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Earth crustal analysis of Northwest Sabah region inferred from receiver function method

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Abstract: Many methods are used to investigate the Earth's crustal with the knowledge of geology and geophysics. Earth crustal analysis beneath the Kota Kinabalu region, located in Northwest Sabah, was performed by using tele-seismic earthquakes as sources. While Sabah geology is highly complex the understanding of its tectonic history has remained ambiguous. The tomography of the Kota Kinabalu region is mainly influenced by the collision between the South China Sea and Sabah margins during the Early Miocene which leads to crustal thickening. At present, the subsurface properties, and structures underlying the Kota Kinabalu region are yet to be recognized. Thus, this study aims to acquire the crustal properties beneath the Kota Kinabalu region through the deployment of a weak-motion seismometer station within the Crocker Range, Sabah, Malaysia. Additionally, the work conducted is to determine the thickness and velocity layer of the Earth's crust up to the Moho boundary. Receiver function analysis was chosen as the method to conduct this study where responses of tele-seismic earthquakes recorded at KKM station were evaluated and processed through 2D rotation, iterative time deconvolution, signal-to-noise ratio analysis, stacking, H-k analysis, as well as forward modelling and waveform inversion. A total of 916 time series data were retrieved from International Seismological Centre (ISC)'s respiratory with only 184 receiver functions were incorporated in this study whereas the remaining 732 receiver functions were deemed noisy and unfit for the next process. The selected receiver functions have an earthquake magnitude greater than 6 mb with a signal-to-noise ratio of greater than 5. The processing steps included in this study are conducted by using open-source computation programs such as Seismic Analysis Coding (SAC) and Generic Seismic Application Coding (GSAC). From the 1-D velocity models inferred from receiver function inversion, the subsurface structural framework and velocity anomalies within the crust beneath the station were interpreted and analysed. With the additional information generated from H-k analysis, it is interpreted that the Earth subsurface beneath the Kota Kinabalu region has the Conrad discontinuity at 26 km depth, the Moho boundary at 40 km depth while the Lithosphere-Asthenosphere boundary was found at 66 km below the surface level. Additionally, the velocity profiles within the Kota Kinabalu's crust show alternating patterns with V_P has the range between 5 km/s to 7 km/s, and V_S has the range of 3 km/s to 4 km/s. The V_P and V_S readings reached 8 km/s and 4.5 km/s respectively as it hits the Moho boundary at 40 km depth.

Keywords: Receiver function, crustal thickness, velocity structure, Kota Kinabalu

INTRODUCTION

Sabah is located on the NE of Borneo island in East Malaysia where the Eurasian, Pacific, Philippines, and Indo-Australian plates meet. It is centrally positioned between three marginal basins which are Sulu, the South China Sea, and Celebes (Balaguru & Hall, 2009). The understanding of the tectonics of Sabah has always been ambivalent due to its geological complexity, with south-easterly subduction in the NW Borneo, and extension in the SE in the Celebes Sea and Makassar Strait (Pubellier & Morley, 2014). 45 million years ago, the southwards subduction of the oceanic crust of proto South China Sea occurred along an active continental margin that extended from northeast Sarawak through Sabah towards the northern Philippines (Metcalfe, 2011). Concurrently, the continental crust of the South China margin is pulled and eventually separated from the Eurasian continent. Subduction of the Proto-South China Sea beneath Sabah terminated soon after the collision of the South China margin with Sabah margin (Figure 1a) (Metcalfe, 2017). The collision between South China Sea margin and Sabah margin during Early Miocene believed to thicken the lithosphere which later penetrated the mantle before separated as a blob which causes an uplift as a result of equilibrium re-establishment (Hall *et al.*, 2008).

On the other hand, the Sabah state capital, Kota Kinabalu, is situated at NW of Borneo along the region where the continental-continental collision occurred. It is underlain by the Late Eocene-Lower Miocene Crocker Formation and Quaternary Alluvium. The collision

