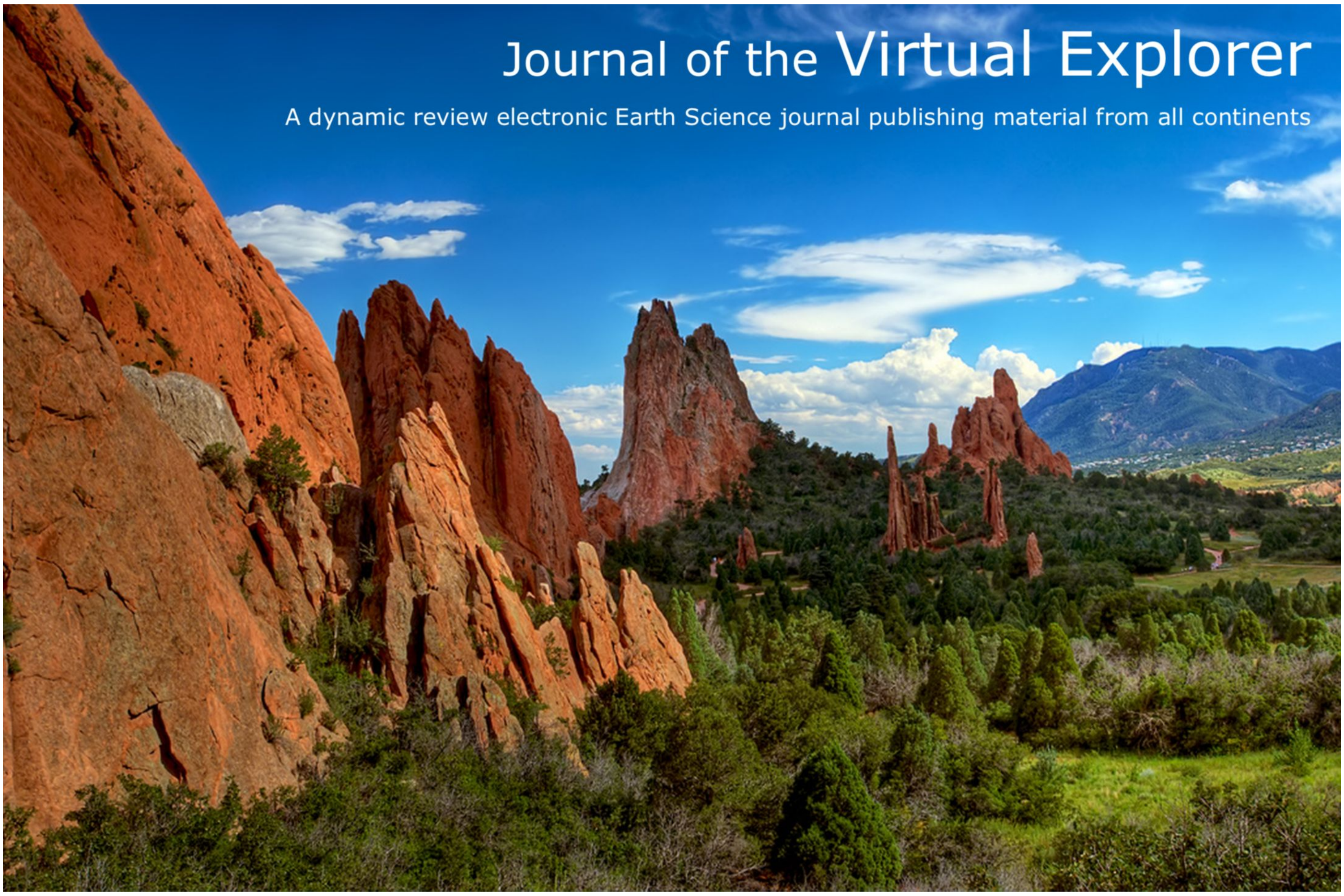

# Seismic Characteristics of the South Indian Granulite Crust

*Abhishek Rai, Shyam S. Rai, Vinod K. Gaur, Keith Priestley*

Journal of the Virtual Explorer, Electronic Edition, ISSN 1441-8142, volume **32**, paper 2
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# Seismic Characteristics of the South Indian Granulite Crust

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**Abstract:** Analysis of broadband seismograms from ten seismic stations located on granulite terranes that surround the Archaean Dharwar Craton of the south Indian shield, indicate that the seismic characteristics of the crust of these exhumed terranes share some characteristics of the western Dharwar Craton but are significantly different from those of the eastern Dharwar Craton. Joint inversion of receiver functions and surface wave dispersion data show that the crust of the western Dharwar and granulite terranes are generally thick (~44 km) and have complex internal structures, whereas the crust of the eastern Dharwar is thinner (~35 km) with insignificant internal structure. The crust beneath the granulites and the western Dharwar Craton has a layered structure and a gradational Moho. Also, the lower crust of these terranes is relatively more mafic (Vs ~3.85-4.15 km/s) compared with those of the eastern Dharwar where Vs is ~3.7 km/s.

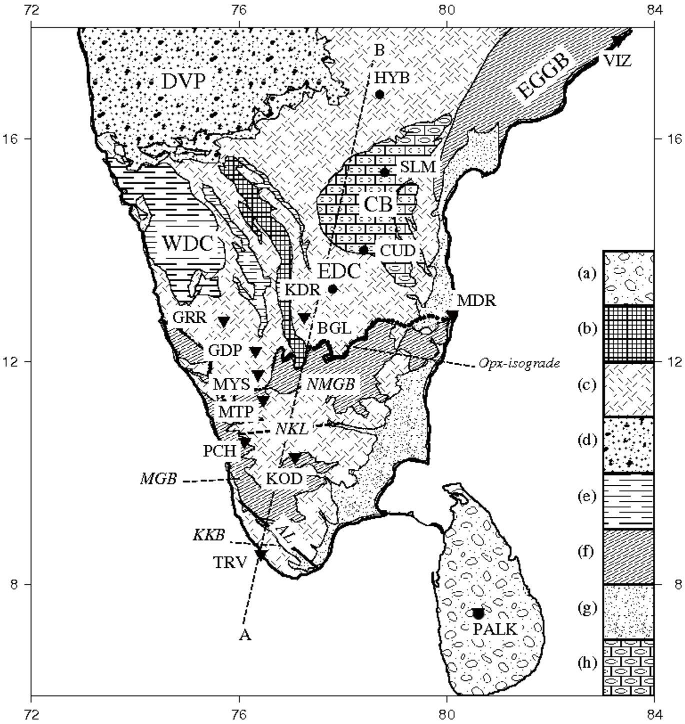
In view of the overall gentle relief of the south Indian shield with seismic characteristics of a classical Archaean craton in the eastern Dharwar, the thicker and seismically less transparent crust of the western Dharwar and the granulites require major geochemical reordering of the underlying lithospheres brought about by subsequent magmatic activity. This study is aimed at providing some depth-differentiated seismic constraints to help formulate tenable models of crust formation in the southern granulites of Indian shield.

