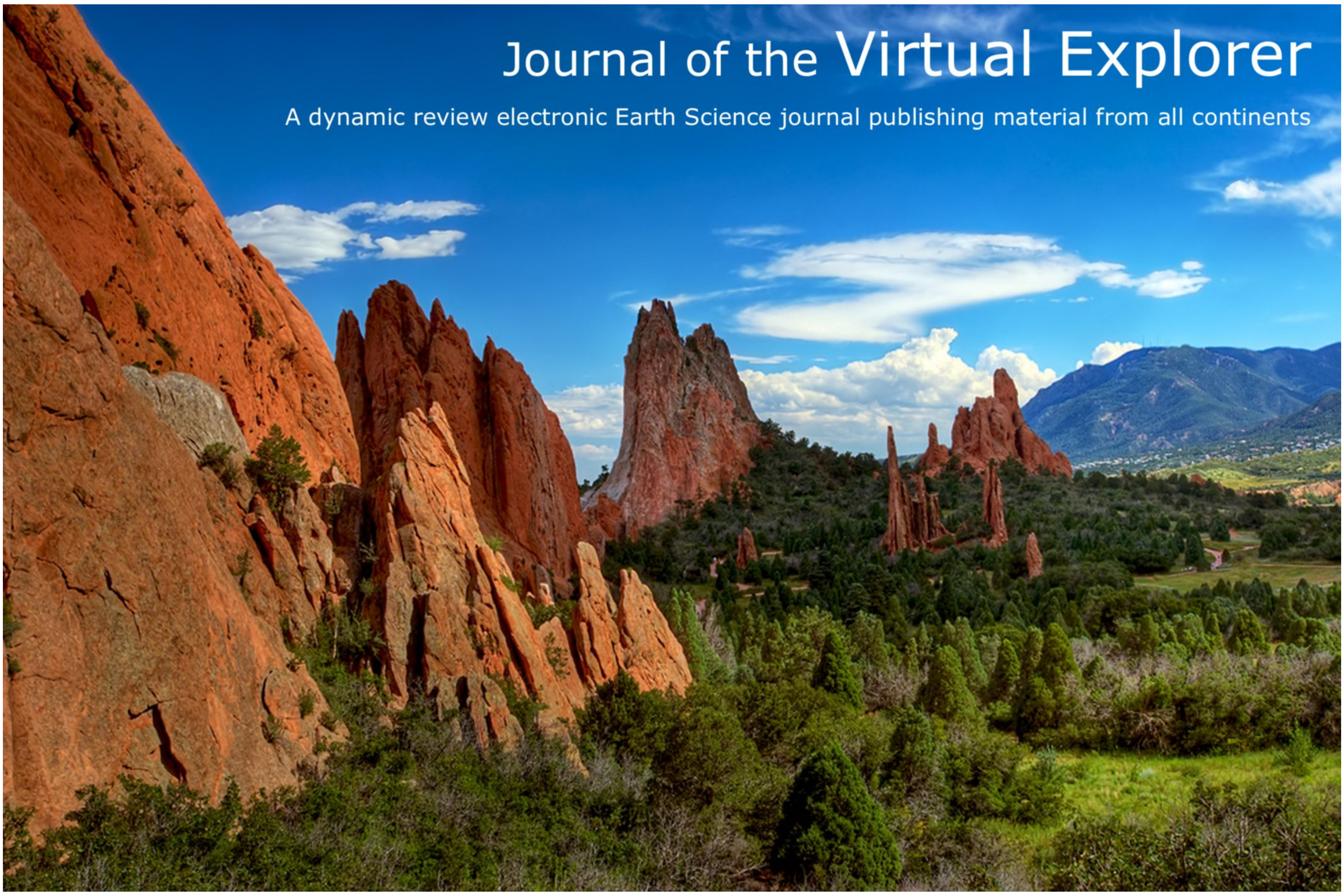

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Vinod K. Gaur

Journal of the Virtual Explorer, Electronic Edition, ISSN 1441-8142, volume **32**, paper 1
In: (Eds.) Talat Ahmad, Francis Hirsch, and Punya Charusiri,
Geological Anatomy of India and the Middle East, 2009.

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Abstract: The paper presents a synthesized interpretation of the crust and upper mantle structure beneath most of the Indian continental lithosphere including that buried beneath the Deccan basalts, based on the published, and some unpublished, analyses of broadband seismic data. It also discusses the anisotropic structure of the Indian continental mantle, widely regarded as isotropic, by exploiting the consistency exhibited by a large number of null results with the small number of non-null results. The parallelism of the pervasive fast direction over much of the shield south of the foreland basin, with the relative asthenospheric flow, predicts the development of foliations in the horizontal plane which would inhibit splitting of the near vertically travelling shear waves such as the SKS. This severe limitation on SKS splitting results in the poverty of non-null results of splitting, which have been mistaken for the isotropic character of the Indian lithosphere.

Citation: Gaur, V. 2009. The Indian Continental Lithosphere. In: (Eds.) Talat Ahmad, Francis Hirsch, and Punya Charusiri, *Journal of the Virtual Explorer*, volume **32**, paper 1, doi: 10.3809/jvirtex.2009.00253

