formation. On the other hand, felsic to intermediate composition of crust with a nearly flat Moho beneath the late Archean EDC could be a consequence of regional delamination of lower crust. However, the crustal scenario within the SGT is quite different. Based on receiver function analysis of data from 14 broadband stations from SGT, Das Sharma et al (2015) suggest that there is a step of 2.5 to 10 km in the Moho depth across the eastern and western segments covering the Namakkal and Madurai blocks accompanied by a compositionally distinct crust. Most of the crustal blocks in DC and SGT have low to moderate Vp/Vs (1.72–1.76) representing felsic to intermediate composition. Exception to the above includes the Archean granulite terrain with high Vp/Vs (1.76–1.81) suggestive of more mafic crust beneath it. However, the receiver function results presented by Das (2015) do not support any distinction between late Archean and Proterozoic crust. Also, it is argued that the Deccan volcanism at 65 Ma did not alter the crustal character beneath DC and SGT (Das et al., 2015).

Singh et al., (2017) examined a large number of existing data from the Indian continent and produced seismic images using 49,682 receiver functions. An updated crustal thickness map has been prepared using the results of controlled source seismics and RFs. The results reveal a (a) thickened crust (>55 km) at the boundary of the Dharwar Craton and Southern Granulite Terrain, (b) clear difference in crustal thickness estimates between Eastern Dharwar Craton and the Western Dharwar Craton, (c) thinner crust beneath the Cambay Basin between the southwest Deccan Volcanic Province and Delhi-Aravalli Fold Belt, (d) thinner crust (40 km) beneath paleo rift zones like the Narmada Son Lineament and Godavari Graben, and (e) very thick crust beneath central Tibet (>65 km) with maximum lateral variations along the Himalayan collision front (Singh et al., 2017).

In a work limited to the Dharwar craton, Singh et al. (2012) computed 1559 receiver functions at 10 stations using waveforms of 777 earthquakes. The results show an interesting observation that the crust beneath the Godavari rift is shallower (33km) compared to that outside it, where it is about 40 km thick.

In the southern Indian shield, the Palghat-Cauvery Shear Zone System (PCSS) and the Palghat-Cauvery Suture Zone (PCSZ) are conspicuous mega features which comprise crustal-scale structures related to multiple episodes of orogeny, crust formation and reworking. It has been observed that the crustal properties across these weak zones are gradually changing. Beneath SGT, the crust is thick (> 38 km) and mafic (Poisson's ratio > 0.25), while, towards PCSZ the Moho gradually gets shallower southward (Kumar et al., 2018). In another study, Paul et al (2018) elucidated a relation between the topography of EDC and crustal thickness in terms of the total elastic thickness. For this purpose, they used receiver function data from 10 stations and suggested that the topography associated with the EDC is regionally compensated with a considerably large Te (30 km), implying low Airy isostatic anomalies and/or low density anomalies. The EDC is found to have an isostatic behavior and average crustal thickness distinctly different from other regions in southern India.

Analysis and modeling of receiver functions at 18 broadband seismic stations along a ~1000 km long seismological profile that cuts across both the EDC and DVP, using H-Vp/Vs stacking and generalized neighbourhood algorithm inversion of the receiver functions, show that the crustal thickness is more in DVP (34–40 km) than in the EDC (32–34 km). The crust beneath the DVP is underplated by magmatic material, forming a gradational Moho. Beneath the EDC, the Moho is sharp and lacks the underplated layer at the crust-mantle boundary (Kumar et al., 2020). A similar profile has been chosen in central India to investigate the crustal structure across the mega suture NSL. The Common Conversion Point (CCP) stacking from 10 station data reveals a duplex nature of the Moho with the crust being distinctly thicker (>52 km) within the rift zone compared to that on either side (40 km) (Kumar et al., 2015). The results favor evidence for high velocity magmatic underplating within the rift zone. Such wide spread magmatism has also been reported in other parts of the central and western parts of the Indian shield.

The RF data provide a good measure of the bulk crustal properties below the receiver, and quite a number of attempts have been made to understand the south Indian crust. However, very few efforts have been reported globally to understand the relation between the crustal properties and its age. In order to address this key issue, Haldar et al. (2018) used data from the Dharwar craton and argued that soon after the formation of the craton, it gradually altered, making it mafic-to-intermediate in bulk composition. They further suggested that the horizontal accretion process dominantly contributes to crustal evolution and reworking of the early Indian Archaean cratons also took place (Haldar et al., 2018).

Pan African Orogeny

Rai et al. (2009) further extended the study beyond the southern Indian shield by analyzing the receiver functions and surface waves from 88 seismological stations located in the continental fragments of Pan-African terranes. Their observation indicates that the average crustal thickness is 37.8 km with Vp/Vs of 1.7 with the thickest value of 43.5 km being beneath Kodaikanal (KOD). They suggest that the Pan-African orogeny was extensive enough to alter the crustal structure of a wide region with a broadly similar signature (Rai et al., 2009).

Eastern and Western Ghats

The Eastern Ghat Belt along the east coast of India, which is a collage of different lithotectonic domains, exposes deep segments of the continental crust, and is considered as a deeply eroded remnant of the present-day Himalayan-type setting. The southern segment of the EGB, around Kondapalli (Andhra Pradesh), records the entire gamut of processes from Palaeoproterozoic rifting to Grenvillian/Pan-African collision (Kumar and Leelanandam, 2008). Choudhury et al. (2016) analyzed data from a few stations along the EGMB, and computed the shear wave velocity. The shear wave velocity structure in the mobile belt shows that crustal thickness varies from 37 to 42 km and average shear velocity varies from 3.67 to 3.78 km/s. A low velocity layer of variable thickness and velocities 3.54–3.7 km/s is also observed in the region indicating the presence of fluid in the crust, which might be responsible for the intraplate earthquakes in this region.

The Western Ghats in the western coast of India is one of the largest escarpments on earth, containing Reunion plume derived Deccan Traps. It is an excellent locale to probe epeirogenic uplift, extension and subsidence in volcanic continental margins. The Western Ghat escarpment is widely considered to be the result of erosionally-driven isostatic uplift since Tertiary. Others have postulated or deduced strong neotectonic activity in the Ghat region. Saikia et al. (2016) presented the receiver function data along a 600 km long profile, including that from the Western Ghats. The Moho depth along the profile varies smoothly between 34 and 41 km, except beneath the Western Ghats and at the contact of eastern and western Dharwar

Craton, where it is offset by ~8 km. The study suggests possible differential uplift of the Western Ghats, as a consequence of India–Madagascar separation and the prominent role of deep crustal structure in the location of the escarpment, compared to the surface process. They further inferred that the presence of long-lived steeply dipping fault separating the two distinct Archean crustal blocks is indicative of a mechanically strong continental lithosphere beneath the Dharwar Craton (Saikia, 2016). Another study on Western Ghats by Gupta et al. (2018) using analysis of the teleseismic receiver functions at 36 broadband seismic stations shows that the crustal thickness is mostly 36 – 40 km. The seismic stations falling in the Western Ghats imaging the mid-Archean Nucleus of the Western Dharwar Craton and Nilgiri hills (ca. 2.2 km elevation) show a crustal thickness of 45 – 50 km. The Vp/Vs ratio is varying between 1.66 and 1.82 all along the Western Ghats.

The Singhbhum craton was devoid of seismological stations for a long time. Under a CSIR program, Mandal (2017) analyzed Rayleigh and Love wave data from 10 broadband stations. He derived a two-layered 40 km thick crust, with a 14-km thick upper-crust of average shear velocity of 3.0 km/s and a 26 km thick lower-crust of average Vs of 3.6 km/s (Mandal, 2017).

Central India (NSL/CITZ)

Krishna et al (2004) investigated the seismograms of the 21 May 1997 Jabalpur deep crustal (focal depth = 36 km) earthquake (Mw 5.8) recorded at 11 stations. A number of prominent phases including P-bar and Lg have been identified and modeled. The P-bar phase is generated and propagates efficiently in the Deccan Trap (Vp, 4.8–4.9 km/sec) covered regions (i.e., even without a lower velocity surface layer) surrounding the earthquake epicenter and the recording stations. The first observations of high-frequency Pn and Sn phases in the Indian shield are also recognized (Krishna et al., 2004). Full waveform modeling suggests a lamellae model with alternating high- and low-velocity layers in the Indian continental uppermost mantle. Additional phases from deeper levels are also recognized such as those from 230, 320, 430, and 680 km (Krishna 2004) indicating a laminar nature of Indian upper mantle. In the same region, across the Narmada lineament, receiver functions analysis suggests a down-warp of the Moho to ~52 km. The Vp/Vs is reported to be 1.84 within the lineament and ~1,73 in the surroundings, suggestive of a high-density mafic mass at depth that compensates the crustal root (Rai et al., 2005).

The uppermost mantle Pn and Sn velocities were further analyzed using the explosion sources (Krishna et al., 2005). Rastogi et al (2005) also observed these phases using data of 224 earthquakes along three different paths (Koyna, Chamoli–Uttarkashi and Kutch), combining the local data from seismic networks and a groomed ISC/NEIC database at regional and teleseismic distances, for the desired phases. The Pn and Sn travel-time anomalies revealed very strong signatures of lateral heterogeneity in the Indian subcontinent. However, in general, the stable continental shield is associated with faster velocities compared to the global average as in the ak135 model. On the other hand, the Himalayan front exhibits slower velocities.

In order to obtain a comparative crustal picture and seismological constraints of the evolution of the different geological units of Indian Precambrian shield, a seismological profile has been chosen in an N-S corridor covering southern granulite terrain to Delhi, on the Aravalli craton. Records from 22 seismographs have been analyzed using receiver function technique. Results suggest that the Archean terrains (Eastern Dharwar, Bastar, Bundelkhand and Aravalli cratons) are underlain by crust with felsic-intermediate composition (Vp/Vs ~ 1.65–1.75), in contrast to the mafic composition (Vp/Vs > 1.78) of crust beneath the Vindhyan basin, Godavari basin, and the Narmada-Son Lineament (NSL). The Moho depth varies between 33 and 43 km with no definite relationship with age of the crust. A duplex Moho (conversions from 35 and 45 km) with a highly mafic underplated lower crust is the characteristic feature of the NSL, signifying its paleo-rift character (Jagadeesh and Rai, 2008).

Indo Gangetic Plain

In addition to the southern Indian shield, the surface wave data also explored the crustal structure of other parts of India. The regional broadband seismograms of earthquakes (magnitude>4.7) originating along the Himalayan arc, recorded by the broadband seismographs of the National Geophysical Research Institute on the southern margin of the Gangetic foreland basin are used to model the multi-mode surface wave group velocity dispersion. The results show a three-layer crust with an average Vs of 3.7 km/s, draped by 2.5 km foreland sediments. The Moho is at a depth of 43 km and 41 km beneath the eastern and the western Ganga basins respectively. Crustal Vp/Vs shows a felsic upper and middle crust beneath the eastern Ganga basin (1.70) compared to a more mafic (1.77) crust in the western Ganga basin (Mitra et al., 2011).

Deccan Volcanic Province

Sarkar et al (2003) investigated the crustal structure of Dharwar craton by inverting the receiver functions at 6 broadband stations from the south Indian shield. Results show that the crust of the Dharwar craton is simpler, and has a lower (about 0.25) Poisson ratio compared to the adjacent Proterozoic crusts. However, the western Dharwar craton crust (thickness ~41 km) has a gradational Moho boundary, is substantially (>7 km) thicker than its eastern counterpart (thickness ~34 km). Interestingly, the crust beneath the Deccan volcanic province situated in the western Indian shield is found to be more or less similar to that of the eastern Dharwar craton. However, the crust in the Godavari graben is markedly different from the Dharwar crust and resembles that of a typical rift-valley (Sarkar et al., 2003). Similar procedure of computation has been adopted by Mohan and Kumar (2004) to estimate the Receiver functions from one broadband and nine short period stations located in the western coast of India and the western Deccan Volcanic Province (DVP). Both the regions are seismically characterized by a thick (36 – 41 km) shield like crust with a Poisson's ratio of 0.26 ± 0.01. Interestingly, based on their observation, they also inferred that the continental crust beneath these regions does not exhibit any typical seismic signatures of magmatic underplating nor appears to be perturbed by the Deccan volcanism (Mohan and Kumar, 2004). Later Mohan and Kumar (2005) analyzed the data at 6 broadband stations from DVP separately and observed the presence of sub-crustal low velocity layer below DVP having a uniform crustal thickness of about 36 km beneath all the stations. It is also observed that the velocity reductions are strong at some stations and relatively weak at other stations in DVP. They argued that this LVL could represent the presence of magma or fluids.