**Citation:** Rai, A., Rai, S., Gaur, V., Priestley, K. 2009. Seismic Characteristics of the South Indian Granulite Crust . In: (Eds.) Talat Ahmad, Francis Hirsch, and Punya Charusiri, *Journal of the Virtual Explorer*, volume **32**, paper 2, doi: 10.3809/jvirtex.2009.00252

## Introduction

Despite considerable advances in our overall understanding of the continental crust, uncertainties concerning the structure, composition and rheology of the deep crust remain unsettled, making it currently difficult to adequately address questions concerning the evolution of the exhumed mid- to lower crust high-grade granulite terranes. It is therefore felt that better constrained knowledge of their depth sections may provide clues to the nature of the lower continental crust and provide credible constrains on the overall composition of their crusts. Several such terranes of exhumed mid- to lower crustal rocks ranging from Archaean to Pan-African in age are found exposed in various parts of the world: Sri Lanka, Adirondacks (United States), Ivrea Zone (Italy), Kapuskasing (Canada), Namaqualand (South Africa), the Napier Complex (Antarctica) and Lofoten (Norway) (Heier, 1973). These high-grade terranes are ideal geological locations for modeling the structure and composition of the deep crust and for reconstructing past geodynamic and magmatic processes through exploration of their fossil imprints in the metamorphic, geochemical, seismic and tectonic characteristics of the crust (Rudnick and Fountain, 1995). The south Indian shield is an amalgamation of cratons and intervening mobile belts assembled between the Archaean and the Proterozoic, together with large tracts of high-grade granulitic terranes, believed to be of lower crust origin (Fig. 1). The shield is comprised of a variety of metamorphic rocks, covered at its margins by thin veneers of Phanerozoic sediments, and in the northwest by the extensive plume-related Deccan Volcanic (DVP) flood basalts erupted along the western rift margin at the end of Cretaceous. The metamorphic terranes range from the low-grade granite-greenstones (~3.4 Ga) of the Dharwar Craton that grade southward into the ~2.5 Ga high-grade granulites and charnockites and further south, across the Noyil-Kaveri boundary, to the Pan-African granulites, and the khondalites of meta-sedimentary origin (Naqvi and Rogers, 1987; Raith *et al.*, 1997).

**Figure 1. Simplified geological map of the south-Indian shield.**



Location of seismic stations whose data were analyzed in this study is shown by inverted triangles; other stations are shown by circles. Important geological terrains include: (a) Sri Lanka granulite terrane, (b) Closepet granite, (c) Peninsular gneiss, (d) Deccan Volcanic Province (DVP), (e) Western Dharwar schists, (f) Granulites/Charnockites (g) Gondwana Sediments, (h) Proterozoic sediments of Cuddapah Basin (CB). (EDC and WDC: Eastern and Western Dharwar Cratons respectively; NMGB: Nilgiri Madras Granulite Belt; MGB: Madurai Granulite Belt; KKB: Kerala Khondalite Belt; AL: Achankovil lineament)

The eastern margin of the Dharwar Craton is fringed by a narrow belt of granulites that forms the eastern passive continental margin of the Indian Peninsula. Together, these high-grade terranes of the Indian shield, covering an area of ~40,000 km$^2$, constitute one of the three largest Precambrian granulite provinces of the world, the other two being Ashuanipi of Canada (90,000 km$^2$) and the wheat belt of Australia (60,000 km$^2$) (Wilson, 1978, Gopalakrishna *et al.* 1986, Percival *et al.* 1992, Newton *et al.* 1998).

On the basis of their geochronological, petrological and mineralogical characteristics, Indian granulites have been grouped into four major blocks: the Nilgiri-Madras Granulite Belt (NMGB), the Eastern Ghat Granulite Belt (EGGB), the Madurai Granulite Belt (MGB), and the

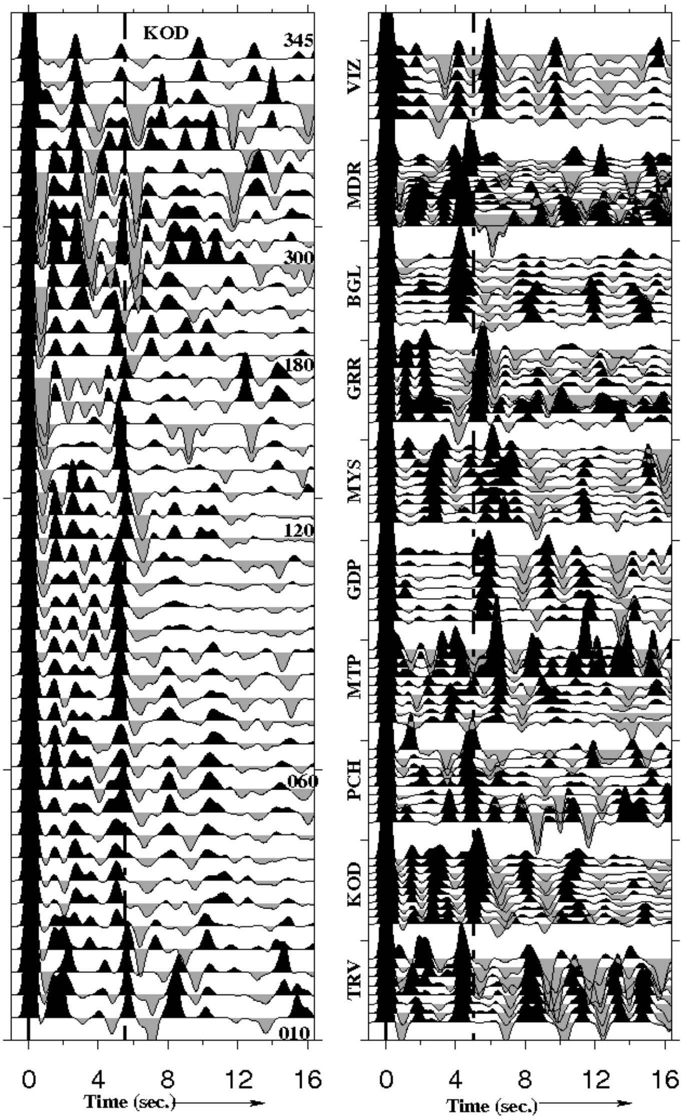
Kerala Khondalite Belt (KKB). The Nilgiri-Madras Granulite belt stretches southward of the lower grade Dharwar granite-gneiss terrane, from which it is separated by a diffused orthopyroxene isograde. The Nilgiri-Madras granulites are dissected by the well-mapped Moyar and Bhavani shear zones, and in the western sector they rise to elevations up to 2300m. forming the Nilgiri Hills. South of the Noyil-Kaveri boundary which in the west marks a remarkable gap in the continuity of elevated coastal tracts of the Western Ghats, lie the Madurai Granulite Belt (MGB) and the Kerala Khondalites Belt (KKB) which are divided by the NW-SE striking Achankovil lineament. Highland massifs of granulite/charnockite formations are major features of the Madurai belt as are the occurrences of sapphirine-bearing granulite lenses, indicating ultra-high-temperature metamorphism (Raith *et al.* 1997). The Eastern Ghat Granulite Belt (EGGB) forms the eastern coast of India. It has all the characteristics of a mobile belt: a linear feature stretching for over 900 km that suffered granulite-facies metamorphism throughout its length and breadth and a prolonged history of mountain building spanning most of the Proterozoic. All these high grade granulite terranes yield late Archaean-early Proterozoic ages for their protoliths and, except for the NMGB and KKB, were extensively reworked by the Neo-Proterozoic Pan-African thermal event (~650 Ma) which affected the then contiguous terranes of southern Gondwanaland from eastern Antarctica through Sri Lanka, southern India, and Madagascar to the Mozambique belt of east Africa and as far north as Arabia.

