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Crustal thickness and velocity structure of southern Peninsular Malaysia

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Abstract: The tectonic setting of Peninsular Malaysia can be described by three distinctive stratigraphic belts, known as western, central and eastern belts. These western and eastern belts which were formed during the Paleo-Tethys subduction process in the Late Paleozoic are separated by the Bentong-Raub suture zone. Although various study had already evaluated this formation process, the geological detail of the region's crust is still relatively unknown. The velocity and detail information of the Earth's crust is crucial in determining the earthquake's location and seismic hazard. The best way to acquire this information is through the receiver function method. The receiver function is computed from the tele-seismic earthquake waveform which involves P-wave, P-S wave as well as pPpS and pSpS + pPsS multiple phases recorded by a three-component seismogram. In this work, the data recorded at the two broadband seismometer stations located in Kota Tinggi, Johor and Bukit Timah, Singapore, were processed and analyzed through the receiver function methodology. Then the crustal thickness beneath the two seismometer stations were estimated through H-k stacking method before the waveform was inverted twice for the final 1-D velocity profile of the region. A total of 889 (for Kota Tinggi station) and 693 (for Bukit Timah station) tele-seismic earthquakes which occurred between 2005 and 2016, were evaluated for the crustal thickness and velocity structure analysis. From the H-k thickness analysis, the crust-mantle boundary was found at 34 km and 30 km for region beneath Kota Tinggi and Bukit Timah stations respectively. In addition, the 1-D velocity profile from the inverted waveform indicate a gradual velocity increment from Conrad boundary (around 10-12 km depth) to Moho thickness in both cases. The findings of these stations' crustal thickness are consistent with the past findings which imply that the thickness for southern Peninsular Malaysia (Johor region) and Singapore is within the 30-35 km.

Keywords: Receiver function, crustal thickness, velocity structure, Peninsular Malaysia

INTRODUCTION

Although Peninsular Malaysia is generally known to be a seismically inactive region with a low number of earthquakes occurring yearly, the importance of the seismological study in the region should not be ruled out given that the Peninsula is surrounded by active tectonic plates. The region often suffers from strong shock originating from Sumatran earthquakes. This has raised some concerns to seismologists in Malaysia, as this may explain the cluster of weak earthquakes recorded at Bukit Tinggi between 2007 and 2009. While the lack of local earthquakes is viewed as a disadvantage towards conducting local seismological studies, the abundance of distant earthquakes recorded by seismological stations in Malaysia and Singapore, is benefiting the seismological community.

The main study area in this paper is located at the southern region of Peninsular Malaysia, where the state of Johor, Malaysia and Singapore is located. Johor and Singapore are part of the Malay Peninsula, which formed the South-east Asian section of Eurasian plate, commonly known as Sundaland (Yan, 2011). Geologically, the Malay Peninsula is split into three north-south regional zones, known as the eastern belt, central belt and western belt (Figure 1). Different tectono-stratigraphic, structural evolution, magmatism and volcanism can be clearly seen between these three belts, particularly along north-south section of the Peninsular Malaysia (Metcalfe, 2013). For example, lower Paleozoic rocks cover most of the western belt while the central and eastern belts of the Malay Peninsula are usually associated with upper Paleozoic rocks. Previous studies on the central and eastern belt also reveal that they represent the fore-arc, arc and continental basement of the Sukhothai Arc, which was developed on the margin of the Indochina Block and separated from Indochina in the Permian by back-arc spreading. The western belt is separated from the central and eastern belts by the Bentong-Raub suture zone (Metcalfe, 2000).

While the region itself is seldom impacted by any major earthquake phenomenon, the permanent broadband sensors installed in Kota Tinggi, Johor and Bukit Timah, Singapore, are very useful for the passive seismic study. The Kota Tinggi station, (International Seismological Center (ISC) code: KOM), is positioned on top of a granite rock, at the location of 1.7922° N, 103.8467° E. From the geological point of view, the station is within the Dohol Formation, which commonly seen at the eastern part of Gunung Sumalayang, Johor. It is composed of shale-siltstone-fine sandstone interbedding, with thickly bedded claystone and thin bed tuffaceous sandstone (Surjono *et al*., 2004).