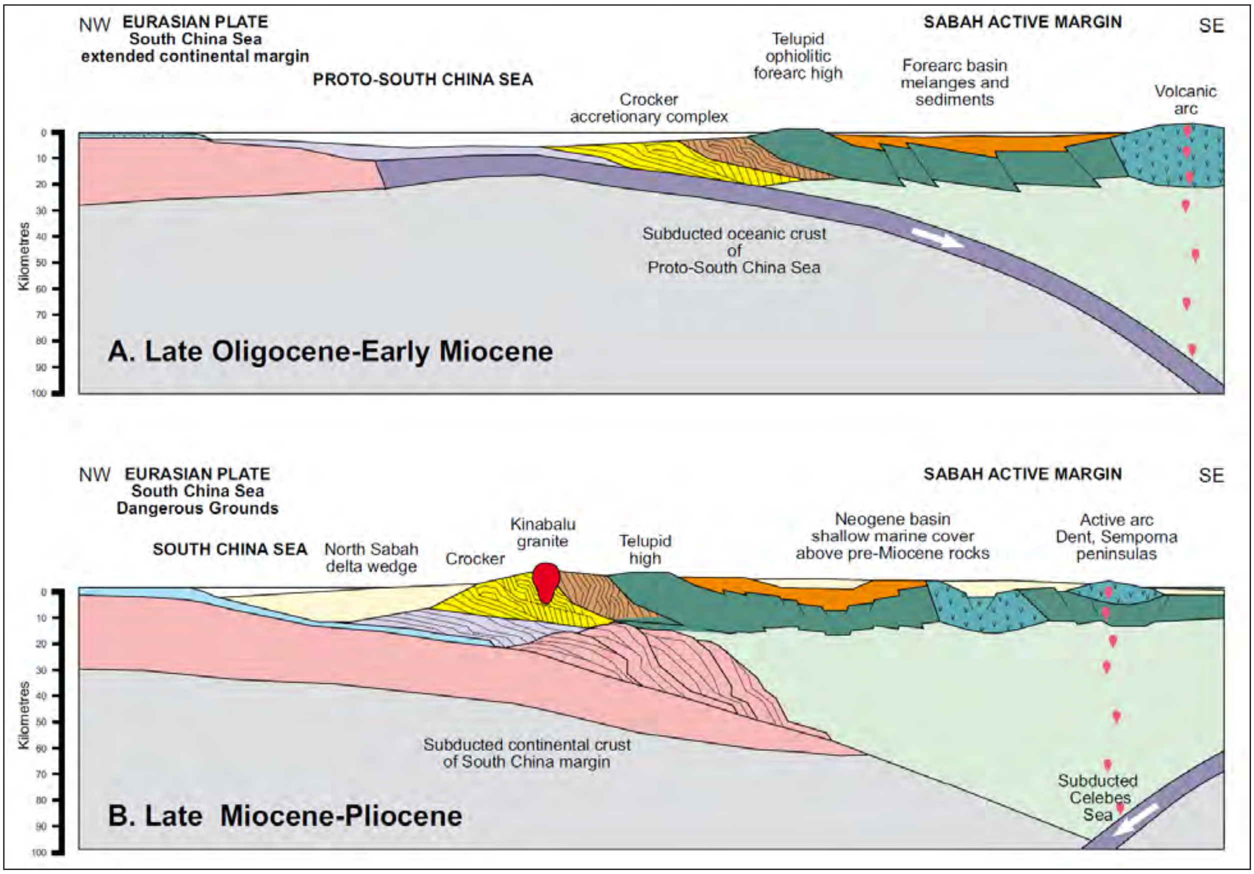

Figure 1: Illustration of subduction of proto-South China Sea (Hall *et al.*, 2008).

between the South China Sea margin and Sabah margin in the Early Miocene eventually uplifted the Crocker formation above sea level and thus, allowing erosion to occur which then formed an unconformity (Figure 1b). A broad range of mountain belt is created along collision margin and although some of the mountain range remained along with the Crocker ranges, most of the areas in the north and south are lowered below sea level due to subsidence.

The absence of a crustal-mantle model in the Kota Kinabalu region leads to an ambiguous understanding of the topography of the study area. Previous studies only hypothesized crustal thickening due to continental-continental collision of the South China Sea and Sabah margins based on the features of surface geology (Sidek *et al*., 2016). The actual crustal thickness and subsurface properties such as the velocity profile beneath the Kota Kinabalu region are not yet explored. Thus, this research aims to analyze the crustal properties beneath the Kota Kinabalu region, as well as to determine the thickness of the Earth's layer above the Moho boundary and to evaluate the velocity profile within the Earth's crust of the study area.

The Kota Kinabalu seismometer station (KKM) used for the study is located at latitude and longitude of 6° 2' 39.48'' N and 116° 12' 52.9164'' E. Geographically, the western side of Sabah where Kota Kinabalu is located is mostly of the mountainous region. This region of high elevation is a part of the Crocker range which separates the East Coast and West Coast of Sabah. The highest elevation is around 4000 m above sea level which is Mount Kinabalu situated 80 km northeast of Kota Kinabalu. KKM station is located at an elevation of about 810 m above sea level (Figure 2).

The principle of isostasy states that the gravitational equilibrium between the Earth's crust and mantle is achieved such that the crust floats on a denser underlying mantle at an elevation depending on its thickness and density. Based on Airy's theory, the rock density across the lithosphere is almost similar, but the crustal blocks have different thicknesses and densities (Pan, 2007). Therefore, a highly elevated crust (e.g. mountainous region) depicts a thicker and denser crust whereas a low elevated crust (e.g. basin and lowlands) indicates a thinner and less dense crust.

The method of study is Receiver Function Analysis which is a passive seismic technique that utilizes responses from tele-seismic earthquakes. In receiver function analysis, data processing such as 2D rotation, iterative time-domain deconvolution, Gaussian filter, and