Because of their intriguing tectonic setting, the two major terranes of the Indian shield, the low grade Archaean Dharwars and the adjoining granulites have been the focus of several scientific investigations. Crustal characteristics of the various segments of the Archean Dharwar Craton have been rather well constrained from receiver functions analysis (Gaur and Priestley, 1997, Rai *et al.* 2003, Sarkar *et al.* 2003, Rai *et al.* 2008), and deep seismic sounding studies (Sarkar *et al.* 2001). These investigations reveal a homogeneous, almost seismically transparent ~35 km thick crust beneath the eastern Dharwar Craton, but a thicker, more complex crust beneath the western Dharwar Craton. Recently a number of geophysical studies have been made over a 200 km long N-S profile in the northern part of the southern granulite terrain. These include reflection seismology (Rao *et al.* 2006, Prasad *et al.* 2006), gravity (Singh *et al.* 2006) and magneto-telluric (Harinarayana *et al.* 2003). These studies reveal thickening of the crust to ~44 km as well as presence of significant features in the deep crust. However, these investigations do not provide any constraint on the details of the subsurface seismic velocity structures of the granulite crust. Models of their genesis and petrology, therefore, still remain largely conjectural. This paper presents a detailed study of the seismic characteristics (crustal thickness, shear-wave structure, and Vp/Vs value) of the south Indian granulite crusts and compares these results with those of the Archean Dharwar Craton to elucidate possible mechanisms that lead to granulitization, and have sustained the long-standing stability of these granulite terranes through Phanerozoic tectonism.

## Data and Methodology

Seismograms recorded at ten sites located on the four south Indian granulite terranes and neighboring Archean Dharwar craton were analyzed to determine the crustal shear-wave structure of these exhumed high-grade terranes (Fig. 1). These seismographs were installed and operated by the National Geophysical Research Institute, the Indian Institute of Astrophysics, the India Meteorological Department, Andhra University and the University of Cambridge, UK. The Visakhapatnam (VIZ) seismic station was located on the Eastern Ghat Granulites, Kodaikanal (KOD) on the highland massif of Madurai Granulites, Trivandrum (TRV) on Kerala Khondalites, Mettuppalayam (MTP) and Madras (MDR) on the Nilgiri-Madras Granulites and Pichi (PCH) close to the Noyil-Kaveri boundary that separates it from the Madurai block. Three additional sites at Mysore (MYS), Gundulpet (GDP) and Gorur (GRR) were located north of the orthopyroxene isograde that separates the granulites from the granite-greenstone terranes of western Dharwars, although dominant rock types in the vicinity of MYS and GDP are of high-grade amphibolites/granulite facies. Between them, these seismograph stations cover most of the major blocks of the Indian shield granulites and thus provide an opportunity to make a comparative study of their crustal cross-sections.

**Figure 2. Receiver Functions**



Receiver functions for KOD, plotted as a function of azimuth (left panel). Moho converted Ps phase can be identified at ~5.15±0.02 s. RFs' for other stations are shown on right panel.

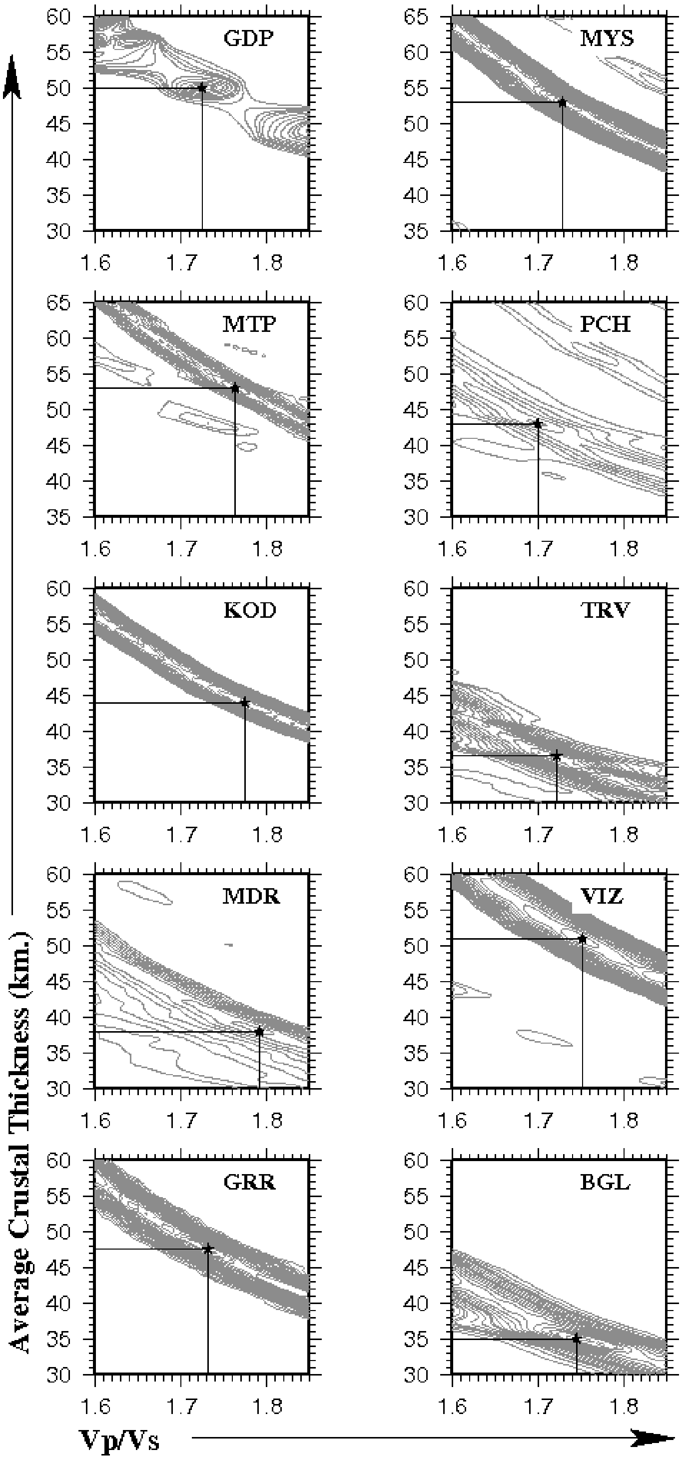
## *Receiver Functions, Crustal Thickness and Vp/Vs value*

Determination of crustal structure beneath a single seismic station using receiver functions is now a well-established seismological technique. We used the P-wave receiver function technique (Langston, 1979, Ammon, 1991) to extract the P-to-S converted phases generated at various sub-surface seismic discontinuities. In the present study, we use time-domain iterative deconvolution technique developed by Liggoria and Ammon (1999) to extract the Ps converted phases. This method, recognizing that the radial seismogram is a convolution of the vertical component with the earth structure, proceeds to extract the impulse function by designing a time series which when convolved with the vertical component, would approximate the horizontal component. This is accomplished by a least-squares minimization of the difference between the observed horizontal seismogram and a predicted signal generated by the convolution of an iteratively updated spike train with the vertical. This procedure renders the resulting receiver functions relatively free from any deconvolution-induced noise such as those observed in the water-level deconvolution technique.

Receiver functions were calculated for all high signal-to-noise ratio seismograms of events with magnitudes greater than 5.5 lying within the epicentral distance range of ~30° and 90°, after ascertaining that they were free from polarization anomalies (Kanasewich, 1975, Jurkevics, 1988). We low-pass filtered these receiver functions by smoothing with a Gaussian of 3.5, thereby eliminating frequencies greater than ~1.7 Hz. Fig. 2 shows the radial component of receiver function for all the seismic stations.

We used the H-σ stacking procedure to determine the thickness (H) and the average Vp/Vs value of the crust beneath the seismograph site (Zandt *et al.* 1995, Zhu and Kanamori, 2000). In this technique, the weighted sum of the receiver function phases (Ps, PpPms and PpSms + PsPms), stack to a maximum for the correct combination of H and Vp/Vs value.