NW India: Cambay and Aravalli-Bundelkhand Region

Joint inversion of teleseismic receiver functions and surface wave data from Archean cratons of the Aravalli–Bundelkhand and Proterozoic Vindhyan basin shows a simple two layered crust with an average Vs of 3.3 km/s in the upper 10 km increasing to 3.7 km/s in the 26–28 km thick lower crust. This upper crustal velocity is significantly less compared to that of either the eastern Dharwar craton (3.5–3.6 km/s) or the global average, suggesting the presence of a highly silica rich upper crust and an intermediate composition of the lower crust (Vijaya Kumar et al., 2012). The Moho is modeled at a depth of 36–38 km with a thin transition (2 km) similar to that in the eastern Dharwar craton. In contrast, the Proterozoic Vindhyan basin has a significantly deeper Moho (44–46 km) with a 4–10 km thick underplated layer (Vs=4.0 km/s) at the base of the crust (Vijaya Kumar et al., 2012).

Rao et al (2015), analysed receiver function data from 58 stations in the northwestern DVP region and inferred large variation in Moho depths from 28 to 43 km in the Kachchh rift, 28 to 38 km in the Cambay rift, 39.5–41.5 km in the northern and eastern parts of the Cambay rift, and 29 to 39 km in the Saurashtra region and South Gujarat. A Moho up-warp of 6 to 7 km has also been indicated in the Saurashtra region owing to a positive buoyancy due to thermal influx affected by the Reunion plume. High crustal Vp/Vs ratios beneath the Kachchh rift (1.8 to 2.05), coastal areas of Saurashtra (1.75 to 2.06), and North Gujarat (1.81 to 1.85) indicate dominance of a mafic/ultramafic crust. Sharma (2018) further investigated the crustal structure in a larger region encompassing the northwest part of India by inverting regionalized group velocity dispersion data in the period range of 6 to 100 s, down to 220 km depth, using the genetic algorithm technique. She estimated a crustal thickness of 35-40 km in Kutch, 32-36 km in Cambay, 34-37 km in the Narmada Rift, 36-40 km in South Rajasthan and Central India, and 34-42 km in Saurashtra, South Gujarat, and other parts of DVP. Evidence for magmatic underplating in terms of a rift pillow beneath Cambay and eastern Saurashtra regions, was presented. Further, the surface wave dispersion study covering the Rajasthan craton and Aravalli mobile belt reveals a two-layer model of the crust. The top layer is 15-km thick with an average shear velocity of 3.12 km/s and the lower-crust is 25-km thick with an average Vs of 3.44 km/sec (Gupta and Mandal, 2020).

NE India

The crustal structure of the north-eastern part of India has not been investigated considerably. Since the region is seismically active, most of the stations were deployed with the objective to monitor the seismic activity. Using travel times of 16 regional earthquakes recorded by a 30-station network comprising 1 Hz vertical component seismometers operated during February- May 1993, Pn velocity and crustal thickness have been computed across NE India. The Pn velocity is found to vary from 8.3 to 8.5 km/s beneath the Shillong Plateau, Mikir hills and Assam valley, significantly higher than those in other parts of India (Rai et al., 1999). The crustal thickness in NE India was also found to be high, varying from 45-49 km under the Shillong plateau and the adjoining region. The presence of a thick crust and high Pn velocity was interpreted in terms of a cold lithosphere, as also indicated by seismicity at depths of 45-51 km in the region (Rai et al., 1999; Mohan et al. 1992). On the other hand, receiver function analysis using broadband data from a ten station network sampling the Shillong plateau, Mikir Hills, Himalayan fore-deep and the Himalayan convergence zone, reveals a remarkably simple crust with thickness (35 km) and Poisson's ratio (0.25), akin to the Indian shield values. A surprisingly thin crust for the uplifted Shillong plateau was explained invoking an uncompensated crust that popped up in response to tectonic forces. In contrast, crustal signatures from Assam valley suggest a thicker crust and higher Poisson's ratio with evidences for a dipping Moho (Kumar et al., 2004). Images of the crust and mantle beneath northeast India obtained by 2D migration of ~1000 broadband P-receiver functions clearly trace a northward dipping Moho from 36 km beneath Tezpur in the Assam Valley, reaching depths centered around 50 km in the sub-Himalayas within a distance of 75–100 km (Ramesh et al., 2005). In addition, based on modelling the RF data from different azimuths at station SHL, it was suggested that the Bengal sediments and the underlying oceanic crust under-thrust the southern part of the plateau, facilitated by EW-NE striking Dauki fault dipping 30^{o} towards northwest (Bora 2014).

Latur and Koyna Seismogenic Regions

Drilling down to 617 m in the Meizoseismal area of the 1993 Latur earthquake revealed a 338 m thick Deccan Basalt sequence underlain by a Peninsular Gneiss basement with an intervening intra-trappean bed of 8 m thickness (Gupta and Dwivedy, 1996a). In situ stress measurements by hydraulic fracturing reveal a maximum principal horizontal stresses (SHmax) of N11°E at 373m depth and N17°E at 592 m depth, with a mean value of N14°E (Srirama Rao et al., 1999). Seismograms of the aftershocks of this earthquake reveal a Pc phase that lags the Pg phase by about 0.6 to 0.8 sec, indicating a low velocity layer (LVL) at 7 to 10 km depth. This highly conductive (inferred from Magnetotelluric soundings), low velocity layer is interpreted as a fluid filled fractured rock matrix that enhances stress concentration in the uppermost brittle part of the crust causing mechanical failure (Gupta et al., 1996). Similar conclusions are drawn from modelling of reflected phases in a seismogram section of aftershocks recorded at 45 seismic stations. Alternating low-velocity layers (LVLs) for P and S waves are inferred at depths of 6.5–9.0 km and 12.3–14.5 km with a 7% velocity reduction and a lower crustal LVL at 24–26 km. The anomalous nature of the upper crust is interpreted in terms of partially- or slightly under-saturated fluids below the hypocentral region of the Latur earthquake and its aftershocks (Krishna et al., 1999). Detailed geological and petrophysical studies on the Late Archean basement cores from this borehole revealed a remarkable drop in the measured P-wave velocity in a number of high density cores. This velocity drop, as high as 15 % in some cores, is primarily attributed to up to 23 % FeO_T (total iron content as ferrous or ferric) enrichment during the course of retrogressive metasomatic reactions driven by mantle fluids, caused by exhumation of deep-seated mafic rocks (Pandey 2016).

Data from a 20-station digital seismic network deployed for twenty months in the Koyna region during 1996- 97 was used for 3-D velocity imaging of the seismogenic crust (0- 10 km) using travel time data of 400 local earthquakes. Up to 4% variations are found for the P- and S-wave velocity with the seismic zone having ~ 2% higher velocity compared to a 2% to 3% lower velocity in the surrounding region. These results argue against the presence of high-pressure fluid zones and suggest a possible linkage with a denser lithology. A segmented and matured nature of the seismogenic fault systems is revealed in the Koyna region where seismicity is possibly controlled by strain build up due to competent lithology in the seismic zone with a deep crustal root (Rai et al., 1999). Similar conclusions were drawn from results of 3-dimensional teleseismic tomography using 780 P-wave travel times recorded by this network. The correlation of high-velocity with the seismic zone suggests that the earthquakes occur in rigid rocks which have the ability to store strain energy and release it as brittle failure (Srinagesh, 2000). 3-D Vp and Vp/Vs tomographic models derived from inverting 7826 P- and 7047 S-P arrival times from 400 local earthquakes recorded by a 100-station seismic network operated for five months in the Koyna-Warna region also suggest high P velocities (~5.9-6.5 km/s) in the source region (Dixit et al., 2014, Kumar and Dixit, 2017). Kumar and Kumar (2019) utilized 4.5 Hz geophone data from 97 temporary stations to investigate the 1D velocity model through the inversion of P and S-times. Suitable station corrections have also been estimated. Further, shear-wave velocity structure of the Koyna–Warna region down to a depth of 10 km determined by inverting group velocity dispersion curves derived from ambient noise correlation and Rayleigh waves from local earthquakes indicates a 0.8 km thick basaltic layer with a shear-wave velocity of about 3.0 km/s, to the east of the western Ghat escarpment. A low-velocity of 3.3 km/s, possibly weathered granitic layer, is found below the traps that is underlain by a granitic basement having a velocity of 3.6 km/s. The velocity structure was found to be similar on either side of the escarpment (Rohilla et al., 2015). Results from P-receiver function analysis indicate that the Moho depth varies between 37.7 and 42 km with an up-warp beneath the seismogenic zone. A higher near-surface velocity (NSV) west of the escarpment is attributed to a thinner layer of Deccan traps compared to a thicker one in the east. An unusually high upper crustal shear-wave velocity of about 4 km/s is found at 5 km depth. It was surmised that this represents rocks having a large strength, capable of sustaining higher stresses. This coupled with preexisting brittle fractures that are triggered by the reservoir load and fluid effects are proposed as causative for the continuous seismicity over the last few decades (Rohilla et al., 2018).

Seismic Structure of the Indian Lithospheric Mantle

The initial investigations of the crust-mantle structure beneath the Indian shield have been attempted utilizing travel times of P and S waves from regional, teleseismic and nuclear explosions, picked from the analog records, and modelling their delays with respect to the standard travel time tables like J-B Preliminary analysis of very long-period surface waves (up to 600 s) recorded by a wide band digital seismograph station (GEOSCOPE), indicates that the crust and upper mantle structure below HYB (Hyderabad, India) are characterized by a high velocity down to a depth of 500 km. Both the group and phase velocities in the period range of 100-350s are found to be faster by 3-4% and 1-3% respectively compared to the global preliminary reference earth model (Rao and Gaur, 1991). The attenuation (Q) structure for the crust and uppermost mantle beneath northern and central India obtained by inversion of fundamental mode Rayleigh and Love waves using Backus and Gilbert formalism reveals a transition from lower to higher attenuation at 100 km depth, which is interpreted as the thickness of the lithosphere, with the Lithosphere-Asthenosphere Boundary (LAB) being not sharply defined (Singh, 1991).

Southern and East Indian Shield Regions

The tomography technique was first applied in India to teleseismic *P*-wave residuals calculated using data from short period (1 Hz) vertical component seismograph stations operated in the Deccan volcanic province (DVP). Evidence for an anomalous region in the upper mantle was presented where the velocity is 1 to 4% higher than in the surrounding regions, in the depth range of 100-400 km (Iyer et al., 1989, Ramesh et al., 1993). Results from these early studies revealed existence of a thick lithosphere beneath the south Indian shield, in accordance with the concept of a tectosphere (Jordan, 1988) that comprises several hundred kilometer thick continental roots of mantle material beneath stable cratons. It is postulated that these roots translate coherently along with the continents, during plate motions (Lam and Jordan, 1987). A decoupled nature of the lithosphere beneath the DVP was also proposed, with the upper 80 km represented by a low-velocity zone that is probably rejuvenated and decoupled from the underlying faster upper mantle that remained unperturbed at least since the Proterozoic period (Ramesh et al., 1990). Anomalously high velocities (1-6% higher) were found in the depth range of 60-300 km beneath the whole of south Indian shield including the Deccan Traps. In contrast, a low velocity zone in the westernmost part of the Deccan Traps and its adjacent mantle in the northwest was interpreted in terms of a warm remnant of the spreading center offset eastwards from the Carlsberg ridge, which might have been the dominant source for the eruption of Deccan flood basalt 65 Ma ago. These results provided the first seismic constraint on the possible source of the Deccan basalt (Srinagesh et al., 1989).

