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Source Mechanism Analysis By Using Tensor Moment Inversion (Study Case : Pidie Jaya Earthquake in 2016 December 7th)

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Abstract. The earthquake event with M 6.7, on 7th December 2106 in Pidie Jaya, inflicted heavy casualties and material losses. In 1967, an earthquake event occurred near Pidie Jaya with M 6.1 which caused by Samalanga fault. However, the Pidie Jaya earthquake, although very close, but was not caused by the Samalanga fault activity. The latest, an unkown fault was considered as an active fault and the location of earthquake sources and and a part of the branching of Samalanga fault. It is very interesting to discuss, generally earthquake in Aceh, always happen on Sumatera fault's path. Analysis of earthquake source mechanism is very important to do, to know the fault characteristic and direction. The analysis in this study involves inversion of tensor moments with isola program on each recording component, which will provide a synthetic wave as a comparison. The earthquake mechanism which obtained from the inversion is strike-slip with left-lateral and has the parameter strike 254°, dip 80°, and rake 48° on the first nodal plane as the true nodal. While, the second nodal has the plane parameter is strike 153°, dip 42°, and rake 165°. From these parameters, the first nodal plane that has a strike 153° is considered to be interpreting the new fault line as it is also followed by the direction of the spread of aftershocks. These result indicate that the Samalanga Fault is not the cause the Pidie Jaya earthquake, and shows the real direction of Pidie Jaya fault from South-West to North-East with lef-lateral orientation.

1. Introduction

Interaction between plate tectonics and local faults makes Aceh region vulnerable to the earthquake events. The interaction occurs because of geodynamic process that cause a relative movement in the interface zone between one fault to others. The movement produces energy which can generate a deformations and can make the occurrence of earthquakes. In the Aceh region, earthquake activity oftenly occurs after several major earthquake events happened from subduction zones. The series of earthquakes can provide stress that will trigger some activity of local fault on land and produce new earthquake sources. Aceh region has five local fault that is quite active and has a recurrence time of 10 - 15 years. In the last decade, two faults have been broken at Tripa, and Samalanga-Sipopok fault in 2013.



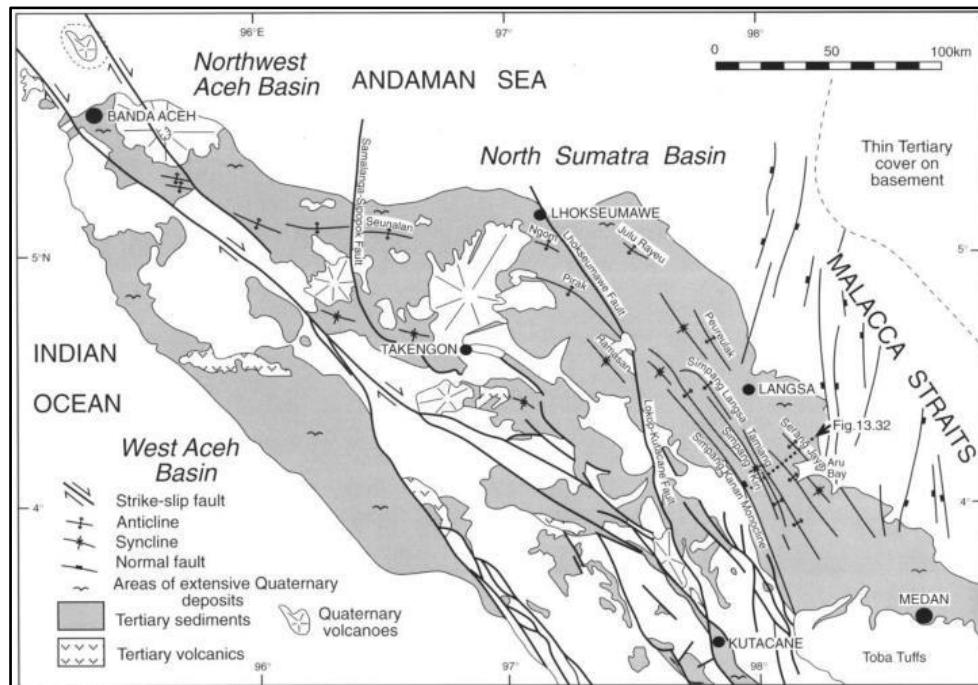


Figure 1. The tectonic map on the basin area at northern part of Sumatra Island [1].