**Figure 3. Vp/Vs value versus crustal thickness**



Vp/Vs value versus crustal thickness for stations of the southern Indian shield.

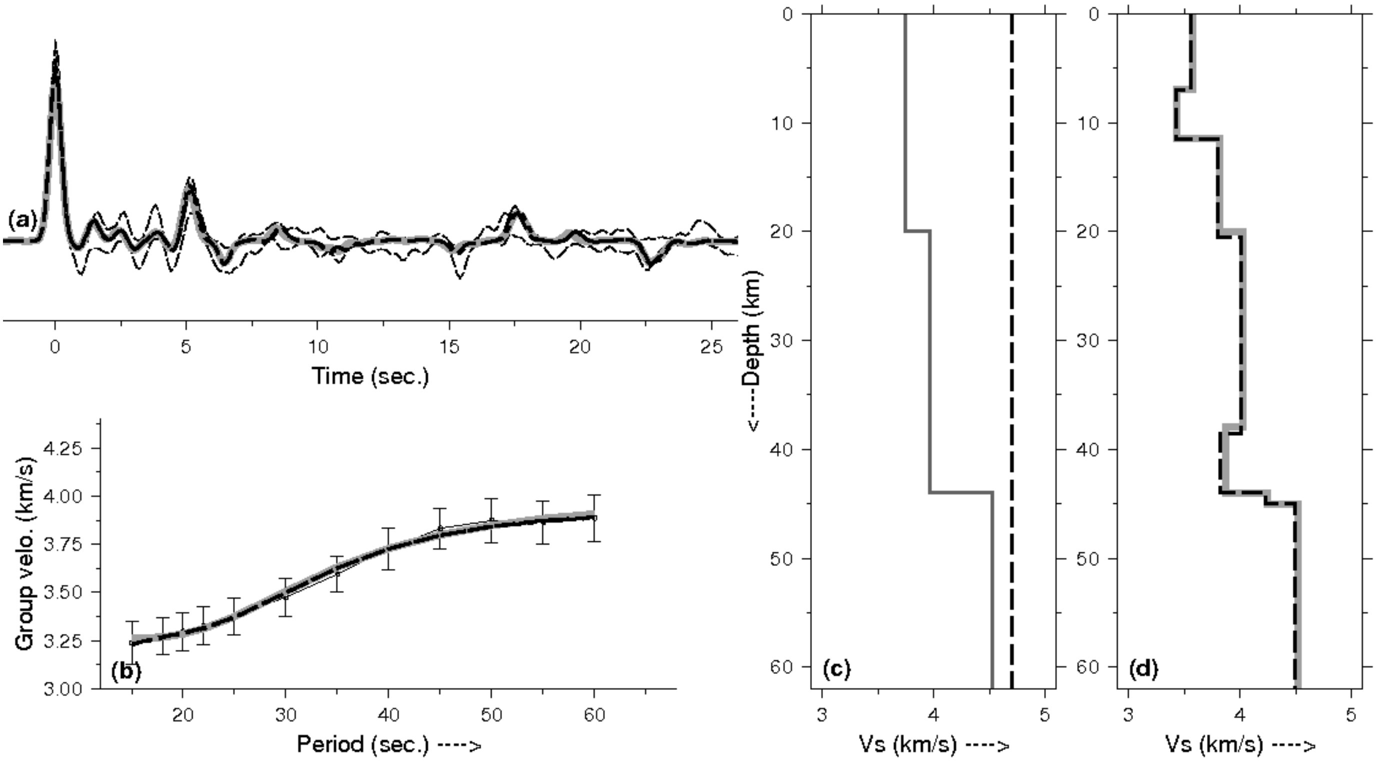
The Vp/Vs and the crustal thickness thus determined provide a first-order estimate of the Moho depth beneath a seismic station, and the petrological character of the crust in term of its Vp/Vs value (or Poisson's ratio) (Christensen 1996). Fig. 3. show the crustal thickness and Vp/Vs value thus determined for each of the seismic station.

### *Crustal Shear-wave Structure*

Receiver functions are more sensitive to the impedance contrast across an interface than the absolute shear-wave speed of the layers. Therefore, analysis and interpretation of converted phases alone suffer from a trade-off between the layer thickness and the average S-wave velocity (Ammon *et al.* 1990). Surface wave dispersion data, on the other hand, are more sensitive to average shear wave velocity at various depth ranges than to their gradients. Joint inverse modeling of both receiver function and surface-wave dispersion data, thus constrain models of the earth structure more tightly than either of these data analyzed separately. Therefore, we inverted P-wave receiver functions jointly with surface wave group velocity data (Julia *et al.* 2000, Hermann, 2004). The method expresses the least squares problem in terms of eigenvalues and eigenvectors extracted by using Singular Value decomposition to estimate a crustal model parameterized by shear wave velocity in a crust consisting of a stack of thin layers.

The analysis also yields the respective covariance and resolution matrices to evaluate the quality of the solution. Surface wave dispersion data were taken from (Mitra *et al.* 2006).

**Figure 4. Crustal shear-wave velocity structure at KOD**



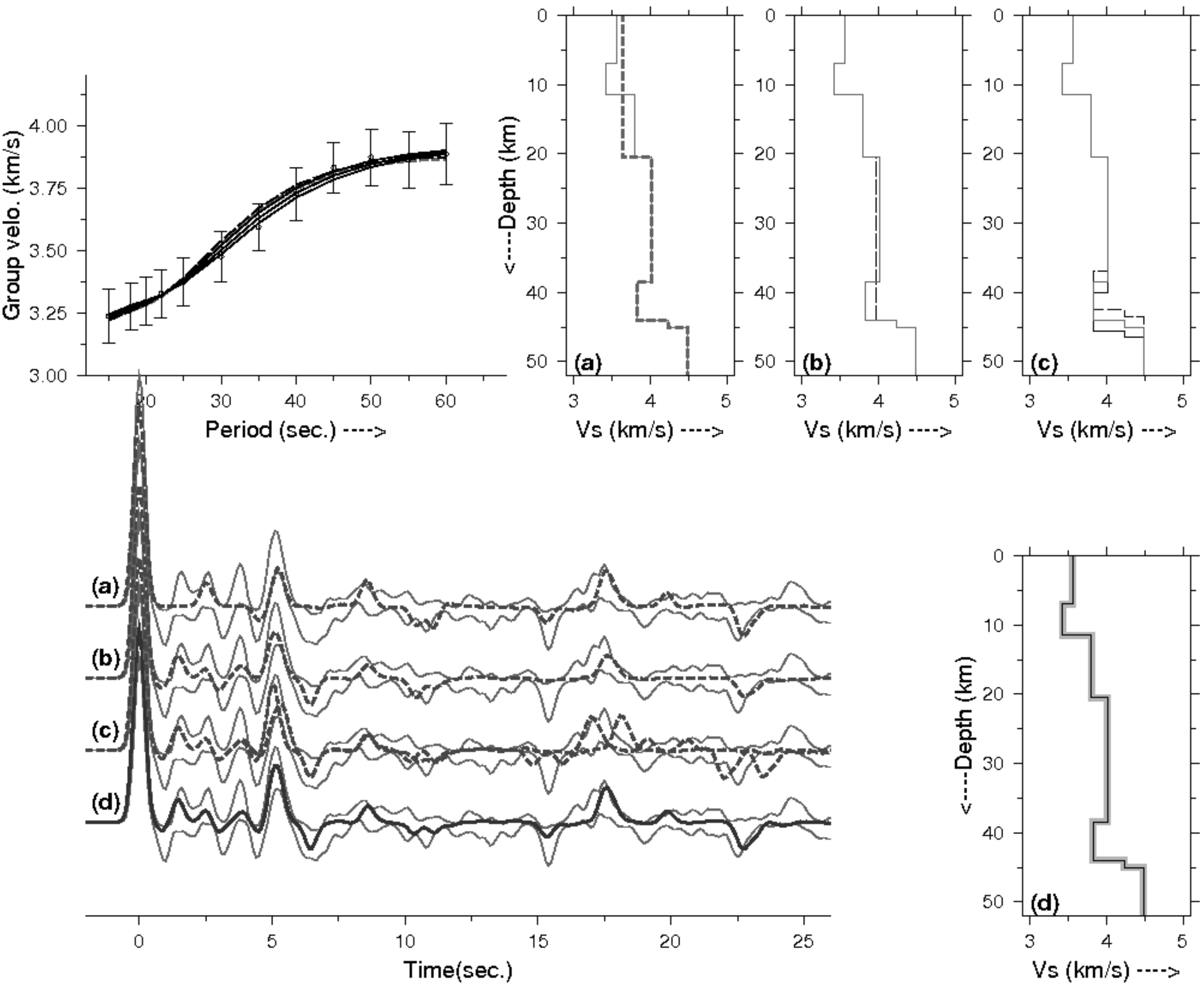
Crustal shear-wave velocity structure at KOD derived by jointly inverting the stacked radial receiver function (a) and surface-wave data (b). Two starting models (a half-space model with shear-wave velocity of 4.7 km/s. and a two-layer model) selected for inversions are shown in (c). The final inverted crustal models are shown in (d) along with observed and synthetic receiver function and surface-wave group velocity (a,b).