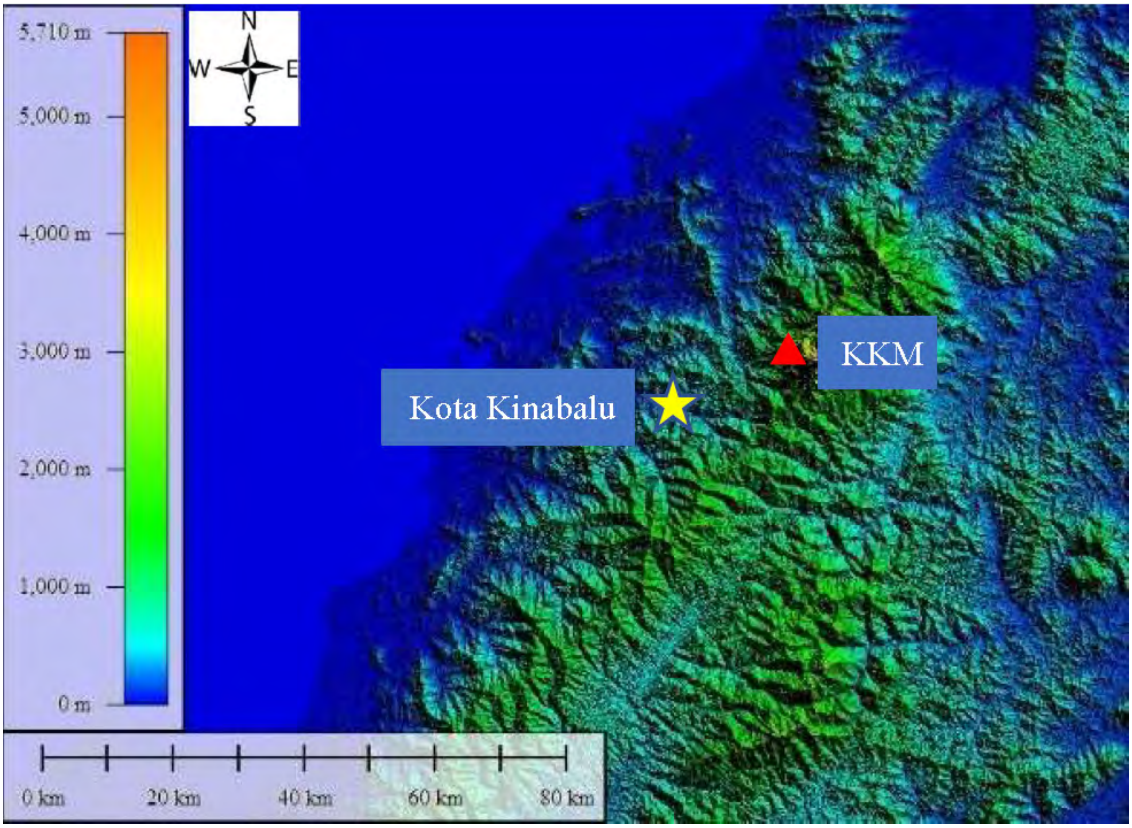

Figure 2: Digital elevation map of Kota Kinabalu region, showing the location of KKM station.

signal stacking are applied. Elimination of noisy data are done via signal-to-noise ratio (SNR) analysis. The crustal thickness (H) and average primary to secondary velocities (Vp/Vs) ratio (k) are estimated by using the H-k analysis technique. This study also includes forward modelling and waveform inversion to create ideal 1-D velocity models that represent the Earth's subsurface properties beneath KKM station (Abdul Latiff & Khalil, 2016). The data processing and modelling in this study are carried out using computer programs such as Seismic Analysis Code (SAC) and Generic Seismic Application Coding (GSAC) which runs in Linux Operating System. Programming codes written and used throughout the study were adopted from Herrmann & Ammon (2002).

METHODOLOGY

Receiver functions are time series data recorded by a 3-component broadband seismometer (Langston, 1977). The receiver function method uses earthquakes as a source of seismic body waves such as P-wave and S-wave to infer on the Earth's structural framework. P-wave is the fastest seismic wave travelling at about 4-8 km/sec in the Earth's crust (Abdul Latiff & Khalil, 2019). The motion of particles is parallel to the direction of wave propagation. P-waves can travel through the molten core and fluid-formed layers; liquid or gas, unlike S-waves which can only propagate through solid. S-wave travels at about 2.5-4 km/sec in the Earth's crust which makes it the second-fastest wave. Typically, the velocity of S-waves is around 60% of that P-waves. However, the velocity varies according to the material composition of the medium in which it travels. S waves oscillate particles in a motion that is perpendicular to wave propagation.

These waves are detected by a device called seismometer at the seismic recording station. A seismogram is a record of the ground motion in a graph form (seismograph) at the recording station in a function of time or time series. It records seismic waves in three-cartesian axes (x,y and z) or in three directions: north-south (BHN), east-west (BHE) and vertical (BHZ) (Figure 3). When body waves arrive at a three-component seismometer station, it provides information about the various path travelled by the waveforms. It contains information on the seismic source structure, its propagation through the mantle as well as the structure beneath the seismic recording station.

Typically, the first arriving wave at the recording station is P-waves followed by S-waves and the later multiples; PpPs, PsPs, PpSs (Figure 4). Transmitted P-waves that are reflected at the Moho to the surface are called multiples whereas S-waves are originated from P-waves which are converted and transmitted into

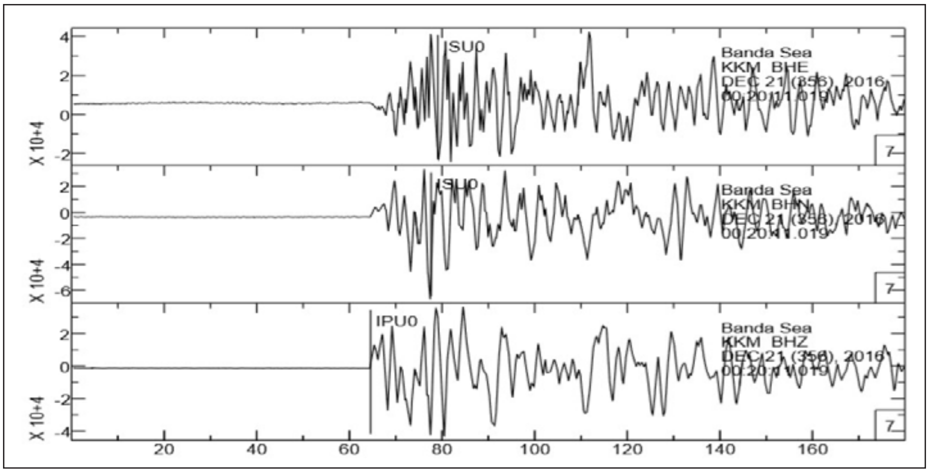

Figure 3: A three-component seismograms at KKM station recorded an earthquake signal originated in Banda Sea.