For a better understanding of the crustal structure of the southern region, another station located in Bukit Timah Hill (ISC code: BTDF), Singapore was included in the analysis. In the previous work based on the joint receiver function and surface wave inversion, the crustal thickness underneath Singapore was found to be between 28 km to 32 km (Macpherson *et al*., 2013), which is slightly shallower

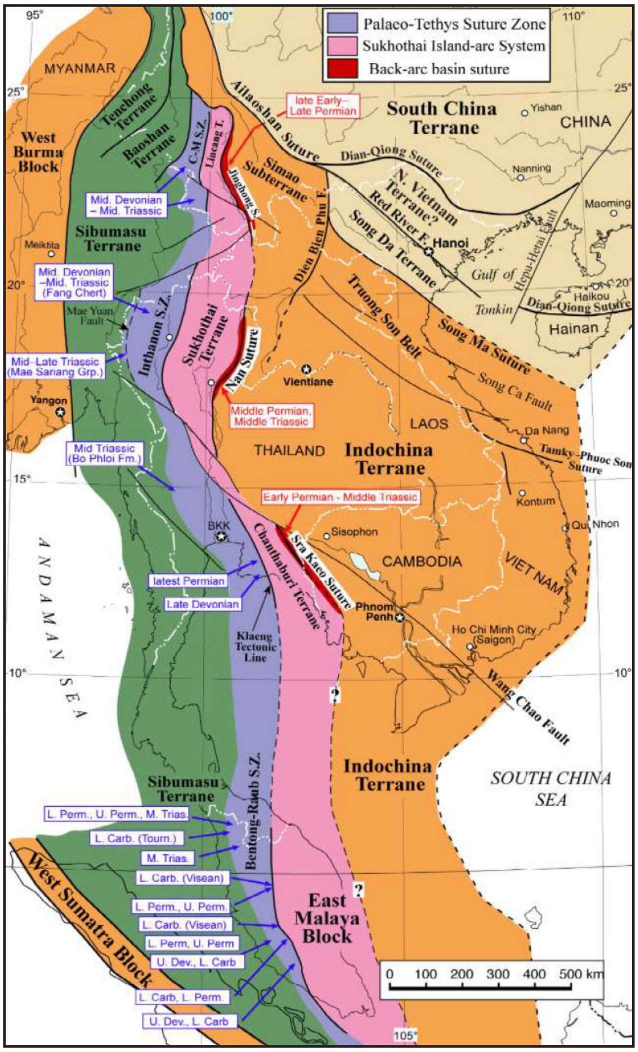

Figure 1: The geological map of Malay Peninsula showing three distinctive North-South belts (from Metcalfe, 2013).

compared to thickness found beneath the Ipoh station (ISC code: IPM) (Abdul Latiff & Khalil, 2017). The BTDF station which is located along the slope of the granite hill (66 m) with the coordinate of 1.3608° N, 103.7729° E is grouped in the Bukit Timah Granite. Generally, this area contains adamellite and granodiorite besides the granite with the variation distribution of quartz, alkali-feldspar, sodic plagioclase and ferromagnesian minerals (Woon & Yingxin, 2009). The broadband, 3-components seismometer was used in this area since 1998, with hundreds of waveforms recorded daily.

METHODOLOGY

Within the region, the geological characterization based on the surface outcrop has been studied extensively, even though the detail of the subsurface is still relatively unknown. Therefore, to obtain the earth properties and characteristic, geophysical data acquisition such as seismic refraction and reflection and potential methods has to be carried out which cost millions of dollars. This can be avoided by incorporating the receiver function method to determine the crustal thickness and velocity properties of the earth's subsurface. The general methodology of receiver function is the analysis of P-wave and P-S converted wave signal recorded at the station. To ensure the high quality and reliable subsurface properties outcome, the waveform acquired must originate from the earthquake ruptured at a distance larger than 30° and less than 100°, with the magnitude of 6.0 Mw and higher. Besides the two primary signals, the interpretation of multiple reverberations such as PpPs, PsPs and PpSs phases are also needed, for the higher details of the earth crustal properties. From the waveform recorded, the earthquake delay time difference, i.e. time taken between P-wave and P-S wave to reach the station, as well as amplitudes of direct and multiple phases, will provide the information of crustal – mantle depth discontinuity and the impedance contrast. Throughout the analysis, only 1-D structure travel time difference was taken into account and this requires the dependency of different wave phase type and slowness information.

