Investigating the Crustal Structure near the Mahakandarawa seismic station in Sri Lanka through the Receiver Function Method

W.M.D.M. Wickramasinghe[1,2], P. Thanoja[1] and N.G.S.S. Gamage[1]*

Department of Physics, University of Sri Jayewardenepura, Nugegoda, Sri Lanka[1]
Institute for Geophysical Research, University of Alberta, Canada[2]

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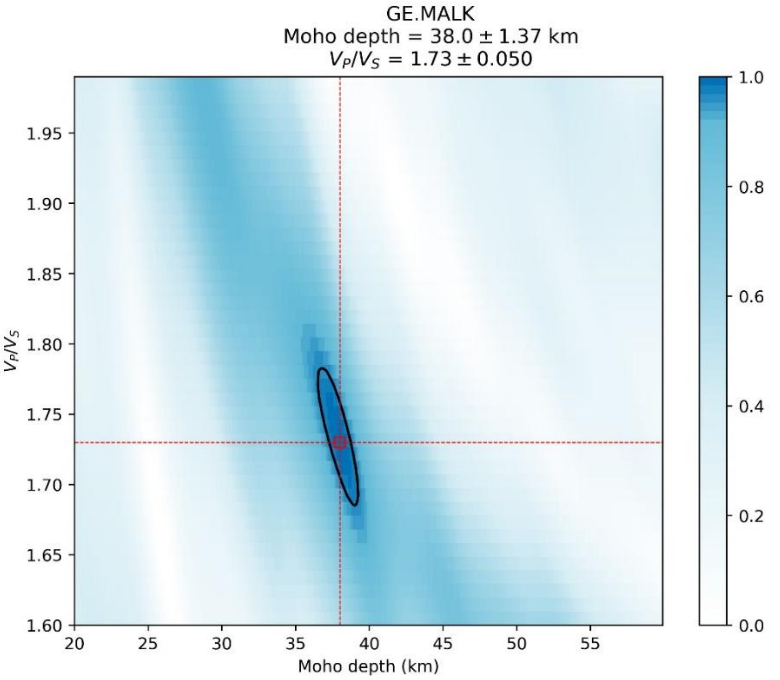

Abstract

Sri Lanka has a very ancient geological history that begins in the Precambrian, when it formed part of the Gondwana supercontinent. It was connected to India, Madagascar, Antarctica, and Africa, sharing the same crustal evolution. When Gondwana began to break apart around 180 million years ago, Sri Lanka drifted with the Indian plate to reach its present position in the Indian Ocean. The present work analyzes the subsurface structure beneath the Mahakandarawa (MALK) broadband seismic station using teleseismic P-wave conversions. A combination of converted wave analysis and H-κ stacking was applied to determine both Moho depth and the velocity ratio of compressional to shear waves. The approach indicates a crustal thickness of nearly 37.8 km with a velocity ratio of 1.73, giving a Poisson's ratio close to 0.25. Such values are typical of silica-rich, felsic material rather than mafic compositions. When compared with previous studies from neighboring Gondwanan fragments such as southern India and Madagascar, which report Moho depths of ~36–39 km and similar felsic crustal compositions, the results from MALK show strong consistency. This agreement reinforces Sri Lanka's geological affinity with East Gondwana and provides new regional constraints on its tectonic evolution, particularly regarding the preservation of ancient felsic crust across separated continental blocks.

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

**Correspondence: sng@sjp.ac.lk*

1. Introduction

Sri Lanka is a geologically ancient island, underlain predominantly by high-grade Precambrian metamorphic rocks that were formed during the assembly of the Gondwana supercontinent. These crustal materials are organized into several key lithotectonic units, namely the Highland Complex, Vijayan Complex, and Wanni Complex, each reflecting distinct metamorphic histories and tectonic settings (Dissanayake and Chandrajith, 1999; Sumanarathna, 2018). During the Jurassic period, as Gondwana began to fragment around 180–200 million years ago, Sri Lanka rifted away together with the Indian plate, drifting northward from its connections with Madagascar, Antarctica, and Africa (Kröner et al., 1987; Jokat et al., 2003).