In **Figure 1**, we can see some faults in Aceh region is part of the Sumatran Fault System. The tectonic pattern of Aceh region is controlled by tectonic plates activity from Indian Ocean subduction. The plate is the oceanic plate (Indo-Australian plate), which moves northward with a velocity 6 - 8 cm/year, with larger densities pounding the European continent - Asia (Eurasian plate) and producing subduction. The subduction resulted a series of front-line non-volcanic arches (forearch islands) such as Simeulue, Nias, Batu, Siberut to Enggano Island. In Central Aceh, after Bener Meriah earthquake in 2013, [2] did passive seismic research to found some unknown active faults and imaging them which has right lateral direction.

Fault is a picture of a plane in the earth crust, having side which connected by an asperity (lock). Both sides have interface zones that are mutually attached due to the pressure and friction force on the surface. After each sides still continue to move, the fault plane would be driven gradually by tectonic forces but still firmly sealed. Most of Aceh region is composed by sedimentary and volcanic rocks from the tertiary and quarter periods. Folds are mostly found in the north and east, due to deformation of rock layers resulting from force and pressure from local faults or tectonic plates. Thus, rocks move from the initial position and form the arch. The folds are subjected to horizontal pressure, resulting in anticline and syncline formation. In addition, the Bukit Barisan mountain range with the path and distribution of volcanic constituent rocks are in the middle. The circuit has a straight-line straightness system, and is called the Sumatran Fault that divides Sumatra Island from Semangko Bay to Banda Aceh. The spread of the epicenter on the land of Aceh, always sourced from the alignment zone of the Sumatran Fault System.

However, the Pidie Jaya earthquake is not, but on the north, near the fault location of Samalanga. In the north of Aceh, the fault of the Samalanga is a branch of the Sumatran Fault that aligns northward, and last, the earthquake occurred in 1967 with M 6.1. On December 7, 2016 at 05:03:36 pm, an

earthquake occurred with M 6.5 located in Pidie Jaya, Aceh, Indonesia. The epicenter coordinates location at 5.25° N and 96.24° E, precisely on land with depth at 15 km and have a distance 18 kilometers southeast from Sigli, and 2 kilometers north from Meureudu. **Figure 2** shows us the earthquake intensity was felt in Pidie Jaya IV SIG-BMKG (VII-VIII MMI), Lhokseumawe, Lhoksukon, Bireun II SIG-BMKG (IV-V MMI), Banda Aceh, Meulaboh II SIG-BMKG (III-IV MMI). According to the National Disaster Management Agency (BNPB) report, at least 104 people died as a result of this earthquake. The initial analysis, Pidie Jaya earthquake hypocenter is not far from the Samalanga fault. However, the assumption that the fault of Samalanga as the cause of the earthquake is not appropriate. The previous quake's epicenter was due to the Samalanga fault activity. After quality control on advanced analysis, the result is far from that fault. A hypocenter occurred in the alignment of an unknown local fault.