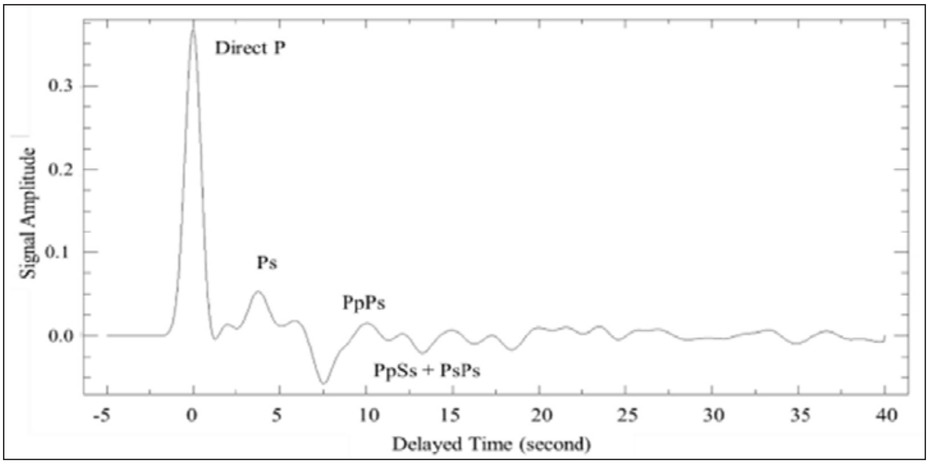

Figure 4: Waveform shows the stack receiver function that was computed at IPM station, with a clear indication of the direct P-arrival, PpPs, PpSs and PsPs multiple phases.

secondary waves as they hit the Moho boundary. The main objective of the receiver function method is to eliminate information on seismic source structure and its propagation path so as to only reserve the information on the local structure beneath the seismic station (Jansson, 2008).

The data used in this research are obtained from IRISDMC (IRIS Data Management Center) using FDSN Web Services. The IRISDMC compiles a record of the Earth's seismicity to support the seismological research community. The selected data are originated from earthquakes with an epicentral distance between 30° to 90° from KKM station and waves magnitude of greater than 6 Mb (body wave magnitude). This is because P-S wave conversion can only take place when the ray path includes both the mantle and the Earth's crust and a higher magnitude of waves produces suitable signal strength. Therefore, 916 time series data from events occurring from the year 2005 to 2016 are retrieved. The location of earthquakes varies within the Earth's Ring of Fire from Pakistan and Central Asia to Japan, New Zealand, and Fiji Islands.

The seismogram is readily cut 60 seconds before and after the arrival of direct P-wave. These steps are done due to the limitations of the program is storing the number of points of data in a file (Kieling *et al.*, 2011). Moreover, the data are also down-sampled into a lower frequency and shifted to a zero-amplitude reference line so that it appears to be less noisy with a smaller time interval. Although the data is in a three-component (ZNE) seismic data, the axis between the earthquake and the station is not aligned and thus, a two-dimensional rotation is conducted to isolate the energy of different wave types. P-waves are mostly confined in the vertical component while the converted S-waves are contained in the radial component. Ultimately, the ZNE coordinate system becomes ZRT respectively.

The iterative time-domain deconvolution process is applied to eliminate the effects of near-source structure and source time functions. The platform of iterative time-domain deconvolution is to minimize the difference between the predicted signal and the observed horizontal seismogram (Torsvik, 2015). A normalized Gaussian filter is also applied to eliminate high-frequency noise in the receiver functions. It is observed that a width factor of below 1.0 generates receiver function with undefined spikes whereas the width factor with values greater than 2.5 will produce a noisy receiver function. Therefore, a width factor of 1.5 is used in the filter to produce optimum results.

The ray paths of seismic waves generated from earthquake events respectively are unique and differ from each other. This is because the Earth's layer is non-homogenous. Back azimuth plot allows the comparison of receiver functions (Figure 5). There are a few receiver functions that do not conform with the others. These receiver functions are identified and eliminated from the stack list. Apart from that, the receiver functions with signal-to-noise ratio smaller than 5 are also eliminated. The remaining receiver functions are summated by using the sum-stack technique in SAC. Consequently, only 184 receiver functions are used further in this study.

A typical receiver function study is unable to eliminate the depth-velocity ambiguity because of its shallow range of slowness. The crustal thickness estimated is only based on the delay of time of the P-to-S conversion phase at Moho without considering the crustal Vp/Vs ratio. By applying H-k analysis, we can reduce the depth-velocity ambiguity present. Therefore, a better approximate value of crustal thickness (H) and the mean of Vp/Vs ratio (k) based on the receiver function time series. Apart from that, we can provide a much-detailed diagnostic of crustal composition than P or S-wave data alone.

H-k analysis incorporates the later arriving multiple converted phases, PpPs and PpSs + PsPs with P-to-S converted phases. The amplitudes of receiver function at the estimated arrival times of these phases by different crustal thicknesses, H and Vp/Vs ratios are stacked thus, producing a stacking algorithm (Zhu & Kanamori, 2000). Consequently, the effects of lateral structural variation are diminished, and an average crustal model is obtained. Based on a given earth structure model, the receiver function can be determined through forward modelling. Nevertheless, the aim of this research is not to attain the receiver function but to obtain the true subsurface structure beneath KKM station via waveform inversion. Forward modelling and inversion are conducted simultaneously until the final model is achieved.