To enhance the signal-to-noise ratio, receiver functions for events lying in small bins of 5° x 5° back-azimuth and epicentral distance were stacked and their ±1σ standard deviation bounds calculated. The input velocity model chosen for initiating the inversion process was a stack of 1.0 to 1.5 km thick layers with half-space velocity of 4.7km/s (Fig. 4c). A homogeneous half-apace model introduces minimum *a priori* information in the inversion process and reduces the possibility of bias creeping into the inverted models. The shear-wave velocity model evolves freely from the half-space model, minimizing the misfit of the two data sets to an optimum level, and exploring the whole range of model space. In the next step of the inversion process, layers with closely similar shear-wave velocity were clubbed together to evolve the next, more simplified, starting model for inversion. This was iteratively repeated till a satisfactory solution was attained that simultaneously provided an optimally good fit to both the receiver function as well as the surface-wave dispersion data (Fig 4a,b).

To examine the dependence of final model on starting model, we inverted the data with another model developed by forward modeling of the primary phases of receiver function and surface-wave data (Fig. 4c, two-layer model, gray line). However, we do not see significant change in the final shear-wave velocity model obtained by joint inversion, starting with these two different models (Fig. 4d). Finally, we also tested the main features of the model obtained by inversion through forward modeling of the receiver function and surface-wave dispersion data (Fig. 5).

The upper and lower crustal layers were smoothed (Fig. 5a,b), depths of the Moho discontinuity was shifted up and down (Fig. 5c), and their effect was observed on the final fit. Minor features which do not significantly distort the fit were removed, and only those were retained which were necessary for an optimum fit between the data and synthetics. The final velocity model thus obtained for KOD (Fig. 5d) can be described as a two-layer crust consisting of an upper layer of 20 km thickness and an average Vs=3.59 km/s, underlain by a 23.5 km thick lower crust with Vs=3.99 km/s. Additionally, the KOD data requires a Moho at 43.5 km and a lower velocity layer in the upper crust (7-11.5 km, Vs=3.39 km/s.) for an optimal fit of the synthetics to the observed RFs'. These are the most robust features of the velocity image beneath KOD. Seismic structure of other granulite stations is described in the following section.

**Figure 5. Test results for significance of main crustal features**

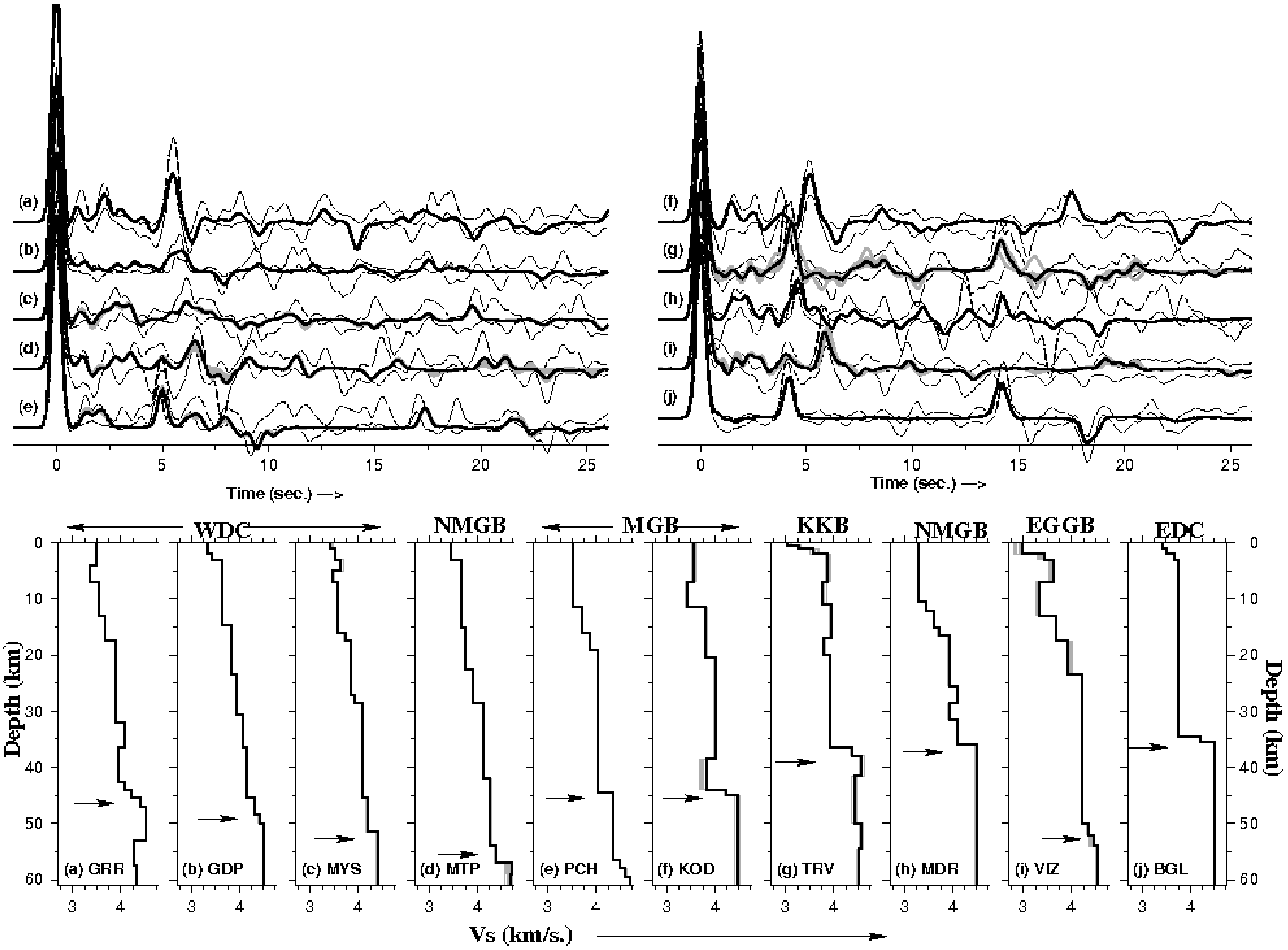


(a) smoothing upper crustal features, (b) smoothing lower crustal features, and (c) moving the moho up or down by 1.5 km. Smoothing degrades the fit of synthetics and real data as shown in corresponding figures. For exp. changing the moho depth, disturbs the fits of phases at 17.5 and 22.5 s., (d) final shear-wave velocity structure.

