Early Results of Eastern Indonesia P-wave Tomography Study Using Regional Events

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Abstract. The tectonic system of Eastern Indonesia is controlled by several major and minor plates, such as Indo-Australian, Australian plate, and Pacific plates. This area is known for its complexity, and high seismic activity. This study tries to image the complex structures beneath this region by employing regional events data and seismic tomography methods. We used five years of regional events catalog provided by the Indonesian Agency of Meteorology, Climatology, and Geophysics. We have sorted 7336 events recorded between 120º – 136º longitude and 0º – 13º(-) latitude consisting of 46446 P and 15467 S wave arrival data. Relocated hypocenter map shows a better constrain location on seismicity along outer Bandar Arc. A dipping pattern of seismicity is seen that is going deeper to the Banda Sea. The seismicity map also images a steep angle pattern of seismicity that could be related to the subduction slab roll-back model at North of Wetar island. Interestingly, we spotted a seismicity gap in West Seram that could be linked with slab tear zone. The checker-board test suggests a proper resolution is still reliable to a depth of 200 km with a less interpretable model at a depth of 300 km. P-wave tomographic models image the high velocity dipping down going slab. The Banda slab is seen to subduct from south Timor Island to the north, from east Tanimbar and Aru Island to west part, and from north Seram Island to south. We observed the down-going slab meet from all directions at about 300 km beneath the Banda sea. P wave tomogram also shows the Timor Island slab has a steeper dip that agrees with the seismicity pattern. Near the Seram island, we identify a low-velocity anomaly zone infiltrate the Banda slab beneath the shallow part of West Seram, which was previously interpreted as slab tear zone. This study also noticed a higher velocity tomogram model at North of Wetar island that might indicate a
back-arc thrust. Lastly, a low-velocity band is also exposed at a shallow depth close to the volcano chain along that Banda volcanic arc.

1. Introduction

Indonesia has frequent seismic activity from the West part in Sumatra to East part in Papua. The Indonesian Meteorology, Climatology, and Geophysical Agency reported 44% of earthquakes in Indonesia occur in eastern part of Indonesia and is the subject of this study. Some recent events are: the 26th September 2019 Ambon’s earthquake with 6.8 magnitude and 10 km depth causing dozens of people died, thousands of people injured, and damaging public facilities. The 30th September 1899 Seram’s earthquake with 7.8 magnitude and 12 km depth took thousands of lives and wreck a lot of buildings. Based on plate reconstruction [1], Indonesia is dominated by three major plate movement which are Indo – Australia, Eurasia, and Pacific Plates. Eastern Indonesia itself mostly be affected by Indo – Australia plate movement toward north and collide with Eurasia plate with convergence rate around 7.7 cm/ year [2] and resulting subduction path along southern part of Indonesia include Banda Arc. The subduction in Banda Arc is unique because it has D – shape geometry or some research said concave spoon/ half-bathtub shape geometry [3]. The curved Banda Arc subduction most likely caused by deformed Australian plate in Banda embayment which give away the unique D – shape and stirred by slab rollback that make the subduction path fitted with Banda embayment. Some study also mentions about slab tear in West Seram Island, to be exact under Buru Island, which indicate because of mantle resistance towards the subduction movement and resulting slab rotation that lead the tearing beneath Buru Island.

As the additional, local structure like back-arc thrust formed in North Wetar Island which happen because the energy accumulation accommodated from subducting slab in Timor Island. Besides that, as the manifestation of subduction, volcanoes are formed along Banda volcanic arc such as Banda Api, Manuk, Serua, Nila, Teon and Damar Volcanoes.

Previous study suggest that Banda Slab is a single system that curved into 180° containing young oceanic crust and mostly formed following the Banda embayment shape and rollback process which lead to crust deformation [4], [5] also found that seismic tomography successfully depicts Banda Slab as a single system that twisted and forming spoon-shaped structure towards Banda Sea as well as conforming the slab rollback scenario. In the other hand with seismicity and fault plane study [6] proposing Banda Slab constructed by two different system. The first one is the Timor – Aru Trough system from south and the second one is the Seram Trough system in the north that joined the Banda Slab because New Guinea Tarera – Aïduna Fault Zone extension.