Introduction

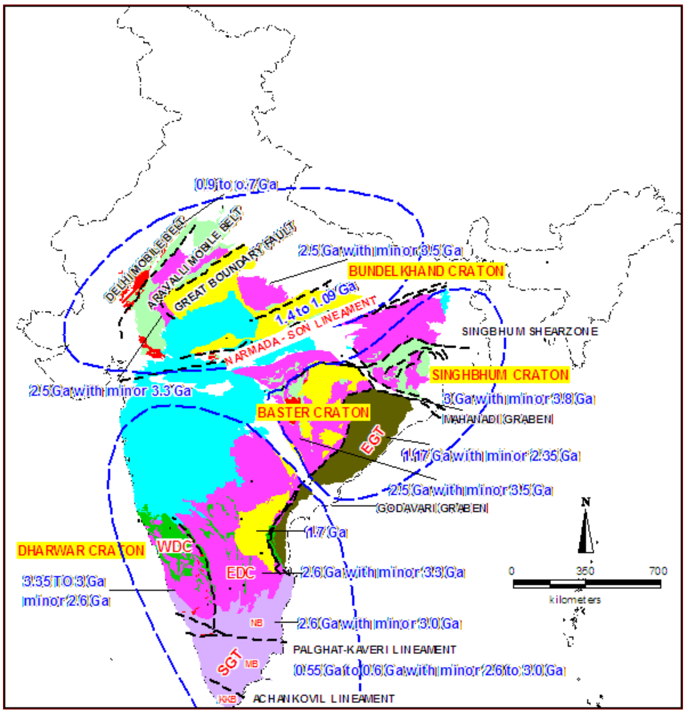
The Indian continental lithosphere is distinguished by spectacular boundaries: the crown of the majestic Himalaya on the north and two Passive continental margins that taper it southward into a peninsula. It is surfaced entirely by a shield, itself a mosaic of Archaean cratons and intervening mobile belts that are exposed over much of the continent except for tracts of sedimentary covers of which the most notable is the Himalayan foredeep. The shield that was mostly amalgamated by early Proterozoic, had apparently remained largely stable up till the Eocene continental collision, except for a few regional extensions resulting in the formation of basins and rifts: the Cuddappah in the eastern Dharwar craton and Bhima & Kaladagi in the western, in addition to the perhaps younger east coast inter-cratonic Godavari and Mahanadi rift basins. More recently, ~50 Ma ago, upon the arrival of its leading continental edge face to face with the Eurasian, the Indian plate, apparently more stolid, underthrust the latter, creating the world's largest high altitude plateau and its southern Himalayan rim. The flexed shield on their southern front was, in time, filled with the material eroded from the rising Himalaya to become a foreland basin superficially intervening the shield and the mountains, except in the southeast where it opens out into the Bengal basin abutting the northern Bay of Bengal. Apart from its flexure, the Indian shield also remained largely undeformed south of the collision boundary, requiring the existence underneath of an ultra strong cratonic core. The shield's outlying limb in the northeast, south of the Brhmaputra valley, was of course fractured along mantle reaching faults (Bilham *et al.*, 2001 and Mitra *et al.* 2005) and up-thrust to become the uncompensated Shillong plateau. However, this process not enacted elsewhere along the arc, could have been the result of a much lesser width of the shield in this region between the collision front and the strong oceanic lithosphere of the Bay of Bengal.

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 ~3,000 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 (Rudnick, 1995) visible on earth today. An interesting speculation stimulated by the new knowledge of the deep structure of Tibet (Priestley *et al.*, 2006), that it represents an early stage in the evolution of cratonic lithospheres, opens up many interesting possibilities of testing this hypothesis by interrogating potentially responsive tracts of continental lithosphere. The Indian continental lithosphere which is a collage of several cratons occupying over 10% of the global cratonic lithospheres, offers particularly instructive possibilities to explore this idea.

The shield

The Indian shield (Figure 1) is superficially bounded on the north by the Himalayan foothills but dipping underneath the Himalaya, it penetrates the underbelly of southern Tibet. It is comprised of 5 Archaean cratons and 3 fringing mobile belts (Ramkrishnan *et al.*, 2008), and bears Proterozoic sedimentary basins, extensive flood basalts, rift valleys filled with coal bearing Gondwana sediments and Cretaceous marine incursions, as well as Tertiary and Quaternary sediments along the coasts, the Himalayan foothills and in river valleys. The shield is broadly divided into a northern block of the Aravalli-Bundelkhand cratons and a southern block of Dharwar-Bastar-Singhbhum cratons by the prominent WSW-ENE trending Central Indian Tectonic Zone (CITZ) which, stretching from the west coast at ~20ºN to ~24ºN in eastern India, is one of the three most striking mobile belts of the continent, also marked by the trans-continental Son-Narmada lineament.

Figure 1. Typical ages of the 5 mapped cratonic elements of the Indian shield



Showing some typical ages of the 5 mapped cratonic elements of the Indian shield, the crescent shaped meso-Proterozoic Cuddappah basin in the eastern Dharwar craton and the fringing mobile belts (After Roger and Naqvi, 1987, Precambrian Geology of India, Oxford University Press)

The southern block cratons fringed by CITZ on the north, occupy a vast area of central, south and eastern India stretching south to ~10ºN and to the east coast passive margin where about its middle three quarters is overthrust by the fringing Eastern Ghat mobile Belt (EGMB). Two inter cratonic rifts of uncertain antiquity striking NW from the east coast, that were apparently reactivated during the Gondwana breakup and became sediment repositories of that age, separate the three cratons of the southern block concealing any deeper structural features that may connect them. On the west, an unknown expanse of the south-central Dharwar craton or a neighbour, is covered by the cretaceous flood basalts covering over 500,000km^2 of the continental surface and perhaps twice as much of the adjoining sea floor, that spewed from the spreading ridge axis since shifted further westwards, presumably in conjunction with an underlying plume.

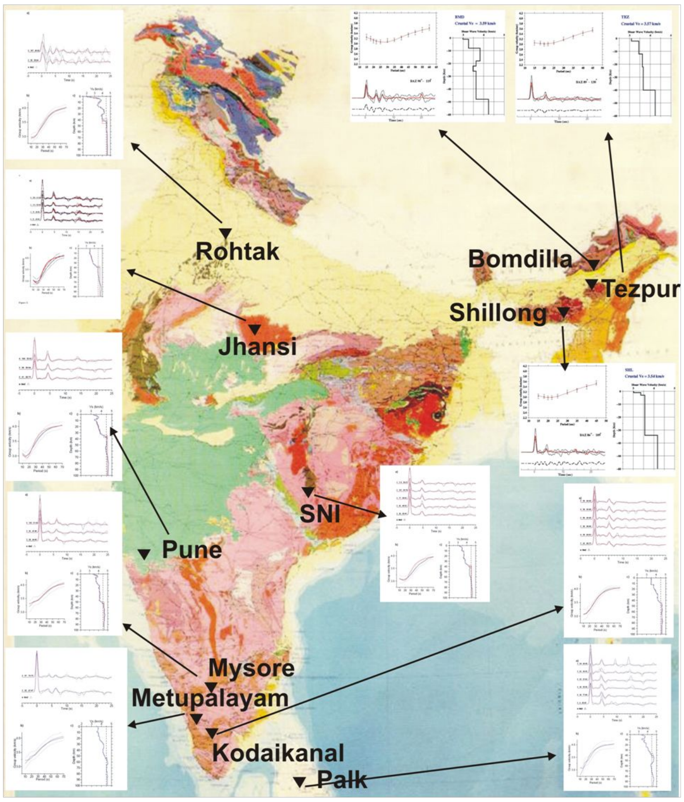
Geologically the best studied, Dharwar craton is a granite greenstone terrane that southwards passes into the higher grade Nilgiri-Madras granulites which apparently represent its lower crustal domain exposed to the surface by northward tilting or by thrusts. The craton whose structural grain is approximately NS is riven in the middle by a NS exposure of the Chitradurg schist belt bordering the narrow 400km long Closepet batholith to its east. The western craton has vestiges of early Archaean (3.3-3.4 Ma) enclaves but apparently suffered a most decisive tectonic event towards the end of that era. The eastern craton of the characteristic greenstones of gold affinity, is somewhat younger. The Nilgiri-Madras granulites which constitute the southern higher grade terranes of the Dharwar craton, are apparently sutured to the 550 Ma southern peninsular Pan African granulites and khondalites along the 10ºN, by the E-W striking high strain Noyil-Kaveri lineament of yet undetermined tectonic lineage. This is the third prominent mobile belt of the continent.