### *The Granulite Terranes of the Indian Shield*

Seismic characteristics (crustal thickness, Vp/Vs value and subsurface shear-wave velocity structure) of the crust beneath other stations located on the south Indian high-grade terranes were determined in the same fashion as described above for KOD. Receiver functions for all sites are plotted in Fig. 2. Receiver functions for the granulite (TRV, KOD, PCH, MTP, MDR, VIZ) and western Dharwar (GDP, MYS, GRR) stations are complex compared to those observed for the eastern Dharwar Craton (BGL) included here for comparison. Most of the radial receiver functions, particularly those from TRV, KOD, MTP, MYS, GRR, and VIZ, show significantly coherent intra-crustal P-to-S converted phases arriving between the direct P- and the Moho-converted Ps phase, indicating a multi-layered seismic structure. Vp/Vs values and crustal thickness for each of these stations were determined using the method described earlier for KOD, and these are summarized in Figures 3, 7 and Table 1. These results indicate a substantially thicker crust (~8 km) beneath the western Dharwar and the granulite terranes than those observed for Archean eastern Dharwar Craton (Rai *et al.* 2003). Some of the granulite terrane stations like KOD, MDR, MTP show relatively higher Poisson's ratio (Vp/Vs greater than 1.75) indicating a more mafic lower crust underneath (Rudnick and Fountain, 1995, Chevrot and van-der Hilst, 2000). A more mafic lower crust has also been inferred from fluid inclusion studies which are well documented in the geological literature of granulites (Friend and Nutman, 1992, Bartlett *et al.* 1995, Mohan *et al.* 1996, Bhattacharya & Sen, 1996, Ray *et al.* 2003). Exceptions to this general observation are a thinner crust at MDR (~38 km) on the eastern edge of the Nilgiri Granulites, and TRV (~36.5 km) located on KKB and relatively lower Vp/Vs (~1.70) at PCH.

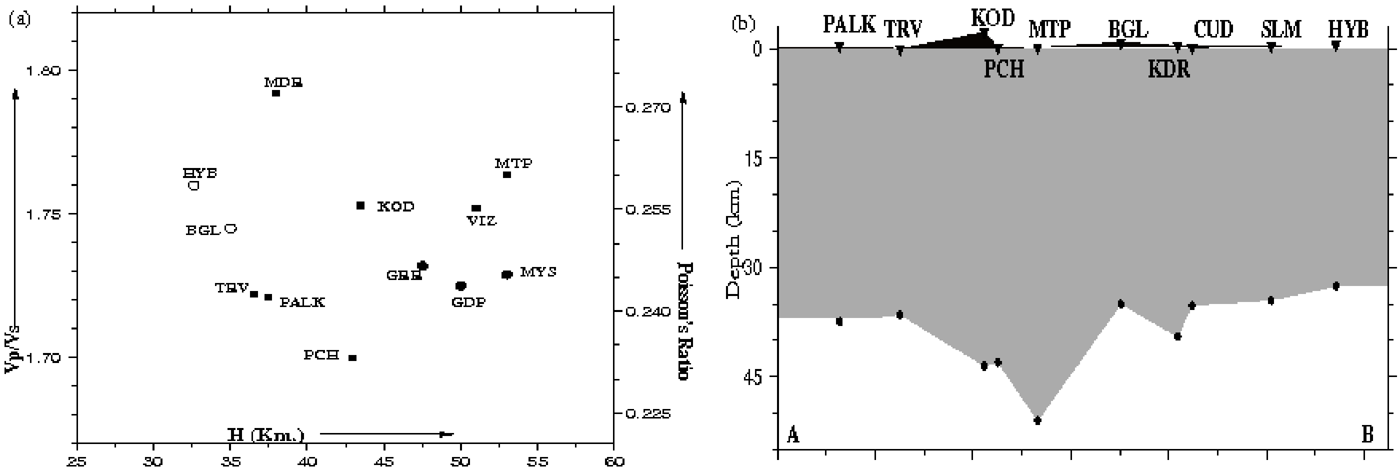
**Figure 6. Seismic velocity structure**



Seismic velocity structure beneath various stations, located on different terranes of the Indian shield. Dashed lines in receiver function plots denote the ±1σ bounds of the stacked receiver functions; solid lines denote the synthetic receiver functions corresponding to shear-wave velocity structure shown at the bottom.

High quality radial receiver functions for these stations from narrow bins of back-azimuths and epicentral distance ranges were stacked to enhance the signal-to-noise ratio and inverted jointly with the respective surface wave data as was done for KOD. The inversion results summarized in Fig. 6 show that the internal structure of the crust of the western Dharwar Craton and of the Granulite terranes is more complex compared to that of the eastern Dharwar, and has a transitional Moho in contrast to the rather sharp Moho beneath the eastern Dharwar. Moreover, the western Dharwar crust is substantially thicker than the eastern Dharwar crust and increases in both complexity and depth southward as one approaches the highly diffused granite-granulite boundary (GDP, MYS in Fig. 6 b,c) and crosses into the adjoining Nilgiri Granulites (MTP in Fig. 6d). Further south, the PCH crust (Fig. 6e), generally considered to be a part of the Nilgiri Granulites, also has a multi-layered structure with a gradational upper crust and a relatively sharp Moho similar to that of KOD (Fig. 6f) in the Madurai Granulites, crustal thickness is also same (~43km). However, it has a lower Vp/Vs value (~1.70) requiring a higher fraction of felsic components possibly created by stacking of two upper crusts. The two remaining granulite sites, TRV and VIZ, lie respectively on the south-western Khondalite (meta-sedimentary granulites) terrane, and the Eastern Ghat Granulites. TRV (Fig. 6g) shows a relatively thinner crust (36.5 km), and Vp/Vs value of 1.72, typical of granulites (Rudnick & Fountain, 1995). In contrast to this, VIZ (Fig. 6i) has a substantially thicker crust (~51 km) like the western Dharwar, a complicated upper crust and a gradational transition to mantle velocities. It is interesting to compare the nature of the lower crust in the western Dharwar and the granulite terranes with the eastern Dharwar. The average lower crust Vs in Eastern Dharwar (station: BGL) is ~3.70 km/s. In contrast, the lower crust Vs at all other stations vary between 3.85-4.15 km/s suggestive of relatively more mafic composition. The upper crust (up to 15 km depth) average velocity for the Western Dharwar and Granulite terrain stations is ~3.65±0.1 km/s.

**Figure 7. Crustal Thickness**



(a) Crustal thickness versus Vp/Vs (Poisson's ratio) beneath various seismic stations in the south Indian shield. Stations on eastern Dharwar (HYB, BGL) are shown by open circles, those on Western Dharwar (GRR, GDP and MYS) are shown by filled circles and Granulite terrane stations are shown by filled squares (some of the values is taken from Gupta *et al.* 2003 and Rai *et al.* 2009). (b) Variation of crustal thickness along traverse AB (Fig. 1).