The upper mantle model derived for the south Indian shield by modeling fundamental mode Rayleigh wave phase-velocity dispersion suggests that the seismic lithosphere is ~155-km-thick and the Indian cratonic root is somewhat thinner than that found for many other cratons (Mitra et al., 2006). The average lithospheric thickness beneath the Eastern Dharwar craton, Bastar craton and Aravalli cratons is suggested to be ~165 km, significantly lower than that in the other undisturbed Archean cratons like Kaapvaal and Siberia (Jagadeesh and Rai, 2008). Images of the lithospheric mantle beneath southeast India encompassing the Eastern Dharwar–Bastar cratons and the adjoining Eastern Ghats mobile belt constructed using Ps and Sp receiver functions, reveal high-velocities in the depth range of 160 to 220 km depth (Lehmann discontinuity) and a mid-lithospheric discontinuity at 80–100 km depth. Invoking a >200 km thick lithospheric root, wide regions covering the Godavari graben and adjoining areas were identified as potential zones for diamond exploration (Sharma and Ramesh 2013). Evidence for mid-lithospheric low velocity at 85–100 km beneath South India was also presented by Rai et al (2013).

Interestingly, 3D P-wave tomographic studies of the granulite terrain show an anomalous pattern of 2-3% lower velocities in the upper mantle (40-177 km) compared to those in the western Dharwar craton (Srinagesh and Rai, 1996). It was postulated that such lateral velocity variation in the crust and upper mantle, and its preservation since late Archaean times, points to the presence of possibly thick and chemically distinct lithospheres that did not participate in mantle convection (Srinagesh and Rai, 1996). Lower velocities in the uppermost mantle along the Eastern Ghat mobile belt compared to those in the Dharwar craton west of it, have been interpreted in terms of a significant thinning of the lithosphere (200 km) as a consequence of Indo–Antarctica separation (Prakasam and Rai, 1998). A probable seismic lithosphere-asthenosphere boundary (LAB) at 120 km depth was detected based on the 1D velocity model derived from surface wave analysis of broadband data of the 2015 Nepal earthquake sequence recorded at 10 broadband stations of a network in the Singhbhum Odisha craton (SOC) and the Chotanagpur Granitic Gneissic terrane (CGGT). This provides evidence for the absence of keel or thick lithosphere below the region (Mandal, 2017).

As far as the LAB is concerned, not much work has been done in the northeastern region of the Indian shield. Based on the analysis of S receiver function analysis to data from a network of broad-band stations in the northeast India and Eastern Himalayan regions, the image the geometry of Indian Plate collision have been brought out. The Indian lithosphere is found to be only 90 km thick beneath the Shillong plateau deepening to 135 km on either side suggestive of a lithospheric up-warp related to the plateau uplift (Uma et al., 2011). The lithosphere thickens northward, with values reaching up to 180 km beneath the Eastern Himalaya.

Northwest India

Seismic velocity structure obtained from S receiver function analysis indicated that the lithospheric thickness varies from ~60 km beneath the Cambay rift to ~110 km beneath the periphery. It is suggested that a thermal plume rising from the mantle transition zone has triggered magma formation and aided the thinning of the lithosphere (Kumar 2016). They further suggest the presence of small amounts of carbonatite-type magma in the asthenosphere and the Cambay Rift Zone might become reactivated by the generation of small pockets of melt at the LAB, due to a thermal anomaly in the upper mantle beneath this currently inactive rift. Modeling of group velocity dispersion characteristics determined from data of 16 regional earthquakes recorded at four stations in Rajasthan, reveals a drop in Vs (~1-2%) at 79-120 km depths, underlying north India, representing a probable seismic lithosphere-asthenosphere boundary (LAB) at 79 km depth. A 1-2% drop in Vs at these depths is attributed to the presence of carbonatite melts in the upper mantle related to the Deccan plume activity (Gupta and Mandal, 2020).

The shear wave velocity (Vs) structure of the crust and upper mantle beneath the northwestern Deccan Volcanic Province was obtained by inverting regionalized group velocity dispersion data in the period range of 6 to 100 s, down to 220 km depth, using the genetic algorithm technique. The lithospheric thickness was found to vary from 80 to 124 km, being thinnest at the junction of Cambay and Narmada rifts, which was proposed as the source zone of volcanic eruption (Sharma et al., 2018). A thin lithosphere has also been observed beneath the Kutch seismic zone. A low-velocity zone at depths ~80 km has been related to the up-warping of the asthenosphere and/or the presence of partial melts (Sharma, 2018). Joint inversion of the regionalized Rayleigh and Love wave group velocities yielded similar results. Low Vs values, negative radial anisotropy and a thin lithosphere (<84 km) in the vicinity of Gulf of Cambay validated the presence of a plume head beneath it, in concurrence with the hypothesis of Indian Plate-Reunion plume interaction. Furthermore, these results affirm that the source of basaltic eruption lies beneath the Gulf of Cambay (Sharma et al., 2020).

Lithospheric Structure on a Continental Scale

The thickness of the lithospheric plates of the different fragments of Gondwanaland around the Indian Ocean estimated using the shear-wave receiver function technique revealed the thinnest lithosphere beneath India. The lithospheric roots in South Africa, Australia and Antarctica are found to be 180 to 300 km deep, whereas the Indian lithosphere extends to only about 100 km depth (Kumar et al., 2007). It is inferred that the plume that partitioned Gondwanaland may have also melted the lower half of the Indian lithosphere, thus permitting faster motion due to ridge push or slab pull (Kumar et al., 2007). An S receiver function study using large amount of data from 59 seismic stations spanning the Indian shield revealed clear conversions from the Lithosphere Asthenosphere Boundary (LAB) that varies in depth from 70-140 km (Figure 5). This study presented a definitive evidence for flexure on a lithospheric scale, with a wavelength of 1000 km. It is postulated that this is primarily caused by the hard collision at ~55 Myr. For a large number of stations, a mid-lithospheric discontinuity has also been seen in addition to the LAB (Kumar et al., 2013). In contrast, a P- receiver function study along a near NS profile indicated that the lithospheric thickness beneath India increases from 120 km in the southern most part to 180 km in northern India. Joint inversion of P and S receiver functions indicated that the S-wave velocity in the upper most mantle at depths <180 km of the Indian shield is low (4.4–4.5 km/s) and does not favor a cold and depleted upper mantle present in other shields of comparable age. A recent metasomatic alteration of the previously cold and depleted mantle keel has been suggested to explain this (Oreshin et al., 2011).

3-D P and S velocity structure of the subcontinent at a 2deg x 2deg lateral resolution obtained by inversion of 52,050 P and 30,423 S arrival times recorded at 413 broadband stations, reveals a heterogeneous nature of the Indian lithospheric mantle (Singh et al., 2014). The cratonic segments of the Indian shield are characterized by high velocity anomalies (3%) at depths shallower than 300 km, with the diamondiferous regions like Wajrakarur revealing high shear wave anomalies down to this depth. In contrast, low velocities in the northwestern DVP suggest that the upper mantle retains imprints of Deccan volcanism which was facilitated by the reactivation of the rift systems. Such signatures are absent beneath the southern Deccan volcanic province (DVP) (Singh et al., 2014). A 3-D lithospheric model of the Indian plate down to 300 km depth, was obtained at a similar resolution by inverting a new massive database of surface wave observations along ~14,000 paths from more than 550 seismic broadband stations spanning the Indian subcontinent and surrounding regions. Results show large variations in lithospheric thickness (120–250 km) beneath the different cratonic blocks. The thickness is ~120 km in the eastern Dharwar, ~160 km in the western Dharwar, ~140–200 km in Bastar and ~160–200 km in the Singhbhum Craton. The central part of India has the thickest (200–250 km) cratonic roots. A low velocity layer is associated with the mid-lithospheric discontinuity in regions with a deep LAB as suggested by Maurya et al. (2016). A recent study by Mandal et al. (2021) characterize the lithospheric thickness in different terranes of the eastern Indian shield through the joint inversion of P-receiver functions and fundamental mode group velocity dispersion data of Rayleigh waves (10–100 s), constrained by S-receiver function modeling. The study observed the crustal thickness of 33 to 45 km while the depth to the lithosphere-asthenosphere boundary reported to be from 98 to 140 km in the region.

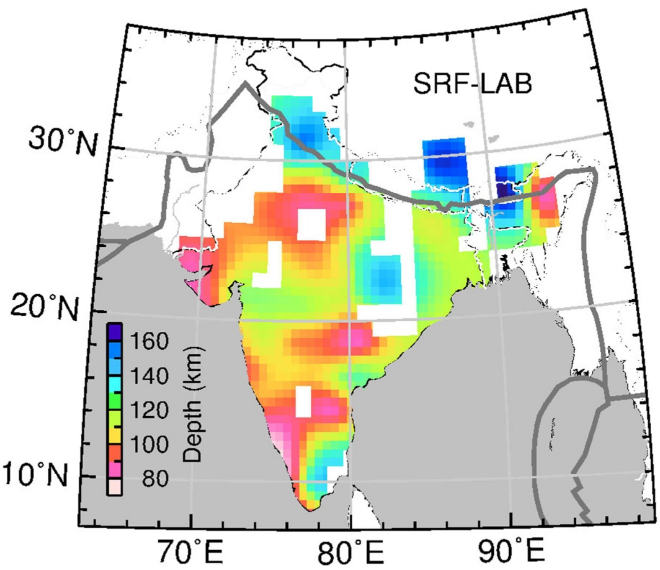

Fig. 5. Image of the LAB beneath India as estimated by S-to-p converted waves technique. The image clearly shows the variability in lithospheric thickness (modified after Kumar et al., 2013).

Methodological Advancements in Seismology for Imaging the Crust and Lithospheric Mantle

An approach to compute the receiver functions using iterative rotation of three component seismograms into P-Sv-Sh is developed. This ensures optimal rotation and clean isolation of phases, which is useful for the computation of receiver functions (P, or S-RF). The approach has been successfully applied to computation of SRF (utilizing S-to-p conversions) and PRF (utilizing P-to-s conversions) using different data sets globally (Kumar et al., 2005; 2006; 2011).

A maiden, albeit idealized, approach to transform P and SV transmission Green's functions into the corresponding reflection quantities for one-dimensional elastic media at pre-critical slowness was developed and its utility demonstrated. The transmission-to-reflection transformation has potential applications for imaging the hitherto elusive shallow mantle discontinuities, since interfering forward and back scattering contributions are effectively separated by component in the resulting reflection Green's functions (Kumar and Bostock, 2006). It is demonstrated for the first time that that P velocity (Vp) and Vp/Vs can be readily computed through solution of a linear system of equations incorporating travel times of direct conversions and free-surface reverberations, representing a range of horizontal slowness (Kumar and Bostock, 2008). In addition, an alternative waveform-stacking approach that involves a 2-D grid search over Vp/Vs and Vp followed by a 1-D line search over crustal thickness is developed (Bostock and Kumar, 2010).

The separation of the structural effects below a seismic station from other effects like source–time functions is a fundamental problem of the receiver function technique. A new and simple technique has been suggested to estimate the three component response at the receiver site without deconvolution or similar methods. This method preserves the P component unlike receiver functions. The method employs amplitude normalization followed by the summation of many seismograms from different events, however, no source equalization is needed. The method also preserves P-to-P reflected phases from the Moho and deeper discontinuities (Kumar et al., 2010).

A new method for estimating contrast in Vs from teleseismic receiver functions using Ps transmitted wave amplitude variation with slowness was initially developed for a horizontal and isotropic Earth layering (Kumar et al., 2014) and then extended to incorporate dipping and anisotropic layering (Kumar, 2015).

Based on the concept of cluster entropy and related information dimension, an approach has been proposed to discriminate between the primary converted waves arising from several depth boundaries such as the Moho, 410 km, and L/X discontinuities. The approach enabled identification of velocity layering beneath the Indian stations, at depths akin to the Lehmann boundary (Ramesh et al., 2010). It is further suggested that the depth to the lithosphere-asthenosphere boundary beneath the cratonic regions of SE India definitely exceeds 200 km.