North of the CITZ, the shield is largely buried under the late Proterozoic Vindhyan sediments and beneath the Cenozoic foredeep along the Himalan arc. The Aravalli and the Budelkhand cratons of this block are separated tectonically by the SW-NE Great Boundary Fault, but superficially by the vast Vindhyan sediments stretching much farther east, that cover all but a limited exposure of the Bundelkhand craton thereby precluding from view the extent of its buried eastern expanse as well as the northern which may extend much farther north, even beneath the Himalaya. Indeed, the almost sudden appearance of the Himalayan fold and thrust belt above the foredeep in the north, and its remarkable syntaxial bends seem to require the buried existence of cratonic keels at the northwest and northeastern extremity of the northern block joined into an extensive along arc cratonic core which together determined the deformation boundary.

Geological investigations over the past half century have unraveled several important characteristics of the Indian shield Archaean cratons. Although, of these, only the Dharwar craton has been extensively studied, several broadly similar features are shared by them in varying degrees, highlighting the characteristic geodynamical processes that operated in the early era of the earth's history, notably faster creation and motion of plates and basaltic slab melting in buoyant subduction to produce the ubiquitous Tonalite Trondjhemite Granodiorite (TTG) gneisses exposed in the cratons.

The five cratons of the shield (Figure 2), or at least its northern and southern blocks developed independently before being subsequently fused, mediated apparently by the subduction-collision process. The dominant rocks in the western Dharwar and Singhbhum cratons ahave been dated to be 3.0 Ga old with enclaves of 3.4 and 3.8 Ga respectively. The eastern Dharwar craton divided from the western by the Chitradurga schist belt as well as the Bastar, Bundelkhand and eastern Aravalli Mewar cratons have ages of 2.5 Ga with minor occurrences of 3.3 to 3.5 Ga rocks. All these cratons, to the extent that they have been investigated, are also dominantly comprised of the TTG gneisses which are believed to be the multiply processed products of primitive earth materials (Drummond and Defant, 1990)

Figure 2. Crustal structure beneath selected sites



Shows the crustal structure beneath selected sites over the Indian continent, each marked by a triplet of sketches signifying the corresponding receiver functions (RF), surface wave dispersion curves(DC), and the inverted crustal structure on the right, distinguished by shear wave peeds with depth, obtained by minimizing the misfits with the measurement determined RF and DC (Charlotte Acton, 2009)

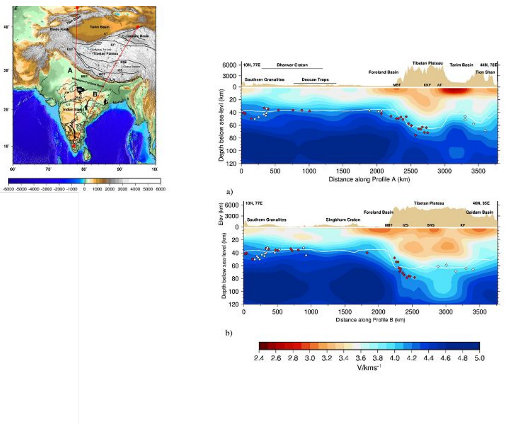
Crustal structure

Archaean shield lithospheres such as the Indian, possess specifically ordered geochemical and thermal structures that have resisted recycling by 3000 million years of mantle convection, and would yet determine the course of future geodynamics. On the basis of well constrained earthquake focal depths, McKenzie et al (2005) showed that beneath the continents, almost all recorded earthquakes lie within the crust, including the deep ones beneath Himalaya and Tibet which lie close to the Moho (Supriyo Mitra *et al.*, 2005). Further, using the slab cooling model to determine the oceanic lithosphere geotherm, and nodule geochemistry for the continental, they showed that most earthquakes occur in materials colder than 600ºC, whether beneath continents or oceans. These results imply that the mechanical strength of the continental lithosphere must reside in the crust and that for it to be yet strong at 600ºC, it must be dry. This identification of the strong continental lithospheric layer with the crust is robustly constrained by an independent estimation (McKenzie and Fairhead, 1997) of the thickness of the elastic layer of the lithosphere found everywhere to lie within the seismogenic layer.

Broadband seismology by furnishing ground motion records over 3 orders of magnitude in frequency and 7 in amplitude, now enable one to map shear wave speed (Vs) variations in the lithosphere, with depth. This is accomplished by isolating fine structures of seismograms for specific analysis using appropriate digital filters. Since Vs is controlled principally by the temperature of the material rather than its composition, shear wave speeds determined from broadband seismograms, can be translated into thermal states at depth. The two most definitive ways to map shear wave speeds at depth, use multi-mode surface wave tomography and travel delays of converted shear waves generated by the first arriving longitudinal waves, at prominent discontinuities, such as the Moho. The latter constitute the Receiver function methodology yielding Moho depths with a resolution of 2-3km depending on the signal to noise ratio, as well as estimates of the average crustal Poisson's ratio as a proxy for the petrological characeter of crustal materials

Motivated by these possibilities, experiments were designed (Rai *et al.*, 2003, 2006), and (Mitra *et al.*, 2005) to investigate the structure of the Indian shield units and especially its disposition beneath Himalaya and Tibet via their seismic characteristics. Recent reinterpretation (Charlotte Acton, 2009, Hazarika *et al.* 2009, Jagadeesh *et al.* 2009) of much of their data using joint inversion of receiver functions and 3-5º resolution surface wave dispersion data for 10-70 secs periods, discussed in the next section, have led to the best constrained seismic characteristic of the Indian continental crust so far, even as several parallel endeavours to further enhance their resolution and fill in critical gaps continue apace and have a long way to go. Inverted crustal structures from receiver functions and surface wave dispersion curves for a few representative regions of the Indian crust are shown in Figure 2, whilst a map of shear wave speed structure along two profiles from southern India to Tibet based on fundamental mode Rayleigh wave tomography, along with crustal depths inverted from receiver functions are shown in Figure 3.

