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Evolution of the Indian Continental Lithosphere: Insights from episodes of crustal evolution and geophysical models

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ABSTRACT
The Indian lithosphere is an ensemble of terranes that had distinctive patterns of thermal evolution through time. Recent researches of a global scale, through thermal modeling and study of mantle xenoliths and xenocrysts, have helped to graduate the properties of the continental lithospheres of the world with characteristic properties of essentially lithospheric thickness and density and intimately related aspects of chemistry (composition) through the three major time bands, broadly the Archaean, the Proterozoic and the Phanerozoic. Viewed from the scales of distinction, the Indian shield lithosphere may be expected to have a dominantly Proterozoic stamp with Archaean lithospheric properties preserved below the Western Dharwar Craton, the Singhbhum Cratonic block and the Bundelkhand cratonic blocks. In the rest of the Shield more dispersed Archaean –Proterozoic lithosphere heterogeneity is envisaged with a poorly preserved Archaean lithosphere. The Phanerozoic impact has been relatively feeble in the south Indian shield and restrictive in the northern parts of the shield but has been sufficient to impart a denser and hotter lithosphere below the latter. An analysis of the geophysical data reveals that the two geophysical parameters, magnetic and gravity more or less conform to expectations of the character of the lithosphere while the velocity structure determined using different rather sophisticated methods provide a disparate picture. A spectrum of seismic thicknesses has been arrived at with a 80-100km thick lithosphere on one end and >200km on the other. Estimations of shallower thickness are a majority. A thin lithosphere is attributed to lithospheric erosion through a basal drag during the post-130Ma drift of the Indian shield and, if true, would erase the expectations of lithospheric properties imbibed through over 3.5 Ga in the span of some 130 million years of drift. Geological contradictions to this conclusion arise from a total absence of any dynamic or magmatic manifestations or a significantly high continental scale heat flow consistent with of such a large scale of erosion except some selected belts of uplift and elevated thermal fields that are related to local extensional structures much older to 130Ma. It seems possible that the low thickness estimates are due to the influence of compositional variations, fluids, partial melting and scattering. Differences in the scales of lithospheric heterogeneity and the wavelengths of geophysical surveys may also have contributed to an uniformly thin lithosphere. This discrepancy underlines the need for integrating more closely spaced seismic velocity studies with the expected compositional heterogeneity across the shield with geological history, geochemistry and potential field and Electro-magnetic signatures down to the 410 discontinuity that may have been the Early Archaean lithospheric thickness.

INTRODUCTION

The structure and evolution of the continental lithosphere has emerged as a frontier area of research largely due advances in seismology, high-pressure mineral physics and numerical modeling techniques and is receiving global attention from earth scientists. Recent contribution bring out global distinctions in the lithospheric evolution of continents of the Earth and the Indian Continental lithosphere stands out unique in several respects in response to an unique style of evolution through time. This review is inspired by some of these publications (eg.Artemieva et al , 2002; Griffin et al , 2012).

Key features in the emerging scenario of the deep structure of the Earth are the several discontinuities (physical and chemical boundary layers) in Earth's interior (Karato, 2003). Of these, we have more definitive information on a relatively thin layer, of variable thicknesses of the order of most probably 150 to ~450 km that has evolved over time as a relatively strong segment of the mantle between earth's crust and the underlying asthenospheric (weak) mantle. This sub-crustal lithospheric mantle (SCLM), also referred to as the tectosphere (Jordon, 1995) and "mantle lid" is thicker below the Continents than the Oceans and participates in continental evolution and, in fact, dictates the trends in the complex patterns of largely conductive transmission of thermal energy from the underlying convecting mantle. Recent researches in material properties have revealed that the lithosphere-asthenosphere boundary that defines the thickness of the SCLM is an interface of temperature, composition, anisotropy and melting. (eg. Rychert and Shearer, 2009).This makes its clear definition difficult, challenging and tentative. It would seem that geophysical techniques are trying to match the resolutions needed to define the poly orogenic and multi-genetic nature of the LAB.

It is widely recognised that the continental crust and the SCLM are co genetic and their composition and structure are interdependent and correlatable. Such a relationship arises out of the fact that the earth processes are determined by the thermal energy of the Earth's interior. The mantle thermal regimes in the Archaean have been distinctive and more enduring and patterns of crustal evolution are tuned to the progressively changing thermal regimes. The changes in the thermal structure of the Earth as a whole lend credence to the concept that the Archaean to Proterozoic transition may have been caused by the change in the style of mantle convection from layered to whole mantle convection patterns that then increased the cooling rate of the earth. (Breuer and Spohn, 1995).

The distinctive features of the lithosphere , comprising the crust and the SCLM, have been graduated in broadly three time bands , the Archaean, the Proterozoic and the Phanerozoic and models have been generated from two approaches, (i) through geothermal modeling (Artemieva and Mooney, 2001; Artemieva, 2006) and (ii) the study of mantle xenoliths and xenocrysts (eg. Griffin et al, 2009a). (See the following section). In the light of the broad time bound distinctions that are emerging in the character of the continental lithosphere, an effort is made in this paper to initially identify potential lithospheric provinces in the Indian Shield in terms of the three time bands from the available evidence of the styles of crust-mantle interactions and then integrate with the distinctive geophysical signatures, mainly the seismic velocity structure. The paper also briefly addresses the evidence ingrained in geophysical signatures on some of processes involved in continental evolution , namely compressional and extensional tectonics, underplating, delamination and large scale crustal exhumation. The results of this review brings out that while it is possible to establish a strong natural linkage between thermal evolution of the Indian Shield with the broad episodes of evolution in the three time bands, seismological picture of deep structure, particularly depth to the LAB is not in conformity and may need to be analysed in terms of compositional and other influences on seismic propagation.

Admittedly, the rudimentary nature of the seismic data available on the Indian SCLM would render this review very tentative, if not a little premature but it is hoped it will underline the importance of lithospheric structure as a whole in modeling crustal tectonics and evolution on the one hand and in planning future courses of geophysical research.

TEMPORAL CHARACTERISATION OF THE LITHOSPHERE

Artemieva and Mooney (2001) suggest that the Early Archaean supercontinent may have been underlain by a 450km thick lithosphere. Karato (2003,p70) relates this possibility to the enriched water content in the mantle in the early Earth which along with the high temperature may have provided a greater thickness of partial melting. Geothermal modeling down to 1300 °C adiabat (Artemieva and Mooney , 2001) portrays thinning of the continental lithosphere with time and a bimodal pattern where the Archaean lithosphere in the North Hemisphere is 300–350 km and that of southern Hemisphere 200–220 km thick. Early Proterozoic lithosphere is assigned a thickness of 200±50 km and the Middle-Late Proterozoic: 140±50 km **(Fig.1).** (Referred to hereafter as the AM model). In a subsequent contribution, based on statistical analysis of continental geotherms, Artemieva (2006) concludes that thick (>250 km) lithosphere is restricted solely to young Archean terranes (3.0–2.6 Ga), while in old Archean cratons (3.6–3.0 Ga) lithospheric roots do not extend deeper than 200–220 km. This prophesies rheology of the mantle of different continents have varied in space influencing also their tectonics.

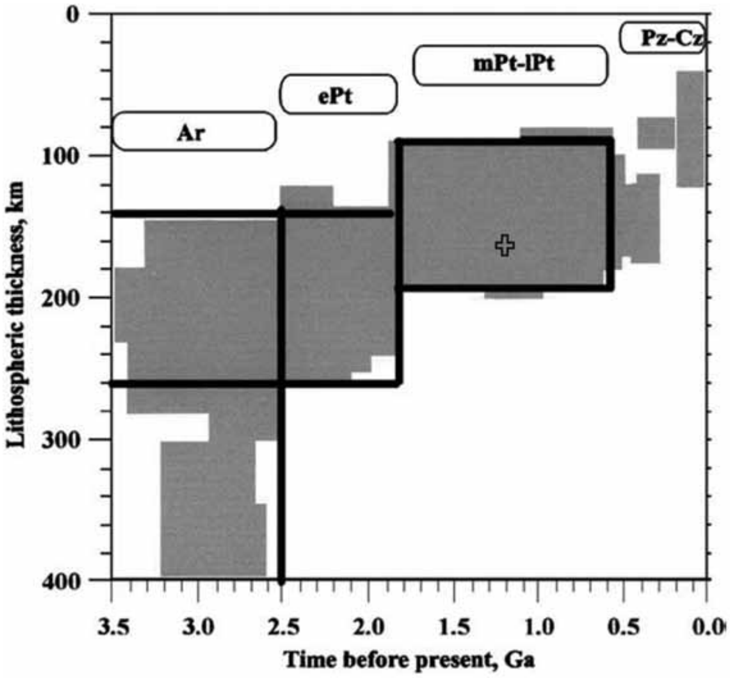

Figure 1. Lithospheric thermal thickness (gray area) versus geologic age of the continental lithosphere. The Archean lithosphere has bimodal thickness distribution centered at ~350 and ~220 km. Key: Ar—Archean;ePt, mPt, lPt—early, middle and late Proterozoic, respectively; Pz— Paleozoic; Cz—Cenozoic (Modified after Artemieva and Mooney , 2001).

Extensive studies carried out on mantle sourced xenoliths and xenocrysts have established that the SCLM is distinctive in the tectono-thermal regimes in the Archaean (>2.5Ga) (referred to as Archons), the Proterozoic (2.5-1.0Ga) (referred to as protons) and the period <1.0Ga (referred to as Tectons) (Griffin et al, 1998, 2009a) (referred to here as the G Or model).The most significant points of difference pertain to the thickness down to the LAB, the heat flow and density (Table1.) Equally significant and also of much importance to geophysics, is the chemistry of the lithosphere mainly in terms of Mg – Fe ratio that determines its density and its capability to subduct. The Archaean SCLM is believed to be most depleted in Fe,Ca and Al and such depletion is traced to the Fe that is extracted out in preference to Mg in the komatiitic and other mafic volcanic differentiates and transferred to the Crust .The Proterozoic SCLM is less depleted and the Phanerozoic the least. This would make the SCLM of the three time bands progressively denser. Processes of metasomatism and underplating especially in the later two time bands also may play an important role in making the lithosphere denser. Some of these aspects are relevant in understanding such processes as delamination and exhumation that frequently come up in geophysical modeling and will be addressed here to the extent data permits.

These models are cited here to highlight the broad temporal constraints on the thickness of the continental lithosphere that will be discussed from the point of view of seismic estimations of lithospheric thickness across space and time of the Indian Shield. It must be emphasized that the thermal model estimates thickness down to the bottom of the conductive layer of the mantle while the xenolith models estimates down to the 200-250m depth of the Diamond Stability Field. There are global and regional seismic tomography estimates that model down to the upper surface of the convective layer (seismic thickness) but are not considered here as data is very scanty (Artemieva and Mooney, 2002).

EPISODES OF CRUST-MANTLE INTERACTION AND LITHOSPHERIC PROVINCES

Crustal architecture

The Indian continental lithosphere (ICL) comprises the Peninsular Shield and its extensions into the Himalaya across the Indus-Ganga-Brahmaputra fore deep of Quaternary and Recent alluvial fill. This

Table 1. (Data from Griffin et al., 2003; O'Reilly et al., 2001 based on mantle nodules, xenoliths and xenocrysts)

Lithosphere characteristics	Archaean (Archon) (> 2.5± Ga)	Proterozoic (Proton) (2.5 to 1.0 Ga)	Phanerozoic (Tecton)* (1.0 Ga)	Composition of the primitive Mantle (McDonough and Sun, 1995)
Depth to LAB (Km)*	180-240	150-180	100-140	
Heat Flow (MWm^{-2})	35-40	40-45	50-55	
Av.Density	3.31 ± 0.016	3.34 ± 0.02	3.36 ± 0.02	
Vp at 100 km, 700^{O}C	8.18	8.08	7.85	
Vs at 100 Km, 700^{O}C	4.71	4.60	4.48	
Mg #mgx100/ (Mg + Fe)	92.7	90.6	89.9	89.3
Mg/Si	1.49	1.43	1.33 – 1.38**	1.25
Ca/Al	0.55	0.80	0.82 – 0.85**	0.73
Cr/Cr+Al	0.16	0.12	0.07 – 0.79**	0.05
Fe/Al	4.66	3.02	1.66 – 2.23**	1.30

*Artemieva and Mooney (2001) based on geothermal modeling down to 1300°C adiabat confirm thinning of the continential lithosphere with time and estimate the following thickness. Archaean- Early Proterozoic: 300-350 Km (N.Hemisphere); 200-220 Km (S.Hemisphere) Early Proterozoic: 200 ± 50 Km Middle-Late Proterozoic: 140 ± 50 Km

** The two Values are for mean Garnet SCLM and mean Spinel SCLM sequentially.

presentation mainly focuses on the Indian shield, that has preserved its Precambrian character to a large extent. Episodes of crust-mantle interactions in the Indian shield are viewed in the three time spans Archaean-Early Proterozoic (>2.0 Ga), the Proterozoic (2.0 – 0.5 Ga) and the Phanerozoic (<0.5 Ga) in preference to the time distinctions followed by two approaches referred to above in keeping with the history of evolution.

Tripartite classification of the Indian Shield

The crust of the Indian shield may be viewed in terms of three tectono-stratigraphic provinces, each of which have been characterized by distinctive styles of thermal crust-mantle interactions in the Archaean, Proterozoic and then in the Phanerozoic **(Fig2).** These include the following.

(i)The Southern Archaean–Early Proterozoic Cratonic Block (SACB), bounded to the south by the South Indian High-Grade Domain (SIHGD) and the east by the Eastern Ghat Mobile belt, (EGMB), that were sequentially exhumed largely in the Proterozoic.

(ii)The northern Archaean–Early Proterozoic Cratonic Block, (NACB) comprising the Bundelkhand craton and the mid to high-grade mid- to lower crustal Chotanagpur Gneissic Complex in the east, that was exhumed largely in the mid- to late Proterozoic. The Shillong Plateau in the NE is an outlying segment that may have been part of the northern block. The SACB and the NACB are separated by a Proterozoic tectonic zone comprising the Central Indian Tectonic Zone (CITZ) that was also involved in the sequences of episodic evolution of the Phanerozoic.

