Identification of Moho Discontinuity Depth Variations and Subduction Slab in North Sumatra Region Using Receiver Function Method

R Pratama*, P Ariyanto, A Wijaya, and S Ariwibowo
Sekolah Tinggi Meteorologi Klimatologi dan Geofisika

*E-mail: rian8pratama@gmail.com

Abstract. Northern Sumatra is an area with a complex structure of the earth's crust. This area is very suitable for studying the state of the lithosphere in the subduction zone, where the average distribution of earthquakes with magnitudes greater than 5.0 occurs due to the movement of the subduction zone. This study aims to map the depth of the Moho discontinuity and subduction slab under 3 seismic stations in northern Sumatra, where 3 broadband sensors are 3 components of the BMKG seismograph network (Meteorology, Climatology and Geophysics) using the receiver function method. This study used teleseismic earthquake data with a distance of 30⁰ - 90⁰. Inversion of the neighbourhood algorithm is used to get the S wave velocity model and the \( \frac{V_p}{V_s} \) value used to migrate the amplitude of the receiver function from the time domain to the depth domain. The depth of the Moho in northern Sumatra varies, under the GSI station the Moho depth is shallow ~ 9 km, while the Moho depth for the other stations is on average 19 - 47 km. The slab is identified at a depth of ~ 35.5 - 192.54 km below the GSI station to the TSI station where the position of the linear station is towards the Indo-Australian subduction zone. The low speed zone can be identified in the study and found to be in the range of ~ 10 - 35 km below the surface of the Toba caldera.

1. Introduction
The island of Sumatra is one of the regions that has a unique tectonic structure so that many geologists and earth experts pay special attention to this island. This is because the island of Sumatra has two geological conditions that can affect seismic activity and the tectonic conditions of the island of Sumatra. First, the subduction zone which is the boundary between the Indo-Australian plate that plunges into the Eurasian plate, this zone has the potential to cause an earthquake with a relatively greater magnitude that is very likely to cause a tsunami. Second, the Sumatra fault zone, also known as the Semangko fault or Sumatran Fault Zone (SFZ). This zone divides the island of Sumatra in two, stretching along the Bukit Barisan mountains, from the Andaman Sea to Semangko Bay [1]. These two zones cause Sumatra Island to be very vulnerable to earthquakes.

Northern Sumatra is an area with a complex structure of the earth's crust to study the state of the lithosphere in the subduction zone, the average distribution of earthquakes with magnitudes greater than five occurs due to the movement of subduction zones, can be seen in Figure 1. This zone extends from the Andamans to the Sunda Strait and continues as far south as Java. Many natural phenomena caused by deformation of the structure of the earth's crust (subduction zone and Mentawai Fault) occur in this region.
Figure 1. Seismic map in northern Sumatra region

The earth's crust is a trigger for natural phenomena such as earthquakes, volcanic eruptions, tsunamis and other natural phenomena. Therefore, research on the structure of the earth's crust which includes subduction slab analysis, Moho depth discontinuity depth analysis of variations in crust thickness, $V_p / V_s$ ratio, and velocity profile are very important parts to understand the geodynamic mechanism of plate movements that occur beneath the earth's surface and its impact on the earth's surface. In addition, the presence of a more localized velocity structure in the study area is expected to be able to improve accuracy in determining the earthquake hypocenter.

The method that the author uses to examine the structure of the northern Sumatran crust is the receiver function method. The receiver function is a time series function that is used to determine the physical condition of the teleseismic wave before entering the receiver or sensor [2]. Research with this method, especially in the Sumatra region, has been carried out three previous studies and obtained the results of crust thickness on the island of Sumatra [3-5].

2. Data and Method

The data to be used in this study are teleseismic signals with epicenter distance criteria $30^\circ$ - $90^\circ$ (see fig.2) and magnitudes greater than 6 (M $>$ 6) recorded on the BMKG seismograph network.