**Table 1. Broad-band station locations and crustal parameters derived in this study**

| Station | Location | Lat. (Deg.) | Long. (Deg.) | Elev. (m.) | H (Km.) | Vp/Vs |
|---|---|---|---|---|---|---|
| TRV | Kerala Khondalites | 8.51 | 76.96 | 10 | 36.5±0.9 | 1.722±0.017 |
| KOD | Madurai Granulites | 10.23 | 77.46 | 2258 | 43.5±0.7 | 1.753±0.015 |
| PCH | Nilgiri Granulites | 10.51 | 76.35 | 142 | 43.0±2.0 | 1.700±0.016 |
| MTP | Northern Granulites | 11.32 | 76.94 | 227 | 53.0±1.1 | 1.764±0.030 |
| MYS | Northern Granulites | 12.31 | 76.62 | 698 | 53.0±2.4 | 1.729±0.030 |
| MDR | Nilgiri-Madras Granulites | 13.07 | 80.25 | 10 | 38.0±1.1 | 1.792±0.041 |
| VIZ | Eastern Ghat Granulites | 17.72 | 83.33 | 3 | 51.0±2.5 | 1.752±0.040 |
| BGL | Eastern Dharwar Craton | 13.02 | 77.57 | 843 | 35.0±1.3 | 1.745±0.020 |
| GDP | Western Dharwar Craton | 11.79 | 76.65 | 761 | 50.0±0.4 | 1.725±0.011 |
| GRR | Western Dharwar Craton | 12.82 | 76.06 | 792 | 47.5±0.8 | 1.732±0.010 |

## Discussion

Seismic characteristics of the crust of four high-grade granulite terranes of the south Indian shield: the Eastern Ghat, the Nilgiri-Madras, the Madurai, and the Kerala Khondalite belts (KKB) have been determined by jointly inverting the receiver functions and surface-wave dispersion data and compared with the structure of the Eastern and Western Dharwars. Converting the P-wave receiver functions in the H-σ domain show that the crusts beneath the Eastern Ghat, the western Nilgiri-Madras, and the Madurai belts are generally thicker by ~8 km compared with that of the Archaean crust in the eastern Dharwar Craton, even though the shield has gentle topography with a maximum relief of ~850 meters. Variations in the crustal thickness along traverse AB (Fig. 1) plotted with respect to elevation (Fig. 7b), show that the lower crust beneath the western Dharwar Craton, the western NMGB, and the EGGB, are not topographically compensated and must therefore, be denser and more mafic. This is further substantiated by the presence of higher shear wave velocity (3.85-4.15 km/s) beneath lower crust of western Dharwar and granulite terranes in contrast with the ~3.7 km/s shear wave speed beneath the eastern Dharwar. The crust beneath two of the coastal sites, TRV in the KKB and MDR the eastern NMGB, are thinner (36.5 and 38 km) compared with the crust beneath the coastal site VIZ (51 km) which lies north of MDR in the EGGB. Our analysis shows that the crust of the granulite terranes is not as seismically transparent as those of the eastern Dharwar Craton, as determined in earlier studies (Rai *et al.* 2003). In particular, the inverted models at these sites, require the incorporation of a shear wave velocity boundary at a depth of 20±2km, with a low shear wave velocity layer in the middle and upper crusts for of KOD, and VIZ. These low-velocity features at upper to mid-crustal depths could have been resulted from the influx of $CO_2$ rich incipient fluids trapped at these depths, as noted in various studies in granulite terranes (Touret, 1995, Bolder-Schrijver *et al.* 2000; Santosh & Tsunogne, 2003, Friend and Nutman, 1992, Mohan *et al.* 1996).

Retrograde metamorphism of granulites to amphibolite and greenschist facies, due to deep seated thrusting and lateral shearing during a transpressive regime (Tenczer *et al.* 2005), can also reduce seismic velocities at upper crustal depths. This indicates possibly, that an extensive crustal reworking has taken place during the upliftment and exhumation of the lower crust in these areas of the "stable" south Indian shield.

Comparison of the seismic characteristics of the south Indian granulite crust with those of the Archaean Dharwar crust, shows that while the granulites share significant similarities with the western Dharwars, notably their larger thickness that are distinctly different from the ~35 km-thick, seismically-transparent Archaean crust of the eastern Dharwar. Furthermore, both the granulite and western Dharwar crusts possess significant intra-crustal features and have higher shear velocities (3.85-4.15 km/s) in their lower crust, representing a more mafic average crustal composition. While these characteristics are understandable for the granulite crust, they are rather surprising for the western Dharwar, believed to have been stabilized by the end of the Archaean. Apparently, this stabilization was predated by significant magmatic invasion notwithstanding the inferred refractory nature of the base of Archaean crusts.

These observations when viewed in the geological perspective of the area, particularly the Pan-African affected transitional region from PCH to as far north as MTP which lies on the southern fringe of the Nilgiri massif apparently uplifted against a north dipping fault at ~650 Ma, can be reconciled by visualizing a soft continental welding of two distinctly different geological realms, brought about by the counter under-thrusting of the intervening Nilgiri block by both the Dharwars and the Madurai-Kerala block, which in the process sheared and uplifted the sandwiched terrane on their leading edges. This process, if it did take place, must have been more intense in the west than in the east along the supposed northern boundary of the Pan-African imprinted Madurai block, to explain the apparently less affected Madras crust.

## Acknowledgments

AKR thanks Cambridge Commonwealth Trust for providing a scholarship to study at the University of Cambridge where this work formed a portion of his Ph.D. research. VKG thanks the Directors of IIA and C-MMACS for providing infrastructure support and the University of Cambridge for travel support. The authors thank Bob Hermann for providing computer programs used in this study and James Jackson for his valuable comments which greatly improved the text. All the figures were made with Generic Mapping Tools. The field program was supported by a Deep Continental Studies project of the Dept. of Science & Technology, N. Delhi.

## References

Ammon, C. J., 1991, The isolation of receiver effects from teleseismic P waveforms, B. Seismol. Soc. Am., 81, 2504-2510.

Ammon, C. J., Randall, G. E., & Zandt, G., 1990, On the non-uniqueness of receiver function inversions, J. Geophys. Res., 95, 15,303--15,318. 10.1029/JB095iB10p15303

Bartlett, J., Harris, N., Hawkesworth, C., & Santosh, M., 1995, New isotope constraints on the crustal evolution of Southern India and Pan-African granulite metamorphism, in India and Antarctica during the Precambrian, pp. 391-397, Memoir of Geological Society of India.

Bhattacharya, S. & Sen, S., 1996, Pressure, temperature and fluid regimes in selected granulite tracts of the Eastern Ghats, India, Extended Abstract, Seminar on "Composition and Evolution of high grade gneiss terrains" Kandy.

Bolder-Schrijver, L. J. A., Kriegsman, L. M., & Touret, J. L. R., 2000, Primary carbonate CO2 inclusions in sapphirine-bearing granulites from Central Sri-Lanka, Journal of Metamorphic Geology,18, 259-269. 10.1046/j.1525-1314.2000.00254.x

Chevrot, S. & van-der Hilst, R., 2000, The Poisson ratio of the Australian crust: Geological and Geophysical implications, Earth Planet. Sc.Lett., 1-2, 121-132. 10.1016/S0012-821X(00)00264-8

Christensen, M., 1996, Poisson"s ratio and crustal seismology, J. Geophys. Res., 101, 3139-3156. 10.1029/95JB03446

Friend, C. & Nutman, A., 1992, Response of zircon u-pb isotopes and whole rock geochemistry to CO2 fluid induced granulite facies metamorphism, Kabbaldurga, Karnataka, South India, Contrib. Mineral. Petrol., pp. 299-310. 10.1007/BF00311193

Gaur, V. & Priestley, K., 1997, Shear wave velocity structure beneath the Archaean granites around Hyderabad, inferred from receiver function analysis, Proc. Indian Acad. Sci., Earth Planet Sci., 106, 1-8.