(iii) The Rajasthan orogenic province (ROP) to the NW of the northern Archaean–Early Proterozoic Cratonic Block that had a distinctive style of orogenic evolution in the Archean through the whole of the Proterozoic culminating towards the close of the Proterozoic on its western fringes in anorogenic bimodal magmatism followed by platformal sedimentation. (<720 Ma- 500 Ma). The northern Archaean–Early Proterozoic Cratonic Block and the Rajasthan orogenic province are separated by a zone of faults, prominently the Great Boundary Fault.

Precambrian thermal interaction

The three provinces have distinctive features that are relevant to understanding the course of thermal interaction between the crust and mantle. The several tectono-stratigraphic units that are involved in the evolution are presented in **Fig3** in the three time bands**.**

The three provinces have some similarities in Archaean litho-stratigraphy and are made up of predominantly polychronous granitic gneisses and several generations of volcano-sedimentary

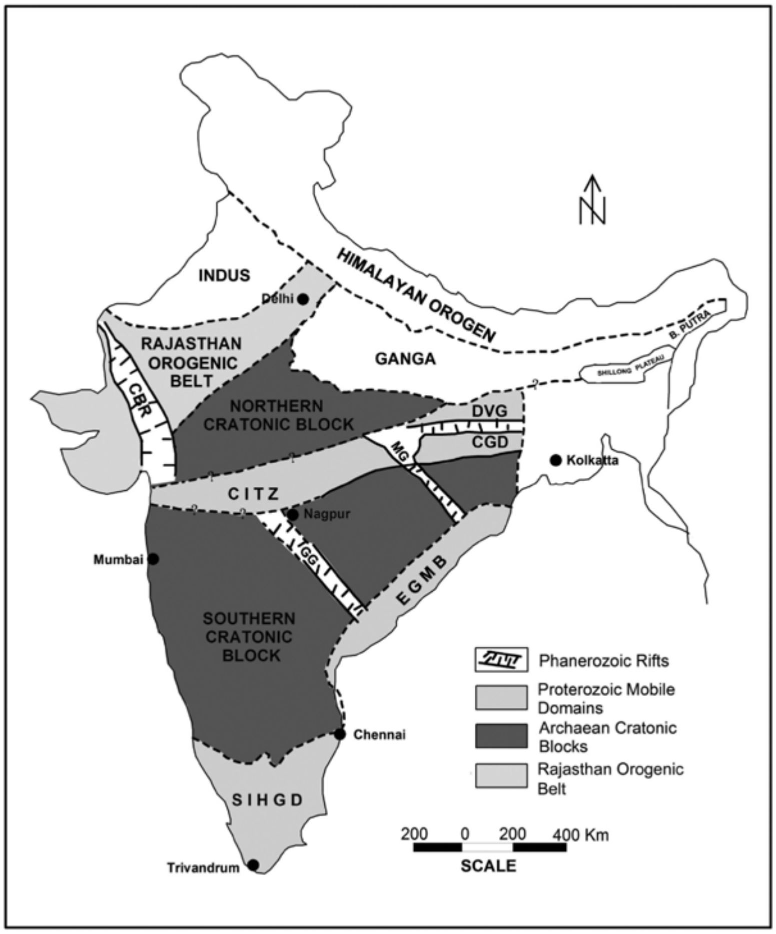

Figure 2. Precambrian Cratonic Blocks and associated Mobile Belts of the Indian shield overprinted by Phanerozoic rift zones. Abbreviations: **ADFB**–Aravalli-Delhi Fold Belt; **CBR**–Cambay Rift; **CGD**–Chotanagpur Gneissic-Granitic Domain; **CITZ**–Central Indian Tectonic Zone; **DVG**–Damodar Valley Graben;**EGMB**–Eastern Ghat Mobile Belt; **GG**–Godavari Graben;**IGA**–Indo-Gangetic Alluvium; **MG**–Mahanadi Graben; **ROB**- Rajasthan Orogenic Belt; **SIHGD**–South Indian High Grade Domain.

formations, that evolved in the time span of the Archaean and Early Proterozoic (~3.5 to ~2.0 Ga). They include greenstone domains and Fe-Mn sediments, the latter not well developed in the Rajasthan orogenic province. Large enclaves of tonalite-trondhjemite-granodiorite (TTG) suites along with greenstone belts (>2.7Ga) occur in different parts as Archean remnants, predominantly in the Western Dharwar Craton (A1 in fig3), the Singhbhum craton (A2) and the Bundelkhand craton (A3) and to a less defined extent in the Bastar and Rajasthan Orogenic Province.. Within the span of the Archaean itself there is a gradual change from an ensimatic to an ensialic environment and there are major differences in the architecture of the crustal elements across the even the cratonic blocks especially in the sequence of magmatic events, the dominance of komatiitic as against tholeiitic magmas and sedimentation. There is a suggestion here that the degree of depletion of the lithosphere across the Archaean continent may not have been uniform resulting *in* density partitioning that may have been a factor in the divergent styles of tectonic evolution, referred to above.

Built into the Precambrian architecture of the Southern Archaean–Early Proterozoic Cratonic Block, Northern Archaean–Early Proterozoic Cratonic Block and the Rajasthan orogenic province are several intra- continental platformal cover sequences of Meso- to Neoproterozoic age (1800–500 Ma) broadly classified under the term "Purana Formations" (Pascoe, 1950) (Fig.2). These basins developed on a strong lithosphere that evolved due to cooling of the earth. The strong lithosphere was subjected to slow extension attended by early magmatism in

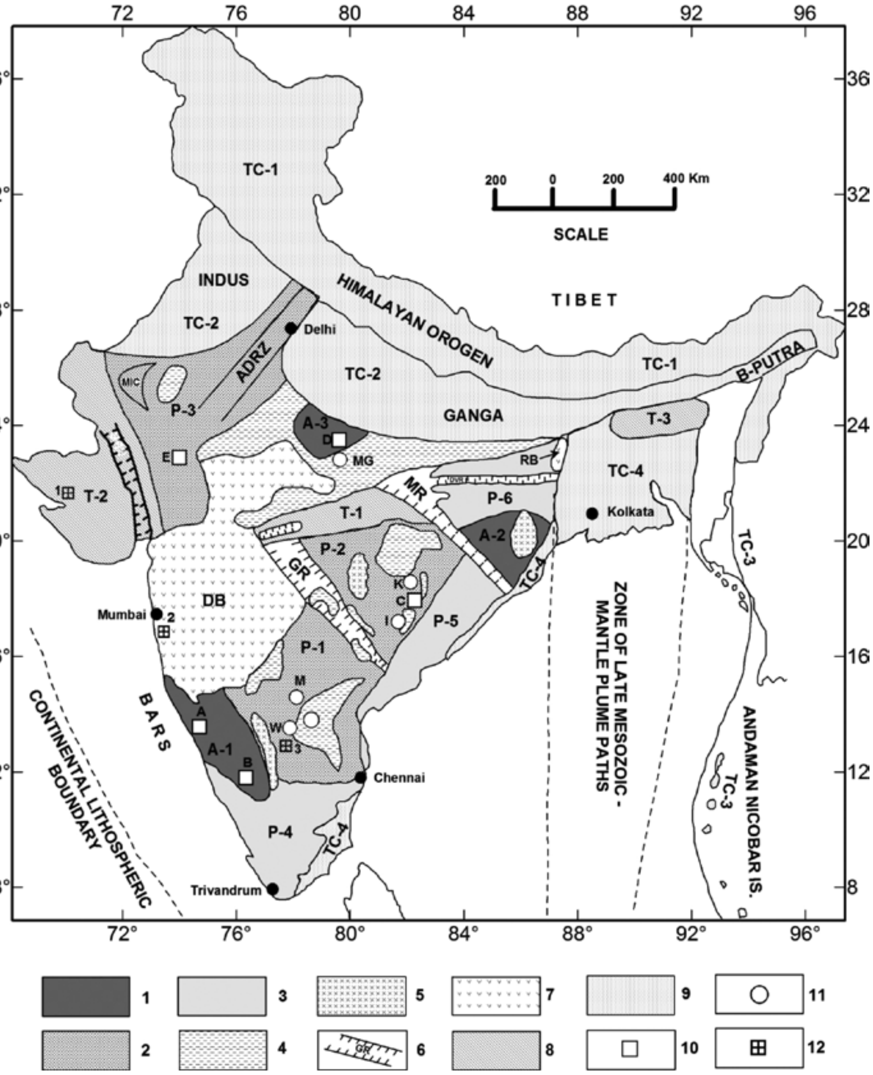

Figure 3. Major geological provinces of India that have claims to distinctive lithospheric mantle.

I. Archaean Cratonic Blocks (> 3.0 Ga): **A-1**–Western Dharwar Cratonic Block; **A-2**–Singhbhum Cratonic Block; **A-3**–Bundelkhand Cratonic Block.

II. Archaean-Early Proterozoic Cratonic Blocks (3.0–2.0 Ga): **P-1**–East Dharwar Cratonic Block; **P-2**–Bastar-Bhandara Cratonic Block; **P-3**–Aravalli-Delhi Cratonic Block. 3. Archaean- Proterozoic Mobile Domains/Belts (3.0–0.5 Ga): **P-4**–South Indian High-Grade Domain; **P-5**–Eastern Ghat High-Grade Domain; **P-6**– Chotanagpur Gneissic Complex. 4. Purana Basins (1.8–0.5 Ga). 5. Major Precambrian Granitic Bodies. 6. Gondwana Basins (0.29 to 0.12 Ga): DVR–Damodar Valley Rift; **GR**–Godavari Rift; **MR**–Mahanadi Rift. 7. Mesozoic Continental Basalts **DB**–Deccan Basalts; **RB**–Rajmahal Basalts. 8. Phanerozoic I. (Pre-Cenozoic; 0.12–0.065 Ga):**T-1**–Central Indian Tectonic Zone; **T-2–**Cambay Volcanic Domain, including Cambay Rift (CBR); **T-3**–Shillong Plateau. 9. Phanerozoic II. (Cenozoic; <0.065 Ga): **TC-1**–Himalayan Orogen; **TC-2**–Indus-Ganga-Brahmaputra Foredeep; **TC-3**–Burmese-Andaman Arc; **TC-4**–Bengal Basin. 10. **TTG** (Tonalite-Trondhjemite Gneiss): A–Anmod Ghat, Goa; B–Gorur-Hassan, Karnataka; C–Merkampara, Bastar, Madhya Pradesh; D–Bundelkhand, Madhya Pradesh; E–Marwar, Rajasthan. 11. Kimberlitic rocks - C–Chelima; I–Indravati; K–Khariar; M–Maddur-Padripadu; MG–Majhgawan; W–Wajrakarur. 12. Locations of mantle xenoliths 1–Bhuj; 2–Murud-Janjira; 3–Wajrakarur. Abbreviations: **ADRZ**–Aravalli-Delhi Rift Zone.

some of the basins (Chakraborty et al, 2010) and emplacement of dyke swarms along extensional fractures in the basement gneissic complex. The dyke swarms are episodic with peak emplacements of 2.4, 2.1, 1.6, and 1.0 (Sarkar and Mallick, 1995). Notably, the dike swarms include diamondiferous kimberlitic emplacements in the time span of 1100-1300 Ma along a long corridor in the interior of the CCR. Their emplacement implies a progressive deepening of the mechanical boundary layer of the lithosphere down to the diamond stability field (> 155 - 185 km) (Karmalkar et al, 2009) by around 1.3 Ga. The thermal events associated with these episodes of magmatism and sedimentation have imparted a Proterozoic stamp on the Archaean lithosphere, (P1, P2).

The Southern Archaean–Early Proterozoic Cratonic Block presents a marked polarity into a central Archaean cratonic region (CCR) bordered by the South Indian High Grade Domain. on the south and the Eastern Ghat Mobile Belt on the east that were exhumed in the Proterozoic through respectively largely isothermal decompression but poly-phased exhumation and are therefore often referred to as mobile belts. The passage from the cratonic core to the high grade mobile belts is transitional and tectonic, though some tectonic breaks have been mapped in the transition zone between the SACB and the Eastern Ghat Mobile Belt The region of Proterozoic Mobile belts *(P3, P4, Fig.3)* saw the continuation of the thermal regimes evidenced by the rather episodic tectonothermal and magmatic evolution of these regions spanning the 2.2 Ga TO 0.5 Ga. Archaean crust and the underlying SCLM in these regions got transformed both in their chemistry and thickness through magmatism and fluid activity that enhanced the positive buoyancy of the lithosphere (Mahadevan, 2003, 2008). This polarity across space and time has been explained by a thermal model of interaction with the mantle thermal regimes by Mahadevan (2003), based on the two paradigms (i) that the Proterozoic was a period of transition from mantle dominated regime of the Archaean to crust dominated regime of the Phanerozoic (Dickin, 1995) and (ii) that with the progressive cooling of the mantle, thermal cells may have become more organized in the Proterozoic. (Durrheim and Mooney, 1991). Another factor that may have led to the exhumation of the LC below the South Indian High Grade Domain and Eastern Ghat Mobile Belt is that both these terrains were open systems to mantle derived fluids and lowering of crustal densities on a large scale due to influx of fluids (water and CO_2) and accompanying metasomatic transformation of the high grade rocks to amphibolites facies assemblages. The increase in positive buoyancy may have been a compelling factor that favored the exhumation. A compelling alternative to this model is the tectonic thrusting up in a plate tectonic compressional regime, commonly invoked that needs to be established primarily from considerations of rheology during a period of very high thermal regimes more than mere uniformitarianism.

The exhumed mobile belts, the South Indian High Grade Domain and Eastern Ghat Mobile Belt on the one hand and the Proterozoic platformal sedimentary basins within the Cratonic regions on the other had a contemporaneous development. A similar relationship holds between the Vindhyan platformal basin in the Northern Archaean–Early Proterozoic Cratonic Block and the Aravalli - Delhi fold belts of the Rajasthan orogenic province .Broadly this contemporaneous development underlines a tectonic linkage that spans some 1300Ma between ~ 1800 to 500 Ma Geophysical modeling of the thermal evolution of the two terrains in terms of source characteristics would be a rewarding exercise. The polarity into craton and exhumed lower crustal segments seen in the Southern Archaean–Early Proterozoic Cratonic Block is not evident in the Northern Archaean Cratonic Block.or the Rajasthan orogenic province, as the thermal regimes below these regions have been more steady through the Archaean and Proterozoic.