In order to compute receiver functions, quite a number of methods have been proposed to perform deconvolution. In general, other methods adopt approaches which address the problem of stability. A new time-domain deconvolution technique called the basis pursuit deconvolution (BPD), has been applied for receiver function computation. It uses an over complete wedge dictionary based on a dipole reflectivity series to define model constraints, achieving higher resolution compared to the other exiting methods. The BPD is very effective for resolving thin layers also, as demonstrated on real data from Kutch, India, where near-surface sedimentary layers are known to be present. The Basis Pursuit Receiver Functions are able to resolve reflections from these layers very well (Sen et al., 2014).

Shallow Structure

The near-surface shear velocities beneath 144 broadband seismic stations of India, determined using 37,635 good quality three-component waveforms from 3849 earthquakes, show a distinct correlation with the geological provinces. Regions of thick sedimentation like Indo-Gangetic plains and Assam fore-deep have anomalously low values (1 km/s), followed by the Godavari graben (2km/s) and the Vindhyan basin (2.2 to 2.7 km/s). The Deccan volcanic province and the cratonic segments have higher NSV values (close to 3.4 km/s), as observed for global continental shields (Singh et al., 2013). Estimates of the sedimentary thickness in the Godavari graben from travel time difference of local S and Sp phases shows a variation from 0.32 at the flanks to 4.32 km at the center (Sushini et al., 2014). Results from nearest neighbourhood algorithm inversion of the initial part of receiver function stacks at ten broadband seismic stations along a north–south profile traversing the Indo-Gangetic plains show low-velocity sediments having shear-wave velocities in the range of 0.72-2.5 km/s with thicknesses increasing south to north from 0.5 to 3.7 km. Low shear-wave velocities and high Vp/Vs ratios in the first layer have been explained by the presence of porous soft sediments. The shallowing of the basement by more than 1.5 km at Kanpur and Lucknow has been explained as a manifestation of the Faizabad ridge (Srinivas et al., 2013). Results of joint inversion of RFs and Rayleigh velocities at 14 stations show significant variability of sedimentary layer thicknesses from 1.0 to 2.0 km beneath the Delhi region to 2.0–5.0 km beneath the Indo-Gangetic Plain and the Siwalik Himalaya, with a decrease in shear velocity from 2.0 km/s to 1.3 km/s (Borah et al., 2015). A high-velocity Deccan Trap layer is identified in Saurashtra, Madhya Pradesh, and Maharashtra regions based on inversion of group velocities of Rayleigh waves generated by 77 regional earthquakes recorded at 38 broadband stations. The thickness of the traps varies between 1.4 and 2.2 km, with a Vs of 2.57–2.86 km/s. A low-velocity (Vs ~1.63–1.95 km/s) sedimentary layer is identified in the Kutch and Cambay regions.

Hales Discontinuity

The first detection the Hales discontinuity beneath India came from analysis of the P -receiver functions derived from waveforms of 297 earthquakes recorded at the Hyderabad station. A seismic discontinuity at 90 km depth is inferred from a prominent signal on the SH receiver functions, interpreted as a layer of depth-localized anisotropy in the lithospheric mantle (Saul, 2000). A joint inversion of P and S receiver functions and teleseismic P and S travel time residuals affirmed the nature of this discontinuity beneath the Dharwar craton, in terms of azimuth dependent variations in S velocity at a depth of ~100 km (Kiselev et al., 2008). Presence of the Hales discontinuity at many locales beneath the Precambrian Indian shield imprinted as positive velocity contrast (4.52 to 4.77 km/s) at a depth of ~80 km is interpreted in terms of delamination of the mafic lower crust. Such a layering in the lithosphere is speculated to be due to a low-density, depleted spinel peridotite (with Archean affinity) lying over higher density fertile garnet peridotite of Proterozoic age. Further, simulations using first-principles molecular dynamics lead to the inference that the cation ordering transition in ferromagnetism olivine might be a potential factor for the Hales discontinuity (Mandal et al., 2012).

DISCUSSION AND CONCLUSIONS

Velocity structure derived from active or passive seismic experiments provides important constraints on the evolution of different provinces and their interrelationship. It further provides an important clue to understand the geodynamics, hazard scenario and resource prospects of a region. For example, precise delineation of crustal parameters provides necessary inputs to estimate the earthquake parameters accurately. The mapping of fine scale faults may also help to understand the seismogenesis of the region.

It is now well known that the Indian subcontinent is composed of diverse tectonic units juxtaposed together during different geological periods. The synthesis of seismic data provides a glimpse of change in the regional velocity scenario as well as basement and Moho depth configurations of the Indian crust (Kumar et al., 1999). Based on results from both active and passive seismic methods, a number of new evolutionary models for the various tectonic units have been suggested by different researchers. Kaila and Tewari (1975) proposed that the Cuddapah basin was created by down-faulting of the crustal block on its western part during Paleoproterozoic, while half of the basin was down-faulted during Neoproterozoic when the upper Cuddapah sedimentation took place. Similar studies indicate that the EDC and WDC are two independent entities with quite different crustal configurations. These two cratons are separated by the Chitadurga Schist belt extending north-south. Vijaya Rao and Rajendra Prasad (2006), propose a model where they argue that the compressional forces brought the Dharwar craton and the southern block close to each other leading to collision during the late Archaean forming the Moyar-Bhavani shear Zone/Mettur Shear Zone and Neoarchean ganulites. However, in central India, the velocity models reveal a different scenario. The seismological and seismic studies show that the crust is 38-42 km thick with higher velocity layers at shallow depths. Such high velocity layer could represent the enclaves of amphibolitic layers engulfed during cratonization of the crust in Proterozoic. Another interesting feature in this region is the fault controlled crustal configuration. It is seen that the deposition of sediments and crustal configurations are quite different across and within the NSL.

Another intriguing observation that emerged from seismic studies in central India is the role of Barwani-Sukta fault (Figure 1b). This fault controls the tectonics of this region by limiting the sedimentation below the trap across the Narmada region. Further, it has been observed that this fault even controls the upper crustal configuration in this region. Just south of NSL, lies the central Indian suture (CIS) zone, which is another important feature in this tectonic zone. Two dipping seismic domains are conspicuous in the seismic migrated section representing a suture between the two crustal blocks. The crustal fabrics near to the suture are characterized by the oppositely dipping reflections indicating a collision zone developed due to the interaction of the Bastar and Bundelkhand cratons (Mall et al. 2008; Mandal et al., 2013a).

The Aravalli-Delhi fold belt is an important geological terrane that developed due to successive amalgamation of Proterozoic orogenic belts on an ensialic basement of Archean age. The seismic section reveals a palaeo-subduction zone during the Mesoproterozoic period, with no major tectono-thermal activity thereafter (Mandal et al., 2018). The dips of various reflections (Mandal et al., 2013b) and the reflectivity pattern reveal the major shear zones which have evolved during various phases of geotectonic activity.

The crustal thickness in the entire western part of India (Saurashtra, Cambay basin, in the region of the Vindhyan and east of the Aravalli formation) varies between 32 and 35 km, whereas beyond the Eastern margin fault of the Cambay basin, the crust deepens to 37 to 40 km. It shows that the crust is uplifted by as much as 4 to 6 km in the eastern part of Saurashtra and Cambay basin, between the two trends of the Aravalli system and the Narmada Fault to the south of the Saurashtra peninsula. Since the region was nearer to the axis of the Reunion plume, this uplift was either concomitant with the rise of the plume prior to the extrusion of the Deccan volcanics or after deposition of the Mesozoic sediments. Uplift of the crust in large parts of the western India, eastern part of Saurashtra peninsula and the Cambay basin was also caused due to passage of the western part of India over the Reunion plume. A large dimension (1000-2000 km) of the head of the Reunion plume (White and McKenzie, 1989) led to underplating in parts of the crust in western India.

The Indian plate was once a part of the greater Gondwanaland and is considered unique place since it has been torched by three major plumes after it separated from the Super-continent Gondwanaland. During this process, the Indian plate lost most of its mass and became thin vis-a-vis its counterparts. Kumar et al. (2007; 2013) using S-to-p converted waves found that the thickness of the Indian plate varies between ~70 and ~140 km. They further argued that the rapid northward drift (~18-20cm/yr) of the Indian lithosphere during the Cretaceous could be due to the reduced thickness of the Indian plate. Within the error bounds, their estimates are consistent with those observed by the analysis of surface waves (Suresh et al., 2008; Bhattacharya et al., 2009), where the lithospheric thickness has been reported to be ~80-~155 km. One of the earliest tomographic study shows that the Indian lithosphere is only ~100 km (Polet and Anderson, 1995) thick. A similar depth value for the lithosphere below Hyderabad station using P-to-s conversions has been reported (Rychert and Shearer, 2009; Bodin, et al., 2014). In contrast, surface wave tomographic images by Maurya et al. (2016) showed distinct lithospheric thickness varying from 120 to 250 km. However, the surface wave estimates in southern granulitic terrain, and in the eastern Dharwar are in agreement with the body wave observations, but for other places there exist significant differences. Interestingly, the thermal data as reported by Pandey and Agrawal (1991) reveal a thin Indian lithosphere. Another, P and S wave tomographic study shows a heterogeneous nature of the Indian lithospheric mantle with high velocity anomalies shallower than 300 km (Singh et al., 2014), with thickness of lithosphere to be ~120 km in the eastern Dharwar, ~160 km in the western Dharwar, ~140–200 km in Bastar, and ~160–200 km in the Singhbhum Craton (Maurya et al., 2016).

In conclusion, we can infer that there is no consensus among various seismological and other studies on the lithospheric thickness of India. It should be noted that surface waves are more sensitive to the velocity unlike the receiver functions, which are sensitive to the sharpness and depths of the discontinuities from where the conversion is taking place. Nevertheless, the negative phase interpreted as a conversion from the LAB by few researchers is unusually shallow for an Archaean continent such as India. The depth range for this discontinuity is close to the depths to a low velocity layer (LVL) observed in the long range reflection profiles, i.e., the 8° discontinuity (Thybo and Perchuc, 1997) and few researchers prefer to call it as mid lithospheric discontinuities (MLD) (e.g. Abt et al., 2010; Selway et al., 2015). However, no universal explanation has been put for its origin especially for stable continental regions. Also the occurrence of MLD is not ubiquitous.

The discrepancies in interpretations now exist in quite a number of other places in the world. We hope that future research using a multidisciplinary approach utilizing dense data sets may resolve these discrepancies.

Acknowledgments: We thank to Dr. V M Tiwari, Director, CSIR-NGRI, for inviting us to write this review on the NGRI's achievements and in understanding the crust and lithosphere of the Indian shield in past glorious 60 years of institute using deep seismic sounding and seismology. We are indebted to the whole DSS and Seismology team of CSIR-NGRI and cooperation from other national and international organizations and scientists for their uninterrupted involvement in such a unique large scale field operation to generate valuable information of our Indian shield. We sincerely thank Director, NGRI for giving us permission to publish this work. The article has reference number of NGRI/Lib/2021/Pub-39.

References

ANCORP Working Group (1999) Seismic reflection image revealing offset of Andean subduction-zone earthquake locations into oceanic mantle. Nature, v.397, pp.341.

Behera, L, Sain, K, Reddy, P.R, Rao, I.B.P., Sharma V.Y.N. (2002) Delineation of shallow structure and Gondwana graben in Mahanadi delta, India using forward modeling of first arrival seismic data. Jour. Geodynamics, v.34, pp.129-141.

Behera, L. (2011) Crustal tomographic imaging and geodynamic implications toward south of southern granulite terrain (SGT), India. Earth Planet. Sci. Lett., v.309, pp.166-178.

Bhukta, S.K., Sain, K., Tewari, H.C. (2006) Crustal structure along the Lawrencepur-Astor profile across the Nanga Parbat. Pure Appl. Geophys., v.163, pp.1257-1277.

Bora, D.K., Hazarika, D., Borah, K., Rai, S.S., Baruah, S. (2014) Crustal shear-wave velocity structure beneath northeast India from teleseismic receiver function analysis. Jour. Asian Earth Sci., v.90, pp.1-14.

Borah, K., Kanna, N., Rai, S.S., Prakasam, K.S. (2015) Sediment thickness beneath the Indo-Gangetic Plain and Siwalik Himalaya inferred from receiver function modelling. Jour. Asian Earth Sci., v.99, pp.41-56.

