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Seismic structure of Sri Lanka using receiver function analysis: A comparison with other high-grade Gondwana terrains

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Abstract

Modeling of receiver functions computed using data from the IRIS broadband station PALK in Sri Lanka reveals a simple crust with a thickness of 34 km. The crust appears to be more felsic with dominance of quartzite, as evidenced by a low Poisson's ratio of 0.25 compared to the global average for Precambrian shields. An overview of crustal composition of the high-grade terrains of Gondwana land reveals that Poisson's ratios mostly lie in the range of 0.24–0.26. These lower than global average values from both Archean and Proterozoic shields, including the metamorphic regions appear to be characteristic of Precambrian shields consistent with the average continental crust composition estimates showing 59% silica content. The two principal mantle discontinuities beneath PALK are found at 418 and 678 km, respectively, which are both deeper than the global averages, suggesting a hotter upper mantle.

Keywords: Receiver functions; Poisson's ratio; Mantle transition zone

1. Introduction

The assembly and dispersal of super continents like the Gondwana has been a subject of worldwide interest. The island of Sri Lanka forms an integral part of East Gondwana assembly (India, Madagascar, Antarctica, and Australia), and is situated just off the southern tip of Indian peninsula separated by the PALK Strait. There have been suggestions that the southeastern part of India was juxtaposed with the northwestern part of Sri Lanka (Katz, 1974, 1978a,b) prior to Jurassic. However, based on the analysis of long wavelength gravity and magnetic anomalies, Agrawal and Pandey (1999) argue that India and Sri Lanka occupied a similar position with respect to each other since about 180 Ma and have traveled together after they broke away from Gondwanaland about 130 Ma ago. Moreover, based on single zircon evaporation ages and Sm–Nd isotopic systematic studies Kröner and Cordani (2003) suggest that the basement rocks of Sri Lanka do not correlate with the crustal domains in southern India or Eastern Africa. While the crustal structure of the Indian shield is now well resolved through extensive deep seismic sounding results (Reddy et al., 2003; Kaila and Krishna, 1992) and receiver function analysis (Kumar et al., 2001; Gupta et al., 2003), little or no information is available regarding the seismic structure of Sri Lanka.

Since August 2000, the University of California, San Diego is operating a permanent broadband station at Pallekele (PALK), Sri Lanka. The station is situated in the Highland Complex (HC) of central Sri Lanka, which hosts quite old rocks having Nd crustal residence ages between 2 and 3 Ga (Cooray, 1994). Inter-banded ortho and paragneisses including pelitic gneiss, metaquartzite, marble and charnockiteic gneiss are the main geological units of this area. Significant parts of the HC rocks are metasediments, probably more than half of them are of plutonic origin.

In this study, we provide estimates of the crustal thickness, Poisson's ratio and image the mantle configuration of Sri Lanka through receiver function (RF) analysis of waveforms from 140 teleseismic earthquakes recorded at the PALK station (Fig. 1). The present analysis includes (a) determination of near surface

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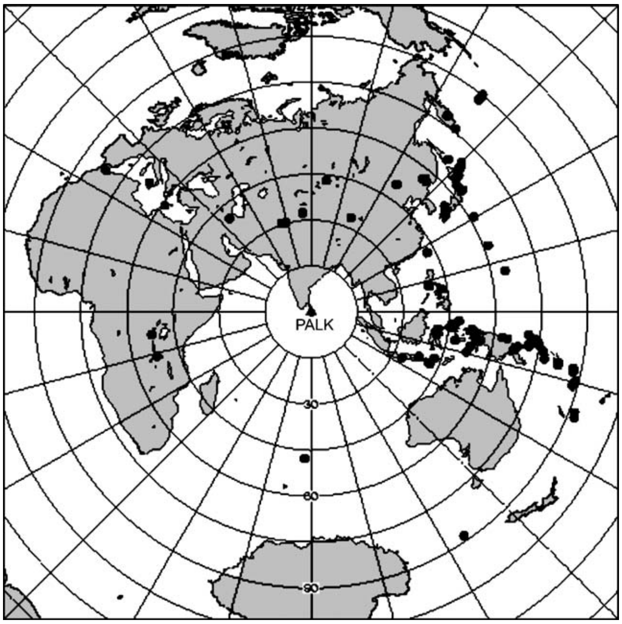