The Rajasthan orogenic province (Fig.2) evolved through a distinctive orogenic cycle (~2.5 to *0.74Ga*) involving distinctive supracrustals of Palaeo- and Neo-Proterozoic ages, the Aravalli and Delhi fold belts, equivalents of which are not well recognized in the Southern Archaean–Early Proterozoic Cratonic Block or the Northern Archaean–Early Proterozoic Cratonic Block. The Proterozoic Aravalli and Delhi orogenies have been overprinted on an earlier Archaean Craton. The sedimentation and subsequent evolution of the fold belts of the Aravalli and Delhi Systems cover much of the Archaean basement, members of which are exposed prominently in the SW part of Rajasthan and as intraformational wedges within extensively rifted the Aravalli and Delhi Basins. There is a paucity of ultramafic komatiitie assemblages amidst the exposed Archaean rocks implying that the Rajasthan Province as a whole may have been made up of a less depleted lithosphere which therefore was denser and capable of being subjected ro rifts. The Aravalli-Delhi orogenies culminated in an anorogenic bimodal magmatism followed by development of platformal basin (~0.74 to ~0.50 Ga). The advent of this phase of development may have eebn heralded in by a process of delamination of the LC and the SCLM. (Sinha Roy, 2008). There is however a lack of seismic data to infer such a process.

Phanerozoic Thermal episodes

The Indian continental lithosphere stabilized by the early Cambrian as a strong buoyant continent. Slow distension and basin formation processes set in some 200 million years later with no accompanying magmatism leading to the development of the Gondwana Coal Basins, a case of slow taphrogenic tectonics, involving mainly the mechanical boundary layer of the SCLM. In the late Mesozoic, however, the lithosphere as a whole was subjected to marked extension and mantle thermal regimes associated with the Rajmahal (~115Ma) and Deccan Continental Volcanism (~ 65 Ma) generally assigned to plume-induced rifting along the Eastern and Western coastal margins. There is, however, growing evidence that Deccan Volcanism, and by analogy, the Rajmahal Volcanism, in the deep continental interiors is sourced by several shallow magma chambers having connections with deeper mantle (Krishnamurthy, 2008; Vijayakumar et al, 2010). Such a model of deep involvement of the SCLM in the interiors of the Indian shield is consistent with a concept of participation of the SCLM as a whole in the Deccan Volcanic event transforming its thickness, density and chemistry. Underplating by basic magmas has rendered several segments of the interior denser giving rise to negative buoyancy. Several geophysical signatures that will be addressed here arise from this interactive evolution in the Phanerozoic.

The Himalayan region chartered a more dynamic course than the Shield region from the Palaeozoic with early instances of active rifting and volcanism (eg. Pir Panjal). The deep crustal structure of the Tibetan Himalaya is characterized by a crustal thickness of some 70 km underlain by SCLM thickness of some 30 kms. Palaeo-thickness of the crust in the South Indian High Grade Domain and the Eastern Ghat Mobile Belt has been estimated to be of the order of some 70km and by analogy comparisons are made with the Himalayan lithosphere. Such a comparison seems simplistic as the SCLM in the Archaean below the South Indian High Grade Domain and Eastern Ghat Mobile Belt may have been > 200km thick and the SCLM being depleted of a lighter density. Such an SCLM may not be expected below the Himalaya as it is a product of the Cenozoic orogeny. What makes the Tibetan Plateau buoyant is the ratio of the Crust to the SCLM that works out to (70/30) 2.3 thereby making the whole lithosphere buoyant. A detailed discussion of the Himalayan lithospheric evolution is not attempted here.

VIEWS THROUGH THE GEOPHYSICAL WINDOW

The following account is based mainly on geophysical investigations that primarily provide data on any or all of the four aspects of lithospheric evolution – (i) Lithospheric thickness/depth to the Lithosphere-Asthenosphere Boundary (LAB), (ii) the relative density variations; (iii)thermal structure across the lithosphere and (iv) modeling geological processes from geophysical data base. A number of recent publications provide the background for this paper and include Mahadevan, (1994); P.R.Reddy (Ed) (2010) and Bijendra Singh and Dimri (Ed) (2008).

Continental scale models of the Lab

Attempts have been made to map the LAB across the whole of India in a singular contribution using shear wave tomography and P-wave tomography the latter with admittedly low resolution. Regional estimates of the depth to low velocity layers, presumed to represent the LAB, have been attempted using P-Wave and shear wave tomography and body-wave and surface wave propagation and Receiver function methodologies. Relative density variation may be read from Bouguer gravity anomaly map and are also reflected in the velocity structure. Thermal data pertains to extensive heat flow measurements. Additional data springs from the Curie isotherm map based on CHAMP satellite data and the geotherm of the LAB contained in a shear wave- tomographic model.

Each of these approaches has their own intrinsic merits and limitations and the results are comparable only with caution. These results are addressed here in a sequence presenting the global (Continental–scale) results first and the regional and sub-regional (more localized) findings.

Thermal boundary of Lithosphere

Shear-wave tomography: Variations in lithosphere thickness have been estimated by Priestly and McKenzie (2006) on a global scale by converting seismic shear wave velocities into temperature profiles and then fitting the geotherms beneath the Eurasian Plate.(herein referred to as the PMK model) An enlarged version of the lithosphere thickness map covering the Indian shield has been made available by Chalapathi Rao and Lehmann (2011), also showing the presently exposed Deccan Traps, Ambadongar carbonatite in NW India and diamondiferous orangeites from the Bastar craton and the diamondiferous kimberlites of Dharwar craton (Fig.4). The PMK model shows a tripartite division of the shield into a southern segment with a lithospheric thickness of ~ 160 km, a central segment extending from the west Coast to beyond Hyderabad covering a southern half of the Deccan Basalt cover region with a lithospheric thickness ranging from ~80-100km passing on to a thicker lithosphere progressively thickening northwards from ~200 to + 300km, underlying the Himalaya and the Tibetan Plateau (not shown in the map). A thin lithosphere (~160km) below the Dharwar craton wherein several kimberlitic dykes of Proterozoic age are known implies lithospheric thinning since the Proterozoic (~1100Ma), (Chalapathi Rao and Lehmann,2011). The lithospheric thickness in the Bastar region is over ~200km where we have the Kodomali diamondiferous kimberlites reported by Chalapathi Rao and Lehman, 2011. In the Dharwar craton,

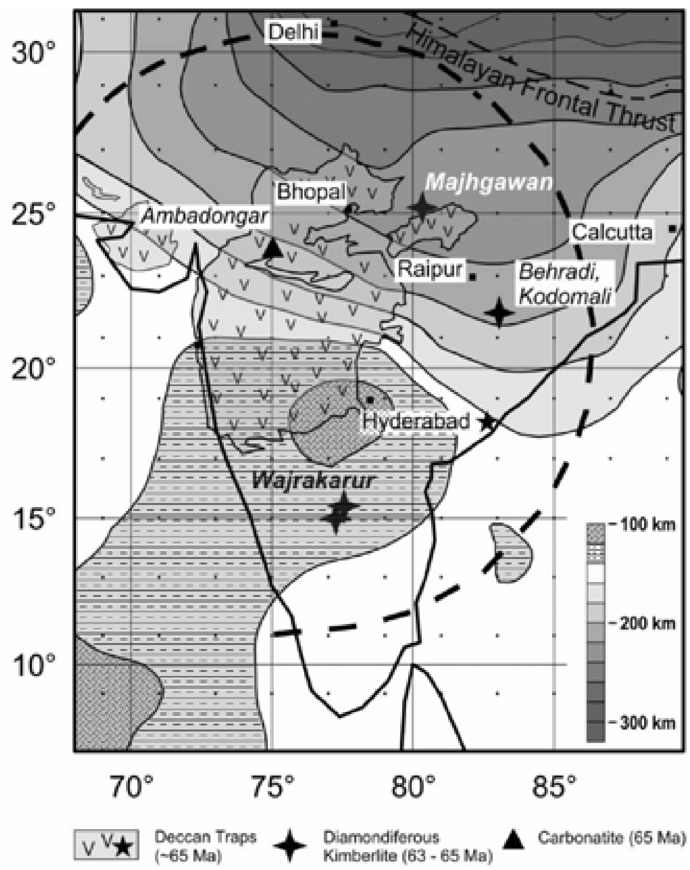

Figure 4. Priestly-Dan McKenzie model of the thickness of the Lithosphere below the Indian subcontinent as a function of the geotherms at the LAB . Presently exposed Deccan Traps, Ambadongar carbonatite in NW India and diamondiferous orangeites from the Bastar and Dharwar cratons are also plotted. Presently exposed Deccan Traps, Ambadongar carbonatite in NW India and diamondiferous orangeites from the Bastar and Dharwar cratons are also plotted. Dashed circle is the postulated Deccan plume (after White and McKenzie, 1989; Cox, 1989) (Figure modified from Chalapathi Rao and Lehman, 2011).

where 1100-1330 Ma diamondiferous kimberlites are known (Fig.4) the estimated lithospheric thickness is less than 140km. This has led to the inference that the lithosphere below this region may have been eroded from depths of >200km to 140km. (Griffin et al, 2009b). Such erosion is traced to the rifting along Eastern and Western continental margin of India in the late Mesozoic, (successively ~120 and 65 Ma) and to the fast drift of India initiated by coastal rifting in the span of the last 65 million years. Surprisingly such erosion that brings the Thermal boundary of the LAB much closer to the MOHO has no manifestations in terms of magmatism in this region.

P-wave tomography: Insights into the continental lithosphere below the Indian shield is provided by (Kennett and Widiyantoro, 1999. Herein called the KW model, it has relatively high resolution picture of the Cambay Rift Zone in Western India and are discussed later. They provide admittedly very low resolution data on the Indian Shield as a whole and needs to be cited only because of the large spatial coverage. These reveal a lighter lithosphere below the South Indian High Grade Domain traceable beyond a depth of 250 km. The lighter lithosphere further extends into the = Eastern Ghat Mobile Belt at 250 km depth, thus unifying the SCLM structure below the two mobile belts, the South Indian High Grade Domain and Eastern Ghat Mobile Belt In contrast, the core of the central Indian region is underlain by a high P-wave velocity ridge-like root, extending northwards into the Himalaya. The high velocity root persists at 250 km depth, beyond which the signals are weak **(Fig.5).** Notably these results bring out a contrast between the low P-wave velocity SCLM below the South Indian High Grade Domain and perhaps the Eastern Ghats, and the higher velocity

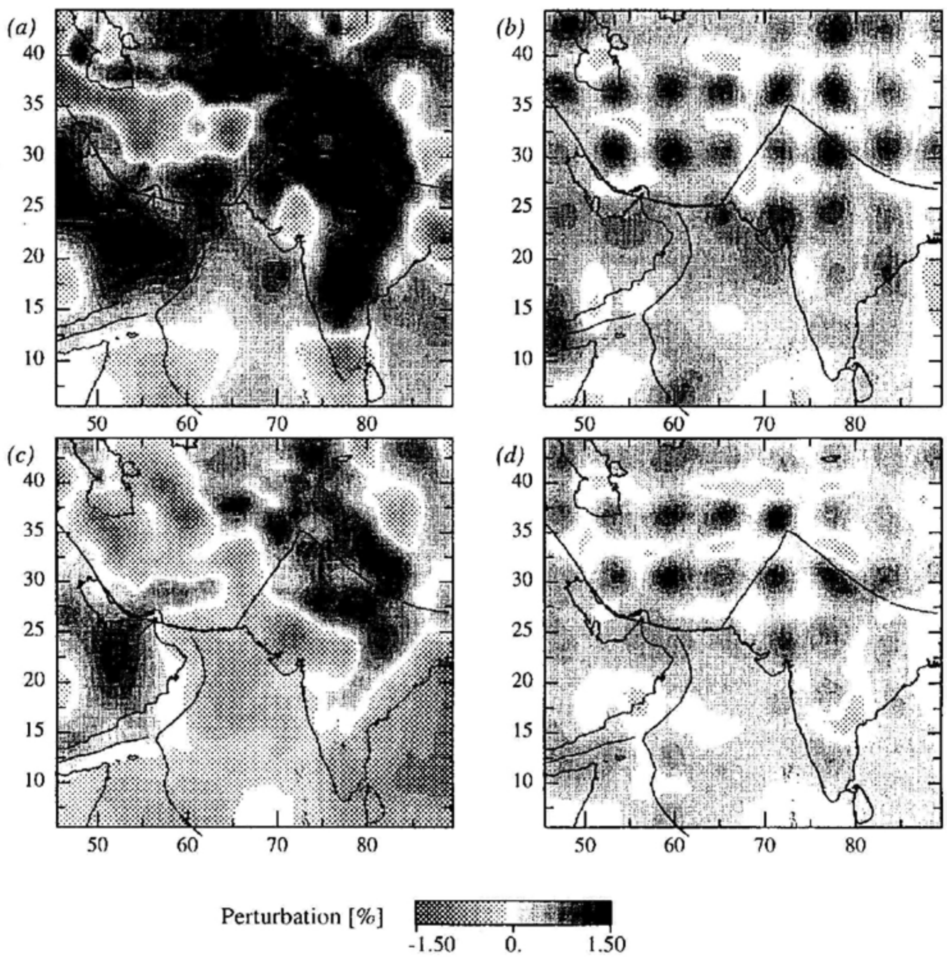

Figure 5. P-wave tomographic model of the lithosphere below the Indian subcontinent at depth levels of 100km and 250km. Note that the resolution for the areas outside the Cambay Basin is very low (after Kennett and Widiyantoro, 1999)

P-wave domain below the core region of Central India. The former is a buoyant lighter lithosphere while the latter is possibly a denser and not so-buoyant a lithosphere. Such a possibility is also reflected in the gravity fields as will be discussed a little later. and the heat flow patterns discussed a little later.

