Crustal Structure Beneath the Pallekale Seismic Station in Sri Lanka using Receiver Function Analysis

W. M. D. M. Wickramasinghe, N. G. S. Shantha Gamage

Department of Physics, Faculty of Applied Sciences, University of Sri Jayewardenepura, Nugegoda, Sri Lanka.

sng@sjp.ac.lk

1. ABSTRACT

Sri Lanka was once part of the East Gondwana supercontinent, which existed around 130 million years ago. This study explores the crustal structure, specifically the crustal thickness and Vp/Vs ratio, beneath the permanent broadband seismic station in Pallekale (PALK), Sri Lanka, using teleseismic P-wave receiver functions combines with the H-κ stacking technique to estimate crustal thickness and the Vp/Vs ratio. Findings from this study indicate a relatively simple crust beneath the PALK station, with an estimated thickness of approximately 38 km and a Vp/Vs ratio of 1.7, corresponding to a Poisson's ratio of ~0.24. Vp/Vs ratios are helpful in distinguishing crustal compositions; lower values (~1.81) typically indicate felsic rocks, while higher values (~1.87) are associated with mafic rocks. Based on this classification, Sri Lanka's crust is felsic, with a high SiO_2 content. Additionally, the crustal composition of Sri Lanka aligns closely with other regions of the Gondwana supercontinent, reinforcing the geological connection between Sri Lanka and Gondwana.

Keywords: Receiver Function, Gondwana, Sri Lanka, Crustal Structure, H-κ stacking

2. INTRODUCTION

Sri Lanka lies to the south of the Indian subcontinent and is an integral part of the East Gondwana supercontinent [1], [2]. During the Gondwana period, Sri Lanka occupied a unique position between the crustal blocks of East Africa and Antarctica, serving as a geological bridge [2],[3]. Some studies suggest that before the Jurassic period, the southeastern region of India was adjacent to the northwestern part of Sri Lanka [4],[5]. According to [6] India and Sri Lanka have shared similar relative positions since their separation from Gondwana around 180 million years ago, moving together as they drifted away.

The Gondwana fragment of Sri Lanka comprises four distinct lithological units: the Wanni Complex (WC), the Kadugannawa Complex (KC), the Highland Complex (HC), and the Vijayan Complex (VC). These units were brought together during the Pan-African collision [7],[8],[9]. Among them, the Kadugannawa Complex is the smallest and lies between the Wanni Complex and the Highland Complex [10],[11]. According to the studies, the Highland complex, which is the oldest complex, was formed under high-temperature sedimentary conditions. It is composed of metaigneous and metasedimentary granulite facies rocks [8],[11].

By the early 2000s, the crustal structure of most of Asia had been well resolved through various seismic techniques. However, there was little or no information available on the crustal structure of Sri Lanka at that time. [1] is one of the very first studies to address this gap using the technique of receiver function. Their study was based on the data from the IRIS broadband seismic station in Pallekale (PALK), Sri Lanka. This station is in the Highland Complex of central Sri Lanka [12].

Despite these initial findings, comprehensive studies on Sri Lanka's crustal thickness and seismic properties remain limited. This study aims to refine previous estimates by analyzing new seismic data collected from the Pallekale (PALK) station between 2020 and 2024. Using receiver function analysis and the H-κ stacking technique, we estimate the crustal thickness and Vp/Vs ratio, offering updated insights into Sri Lanka's deep geological structure and addressing gaps.

2. METHODOLOGY

The receiver function technique analyzes seismic wave conversions at velocity discontinuities, where P-waves partially convert into S-waves, producing Ps phases and multiple reverberations (PpPs, PpSs+PsPs) [13]. The Ps phase, delayed relative to the direct P-wave due to slower S-wave velocity, provides depth information when a velocity model is available and near-vertical ray paths are assumed [14],[15].

To compute receiver functions, data from 850 earthquakes (magnitude >5.5, 30°–90° epicentral distance) recorded at the PALK station (2020–2024) at a 40 Hz sampling rate were processed. The data were detrended, filtered using a Butterworth bandpass filter (0.05–2 Hz), and trimmed to 10 seconds before and 120 seconds after the P-wave arrival. Waveforms with signal-to-noise ratios >2.5 were rotated to radial and transverse components, and source/instrument responses were removed via deconvolution [16],[17]. Receiver functions were then computed using frequency-domain deconvolution with a water level of 0.001 and a Gauss factor of 2.5.