Fig. 1. Azimuthal distribution of the teleseismic earthquakes used in this study. Triangle indicates the station location and filled circles denote the hypocentral locations.

velocity and construction of receiver functions through 3-D rotation of the three component recordings, (b) estimation of Moho depth and the average Poisson ratio of the crust using a grid search approach (Zhu and Kanamori, 2000), (c) forward modeling of the RF's to obtain the shear wave velocities of the crust, (d) imaging the disposition of various velocity discontinuities in the sub-crustal lithosphere and mantle transition zone (410 km and 660 km) beneath the station.

2. Crustal structure using receiver functions

As the computation of receiver functions requires data corresponding to near vertical incidence of body waves, teleseismic events lying between 30° and 100° distance range from the station have been used. The three component data segments were extracted based on the events listed in the CMT catalogue and supplemented with complete event information. Using IASP91 (Kennett and Engdahl, 1991) tables the waveforms were cut to have a length of about 120 s data starting a little ahead of the theoretical P arrival times at the station. For each of the recorded seismograms, the signal-to-noise ratio (SNR) was computed based on the ratio of the P-coda energy and pre-P-onset noise. Only high SNR seismograms ($SNR \geq 2.5$) were subsequently used for computing the receiver functions. All traces have been rotated from the ZNE coordinate system into a ray coordinate system LQT, where, in the L, Q and T components almost pure P, SV and SH energy, respectively, is registered (Vinnik, 1977; Kind et al., 1995; Yuan et al., 1997), using a proper near surface velocity at the station. On the Q component the P energy nearly disappears, making usually the Ps converted phase from a discontinuity at a depth as the first onset. The Q components are then deconvolved with the respective L components, by simple spectral division in the frequency domain. The deconvolution involves water level stabilization and additional low pass filtering with a Gauss function, which limits the frequency band to that of the data, and suppresses high-frequency noise. These Q receiver functions are independent of the source and common path effects and are readily comparable with one another (Langston, 1977). A distance move-out correction for P to S converted phases, corresponding to IASP91 model and for a reference epicentral distance of 67° is then applied. This correction makes the travel time curves of the converted phases parallel to the P curve (Yuan et al., 1997). For a horizontally stratified medium, the converted phases from all depths with different slowness values thus align parallel to P, while the multiples are inclined.

The receiver functions for the station PALK, move-out corrected for the converted phases and averaged over narrow slowness bins shown in Fig. 2, clearly depict sharp Moho conversions (P_MS) at 4.25 s followed by distinct P and S multiples ($P_{pM}S$, $P_{sM}S$) at 15.05 and 19.8 s, with no indications for conversions from intra-crustal layers. As a first step towards quantification of the crustal structure, the Moho depth (Z_M) and average crustal Poisson's ratio (σ) are determined in Fig. 3, following the approach of Zhu and Kanamori (2000). This scheme performs a grid search over the σ–Z_M space, to determine that σ–Z_M pair, which best explains the observed Moho conversion and its P and S multiples. The clear Moho multiples have resulted in well-constrained estimates of 0.25 ± 0.01 for σ