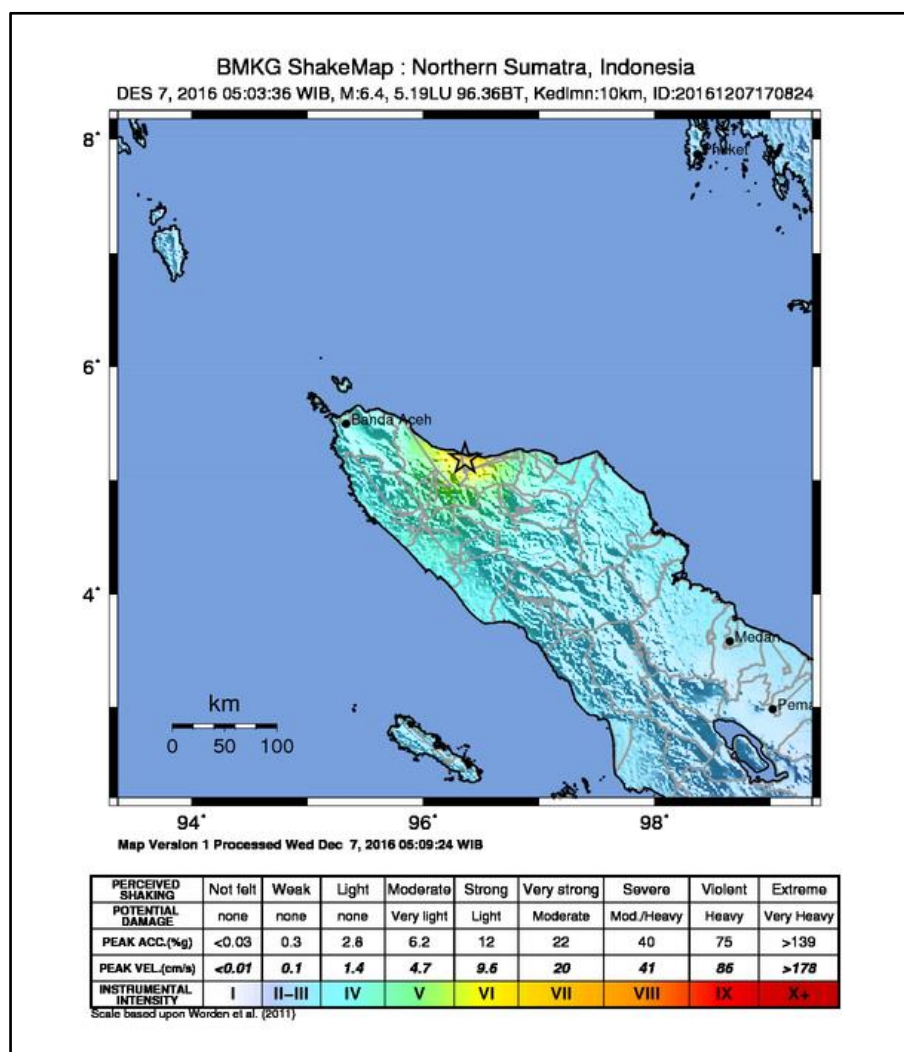


Figure 2. The shakemap of Pidie Jaya earthquake from BMKG with MMI scale.

Parameters that released by USGS provide some information if this earthquake occurred on land and was generated by strike-slip activity in the direction of south-western-trending strike, and unknown type and name of fault. BMKG released the distribution of aftershock which also follows the strike direction on the nodal plane which has a south-northwest trending strike. Therefore, the orientation of the fault, structure and type of fracture in the Pidie Jaya earthquake requires ongoing analysis. It is necessary to map the straightness, type, structure and fault properties, which can later be used to

design a mitigation. The analysis in this study aims to model and analyze the source mechanism, and compare it with several other models.

Modeling of source mechanism is done by applying the inversion method to tensor moment. Analysis and modeling of earthquake source mechanism by inversion on moment of tensor conducted by Isola (Isolated Asperities) program and using green function [3]. The concept of green function with discrete wave number method from [4] and [5], to produce synthetic data on displacement waveform. The entire wave is used and the green function is calculated. The moment tensor of sub-events is obtained by minimizing leastsquare from a match between the observation and synthetic signals, while the position and time of the sub-events are optimized through grid-search. Solutions and approaches in Isola use the concept of multi point-source by doing iterative deconvolution techniques, previously performed by [6]. The solution of earthquake source mechanism with Isola has been successful and widely applied by many researchers from Indonesia as well as outside.

Modeling the source mechanism with the Isola will produce the M_w (moment magnitude) value, the moment tensor value on each resultant of the x, y, z, azimuth, plunge, DC (Double Couple), CLVD (Compensated Linear Vector Dipole) components, centroid time and the value of reduction variance. [7] analysed and got a solution for 2009 and 2010 Himalaya earthquake, with applied a frequency band filter for inversion with range 0.02 - 0.11 Hz (2009 earthquake) and 0.08 - 0.20 Hz (2010 earthquake). [8] conducted an analysis to identify source mechanisms on 15 earthquakes with a magnitude range of moments (M_w) 4.1 - 6.4, which occurred in ten major segments located along the Sumatera Fault System. Many researchers get the focal mechanism of earthquake by using the Isola program because it based on GUI Matlab and easy to learn. The tensor moment inversion method in Isola program is very good to modeling the focal mechanism of earthquake which use near-field station.

