

Seismic Imaging of the Indian Continental Lithosphere

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We summarize here significant contributions of Indian researchers during the period 2008-11 in the domain of structural seismology dealing with multi-scale seismic imaging of Indian crust and mantle to retrieve the earth's physical and geometrical properties aimed at understanding the processes responsible for generation and evolution of the continent, and its linkage with the earthquake genesis. Most contributions emanated from mathematical modeling of earthquake waveforms and their phase travel time measurements as recorded on specifically designed network of digital broadband seismographs from different geological terrains of age from 3.4 Ga to the recent. The seismological products from these contributions include multi-dimensional elastic property of terrains, model of mantle flow arising from study of seismic anisotropy, the deep mantle stratigraphy and earthquake mechanics. These have been modeled in terms of earth and earthquake processes in the region.

Key Words : Crustal Thickness; Cratonic Lithosphere; Subducted Plates; Mantle Discontinuity

Introduction

Formation of the continents, surface morphology, occurrence of natural resources and earthquakes at specific locales of the Earth are closely linked to the processes operating in the earth's interior that create, modify, and destroy the lithosphere. The fact that these processes have operated in the past and continue to do so is reflected in the variation of surface topography, diversity of rock types and their age besides their distinct physical and chemical properties. Evidently, this has contributed to the rich assortment of unique rock suites and tectonic elements of India that preserve the most complete records of geologic evolution from over 3600 million years to the very recent time. The Indian continental lithosphere which is a collage of several cratons occupying over 10% of the global cratonic lithospheres, offers particularly instructive possibilities to comprehend the representative frozen tectonic processes that affected the pristine deep Earth configuration leading to the present-day disposition of the various geological blocks (like Dharwar, Bastar, Aravalli-Bundelkhand and Singhbhum cratons, Southern Granulite Province, Deccan Volcanic Province and Central Indian Tectonic Zone) besides mapping the active Himalaya-Tibet segment of India.

An outstanding question being addressed by earth scientists today begs the understanding as to how continental lithospheres formed in the early earth and, in particular, how did they come to acquire their distinctively

processed geochemical and rheological structure from those of the primitive earth, which would guarantee an extraordinary immunity to disruption despite a vigorously convecting mantle. For, a significant proportion of those created by ~3000 Ma have managed to survive being dragged down the mantle, through the vicissitudes of the earth's turbulent history, to constitute at least 14% of their total expanse visible on earth today. To comprehend these issues, during the past half-decade, several exciting research directions have been explored utilising dense data combined with novel techniques to yield unprecedented high-resolution images of India that are expected to provide new insights into the nature and role of past and present processes that operate inside the Earth.

The Crustal Structure

Archaean shield lithospheres such as the Indian, are required to possess specifically ordered geochemical and thermal structures to have survived over 3000 million years of mantle convection, and would yet determine the course of future geodynamics. Broadband seismology offers the distinct possibility to map shear wave speed variations with depth to arrive at the thermal states and obtain estimates of the average crustal Poisson's ratio that are a good proxy for the petrological character of crustal materials. The two most definitive ways to accomplish these is to use multi-mode surface wave tomography and travel delays of converted shear waves generated at prominent discontinuities, such as the Moho adopting the receiver

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function technology. These possibilities motivated several researchers to design experiments to investigate the structure of the Indian shield units and especially its disposition beneath Himalaya and Tibet via their seismic characteristics.

Much of their data using joint inversion of receiver functions and 3-5° resolution surface wave dispersion data for 10-70 secs periods have led to the best constrained seismic characteristic images of the Indian continental crust so far. Significant results of these investigations include the following :