Gravity Signature: The Bouguer field

The Bouguer gravity across Indian shield reveals strong negative fields ranging from –70 to –130 mgal in the southern part of the shield,–70 to +10mgal in the central Indian region and again 70 to > –270 mgal in the Ganga Basin and the Himalaya (Verma, 1985; Raval, 2003). Mahadevan (2007) emphasized that the long wavelength gravity fields of India suggest a density related partitioning of the Indian lithosphere into a southern segment that is lighter and buoyant and the northern segment with a central core that is denser and less buoyant and the Himalaya on the north again of a lighter and buoyant lithosphere. This broad tripartite division finds expression in the low-pass filtered regional Bouguer anomaly map of India for wavelength of the first segment of the spectrum (> 523 km) related to source depths of about 180 km (Fig.6)

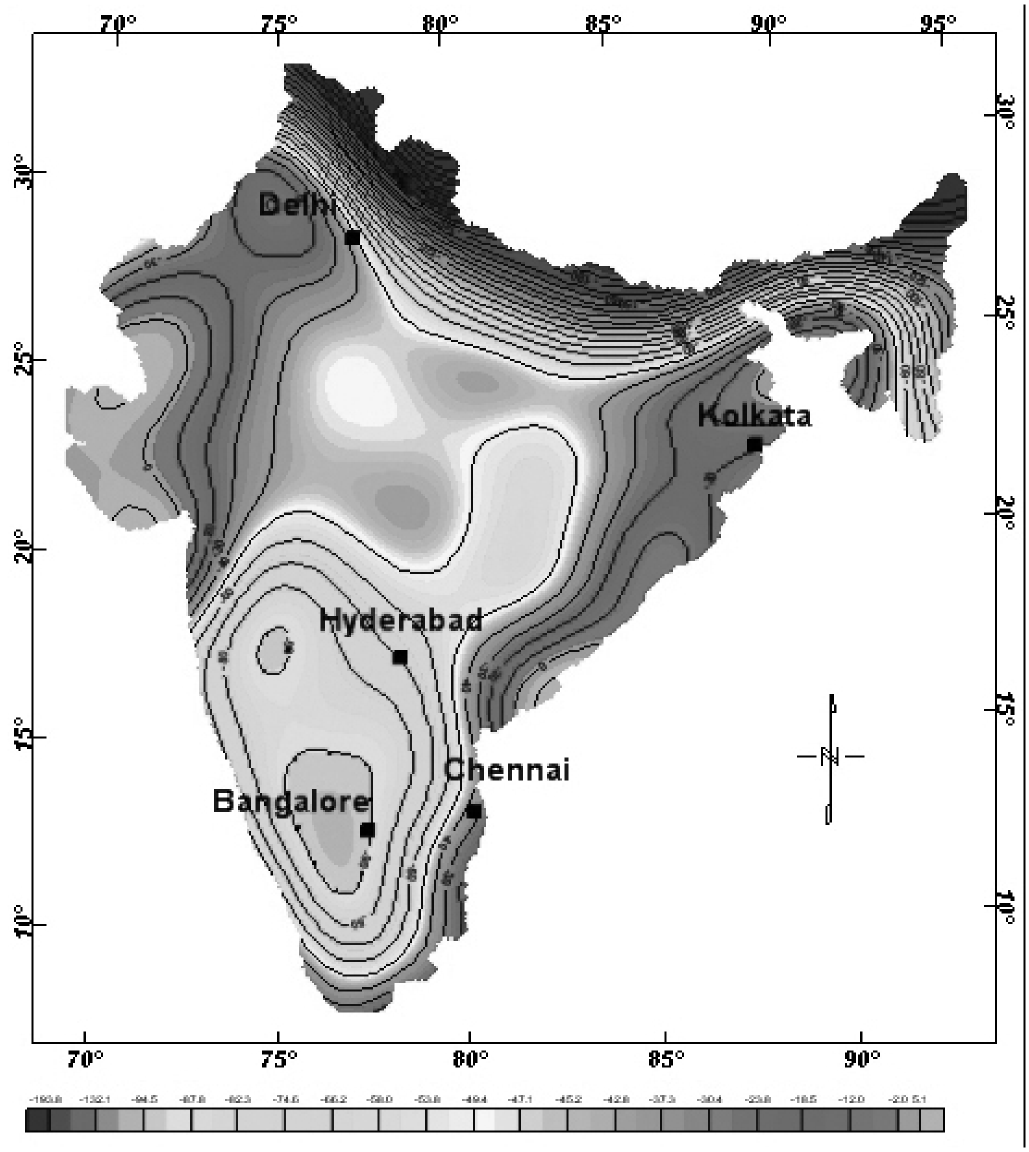

Figure 6. Low-pass filtered regional Bouguer anomaly map of India for wavelength of the first segment of the spectrum (523km) related to sources in the lithosphere. See plots of diamondiferous kimberlites of Bastar and the Dharwar cratons plotted (modified after Misra and Ravi Kumar, 2008).

Regional inputs

Ravi Kumar et al 2001Interpreting teleseismic waveform data recorded in 10 stations in India covering the region Ajmer in the north, Bokaro in the east , Bhuj in the west and Trivandrum in the south, Ravikumar et al (2001) identify distinctive features in the Crust and shallow mantle between the Southern Archaean cratonic block and the dominantly Proterozoic ccrust in the northern part of the shield. The former presents a rather simple structure with crustal thicknesses of 33-39km and a Poisson's ratio of 0.25 with no prominent intracrustal discontinuities . This region is underlain by a sharp MOHO that has a sharp velocity contrast resulting in clear P-S conversions The latter presents a more complex structure with crustal thickness exceeding 40km and has additional seismic discontinuities and weak P-S Moho conversions.

Surface wave dispersion studies have been carried out by Mitra et al., (2006) using Rayleigh wave–phase velocities for periods up to 200 sec. of earthquakes largely sourced in the north but also a few in reverse directions. The seismic stations used are along two nearly N-S paths between Bhopal and Kodaikanal and Hyderabad and Kodaikanal and cover largely the Bastar Cratons in the north of Southern Archaean–Early Proterozoic Cratonic Block, the Dharwar craton in the south and fringes of the South Indian High Grade Domain.. The preferred seismic velocity model displays a 155 km thick seismic lithosphere comprising 35 km of crust and 120 km of high velocity upper mantle lid underlain by a LVL, where the shear wave velocities drop to 4.4 km/sec at ~230 km depth and then have a positive trend down to ~360 km depth, overlying a half space Vs of 5.06 km/sec. The authors conclude that the lithosphere is thinner below the Indian shield than in other continents. The above results compare well with an earlier model IP 11 of Bhattacharya (1981) based on Rayleigh wave group velocity dispersion for periods up to 100 sec. The wave paths used for this model were for easterly sourced earthquakes near Shillong and Bokaro recorded at Poona and Koyna and vice versa. The results reveal an upper mantle lid of 140 km above the LVZ in the Central Indian region. Of relevance in this regard are two other models generated by Bhattacharya (1974) using variation of group velocity with period for Rayleigh waves of periods 6 to 80s and Love waves of periods 11 to 97s for earthquakes from northerly sources along two profiles. The two profiles include the New Delhi-Kodaikanal (IP-3M) and Poona-Kodaikanal (IP-4M). The former passes through the central part of the shield and includes the area covered by the Mitra model just described. The IP-3 M model has a zone of anisotropy with SH velocity of 4.80 km/s and SV velocity of 4.58 km/s between 60 km and 160 km overlying a clear low velocity zone between 160 and 280 km with the S-wave velocity lowered to 4.55 km/s. The IP 4M profile runs along the eastern fringes of the Western Ghats (Sahyadris). In this model, the LVL underlies a 60 km thick lithospheric high velocity lid. No anisotropy is reported. The results of S-wave studies reported above reveal that thickness of the mantle lid is about 155km in the core of the Shield but thins down to 60 km along the continental margin activated by Deccan Volcanism. This range of thickness of the lithosphere is possibly a result of sequential evolution during the Proterozoic and the Late Mesozoic tectono-thermal events, an aspect addressed in the discussion.

Kumar et al (2007) estimate the depth to the LAB in the region of the Indian Ocean and the surrounding continents that once formed the Gondwanaland using S- to- P converted waves. Receiver functions from below six seismic stations, Dharwar (DHD), situated on the western Dharwar craton, Hyderabad (HYB) and Cuddapah(CUD) situated on the Eastern Dharwar craton, Kothagudem (KGD) situated within the Godavari rift zone, Bhopal (BHPL) in Central India and Bokaro (BOKR) in the Chotanagpur Gneissic Complex of Eastern India , indicate a lithospheric thickness of 80–100 km. It is suggested that the originally thick Indian lithosphere has been thinned by its passage over mantle plumes after the Gondwana break-up initiated at 130Ma.

Jagadish and Rai (2008), through a receiver function analysis of waveforms on 22 broadband seismographs along a N–S corridor, from southern granulite terrain to Delhi conclude that the Archean terrains below the Eastern Dharwar, Bastar, Bundelkhand and Aravalli cratons are underlain by crust with felsic-intermediate composition (Vp/Vs ~1.65–1.75) in contrast to mafic composition ($Vp/Vs > 1.78$) of crust beneath Vindhyan basin, Godavari basin, and the Narmada-Son Lineament (NSL) of Proterozoic age. They infer that the Moho depths varies between 33 and 43 km unrelated to the age of the crust. Duplex Moho with highly mafic underplated lower crust below Narbada-Son lineament, signifies its paleo-rift character. A major suggestion emerging from this contribution is the possibility of a layered lithosphere beneath parts of India characterized by the Hales discontinuity that separates an upper layer with shear velocity (*V*s) ~4.52 km/s from a lower one with Vs ~4.77 km/s, that may be accounted for by a low-density, depleted spinel peridotite (with Archean affinity) lying over higher density fertile garnet peridotite of Proterozoic age.

Sub-regional inputs

Sub-regional geophysical studies address mainly the lithosphere below (i) the Dharwar craton and the SIHGD bounding it to the south and (ii) The EGMB and the Bounding Dharwar Craton and (iii) the Deccan Volcanic province, including the platformal region of Deccan Trap Cover in Southern Archaean–Early Proterozoic Cratonic Block and the rifted Cambay Basin in the NW.

Coincident seismic reflection – refraction surveys have been conducted on profiles across the South Indian High Grade Domain; the Central India Tectonic Zone (CITZ) and the Delhi fold Belt of Rajasthan. These are focused largely on crustal features and are therefore not discussed in this section. Features of relevance to understand the operation of various Earth Processes contained in these profiles are addressed in the next section of the paper.

Dharwar Craton-SIHGD –Deccan Volcanic Province

Detailed regional P-wave tomography by NGRI, initiated under the guidance of H.M. Iyer (USGS), is the beginning of active research in this field and much of our more concrete perceptions of the Indian continental lithosphere spring from this intiative (Iyer et al., 1989; Rai et al., 1992; Ramesh et al., 1990, 1993; Srinagesh and Rai, 1996). The areas investigated include the region of Deccan trap platformal cover in the NW, designated as Deccan Volcanic Province (DVP), almost the whole of the Dharwar Craton and the South Indian High Grade Domain. to its south (***blocks A-1, P-1 and P-4 in Fig. 3***). The results point to deep P-wave velocity roots forming a tectosphere decoupled from and translating coherently with the underlying low velocity layer. The thickness of the tectosphere below the Dharwar craton and its extensions below the Deccan basalt cover, have different estimated depths within the 410 km discontinuity. Iyer et al. (1989) infer a depleted lighter (~1%) lithospheric roots consistent with a lowering of iron content. Within such a broad frame work differences have been brought out in the lithospheric structure across the areas investigated. In the region below the DVP, the presence of relatively higher velocity lithospheric mantle is inferred over most of the DVP and the Dharwar Craton. In the NW part of the DVP (below the region between Poona and Dhule), a region of extensive tholeiitic dyke swarms, consistent slower arrivals from all azimuths indicate the presence of a shallower low velocity anomaly (Ramesh et al., 1993). Anomalous upper mantle low velocity signatures are also reported below the Kaladgi-Bhima Proterozoic basins and the Godavari Gondwana rift (Rai et al., 1992). These imply overprinting of younger events on an Archaean lithosphere. In contrast to the Dharwar Craton, the South Indian lithosphere portrays a low velocity zone beneath the South Indian Shield (SIS) with an average velocity contrast of –3%. Ramesh et al. (1990) estimate a thickness of 80 km for a low velocity zone underlain by 80 to 400 km deep high velocity. The differences in anisotropy, stress patterns and character of velocity anomalies between the upper 80 km and the underlying mantle lead the authors to suggest the presence of a decoupled system beneath the South Indian Shield (SIS).The mantle below the 80 km depth remained unperturbed since the Proterozoic. In the subsequent papers on the South Indian Shield, Rai et al. (1992, 1993) and Srinagesh et al. (1996) present lithospheric roots of varying depths 200/177 km, beyond which the lithosphere below the Dharwar and South Indian High Grade Domain become more homogeneous.

Receiver function studies by Saul et al (2000) and Gupta et al (2003) have consistently identified a thick crust, 41-52 km below the Archaean Western Dharwar Craton and a thinner crust 31-34 km below the EDC that has a Proterozoic over printing, and also below the Cuddapah Basin the north and the region of Deccan Trap cover in the NW.A seismic discontinuity is identified at a depth of ~90km below the Dharwar craton and the 406 and 659km discontinuities are close to global averages.

Kiselev et al (2008) invert jointly *P* and *S* receiver functions and teleseismic *P* and *S* travel time residuals at 10 seismograph stations in the South Indian Shield and arrive at, perhaps, most surprising conclusion, namely the lack of the high velocity mantle keel with the *S* velocity of ~4.7 km s−1, typical of other Archean cratons. The *S* velocity in our models is close to 4.5 km s−1 from the Moho to a depth of ~250 km. This model contradicts the findings of Mitra et al cited above and is preferred by the authors on seismological grounds. Kiselev et al draw a parallel with the contrasting shear wave velocity structure below the NW and NE Himalaya and between Eastern and Western Tibet. The estimate a crustal thickness of ~31 km for the EDC with predominantly felsic velocities and around 55 km for the WDC with predominantly mafic velocities confirm the earlier findings of Gupta et al (2003) and the possibility of wide variations in the MOHO possibly related to the crustal mantle interaction and processes like eclogitisation (Nemeth et al, 1996). The fact that the region in question has been the venue for the emplacement of two generations of dyke swarms of ~80 and 65 Ma ages (Cretaceous Volcanism) opens up the possibility that there may be basaltic underplating below the crust that may add to the MOHO thicknesses.

Interpreting the wavefield of mine tremors at the Gauribidanur Seismic array, Krishna and Ramesh (2000) identify below the EDC a seismic model comprising a wave guide Pg with random successions of high and low velocity layers in the upper crust; a transitional Moho at a depth of 34-36km and a Pn velocity of 8.2 km/s and a gradient of 0.013sec^{-1}, a Poison ration increasing from 0.24 below the MOHO to 0.27 at about 60km depth in the mantle.