2. Materials and Method

To do a calculation, the digital waveform of seismogram with 3 components (NS, EW, and UD) is needed and used in this research. Data was taken and downloaded from BMKG (Meteorology Climatology and Geophysics Agency of Indonesia), and also taken from IRIS Wilber3 for regional stations from Thailand and Malaysia. All data selected for Pidie Jaya earthquake on 7 December 2016 with M 6.5 are from IA (Indonesia) with 3 stations, MY (Malaysia) 3 stations, and TM (Thailand) 2 stations. The selected stations are combined between local and regional with seismograph sensor type is broadband (0.000 - 50.000 Hz). In addition, polezero data, velocity model data and earthquake parameter data are required as initial inputs. The waveform data used in the SAC (Seismic Analysis Code) format. Polezero data is used to obtain real earthquake recording by eliminating the instrument response, because the received waveform data is still combined data in the form of convolution between waveform, path, and response instrument.

We used the velocity model used in this paper from global tomography model, given the absence of local model that is suitable with geological and tectonic conditions in the research area. The method which used to calculate the source mechanism solution in the Isola program is doing a inversion on moment tensor in each axis (x, y, z) and iterated by deconvolution [9]. The green function is used to generate synthetic signals based on the structure and model of the earth, in which the signal is considered a waveform model to be seismographically recorded from the signal. The green function is calculated by applying the discrete wavenumber method. Synthetic results from calculations with green functions in the form of displacement data will be compared with observation. The parameters of the earthquake source will be estimated by the inversion method using the model of the green function. With green function, estimation can be done because using synthetic signal. The synthetic

signal will be compared with the observation signal, the comparison will show the fitting waveform of the three best components. Good fittings are seen with overlapping overlays.

Accuracy was measured by overlaid observed signals with synthetic signals. To get an overlay form, try and error method must be done by giving good band-pass filter in order to get the fit and best inversion result. The model will has a value of reduction variance (0 - 1) which is a measure of the compatibility of the observed signal and the accuracy of the synthetic signal. The big reduction variance will signify the results more accurate, precise and represent the tectonic structure in there. The measured reduction variance is obtained by providing the appropriate band-pass filter with 4 corner (f1, f2, f3, f4). The inversion used in the ISOLA-GUI program is deviatoric doment densor inversion which calculates the inversion process on the basic components of tensor moments. DC (Double Couple) and CLVD (Compensated Linear Vector Dipole) which used in inversion is the most common and good method [10]. The result of the source mechanism obtained from tensor moment inversion still contains ambiguity. The ambiguity is due to the existence of two nodal fields in earthquake source modeling in the form of strike, dip and rake parameters of both nodal fields. The ambiguity in this case means that the researcher must determine the "true fault plane" of the two fields.

3. Result and Discussion

Observation signal used for green function and inversion from 13 local and regional stations around Aceh province, Malaysia, and Thailand. From 13 stations, only 8 stations that had sufficiently good variant values which obtained from the trial and error process. For visual inspection, we overlaid the comparative results between synthetic and observational signals. Here is the 8 station location which used in this study, and global velocity model.