Once interpreted, the seismograms are then rotated to the ZRT-coordinate ray system according to the back azimuth incident wave. This step is necessary to isolate the converted S-phase from the direct P-wave. Each seismogram is rotated from the vertical (Z), north-south (N-S) and east-west (E-W) components into the Z, radial (R) and tangential (T) components respectively. As a result, the Z-component points in the direction of the direct P-wave, with the R-component is propagate perpendicular to the Z-component. Meanwhile, the T component is perpendicular to both Z and R components. The Z, R and T components contain mainly P-energy, SV-energy and SH-energy, respectively.

Since only the earth reflectivity is the desirable information within the recorded seismogram, thus there is a need to remove the source and wave propagation path effect. This was conducted through the deconvolution of the R component from the Z component that can be conducted whether in time or frequency domain. The most common deconvolution method in receiver-function studies is through the frequency domain division with the addition of water level stabilization coefficient (Clayton & Wiggins, 1976). Nevertheless, due to the low signal to noise ratios of the tele-seismic earthquake data obtained, the receiver functions were computed using the time-domain iterative deconvolution technique (Ligorria & Ammon, 1999) rather than frequency domain deconvolution. In the iterative deconvolution process, the differences between the resultant convolution of the observed vertical component with a spike function, and the recorded radial component were regularly computed and updated. This method produces a comparably better noise suppression deconvolution outcome compared to frequency domain deconvolution even though the computation process is longer.

From the receiver function waveform that was produced by the deconvolution method, the H-k stacking algorithm was implemented to determine the earth crustal thickness from the interpreted phases (Zhu & Kanamori, 2000). In the H-k stacking method, the delay times of P to S conversion, PS, and the later arriving multiples crustal reverberations (multiples) such as PpPs and PpPs + PpSs were calculated for each pair of the pre-identified H (thickness) and k (V_p/V_s) range. In addition, the H-k method also requires the input of mean P-wave velocity above the discontinuity and the average horizontal slowness value. Through the initial experimentation, the suitable P-wave velocity and slowness estimation of the earth crustal thickness and its corresponding velocity ratio is 6.3 km/s and 0.06 s/degree, with the resultant outcome producing a good estimation indicator. However, it should bear in mind that the H-k stacking approach does not necessarily produce the accurate crustal thickness depth reading, due to input parameter limitation before the staking procedure taking place.

The estimated depth of crust-mantle boundary found in the H-k analysis was then used as a guide in developing the initial P-wave velocity model for the inversion procedure. The inversion process, which involves a forward modelling procedure, requires a synthetic receiver function determination based on a given earth structure model. The focus of this study, however, is not to find the receiver function, but rather to determine the earth structure that generated the receiver function. Waveform inversion is a data-fitting procedure that aims at obtaining estimates of crustal properties from the receiver function. Given an initial model of the subsurface parameters, the data are predicted by solving the wave-equation. The model is then updated through forward modeling in order to reduce the misfit between the observed and predicted data. This procedure is repeated in an iteratively manner until the misfit between the model and receiver function data is satisfactorily small (Ligorria & Ammon, 1999). To perform the waveform inversion, an initial model needs to be defined. Since there is no existing velocity model for the whole Peninsular Malaysia region, a two-phase inversion process was implemented, incorporating two different initial velocity models. In the first phase, a single velocity function was used to identify the receiver function inversion pattern after 100 iterations. Once the subsurface pattern of the region is obtained, the second inversion was run by adopting the IASP91 velocity model, with the aim to determine the earth's subsurface velocity profile.