Eastern Ghat Mobile belt (EGMB) and Dharwar Craton

Das Sharma and Ramesh (2009) and Ramesh et al (2010a) utilise the P and S receiver function imaging technique, and identify two distinct westerly dipping interfaces at depths centered on 150 km and 200 km in the EGMB (Fig.7). Significantly, the presence of these structures signal that the depth to the LAB may exceed 200kms below the EGMB and may have been in existence since the Meso-Proterozoic at least. Presence of velocity layering in the depths of the Lehman boundary have been also demonstrated

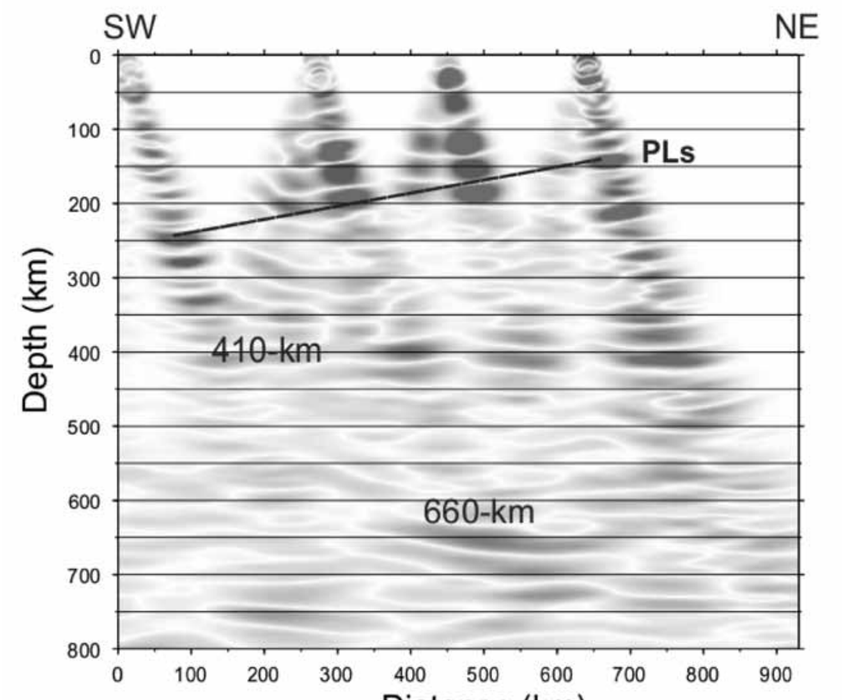

Figure 7. Ps migrated image along NE-SW (14°N–76°E; 19°N–83°E) direction showing clear presence of westerly dipping interfaces in the depth range of ~ 160-200 km transcending the surficial EGMB-craton divide into the craton. This image also shows a relatively flat 410-km across the study region accompanied by a diffused 660-km boundary (after Das Sharma and Ramesh, 2009).

by Ramesh et al (2010b) below the Hyderabad and Cuddapah stations along with four other stations outside India and viewed together with the EGMB results, demonstrate that the lithosphere below the SE cratonic areas of the SI Shield may extend to depths of the Lehman discontinuity (180-330Km) (Ramesh et al , 2010b). As a corollary they consider the shallow LVLs modeled as the LAB by Kumar et al (2007) is a "birth mark "related to the evolution of the older Archaean-Proterozoic cratons.

DVP- Cambay rift zone

The KW model of the Cambay graben (Kennett and Widiyantoro, 1999) portrays with high resolution in the Cambay rift zone, a cylindrical prism of lowered seismic velocities in a matrix of relatively higher velocities in the rest of the Peninsular Shield. The Late Mesozoic Cambay rift is cradled between the Precambrian continental regimes of the Saurashtra and Rajasthan blocks on the west and east, where the MOHO depths are of the order of 38 to ~40 km (Kaila and Krishna, 1992). The anomaly connects with a more extensive LVZ below 200 km depth which extends southwards and become not perceptible in the tomographic frame. The anomaly is explained as due to elevated temperatures along the rift, consistent with a high heat flow or alternatively due to variation in chemistry or the presence of localized anisotropy. The lowered seismic speeds extend into the SONATA Belt. It seems to terminate at the Narmada lineament as further south, it has not been traced (Fig.5).

DVP –Platformal Cover

Teleseismic receiver function analysis of the 350 km long N-S profile from south of the Narmada (Ravi Kumar and Mohan, 2005) has led to the delineation below the DVP of sub-Moho low velocity zones with velocity reductions in the range of 0.1 to 0.4 km/s in the receiver function stacks at individual stations., confirming earlier P-wave tomography results of Ramesh who reported a 1-5% lighter lithosphere to a depth of 200 km along the western coastal margins of the Deccan Trap region. However, a normal mantle transition zone of a thickness of around 252 km and normal depths to the 410 and 650 km discontinuities is observed in the velocity model. Notably the low velocities that characterize the Cambay Basin do not extend into this region and is confined to the Cambay Basin. There is , however, an absence of any anomalous structures in the deeper zones of the SCLM that is consistent with a plume model or incubation models, as popularly conceived. A similar scenario emerges from the tomographic studies (Iyer et al., 1989; Rai et al., 1992; Ramesh et al., 1990, 1993; Srinagesh and Rai, 1996) already cited.

The presence of sub-Moho as well as Lower Crustal LVLs is consistent with LVLs below the Koyna region of the DVP seen in the synthetic seismograms based on DSS data (Krishna et al., 1991). The impact of Deccan volcanism is manifested in the Indian shield in the emplacement of very large dyke swarms many of which have been feeder dykes. Instances of very significant underplating with basaltic rocks have been noted in the sub-crustal segments of the Cambay Basin and to a lesser extent in the SONATA Belt . The profiles also do not portray any prominent LVLs reported in the Central Indian region using shear wave velocity structure by Bhattacharya (1974, 1981) and Mitra et al. (2006) discussed later. The absence of evidences of any profound thermal impact in the receiver function experiments cited above, highlight the resistance offered by a tectosphere to any attempts at breaking it up, except along prominent rift zones.

Heat Flow

The results of the extensive heat flow and heat generation studies carried out in India are reviewed by R.U.M.Rao et al (2003) and by Roy (2008). The bearing of these results in the tectonic evolution are highlighted here. Status of our present data base is reflected in Fig.8A.

As may be seen from fig.8a, the higher ranges of heat flow of a range 50 to 80 $mWm^{-2}$are confined to the Cambay Rift and the Sonata rift zone ; and the Damodar valley Gondwana rift. These rifts are associated with the episodes of Deccan (65Ma) and Rajmahal (115 Ma) thermal (volcanic) events. These regions are characterized by large number of thermal springs and advective contributions to the heat flow cannot be ruled out (Mahadevan, 1994). Projecting such values of heat flow to estimate mantle depths gives erroneous estimates. Nevertheless the high heat flow in these regions may be related to thinning of the lithosphere due to rifting. The heat flow in the rest of the Indian shield where data is available, ranges from 27 to 50 mWm^{-2}

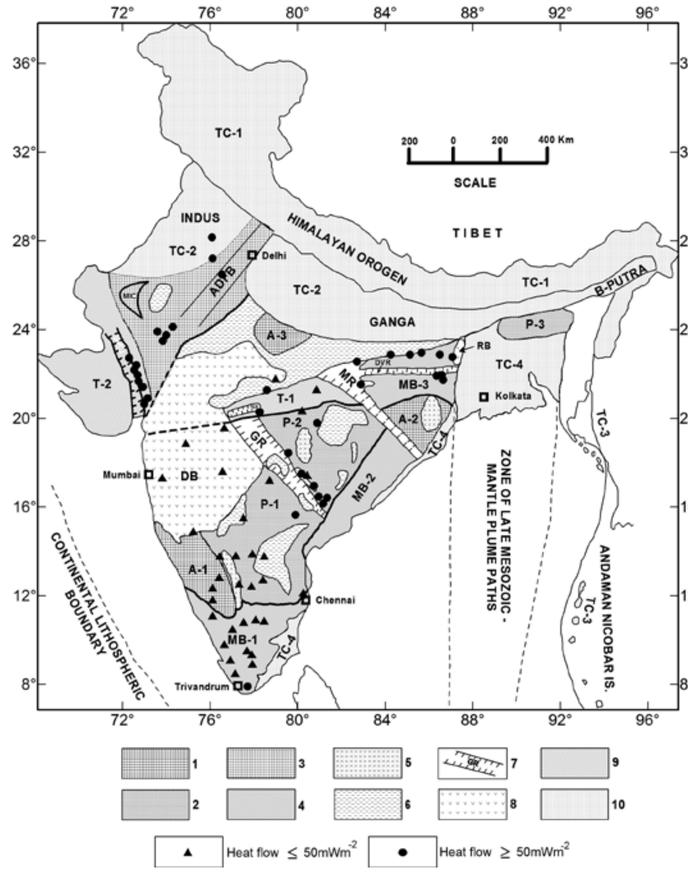

Figure 8 A. Thermal structure of the Lithosphere illustrating surface - Heat Flow.

Carefully estimated thermal gradients in the Sonata Rift zone seems to intercept the 1350°C adiabat at around 155 km, consistent with the shear wave velocity model of Mitra et al., 2006, while that in the Dharwar- South Indian High Grade Domain intercepts at ~220 km. (Roy, NGRI, pers. comm.).Mantle heat flow has been carefully estimated only for the Dharwar Craton, the southeastern part of the Deccan Traps cover and the South Indian High Grade Domain.In the Dharwar Craton, the estimates range from 11 to 19 mWm^{-2} similar to other Precambrian provinces of the world (Roy, NGRI, pers. comm). A similar estimate, 12 mWm^{-2}, has been obtained from the Latur area in the region of Deccan Trap cover from measurements in the basement rock formation underlying the Traps and a well-constrained crustal heat production model. The uniformity in mantle heat flow in the two regions suggest that the crustal thermal structure in the Dharwar Craton extends to the north beneath the relatively thin, ~65 My old, Deccan flood basalt cover, at least in the southern part of the Deccan Traps (Roy and Rao, 1999). The estimates from the South Indian High Grade Domain are significantly higher, ranging from 25 to 30 mWm^{-2} in the northern block of the South Indian High Grade Domain consistent with both lower seismic velocities and LILE-enrichment in the upper mantle (Rao et al., 2003). Moho temperatures of 285 °C to 410 °C and 580 °C to 660 °C have been estimated respectively in the Dharwar (Archaean) Craton and the Northern block of South Indian High Grade Domain.

A major constraint in heat flow estimations, in especially some of the Gondwana basins, the SONATA Belt and the West Coast including Cambay Basin, is the prevalence of several thermal springs which provide a strong, highly localized advective element to the heat flow in the upper few kilometers of the crust. Under such conditions, any heat flow measured may not be reflective of conductive regional heat flow. The ongoing debate whether Indian plate is much hotter than other continental plates and some of the estimates of thickness of the lithospheric mantle lid based on surface heat flow suffer from

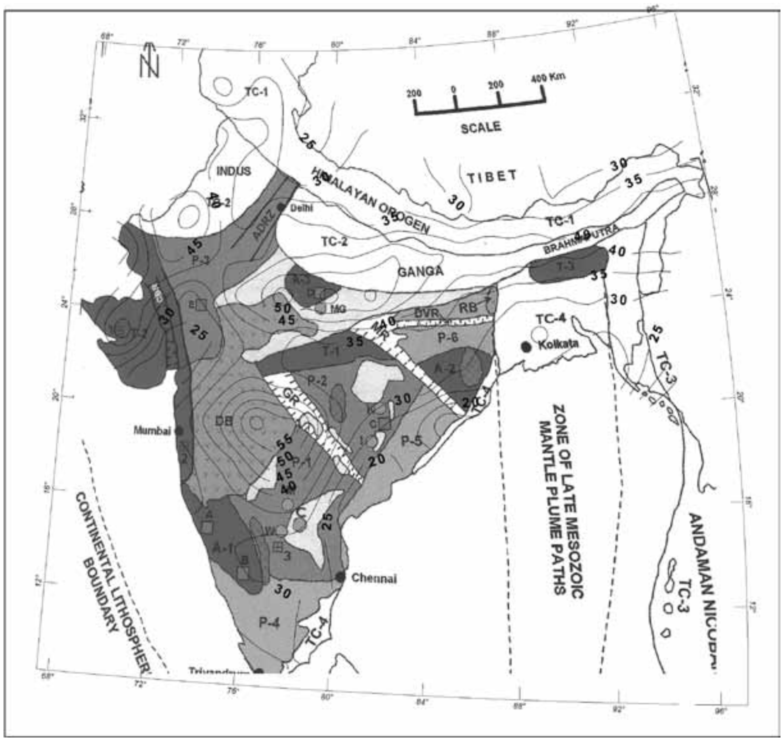

Figure 8 B. Thermal structure of the Lithosphere illustrating surface - the Curie Isotherm.

these limitations (Mahadevan, 1994). There is no data on the mantle contributions to the heat flow for most of the areas, underlying the need for more systematic studies in the heat flow in the rest of the shield similar to the studies now completed in the Dharwar Craton and the South Indian High Grade Domain.. However, comparisons between the Curie isptherm and LAB isotherms bring out some interesting conclusions (see below).

Curie and LAB Isotherms

A comparison of the Curie isotherm map (Mita Rajaram et al, 2009, (Fig.8B) with the isotherms of the LAB (~1300°C) (Fig.4) estimated from shear wave velocity (Priestly and McKenzie, 2006) bring out a total lack of correspondence. The largest difference is with regard to the deepest contours of the Curie isotherm of Hyderabad. The only correspondence seen is in the Cambay Basin, a Cenozoic rift zone. Such a relationship may be related to the fact that the crustal temperatures are largely governed by the radiogenic heat generated largely in the upper crust and the heat that wells out of the mantle through conductive transfer through the SCLM is not very significant. However, in regions of strong extension and active rifting , like Cambay, the heat transfer from the upwelling asthenosphere is significant due to both exhumation of the asthenosphere and advective heat flow (cf. Jaupart et al, 2002). Such a picture renders unreliable estimates of lithospheric thickness from thermal gradients in the crust. These conclusions have great relevance to the concepts of a thin mantle proposed on the basis of seismic modeling (see under discussion).