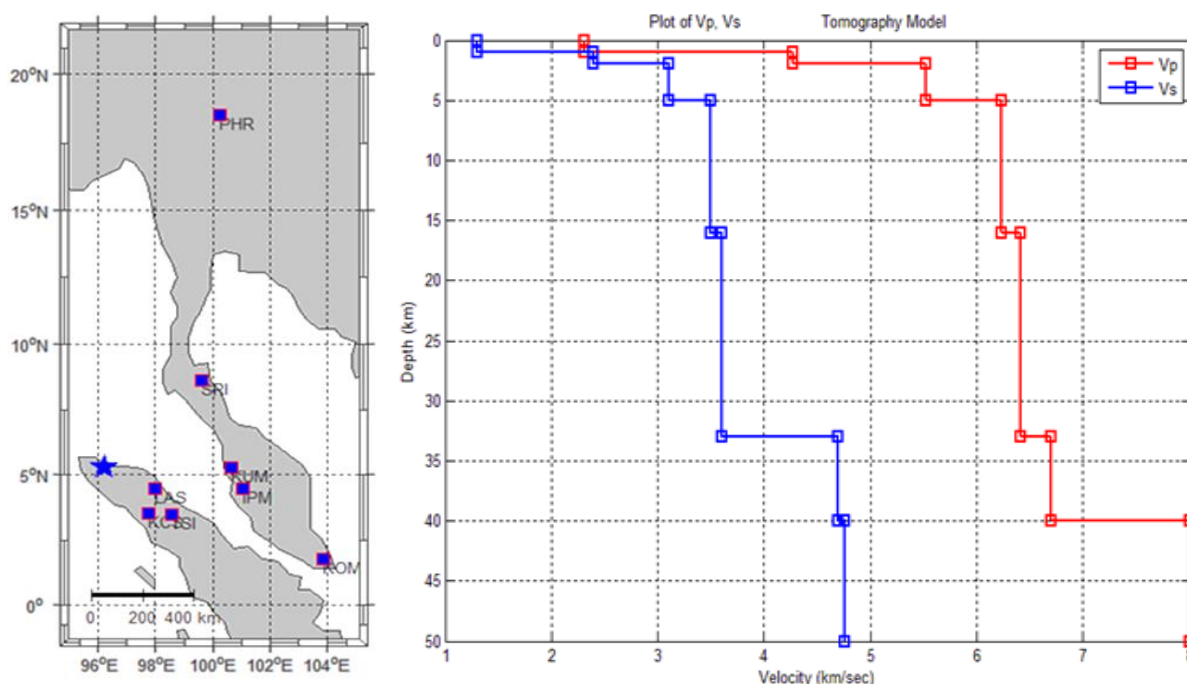


Figure 3. The location of stations which used to do a calculation (left), the global velocity model which used in this research, blue color (Vp) and red color (Vs)(right).

In the processing of Isola, we give the signal duration as an input to do a green function is 409.6 seconds, which is the duration recommended in the Isola program. The 409.6 second duration is used,

since the estimation has covered the entire waveform of each station. The velocity model that used in this research is the global velocity model and shown in **Figure 3**. This velocity model describes the current model of global seismic wave velocity (P wave and S wave). Analysis results from BMKG, that has good quality control, was used as an input for hypocentre location information in Isola. Then, we also got the foreshock from BMKG and any references to assesment the direction fault, because foreshock distribution will show the true nodal plane and follow the strike of earthquake focal mechanism.

The filter used for velocity data conversion to displacement data in the inversion process which shows in **Figure 4** is 0.01 - 0.025 Hz. This filter was used because accordance with [11], which suggesting that low frequency filters for displacement data are useful to get a good point source solution. The type of inversion used in this model is deviatoric moment tensor. **Figure 4** shows the matching data in displacement between the observed signal and the synthetic signal in the three component of seismogram (NS, EW, Z).