Figure 3. Shear wave speed sections



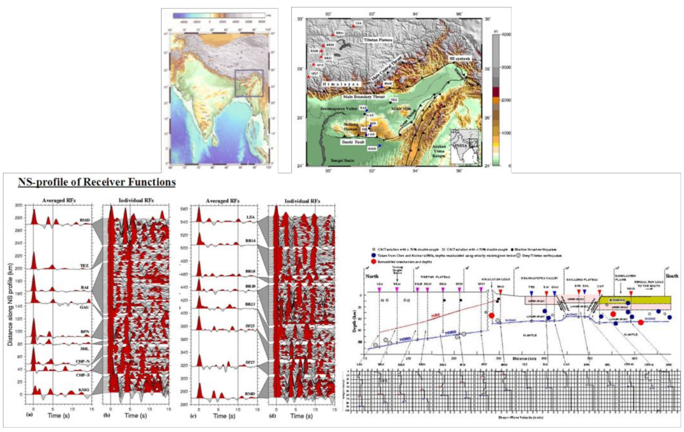
Shear wave speed sections along profiles A and B respectively (top left), the topography plotted above being at a smaller scale. Red diamonds represent Moho depths from joint inversion of surface wave dispersion data and receiver functions, and the white represent Moho depths obtained by grid search stacking of receiver functions or simple depth migration. The white lines mark the crustal thickness estimate from isostasy (sm = 3.3 Mg/m^3, and sc = 2.8 Mg/m^3 (Charlotte Acton, 2009)

Significant results of these investigations include the following:

- that the crustal structure of the various shield areas of the continent are intermediate between that of the eastern Dharwar craton and the western.
- that the eastern Dharwar craton from Bangalore in the south to Hyderabad at ~17ºN, including several off profile sites has a seismically transparent crust with a typical crustal thickness of 32-38km, an average crustal shear wave speed of ~3.7km/s and Vp/Vs of 1.7. It is also characterized by the absence of any seismically distinguishable high speed layer in the lower crust.
- The western Dharwar crust beneath the 3.4 Ga greenstone belts, by contrast, has a thickness of 48-52km, an abrupt increase across the longitudinally stretching Closepet gramite, which occurs largely within a 50km wide transitional region to its west. The western Dharwar crust is thickest around Mysore but decreases to ~40km towards the western coast. It has a uniformly higher average shear wave speed of ~4km/s, and a persistent intra-crustal feature varying between 10 and 20km below which the shear velocity is even higher. Remarkably, however, the crustal structure beneath the Deccan basalt cover to the north of the western Dharwar craton, is similar to that of the easten Dharwar with a simple transparent seismic structure, an average crustal shear wave speed of 3.74km/s and Moho depths varying from 36-38km.
- The crustal structure beneath the 550 Ma Pan African Madurai granulites and Kerala khondalites, which are distinguished from the 2500 Ma Dharwar craton Granulites, lying north across the E-W Noyil-Kaveri high strain zone, albeit inadequately sampled, is typified by those beneath Trivandrum on the southwest coast and Kodaikanal at 2300 metres, east of the southern stretch of western Ghats. The average crustal thickness beneath Trivandrum is ~36km and a shear wave speed of 3.83km/s whilst those beneath Kodaikanal are 46km and a somewhat higher speed of 3.9km/s. The lower crust of Kodaikanal, however, has high, mafic type, shear wave speed of 4.0-4.2km/s. One seismic station at Metupalyam that samples the foot of the Nilgiri hills has similar crustal shear wave speed but has a much thicker crust equal to 54km. On the other hand, the crust beneath the highland complex of central Sri Lanka, also a part of the Pan African terrane, sampled by just one seismic station at Pallekele, is similar to that of Trivandrum, with a crustal thickness of 40km and an average shear wave speed of 3.88km/s which is intermediate between that of Trivandrum and Kodaikanal.
- The two east coast cratons of Bastar and Singhbhum largely remain terra-incognita save some disjointed results. A single seismic station SNI on the Bastar craton yielded a crustal thickness of 40km and a shear wave speed of ~3.5km/s

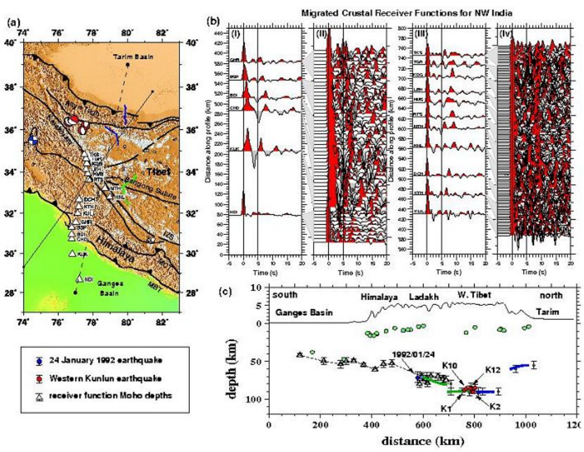
- North of the CITZ, the Bundelkhand craton also has a simpler crust with an average shear wave speed of 3.7km/s and crustal thickness of 38km beneath Jhansi, thickening to 46km beneath Allahabad ~300km to the east, on the southern edge of the foredeep.
- A single seismic station at Mount Abu shows the crust, just west of the Mewar craton, to be 44km with an average wave speed of 3.77km/s. This being similar to the crust at Rohtak and substantially different from that ~50km to its east at Delhi (~36km and 3.67km/s) strongly argue for the Mount Abu-Rohtak Aravalli ridge to be a divider of crustal types.
- The Proterozoic Godavari and Vindhyan basins have thicker (40-44km) crust and an average shear wave speed of 3.8km/sec., but are underlain by a higher speed (4.4km/s) basal layer. The crust is much thicker (48-50km) beneath the Narmada Son lineament.
- Crustal structures beneath the western, eastern and central Lesser Himalaya (Manali, Almora, Gangtok and Bomdila), show a gently northward dipping Moho, except beneath Sikkim where it dips towards the south (Charlotte Acton, 2009), 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. These are respectively shown in figures 4 and 5.