DATA AND PROCESSING

The study focused on defining the crustal and upper mantle seismic structures of southern Peninsular Malaysia where there are two broadband stations continuously sharing data with the ISC community. Receiver functions were computed between 2005 till 2016 which involve 889 (KOM) and 693 (BTDF) earthquakes within the epicentral distances of 30°–100° from the respective station. To ensure the strong signal recorded, only earthquakes with magnitudes, M_w larger than 6.0 were chosen. The vast data availability has allowed a more comprehensive subsurface velocity characterization compare to the previous work in the area which involve only 61 (KOM) and 271 (BTDF) earthquakes (Macpherson *et al.* (2013), Kieling *et al*. (2011)). From the earthquake tabulation, most of the earthquake analyzed originated from the north-east (back azimuth of 0°–90°) and south-east (90°–180°) where the daily earth's crust ruptures occurred. Before the crustal thickness and velocity inversion were carried out, the signal to noise ratio (SNR) criteria of each of the waveform were analyze individually, with the receiver function's SNR less than 5 were discarded from further investigation. This SNR criterion saw 50% of the data from KOM station (441 recorded waveform) and almost 90% of the data from BTDF station (620 recorded waveforms) were eliminated, with remaining signal with good SNR were used in the H-k and velocity inversion analysis.

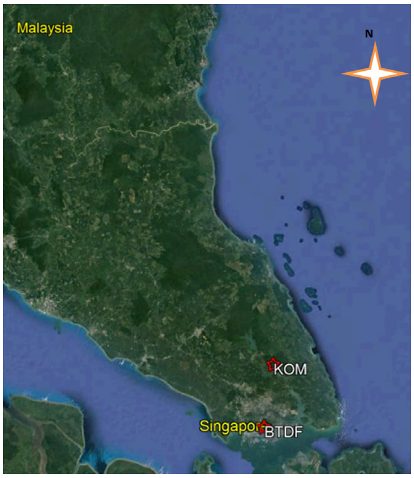

Figure 2: The earth surface map of Peninsular Malaysia with the location of KOM and BTDF seismological stations (red star). Image from Google Earth.

The resultant receiver functions at station KOM show the good P-wave arrival at zero time as well as P-s converted wave arrival from Moho boundary at 4 seconds (Figure 3). In addition, the recorded signal with earthquake originated from 90°–180° back azimuth (2nd quadrant) contains an additional multiple phase at 5.5 seconds, immediately after the P-s phase. This complex phase is probably related to the wave propagation disturbance and / or poor source signature of the earthquakes that occurred in New Zealand and Fiji. At the later duration, a strong PpPs phase can be seen clearly at 14 seconds with relatively weaker PpSs+PsPs multiple at 18 seconds. Beyond 20 seconds of the waveform, several coherent multiple phases can be seen, particularly the 1st and 2nd quadrant earthquakes. However, due to limited waveform available from 3rd quadrant in addition to poor coda wave signal in 4th quadrant, there is no further phase interpretation conducted for this station.

Meanwhile, the BTDF receiver function shows a coherent P-wave arrival (0 second) and P-s wave arrival (4 seconds) (Figure 4) dominated by earthquakes recorded from 0°–90° back azimuths (1st quadrant). The multiple phases are less dominant compared to KOM station, with semi-coherent PpPs phase can be interpreted at 14 seconds while poor and chaotic PsPs + PpSs phases was observed at 17-18 seconds. It should be noted that, due to poor signal to noise for earthquake signals recorded from other quadrants, the interpretation of the crust beneath the Singapore region is limited to the first quadrant's earthquake waveform.