Borah, K., Rai, S.S., Gupta, S., Prakasam, K.S., Kumar, S., Sivaram, K. (2014) Preserved and modified mid-Archean crustal blocks in Dharwar craton: Seismological evidence. Precambrian Res., v.246, pp.16-34.

Borah, K., Rai, S.S., Prakasam, K.S., Gupta, S., Priestley, K., Gaur, V.K. (2014) Seismic imaging of crust beneath the Dharwar Craton, India, from ambient noise and teleseismic receiver function modelling. Geophys. Jour. Internat., v.197(2), pp.748-767.

Bostock, M.G., Kumar, M.R. (2010) Bias in seismic estimates of crustal properties. Geophys. Jour. Internat., v.182(1), pp.403-407.

Burdick, L.J., Langston, C.A. (1977) Modeling crustal structure through the use of converted phases in teleseismic body-wave forms. Bull. Seismol. Soc. America, v.67(3), pp.677-691.

Chandrakala, K., Mall, D.M., Sarkar, D., Pandey, O.P. (2013) Seismic imaging of the Proterozoic Cuddapah basin, south India and regional geodynamics. Precambrian Res., v.231, pp.277-289.

Chaudhuri, K., Borah, K., Gupta, S (2016) Seismic evidence of crustal low velocity beneath Eastern Ghat Mobile Belt, India. Physics Earth Planet. Inter., v.261, pp.207-216.

Chowdhury, K., Hargraves, R. (1981) Deep seismic soundings in India and the origin of continental crust. Nature, v.291 pp.648–650, doi:10.1038/291648a0.

Damodara, N., Vijaya Rao, V., Sain, K., Prasad, A.S.S.S.R.S. (2017) Basement configuration of the West Bengal sedimentary basin, India as revealed by

seismic refraction tomography: its tectonic implications. Gephys. Jour. Internat., v.208, pp.1490-1507.
Das, R., Saikia, U., Rai, S.S. (2015) The deep geology of South India inferred from Moho depth and Vp/Vs ratio. Geophys. Jour. Internat., v.203(2), pp.910-926.
Davey, F.J., Stern, T.A. (1990) Crystal Seismic observations across the convergent plate boundary, North Island, New Zealand. Tectonophysics, v.173(1-4), pp.283-296.
Dixit, M.M., Kumar, S., Catchings, R.D., Suman, K., Sarkar, D., Sen, M.K. (2014) Seismicity, faulting, and structure of the Koyna Warna seismic region, Western India from local earthquake tomography and hypocenter locations. Jour. Geophys. Res.: Solid Earth, v.119(8), pp.6372-6398.
Dixit, M. M., Satyavani, N., Sarkar, D., Khare, P., Reddy, P. R., (2010). Velocity inversion in the Lodhika area, Saurashtra peninisula, western India. First Break, v.18, pp.499-504.
Durrheim, R.J., Mooney, W. D. (1994) Evolution of the Precambrian lithosphere: seismological and geochemical constraints. Jour. Geophys. Res.: Solid Earth, v.99(B8), pp.15359-15374.
Gaur, V.K., Priestley, K.F. (1997) Shear wave velocity structure beneath the Archaean granites around Hyderabad, inferred from receiver function analysis. Proc. Indian Acad.f Sci.-Earth Planet. Sci., v.106(1-2), pp.1-8.
Gupta, A.K., Mandal, P. (2020) Delineation of Average 1-D Shear Velocity Structure below North India by Surface Wave Dispersion Study. Jour. Geol. Soc. India, v.96(1), pp.58-64.
Gupta, Harsh K., Rao, R.U.M., Srinivasan, R., Rao, G.V., Reddy, G.K., Dwivedy, K. K., Banerjee, D.C., Mohanty, R., Satyasaradhi, Y.R. (1999) Anatomy of surface rupture zones of two stable continental region earthquakes 1967 Koyna and 1993 Latur, India. Geophys. Res. Lett., v.26, pp.1985-1988.
Gupta, H.K., Narain, H. (1967) Crustal structure in the Himalayan and Tibet Plateau region from surface wave dispersion. Bull. Seismol. Soc. Amer., v.57(2), pp.235-248.
Gupta, H.K., Nyman, D.C., Landisman, M. (1977) Shield-like upper mantle velocity structure below the Indo-Gangetic plains: inferences drawn from long-period surface wave dispersion studies. Earth Planet. Sci. Lett., v.34(1), pp.51-55.
Gupta, H.K., Rao, R.U.M., Srinivasan, R., Rao, G.V., Reddy, G.K., Dwivedy, K.K., Banerjee, D.C., Mohanty, R. and Satyasaradhi, Y.R. (1999) Anatomy of surface rupture zones of two stable continental region earthquakes, 1967 Koyna and 1993 Latur, India. Geophys. Res. Lett., v.26(13), pp.1985-1988.
Gupta, H.K., Sarma, S.V.S., Harinarayana, T., Virupakshi, G. (1996) Fluids below the hypocentral region of Latur earthquake, India: Geophysical indicators. Geophys. Res. Lett., v.23(13), pp.1569-1572.
Gupta, H.K. and Dwivedy, K.K. (1996a) Drilling at Latur Earthquake Region Exposes a Peninsular Gneiss Basement. Jour. Geol. Soc. India, v.47, pp.129-131.
Gupta, H. K., Douglas C. Nyman., Landisman, M., (1977) Shield-like upper mantle velocity structure below the Indo-Gangetic Plains: Inferences drawn from long-period surface wave dispersion studies, Earth and Planet. Sci. Lett., v.34(1), pp.51-55
Gupta, M.L., Sundar, A., Sharma, S.R. (1991) Heat flow and heat generation in the Archaean Dharwar cratons and implications for the Southern Indian Shield geotherm and lithospheric thickness. Tectonophysics, v.194(1-2), pp.107-122.
Gupta, M.L. (1993) Is the Indian Shield hotter than other Gondwana shields? Earth Planet. Sci. Lett., v.115(1-4), pp.275-285.
Gupta, S., Kanna, N., Kumar, S., Sivaram, K. (2018) Crustal thickness and composition variation along the Western Ghats of India through Teleseismic Receiver Function Analysis. Jour. Geol. Soc. India, v.92(5), pp.523-528.
Haldar, C., Kumar, P., Kumar, M.R., Ray, L., Srinagesh, D. (2018) Seismic evidence for secular evolution and alteration of Archaean crust in Indian shield. Precambrian Res., v.304, pp.12-20.
Gupta, S., Rai, S. S., Prakasam, K. S., Srinagesh, D., Bansal, B. K., Chadha, R. K., Priestley, K (2003) The nature of the crust in southern India: implications for Precambrian crustal evolution, Geophy. Res. Lett. v. 30, 8, 1419, doi:10.1029/2002GL016770.
Hoffman, P.F. (1988) United plates of America, the birth of a craton: Early Proterozoic assembly and growth of Laurentia. Annual Rev. Earth Planet. Sci., v.16(1), pp.543-603.
Iyer, H.M., Gaur, V.K., Rai, S.S., Ramesh, D.S., Rao, C.V.R., Srinagesh, D., Suryaprakasam, K. (1989) High velocity anomaly beneath the Deccan volcanic province: Evidence from seismic tomography. Proc. Indian Acad. Sci.-Earth Planet. Sci., v.98(1), pp.31-60.
Jagadeesh, S., Rai, S.S. (2008) Thickness, composition, and evolution of the Indian Precambrian crust inferred from broadband seismological measurements. Precambrian Res., v.162(1-2), pp. 4-15.
Jordan, T.H. (1988) Structure and formation of the continental tectosphere. Jour. Petrol., v.1, pp.11-37.
Julia, J., Jagadeesh, S., Rai, S.S., Owens, T.J. (2009) Deep crustal structure of the Indian shield from joint inversion of P wave receiver functions and Rayleigh wave group velocities: Implications for Precambrian crustal evolution. Jour. Geophys. Res.:Solid Earth, v.114(B10), doi:10.1029/2008JB006261.
Kaila, K.L., Murthy, P.R.K., Dixit, M.M., Lazarenko, H.A. (1981a) Deep crustal structure of Koyna, Maharashtra. Jour. Geol. Soc. India, v.22, pp. l-16.
Kaila, K.L., Murty, P.R.K., Rao, V.K., Kharetchko, G. (1981b) Crustal structure from deep seismic sounding along the KOYII (Kelsi–Loni) profile in the Deccan trap area, India. Tectonophysics, v.73, pp.365–384.
Kaila K.L., Roy Chowdhury, K., Reddy, P.R., Krishna, V.G., Hari Narain, Subbotin, S. I., Sollogub, V. B., Chekunov, A.V., Kharetchko, G.E., Lazarenko, M. A. and Ilchenko, T. V. (1979) Crustal structure along the Kavali-Udipi profile in the Indian peninsular shield from deep seismic sounding. Jour. Geol. Soc. India, v.20, pp.307–33.
Kaila, K.L., Bhatia, S.C. (1981) Gravity study along Kavali–Udipi deep seismic sounding profile in the Indian peninsular shield: some inferences about origin of anorthosites and Eastern Ghat orogeny. Tectonophysics, v.79, pp. 129-143.
Kaila, K.L., and Tewari, H.C. (1985) Structural trends in the Cuddapah basin from deep seismic soundings (DSS) and their tectonic implications. Tectonophysics, v.115, pp.69-86
Kaila, K.L. Krishna, V.G. (1979) A new computerised method for finding effective velocity from reversed reflection travel time data. Geophysics, v.44, pp.1064-1076.
Kaila, K.L., Tewari, H.C. Roy Chowdhury, K., Rao, V. K., Sridhar, A.R., Mall, D.M. (1987) Crustal structure of the northern part of the Proterozoic Cuddapah basin of India from deep seismic soundings and gravity data. Tectonophysics, v.140, pp.1-12.
Kaila, K. L., Krishna, V.G., Mall, D.M. (1981c) Crustal Structure along Mehmadabad-Billimora profile in the Cambay Basin, India, from Deep Seismic Soundings. Tectonophysics, v. 76, pp.99-130.
Kaila, K.L., Murty, P.R.K. and Mall, D.M. (1989) The evolution of the Vindhyan basin vis-à-vis the Narmada-Son lineament, central India, from deep seismic soundings. Tectonophysics, v.162, pp.277-289.
Kaila, K.L., Tewari, H.C., Krishna, V.G., Dixit, M.M., Sarkar, D., Reddy, M.S. (1990) Deep seismic sounding studies in the north Cambay and Sanchor basins, India. Geophys. Jour. Internat., v.3, pp.621-637.
Kaila, K.L., Reddy, P.R. (1967) Crustal structure in India. Ann. Rep. National Geophys. Res. Inst, v.68, pp.24-26.
Kaila, K.L., Reddy, P.R., Narain, H. (1968) Crustal structure in the Himalayan foothills area of north India, from 'P' wave data of shallow earthquakes. Bull. Seismol.Soc. Amer., v.58(2), pp.597-612.
Kaila, K.L., Reddy, P.R., Narain, H. (1968) P-wave travel times from shallow earthquakes recorded in India and inferred upper mantle structure. Bull. Seismol. Soc. Amer., v.58(6), pp.1879-1897.
Kanna, N., Gupta,S. (2020) Crustal seismic structure beneath the Garhwal Himalaya using regional and teleseismic waveform modelling, Geophys. Jour. Int., v.22 (3), pp. 2040–2052. doi:10.1093/gji/ggaa282
Kiselev, S., Vinnik, L., Oreshin, S., Gupta, S., Rai, S. S., Singh, A., Kumar, M.R. and Mohan, G. (2008) Lithosphere of the Dharwar craton by joint inversion of P and S receiver functions. Geophys. Jour. Internat. v.173(3), pp.1106-1118.
Krishna, V.G. (2004). Propagation of regional seismic phases in the Indian shield: constraints on crustal and upper mantle velocity models. Bull. Seismol. Soc. Amer., v.94(1), pp.29-43.
Krishna, V.G., Kaila, K.L., Khandekar, G. (1992) Upper mantle velocity structure in the Mediterranean and surrounding regions from seismological data. Tectonophysics, v.201(3-4), pp.277-301.
Krishna, V.G., Rao, C.V.R.K., Gupta, H.K., Sarkar, D., Baumbach, M. (1999) Crustal seismic velocity structure in the epicentral region of the Latur earthquake (September 29, 1993), southern India: inferences from