Figure 4. Northeastern Himalayan collision zone



Showing the crustal structure (bottom right) along a 700km long profile across the northeastern Himalayan collision zone from the Bengal basin to Lhasa, based on joint inversions of both receiver functions (bottom left) and surface wave dispersion curves (not shown); the Indian Moho is seen to have penetrated right through the Himalaya to Lhasa. Seismic stations locations are show on the top right (Mitra *et al.*, 2005)

Figure 5. Northwestern Himalayan collision zone



Showing the crustal structure (bottom right) along a 700km long profile across the northwestern Himalayan collision zone from Delhi on the north Indian shield to Taksha on the Karakoram fault, zone, based on joint inversions of both receiver functions (top right) and surface wave dispersion curves (not shown); the Indian Moho is seen to have penetrated right through the Himalaya to Karakoram. Seismic stations locations are show on the top left (Rai *et al.*, 2006)

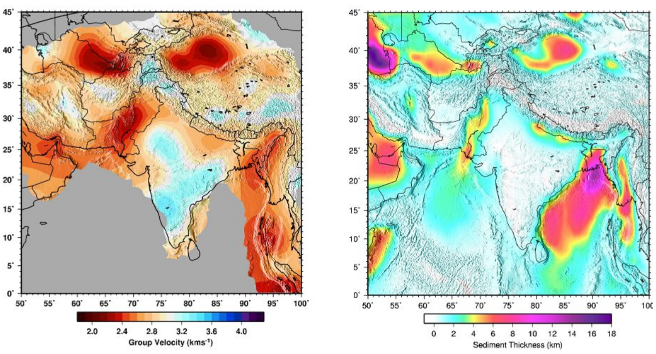
- Data along the eastern profile also show that whilst the crustal structure in northeastern India is broadly similar to that of the eastern Dharwar craton, the crust beneath the Shillong plateau is thinner by ~4km compared with that of the Brahmaputra valley requiring the ~1km high uncompensated Shillong 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 (Mitra *et al.*, 2005).

The Upper mantle

The topography of Asia is dominated by the results of Indo-Eurasian continental collision still continuing apace at ~5 cm/yr (Paul *et al.* 2001). Large scale tectonics on earth is constrained by the behavior of the outer brittle lithospheric caps or plates in response to the heat transfer from the interior. A consideration of the thermo-mechanical properties of the entire cratonal lithospheres inclusive of their crusts is, therefore central to understanding the structure and evolution of the Indian shield. Studies of mantle nodules geochemistry, especially of the diamondiferous, have shown that several cratons have lithospheric roots as deep as 250km. 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 dimensions, and inversions thereof in terms of the shear wave speed structure of the mantle lithosphere to shed light on its temperature regimes.

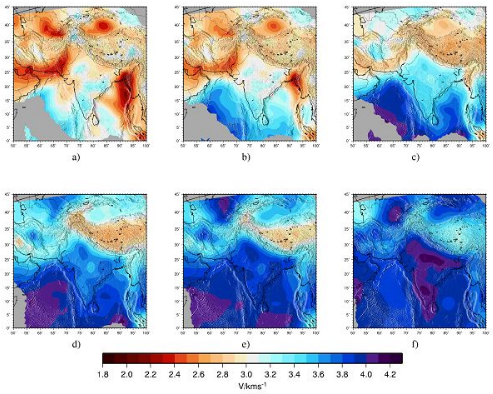
Results of a recent such analysis (Charlotte Acton, 2009) based on 4054 source-receiver paths covering most of India and Tibet, are shown as group velocity maps in Figure 6 for the 10 sec period and in Figure 7 for a few longer periods (15,20,30,40,50,70 seconds) constrained to a lateral resolution of 3-5º. The 10 seconds map (depth sensitivity of ~12km) clearly highlight the low velocity areas occupied by prominent sedimentary basins: the Tarim basin in Tibet, the Katwaaz basin in Pakistan, as well as the Himalayan foredeep and the Bengal basin, virtually reproducing Laske's (1997) sediment thickness map shown on the right. It also maps the 5 cratonic exposures as contiguous higher velocity areas little distinguished from the intervening mobile belts. Whilst Tibet remains hot down to 70km, the strong signatures of the sedimentary basins progressively disappear at around mid-crustal depths (~20 sec. period) even as the cratons begin to acquire sharper outlines coalescing their roots at ~100km (70 sec period) to appear as a continental scale cratonic core. This, much 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. The imaging depth in this analysis to about 100km was limited by the shorter source-receiver paths used, which incidentally enhanced the high frequency contents of the signals thereby improving the resolution at shallow depths. Interestingly, Priestley *et al.* (2006), using longer source-receiver paths and therefore longer periods and with less resolution, discovered a high velocity core beneath Tibet at ~280km depth, virtually spilling south across the Himalaya to join the northern block Indian cratonic core (Figure 8). 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. Indeed, 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.

Figure 6. Velocity and thickness



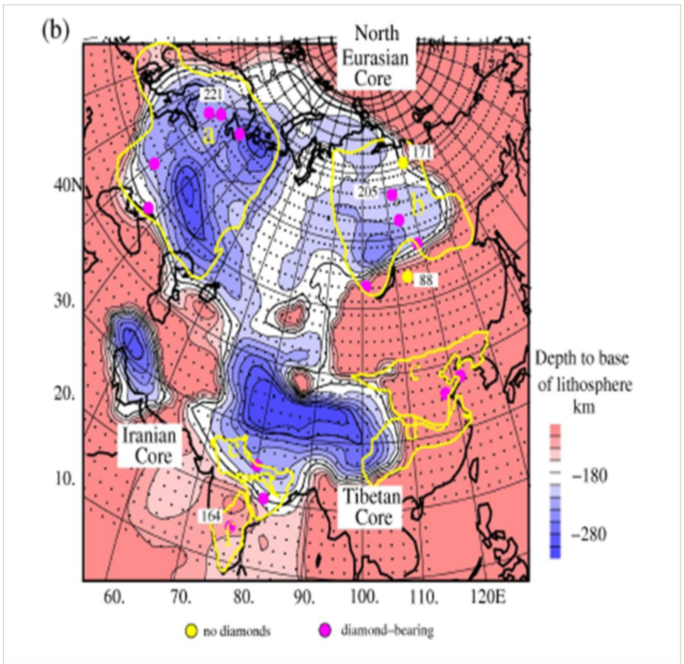
Left: the map shows the distribution of Rayleigh wave fundamental mode group velocity for the 10 seconds period (peak sensitivity approximately l/3 = ~12km). Areas with errors >0.25km/s are clipped in grey. Right: Sediment thickness map from Laske and Masters(1997), left: (Charlotte Acton, 2009)

Figure 7. Velocity maps



Fundamental mode Rayleigh wave group velocity maps for 15, 20, 30, 40, 50 and 70 seconds periods respectively. Areas with group velocity errors >0.25km/sec and those not covered by this study are clipped in grey (Charlotte *et al.* 2009)