The present lithological architecture of the island records this deep history: the granulite-grade Highland Complex represents the deeply reworked crust of central Sri Lanka, the Vijayan Complex preserves lower-grade Proterozoic crust in the east, while the Wanni Complex reflects intermediate metamorphic conditions to the west (Kehelpannala, 1997). In addition, smaller units such as the Kadugannawa Complex and Highland-Wanni transitional zones preserve evidence of shearing, magmatism, and younger intrusions that further modified the crust, highlighting Sri Lanka's role as a key fragment of Gondwana's tectonic puzzle (Cooray, 1984; Dissanayake and Chandrajith, 1999).
The MALK station, situated within the Wanni Complex, has been operated by the German Research Centre for Geosciences (GFZ) since 2010. In this study, we investigated the properties of the crust structure using the teleseismic earthquake data from MALK station. Several studies of Sri Lanka using seismic techniques have revealed that recent seismic activity has increased in offshore (Gamage, 2017) and onshore of Sri Lanka and therefore seismic techniques can be used for studying crustal structure of Sri Lanka (Gamage et al., 2018a; Gamage et al., 2019; Wickramasinghe and Gamage, 2025).

The Earth's crust forms the outermost solid shell, averaging ~35 km thick beneath continents and ~7 km beneath oceans, which is negligible compared to the planet's mean radius of ~6,371 km and contributes only a small fraction of its total volume. The crust has two distinct layers: Oceanic crust and Continental crust (Hart, 2014). Compositionally, continental crust is largely granitic whereas oceanic crust is dominantly basaltic, both exhibiting relatively low seismic velocities compared to the underlying mantle. The crust is separated from the mantle by the 'Mohorovičić discontinuity' (Moho), a boundary recognized by a sharp increase in seismic wave velocities caused by the transition from crustal rocks to denser peridotite mantle material (Dziewonski and Anderson, 1981). The Moho depth varies from ~5–10 km beneath oceans to ~30–70 km beneath continents. Beneath this boundary, the mantle shows additional velocity changes at depths near 410 km and 660 km, reflecting mineral phase transitions in olivine and related polymorphs. These seismic discontinuities, together with the Moho, provide critical constraints on the compositional and rheological layering of the Earth's interior (Ranalli and Adams, 2013). When seismic waves pass through Moho boundary, a noticeable change in their velocity can be observed due to the changes in the densities of rocks (White, 1988). This velocity change gives rise to a seismic wave conversion. The technique of receiver is implemented based on this conversion. Moho depth of offshore and onshore of Sri Lanka has been studied in several studies (Gamage, 2017; Rathnayake et al., 2017; Gamage et al., 2018a).

Receiver Function technique is one of the most impactful seismic techniques developed in the 20th century (Prodehl et al., 2013). When compared with techniques like body wave and seismic wave tomography, one of the major advantages of this technique is that it can provide valuable insights from data recorded at a single seismic station whereas most techniques like seismic tomography require a network of stations (Vinnik, 2019). This makes receiver functions exceptional and more efficient, especially in regions with limited seismic coverage.

By the early 2000s, the crustal structure of Sri Lanka was still poorly understood compared to most of Asia. Pathak et al., 2006 carried out one of the first detailed investigations at Pallekale (PALK) station, reporting a Moho discontinuity depth of 34 ± 1 km, Poisson's ratio of 0.25 ± 0.01, and mantle discontinuities at depths of 418 km and 678 km, which they interpreted as evidence for elevated mantle temperatures beneath the region. Subsequent work by Rai et al., 2009 refined these results, estimating

*Correspondence: sng@sjp.ac.lk

a Moho depth of 37.5 ± 1.0 km and a Vp/Vs ratio of 1.721 ± 0.02 at the same station. Building on these findings, Dreiling et al., 2020 employed data from a temporary seismic network across the island and mapped Moho depths ranging from 30 to 40 km, with the thickest crust beneath the central Highland Complex (38–40 km) and the thinnest along the west coast (30–35 km), while also reporting Vp/Vs ratios range from 1.60 to 1.82. More recently, Mukherjee et al., 2020 further refined the crustal model, estimating a thickness of ~38 km, shear-wave velocities of 3.7–3.8 km/s, and Vp/Vs ratios of ~1.72 for the Highland Complex and ~1.79 for the Wanni Complex, emphasizing the structural similarities of the Highland Complex with other Gondwanan fragments. Wickramasinghe and Gamage (2025) estimated the crustal structure beneath the Pallekale seismic station in Sri Lanka using receiver function analysis. They reported a crustal thickness of approximately 37.9 km and a Vp/Vs ratio of about 1.70.