modelling of the aftershock seismograms. Tectonophysics, v.304(3), pp.241-255.
Krishna, V.G., Rao, V.V. (2005) Processing and modelling of short–offset seismic refraction—coincident deep seismic reflection data sets in sedimentary basins: an approach for exploring the underlying deep crustal structures. Geophys. Jour. Internat., v.163(3), pp.1112-1122.
Kumar, M.R., Bostock, M.G. (2008). Extraction of absolute P velocity from receiver functions. Geophys. Jour. Internat., v.175(2), pp.515-519.
Kumar, M.R., Bostock, M.G. (2006) Transmission to reflection transformation of teleseismic wavefields. Jour. Geophys. Res.: Solid Earth, v.111(B8), doi:10.1029/2005JB004104.
Kumar, M.R., Mohan, G. (2005) Mantle discontinuities beneath the Deccan volcanic province. Earth Planet. Sci. Lett., v.237(1-2), p.252-263.
Kumar, M.R., Raju, P.S., Devi., E.U., Saul, J., Ramesh, D.S. (2004) Crustal structure variations in northeast India from converted phases. Geophys. Res. Lett., v.31(17), doi:10.1029/2004GL020576.
Kumar, M.R., Singh, A., Kumar, N., Sarkar, D. (2015). Passive seismological imaging of the Narmada paleo-rift, central India. Precambrian Res., v.270, pp.155-164.
Kumar, M.R., Singh, A., Rao, Y.B., Srijayanthi, G., Satyanarayana, H.V., Sarkar, D. (2018) Vestiges of Precambrian subduction in the south Indian shield? - A seismological perspective. Tectonophysics, v.740, pp.27-41.
Kumar, P., (2019). Recent Seismological Investigation in India. Procd. Indian Natn. Sci. Acad., v.85(2), pp.431-451.
Kumar, P., Kawakatsu, H. (2011) Imaging the seismic lithosphere asthenosphere boundary of the oceanic plate. Geochemistry, Geophysics, Geosystems, v.12(1), Q01006, doi:10.1029/2010GC003358
Kumar, P., Kind, R., Yuan, X. (2010) Receiver function summation without deconvolution. Geophys. Jour. Internat., v.180(3), pp.1223-1230.
Kumar, K.P., Mohan, G. (2014). Crustal velocity structure beneath Saurashtra, NW India, through waveform modeling: Implications for magmatic underplating. Jour. Asian Earth Sci., v.79, pp.173-181.
Kumar, P., Ravi Kumar, M., Srijayanthi, G., Arora, K., Srinagesh, D., Chadha, R.K., Sen, M.K. (2013) Imaging the lithosphere asthenosphere boundary of the Indian plate using converted wave techniques. Jour. Geophys. Res.: Solid Earth, v.118(10), pp.5307-5319.
Kumar, P., Sen, G., Mandal, P., Sen, M. K. (2016) Shallow lithosphere-asthenosphere boundary beneath Cambay Rift Zone of India: inferred presence of carbonated partial melt. Jour. Geol. Soc. India, v.88(4), pp.401-406.
Kumar, P., Yuan, X., Kind, R., Ni, J. (2006) Imaging the colliding Indian and Asian lithospheric plates beneath Tibet. Jour. Geophys. Res.: Solid Earth, 111(B6), B06308, doi:10.1029/2005JB003930.
Kumar, P., Yuan, X., Kind, R., Kosarev, G. (2005) The lithosphere asthenosphere boundary in the Tien Shan Karakoram region from S receiver functions: Evidence for continental subduction. Geophys. Res. Lett., v.32(7), L07305, doi:10.1029/2004GL022291.
Kumar, P., Yuan, X., Kumar, M.R., Kind, R., Li, X., Chadha, R.K. (2007) The rapid drift of the Indian tectonic plate. Nature, v.449(7164), pp.894-897.
Kumar, P., Tewari, H.C., Sreenivas, B. (2019) Seismic structure of the Central Indian Crust and its Implications on the Crustal Evolution, Jour. Geol. Soc. India, v.93, 00.163-170.
Kumar, P., Tewari, H.C. and Khandekar, G. (2000) An Anomalous high velocity layer at a shallow crustal depth across the Narmada zone. India. Geophys. Jour. Internat., v.142, pp.95-107.
Kumar, P., Tewari, H.C., and Sain, K. (1999) Velocity-Depth relationship in selected parts of Indian crust. Jour. Geol. Soc. India, v.54, pp.129-136.
Kumar, P. (2002) Seismic structure of the continental crust in the central Indian region and its tectonic implications. Ph.D. Thesis, Osmania University, Hyderabad, India.
Kumar, T.V., Jagadeesh, S., Rai, S. S. (2012) Crustal structure beneath the Archean–Proterozoic terrain of north India from receiver function modeling. Jour. Asian Earth Sci., v.58, pp.108-118.
Kumar, S., Dixit, M.M. (2017) Three-dimensional velocity structure of the Koyna-Warna region using local earthquake tomography. Jour. Geol. Soc. India, v.90(6), pp.692-697.
Kumar, S., Gupta, S., Kanna, N., Sivaram, K. (2020) Crustal structure across the Deccan Volcanic Province and Eastern Dharwar craton in south Indian shield using receiver function modelling. Physics Earth Planet. Inter., v.306, pp.106543.
Kumar, S., Kumar, P. (2019) One-Dimensional Velocity Model, Station Correction and Earthquake Relocation of Local Earthquakes in the Koyna–Warna Region, India. Pure Appl. Geophys., v.176(11), pp.4761-4782.
Kumar, K. Vijay, Leelanandam, C. (2008) Evolution of the Eastern Ghats Belt, India: A Plate Tectonic Perspective, Jour. Geol. Soc. India, v.72(6), pp.720-749.
Kumar, M.R., Rao, N.P. (2000) Active tectonics of the Indian plate margins using centroid moment tensor data. Visakha Sci. Jour., v.4, pp.85-96.
Krishna, V.G., Kaila, K.L., Rao, G.S.P. and Reddy, P.R. (1990) Reflections from low angle thrusts at mid crustal depths: Examples from the Proterozoic Cuddapah basin, south Indian shield, paper presented at 4th International Symposium on Deep Seismic Reflection Profiling of the Continental Lithosphere, Bayreuth, Germany.
Lerner Lam, A.L., Jordan, T.H. (1987). How thick are the continents? Jour. Geophys. Res.: Solid Earth, v.92(B13), pp.14007-14026.
Lundberg, N., Reed, D.L., Liu, C.S., Lieskes Jr., J.H. (1997) Forearc-basin closure and arc accretion in the submarine suture zone south of Taiwan. Tectonophysics, v.274, pp.5-24.
Mall, D.M., Pandey, O.P., Chandrakala, K., Reddy, P.R. (2008) Imprints of a Proterozoic tectonothermal anomaly below the 1.1 Ga kimberlitic province of Southwest Cuddapah basin, Dharwar craton (Southern India). Geophys. Jour. Internat., v.172, pp.422-438.
Mandal, B. Vijaya Rao, V., Sen, Mrinal K., Karuppannan, P., Sarkar, D. (2018) Common Reflection Surface Stack Imaging of the Proterozoic Chambal Valley Vindhyan Basin and Its Boundary Fault in the Northwest India: Constraints on Crustal Evolution and Basin Formation. Tectonics, v.37, pp.1393-1410.
Mandal, B. Vijaya Rao, V., Sen, Mrinal K., Mann, J. (2014) Deep seismic image enhancement with the common refection surface (CRS) stack method: evidence from the Aravalli–Delhi fold belt of north western India. Geophys. Jour. Internat., v.196, pp.902-917.
Mandal, B., Sen Mrinal K., Vijaya Rao, V. (2014). New seismic images of the Central Indian Suture Zone and their tectonic implications. Tectonics, v.32, pp.908-921.
Mandal, B. Vijaya Rao, V., Sarkar, D., Bhaskara Rao, Y.J., Raju, S., Karuppannan, P., Sen, Mrinal K., (2017) Deep crustal seismic reflection images from the Dharwar craton, Southern India-evidence for the Neoarchean subduction. Jour. Geophys. Internat., v.2, pp.777-794.
Mandal, B., Vijaya Rao, V., Karuppannan, P., Laxminarayana, K. (2021) Mechanism for epeirogenic uplift of the Archean Dharwar craton, southern India as evidenced by orthogonal seismic reflection profiles. Scientific Reports, v.11, 1499(2021).
Mandal, B. Vijaya Rao, V., Karuppannan, P., Raju, S. Ganguli, S. (2021) Thick-skinned tectonics of the Achankovil Shear Zone, southern India, inferred from new deep seismic refection image: Constraints on the East African Orogen. Precambrian Res., v.356, 106110. https://doi.org/10.1016/j.precamres.2021.106110.
Mandal, N., Chakravarty, K.H., Borah, K., Rai, S.S. (2012). Is a cation ordering transition of the Mg Fe olivine phase in the mantle responsible for the shallow mantle seismic discontinuity beneath the Indian Craton? Jour. Geophys. Res.: Solid Earth, v.117(B12), B12304, doi:10.1029/2012JB009225
Mandal, P., Joshi, J., Sudesh Kumar, S., Bhunia, Rajendra & Rastogi, B. K. (2004) Low Coda Q c in the Epicentral Region of the 2001 Bhuj Earthquake of M w 7.7. Pure Appl. Geophys., v.161, pp.1635–1654).
Mandal, P. (2007) Sediment thicknesses and Q s vs. Q p relations in the Kachchh Rift Basin, Gujarat, India using Sp converted phases. Pure Appl. Geophys., v.164(1), pp.135-160.
Mandal, P. (2017) Lithospheric thinning in the Eastern Indian Craton: Evidence for lithospheric delamination below the Archean Singhbhum Craton? Tectonophysics, v.698, pp. 91-108.
Mandal, P. (2017) Group velocity dispersion characteristics and one-dimensional regional shear velocity structure of the eastern Indian craton. Jour. Asian Earth Sci., v.134, pp.231-243.
Mandal, P., Kumar, P., Sreenivas, B., Babu, E.V. S.S.K., and Rao, Y. J. B., Variations in crustal and lithospheric structure across the Eastern Indian Shield from passive seismic source imaging: Implications to changes in the tectonic regimes and crustal accretion through the Precambrian. Precambrian. Res., v.360, 106207, doi:10.1016/j.precamres.2021.106207.
Mohan, G., Kumar, M. R. (2004) Seismological constraints on the structure and composition of western Deccan Volcanic Province from converted phases. Geophys. Res. Lett., v.31, L02601, doi:10.1029/2003GL018920.

Mathur, L.P., Rao, K. L. N., Chaube, A. N. (1968) Tectonic framework of Cambay Basin, India. Bull. ONGC, v.5 pp.7-28.

Maurya, S., Montagner, J.P., Kumar, M.R., Stutzmann, E., Kiselev, S., Burgos, G., Rao, N.P.C., Srinagesh, D. (2016) Imaging the lithospheric structure beneath the Indian continent. Jour. Geophys. Res.: Solid Earth, v.121(10), pp.7450-7468.

Meissner, R. (2002) The little book of planet Earth. Springer Science & Business Media.

Mitra, S., Kainkaryam, S.M., Padhi, A., Rai, S.S., Bhattacharya, S.N. (2011). The Himalayan foreland basin crust and upper mantle. Physics Earth Planet. Inter., v.184(1-2), pp.34-40.

Mitra, S., Priestley, K., Gaur, V.K., Rai, S. S. (2006) Shear-wave structure of the south Indian lithosphere from Rayleigh wave phase-velocity measurements. Bull. Seismol. Soc. Ame., v.96(4A), pp.1551-1559.

Mohan, G., Rai, S.S. (1992) Imaging of seismic scatterers beneath the Gauribidanur (GBA) array. Physics Earth Planet. Inter., v.71(1-2), pp.36-45.

Mohan, G., Rai, S.S., Panza, G.F. (1992) Seismic heterogeneities in the Indian lithosphere. Physics Earth Planet. Inter., v.73(3-4), pp.189-198.