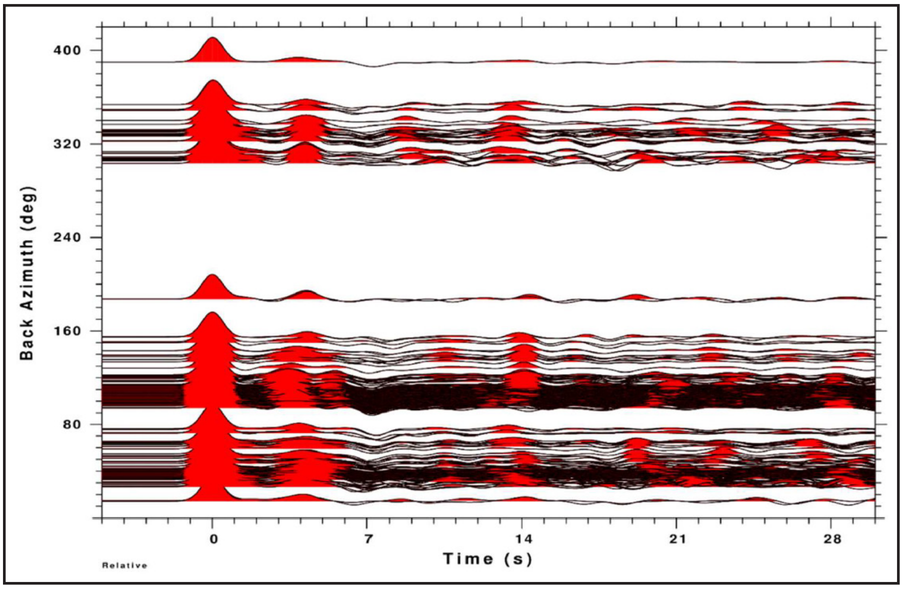

Figure 3: Receiver function of KOM station because of waveform rotation and deconvolution process. There are 448 waveforms adopted from tele-seismic earthquake in between 2005 – 2016.

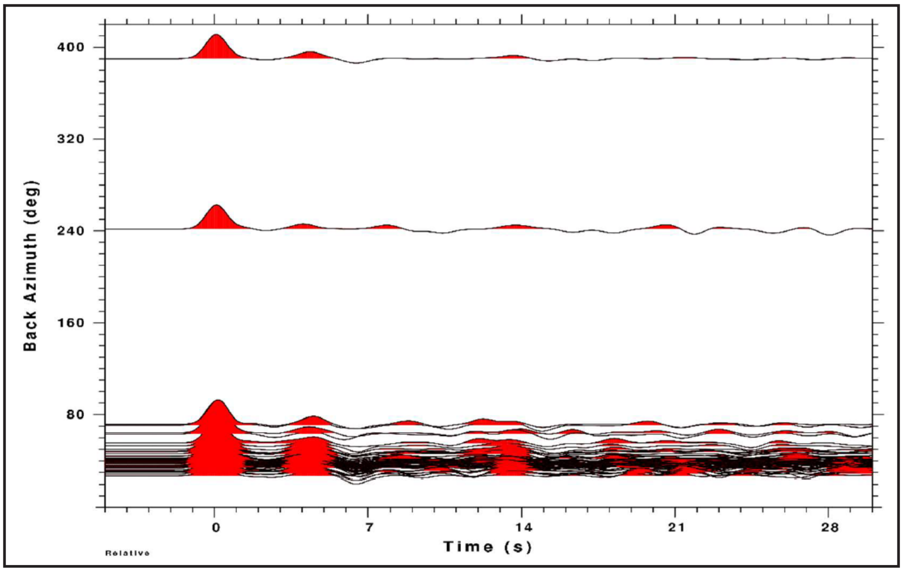

Figure 4: Receiver function of BTDF station because of waveform rotation and deconvolution process. There are 73 waveforms adopted from tele-seismic earthquake in between 2005 – 2016.

CRUSTAL STRUCTURE ANALYSIS

Before the H-k stacking analysis was carried out, the deconvolved receiver function was summed and stacked, according to the recording station. From the contour of confidence level, the crustal thickness for KOM and BTDF are 34 km (Figure 5) and 30 km (Figure 6) respectively. This corresponds to V_p/V_s ratio of 1.68 (KOM) and 1.83 (BTDF), which are similar to the V_p/V_s of the station located on the other part of Peninsular Malaysia (Woon & Yingzin, 2009). The KOM's H-k stacking result also shows three other possible depths and V_p/V_s outcome, albeit a much lower confidence percentile from the stacking output as well as a very high V_p/V_s ratio ($V_p = 1.9V_s$ and $V_p = 2.2V_s$), and far exceed the global average at 1.78 (Ammon *et al*., 1990). The appearance of other possible depth contour is probably due to chaotic multiple phase seen in the deconvolution outcome.