In this study, we extend previous work by providing new estimates of crustal thickness and velocity ratios (Vp/Vs) for Sri Lanka using receiver function analysis and the H–κ stacking technique, based on seismic data recorded at the MALK station between 2020 and 2024.

2. Methodology

A Receiver function is a seismological technique that isolates P-to-S and S-to-P converted phases from teleseismic waveforms, providing valuable constraints on crustal thickness, seismic velocity contrasts, and lithospheric discontinuities (Langston, 1979; Ammon, 1991). The technique of receiver is based on the principle of Seismic wave conversion. When P waves pass through a sharp velocity discontinuity like Moho discontinuity, a portion of the energy undergoes a phase conversion producing P to S converted phases (Ps) and their multiple reverberations (PpPs, PpSs+PsPs) (Lay and Wallace,1995). Since the Vs is lower than Vp, the Ps phase will follow the direct P phase by a time that increases with the depth of the interface (Shearer,2019) . By approximating rays to be near vertical, a measurement of the depth of any discontinuity can be obtained using this time difference, provided the velocity model is known (Zhu and Kanamori, 2000).

To generate receiver functions, we used earthquake records collected at the MALK station between 2020 and 2024, sampled at 20 Hz. A total of 725 teleseismic events with magnitudes larger than 5.5 and epicentral distances of 30°–90° were selected for the analysis. The waveforms were first detrended and band-pass filtered with a Butterworth filter in the frequency range of 0.05–2 Hz. P-wave arrival times were calculated using the global iasp91 reference velocity model, and each trace was cut to a time window extending from 10 seconds before to 120 seconds after the P arrival. To maintain data reliability, only seismograms with a signal-to-noise ratio greater than 2.5 were retained. Finally, the horizontal components were rotated from north–south and east–west orientations into radial and transverse directions for further processing.

The seismogram is the graphical or digital record of ground motion generated by a seismograph in response to seismic waves from earthquakes or other sources. By deconvolving source response and instrument response can be effectively removed, resulting in only the structure response (Langston, 1979; Bostock, 1997). Receiver functions were computed through frequency-domain deconvolution, using a water level of 0.001 and a Gaussian filter factor of 2.0. High-quality receiver functions were then selected through careful manual inspection.

To estimate crustal structure, the H–κ stacking technique was applied. This method stacks receiver functions from teleseismic earthquakes by summing their amplitudes at the predicted arrival times of the Moho-converted Ps phase and its associated multiple phases (PpPs and PpSs+PsPs) for a range of crustal thicknesses (H) and Vp/Vs ratios. The optimal values of H and Vp/Vs are determined at the point where the stacked amplitudes of all three phases show the strongest coherence, providing robust estimates of Moho depth and the Vp/Vs ratio beneath the station (Zhu and Kanamori, 2000). This approach relies on the assumption that Moho generates the most prominent P-to-S converted phases (Ogden, 2019). The time delays between the direct P wave and the Ps, PpPs, and PpSs+PsPs phases are expressed by equations (1), (2), and (3), respectively. Based on these theoretical arrival

*Correspondence: sng@sjp.ac.lk

times, all receiver functions are stacked, and the summed amplitudes are calculated according to equation (4).

$$t_{Ps} = \frac{H}{V_p}\left(\sqrt{\frac{V_p^2}{V_s^2} - p^2V_p^2} - \sqrt{1 - p^2V_p^2}\right) \quad \text{--------- (1)}$$

$$t_{PpPs} = \frac{H}{V_p}\left(\sqrt{\frac{V_p^2}{V_s^2} - p^2V_p^2} + \sqrt{1 - p^2V_p^2}\right) \quad \text{---------- (2)}$$

$$t_{PpSs+PsPs} = \frac{2H}{V_p}\left(\sqrt{\frac{V_p^2}{V_s^2} - p^2V_p^2}\right) \quad \text{---------- (3)}$$

$$s(H,\kappa) = \sum_{j=1}^{N} \omega_1 r_j(t_1) + \omega_2 r_j(t_2) - \omega_3 r_j(t_3) \quad \text{---------- (4)}$$