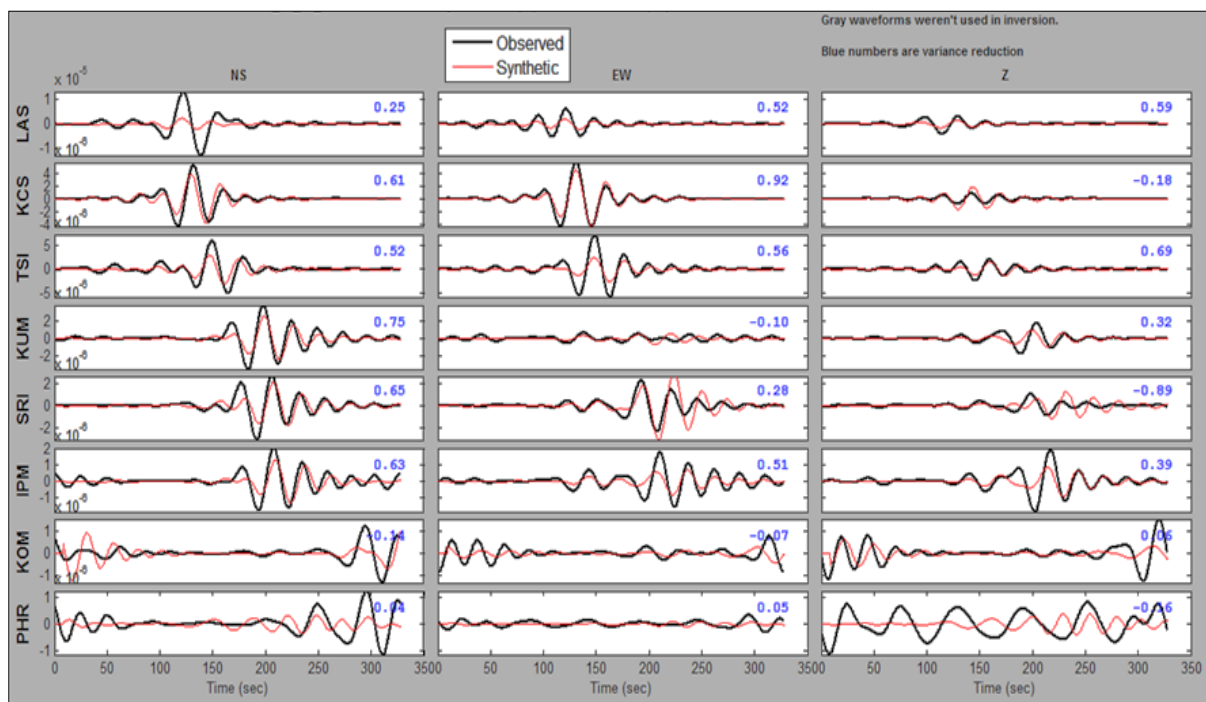


Figure 4. The overlay graph between observation with synthetic signal.

The black signal is an observation signal while the red color signal is a synthetic signal. The value in blue is the value of the variance reduction (0-1). The presented picture is the final result to get a source mechanism model in this research after do a try and error method. This result is obtained directly through Isola's GUI program which runs with Matlab program. Based on Figure 5, there are 8 stations obtained from the inversion on waveform with 3 components. There are 3 stations with initial name LASI, KCSI and TSI with IA code from Indonesia. The value of the match rate between synthetic seismogram and observation of LASI stations on NS, EW and Z components, respectively are 0.25, 0.52 and 0.29. KCSI has a match rate between synthetic seismogram with observations on NS, EW and Z components with value 0.61, 0.92 and -0.18. The level of compatibility between synthetic seismogram and observation of TSI stations on NS, EW and Z components respectively are 0.52, 0.56 and 0.69.

The stations from Malaysia are 3 stations with initial name KUM, IPM and KOM with MY code. The value of the compatibility level between synthetic seismogram and observation of KUM stations on

NS, EW and Z components respectively are 0.75, -0.10 and 0.32. IPM has a good match value between synthetic seismogram and observation on each component of NS, EW and Z, with value 0.63, 0.51 and 0.39. The match value between synthetic seismogram and observation at KOM stations on NS, EW and Z components are -0.14, -0.07 and 0.06, respectively. There are 2 stations with initial name SRIT and PHRA from Thailand was used in this research. The match value between synthetic seismogram and observation at SRIT station on NS, EW and Z component are 0.65, 0.28 and -0.89, respectively. PHRA has good value between synthetic and observations on NS, EW and Z components, the value are 0.04, 0.05 and -0.16.

Based on the reduction variance value, the matching data which shown in Figure 5 generally seems quite relevant, there are only two stations on the Z (vertical) component that still have minus variance values, that is the best value resulting from the trial and error process. The average variance for the four stations used was 0.70 (70%). Based on the value of variance, the results obtained in this study is quite relevant when associated with the actual situation.

4. Focal Mechanism

Earthquakes are caused by fault movement with certain motion as its characters. The fault motion model and the causative character of the earthquake can be identified based on the earthquake moment tensor. This moment tensor is used to describe the direction of earthquake-causing forces. The movement of fault is one of the source parameters cause a vertical deformation in the source area and produce an tectonic earthquake. The fault parameter is also known as the solution of focal mechanism. The focal mechanism is the direction and fault orientation of the tectonic earthquakes. The focal mechanism is divided into four types: strike slip, normal, reverse and oblique.

In general, the angle forming parameters of the faults are strike angle, dip and slip. At the time of the earthquake occurrence, there are two fields that become the reference in determining tensor moment that is auxiliary plane and perpendicular between each fault plane. Based on the results of the strike, dip and rake parameters, we can see the characteristics of the first plane parameters with the strike = 254° , dip = 80° and rake = 48° and the second plane of the strike value = 153° , dip = 42° and rake = 165° . Then, we plotting the fault plane with GMT (Generic Mapping Tool) to obtain the pattern of fault plane formed is strike-slip fault (**Figure 5**).