GEOPHYSICAL SIGNATURES AND TECTONIC PROCESSES

Geophysical models of crustal/ lithospheric structure have thrown light on many geological processes constraining lithospheric evolution (Sain, 2008). Velocity structure has been interpreted to gain insights into processes of underplating, Crustal and sub-crustal reflectivity has been used to interpret collision and extensional tectonics (Mooney and Meissner, 1992). Presence of low velocity zones in sub-Moho regions and lamellae structures of low and high velocity have relevance to episodes of crust-mantle interaction. Sain (2008) and Vijaya Rao (2008) draw attention to some of these applications.

Evidences of underplating:

Prominent development of a P_v layer of 7.2 to 7.6 km/s in the DSS profiles is interpreted as an evidence of basaltic underplating across the Proterozoic Cuddapah Basin and the Archaean EDC to its west (Reddy et al, 2004; Rai et al, 1996), (Fig. 9C), the Gondwana Mahanadi Graben (Behera et al, 2004 (Fig. 9B) and the Cenozoic Cambay rift (Tewari et al, 1995) (Fig. 9A). A few profiles across the SONATA belt provide evidences of rather thin underplating. The underplating of these basins is related to a history of extensional tectonics, accompanied with magmatism. The basins of strong underplating stand testimony to the onset of high asthenospheric temperatures and upwelling of the asthenosphere and consequent decompression melting and high extension rates (Fountain, 1989). The extension rates and asthenospheric temperatures below Cambay have been high whereas in the continental interior in the Sonata Basin it has been comparably very low. Underplating in these basins may be related to the Deccan Volcanism. The underplating in the Gondwana Mahanadi basin is a late event as no volcanism is associated with the early nucleation of the Gondwana Basins in the Late Permian and the growth of the basins till close of the Jurassic (120 Ma). Their development is attended by a weak to moderate extension under conditions when the mantle below was relatively cold. Underplating in the Mahanadi basin may be related to the Rajmahal Volcanism in Eastern India (~115 Ma) or to the Deccan Volcanism (~65Ma).The underplating in the basal part of the Cuddapah basin correlates well with the presence of basic sills in the Basal beds of the Basin and testifies to a model of basin evolution initiated by the thermal upsurge around ~1800 Ma and the thermal subsidence that followed.

Exhumation of the Lower Crust.

The South Indian High Grade Domain and the Eastern Ghat Mobile Belt are known to be exhumed deeper crust of the Indian shield since long and have been explained by different mechanisms such as crustal tilt and erosion (Fermor, 1936) , buoyancy (Mahadevan, 2003) and compressional (plate) tectonics (Drury et al , 1984).The DSS profiles of almost all rift basins show evidences of thinning of the upper crust and a uplifted Lower Crust, as exemplified by the Cambay Basin, many profiles across the SONATA belt and the Mahanadi Gondwana Graben. Outcropping belts of granulite facies rocks along the fringes of the rifted basins Mahanadi and Godavari stand testimony to the thinning of the crust due to the rifting.

Delamination of Lower Crust.

There is no evidence of the absence of the Lower Crust layer in any of the seismic profiles. This may be due the fact that the Indian continental crust has been very buoyant from the Archaean and not amenable to delamination processes. However, Jagadeesh and Rai (2008) opine that the "Present day felsic – intermediate character of the Indian Archean crust could be a consequence of post-formation modification of the initial mafic lower crust through the process of lithospheric delamination". This aspect therefore needs more careful evaluation.

Lithospheric reflectivity and tectonics

Dipping seismic reflecting surfaces in the profiles across the Nagaur –Jhalawar transect in Rajasthan, the Mungwani- Kalimati transect across the Central Indian Tectonic zone (Reddy et al, 2000) and the Kuppam-Palani transect across the South Indian shield (Reddy et al, 2003; Vijaya Rao et al, 2006), have been interpreted as indicating the directions of subduction and collision largely from nearness to regional fractures and a bi-modal gravity signature and similarities to reflectivity textures in other examples of compressional and extensional settings elsewhere in the world (Fig.10A, B and C)

The most comprehensive interpretations of the plate tectonic controlled interactions in the Rajathan profile is offered by Sinha Roy (1995) in terms of the kinematic models of crustal-scale structural evolution fitting in both the flat and dipping reflectors. Vijaya Rao (2008) addresses the geodynamic processes operating and associated lithospheric evolution of these zones. Probable rheological models representing the seismic structures are briefly outlined. Krishna and Vijaya Rao (2011) identify several steeply dipping isolated reflections in a NW segment of the profile close to the South Delhi Thrust fault and these floating reflectors are modeled as stacks of alternating high and low-velocity layers in the Lower Crust and

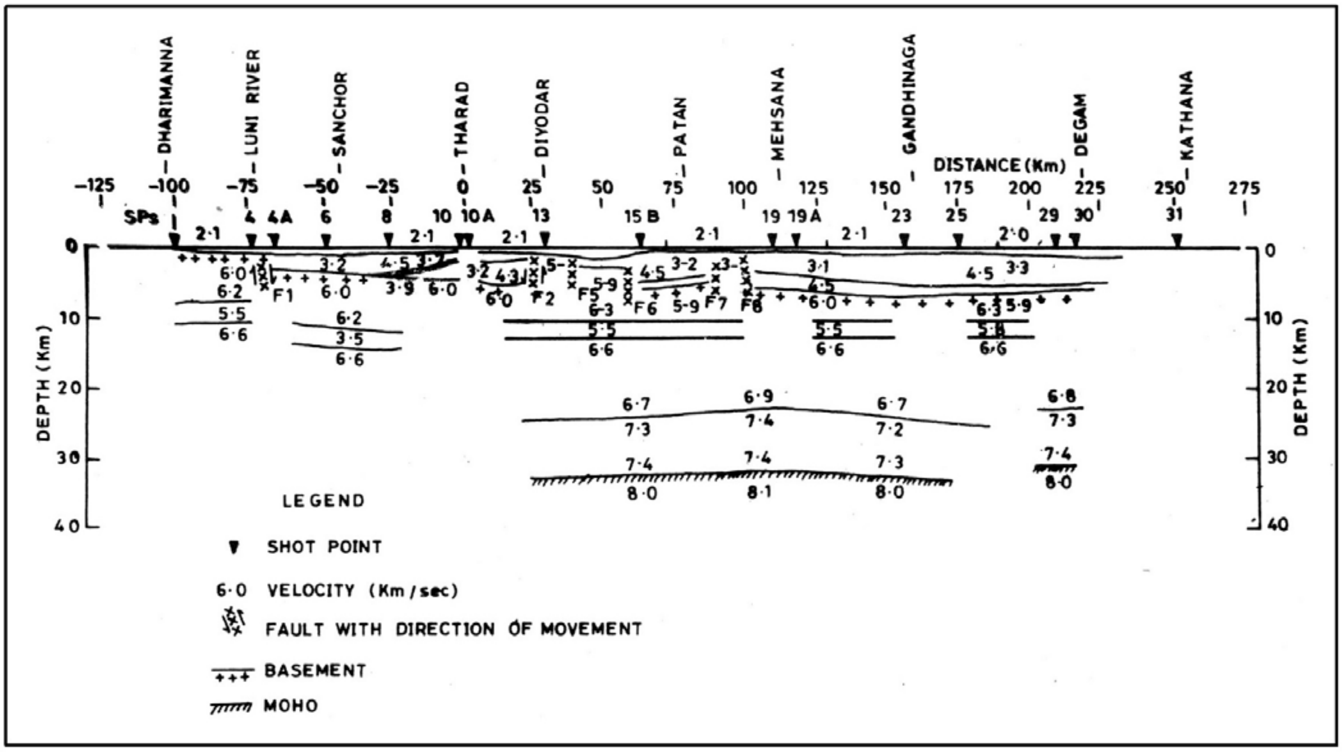

Figure 9 A. Crustal velocity structures picturing subcrustal underplationg across the Cambay rift basin (after Kaila et al, 1981)

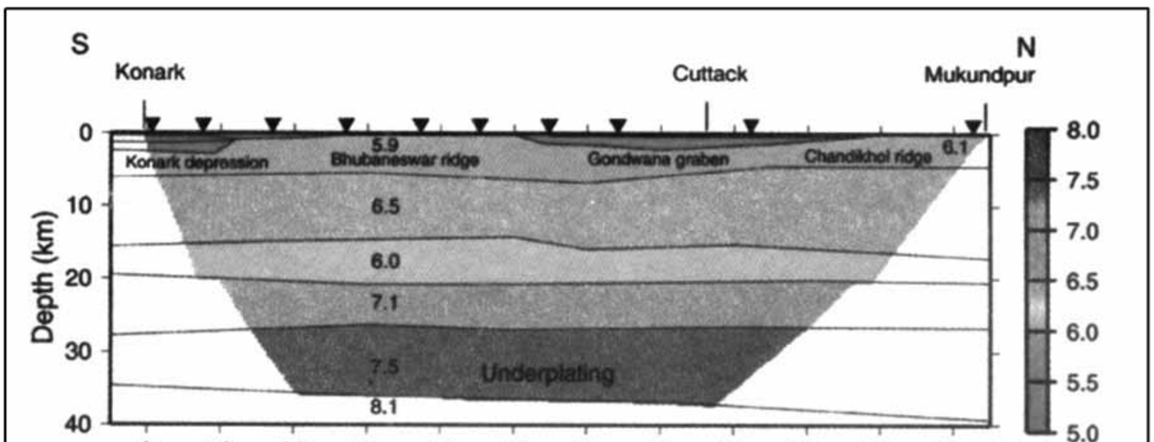

Figure 9 B. Crustal velocity structures picturing subcrustal underplationg across the Mahanadi Basin (after Behera et al 2004)

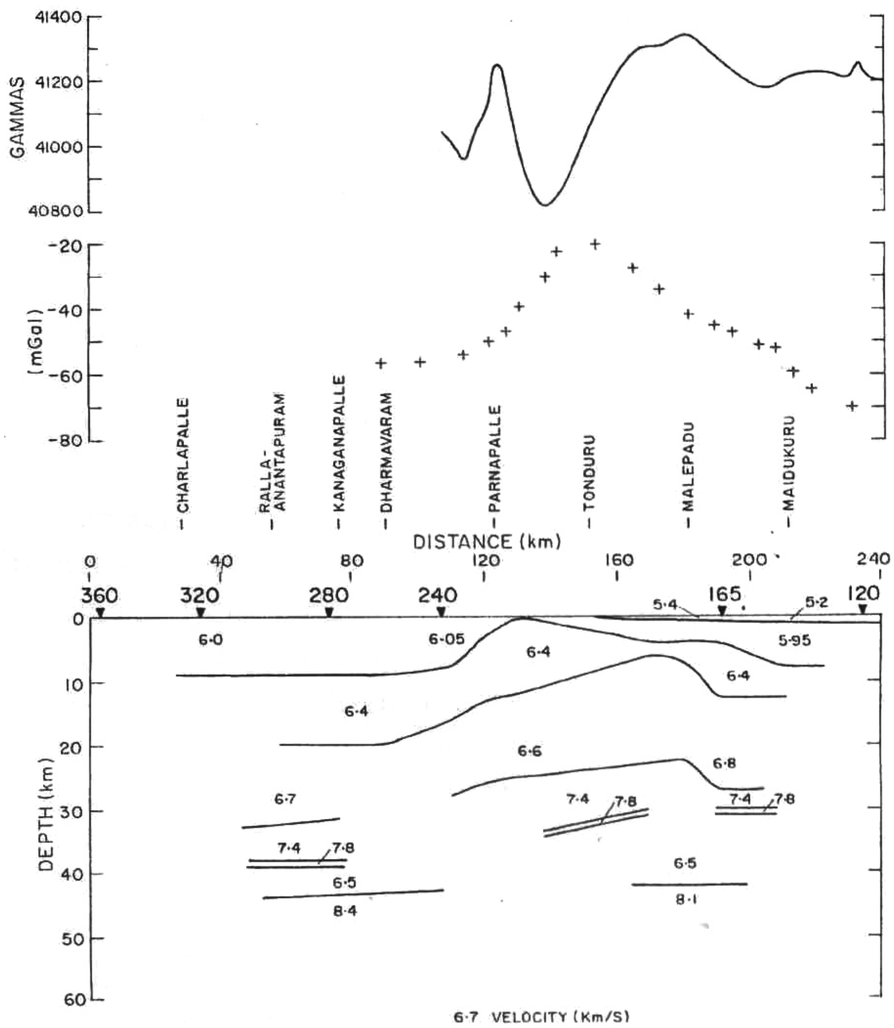

Figure 9 C. Crustal velocity structures picturing subcrustal underplationg across the Cuddapah Basin and the marginal Eastern Dharwar Craton (after Reddy et al, 2004).

Upper Mantle lithosphere (Fig. 10A). This lamellar velocity structure is interpreted as having developed during the Meso-Proterozoic collisional episode related to the Delhi Orogeny. The terrane bounding the reflection zones to the NW is the Marwar region that had a strong extensional history with attendant magmatism in the culminating phases of Delhi Orogeny, as stated earlier. The reflective features being related to this extensional event is an alternative that needs to be examined.

In the Central Indian profile converging reflections are taken as evidence of plate tectonic collision regimes (Reddy and Satyavani. 2001) (Fig.10B-1). The profile runs across the SONATA tectonic zone which has a prominent rift history and like the Palghat –Cauvery Rift zone a prominent Precambrian rift. Rift basins are known to have well developed reflectors. (Milkereit, B and J.Wu. 1996). Some of the domical reflections in this profile seem related to the exhumation of the lower crust (Fig 10B-2).