Here, p denotes the ray parameter, and $r_j(t_i)$represents the receiver function amplitudes at the predicted arrival times of Ps, PpPs, and PsPs+PpSs for the *j*-th receiver function, corresponding to a crustal thickness H and Vp/Vs ratio as defined in equations (1)–(3). The third term carries a negative sign because the PsPs+PpSs phase generally exhibits a negative amplitude. N indicates the total number of receiver functions included in the analysis. The terms ω_1, $\omega_{2,}$ ω_3 denote the weighting factors assigned to Ps, PpPs, and PsPs+PpSs, respectively, with the condition that $\omega_1 + \omega_2 + \omega_3 = 1$ (Ogden, 2019). In practice, the Ps phase is usually given the highest weight since it tends to have the largest amplitude and clearest arrival. In contrast, PpPs and PsPs+PpSs typically have lower amplitudes and are therefore assigned to smaller weights. Additionally, a low weight is assigned to PsPs+PpSs due to the typically low SNR of the phase (Eaton et al., 2006). However, there is no definite value that should be assigned. The often-assigned ratios are 0.6:0.3:01, 0.5:0.3:0.2, 0.34;0.33:0.33 and 0.7:0.2:0.1 (Ogden, 2019; Mukherjee et al., 2020; Zhu and Kanamori, 2000).

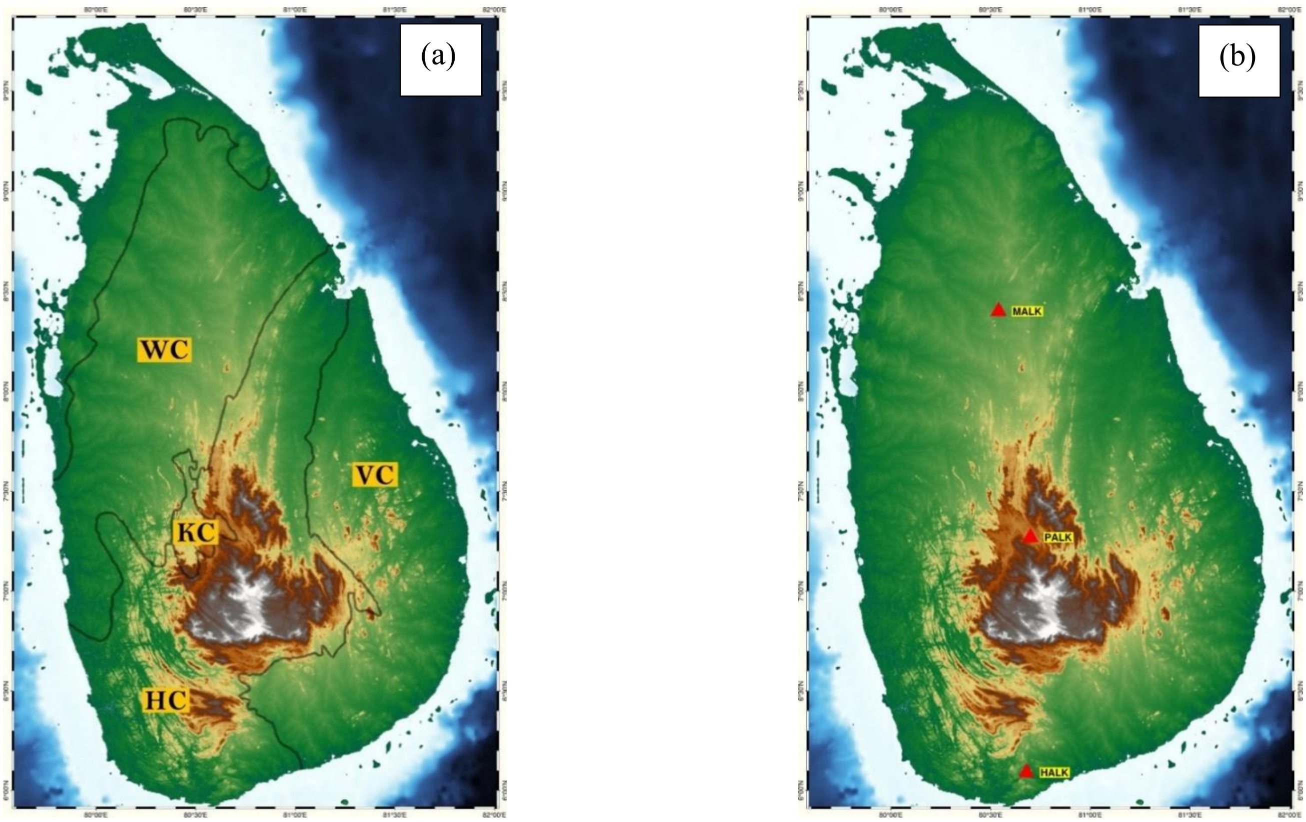

Figure 1. (a) Topographic and geological map of Sri Lanka showing major lithological units: HC:-Highland complex, VC:-Vijayan complex, WC:-Wanni complex, and KC:-Kadugannawa complex (b) Location of seismic stations MALK , PALK and HALK, marked by red triangles