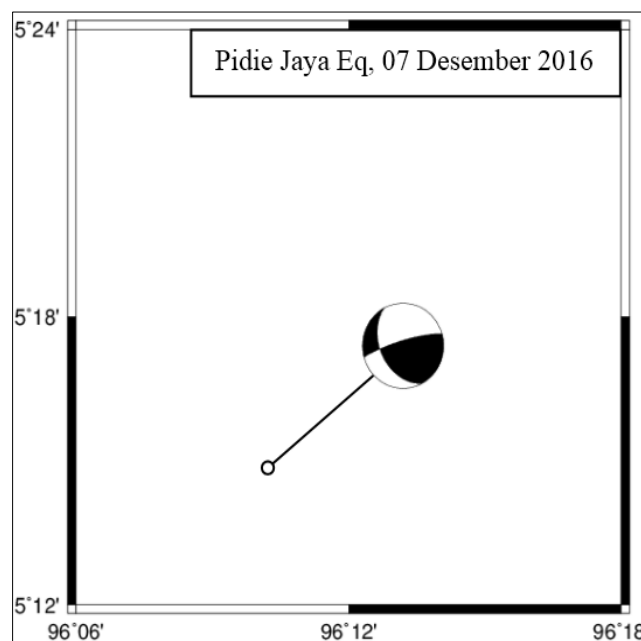


Figure 5. Earthquake Mechanism Solution.

Based on the strike, dip and rake value, each node field on the beach ball of the earthquake focal mechanism which generated by ISOLA can be compared with the focal mechanism generated by GFZ, GCMT and USGS (**Table 1**). From the data processing using ISOLA-GUI, program and the result of beachball depiction with GMT on the picture shows that there is no significant difference between the processing result using ISOLA with the processing result from GFZ and USGS. So, the results obtained from this data processing can be said quite accurate.

Table 1. The difference model of each focal mechanism component.


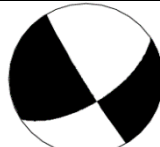
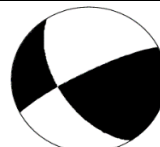

GFZ	GCMT	USGS	Author
(Strike, dip, slip)	(Strike, dip, slip)	(Strike, dip, rake)	(Strike, dip, rake)
			
(NP1= 148°, 79°, 170°) (NP2= 240°, 80°, 11°)	(NP1= 57°, 63°, -4°) (NP2= 148°, 87°, -153°)	(NP1= 243°, 81°, 33°) (NP2= 147°, 57°, 170°)	(NP1= 254°, 80°, 48°) (NP2= 153°, 42°, 165°)

Figure 6 shows us a difference of parameter information like latitude, longitude, depth and magnitude which obtained from GFZ, GCMT, USGS and BMKG data. The blue star shows the epicentre from GFZ, the yellow star shows epicentres from GCMT data, the green star shows the location of epicentre from USGS data and the white star indicates the location of the main quake generated by the author from BMKG station. The red dots indicate the spread of aftershocks from BMKG that occurred on December 7, 2016 in Pidie Jaya District which has direction from North-West (NW) to East-South (ES).