The initial estimation of crustal thickness beneath the KOM and BTDF was then used to set-up the initial velocity model for the receiver function waveform inversion analysis. Waveform inversion is a well-known non-linear non-uniqueness process, where the resultant velocity model depends on the several trade-in factors, particularly the initial velocity model. To solve this problem, many studies considered the linearized iterative inversion problem, which applies to both synthetic and observed data. There are other approaches, either through different optimization solution such as genetic algorithm, neighborhood algorithm and simulated annealing (Jacobsen & Svenningsen, 2008), or by the integration of receiver function inversion with surface wave dispersion procedure (Julia *et al*., 2000). While each of the solution proposed has their advantage, none of them is capable to fully solve the non-discriminative solution.

In this study, a two-steps inversion workflow was used to lower the uncertainty from the inversion outcome. The first inversion process used a single and fix velocity value at 8 km/s for P-wave and 4.5 km/s for S-wave, to locate the 'jump' pattern in both P and S-wave velocity function during the inversion process. Since the velocity was fixed from surface level to 100 km depth, the resultant output velocity model was not influenced by the sudden velocity increase in existing velocity model. Throughout the optimum iterations process with damping factor of 0.5 and smoothness value of 0.4, the 1st inversion step allow a validation process of H-k stacking analysis, by locating the sudden velocity increase in both P and S velocity components.

From the 1st inversion step of the KOM station, the sudden P and S-waves velocity increase was found at 12 km and 34 km (Figure 7). These velocity changes were interpreted as the upper crust – lower crustal – upper mantle layers, consistent with the change in rock type. The Conrad discontinuity was interpreted at 12 km while the Moho discontinuity was interpreted at 34 km. We use this information in developing the 2nd and final inversion procedure, by modifying the IASP91 velocity model to serve as the initial velocity model. The IASP91 velocity model was chosen based on the following reasoning; i) similar initial model used by Malaysia Meteorological Department in their previous hypocenter relocation work, which was found accurate (Abdul Latiff & Khalil, 2016), ii) the regular and consistent velocity sampling interval compare to AK135F, PREM and crust1.0 model. In the existing IASP91 model, velocity changes drastically at 20 km (to indicate the Conrad discontinuity) and 35 km (to indicate Moho discontinuity) within the crustal region. Using the findings from the 1st inversion, the IASP91 model was modified to 12 km (first velocity change) and 32 km (second velocity change). After optimum number of iteration in the 2nd inversion, with similar coefficients as in the 1st inversion procedure, the final velocity model was found consistent with the previous inversion scheme, as large velocity differences were recorded at both 12 km and 34 km (Figure 8). Although the P and S waves velocity slightly dropped at 18 km depth, the velocity increase gradually from Conrad boundary to Moho boundary signaling the steady earth's subsurface properties in between 20 km - 30 km depth.

Following the similar inversion procedure as in the KOM station, the drastic velocity changes beneath BTDF station was found at 10 km and 30 km (Figure 9). The

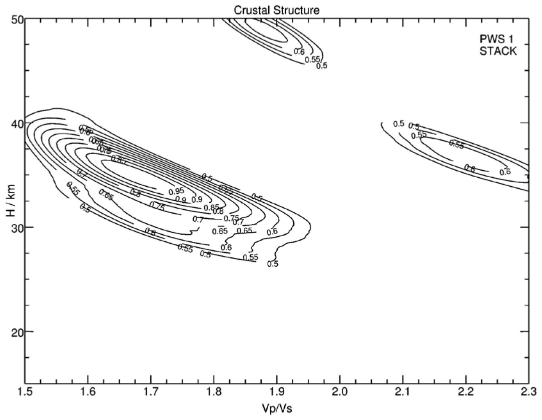

Figure 5: H-k contour map indicates the thickness of crust-mantle boundary (y-axis) vs.V_p/V_s ratio (x-axis). The thickness beneath Johor region (KOM station) was found at 34 km with V_p/V_s ratio at 1.68.