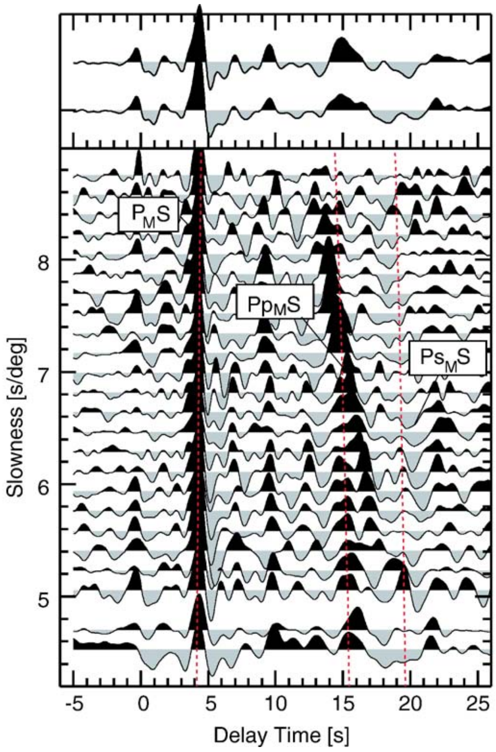

Fig. 2. Radial receiver functions (RFs) at station PALK move-out corrected for converted phases and averaged over narrow slowness bins. The bottom trace on the top panel indicates summation of these move-out corrected RFs while the top trace is a summation of the RFs move-out corrected for multiples. The Moho conversion is indicated by P_MS, while $P_{pM}S$ and $P_{sM}S$ denote its P and S multiples. Vertical dotted lines join travel times computed using the derived crustal model, as a function of slowness.

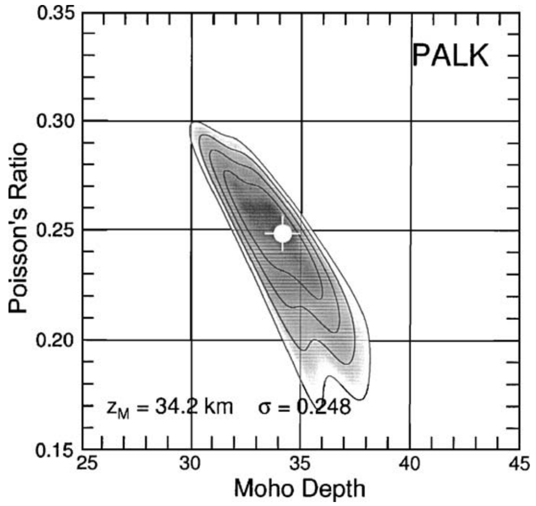

Fig. 3. Estimation of Moho depth (Z_M) and Poisson's ratio (σ) using a grid search approach.

and 34 ± 1 km for Z_M, beneath the station. While the determination of the Poisson's ratio is fairly reliable, the Moho depth estimate depends on the assumed average P-velocity of the crust (V_p). In general, a variation of 0.1 km/s in V_p alone would result in a crustal thickness variation of about 1 km. In the absence of any a priori knowledge of the crustal velocities underneath the station, we use the average obtained by forward modeling of the receiver functions (Fig. 4), which is reasonably accurate.

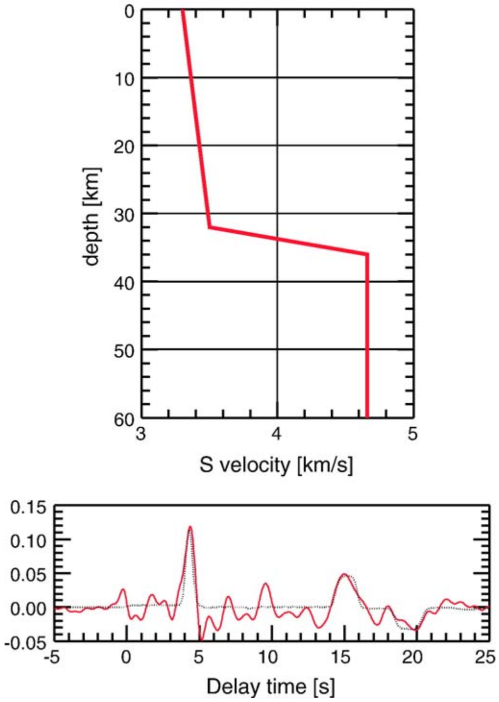

Fig. 4. Shear velocity model for PALK obtained by forward modeling of the summation trace of the receiver functions. Top panel shows the fit of the observed stack (red) and the synthetic one (black) generated by the velocity model shown. Note the presence of a sub-crustal discontinuity at 90 km. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Poisson's ratio and crustal thickness values of the high-grade terrains in Gondwana, at a glance