This study expected to map the slab geometry along Banda Arc include the tearing zone under Buru Island in West Seram and back-arc thrust structure in North Wetar to validate which structure dominantly generate earthquake with high potential risk of destruction and also the volcanoes activity along Banda Volcanic Arc.

2. Data and Method

The research took place in Eastern Indonesia, to be specific in Banda Arc. This research is a collaboration between Universitas Pertamina with Indonesian Meteorology, Climatology, and Geophysical Agency (BMKG). Earthquake data provided by BMKG from 2015 – 2019 constraints latitude 10.617°S until 0.220°S and longitude 122.695°E until 133.440°E. The data consists of travel time from each event in each seismic station along with its hypocenter parameter such as longitude, latitude, origin time, depth, and magnitude. There are 22 total seismic stations and 7336 total events with 46446 P-wave observation and 15467 S-wave observation.
Based on seismicity map, the possibility of slab subduction shown by the earthquake event pattern from shallow in outer Banda Arc and getting deeper beneath Banda Sea, The east Timor Trough signify the deeper slab area for its earthquake events appear until 600 – 700 km, this area also have probable a steeper dipping slab shown by abrupt change in earthquake depth change from south to north. Besides, seismicity gap likely appears in west of Timor Island, this also confirmed by International Seismological Centre (ISC) and United States Geological Survey (USGS) catalog data event. The Weber Deep area likewise shown rare seismic activity, [7] explain the lack of seismic event due to low angle normal fault, further explanation also mention that the low frequency could indicate energy accumulation which lead to larger event. Moreover, there is a seismic jump pattern found in Seram specifically beneath Buru Island, the seismic event occurs in the shallow area until depth 200 km, then it’s unlikely happen between 200 km – 400 km, but then continuously shows seismic event again after depth 400 km. As additional, in the north Wetar Island, revealed a thrusting pattern from north to south in a shallow feature around 100 km.

Figure 1. Earthquake and station data distribution

22 total BMKG seismic station utilized in this study distributed from Flores, Timor, Tanimbar, Aru, Papua New Guinea, Seram, Buru and many more surrounding Island. The station distribution is likely uneven due to the installment difficulty in some area, Timor and Seram island is quite dense distributed meanwhile Banda Sea, Aru, Tanimbar still rarely has station around it.
Travel time seismic tomography applied in this study to image subsurface based on seismic velocity model. This method utilizes earthquake propagation travel time from source to receiver, AK135 velocity [8] as initial model and pseudo-bending ray tracing [9]. Model parameterization be solved by dividing the study area into several grid horizontally (x, y) for longitude and latitude and vertically (z) for depth. Grid interval made in 60 km for x and y axis but 100 – 200 km for outer focus area and varies from 30 – 60 – 120 km for z axis depends on how much earthquake event there to cover our inversion. In the shallower area with denser events applied smaller grid, while deeper area with rare seismic activity applied sparser grid. The determination of grid will affect the ray coverage in inversion process as well as the final resolution.

The process done by SIMULPS12 [10] which simultaneously inverse seismic velocity model and hypocenter location. As a result of using slowness, the inversion process using non-linear inversion with linear approaching to solve the inversion problem. Sometimes, in the inversion process we also face matrix singularity problem due to the lack of ray tracing data in several grids. As the solution for this, we use damping parameter. Optimum damping parameter obtained from trade-off curve between data and model variance [11]. It is associate with significant reduction of data variance and at the same time did not increase the model variance significantly. In this study, we use 70 as optimum damping parameter with 0.34155 s² data variance and 0.01118665 km²/s² model variance.

3. Results & Discussions

There is not much difference between hypocenter distribution before and after relocation, the main change is the reduction of earthquake fix depth in shallow area as well as deep event seemingly diminished due to lack of seismic station that record the data. While other part did not change that much and still shows similar patterns. This happen because BMKG data even before relocation process already has an acceptable residual time value for each earthquake in every station, hence we only need to improve the residual error. After relocation, we can enhance the residual time value in 0 s which make the residual error smaller and improved the data quality significantly.
Figure 2. Residual time histogram; Residual RMS error, Earthquake magnitude histogram, and Hypocenter distribution before and after relocation