- * The eastern Dharwar craton from Bangalore in the south to Hyderabad at ~17°N, including several off profile sites has a seismically transparent crust with a typical crustal thickness of 32-38 km, an average crustal shear wave speed of ~ 3.7 km/s and V_p/V_s of 1.7. It is also characterized by the absence of any seismically distinguishable high speed layer in the lower crust.
- * In contrast, the western Dharwar crust, beneath the 3.4 Ga greenstone belts, has a thickness of 48-52 km, an abrupt increase across the meridional Closepet granite, with an uniformly higher average shear wave speed of ~ 4 km/s. Remarkably, however, the crustal structure beneath the Deccan basalt cover to the north of the western Dharwar craton is similar to that of the eastern Dharwar with a simple transparent seismic structure and an average crustal shear wave speed of 3.74 km/s. The Moho depths vary from 36 to 38 km.
- * Further south, the crustal structure beneath the 550 Ma Pan African Madurai granulites and Kerala khondalites is typified by that beneath Trivandrum barring a few exceptions. The average crustal thickness beneath Trivandrum is ~36 km and a shear wave speed of 3.83 km/s.
- * The two Eastern India cratons, Bastar and Singhbhum, largely remain terra-incognita save some disjointed results. For example, a single seismic station on the Bastar craton yielded a crustal thickness of 40 km and a shear wave speed of ~ 3.5 km/s. North of the CITZ, the Bundelkhand craton also has a simpler crust with an average shear wave speed of 3.7 km/s and crustal thickness of 38 km beneath Jhansi, thickening to 46 km beneath Allahabad ~300 km to the east, on the southern edge of the foredeep. The crustal structure of the various shield areas of the continent is thus intermediate between that of the eastern Dharwar craton and the western counterpart.
- * The Proterozoic Godavari and Vindhyan basins have

thicker (40-44 km) crust and an average shear wave speed of 3.8 km/sec., but are underlain by a higher speed (4.4 km/s) basal layer. The crust is much thicker (48-50 km) beneath the Narmada Son lineament.

- * Crustal structures beneath the western, eastern and central Lesser Himalaya, show a gently northward dipping Moho, except beneath Sikkim where it dips towards the south, overlain by a complex structure representative of the shaved off upper crust of the Indian plate over-thrust upon itself. Two seismic profiles traversing the Himalaya map the Indian Moho right through the Himalaya and the suture zone into southern Tibet as far north as Lhasa in the east and Karakoram in the west.
- * Seismic imaging of the crust and Moho of the Garhwal Himalaya shows a nearly horizontal Moho at 35-40 km depth beneath the Lower Himalaya which abruptly steepens to a dip of 15-27° beneath the Higher Himalaya. This transition to a steeply-dipping Moho, which occurs over a horizontal distance of 10-20 km, implies a sharp flexure of the Indian plate, and therefore a significant loss of strength in the lithosphere. The transition is located spatially beneath both the abrupt rise in elevation at the base of the Higher Himalaya and the speculated location of a mid-crustal ramp in the Main Himalayan Thrust (MHT). This abrupt rise in elevation (or physiographic transition) has been attributed in kinematic models to this ramp in the MHT (the detachment at the base of the Indian lithosphere). Both of these features are located spatially above observed flexure of the Indian plate, suggesting that deep tectonic orogenic processes may play a role in shallower crustal and morphological features.
- * Crustal structure in northeastern India is broadly similar to that of the eastern Dharwar craton, the crust beneath the Shillong plateau is thinner by ~ 4 km compared with that of the Brahmaputra valley requiring the ~1 km high uncompensated Shillong plateau crust to be upthrust along mantle reaching faults. This as well as the better constrained focal depths of earlier located upper mantle earthquakes beneath Shillong, which are all found to lie within the lower crust demonstrate that the plateau's lower crust is at least as strong as its underlying mantle, refuting the validity of the long held sandwich model of crustal rheology in this part of the globe.

The eastern and the western Dharwar cratons, both containing vestiges of early Archaean but stabilized by the late Archaean, represent the two extreme crustal types of

the continent. The eastern Dharwar craton is a seismically transparent, classical Archaean crust with a thickness of ~32-38 km and average shear velocity of 3.8 km/s. The western, in contrast, except for sites near the coast, is thicker (48-52 km), less felsic with a higher average shear wave speed of ~3.96 km/s and has a significant intra-crustal layer at 10-20 km depth below which the shear wave speeds are >4 km/s, suggesting the operation of plate tectonic processes as early as the 3.3 Ga age of the overlying greenstones. Other cratons of the continent including the undercarriage of the Deccan basalts, have thicknesses and average shear velocities within and near the ranges characterizing the eastern Dharwar craton, except that those north of the CITZ are more felsic requiring mafic cleansing, most likely by forging the development of eclogites in their deeper roots and their subsequent loss by gravitational foundering. These results are broadly similar to those obtained for other cratonic and Proterozoic crusts in the world, supporting the basic hypotheses to explain the processes of melt depletion that created a buoyant crust resting over a depleted and therefore refractory protective upper mantle. However, the evolutionary history of individual cratons must vary in detail as to the extent of their material processing depending on the prevailing thermodynamic conditions at the time of their formation.