The seismic profile across the SIHGD shows prominent divergent reflection fabric with reflection lamellae dipping southwards in the northern half of the profile and northwards in the southern half (Fig 10C). The south dipping segment has been modeled (Vijaya Rao et al, 2006) as part of a southward subduction of the decoupled Lower crust along with the upper mantle of the Dharwar craton on the north. A major characteristic of the South Indian High Grade Domain is the large scale spatially differential exhumation of the Lower crust due, debatably, to a positive buoyancy. Episodic late

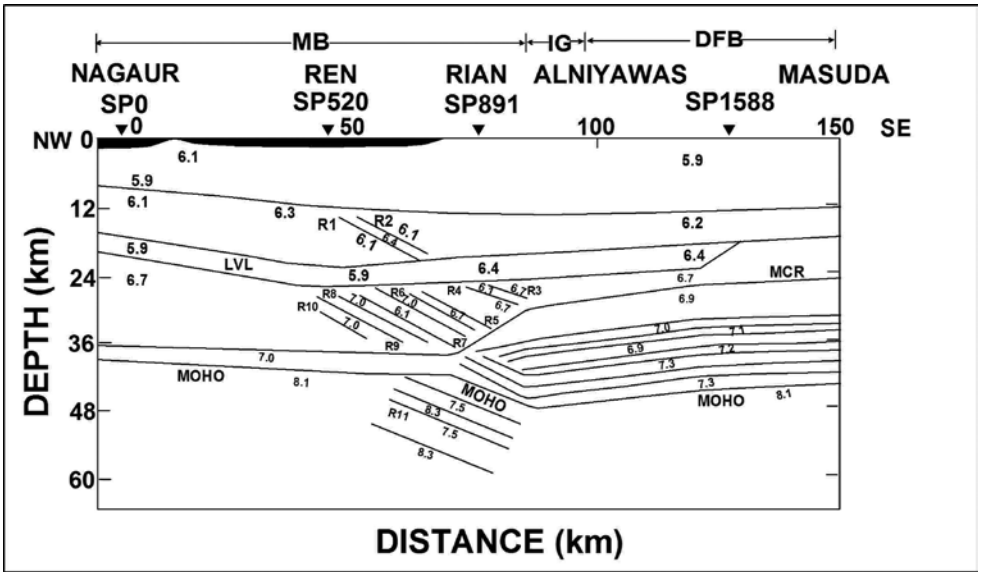

Figure 10 A. Seismic reflective textures along the Nagaur – Masuda section of the Nagaur- Jhalawar profile (after Krishna and Vijaya Rao,2011)

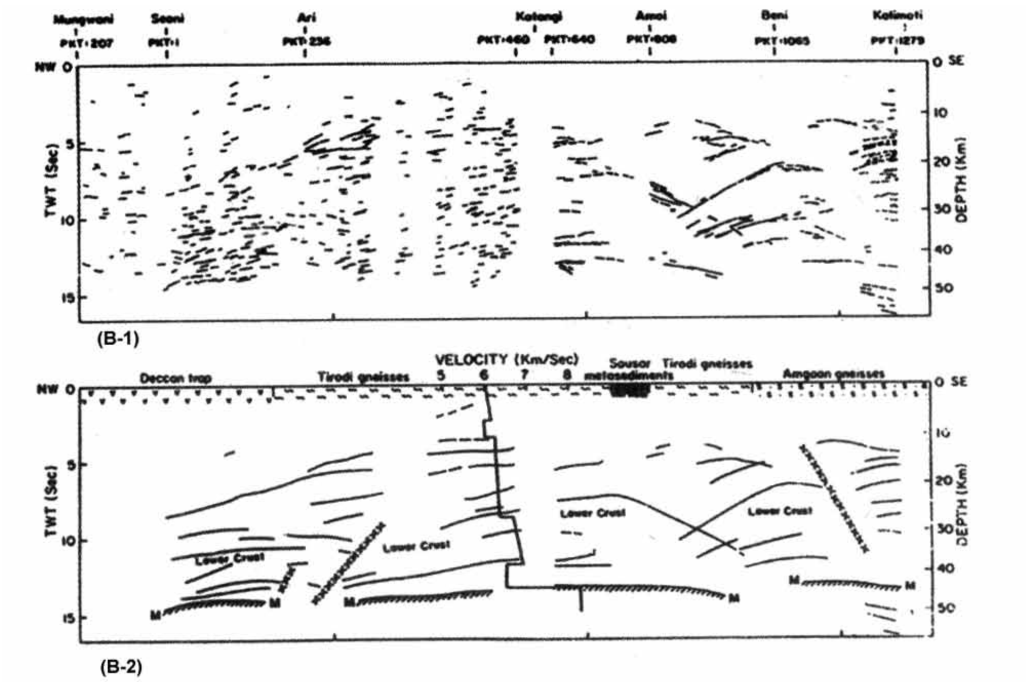

Figure 10 B. Seismic reflective textures along the Mungwani-Kalimati Transect across the CITZ (after Reddy et al, 2000)

to post orogenic ultramafic-mafic-and syenitic and carbonitite magmatism (~1.2 to ~0.60Ga) in an extensional tectonic environment is a major event that marks the last phases (1200-600 Ma) of the Proterozoic orogeny in the region (Mahadevan, 2008). In this context, the opposing reflectivity lamellae and a few minor domical reflective features in the profile may be the result of differential domical exhumation of the Lower Crust in an extensional tectonic setting and the minor domical reflecting lamellae seen in the northern half due to the emplacement of the alkaline and associated bodies. Both the south dipping and north dipping segments would be explained by a model of differential exhumation.

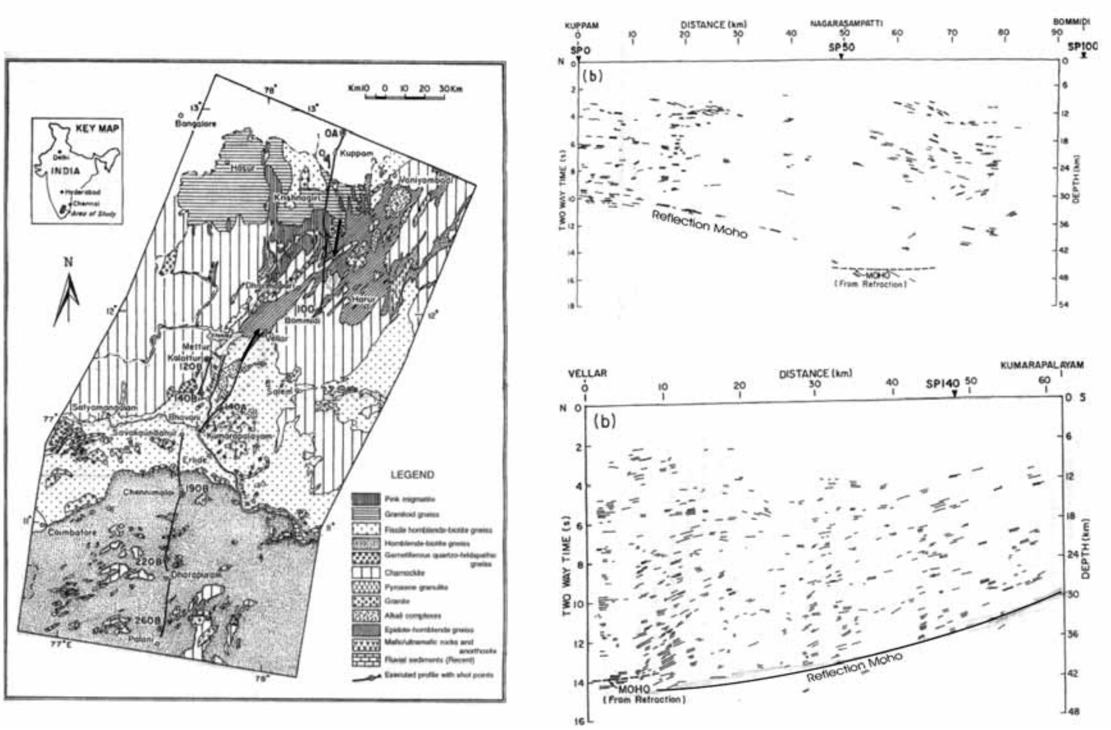

Figure 10 C. Seismic reflective textures along the Kuppam-Palani transect across the Dharwar – SIHGD in south India . C1- Geological map of SIHGD showing the Kuppam-Transect region: C2- Seismic reflectors between Kuppam-Bommidi and C3- seismic reflectors below the Vellar- Kumarapalayem Section (compiled from data from Reddy et al, 2003).

A major constraint in relating dipping reflectors to tectonics arises from the fact that they are common in both compressional and late orogenic extensional regimes. Clowes et al (1966, p.85) point out, "With respect to reflection geometries , if there is evidence at surface for extension , then consideration of an extensional origin of the reflectivity is appropriate; in the absence of such evidence, extrapolation into the surface would appear to be ad hoc". In all the three profiles discussed above, there are strong evidences of extensional tectonics and attendant magmatism largely as a late orogenic phenomenon. There is a strong possibility that these features are multi-genetic in origin (Mooney and Meissner, 1992) and until we have criteria to distinguish these reflectivity structures taking into consideration the rheological and thermo-mechanical consideration, as illustrated in the work of Beumont and Quinlan (1994), the correlations with tectonics may remain equivocal.

Low velocity zones and Lamellar structure of the MOHO zone:

Several instances of alternating high and low velocity zones, some giving closely interbanded lamellar structures have been traced in the sub-Moho shallow depths in different parts of the shield. Modeling the seismograms of the deep (focal depth 36km) 21st May 1997 Jabalpur Earthquake Krishna (2004) established that the High frequency Pn and Sn phases generated in this earthquake are consistent with a lamellae model of alternating high and low velocity layers that characterize the uppermost mantle covering a depth up to ~100km below this region . A tentative plausible P velocity model for the deeper mantle reveals velocity discontinuities at average depths of 230, and 320 km and again at the 430 and 660 km, suggesting significant stratification of the upper mantle B region in the region. The authors have also established that that the P-bar phase is well generated and propagates efficiently in the Deccan Trap region, even without a LVL surrounding the earthquake epicenter and recording stations (Fig.11A). Murthy et al (2008) infer below the Hirapur –Mandla DSS profile across the SONATA belt , west of Jabalpur, two alternate low velocity layers (velocity 7,2 km/s separated by 6 km thick high velocity layer 8.1 km/s. Prominent reflection phases are modeled at depths of 49, 51, 57 and 60 km. These features reveal a lamellar structure with varying structural

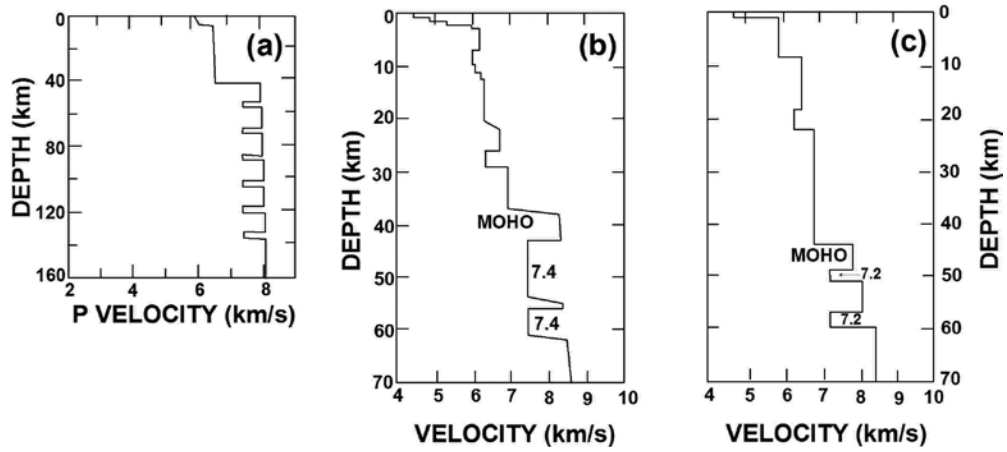

Figure 11. P-wave LVLs observed in a 2-D velocity model in the Lower Crust and sub-Moho region (A) below Jabalpur, Sonata Belt Central India (after Krishna , V.G , 2004); (B) Hirapur-Mandla Profile in the Sonata belt (after Murty et al , 2005) and (C) Below Koyna region , Western India (after Krishna et al, 1991.

and mechanical properties (Fig.11B). The synthetic seismograms computed using velocity-depth model of the two Koyna profiles I and II by Krishna et al (1991) bring out 1-2 km wide transitional MOHO at a shallow depths of 35.5- 38 km followed by prominent low velocity layers of 7.4 km/s down to depth between 42 and 62 kms (Fig. 11C). Modeling the aftershock seismograms of the Latur earthquake of 29 September 1993, Krishna et al (1999) recognize alternating LVLs with ~ - 7% velocity reduction for both P and S waves in upper crust of the Latur area at depths of 6.5 to 9.0 km and 12.5 to 14.5 km and 24-26 km. The Moho is placed at 35-37kms. Modeling DSS data, Reddy et al (2004) identify below the SW margin of the Cuddapah basin and the Eastern Dharwar Craton further west a velocity layer of 7.4 km/s. This layer is underlain by two Moho discontinuities at depths of 37 km and 45 km the upper one with a Pn velocity of 7.8 km/s and the lower one with a velocity of 8.4 km/s. The intervening LVL has a velocity of 6.5km/s. Interpreting the wavefield of several mine tremors at the Gauribidanur Seismic array , Krishna and Ramesh (2000) identify below the Eastern Dharwar Craton a seismic model comprising a wave guide Pg with random successions of high and low velocity layers in the upper crust; a transitional Moho at a depth of 34-36 km and a Pn velocity of 8.2 km/s and a gradient of 0.013 sec^{-1}, a Poison ration increasing from 0.24 below the MOHO to 0.27 at about 60km depth in the mantle. A tentative plausible P velocity model for the deeper mantle reveals velocity discontinuities at average depths of 230, and 320 km and again at the 430 and 660 km, suggesting significant stratification of the upper mantle B region in the Indian shield.

The presence of LVL and lamellar structures in the crust and the sub-Moho region may be due to fluid rich zones, pore pressures and/or temperature, factors that constrain the processes of dynamic changes in the sub-Moho region.

DISCUSSION

The Indian continental lithosphere is viewed in this paper as an ancient Archaean continent that evolved into distinct tectono-thermal regimes due to differences in thermal interaction with the evolving mantle in the Proterozoic and the Phanerozoic. At the close of the Archaean the Indian continent may have stabilized into a large continent to the two-layered heat flow structure of the mantle as evidenced by the overall stability in the period of 2.0 Ga to 1.8 Ga all over the Indian Shield. In the mid- to late Proterozoic (1.8 to 0.50 Ga) , a differential activation of both geodynamic and magmatic episodes stand witness to a changed differential impact across the different tectono-thermal regimes that may have been heralded by a change from a two-layered to whole mantle convection as proposed by Breuer and Spohn, 1995. The 410 and 660 discontinuities are, however, preserved in many seismic profiles across the continent that implies that the change over to the whole mantle convection was perhaps transitional between the two systems of thermal convection.