Figure 8. Mantle thickness



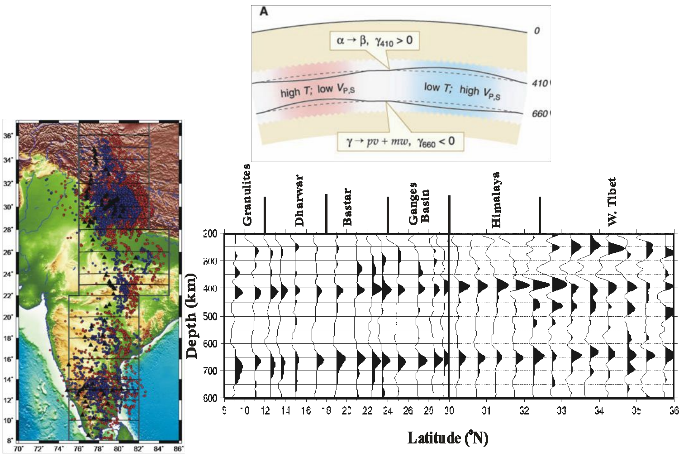
Top sketch shows the thickness of the Mantle Transition zone as the Mantle thermometer. Bottom left shows the piercing points of Ps phases at 410 and 660km depth levels; bottom right shows the stacked receiver functions along 80°E. Time is measured from the P arrival time. Global average time for 410 and 660s are 44 and 68 s corresponding to a distance of 67°. Conversions for 410 and 660km are clear for stations for both the regions, while 475 is observable only at Ladakh stations (Prakasam *et al.*, 2009)

Exploring the Collision Process: Mantle anisotropy and the Mantle Transition Zone (the Mantle thermometer)

The Mantle thermometer

The ongoing Indo-Eurasian collision, by deforming a large part of the continental lithosphere to transform much of their earlier structures into the world's largest high-altitude plateau and its southern rim of the spectacular Himalaya remains the most dominant geodynamic process operating on earth. It is thus potentially the most evocative natural laboratory to investigate the yet obscure processes that are responsible for their dramatic expressions and of lesser ones elsewhere on the globe. High resolution imaging of the crust and upper mantle expected to reveal some of their implied signatures, now made possible by broadband seismology and new insights from mineral physics, make it a particularly propitious time to address this problem. Two end-member models envisage India's continued underthrusting of Himalaya-Tibet by penetration i) of the entire Indian plate into Tibet (Argand 1924; Barazangi and Ni, 1982), and ii) only of its delaminated crust (Bird, 1978; Houseman *et al.*, 1981; Molnar, 1988). Fortunately, these models have mutually exclusive implications which are testable. The first model would be expected to show high velocities in the shallow upper mantle across the Himalaya and Tibet upto the leading edge of the penetrating Indian plate, with little lateral perturbation of the underlying mantle temperature distribution which can be detected by variations in the relative depths of the two prominent mantle zone discontinuities governed by the Clapeyron condition. The second model, on the other hand, should show low velocities in the shallow upper mantle overlying the dipping, high velocity subducted or delaminated lithosphere. If the cool, higher velocity sinking slab were to reach transition zone depths, its thermal affects should then result in the appearance of a significant transition zone topography. Results of an experiment designed (Prakasam *et al.* 2009) to image the prominent mantle zone discontinuities at ~410 and 660km, across India, western Himalaya and Ladakh (the Indian territory of south-western India) whilst at the same time constraining the shear wave speed structure in the crust to improve the resolution, show that these two second order discontinuities run parallel to each other right across the north Indian plains and Himalaya to the Karakoram (Figure 9), except for an upwarp beneath Himalaya-Tibet, most likely because of the presence of the high velocity Indian mantle above. This result coupled with the higher shear wave speed below 100km in Tibet, reported by Priestley *et al.*(2006), based on Rayleigh wave tomography, strongly argue for the reality of Argand's model setting the scene for the fusion of the transcontinental cratonic cores Beneath northern India and Tibet.

Figure 9. Cold mantle depth

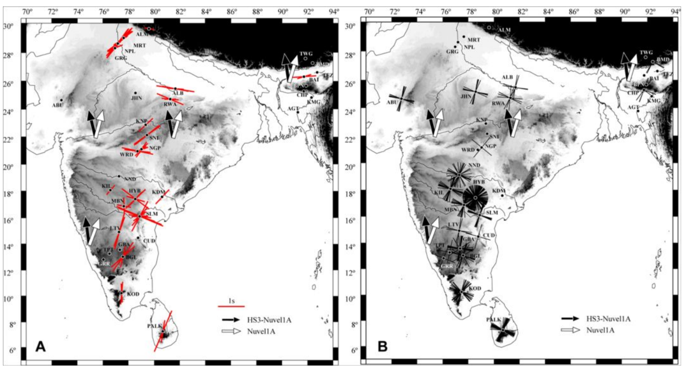


Showing depths to the base of the lithosphere extending to over 280km beneath Eurasia-northern India, mapped through multimode Rayleigh wave dispersion velocities. The image clearly shows the existence beneath all of Tibet, of an extensive cold mantle forming a cratonic core (Copley and McKenzie, 2007).