The choice of water-level parameter value is arbitrary. To determine the most optimal value, all the data were subjected to four different water levels: 0.001, 0.01, 0.1, and 0.5. Another important parameter in the deconvolution process is the Gauss parameter. It controls the level of detail present in the receiver function. For each water-level value, receiver functions were calculated with five different Gauss parameters ranging from 0.5 to 2.5 with 0.5 increments. The Gaussian filter acts as a low-pass filter, and the values 0.5, 1.0, 1.5, 2.0, and 2.5 correspond to approximately 0.2, 0.3, 0.7, 0.97, and 1.2 Hz corner frequencies. Based on the quality of the receiver functions, the optimal values for the Gauss values and water level were chosen through the trial-and-error method.

Crustal thickness (H) and average Vp/Vs ratio (κ) were determined using the H-κ stacking technique by optimizing the objective function S(H,κ) [15]. H and κ were varied between 20–60 km and 1.6–2.0, respectively, to find the pair maximizing S, representing the crustal thickness and Vp/Vs ratio. t_1, t_2 and t_3 are predicted Ps, PpPms and PpSms + PsPms arrival times corresponding to crustal thickness (H) and Vp/Vs ratio.

$$s(H,\kappa) = \sum_{j=1}^{N} \omega_1 r_j(t_1) + \omega_2 r_j(t_2) - \omega_3 r_j(t_3) \qquad \text{---------- (1)}$$

P is ray parameter, $rj(t\ i)$ are the receiver function amplitudes for the j-th receiver function, corresponding to depth H and Vp/Vs. $\omega1$, ω2 and ω3 are called the weighting factors of Ps, PpPs and PsPs+PpSs respectively and ω1+ ω2+ ω3=1. In this study, we used a Vp of 6.4 km/s, which is a representative average for the Sri Lankan crust based on previous seismic studies. The weighting factor of 0.3:0.5:0.2 was chosen to give the strongest emphasis on Ps phases while still maintaining the influence of the other phases for a more robust estimation of crustal parameters.

3. RESULTS AND DISCUSSION

More than 80% of events lie between back-azimuth angles in the range of 30°-120°, concentrated in the northeast-southeast direction relative to Sri Lanka. This aligns with the active plate boundaries of the Indonesian and West Pacific plates, which are well-known for frequent earthquakes [10],[18],[19]. Direct P phase arrives at zeroth second. A clear Moho converted Ps arrives at approximately 4.4 seconds followed by PpPs and PpSs+PsPs phases at ~14.8 seconds and ~20 seconds (Fig.2). Another peak is visible between the Ps and PpSs phase around 8-10 seconds. Following [1] and [10], this peak is more likely to be a multiple reflection of an intra-crustal conversion. A corresponding converted phase is not clearly visible in the stacked receiver functions. However, in some receiver functions, a small amplitude phase is visible before the Ps phase, potentially the intra-crustal conversion corresponding to the multiple reflections.

The Vp/Vs ratio serves as an indicator to differentiate between felsic and mafic crystalline rocks [20]. Based on the approximate Vp/Vs range, crustal rocks are classified into three categories: felsic, intermediate, and mafic [21]. The estimated Vp/Vs values from this study are less than 1.76, indicate a predominantly felsic crustal composition beneath the region.

Sri Lanka's crust predominantly consists of metamorphic rocks derived from sedimentary and granitic igneous rocks [10]. While progressive metamorphism generally results in higher Vp/Vs ratios [22], this study reports moderate Vp/Vs ratios for Sri Lanka's crust. These values, however, are not uncommon and are comparable to those observed in the southeastern part of Madagascar [23], the Kerala Khondalite Belt in southern India [24], and the Tanzania Craton and Mozambique Belt in Africa [25]. In addition to the Vp/Vs ratio, the crustal thicknesses obtained from this study align well with those reported for other Gondwana regions (Table 1, Fig. 3). These findings reinforce Sri Lanka's unique position within the Gondwana supercontinent.