*Correspondence: sng@sjp.ac.lk

Table 1. Details of the MALK seismic station, including coordinates, elevation, and network information.

Station	Station code	Network	FDSN	Latitude (°N)	Longitude (°E)	Elevation (m)
Mahakandarawa	MALK	GEOFON	GE	8.40	80.54	113

The crustal thickness (H) was tested over a range of 20–60 km with increments of 0.1 km, while the Vp/Vs ratio (κ) was varied between 1.6 and 2.0 in steps of 0.01. For each combination of H and κ, the objective function (eq(4)) was computed. Previous studies in the region have adopted different P-wave velocities (Vp), commonly using values such as 6.3 km/s, 6.4 km/s, and 6.5 km/s (Dreiling et al., 2020; Rai et al., 2009; Mukherjee et al., 2020; Pathak et al., 2006). In the present analysis, Vp was systematically evaluated across the range of 6.3–6.5 km/s in 0.1 km/s increments. In addition, several weighting factor combinations were applied to the data. Among these, the ratio 0.5:0.4:0.1 produced the most consistent results, yielding the smallest uncertainties in both Moho depth and Vp/Vs ratio estimates (Figure 2).

3. Results

3.1 Receiver Function Analysis

Receiver functions were calculated using a Gaussian parameter of 2.0, as larger values tended to introduce additional noise into the results. For the MALK station, over 85% of the events used in the receiver function analysis fall within back-azimuths of 30°–120°, primarily concentrated toward the northeast–southeast of Sri Lanka. The outcome of the analysis is presented in Fig. 2. The direct P phase appears at 0 seconds, followed by a distinct Moho-converted Ps arrival at approximately 4.7 seconds. The multiple phases, PpPs and PsPs+PpSs, arrive near 15.3 seconds and 19 seconds, respectively. The amplitude of the latter phase is relatively weak, and no prominent peak is observed.

3.2 H-κ Stacking Results

The variation of P wave velocity (Vp) by 0.2 km/s results in a variation of Moho depth by approximately 1.5 km. However, it does not have a significant effect on Vp/Vs ratio.
In the H–κ grid, the red dot represents the location of the maximum amplitude, while the black contour outlines the associated uncertainty range of the measurement (Figure 3). For different weighting factors, Moho depth and Vp/Vs ratio show similar values. However, there is a noticeable difference in the uncertainties associated with each measurement. As the weight assigned to w1 increases while weights assigned to w2 and/or w3 decrease, uncertainty values increase. It is also observable that the broadening of the black contour occurs. However, the position of the peak remains unchanged. This indicates that the estimated values of H and κ remain largely stable despite variations in the weighting factors.