Anisotropy

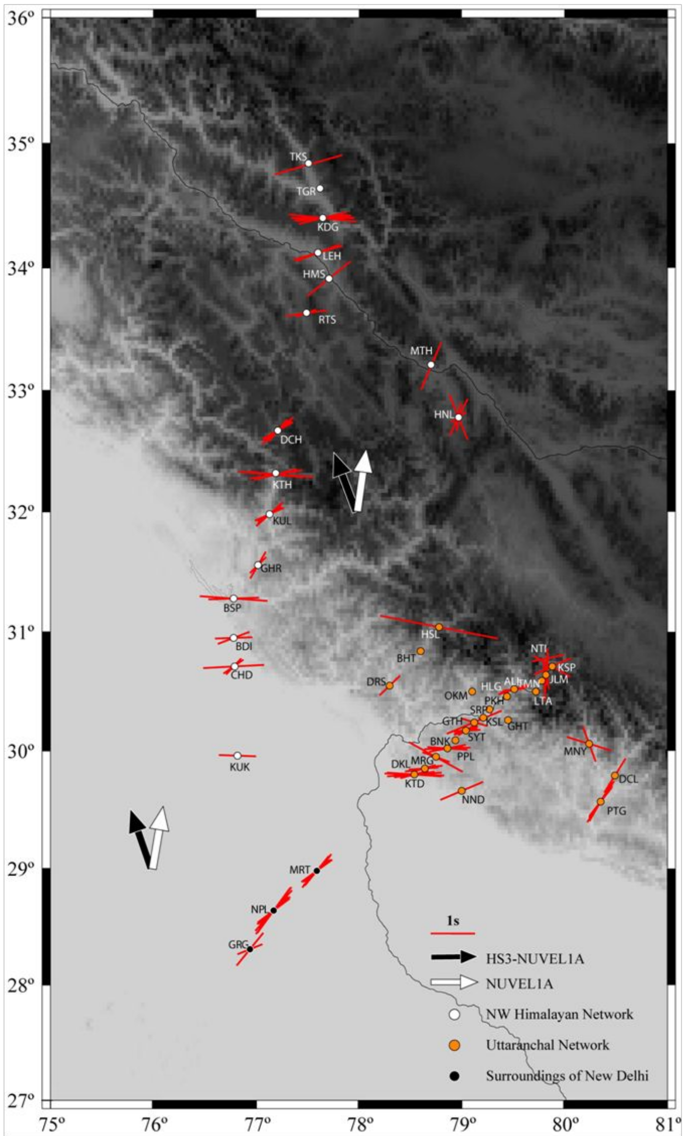
Another detectable signature of the deformation field, both in the crust and the upper mantle, is the induced alignment of rock fabrics and elastically anisotropic minerals, which is amenable to investigation through the observed birefringence of shear waves. Most rock forming minerals are anisotropic, principally quartz (~40% Vs anisotropy) in the crust and olivine in the mantle. Shear waves split into fast and slow orthogonally polarized waves when encountering such materials except when their initial planes of polarization are either parallel or perpendicular to the axes of anisotropy. The component polarized along the fast direction leads the other. Its azimuth and the lead time which can be determined from data, are measures of the anisotropy of the medium which can be calculated from these observed quantities. Non split polarization or null results would therefore signify either the absence of anisotropy or, if present, its fast or slow direction. A largely preferred approach to investigating mantle abisotropy is to study the core refracted phases (SKS) which are simpler to detect and interpret, because being converted from longitudinal waves at the core-mantle boundary, they are cleansed of all information about the source side anisotropy and are necessarily polarized in the radial direction because their energy is confined to the plane of propagation. Inferences about the causative strain field drawn from seismic anisotropy generally assume the mediating processes of Asthenospheric flow which, in simple shear, will have the tendency to align the olivine *a* axis, or creep which may occur as *dislocation creep* involving motion of crystalline dislocations within grains or *diffusion creep* involving solid state diffusion between grain boundaries. The former is understood to preferentially align the *a* axis of the mantle mineral olivine along the minimum strain axis. Diffusion creep which for long was regarded as producing no anisotropy (*e.g.*, Savage, 1999), has, however, been shown (Sundberg *et al.*, 2008) to produce crystal preferred orientation in materials possessing significant grain boundary anisotropy, with a tendency to minimize the viscosity of the aggregate. Non-null results over much of the shield reported from several studies in the past, have engendered the view that the Indian continental lithosphere had no detectable anisotropy and somehow escaped being branded by deformation events. Results of an experiment designed to generate the maximally consistent picture of anisotropic fast directions in the Indian continent and the Himalaya, using both null and non-null determinations are shown in Figure 10 (Maggy Heintz *et al.* 2009). The most remarkable result of this analysis demonstrates that the Indian plate, contrary to the hitherto held view of being isotropic, is definitely not so, and that it has ingrained in it consistent NNE-SSW anisotropic fast axis over much of the shield south of the Himalayan foredeep, aligned to its convergence velocity with respect to Eurasia, mediated by the relative asthenospheric flow underneath. Indeed, one of the attendant consequences of the alignments thus induced, would be to create foliations in the horizontal plane which would inhibit splitting of the near vertically traveling shear waves such as the SKS. The relative poverty of detectable shear wave splittings over India, could therefore be a signature, more strongly, of the shear mediated horizontal foliation planes in the basal lithosphere rather than the result of a nearly isotropic plate. Notably, however, these NNE-SSW striking fast axes dominating the continent from as far south as Sri Lanka, turn almost by 90º on approaching the Himalayan belt, to become perpendicular to the compression axis. This result would have been easier to interpret in terms of dislocation creep with its tendency to align the *a* axis of olivine perpendicular to the maximum compressive stress, if this trend had been observed throughout the plate, because the Indian plate being manifestly very strong, must transmit stresses within the plate without any significant stress drops within. The only other process that would explain it, would be the turning of the asthenospheric flow by the under-thrusting Indian plate acting as a barrier, a result observed in several subduction zones (Savage, 1999). Further north at Ladakh stations, the fast anisotropy directions have highly variable directions from the NUVEL 1A orientation at Hanle to along strike orientations further north at Khardungla (Figure 11). A coherent explanation for this wide variation is at presented not warranted by the data, although it must be mentioned that 10 years of well constrained GPS Geodesy results attest to the fact that the thick Ladakh crust south of the Karakoramm, flows arc normally over the Indian plate at ~18 mm/yr (Figure 12) accompanied by an equal stretching of the arc represented by the Leh-Lhasa line (Jade *et al.*, 2008), also corroborated by the work of Copley & Mckenzie (2007) who visualize Tibet flowing over India much like honey (Figure 13), a condition facilitated by its hotter lower crust alluded to earlier.

Figure 10. Analyzed anisotropy



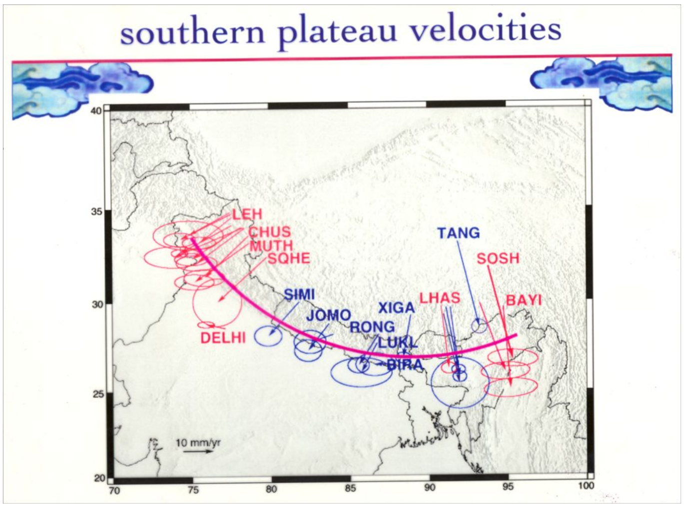
Maps showing the analyzed anisotropy, A (non-nulls), fast polarization direction in red (length proportional to dt, and B (Nulls) marking the two potential directions at right angles. Black and white arrows represent Indian plate velocities in two reference frames: HS3-NUVEL1A (Gripp & Gordon 1990), constrained with respect to the deep mantle, and NUVEL1A (DeMets *et al.* 1990), with respect to a fixed Eurasia (Maggy Heintz *et al.*, 2009).