Country	Location	Station name	Poisson's ratio	Crustal thickness (km)	References
South India	Northern Granulites	GDP	0.24	51.0	Gupta et al., 2003
	Northern Granulites	MYS	0.26	48.0	Gupta et al., 2003
	Northern Granulites	MTP	0.28	60.0	Gupta et al., 2003
	Nilgiri Granulites	PCH	0.26	39.0	Gupta et al., 2003
	Kerala Khondalites	TRVM	0.254	35.9	Kumar et al., 2001
	Madurai Granulites	KOD	0.253	43.0	Gupta et al., 2003
	Nilgiri – Madras granulites	MDRS	0.266	38.0	Gupta et al., 2003
Antarctica	Eastern Antarctica	SYO	–	37.0	Kanao, 1997
East Africa	Mozambique Belt	KIBE	0.25	37.2	Last et al., 1979
East Africa	Tanzanian Craton	MBWE	0.25	36.0	Last et al., 1979
East Africa	Tanzanian Craton	PUGE	0.26	36.2	Last et al., 1979

Considering the high-grade metamorphic rocks in the HC, where the station is situated, Poisson's ratio of 0.25 appears to be on the lower side. However, such a low value appears reasonable in view of presence of migmatitic rocks with a mixture of metasediments dominant in quartzite, beneath station PALK. An abnormally low (0.08–0.10) Poisson's ratio of quartzite (Christensen, 1996; Christensen and Mooney, 1995) would have resulted in reduction of the observed average crustal Poisson's ratio.

Interestingly, stations located on various segments of the Southern Granulite Terrain (SGT) of the Indian shield (see Table 1) mostly show low Poisson's ratios centered on 0.25. Additionally, the Poisson's ratios from East Africa and Antarctica fall in the range 0.23–0.25 with the exception of one value exceeding 0.26. An overview of crustal composition of the high-grade terrains of Gondwana land (Table 1) reveals that Poisson's Ratios mostly lie in the range of 0.24–0.26. Recent results from the other Precambrian terrains of the Indian shield (Kumar et al., 2001) also show low uniform Poisson's ratios close to 0.25. All these lower than global average σ values from both Archean and Proterozoic shields, including the metamorphic regions seem comparable among themselves, appear to be characteristic of Precambrian shields consistent with the average continental crust composition estimates (Rudnick and Fountain, 1995) showing 59% silica content.

The stacked receiver function obtained after move-out correction for converted phases has been modeled adopting a forward modeling shown in Fig. 4 strategy, drawing constraints from the Poisson's ratio estimates, by generating synthetics using the reflectivity technique. From velocity model we find a crust of constant gradient having thickness of 34 km fits the