Deep Structure of the Indian Lithosphere

Pointed investigations to determine the deep structure of the Indian lithosphere have been woefully inadequate for various reasons. The foregoing account of the Indian lithosphere is not intended to be exhaustive but highlights some aspects considered significant by these authors. Nevertheless, an attempt is made to capture the anisotropic character of the Indian lithosphere, tectonic scars preserved within the lithosphere besides state of the underlying mantle transition zone.

Anisotropy

A detectable signature of the deformation field, both in the crust and the upper mantle, is the induced alignment of rock fabrics and of elastically anisotropic minerals, which are amenable to investigation through the observed birefringence of shear waves. A largely preferred approach to investigate mantle anisotropy involves study of the core refracted phases (SKS) which are simpler to detect and interpret. Being converted at the core-mantle boundary from longitudinal waves with energy confined to the plane of propagation, they are cleansed of all information about the source side anisotropy and are necessarily polarized in the radial plane. Inferences about the causative strain field drawn from seismic anisotropy generally assume the mediating processes of i) Asthenospheric flow which, in

simple shear, will have the tendency to align the olivine *a* axis, and ii) creep which may occur as *dislocation creep* involving motion of crystalline dislocations within grains or *diffusion creep* involving solid state diffusion between grain boundaries.

Results from several experiments yield a maximally consistent picture of anisotropic fast directions in the Indian continent and the Himalaya, using both null and non-null determinations. The most remarkable result is that the Indian plate, contrary to the hitherto held view of being isotropic, has ingrained in it consistent NNE-SSW anisotropic fast axis with split times on the order of 1s over much of the shield south of the Himalayan foredeep. This direction is aligned to its convergence velocity with respect to Eurasia or the relative asthenospheric flow underneath. Notably, however, these NNE-SSW striking fast axes dominating the continent from as far south as Sri Lanka, turn almost by 90° on approaching the Himalayan belt, to become perpendicular to the compression axis. One possible explanation for this is turning of the asthenospheric flow by the under-thrusting Indian plate acting as a barrier, a result observed in several subduction zones.

Interestingly, while the sources of crustal anisotropy in the Indian lithosphere appear to lie in its frozen structural fabrics induced by past tectonic events, those of mantle anisotropy are dominated by ongoing motion of the Indian plate with respect to the underlying asthenosphere. This does not, however, warrant the inference that the Indian lithospheric crust is decoupled from the underlying mantle. Indeed, the cratonic cores that occupy much of the Indian continental uppermost mantle extending to depths of over 150 km, strongly attest to its robustly coherent crust-mantle architecture. Because of such well determined constraints from deformation studies and the controversy surrounding the S-receiver function results from the cratonic cores such as the Eastern Dharwar craton (EDC), veracity of a thin Indian lithosphere model (~100-km thick) seems rather far-fetched.

Images of Relict Subducted Plates

The Proterozoic Eastern Ghats Belt (EGB) of India is often believed to be the ancient analogue of the present day Himalayas. However, geological and geophysical signatures that can be traced and linked to the EGB orogen due to a Precambrian collision episode are sparse and evidence of such a geotectonic process in the deep lithosphere remains elusive. For, unambiguous recognition of sutures in Archean and Proterozoic terranes is a rarity and is often controversial. This presents an excellent opportunity to look for relict signatures of ancient collisions in the underlying lithosphere. Employing a new facet of the S-receiver function imaging technique to the data from