In this study, 1-D velocity models via 2-passes receiver function inversion are produced (Julia *et al.*, 2000). The two initial models which are used for the 1st pass inversion and 2nd pass inversion are Earth model with constant velocity and the modified IASP-91 respectively. Several 100 iterations and a smoothness trade-off parameter of 0.4 was designated to generate these velocity models. The time window is set from -5s to 30s of the receiver function waveforms. The first pass receiver function inversion is conducted before the second pass receiver function inversion which resulted in intermediate velocity models. The IASP-91 model is modified based on the velocity trend and significant changes in the intermediate model. According to Incorporated Research Institutions for Seismology (2017), the IASP-91 reference model is a parameterized velocity model that has been constructed to be a summary of the travel time characteristics of the main seismic phases. Subsequently, the second pass receiver function inversion is carried out based on the

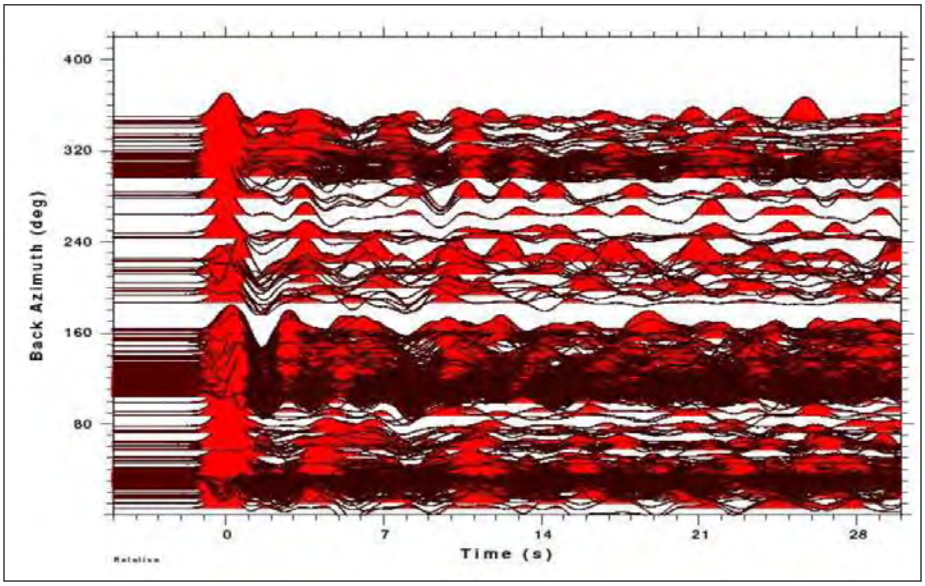

Figure 5: Back azimuth plot of 916 receiver functions, stacked together for waveform analysis.

modified IASP-91 model. The final velocity models are then produced to be interpreted and analysed to infer on the subsurface properties and structural framework beneath KKM station.

CRUSTAL MODEL BENEATH KOTA KINABALU REGION

Receiver functions

The signal-to-noise ratio analysis resulted in eliminating 732 receiver functions from the initial 916 receiver functions extracted from IRISDMC. There were only 184 receiver functions with signal-to-noise ratio of greater than 5. Figure 6 shows back-azimuth plots of the resultant 184 receiver functions. The resultant receiver functions at KKM station show the arrival of Ps converted wave at time 3.5 seconds in the 1st, 3rd and 4th quadrants. Furthermore, the recorded signal with earthquake originated from 270° to 360° back azimuth (4th quadrant) contains an additional weak multiple phase at 7.5 seconds, immediately after the Ps phase. This phenomenon might be due to wave propagation disturbance and /or poor source signature of the earthquakes occurred in India, Pakistan, China, and Russia. At 11 seconds, particularly in the 1st, 3rd and 4th quadrants, PpPs phase is detected. At a later duration, the receiver functions with an earthquake occurring in the 1st quadrant depict relatively weaker PsPs + PpSs multiples at 14 seconds. However, due to noisy and inconsistent waveforms generated from earthquakes from 2nd quadrant, no phase interpretation is made further for this station.

The outcome of the stacking process is the summated stack of observed receiver functions where coherent signals are emphasized, noise is suppressed, and an increase of overall signal-to-noise ratio. It also provides a better representation of the resultant receiver functions. Figure 7 shows the summated stack of resultant receiver functions.

H-k analysis

H-k analysis is a method of estimating the crustal thickness and average Vp/Vs ratio based on the receiver function time series (Torsvik, 2015). The y-axis represents the crustal thickness in kilometres (H), while the x-axis represents the Vp/Vs ratio (k). The result of H-k analysis is portrayed in a contour plot (Figure 8). Each contour plot holds a value of percentile confidence regions accordingly. Based on the analyss, the highest value of the percentile confidence region is 0.95 or 95% which indicates a crustal thickness of about 43 km with a Vp/Vs ratio of 1.55. Therefore, it is assessed that the Moho depth is at a depth of approximately 43 km beneath KKM station. This estimation will be further clarified with the outcomes of forward modelling and inversion processes.

Velocity models

The interactive iterative process of forward modelling and waveform inversion generates velocity models that can be interpreted to give an idea about the subsurface properties and structures underneath KKM station. In this project, 2-passes receiver function inversion is conducted whereby the first inversion produced intermediate velocity models that is analyzed and used to modify the IASP-91 model so to generate the final velocity models from the second inversion. In these models, two lines of the colour red and blue are depicted to represent the input models and