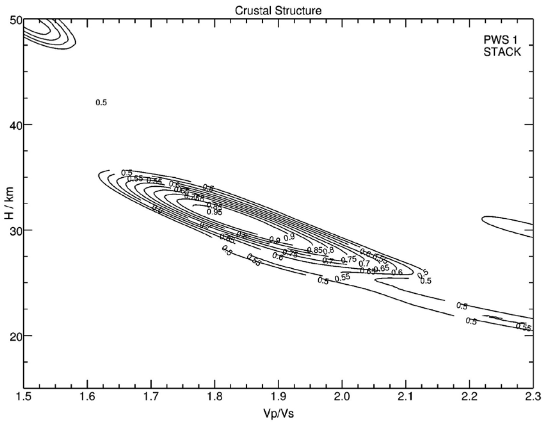

Figure 6: H-k contour map indicates the thickness of crust-mantle boundary (y-axis) vs. V_p/V_s ratio (x-axis). The thickness beneath Singapore region (BTDF station) was found at 30 km with V_p/V_s ratio at 1.81.

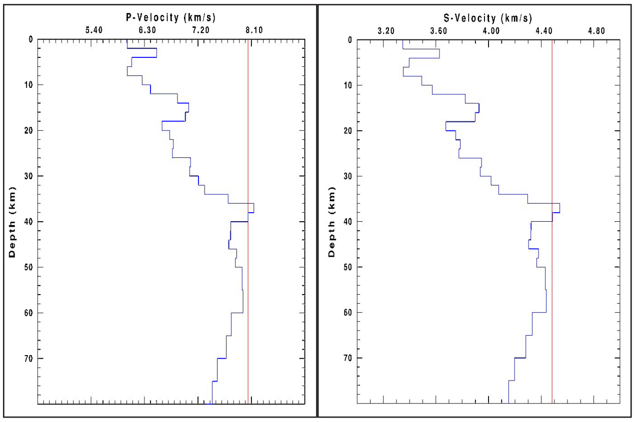

Figure 7: First-pass of receiver function inversion for KOM station as a result from tele-seismic earthquake after 100th iteration (blue) based on the initial single function velocity model (red) for (a) P-wave velocity (b) S-wave velocity.

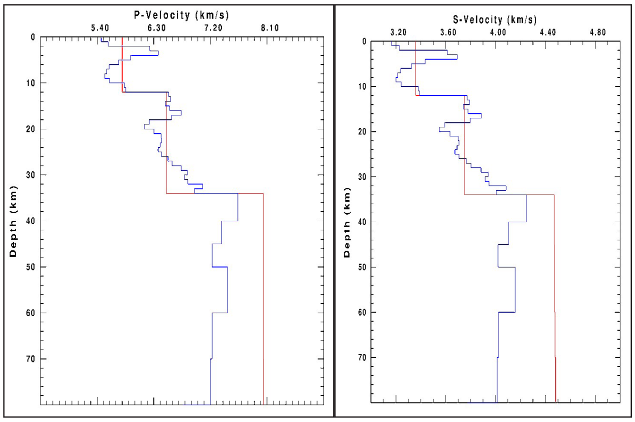

Figure 8: Second-pass of receiver function inversion for KOM station as a result from tele-seismic earthquake after 100th iteration (blue) based on the initial IASP91 velocity model (red) for (a) P-wave velocity (b) S-wave velocity.