Figure 2. Earthquake distribution with a distance of $30^\circ$ - $90^\circ$ from the location of the station
The receiver function is a time series function obtained by processing the three component seismogram data so that only the relative response of the earth's structure under the receiver sensor is formed when a teleseismic wave passes through a boundary layer below the earth's surface with a contrast impedance. Clayton [6] showed a general equation for a seismic wave that was recorded on a seismometer that had corrected the instrument.

Bath [7] have grouped them into 6 phases, in the first phase, some energy will be transmitted directly to the surface of the earth (Pp). In the second phase, part is reflected and part is converted to S (Ps) waves. The amplitude of the Ps conversion phase is affected by the amount of impedance contrast at the boundary layer (see fig.3).

![Image of seismic wave conversion phases](image)

**Figure 3.** Seismic wave conversion phase and its reflecting phases as they pass through the Earth's surface layer and the Moho layer (modified by Yunartha, 2013).

In this study the authors used the 2-D RTZ rotation as previously researched [8] that only rotates the horizontal seismogram component in accordance with the azimuth of the direction of the earthquake coming, where the Z component shows the same direction as the original ZNE recording then iterative deconvolution is carried out using horizontal and vertical component seismogram cross correlation [9]. For processing the receiver function we use a CPS (Computer Program for Seismology) [10]. We apply neighbourhood algorithm (NA) in this study to derive S wave velocity model through inversion method [11]. All receiver functions at each station were stacked before inversion process. For the inversion process, we cut the receiver function’s time window from 5 s before the direct P wave arrival to 25 s after it. We divided the crustal parameters for the inversions into six horizontal layers: sediment, basement, upper crust, middle crust, lower crust and upper mantle. Each layer contains four parameters describing the thickness of the layer (km), \( V_p/V_s \), the S wave velocity at the top and bottom of each layer. We set the initial parameter after trial and error with low misfit. We calculated the NA inversion with 5000 iterations refers to research that has been done using the same inversion [12] to get the best S wave velocity models. To derive the depths of subduction slab, we using migration technique. We use initial velocity model from NA result to get migration time to depth.

3. Results and Discussion
In this study the location of the station used has represented 3 zones in northern Sumatra, namely: the front arc ridge zone (Fore arc ridge), the front arc basin zone and the back arc basin zone. Each of these zones has different characteristics to the receiver function signal generated due to the influence of different subsurface structure in each of these zones. The station used is also linear from the southern end to the north end of the northern Sumatran region so that it can see the form of subduction slabs in this area.
3.1. GSI station

The results of NA inversion in the form of S wave velocity model and $Vp/Vs$ ratio based on depth can be seen in Fig. 4. At the GSI station, the S wave velocity profile shows a 2.1 km thick sedimentary layer marked by a low S wave velocity at less than ~ 2.47 km / s and $Vp/Vs$ 2.26. Then an increase in the speed of the S wave to 3.1 km / s to a depth of ~ 5 km. S wave velocity then decreases to a speed of 3 km/s followed by an increase in the value of the velocity $Vp/Vs$ to 1.92 to a depth of less than 8.3 km, this is likely due to the influence of magma from the caldera toba. The Moho layer is estimated at a depth of ~ 11.2 km marked with a positive velocity gradient that is quite significant up to a velocity of ~ 3.61 km / s.

Figure 4. Neighbourhood algorithm result for GSI station (a) velocity structure S wave, red lines represent the best fitting model. The grey shaded area indicates all models seek in the inversion (b) the observed and predicted receiver function.
The migration results from the local velocity model can be seen in Fig. 5 indicating the estimated Moho depth at the GSI station is estimated to be at a depth of 9 km where the Moho depth is associated with the Ps wave phase marked by a black dashed line. Whereas the subduction slab is at a depth of about 35.5 km, which is shown by the second Ps conversion phase which is marked by a Dotted Green line. This result is supported by previous studied [13] in Sumatra which stated that the depth of the slab under the GSI station ranged from 20 km - 40 km by the relocation method and was [14] using the tomography method, the slab depth ranged from 30 km - 38 km.