Mohan, G., Rai, S.S., Panza, G.F. (1997) Shear velocity structure of the laterally heterogeneous crust and uppermost mantle beneath the Indian region. Tectonophysics, v.277(4), pp.259-270.

Murty, A.S.N., Mall, D.M., Murty, P.R.K. and Reddy, P.R. (1998) Two dimensional Crustal Velocity structure along Hirapur- Mandala Profile from Seismic Refraction and Wide-angle Reflection Data Pure Appl. Geophys., v.152, pp.247-266.

Murty, A. S. N., Tewari, H. C., Kumar, P. and Reddy, P. R. (2005) Subcrustal Low Velocity Layers in Central India and their Implications, Pure Appl. Geophys., v.162, pp.2409-2431.

Narain, H., Gupta, H.K. (1968) Koyna earthquake. Nature, v.217(5134), pp.1138-1139.

Oreshin, S.I., Vinnik, L.P., Kiselev, S.G., Rai, S.S., Prakasam, K.S., Treussov, A.V. (2011) Deep seismic structure of the Indian shield, western Himalaya, Ladakh and Tibet. Earth Planet. Sci. Lett., v.307(3-4), pp. 415-429.

Paul H., Ravi Kumar, M., Tiwari, V.M., Srinagesh D., Chadha, R.K. (2018) Density contrast across the Moho beneath the Indian shield: Implications for Isostasy. Jour. Asian Earth Sci., v.154, pp.67-81. doi: 10.1016/j.jseaes.2017.12.009.

Pandey, O.P., Tripathi, P., Vedanti, N., Sarma, D.S. (2016) Anomalous seismic velocity drop in iron and biotite rich amphibolite to granulite facies transitional rocks from Deccan volcanic covered 1993 Killari earthquake region, Maharashtra (India): a case study. Pure Appl. Geophys., v.173(7), pp.2455-2471.

Percival, J.A., Williams, H.R. (1989) Late Archean Quetico accretionary complex, Superior province, Canada. Geology, v.17(1), pp.23-25.

Phinney, R.A. (1964) Structure of the Earth's crust from spectral behavior of long period body waves. Jour. Geophys. Res., v.69(14), pp.2997-3017.

Prakasam, K.S., Rai, S.S. (1998) Teleseismic delay-time tomography of the upper mantle beneath southeastern India: imprint of Indo—Antarctica rifting. Geophys. Jour. Internat., v.133(1), pp.20-30.

Radhakrishna, B.P., Naqvi, S.M. (1986), Precambrian continental crust of India and its evolution, Jour. Geol., v.94, pp.145-66.

Rajendra Prasad, B., Behera, L., Kotesawara Rao, P. (2006) A tomographic image of upper crustal structure using P and S waveseismic refraction data in the southern granulite terrain (SGT), India. Geophys. Res. Lett., v.33, L14301, doi:10.1029/2006GL026307.

Rai, A., Gaur, V.K., Rai, S.S., Priestley, K. (2009) Seismic signatures of the Pan-African orogeny: implications for southern Indian high-grade terranes. Geophys. Jour. Internat., v.176(2), pp.518-528.

Rai, S.S., Borah, K., Das, R., Gupta, S., Srivastava, S., Prakasam, K.S., Sivaram, K., Sudesh K., Meena, R. (2013) The south India Precambrian crust and shallow lithospheric mantle: Initial results from the India Deep Earth Imaging Experiment (INDEX). Jour. Earth System Sci., v.122(6), pp.1435-1453.

Rai, S.S., Prakasam, K.S., Agrawal, N. (1999) Pn wave velocity and Moho geometry in north eastern India. Proc. Indian Acad. Sci.-Earth Planet. Sci., v.108(4), pp.297-304.

Rai, S.S., Priestley, K., Suryaprakasam, K., Srinagesh, D., Gaur, V.K., Du, Z. (2003) Crustal shear velocity structure of the south Indian shield. Jour. Geophys. Res.: Solid Earth, v.108(B2), 2088, doi:10.1029/2002JB001776.

Rai, S., Kumar, T.V., Jagadeesh, S. (2005) Seismic evidence for significant crustal thickening beneath Jabalpur earthquake, 21 May 1997, source region in Narmada–Son Lineament, central India. Geophys. Res. Lett., v.32. doi:10.1029/2005GL023580.

Rai, S.S., Sarma, P.R., Prakasam, K.S., Rao, V.K. (1996) Seismic evidence for thick and underplated late Archaean crust of eastern Dharwar craton. Proc. Indian Acad. Sci.-Earth Planet. Sci., v.105(4), pp.431-439.

Rai, S.S., Singh, S.K., Sarma, P.R., Srinagesh, D., Reddy, K.N.S., Prakasam, K.S., Satyanarayana, Y. (1999) What triggers Koyna region earthquakes? Preliminary results from seismic tomography digital array. Proc. Indian Acad. Sci.-Earth Planet. Sci., v.108(1), pp.1-14.

Rai, S.S., Vijay Kumar, T., Jagadeesh, S. (2005) Seismic evidence for significant crustal thickening beneath Jabalpur earthquake, 21 May 1997, source region in Narmada–Son lineament, central India. Geophys. Res. Lett., v.32(22), doi:10.1029/2005GL023580.

Rajendraprasad, B., Klemperer, S.L, Rao, V.V, Tewari, H.C., Khare, P. (2011) Crustal structure beneath the sub Himalayan fold–thrust belt, Kangra recess, northwest India, from seismic reflection profiling: Implications for Late Paleoproterozoic orogenesis and modern earthquake hazard. Earth Planet. Sci. Lett., v.308 pp.218-228.

Raju, A.T.R. (1968) Geological Evolution of Assam and Cambay Tertiary Basins of India. Am. Assoc. Pet. Geol. Bull., 52: 2422-2437.

Raju, A.T.R., Chaube, A.N. and Chowdhary, L.R., 1971. Deccan Trap and the geologic framework of the Cambay Basin. Bull. Volcanol., v.35 pp.521-538.

Ramesh, D.S. (2004) On the efficacy of recent crustal images of the Indian shield from receiver functions. Curr. Sci., v.87(5), pp.573-582.

Ramesh, D.S., Rai, S.S., Srinagesh, D., Gaur, V.K. (1990) Seismological evidence for a decoupled lithospheric segment in south Indian shield. Geophys. Jour. Internat., v.102(1), pp.113-120.

Ramesh, D.S., Raju, P.A., Sharma, N., Sharma, S.D. (2010) Deciphering shallow mantle stratification through information dimension. Lithosphere, v.2(6), pp.462-471.

Ramesh, D.S., Ravi Kumar, M., Uma Devi, E., Solomon Raju, P., Yuan, X. (2005) Moho geometry and upper mantle images of northeast India. Geophys. Res. Lett., v.32(14), doi:10.1029/2005gl022789.

Ramesh, D.S., Srinagesh, D., Rai, S.S., Prakasam, K.S. (1992) Anomalous granulite crust of South India—signatures from converted teleseismic waves. Proc. Indian Acad. Sci.-Earth Planet. Sci., v.101(3), pp.283.

Ramesh, D.S., Srinagesh, D., Rai, S.S., Prakasam, K.S., Gaur, V.K. (1993) High-velocity anomaly under the Deccan volcanic province. Physics Earth Planet. Inter., v.77(3-4), pp.285-296.

Ramesh Kumar, M.R., Prabhu Dessai, U.R. (2004) A new criterion for identifying breaks in monsoon conditions over the Indian subcontinent. Geophys. Res. Lett., v.31(18), doi: 10.1029/2004GL020562.

Rao, C.R., Gaur, V.K. (1991) Preliminary results from very long period data collected by a broad band digital seismic station. Proc. Indian Acad. Sci.-Earth Planet. Sci., v.100(4), pp.369-378.

Rao G.S.P., Tewari, H.C. (2005). The seismic structure of the Saurashtra crust in northwest India and its relationship with the Reunion Plume. Geophys. Jour. Internat., v.160, pp.318-330.

Rao, K.M., Kumar, M.R., Rastogi, B.K. (2015) Crust beneath the northwestern Deccan Volcanic Province, India: Evidence for uplift and magmatic underplating. Jour. Geophys. Res.: Solid Earth, v.120(5), pp.3385-3405.

Rao, S.S., Chary, K.B., Gowd, T.N., Rummel, F. (1999) Tectonic stress field in the epicentral zone of the Latur earthquake of 1993. Proc. Indian Acad. Sci.-Earth Planet. Sci., v.108(2), pp.93-98.

Rastogi, B.K., Bergman, E.A., Engdahl, E.R. (2005) Improved earthquake locations and estimation of Pn and Sn path anomalies for India, using multiple event relocation and reference events. Curr. Sci., v.88, pp.1586-1591.

Rastogi, B.K., Rao, B.R., Rao, C.V.R.K. (1986) Microearthquake investigations near Sriramsagar reservoir, Andhra Pradesh State, India. Physics Earth Planet. Inter., v.44, pp.149-159.

Reddy, P.R., Chandrakala, K., Sridhar, A.R. (2000) Crustal velocity structure of the Dharwar craton, India, Jour. Geol. Soc. India, v.55, pp.381-386.

Reddy, P.R., Rajendraprasad, B.R., Vijaya Rao, V., Sain, K., Prasad Rao, P., Prakash, Khare, Reddy, M. S. (2003) Deep seismic reflection and refraction/wide-angle reflection studies along Kuppam-Palani transect in the southern Granulite Terrain, Mem. Geol. Soc. India, no.50, pp.79–106.

Rohilla, S., Kumar, M.R., Rao, N.P., Satyanarayana, H.V.S. (2018) Shear Wave

Velocity Structure of the Koyna–Warna Region, Western India, through Modeling of P Receiver Functions Shear Wave Velocity Structure of the Koyna–Warna Region, Western India. Bull. Seismol. Soc. Amer., v.108(3A), pp.1314-1325.

Saikia, D., Kumar, M. R. K., Singh, A. (2020) Paleoslab and plume signatures in the mantle transition zone beneath Eastern Himalaya and adjoining regions. Geophys. Jour. Internat., v.221 pp.468-477, doi:10.1093/gji/ggaa012.

Saikia, U., Rai, S.S., Meena, R., Prasad, B.N.V., Borah, K. (2016) Moho offsets beneath the Western Ghat and the contact of Archean crusts of Dharwar Craton, India. Tectonophysics, v.672, pp.177-189.

Selway, K., Ford, H., Kelemen, P. (2015) The seismic mid-lithosphere discontinuity. Earth Planet. Sci. Lett., v.414, pp.45-57.

Sridhar, A.R. and Tewari, H.C. (2001) Existence of a sedimentary basin under the Deccan volcanics in the Narmada region, Jour. Geodynamics, v.31, pp.19-31.

Rohilla, S., Purnachandra Rao, N., Gerstoft, P., Shashidhar, D., Satyanarayana, H.V.S. (2015) 0120140091Shear Wave Velocity Structure of the Koyna–Warna Region in Western India Using Ambient Noise Correlation and Surface Wave Dispersion. Bull. Seismol. Soc. Amer., v.105 pp.473–479.

Sain, K., Kaila, K.L. (1994) Inversion of wide-angle seismic reflection times with damped least squares, Geophysics, v.59, pp. 1735-1744.

Sain, K., Reddy, P.R., (1995) Direct calculation of thicknesses for high-velocity and underlying low-velocity layers using post-critical reflection times in a seismic refraction experiment. Jour. Appl. Geophysics, v.34(2), pp.125-136.

Sain, K., Kaila, K.L., (1996a) Ambiguity in the solution to the velocity inversion problem and a solution by joint inversion of seismic refraction and wide-angle reflection times, Geophys. Jour. Inter., v.124(1), pp.215–227, doi:10.1111/j.1365-246X.1996.tb06365.x.

Sain, K., Kaila, K.L. (1996b) A direct method of calculating interval velocities and layer thicknesses from wide-angle seismic reflection times, Pure Appl. Geophys, v.146, pp.343–363.

Sain, K., Kaila, K.L. (1996) Direct Calculation of Interval Velocities and Layer Thicknesses from Seismic Wide-Angle Reflection Times, Geophys. Jour. Int., 125, v.1, pp.30–38, doi:10.1111/j.1365-246X.1996.tb06532.x.