the EGB and the adjoining Eastern Dharwar craton (EDC) regions, the hitherto elusive signatures of the depth disposition and lateral extent of this collision episode are captured. Utilizing two important modifications introduced to the recently developed S-receiver function technique in conjunction with the conventional P receiver function approaches, analyses of over 2,000 receiver function data reveal a robust westerly dipping feature in the depth range 150-200km beneath an approximate area of $\sim 2 \times 10^5$ km² covering the EGB and the adjoining cratonic land mass. This westerly dipping feature is interpreted as a relict collision signature of a convergence event ~ 1.6 Ga in the light of available geochronological, geological and petro-tectonic evidence. These findings show dominance of the older westward subduction over the postulated eastward subduction in the evolution of the EGB. Preservation of such relict structures since the Mesoproterozoic despite energetic processes such as the Gondwanaland breakup and the rapid movement of the Indian plate during the Cretaceous could result from a mechanically strong, buoyant and thick (> 200 km) lithospheric keel beneath the Indian shield. This keel translates coherently with the overlying lithosphere preserving the delineated ancient orogenic structures. These findings, therefore, argue for a thick lithosphere beneath the study region and directly contradict any model that envisages a thin Indian lithosphere. Thus, any geodynamic consequence such as rapid Indian plate transit during the Cretaceous that follows from a thin lithosphere model appears untenable. Finally, drawing analogy from similar tectonic settings of Proterozoic age around the globe, these results add to the growing body of evidence that supports the operation of present day plate tectonic processes even during the Precambrian. Further, reported presence of such relict subducted slabs related to the Himalayan orogeny beneath eastern Himalaya and southern Tibet manifested in terms of a thickened mantle transition zone (MTZ) lends support to repeated operation of Wilson cycle in formation of the continents.

Character of the Indian Upper Mantle

Rayleigh wave dispersion curves which are sensitive to the shear wave structure in the vertical plane containing the source-receiver path, allow one to determine average Rayleigh wave phase and group velocities in this plane at various periods, each with their characteristic peak depth sensitivities at approximately a third of the wavelength. With a sufficient number of such intersecting source receiver paths available, these observations allow one to perform a tomography of the region under study in 3-D, and inversions thereof in terms of the shear wave speed structure of the mantle lithosphere to shed light on its temperature regimes.

Recent results based on such surface wave analysis of 4054 source-receiver paths covering most of India and Tibet reveals:

- * Cratons of the shield are mapped as contiguous higher velocity areas little distinguished from the intervening mobile belts. The cratons with their roots coalesced beyond 100 km depth (70 sec period) appear as a continental scale cratonic core while the Tibet remains hot down to 70 km.
- * Larger extent of deeper cratonic expressions suggests the existence of hitherto unsuspected cratonic elements beneath much of the Cretaceous flood basalts as well as all along the Himalayan foothills right up to the two syntaxial bends at their extremities.
- * Interestingly, longer source-receiver paths and therefore longer periods but with less resolution, suggest a high velocity core beneath Tibet at ~ 280 km depth, virtually spilling south across the Himalaya to join the northern block Indian cratonic core.

As cratonic cores under compression can only fuse and get stronger, one may visualize a future, a few million years hence, with Himalaya and Tibet eroded to expose a large cratonic expanse stretching southward into the Indian continent. Thus, one may well speculate whether in the lithospheric architecture of Himalaya and Tibet fashioned by India's long continuing northward advance, we are witnessing the process of a craton in the making?

The Earth's mantle transition zone, delimited by the global 410-km and 660-km seismic discontinuities, reacts to temperature variations by thinning in response to heating or thickening due to cooling. This anti-correlated response of the 410-km and 660-km boundaries to thermal anomalies is due to vertical shifts of i) the $a@b$ phase transitions in olivine at the 410-km depth interface, and ii) the dissociation from g-phase to perovskite + magnesiowüstite at 660-km discontinuity. The nature of thermal anomaly dictates the direction of deviation in MTZ thickness from a global average value of ~ 250 km (~ 24 s), measured as $P660s-P410s$ differential times (t_{MTZ}) of P-to-S converted seismic waves. Thus, a geophysically robust parameter like t_{MTZ} acts as a mantle thermometer when a geodynamic process affects the MTZ to induce topography of this transition zone. Results of experiments designed to image the prominent mantle zone discontinuities at ~ 410 and 660 km, across India, western Himalaya and Ladakh show that these two second order discontinuities run parallel to each other right across the north Indian plains and Himalaya to the Karakoram, except for an upwarp beneath Himalaya-Tibet, most likely because of the presence of the high velocity Indian mantle above. These results have important implications to follow, such as: (i) coupled with the above

cited higher shear wave speed below 100 km in Tibet based on Rayleigh wave tomography, these results strongly argue for the reality of penetration of the entire Indian plate into Tibet setting the scene for the fusion of the transcontinental cratonic cores beneath northern India and Tibet, (ii) the relatively unperturbed MTZ thickness in the Indian shield regions suggests that thermal imprints related to stupendous plume activity did not disrupt the core craton architecture testifying their survival and resilience through geologic times resisting processes of attrition.