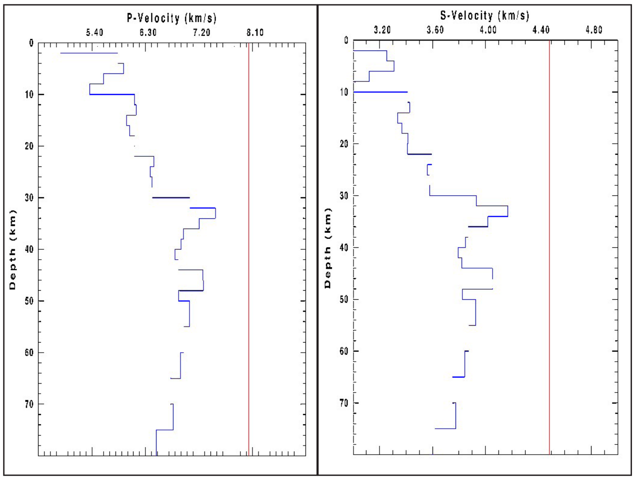

Figure 9: First-pass of receiver function inversion for BTDF station as a result from tele-seismic earthquake after 100th iteration (blue) based on the initial single function velocity model (red) for (a) P-wave velocity (b) S-wave velocity.

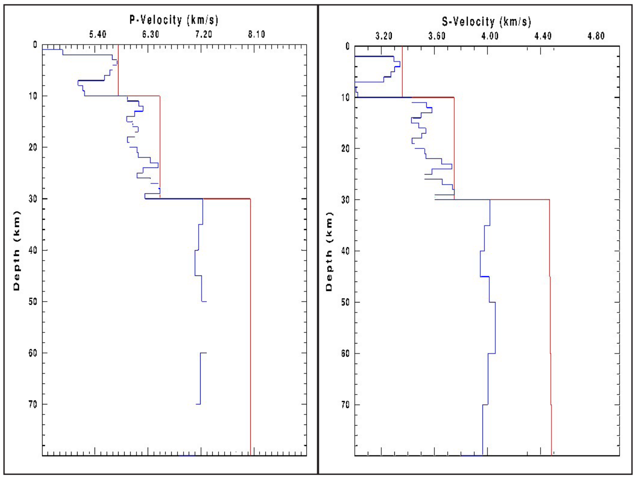

Figure 10: Second-pass of receiver function inversion for BTDF station as a result from tele-seismic earthquake after 100th iteration (blue) based on the initial IASP91 velocity model (red) for (a) P-wave velocity (b) S-wave velocity.

distinctive two boundaries then were used to modify the IASP91 velocity model for the second inversion procedure. As a result, the final velocity inversion can be clearly seen at 10 km (Conrad discontinuity) and 30 km (Moho discontinuity) (Figure 10). These findings are consistent with the H-k stacking analysis for BTDF station which was found at 30 km depth as well.

The result obtained from H-k and receiver function inversion are consistent with the hypothesis proposed from the receiver function observation, that the crustal thickness and velocity structure of Johor and Singapore are thinning towards the south. From the depth of 12 km (Conrad discontinuity) and 34 km (Moho discontinuity) beneath the Kota Tinggi region, the depth to the earth crust is reduced by 2-4 km towards the south (Singapore). It may carry a significant development of the tectonic evolution of Malay Peninsula and its surrounding basins as the area towards the south of Peninsula probably contain a shallower crust-mantle boundary. Another important observation was found at 70 km depth, as both P and S-waves velocity profile travel slightly slower, which signal the asthenosphere zone of the Malay Peninsula.

CONCLUSION

We presented the crustal structure of the southern Peninsular Malaysia where the H-k and 1-D velocity inversion analyses show a consistent and robust result. Through the receiver function modelling and inversion method, the crustal thickness and velocity structure underneath the KOM and BTDF seismological stations located at the southern Malay Peninsula were determined. The finding was compared to previous receiver function analysis for both KOM and BTDF station, and found that our analysis shows a close similarity in term of crustal thickness, with 34 km (KOM) and 30 km (BTDF) of the earth's crust was found in this study compared to 30-34 km in previous published work. In addition, the velocity composition beneath southern region of peninsular Malaysia might indicate thinner crustal layer from north to the south as shallower Conrad and Moho discontinuity were found beneath BTDF station. It signifies the evolution of Malay Peninsula tectonic from north to south which currently lack evaluation and is relatively unknown. However, different crustal technique analysis is possibly required, such as surface wave dispersion analysis and ambient noise tomography study, to validate the 1-D velocity model obtained in the analysis. In addition, further investigation of the seismic stations located nearby KOM and BTDF are also needed to obtain a comprehensive 3D velocity tomography of the Malay Peninsula.

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