**Correspondence: sng@sjp.ac.lk*

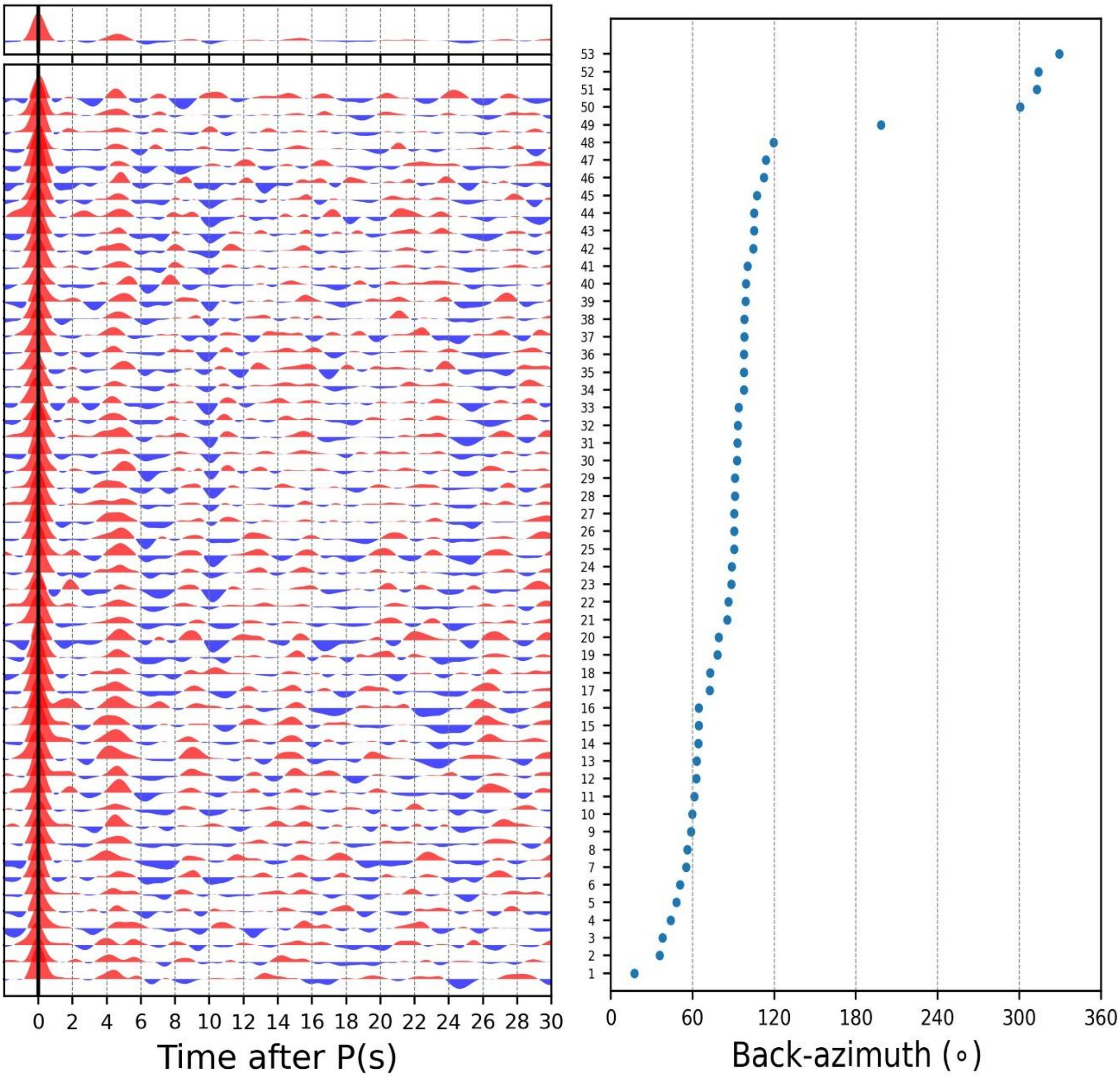

Figure 2. Radial receiver functions with a Gaussian width of 2.0 are displayed for the MALK seismic station (left), organized by increasing back-azimuth angle (right). The top-left panel presents the stacked receiver functions, where the solid black line marks the direct P arrival and the dashed lines indicate the Moho-converted and multiple phases. The right panel illustrates the back-azimuth distribution of individual earthquakes corresponding to the receiver functions shown on the left.