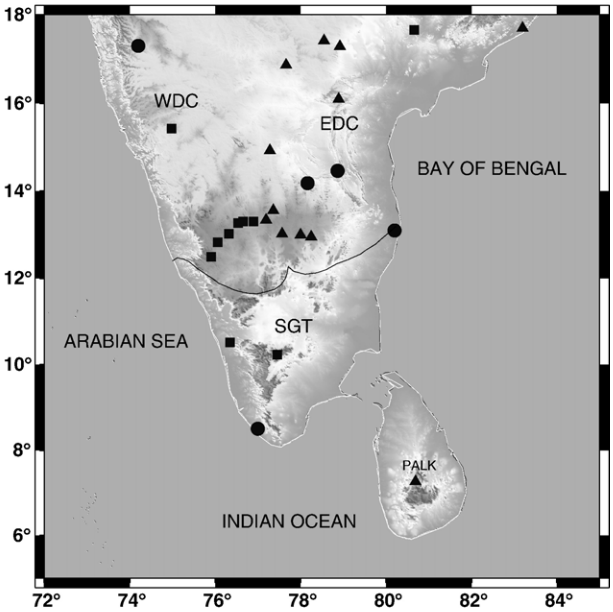

Fig. 5. Crustal thickness map of south India and Sri Lanka. SGT: Southern Granulite Terrain; WDC: Western Dharwar Craton; EDC: Eastern Dharwar Craton. (i) Triangles denote stations having Moho depth up to 35 km. (ii) Circles denote stations having Moho depth in the range 35–40 km. (iii) Squares denote stations having Moho depth more than 40 km.

observed receiver functions very well. The large amplitudes of the Moho conversion and the multiples necessitate a large velocity contrast of 1.1 km/s across the Moho. A comparison of the crustal thickness value with the estimates from the south Indian shield (Fig. 5) shows that it shares a value similar to those of the Eastern Dharwar Craton and TRVM, MDRS on the Southern Granulite Terrain. However, recent results from DSS studies (Reddy et al., 2003) report a thick crust (40–45 km) in the Southern Granulite Terrain, a moderately thick crust with a thickness of 40 km in the western Dharwar craton and comparatively thin crust (average 37 km) in the eastern Dharwar craton.

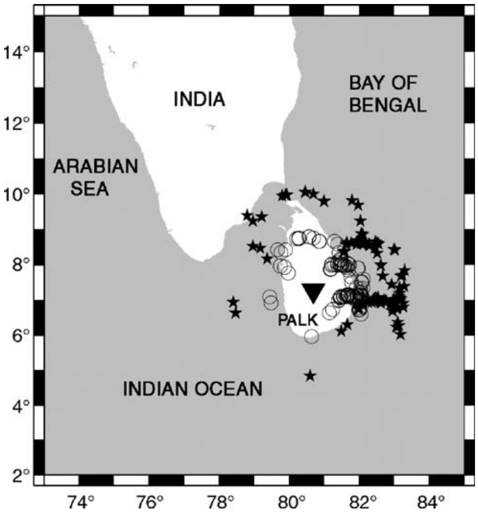

Fig. 6. Piercing points of the P-to-S converted phase at depths of 410 (open circles) and 660 km (stars) for all the events.

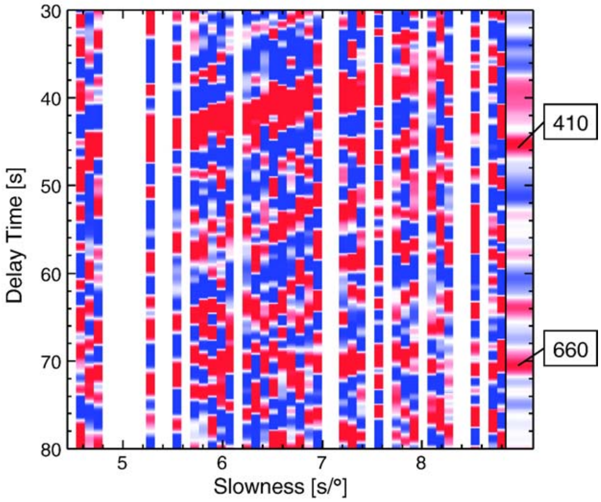

Fig. 7. Image of the radial receiver functions as a function of slowness, depicting the upper mantle discontinuities.

Interestingly, the radial receiver functions in Fig. 2 indicate a phase close to 9.5 s, which appears to have a slight inclination w.r.t the slowness axis. The amplitude of this phase seems to get enhanced when the receiver functions are stacked after a move-out correction for multiples, suggesting that it is more likely to be a multiple than a converted phase. However, a corresponding converted phase from an intra-crustal layer is not directly observable, suggesting that this feature could have been caused either by a dipping and/or anisotropic nature of the Moho. Synthetic tests with a dipping Moho alone have indicated that a phase close to 9.5 s with comparable amplitude can be generated by a Moho dip close to 10°. Inadequacy of data, particularly in the western azimuths does not permit us to unambiguously ascertain the exact causative of this phase, whether due to anisotropy or a result of dipping interfaces.