Figure 11. Fast anisotropy polarization directions



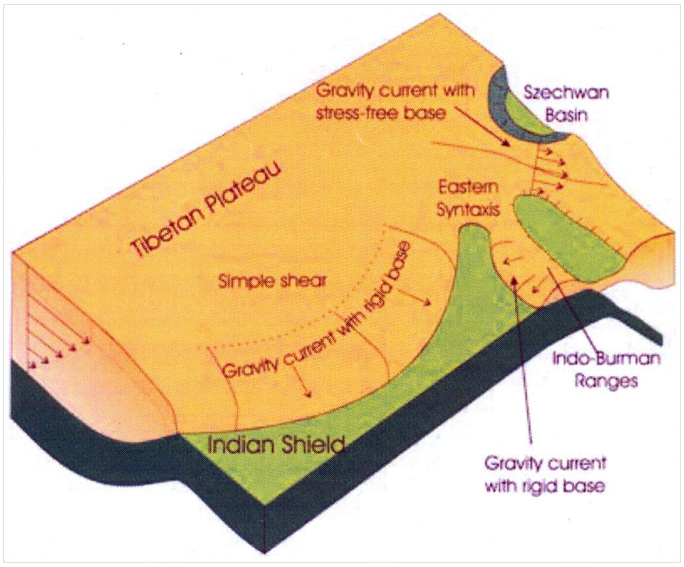
Showing the fast anisotropy polarization directions of core refracted shear wave phases, determined at northwestern India sites from the Ganga plains to the Karakoram (Maggy Heintz *et al.*, 2009).

Figure 12. Site velocities



Showing site velocities along the arc from Ladakh in the trans-Himalayan northwest to Bomdila in the eastern Himalaya. The arc normal convergence at about a uniform 18 mm/y all along the arc testifies to the viscous like flow of the western Tibet crust in Ladakh over the Indian plate. A consequential distending of the arc represented by the annual extension of the Leh-Lhasa line by ~16 mm, not shown in the figure, corroborates this interpretation (Jade *et al.*, 2005).

Figure 13. Cartoon



A cartoon Copley and McKenzie (2007) showing the southward flow of the Tibettan crust over the rigid underthrusting Indian plate, using the fluid flow equations of Newtonian rheology, driven by topographically exerted pressure gradients. A viscosity of 1020 Pa s, reproduced the surface velocities at Muth and Leh in Ladakh, determined by Jade *et al.* (2005), vide the previous figure.

Epilogue

The Indian continental lithosphere is an extraordinary feature of the globe. Its stolid crust continues to cleave through Tibet at 2 metres a century. Over the past 50 Ma of this longstanding process, south Asia has been thickened and raised into the largest high altitude plateau on the globe apparently resting on a large expanse of cold mantle below 100km, which would most likely survive as a cratonic core insulating the overlying remnants of the eroded plateau from the convecting mantle underneath. The continental Indian plate exposing 5 cratonic blocks separated by mobile belts, basins and a vast cover of Deccan basalts, in seismic images, is also supported at depth, by an extensive more or less continuous cratonic core stretching from the Himalayan arc southward to the Dharwar craton and further south, notwithstanding their-apparent absence in the east, most likely a result of sparser data coverage. In a future time these two extensive cratonic cores of India and Tibet would most likely fuse to once again create a large composite lithospheric unit, a testimony to their extraordinary encounter in the Cenozoic. Meanwhile, Tibet would continue to spread arc-normally over India as it does today, sliding over the Himalayan decoulement, and more haltingly in a stick-slip manner, on encountering the weight of the Great Himalaya, creating every few hundred years a great earthquake along some segment of the arc where accumulating strains have reached the failure limit.

The crustal structures of the various cratonic crusts, both exposed and buried, as gleaned from joint inversions of receiver function and surface wave dispersion data, allow one to create a perspective for insightful rooting of potentially more consequential new questions. The eastern and the western Dharwar cratons, both containing vestiges of early Archaean but stabilized by the late archaean, and separated by a ~50km wide transition zone between the narrow 400km long Closepet granite and the Chitradurg schists, represent the two extreme crustal types of the continent. The eastern Dharwar craton is a seismically transparent, classical Archaean crust with a thickness of ~32-38km and average shear velocity of 3.8km/s. The western, in contrast, except for sites near the coast, is thicker (48-52km), less felsic with a higher average shear wave speed of ~3.96km/s and has a significant intra-crustal layer at 10-20km depth below which the shear wave speeds are >4km/s, suggesting the operation of plate tectonic processes as early as the 3.3 Ga age of the overlying greenstones (Charlotte *et al.*, 2009). 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 (Christensen and Mooney, 1995), 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.

The foregoing account of the Indian continental lithosphere is not intended to be exhaustive and necessarily exposes a limited perspective that highlights the aspects considered significant by the author, particularly in the context of enquiry driven experiment design and investigations. Their results too have been summarily stated and further details of the studies would be found in the corresponding publications referred to in the text. Because of the limitations on space, the text has been largely devoted to what is considered germane to the larger picture rooted primarily in Archaean complexes, supported by more definitive results, albeit their severely limited representation and yet to be improved resolutions, at the expense of many other contributions that appeared tentative or merely confirmatory.

Pointed investigations to determine the deep structure of the Indian lithosphere have been woefully inadequate, partly because of the disproportionately small volume of earth science activity in the country compared for example to biological sciences. Hypothesis driven studies have occupied an even lesser space in preference to diagnostical which has of course greatly expanded in recent years with better availability of analytical systems. However, even these endeavors have shied away from the potentially more revealing earth archives of the Indian Archaean, notably the bastar and Singhbhum cratons Even factual data about their structural and metamorphic structures are too sparse for serious hypothesis formulations. Meanwhile, the proportion of data generation activity focused on ad hoc problems ending in superficial interpretation, to incisive analysis, remains overwhelmingly large.

Critical research issues, even their articulation, therefore remain in being without which one of the potentially most evocative lithospheres of the globe is likely to remain the least well understood. To take just one example, there is very little systematic work on mantle zenoliths to determine the geotherm within the Indian cratonic lithospheres, an insightful knowledge to spur hypotheses about their stabilization history.

Acknowledgements

This paper is largely drawn from its larger perspective, the Indian Lithosphere, published in the Platinum Jubilee issue of the Indian Academy of Sciences. Data for the seismic studies described above were abstracted from seismograms generated by IRIS and the Chinese networks, PASSCAL experiments, INDEPTH II/III, and the Indian Institute of Astrophysics/Cambridge University, NGRI and IMD stations. Data analyses were performed by S.S. Rai, Supriyo Mitra, Keith Priestley, Charlotte Acton and Maggy Heintz. Deep appreciation is acknowledged of the unstinted support received from the Directors of the Indian Institute of Astrophysics, the CSIR Centre for Mathematical Modelling and Computer Simulation, the Physical Research Laboratory and the Indian Institute of geomagnetism at various stages of the work.

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