The Proterozoic thermal impact was great over the Rajasthan Orogenic Province, where it heralded a long period of orogenic evolution characterized by distinctive geodynamic and stratigraphic settings, magmatism and metallogeny. If one may speculate, this distinction was forced by possibly a thinner, denser, less chemically depleted lithosphere that this region imbibed in the Archaean.

In the southern and northern Archaean- early Proterozoic Cratonic Blocks, the thermal flux of the mantle was much weaker. In the southern cratonic block, however, the peripheral regions, that evolved into the high-grade mobilebelts (mobile belts) had a larger thermal impact, that was distinctively more intense and interactive leading to exhumation of the Lower Crust. As a result the cratonic interior regions retain more of the Archaean signatures in fossil domains, mainly in the Western Dharwar Craton, Singhbhum and Bundelkhand cratons (Fig.3) but are otherwise transformed both physically (thickness and velocity structure) and chemically (not discussed in this paper). Barring a few early magmatogenic events, lithospheric evolution involved mainly the mechanical boundary layer of the lithospheric mantle, providing a slow extensional growth of the several Proterozoic sedimentary basins. The mobile belts were more intensely transformed and barring a few relict Archaean geochrons, imbibed a total Proterozoic stamp. Dynamic evolution manifested in different styles of exhumation and episodic anorthositic and alkaline –ultramafic volcanism in the early stages and both calc-alkaline and alkaline high –potassic granites towards the close of the Proterozoic. The latter events are correlated with the Pan-African thermal/orogenic episodes.

The early part of the Phanerozoic was a quiet stable period until around 290Ma when slow distension with no magmatism led to the development of the Gondwana Coal basins. The Central Indian cratonic regions and adjoining mobile belts could be extended more efficiently than the southern buoyant lithosphere of the Dharwar and the southern high-grade domain that resisted the distensional dynamics. The rather quiet and slow sedimentation that characterized the Gondwana Basin development was terminated around 130 Ma by the initiation of continental rifting along the East Coast possibly due to an encounter with the Crozet and Kerguelan thermal plumes or alternatively a large thermal influx from the core-mantle boundary and ushered in the Rajmahal magmatism. This was followed by rifting along the West Coast possibly due the impact of the Reunion and Marion plumes in the time span of 90 to 65 Ma that ushered in the extensive Deccan continental basalt magmatism. The impact of these two episodes of continental scale volcanism is reflected in the underplating of basaltic rocks inferred in many basins discussed here and development of several rest magma chambers in the continental interiors. Seismologists are divided on the extent of the effect of these events on the structure of the lithosphere, especially in the light of the accompanying northward drift of the Indian Shield (to be discussed later).

The distinctive style of evolution of the mobile belts, the SIHGD and the EGMB may have been initiated by either a process of rifting or demalmination of the SCLM thant then eposes the Crust to the high tnermal regimes in the asthniospheric mantle. However more seismic data is needed to infer the excat processes that led to a distinctive trend in evolution. A similar possibility applies in the case of the anorogenic magmatism that was ushered in the in the Marwar region of Rajsthan by the end of the Proterozoic.

Several temporal distinctions in lithospheric structure and composition have been arrived at through thermal modeling and xenoliths studies. In the light of these distinctions, a large part of the Indian Shield has a lithosphere characteristic of the Proterozoic with some islands of Archean cratonic blocks preserved. The Phanerozoic imprint is expected to be larger in the Central part of the shield, in the northern cratonic block and the Rajasthan orogenic province (Figs 2 and 3). Such a prediction finds support in the long wavelength gravity fields that suggest a buoyant lighter segment in the south and a denser segment in the north consistent with the geological framework. The seismic velocity structure across the Indian shield estimated by many different techniques presents a rather unexpected picture**.** Different seismic methodologies have been used in the estimation of the lithospheric structure and the results polarize into a majority of them inferring a shallow depth to the LAB <140 kms or even 80- 100km. This implies a very thin lithosphere below the Indian shield imparting to it a Phanerozoic stamp. Others present evidences of a deep lithosphere extending down to 200 km or even to the depths of the Lehman discontinuity (180-320 km).

An explanation for the thinning of the Indian Shield has been sought in (i) the two major events of continental- scale rifting along the eastern and western margins of India and the large scale partial melting of the mantle that gave rise to the extensive Rajmahal and Deccan basaltic flows (Griffin W.L. personal communication) and (ii) in the basal drag during the fast northward drift of the Indian plate (Mitra et al 2006). These possibilities do not explain the northward thickening of the lithosphere to depths of 200km in Central India and beyond to 300km below the Himalaya in the only global shear wave tomographic model. Further, there are no significant dynamic or magmatic changes in the South Indian shield that can be related to the aggressive thinning of the lithosphere by an order of some 50kms in the post 130 Ma time span except some local uplifts. In fact in the heat flow in the whole of the South Indian Shield is the lowest in the shield and the slightly higher heat fluxes seen in the Central Indian region are partly advective and partly due to the remnant heat of the two episodes of Rajmahal and Deccan Volcanism. A comparison of the the surface heat flow structure with the Curie isogeotherms (~550^{o}C) and the LAB isotherms (~1300^{o}C) presented in this paper focuses on this aspect. Artemeiva and Mooney (2002) provide a basal drag mechanism of lithospheric evolution by which the thick lithospheric keels can be preserved.

There are also basic questions of resolution and genetic factors involved in relating Vs and also V s-p conversions to viscosity boundaries. Vs and Qs anomalies are influenced almost evenly by temperature and other non-thermal factors such as compositional variations, fluids, partial melting and scattering. (Griffin et al,1998, Artemieva, 2004). There are suggestions that these LVLs are intra-lithospheric "birth marks" (Das Sharma and Ramesh (2009) and possibly a global feature in the cratons, most unlikely related to the LAB, as they are inconsistent with well constrained surface wave and teleseismic travel time data (Romanowicz,2009).

The South Indian high-grade domain and the Eastern Ghat mobile belt are regions of large events of ultramafic, ultrabasic and alkaline and acid magmatism and intense metasomatic changes with alkaline and fluid influx in the Proterozoic. One can expect considerable compositional variations and fluid –rich layers in the upper lithosphere. The mantle below the MOHO underlying the Soth Indian HIGH Grade Domain is suspected to be layered due possibly to alternating high and low velocity zones (Reddy et al, 2003). Fe depletion resulting in a lighter lithosphere (up to ~1%) was inferred by P-wave tomography by Iyer et al (1949) and may also influence shear wave transmission. In the Phanerozoic Deccan Basalt region covering a greater part of the Central India and parts of the eastern margins of the Deccan flows , several ponded magma chambers of primary source magmas have been suggested (Krishnamurthy, 2008; Vijaya kumar et al, 2010) that would have solidified by now. These have a capacity to generate density and fluid-rich discontinuities that can influence seismic transmissions.

In view of these considerations, it is necessary to investigate whether the shear wave discontinuities represent the LAB or intra –lithospheric discontinuities due to very dominant non-thermal causes. The depths down to the transition zone need to be investigated in detail so that the status of what is configured as the LAB may be evaluated. Such an investigation is called for as the Early Archaean lithosphere is now suspected to have extended to the 450 km and subsequent evolution can in such a case leave many significant fossil features in this region. Jagadeesh and Rai (2008) and Ramesh et al (2010a and b) have already made a significant breakthrough in this direction.

Assigning a non-rheological cause for the seismic boundary layer identified as LAB raises the question as to why there is a consistent change in seismic velocity in the depth range of 80 to 100km across a large part of the Indian shield. The possibility of a distinct chemical boundary layer at this depth needs to be examined, where several of the factors such as pore pressures, fluid enrichment and anisotropy could converge to one depth zone.

This paper addresses mainly the thermal impact of the evolving mantle on continental eviolution with respect to the Indian Shield and much of the aspects of geodynamic evolution are not discussed here. Constructive and progressive efforts have been made to relate geophysical signatures to inferring such processes and the progress made in this direction has been briefly reviewed in the paper. The multi-genetic origin of several of the signatures need careful consideration to identify what may be subtle differences in the geophysical signatures.

A model of the thermal interactions envisaged in this paper is presented in figure 12.

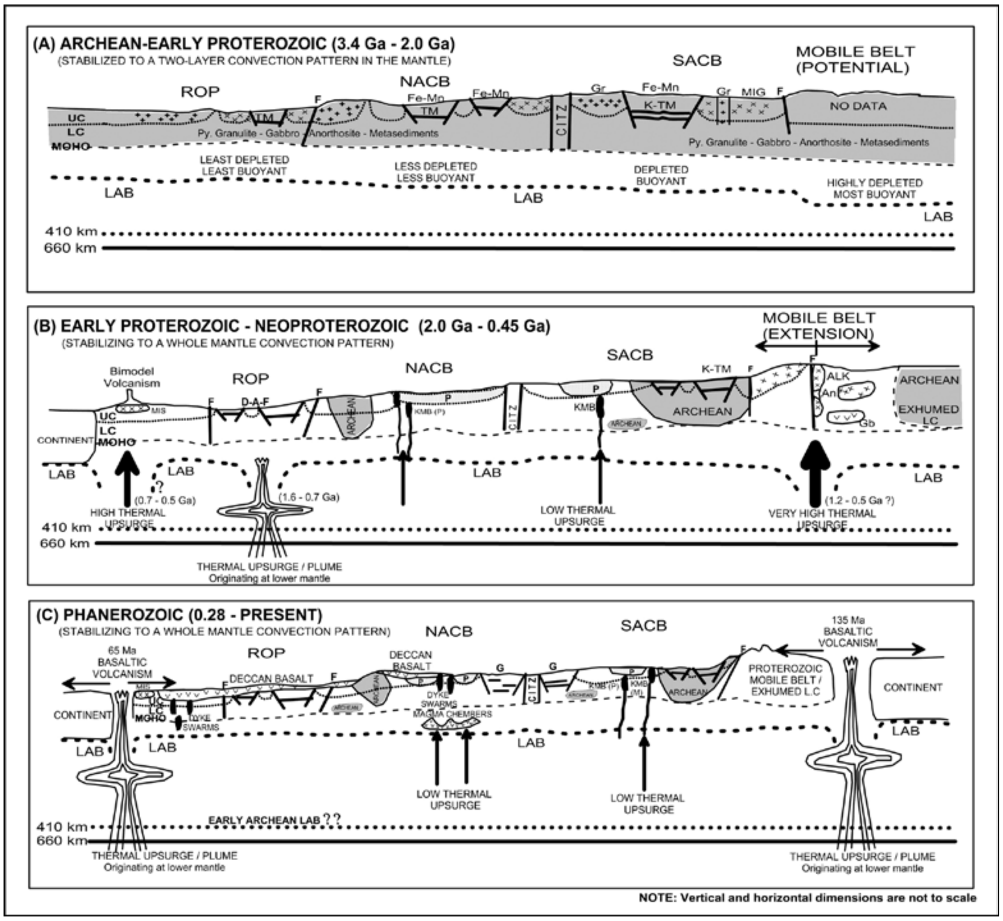

Figure 12. Cartoon showing the major landmarks in crust-mantle thermal interactions and evolution of the continental lithosphere below the Indian Shield.

A. Generalised picture of the lithosphere at the end of the Archaean-Early Proterozoic (>3.4 to 2.0Ga) when a dominantly Archaean lithosphere prevailed with distinctive regions of chemical depletion and consequent differences in density and chemistry that determined the buoyancy.

B. Interaction with a major thermal upsurge or Plume emerging from the Lower Mantle – Core Boundary below the Rajasthan Orogenic Province (1.6 -0.70Ga) and High thermal upsurges below the high-grade Mobile Belt (?1.2 to 0.5 Ga) and low thermal upsurge below the NACB and SACB.A high thermal upsurge in the late Proterozoic (0.70-0.50 Ga) may have heralded in the anorogenic Malani Igneous province in Western Rajasthan. The stress fileds during the earlier Rajasthan Oorgeny may have been highly compressional while those of the later Proterozoic more extensional.

C. Strong episodic Plume interaction in an extensional environment along the eastern and western margins of the shield lead to the two generations of continental Basalt Volcanism and continental scale rifting. The continental interiors were affected by high fluid enrichment and formation of some intra continental magma chambers connected to deep mantle.

Position of LAB shown in B and C is debatable as to whether it is an intracontinental discontinuity due to non-rheological causes or a true rheological boundary between the lithosphere and asthenosphere.

Abbreviations:
ROP- Rajasthan Orogenic Province. **NACB-** Northern Archaean – Early Proterozoic Belt. **SACB** – Southern Archaean-Early Proterozoic Belt.
Alk- Alakline rocks. An- Anorthosite. **CITZ-** Central Indian Tectonic Zone; **D-A-F-** Delhi-Aravalli Fold Belt. **F-** Fault; Gn-Gneisses; Fe-Mn – Iron- Manganese sediments. G- Gondwana graben. Gb- Gabbro; Gr.Gn-Granite-gneiss; K.T.M-Komatiite-Tholeiite Magmatism; Mig.-Migmatites; KMB(P)- Diamondiferous Kimberlitic rocks (Proterozoic); KMB (M)- Diamondiferous Kimberlitic rocks (Mesozoic) L.C. Lower Crust. LAB- Litjhosphere- asthenosphere Boundary. MIS-Malani Igneous Suite. P-Purana Basins. TM- Tholeiite Magmatism; U.C- Upper Crust.

FUTURE GEOPHYSICAL INPUTS

Several methodological developments , such as Introduction of noise suppressing and signal enhancing processing techniques (ex.Pre stack Depth Migration and common reflection surface stack) have brought out recently some finer structural details, hither to not imaged. While the basic results and conclusions made from reflectivity patterns and velocity information (made earlier and in this paper) remain unchanged to a major extent, a careful review of these emerging results would be most relevant in evolutionary interpretations. A major constraint in integrating geology with geophysics arises from the mismatch between the scales of lithospheric heterogeneity and the wavelenghths of geophysical modeling. In this regard,larger inputs into an integrated seismological approach are necessary. As suggested by Reddy, P.R (2012), it is essential to enhance the data acquisition component by deploying seismic arrays(similar to US Array, European Array etc) and carry out co-ordinated active and passive seismic studies with detailed thermal-electrical-density structure of the lithosphere and acquisition of more information on lithosphere dynamics, crustal and lithospheric chemistry and material properties. (personal communication from P.R. Reddy). Regions of Eastern Indian shield need larger inputs so that we have a more complete picture of the lithospheric properties below these regions.

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