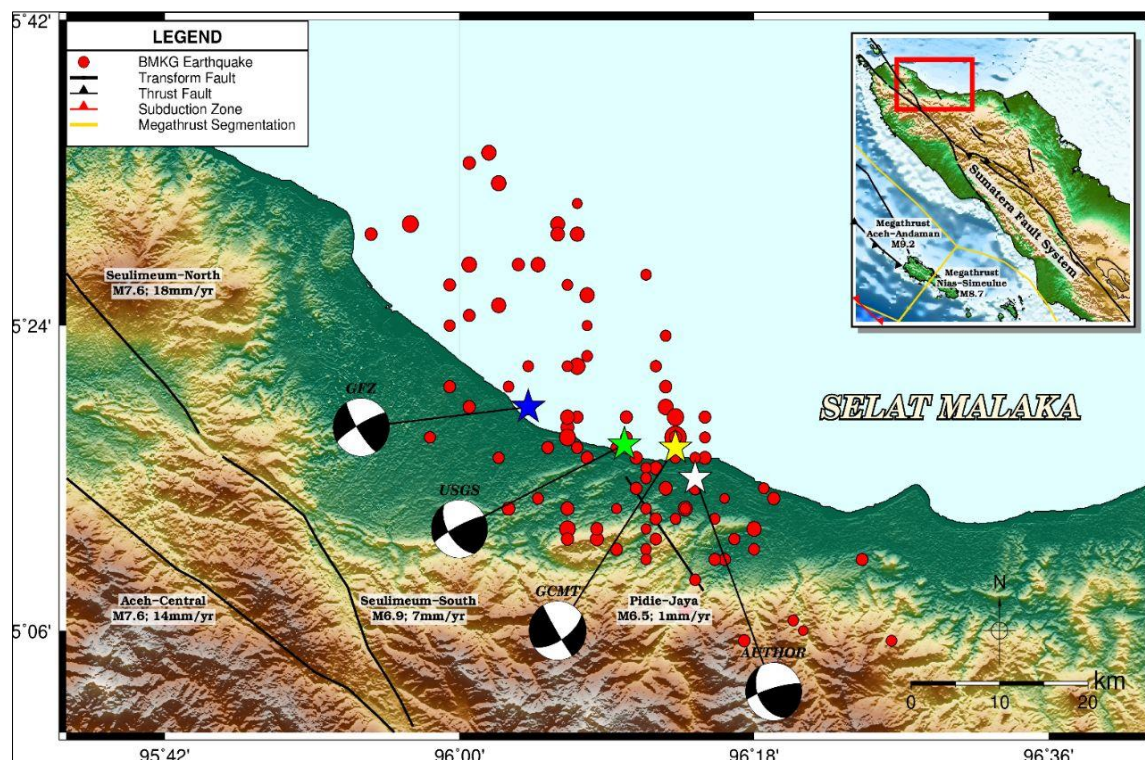


Figure 6. The comparison of focal mechanism solution (Author, GCMT, USGS, and GFZ) with the spreading of foreshock.

Figure 6 shows the result of earthquake source mechanism which obtained from tensor moment inversion process. Based on the source mechanism parameter, Pidie Jaya earthquake has a oblique (strike-slip with vertical movement) fault mechanism solution with two nodal planes. First nodal plane has strike 254° , dip 80° , rake 48° and the second nodal plane has strike 153° , dip 42° , rake 165° . The result of earthquake source parameter still contains the ambiguity because there are two nodal planes in which one of the two nodal fields is the "true fault plane" and the other is the "auxiliary plane". To avoid ambiguity, foreshock analysis is needed to know the direction of straightness fault. The foreshock obtained follows the direction of the first nodal plane with strike direction 254° . From [12], we can see the result has a directional fracture directed South-West (SW) to North-East (NE), and opposite with BMKG result. [12] used a temporary network to analysed the foreshock and local velocity model to get the focal mechanism with Cut and Paste method, than BMKG result which used global velocity model. This result will refer to [12] with has aftershock which follow the focal mechanism strike from South-West (SW) to North-East (NE).

In comparison, the Global Centroid Moment Tensor (GCMT) catalog released the focal mechanism solution of Pidie Jaya earthquake. The solution has the first nodal plane with strike = 57° , dip = 63° , slip = -4° , and second nodal plane with strike = 148° , dip = 87° , slip = -153° . The GCMT Catalog for the mechanism solution is made using seismic data from remote stations (teleseismic), not local or regional data. For parameters of major and subsequent seismic hypocenter locations using localized results from BMKG with 140 epicenter sites. According to [12], the nodal field closest to the hypocenter location is estimated as the "actual fault zone".

5. Conclusions

From this research, we can get the focal mechanism solution of Pidie Jaya Earthquake by combine regional and local station, also successful to analyse this fault with seismology method and approach. From that, we can give an assessment to specify the pidie jaya fault, as we know together which cause of this earthquake. The fault has a strike-slip mechanism with dextral movement and the direction from North-West (NW) to East-South (ES). This result has not much different than others result, that mean we did a good procedural and get the good model too. The novelty in this paper about how to combined the local and regional stations with azimuth $< 180^\circ$, used global velocity model and got best fitting waveform. Next, we can know how the filter range for all station, and how the waveform characteristic in that field.

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