Nature of the Shallow Mantle Discontinuity

A new joint seismological-theoretical molecular dynamic simulation approach has been pursued to provide evidence for shallow mantle discontinuity, like the Hales, and also the role of the presence of iron into creating the velocity contrast at the corresponding depth level in the mantle. First-principle molecular dynamics simulations have been used to study the behaviour of cation ordering in the non-equivalent octahedral sites of Mg-Fe olivine solid solutions. Theoretical calculations confirm the previous experimental findings that Mg²⁺ and Fe²⁺ can inverse their octahedral site occupancy at the transition temperature (T_t). Under the ambient pressure T_t is calculated to be 520°C, which agrees fairly with the experimental finding. Using the Indian continental geotherm, a depth of around 75 Km is estimated that corresponds to the calculated transition pressure and temperature of cation ordering. This correlates well with the depth of Hales discontinuity marked by a increase of shear wave velocity by 4%. Further, the isotropic bulk and shear moduli was computed employing the Hill's average method varying the iron content. For olivine solid solutions with 12.5% iron, the ordering transition increases V_s from 4.5 to 4.7 Km/s. Both the inferences, viz. depth of discontinuity and magnitude of velocity increase find support from modelling of teleseismic earthquake waveforms recorded over broadband seismographs on Dharwar Craton. This leads to conclude that cation ordering transition in ferromagnesian olivine can be a potential factor for the Hales discontinuity in Earth's mantle.

Seismic Hazard of the Kachchh Rift Region, Gujarat

In the aftermath of the deadly 2001 Bhuj earthquake in Gujarat, India, several seismological studies were launched to image the Kachchh rift zone (KRZ) in unprecedented detail to understand the role of the underlying lithosphere and capture the seismogenic structures responsible for this devastation with a view to characterise the seismic hazard of the region. Such a concerted efforts yielded new knowledge about earthquake genesis in rift-related

intraplate settings such as the KRZ, the attendant state of the lithosphere besides accurate assessment of the associated seismic hazard. Some important findings that emerged from a decade-long research in the KRZ are summarised as: (i) a 7 km depth change in the seismogenic base beneath the Kachchh seismic zone (KSZ) based on precise relocations of the 2001 Bhuj aftershocks (ii) V_p and V_s tomograms map strong lateral velocity heterogeneity consisting of high and low velocity patches suggestive of a highly deformed and/or heterogeneous crust beneath the KRZ (iii) joint inversion of P-wave receiver function and surface wave dispersion data delineates an updoming of the Moho (3-7 km) as well as the asthenosphere (6-12 km) beneath the central Kachchh rift zone (KRZ), relative to the surrounding unrifted parts of the KRZ besides revealing a thin lithosphere (~70 km) beneath the KRZ region, (iv) documentation of strong rift axis parallel SKS anisotropy with a delay of 1.6 s induced by possible rift-parallel flows within the 76±6 km-thick lithosphere.

All these anomalous observations mapped at a fine scale are argued to be closely linked to the Deccan/Reunion mantle plume-lithosphere interaction about 65 Ma ago. The resultant large-scale mass heterogeneities in the crust and upper mantle by way of volatile rich/absent intrusions related to the Deccan plume activity are assigned a key role in generating these intraplate earthquakes.

Towards assessing the seismic hazard of the KRZ, as a first step, the sediment thicknesses and Q_p vs. Q_s relationships in the Kachchh basin have been modeled using S_p converted phase (from the sediment-basement transition). The sediment (with $V_s=0.9$ km/s) thicknesses were found to vary from 0.85 to 1.53 km, whereas, estimated Q_p vs. Q_s relationships reveal the presence of wet attenuative sediments within the Kachchh basin. The site response estimates obtained by the inversion of S-wave spectra from strong-motion data of earthquakes occurring in KRZ reveal larger site response (>1.2) values in the 0.2–1.0 Hz frequency band. These are attributed to the probable presence of soil class C ($360 < V_s = 760$ m/sec) and D ($180 < V_s = 360$ m/sec) in the Kachchh basin. The site response study also confirms that geological contacts and thickness of various sedimentary formations control the spatial variation in site response in the KRZ. Thus, these results from the research work on the 1-D and 3-D crustal seismic velocity structure, various attenuation relationships of the seismic wave phases and site amplification in the Kachchh area can form key inputs for studying wave propagation and earthquake hazard related risk in the basin.

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