![Figure 5. Migration receiver function GSI station](image)

3.2. PSI station
The results of NA inversion in the form of S wave velocity model and $V_p/V_s$ ratio based on depth can be seen in Fig 6. At the PSI station, the S wave velocity profile shows the existence of a low S wave velocity at depths of less than 1 km with speeds of less than ~ 2.2 km/s. Then an increase in the velocity of the S wave to 3.28 km/s to a depth of ~ 8 km. The S wave velocity then decreases to 2.62 km/s followed by an increase in the velocity value of $V_p/V_s$ to 1.9 to a depth of less than 18 km, this is likely due to the influence of magma from the caldera toba. The Moho layer is estimated at a depth of ~ 32.2 km marked with a positive velocity gradient that is quite significant up to ~ 3.91 km/s.
Figure 6. Neighbourhood algorithm result for PSI station (a) velocity structure S wave, red lines represent the best fitting model. The grey shaded area indicates all models seek in the inversion (b) the observed and predicted receiver function.

Migration results using the local velocity model can be seen in Fig. 7, based on the migration results, Moho estimates that the station is at a depth of about 34.5 km indicated by a fairly stable Psv conversion phase marked by a black dotted line, This is not much different from the results of research [5] who stated that Moho was under the PSI station about 33 km using the H-κ stacking method and 35 km with receiver function method from previous studied [15]. Subduction slab was at a depth of about 157.46 km marked by a green dotted line on positive phase which has an amplitude not too strong but stable. Under this station there is also a low velocity zone area at a depth of about 14.5 km marked by a line, this is due to the location of the PSI station adjacent to the Toba caldera.
3.3. TSI station

The results of NA inversion in the form of S wave velocity model and \( V_p/V_s \) ratio based on depth can be seen in Fig 8. At the TSI station, the S wave velocity profile shows a 3 km thick sedimentary layer characterized by a low S wave velocity at a depth of less than 2.5 km with a velocity of \( \sim 1.48 \) km/s and a high \( V_p/V_s \) ratio to \( \sim 2.56 \). The S wave velocity then increased to 3.82 km/s to a depth of \( \sim 8 \) km, then a decrease in the speed of the S wave to 3 km/s to a depth of 12.1 km. The depth of the Moho layer is estimated at \( \sim 27 \) km depth marked by a positive velocity gradient of up to \( \sim 3.63 \) km/s.
Figure 8. Neighbourhood algorithm result for TSI station (a) velocity structure S wave, red lines represent the best fitting model. The grey shaded area indicates all models seek in the inversion (b) the observed and predicted receiver function.

Based on the migration results shown in Fig 9, it is estimated that Moho at this station is at a depth of about 35.5 km indicated by a fairly stable Ps conversion phase marked by a black dotted line, subduction slab is at a depth of about 192.54 km which is marked by a green dotted line in the positive phase which has an amplitude that is not too strong but stable. Under this station there is also a low velocity zone area at a depth of about 48 km marked by a yellow dotted line, this is probably due to the location of the TSI station adjacent to Mt. Sinabung.
4. Conclusion

The results of velocity modeling using the inversion of the neighbourhood algorithm at 3 BMKG seismic stations obtain varying S wave velocity and are used to migrate the amplitude of the receiver function to depth and successfully describe the presence of Moho, low velocity zones and Subduction Slabs in the north Sumatra region. Moho depth in of 9 - 42.54 km, there is a thickening of the earth's crust to 15 km in the area around the volcano arc. The low velocity zone is identified from the at depths of 10-35 km caused by the presence of magma chamber of Toba Caldera and the depth of the slab identified at ~ 35.5 km beneath the GSI station, at ~157.46 km beneath PSI station, at ~192.54 km beneath the TSI station.

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