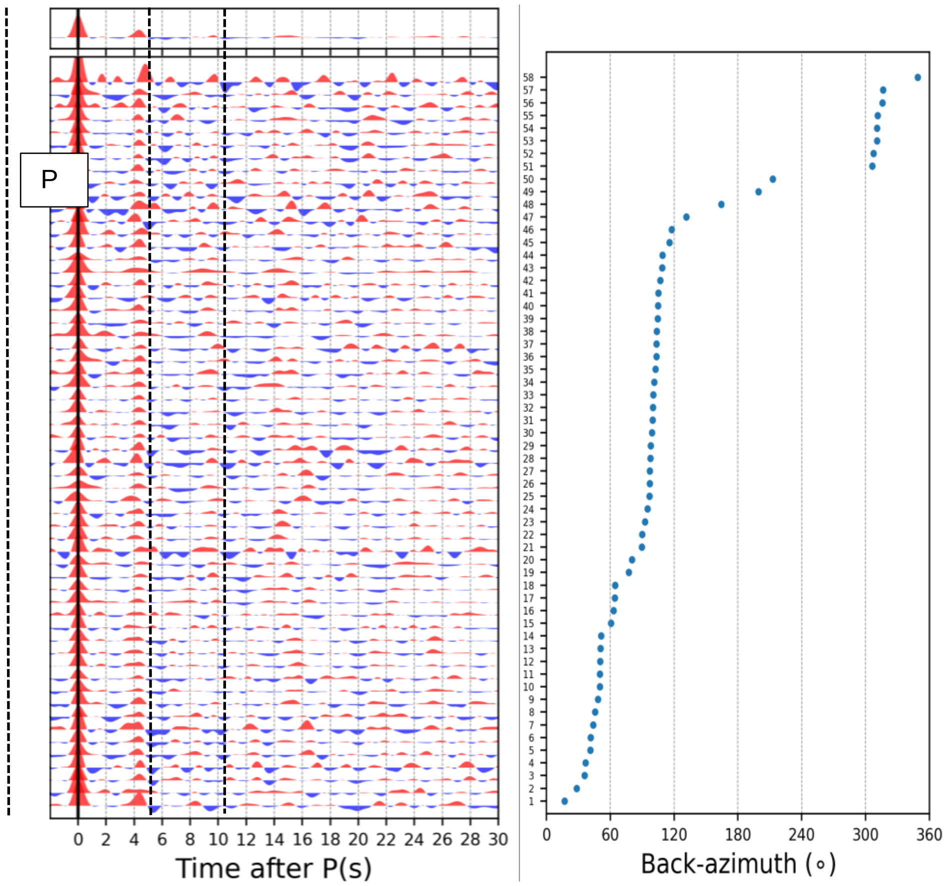

Figure 1: Radial receiver functions (left) sorted by increasing back-azimuth angle(right). The top panel(left) shows the summation of the receiver functions. Solid black line marks the P arrival. Dashed lines mark converted phases and multiples from Moho. The right panel shows the back-azimuth angle for individual earthquakes plotted in the respective left panel

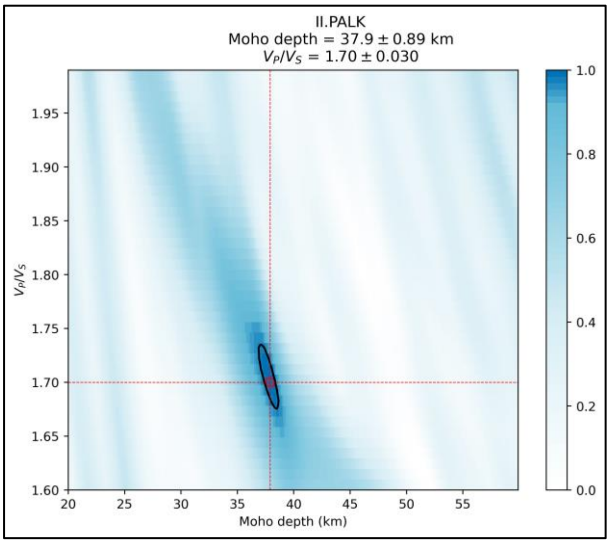

Figure 2: Estimation of Moho depth and Vp/Vs ratio and uncertainties associated with the measurements at PALK station for a Vp=6.4km/s and a weighting factor of 0.3:0.5:0.2 (w1: w2: w3).