Sain, K., Kaila, K. L. (1996) Interpretation of first arrival travel times in seismic refraction work. Pure Appl. Geophys., v.147, pp.181–194.

Sain, K, Bruguier, N. Murthy, A.S.N., Reddy, P.R. (2000) Shallow velocity structure along the Hirapur-Mandla profile in central India, using travel time inversion of wide-angle seismic data, and its tectonic implications. Geophys. Jour. Int., v.142, pp.505-515.

Sarkar, D., Chandrakala, K., Devi, P. P., Sridhar, A. R., Sain, K., Reddy, P. R., Sarkar, D. (2001) Crustal velocity structure of western Dharwar craton, South India. our Geodynamics, v.31(2), pp.227-241.

Sarkar, D., Kumar, M.R., Saul, J., Kind, R., Raju, P.S., Chadha, R.K., Shukla, A.K. (2003) A receiver function perspective of the Dharwar craton (India) crustal structure. Geophys. Jour. Internat., v.154(1), pp.205-211.

Sarkar, D., Sain, K. (2017) Deep Seismic Sounding Experiments in the Koyna RTS Region: An Overview of the Results. Jour. Geol. Soc. India, v.90, pp.663-669.

Saul, J., Kumar, M.R., Sarkar, D. (2000) Lithospheric and upper mantle structure of the Indian Shield, from teleseismic receiver functions. Geophys. Res. Lett., v.27(16), pp.2357.

Schneider, D., Holm, D., and Lux, D. (1996) On the origin of Early Proterozoic gneiss domes and metamorphic nodes, northern Michigan: Canadian Jour. Earth Sci., v.33, pp.1053–1063.

Sen, M.K., Biswas, R., Mandal, P., Kumar, P. (2014) Basis Pursuit Receiver Function Basis Pursuit Receiver Function. Bull. Seismol. Soc. Amer., v.104(6), pp.2673-2682.

Sharma, J., Kumar, M.R., Roy, K.S., Roy, P.N.S. (2018) Seismic imprints of plume lithosphere interaction beneath the northwestern Deccan Volcanic Province. Jour. Geophys. Res: Solid Earth, v.123(12), pp.10-831.

Sharma, S. D., Prathigadapa, R., Kattamanchi, S., Ramesh, D.S. (2015) Seismological mapping of a geosuture in the Southern Granulite Province of India. Lithosphere, v.7(2), pp.144-154.

Sharma, S.D., Ramesh, D.S. (2013) Imaging mantle lithosphere for diamond prospecting in southeast India. Lithosphere, v.5(4), pp.331-342.

Sharma, V., Sircar, A. (2020) Petroleum geochemical characterization of the shales from tertiary formation of Western Cambay Basin, India. Internat. Jour. Earth Sci., v.109(5), pp.1529-1546.

Singh, A., Kumar, M.R., Raju, P.S. (2010) Seismic structure of the under thrusting Indian crust in Sikkim Himalaya. Tectonics, v.29(6), doi:10.1029/2010TC002722

Singh, A., Kumar, M. R., Kumar, N., Saikia, D., Raju, P. S., Srinagesh, D., Purnachandra Rao, N., Sarkar, D. (2012) Seismic signatures of an altered crust and a normal transition zone structure beneath the Godavari rift. Precambrian Res., v.220–221, pp.1– 8.

Singh, A., Kumar, M.R., Srinagesh, D. (2013) Near surface shear velocities in diverse geological segments of India. Bull. Seismol. Soc. Amer., v.103(1), pp.317-327.

Singh, A., Ravi Kumar, M., Mohanty, D.D., Singh, C., Biswas, R., Srinagesh, D. (2017) Crustal structure beneath India and Tibet: New constraints from inversion of receiver functions. Jour. Geophys. Res.: Solid Earth, v.122(10), pp.7839-7859.

Singh, A.P. (1999) The deep crustal accretion beneath the Laxmi Ridge in the northeastern Arabian Sea: the plume model again. Jour. Geodyn., v.27(4-5), pp.609-622.

Singh, A.P., Kumar, N., Rao, B.N., Tiwari, V.M. (2021). Geopotential evidence of a missing lithospheric root beneath the eastern Indian shield: An integrated approach. Precambrian Res., v.356, pp.106116.

Singh, D.D. (1991) Anelasticity of the crust and upper mantle beneath north and central India from the inversion of observed Love and Rayleigh wave attenuation data. Pure Appl. Geophys, v.135(4), pp.545-558.

Singh, D.D., Rastogi, B.K. (1978) Crustal structure of the peninsular shield beneath Hyderabad (India) from the spectral characteristics of long-period P-waves. Tectonophysics, v.51(3-4), pp.127-137.

Singh, H.K., Kumar, Y., Chandrasekharam, D., Gurav, T., Singh, B. (2014) High-heat-producing granites of East Dharwar Craton around Gugi, Karnataka, and their possible influence on the evolution of Rajapur thermal springs, Deccan Volcanic Province, India. Geothermal Energy, v.2(1), pp.1-12.

Singh, S.K., Dattatrayam, R.S., Shapiro, N.M., Mandal, P., Pacheco, J.F., Midha, R.K. (1999). Crustal and upper mantle structure of Peninsular India and source parameters of the 21 May 1997, Jabalpur earthquake (Mw= 5.8): Results from a new regional broadband network. Bull. Seismol. Soc. Amer., v.89(6), pp.1631-1641.

Snyder, A., England, R.W., McBridge, J. H. (1997) Linkage between mantle and crustal stctures bearing on inherited stctures on NW Scotland. Jour. Geol. Soc. London, v.154, pp.79-83.

Srijayanthi, G., Kumar, M.R., Sirisha, T., Sushini, K., Prasad, G.S., Raju, P.S., ... Rao, N.P. (2012) The ISLANDS network in the Andaman–Nicobar subduction zone. Seismol. Res. Lett., v.83(4), pp.686-696.

Sinha-Roy, S., Malhotra, G., Guha, D.S. (1995) A transect across Rajasthan Precambrian terrain in relation to geology, tectonics and crustal evolution of south central Rajasthan. *In:* Sinha-Roy, S. and Gupta, K.R. (Eds.), Continental Crust of Northwestern and Central India. Mem. Geol. Soc. India, no.31, pp.63-90.

Sollogub, V. B., Chekunov, A. V., Kharecho, G. E., Tripolsky, A., Babinets, V. A., (1977) Strcuture of the Earth's crust in the region of old platforms. Publ. Int. Geophys. Pol. Acad. Sci., v.A-4 (115), pp.457-466.

Srinagesh, D., Chadha, R.K., Raju, P.S., Suresh, G., Vijayaraghavan, R., Sarma, A.N.S., Murty, Y.V.V.B.S.N. (2015) Seismicity studies in eastern Dharwar craton and neighbouring tectonic regions. Jour. Geol. Soc. India, v.85(4), pp.419-430.

Srinagesh, D., Rai, S.S. (1996) Teleseismic tomographic evidence for contrasting crust and upper mantles in south Indian Archaean terrains. Physics Earth Planet. Inter., v.97(1-4), pp.27-41.

Srinagesh, D., Rai, S.S., Ramesh, D.S., Gaur, V.K., Rao, C.V.R. (1989) Evidence for thick continental roots beneath South Indian Shield. Geophys. Res. Lett., v.16(9), pp.1055-1058.

Srinagesh, D., Singh, S., Reddy, K.S., Prakasam, K.S., Rai, S.S. (2000) Evidence for high velocity in Koyna seismic zone from P wave teleseismic imaging. Geophys. Res. Lett., v.27(17), pp.2737-2740.

Srinagesh, D., Mandal, P., Raghavan, R.V., Gupta, S., Suresh, G., Srinivas, D., Saha, S., M. 30 Sekhar, K. Sivaram, S. Kumar, P.S. Raju, A.N.S. Sarma, Y.V.V.S.B., Murthy, N.K. Borah, B. Naresh, B.N.V. Prasad, V.M. Tiwari, (2019) Digital seismic network: to map Himalayan orogen and seismic hazard. Curr. Sci., v.116(4), pp.518-519.

Srirama Rao, S. V., Chary, K. B., Gowd, T. N., Rumme, F. (1999) Tectonic stress field in the epicentral zone of the Latur earthquake of 1993. Proc.

Indian Acad. Sci. (Earth Planet Sci.), v.108, pp.93–98. doi:10.1007/BF02840487.

Srinivas, D., Srinagesh, D., Chadha, R.K., Ravi Kumar, M. (2013) Sedimentary thickness variations in the Indo Gangetic foredeep from inversion of receiver functions. Bull. Seismol. Soc. Amer., v.103(4), pp.2257-2265.

Srivastava, H.N., Verma, R.K., Verma G.S., Chaudhury, H.M. (1984) Crustal studies of the Koyna region using explosion data from deep seismic soundings. Tectonophysics, v.110, pp.61-72.

Sushini, K., Srijayanthi, G., Raju, P.S., Kumar, M.R. (2014) Estimation of sedimentary thickness in the Godavari basin. Natural Hazards, v.71(3), pp.1847-1860.

Talwani, P. (1997) Seismotectonics of the Koyna-Warna Area, India. Pure Appld. Geophys., v.150, pp.51.

Tandon, A. N. and Chaudhury, H.M. (1964) Thickness of earth's crust between Delhi and Shillong from surface wave dispersion. Indian Jour. Met. Geophys., v.13, pp.385–394.

Tewari, H. C., and Kumar, P. (2003) Deep Seismic Sounding Studies in India and its Tectonic Implications, In: Geophysics: Window to Indian Geology, Ed. Mita Rajaram, Virtual Explorer, 12,30-54, http://virtualexplorer.com.au/journal/2003/12.1–550.

Tewari, H.C., Rao, V.K. (1990) Crustal velocity model in the eastern part of the Indian Peninsular shield. Jour. Geol. Soc. India, v.36, pp. 475–483.

Tewari, H.C., Murty, A.S.N., Kumar, P., Sridhar, A.R. (2001) A Tectonic model of Narmada region, Curr. Sci., v.80, pp.873-878.

Tewari, H.C., Prasad, B.R. and Kumar, P. (2018) Structure and Tectonics of the Indian Continental Crust and Its Adjoining Region, Elsevier, ISBN: 9780128136850.

Tewari, H. C., Kumar, P. (2020) Lithospheric framework of the Indian subcontinent through Seismic and Seismological Studies, Episodes, v.43(1), pp.622-637, doi:10.18814/epiiugs/2020/020041.

Vijay Kumar, T., Jagadeesh, S., Rai, S. S. (2012) Crustal structure beneath the Archean–Proterozoic terrain of north Indiafrom receiver function modelling. Jour. Asian Earth Sci., v.58, pp.108-118.

Vijaya Rao, V., Rajendra Prasad, B. (2006) Deep seismic reflection study over the Vindhyans of Rajasthan: Implications for geophysical setting of the basin. Jour. Earth Syst. Sci., v.115, pp.135–147.

Vijaya Rao, V., Murty, A.S.N., Sarkar, D., Bhaskar Rao, Y.J., Khare, P., Prasad, A.S.S.S.R.S., Sridhar, V., Raju, S., Rao, G.S.P., Karuppannan, P., Prem Kumar, N., Sen, Mrinal K. (2015) Crustal velocity structure of the Neoarchean convergence zone between the eastern and western blocks of Dharwar Craton, India from seismic wide-angle studies. Precambrian Res., v. 266, pp.282-295.

Vijaya Rao, V., Sain, K., Reddy, P.R., Mooney, Walter D. (2006) Crustal structure and tectonics of the northern part of the Southern Granulite Terrane, India. Earth Planet. Sci. Lett., v..251, pp. 90-103.

Rao, G.S.P., Tewari, H.C. (2005). The seismic structure of the Saurashtra crust in northwest India and its relationship with the Reunion Plume. Geophys. Jour. Inter., v.160, pp.318-330.

Vinnik, L.P. (1977) Detection of waves converted from P to SV in the mantle. Physics Earth Planet. Inter., v.15(1), pp.39-45.

(Received: 22 March 2021; Revised form accepted: 19 July 2021)