To determine which tomogram area that has acceptable resolution, therefore we can interpret confidently, we performed checkerboard resolution test (CRT) and Derivative Weight Sum (DWS). We use all the same parameterization but using synthetic velocity model with additional 5% noise. Based on the CRT, for shallower area, Seram and Timor Island shows a high resolution while the deeper area shows a better resolution around Banda Arc to Banda Sea. Besides, the resolution is well-solved and reliable to interpret until depth 200 km. This proved by the DWS which show the density of ray length through the grid, Seram and Timor Island both shows a denser ray coverage in shallower area, while in the depth between 100-300 km shows quite dense ray in northwest of Banda Sea.
Figure 3. Checkerboard Resolution Test and Derivative Weight Sum result for each depth.
Whereas in depth beneath 300 km is likely less interpretable due to lack of ray coverage. DWS shows the ray only cover some little area in the northwest of Banda Sea. However, it also confirmed that we still have seismic ray down to depth 600 km resulting the possibility of structure reach depth 600 km or more. This resolution is most depending on the seismic station location and earthquake distribution, in this study seismic stations are a lot tighter in the Timor, Seram and West Papua which make this area receive more earthquake ray which make the resolution well resolved and more interpretable than the rest of the area.

**Figure 4.** Result of P-wave tomography from depth 0 – 600 km. Blue and red portray positive and negative anomaly respectively.

Looking at the horizontal slice tomogram, in Timor, Tanimbar and Aru (Banda Arc Segments) shown positive anomaly depict by blue color move from south to northwest around Banda Sea continuously as depth increases. Moreover, positive anomaly also visible in Seram Segment moving from northeast to southwest as depth increases. Thus, those positive anomalies interpreted as Indo-Australia’s subducted slab plate from Banda Arc to Banda Sea forming the spectacular Banda curve slab until depth approximately 600 km. While negative anomaly shown clearly in depth 30 km around Alor (north of Timor Island), and small island along Banda Arc known as “Banda Ring of Fire”, this negative anomaly depicts by red color in shallow area till depth approximately 80 – 100 km. Beside that negative anomaly also found in west of West Papua in depth 10 – 30 km.
Figure 5. Vertical slice of tomogram from A – L (the cross-section line shown in fig.4 depth 600 km)
In vertical slice tomogram, the positive anomaly distributed fit with the possibility of slab from south of Timor Island and north of Seram Island. In cross-section A, B, C, and D, the positive anomaly shown a specific steep dipping until 600 km in west of Timor Island due to the possibility of rollback extension from Java – Sumatera Slab. Furthermore, in the cross-section D, in the north area near Seram Island, there is a positive anomaly in shallow depth influenced by Seram Slab, but then discontinue until depth 300 – 350 km, the positive anomaly is reappear back in the depth more than 350 km, some of previous research [12],[3] said there is a possibility of break-off or tearing slab beneath west of Seram thus its showing negative anomaly infiltrate the positive anomaly along Seram Slab. In cross-section E, F, G and H, the Slab from both direction Seram in north and Timor in south showing a clear positive anomaly alongside with the hypocenter location subducted and meet in depth approximately 400 – 500 km. These also shows how the slab subducting from east to west proven by the east part is more shallower or sloping than the west part. Moreover, the cross-section I, J, K, L shows the same pattern where slab depict in positive anomaly from north and south and increasingly sloping to east where its start subducting.

Local structure like back-arc thrust feature and volcanic activity could be identified by the tomography as well. The back-arc thrust depicted in the north of Wetar Island shown by positive anomaly shown in cross-section D and F. This also supported by hypocenter distribution in that area dominated with shallow earthquake below 100 km. This back-arc thrust formed as the result of subducting plate in Timor Island which make a pressure accumulation in north of Wetar. Besides, negative anomaly found along Banda Volcanic arc in depth 30 – 80 km known as volcanic front-line zone. Famous volcanoes along that zone such as Banda Api, Manuk, Serua, Nila, Teon and Damar shown negative anomaly beneath them which interpreted as partial melting and magma chamber of those volcanoes.

4. Conclusion
As for the conclusion, Banda geological features are depicted successfully using earthquake travel time tomography. Banda Slab subducted around Banda Arc, from Timor Island in the south and Seram island in the north shown by positive anomaly dipping down until depth 600 km. Wetar back-arc thrust also identified with positive anomaly in depth less than 100 km, and the volcanic activity around the area portrayed as negative anomaly beneath the Banda Volcanic Arc.

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