**Correspondence:* sng@sjp.ac.lk

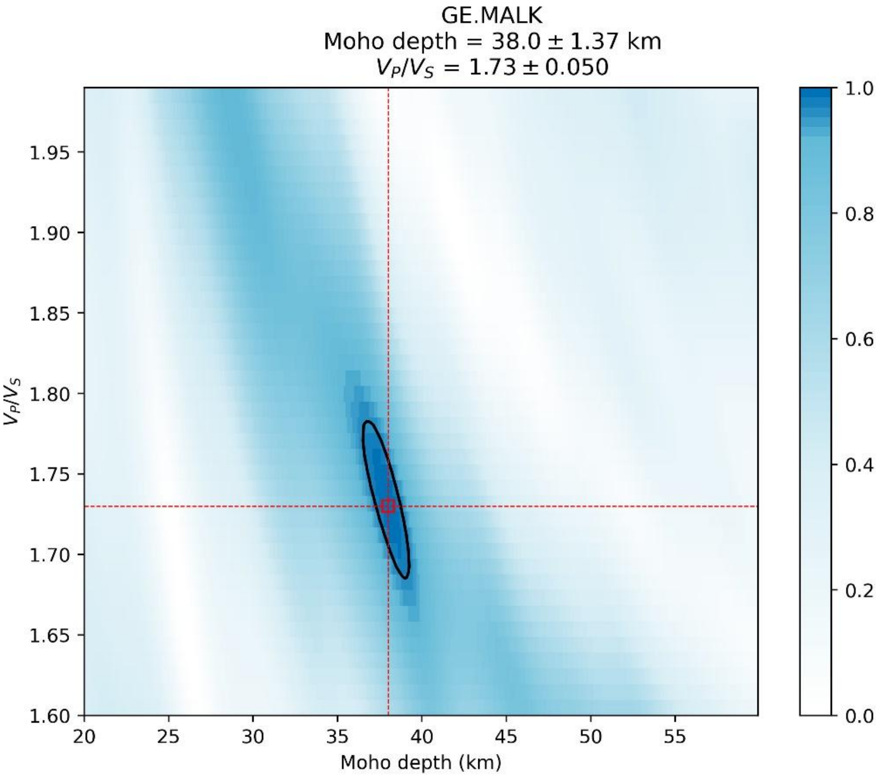

Figure 3. Moho depth and Velocity ratio(Vp/Vs) , along with their associated uncertainties, were estimated at the MALK station using a P-wave velocity of 6.3 km/s and weighting factors of 0.5:0.4:0.1 (w1:w2:w3). The color scale represents the normalized stacking amplitude (0.0–1.0) from the H–κ analysis, with darker blue indicating higher amplitudes and thus better-fitting solutions. The black contour encloses the confidence region around the best fitting solution (red cross). This combination of weights yielded the most reliable results, with the lowest measurement uncertainty.

4. Discussion

The H-κ stacking results of (Mukherjee et al., 2020) indicated a relatively shallow Moho depth of about 36.3 km and a comparatively high Vp/Vs ratio of 1.79 beneath the MALK station. In contrast, their subsequent Neighborhood Algorithm (NA) modeling produced a Moho depth of 37.5 km, which is more consistent with our estimates. Similarly, (Dreiling et al., 2020) reported a Moho depth of 37.5 ± 0.9 km and a Vp/Vs ratio of 1.74 ± 0.02 based on H-κ stacking, assuming a crustal Vp of 6.5 km/s. When applying the same Vp value, our analysis indicates a thicker crust with the Moho at approximately 38.5 km however their result also applied Bayesian inversion, yielding a Moho depth of 38.2 ± 0.7 km, which closely matches our observations, though our results carry a larger uncertainty. The velocity ratio of the p wave and s wave(Vp/Vs) is widely used as a diagnostic parameter for interpreting crustal composition. It provides a means of distinguishing between felsic (quartz-rich) and mafic (quartz-poor) lithology. According to Das et al., 2015, crustal rocks can be classified based on their Vp/Vs ratio: values below 1.76 are characteristic of felsic compositions, ratios between 1.76 and 1.81 correspond to intermediate compositions, and ratios in the range of 1.81 to 1.86 are indicative of mafic compositions. In our study, the estimated Vp/Vs values are consistently below 1.76, suggesting that the crust beneath the study area is predominantly felsic. However, a previous study by Mukherjee et al., 2020 reports a higher Vp/VS value for MALK suggesting an intermediate crust in the Wanni complex. However, in our study, we were unable to detect such high value.

*Correspondence: sng@sjp.ac.lk

Table 2. Crustal thickness (H) and Vp/Vs ratio beneath MALK: results from this study compared with earlier studies.

Study	H(km)	Vp/Vs	Vp (km/s)
(Mukherjee et al., 2020)- H-κ stacking	36.30	1.790	6.4
(Mukherjee et al., 2020)- NA modeling	37.5	1.790	6.4
(Dreiling et al., 2020)- H-κ stacking	37.5	1.74	6.5
(Dreiling et al., 2020)- Bayesian approach	38.2	1.77	6.5
Current study	38.0	1.73	6.4

Table 3. Comparative Analysis of Crustal Properties in Sri Lanka and Adjacent Gondwana Regions