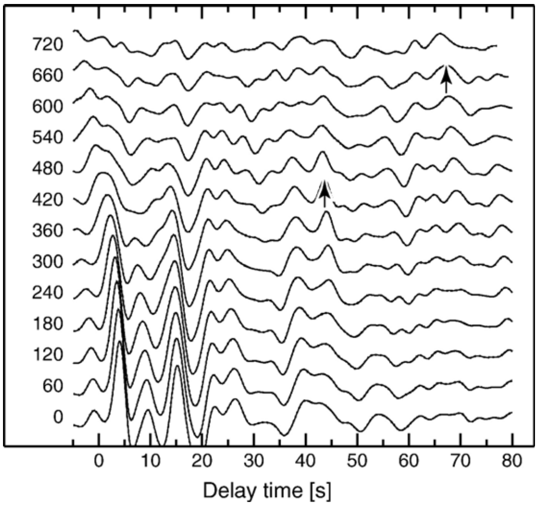

Fig. 8. Stacked radial receiver functions for station PALK. Move-out time corrections for stacking are calculated for the trial conversion depths indicated to the left. The detected converted phases from 410 and 660 km discontinuities are marked by arrows.

3. Upper mantle discontinuities

To distinctly map the upper mantle discontinuities the receiver functions have been filtered using a low Gauss value of 1 Hz. To have an idea about the region sampled by the receiver functions, the piercing points at depths of 410 and 660 km, for all the events, obtained by ray tracing using slowness of the P-wave are shown in Fig. 6. To map the spatial distribution of the mantle discontinuities, the receiver functions in the slowness range of 4.4 to 8.8 s/° are move-out corrected for converted phases and stacked into 50 bins and plotted as an image (Fig. 7). This image showing the clear conversions from the Moho and its corresponding multiples also traces the conversions from the 410 and 660 km discontinuities, close to 45 and 70 s, which are clearly evident on the summation panel to the right. However, a signal strongly inclined with respect to the slowness axis seems to interfere with the conversion from the 410 km discontinuity while the 660 km signal appears broader. To further facilitate identification of the converted phases from these discontinuities a delay and sum technique (Vinnik, 1977) has been applied to the receiver functions. In this approach, the receiver functions are stacked with move-out corrections for a range of conversion depths from 0 to 720 km. A phase that gets enhanced close to the expected arrival time from the phasing depth qualifies for a true converted phase. It can be seen from Fig. 8 that the conversion from the 410 km discontinuity is particularly well brought out at a delay time of 44.9 s. The 660 km discontinuity, although weak, has a corresponding conversion at 69.7 s. It may be noted that these times are later than those predicted by the standard earth models, which are close to 44 and 68 s, respectively, for the 410 and 660 km discontinuities. The delay times for PALK when translated into depth using the IASP91 model for an average slowness of 6.4 s/° correspond to 418 and 678 km, respectively. The deepening of both the 410 and 660 km discontinuities is suggestive of a hotter mantle beneath Sri Lanka. It is interesting to note that the disposition of the 410 and 660 km discontinuities in the south Indian shield and the Deccan Volcanic province are close to the global averages (Saul et al., 2000, Kumar and Mohan, 2005).

4. Conclusions

(1) A simple 34 km thick crust with a lower than expected Poisson's ratio (0.25) for a high-grade metamorphic terrain is delineated beneath PALK. Such a low Poisson's ratio value is shared with the adjacent SGT of India and other high-grade terrains of eastern Gondwana assembly of Africa, Antarctica, India, and Sri Lanka.

(2) The 410 and 660 km discontinuities beneath the study region are found to be deeper than the Global averages, suggestive of lowering of the upper mantle velocities indicating higher temperatures within the mantle.

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