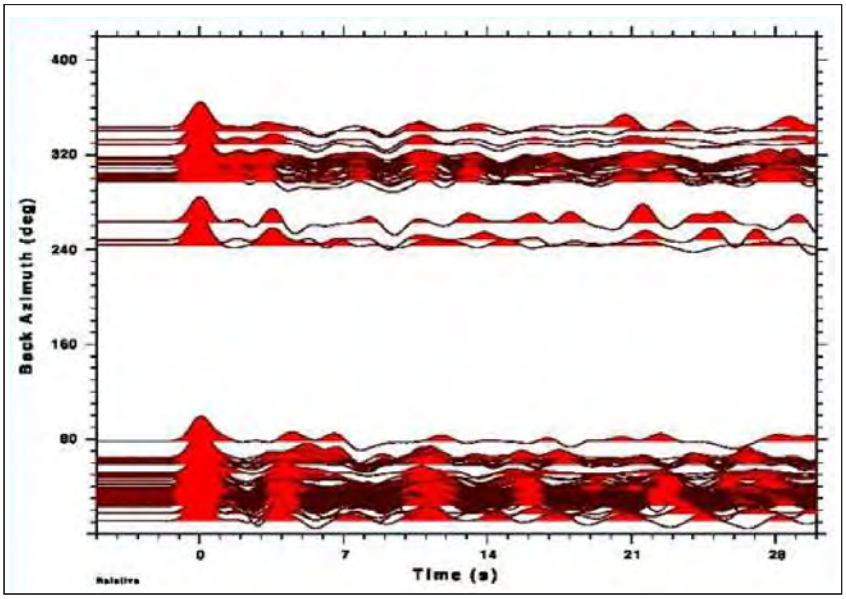

Figure 6: Back-azimuth plots of selected 184 receiver functions, as a result of signal-to-noise criterion implementation.

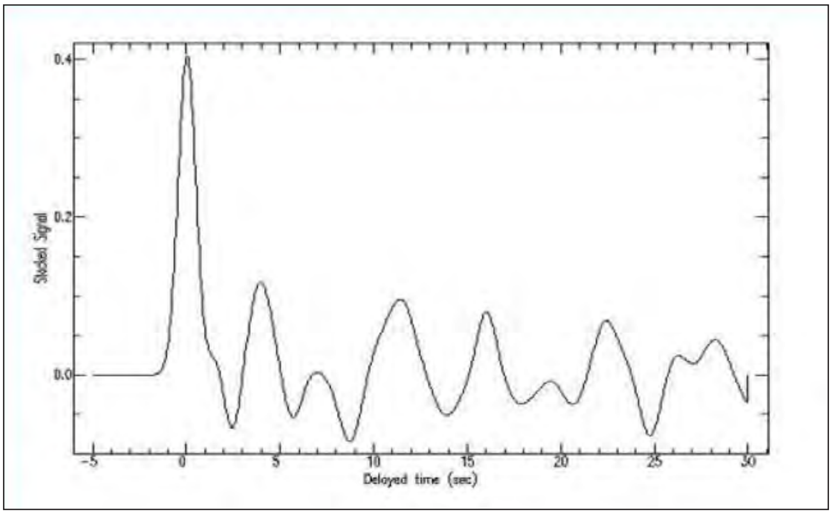

Figure 7: Summated stack of receiver functions of 185 waveforms in Figure 7.

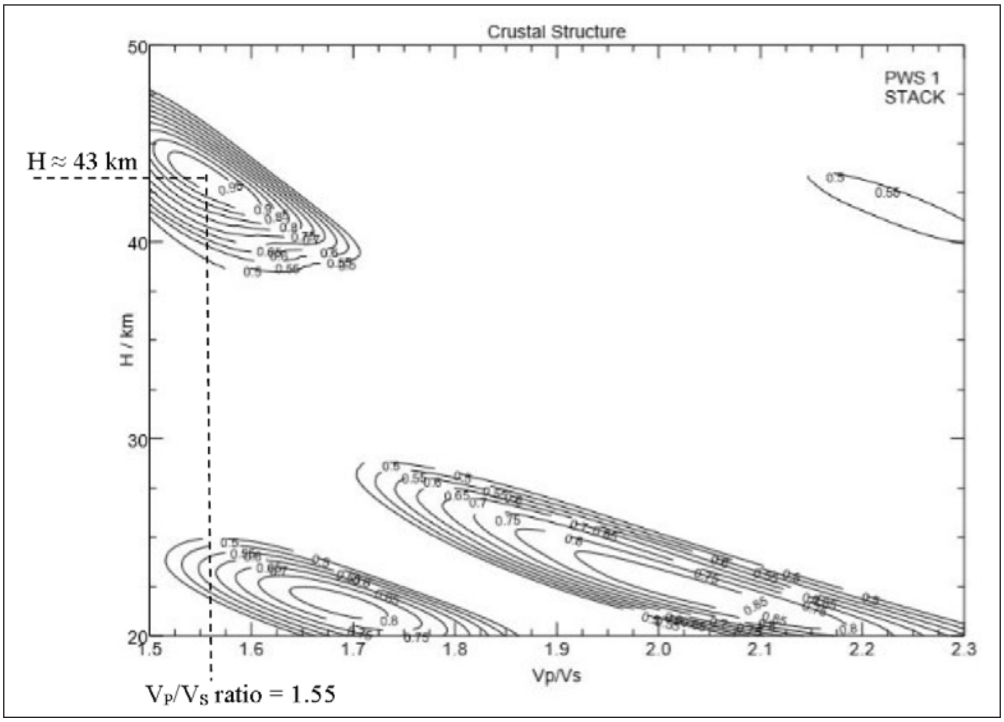

Figure 8: H-k plot analysis indicates the thickness (H) and V_P/V_S ratio beneath Kota Kinabalu region.

the velocity model generated from the receiver function inversion (Figure 9).

Based on the first inversion intermediate velocity models, three significant velocity changes are observed. Firstly, at depth 26 km beneath KKM station, both P-velocity and S-velocity experienced an increase from 6.2 km/s to 6.8 km/s and from 3.5 km/s to 3.9 km/s respectively. Secondly, at depth 40 km, both P-wave and S-wave velocity reached nearly 8.0 km/s and 4.5 km/s which are average velocities of P-wave and S-wave in the upper mantle. Thirdly, both P-wave and S-wave experienced a substantial drop in velocity indicating a low-velocity zone (LVZ).