Study	Region	H(km)	Vp/Vs	Method
(Andriampenomanana et al., 2017)	Anosyen-Androyen, Southern Madagascar	35	1.73	H-κ stacking
(Rai et al., 2013)	Kerala Khondalte Block, South India	33-39	1.71–1.74	H-κ stacking
(Last et al.,1997)	Tanzania Craton, Africa	37–42	1.70–1.76	Forward modeling
(Last et al.,1997)	Mozambique Belt, Africa	36–39	1.70–1.78	Forward modeling
Present study	Sri Lanka	38	1.73	H-κ stacking

Sri Lanka's crust is primarily composed of metamorphic rocks that originated from sedimentary and granitic protoliths (Dreiling et al., 2020). Although progressive metamorphism is generally associated with elevated Vp/Vs ratios (Christensen, 1996), our analysis indicates moderate values for the Sri Lankan crust. These ratios are not anomalous, as comparable measurements have been reported in other Gondwanan fragments, including southeastern Madagascar (Andriampenomanana et al., 2017), the Kerala Khond alite Belt of southern India (Rai et al., 2013) , and both the Tanzania Craton and Mozambique Belt in Africa (Last et al.,1997). Furthermore, the crustal thickness derived in this study aligns well with those of these regions (Table 3; Figure 4), reinforcing Sri Lanka's tectonic affinity within the Gondwana supercontinent.

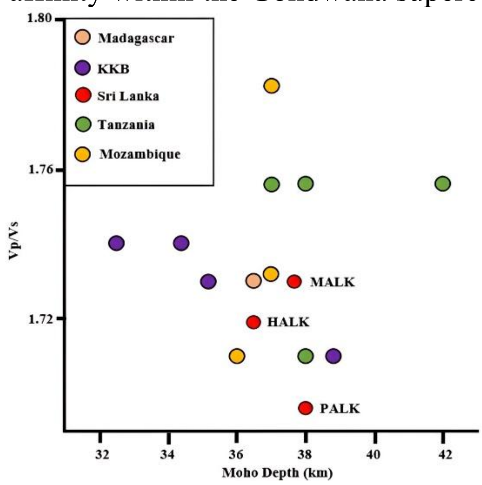

Figure 4. Crustal thickness and Vp/Vs ratio comparison. The figure presents results from this study (Sri Lanka, shown as a red circle) alongside previously reported values from Madagascar, the Kerala Khondalite Belt (KKB) of southern India, and the Tanzania–Mozambique Belt in Africa. Modified after: (Mukherjee et al., 2020)

*Correspondence: sng@sjp.ac.lk

When compared with previous studies (Mukherjee et al., 2020; Dreiling et al., 2020) provided initial constraints on crustal structure beneath the MALK station, the present study refines these estimates by incorporating updated weighting strategies and parameter assumptions, resulting in slightly greater crustal thickness and lower Vp/Vs ratios. This suggests a more felsic crustal composition than previously inferred, offering a contrasting interpretation of the Wanni Complex. By situating these findings within a broader Gondwanan framework (Table 3), our study strengthens the regional context of Sri Lanka's crustal properties and provides a more integrated comparison across adjacent continental fragments.

5. Conclusions

In this work, the crustal structure beneath the MALK seismic station was investigated using receiver function modeling. This approach is particularly effective in regions where seismic network coverage is sparse. To estimate the Moho depth and the Vp/Vs ratio, we applied the H–κ stacking technique. The method provides several benefits, including enhancement of the signal-to-noise ratio (SNR), automatic identification of the Ps phase and its multiples, and simultaneous utilization of multiple receiver functions. A limitation, however, lies in its sensitivity to the assumed P-wave velocity (Vp), which directly influences the Moho depth estimate. For example, a change of 0.2 km/s in Vp produces a variation of ~1.5 km in Moho depth, though the Vp/Vs ratio remains largely unaffected. Additionally, Weighting factors do not alter the results themselves but influence the associated uncertainties. From the combined receiver function analysis and H–κ stacking, we determine that the crust beneath Sri Lanka is about 38 km thick, with a Vp/Vs ratio of ~1.73. This relatively low ratio (<1.76) suggests a felsic composition with high silica content. These results are consistent with observations from other Gondwanan fragments, including the Kerala Khondalite Belt of southern India, Tanzania, and Madagascar, supporting Sri Lanka's geological affinity with the ancient Gondwana supercontinent.

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**Correspondence:* sng@sjp.ac.lk

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**Correspondence: sng@sjp.ac.lk*