Table 1: Comparison of Crustal Properties in Sri Lanka and Gondwana Regions

Study	Region	H(km)	Vp/Vs	Method
[2]	Anosyen-Androyen, Southern Madagascar	35	1.73	H-κ stacking
[3]	Kerala Khondalte Block, South India	33-39	1.71–1.74	H-κ stacking
[4]	Tanzania Craton, Africa	37–42	1.70–1.76	Forward modeling
[4]	Mozambique Belt, Africa	36–39	1.70–1.78	Forward modeling
Present study	Sri Lanka	37.9	1.70	H-κ stacking

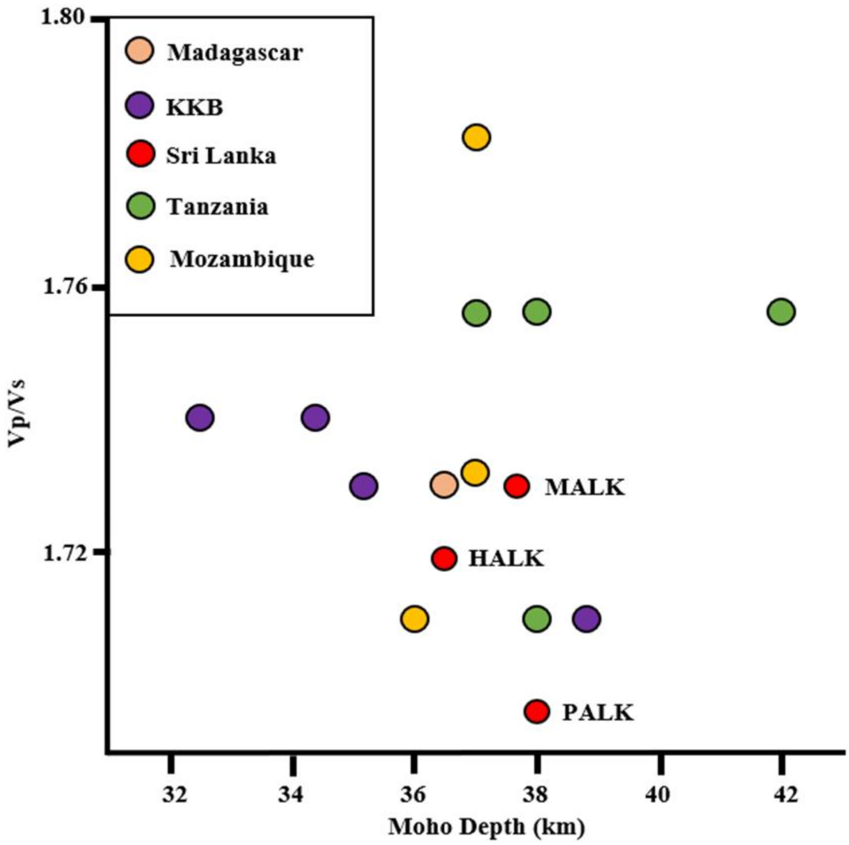

Figure 3: Comparison of Crustal Thickness and Vp/Vs Ratios. This illustration shows the crustal thickness (Moho depth) and Vp/Vs ratios estimated from the present study (Sri Lanka, red circle) Modified after:[12]

5. CONCLUSION

This study determined the crustal structure beneath the PALK seismic station using receiver function modeling, a method particularly effective in regions with limited seismic coverage. The H-κ stacking technique was employed to estimate the Moho depth and Vp/Vs ratio, offering advantages such as enhanced signal-to-noise ratio (SNR), improved detection of Ps phases and multiple reverberations, and simultaneous analysis of multiple receiver functions. From this analysis, the crustal thickness was estimated at approximately 37.9 km, and the Vp/Vs ratio at about 1.70. The low Vp/Vs ratio (<1.76) suggests a felsic crust with high silica content. These findings are consistent with studies from other Gondwana regions, such as the Kerala Khondalite Block in South India, Tanzania, and Madagascar, further supporting Sri Lanka's geological connection to the ancient Gondwana supercontinent.

6. REFERENCES

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