Gopalakrishna, D., Hansen, E., Janardhan, S., & Newton, R., 1986, The southern high-grade margin of the Dharwar craton, Journal of Geology, 94, 247-260. 10.1086/629026

Gupta, S., Rai, S., Prakasham, K., Srinagesh, D., Bansal, B., Chadha, R., Priestley, K., & Gaur, V., 2003, The nature of South Indian crust: Implications for Precambrian crustal evolution, Geophy. Res. Lett.

Harinarayana, T., Naganjaneyulu, K., & Patro, B., 2003, Detection of a collision zone in south Indian shield from magnetotelluric studies, Gondwana Res., 10 (1-2), 48-56. 10.1016/j.gr.2005.12.006

Heier, K., 1973, Geochemistry of granulite facies rocks and problems of their origin, Geophys. J. R. Astr. Soc., 273, 429-442.

Hermann, R., 2004, Computer Programs in Seismology, vol.-VI, USA. Juli`a, J., Ammon, C., Herrmann, R., & Correig, A., 2000, Joint inversion of receiver function and surface wave dispersion observations, Geophys. J. Int.,143, 99-112.

Jurkevics, A., 1988, Polarization analysis of three-component array data, B. Seismol. Soc. Am., 78, 1725-1743.

Kanasewich, E.-R., 1975, Time sequence Analysis in Geophysics, The University of Alberta Press.

Langston, C., 1979, Structure under Mt. Ranier, Washington, inferred from teleseismic body waves, J. Geophys. Res., 84, 4749-4762. 10.1029/JB084iB09p04749

Ligorria, J. P. & Ammon, C. J., 1999, Iterative Deconvolution and Receiver-Function Estimation, B. Seismol. Soc. Am., 89,1395-1400.

Mitra, S., Priestley, K., Gaur, V., Rai, S., & Haines, J., 2006, Variation of rayleigh wave group velocity dispersion and seismic heterogeneity of the Indian crust and uppermost mantle, Geophys. J. Int., 164, 88-98. 10.1111/j.1365-246X.2005.02837.x

Mohan, A., Prakash, D., & Motoyoshi, Y., 1996, Decompressional p-t history in sapphirine-beasing granulites from Kodaikanal, southern India, Journal of South Asian Earth Sciences, 14, 231-243. 10.1016/S0743-9547(96)00061-X

Mohan, A., Prakash, D., & Sachan, H. K., 1996, Fluid inclusions in charnockites from Kodaikanal massif South India: P-T record and implications for crustal uplift history, Mineralogy and Petrology, 57, 167-184. 10.1007/BF01162357

Naqvi, S. M. & Rogers, J. J. W., 1987, Precambrian Geology of India, Oxford monographs on Geology and Geophysics.

Newton, R., Aranovich, L., Hansen, E., & Vacdenheuvel, B., 1998, Hypersaline fluids in Precambrian deep-crustal metamorphism, Precambrian Research, 91, 41-63. 10.1016/S0301-9268(98)00038-2

Percival, J., Mortensen, J., Stern, R., Card, K., & Begin, N., 1992, Giant granulite terrains of northeastern Superior Province: The Ashuanipi complex and Minto block, Canadian Journal of Earth Sciences, 29, 2287-2308.

Prasad, B., Behera, L., & Rao, P., 2006, A tomographic image of the upper crustal structure using P and s-wave seismic refraction data in the southern granulite terrain, India, Geophy. Res. Lett., 33, 10.1029/2006GL026307.

Rai, A., Rai, S., & Gaur, V., 2008, Crustal stress patterns: Analysis of Ps splitting for seismic anisotropy, Current Science, 94, 7, 911-915.

Rai, A., Gaur, V. K., Rai, S.S. and Priestley, K. 2009. Seismic signatures of the Pan-African orogeny: implications for southern Indian high-grade terranes. 176, 518-528.

Rai, S., Priestley, K., Suryaprakasam, K., Srinagesh, D., Gaur, V., & Du, Z., 2003, Crustal shear velocity structure of the south Indian shield, J. Geophys. Res, 108, 2088-2099. 10.1029/2002JB001776

Raith, M., Karmakar, S., & Brown, M., 1997, Ultra-high-temperature metamorphism and multi-stage decompressional of saphirrine granulites from the Palni-Hill ranges, southern-India, Journal of Metamorphic Geology, 15, 379-399. 10.1111/j.1525-1314.1997.00027.x

Rao, V., Sain, K., Reddy, P., & Mooney, W., 2006, Crustal structure and tectonics of the southern granulite terrane, Earth Planet. Sc. Lett., 251, 90-103. 10.1016/j.epsl.2006.08.029

Ray, L., Kumar, P., Reddy, G., Roy, S., Rao, G., Srinivasan, R., & Rao, R., 2003, High mantle heat flow in a Precambrian granulite province: Evidence from southern India, J. Geophys. Res., 108.

Rudnick, R. L. and Fountain, D. M., 1995, Nature and Composition of the Continental crust: A lower crustal perspective, Rev. Geophys.,33, 3, 267-309. 10.1029/95RG01302

Santosh, M. & Tsunogne, T., 2003, Extremely High Density Pure CO2 Fluid Inclusions in a Garnet Granulite from Southern India, The Journal of Geology, 111, 1-16. 10.1086/344578

Sarkar, D., Chadrakala, K., Devi, P., Sridhar, A., Sain, K., & Reddy, K., 2001, Crustal velocity structure of western Dharwar Craton, South India, Journal of Geology, 31, 227-241.

Sarkar, D., Kumar, M., Saul, J., Kind, R., Raju, P., Chadha, R., & Shukla, A., 2003, A receiver function perspective of the Dharwar craton (India) crustal structure, Geophys. J. Int., 154, 205-211. 10.1046/j.1365-246X.2003.01970.x

Singh, A., Kumar, N., & Singh, B., 2006, Nature of the crust along kuppam-palani geotransect (south India) from gravity studies: Implications for precambrian continental collision and delamination, Gondwana Res., 10, 41-47. 10.1016/j.gr.2005.11.013

Tenczer, V., Hauzenberger, C., Fritz, H., Wallbrecher, E., Muhongo, S., Mogessie, A., Hoinkes, G., Loizenbauer, J., & Bauernhofer, A., 2005, The metomorphic evolution of the Mozambique belt in central Tanzania: new petrological and geochronological data, Geophysical Research Abstracts, 7, 03986.

Touret, J., 1995, The role and nature of fluids in the continental lower crust, in India and Antarctica during the Precambrian, edited by M. Yoshida & M. Santosh, pp. 143-160, Memoir Geological Society of India.

Wilson, A., 1978, Comparison of some of the geochemical features and tectonic setting of Archean and Proterozoic granulites with particular reference to Australia, in Archean Geochemistry, pp. 241-267.

Zandt, G., Myers, S. C., & Wallace, T. C., 1995, Crust and mantle structure across the Basin and Range-Colorado Plateau boundary at 37o N latitude and implementation for Cenozoic extensional mechanism, J. Geophys. Res., 100, 10529-10548. 10.1029/94JB03063

Zhu, L. & Kanamori, H., 2000, Moho depth variation in southern California from teleseismic receiver functions, J. Geophys. Res., 105, 2969-2980. 10.1029/1999JB900322