Consequently, the IASP-91 is modified based on the interpretations of the intermediate velocity models especially at depth 26 km, 40 km, and 66 km. The second and final P-wave and S-wave velocity models for KKM station are depicted in Figure 10. At depth of 26 km beneath KKM station, there is a significant increase in P-wave velocity of the final model from 6.2 km/s to 6.8 km/s as well as an increase in the S-wave velocity from 3.6 km/s to 4.0 km/s. This indicates that

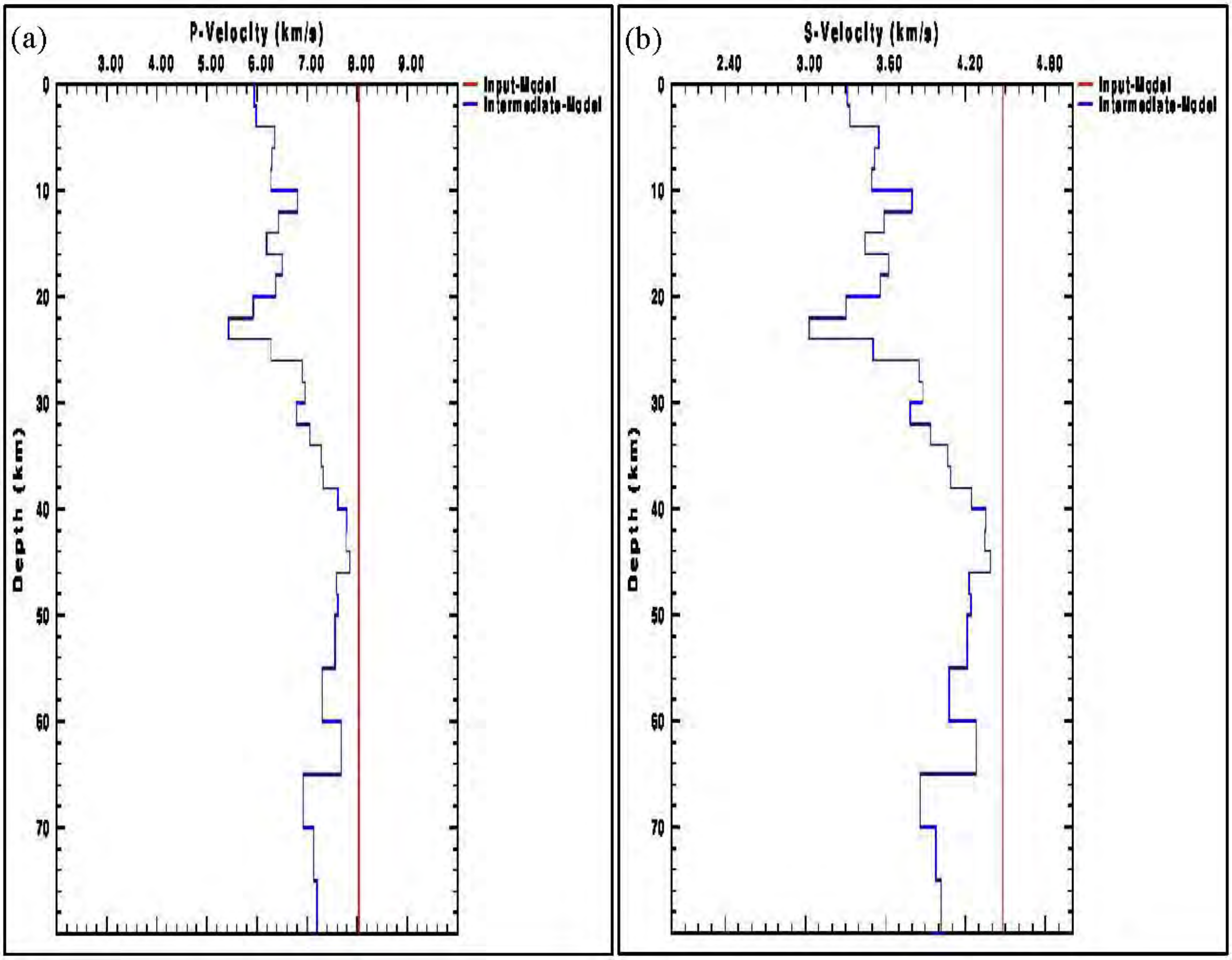

Figure 9: Velocity model after the 1st inversion for (a) P-wave model and (b) S-wave model.

the Conrad discontinuity that exists between the upper crustal layer and the lower crustal layer is detected at 26 km depth. The range of P-wave velocity in the upper crust 5.4 km/s to 6.6 km/s whereas the range of P-wave velocity in the lower crust is 26 km is 6.2 km/s to 7.2 km/s.

Furthermore, at a depth of 40 km beneath the station, both P-wave and S-wave velocities reached 8.0 km/s and 4.5 km/s respectively. The average P-wave velocity in the uppermost mantle should be greater than or equal to 7.6 km/s (Mooney *et al*., 2002). Thus, the Moho boundary is at depth 40 km beneath KKM station. At greater depths of more than 40 km, the P-wave and S-wave velocities decrease linearly. At depth 66 km beneath KKM station, it is observed that both P-wave and S-wave velocities experienced a low-velocity zone which indicates the lithosphere-asthenosphere boundary. The S-wave velocity substantially decreased from 4.3 km/s to 3.7 km/s. A low-velocity zone which generally occurs near the lithosphere-asthenosphere boundary is usually characterized by a huge drop in S-wave velocity. This is because the low-velocity zone signifies a certain degree of partial melting and S-waves are unable to pass through liquids.

Previously, the estimated crustal thickness from H-k analysis is about 43 km beneath the station with Vp/Vs ratio of 1.55. The interpretations of the final velocity models do not vary too much from the results estimations from H-k analysis. Thus, the outcomes from waveform inversion are proven reliable and suitable. Hence, a crustal-mantle model beneath KKM station in Kota Kinabalu is constructed with 40 km of crustal thickness above the Moho boundary (upper crust of 26 km thick and lower crust of 14 km thick). Additionally, the lithosphere-asthenosphere boundary is detected by the low-velocity zone at 66 km depth underneath the station. The crust beneath the Kota Kinabalu region appeared to be thicker than the average continental crust which is about 35 km. This might be due to the crustal thickening that occurred after the continental-continental collision of the South China Sea margin with Sabah margin which also produced a broad range of mountains along the collision margin.

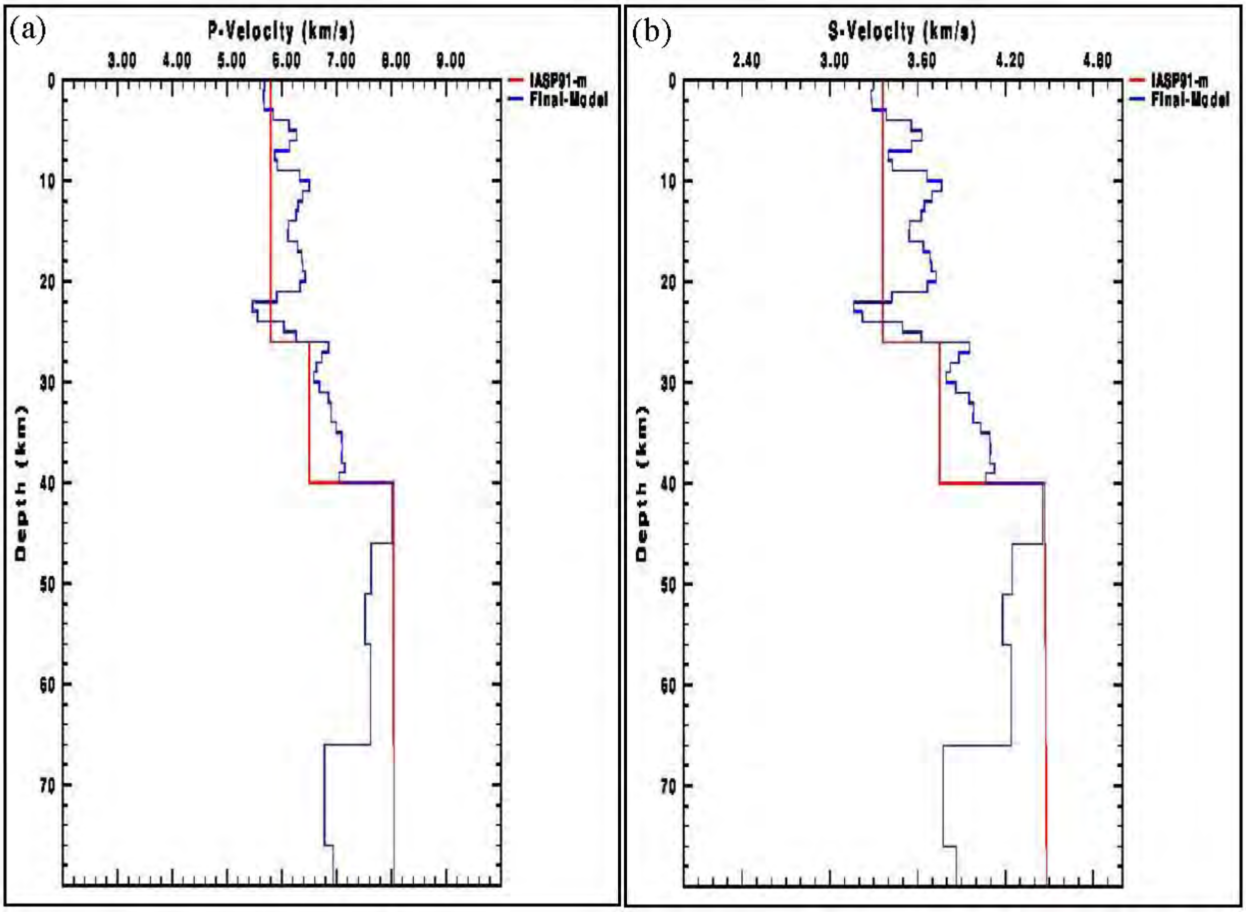

Figure 10: Velocity model after the 2nd and final inversion for (a) P-wave model and (b) S-wave model.

CONCLUSION

The receiver function from tele-seismic earthquakes generated 1-dimensional P-wave and S-wave velocity models in which the crustal properties beneath KKM station are discovered. The explications of these 1-D velocity models show that the Conrad discontinuity is detected at depth 26 km, the Moho boundary is at depth 40 km whereas a low-velocity zone occurred at 66 km depth which indicates the lithosphere-asthenosphere boundary. Hence, the crustal thickness is 40 km consisting of 26 km of the upper crust and 14 km of the lower crust. The velocity input within the crust has a P-velocity range of 5 km/s to 7 km/s and S-velocity range of 3 km/s to 4 km/s. The P-velocity and S-velocity reached 8 km/s and 4.5 km/s as it hits the Moho boundary at 40 km depth beneath the station. These velocity profiles and crustal thickness are proven reliable by cross-checking the results with H-k analysis. Consequently, the very first crustal-mantle model in the Kota Kinabalu region is thus created offering a new subsurface geological perspective within the region.

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