FOCAL MECHANISM DETERMINATION OF LOCAL EARTHQUAKES IN MALAY PENINSULA

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ABSTRACT

Since November 30, 2007, small local earthquakes have been observed in the Malay Peninsula near the Bukit Tinggi area. The total number of these events in the Malay Peninsula is 30 until the end of 2010, including the newly recorded small earthquakes in Jerantut, Manjung and Kuala Pilah, which occurred in March, April and November in 2009, respectively. Although hypocenters and magnitudes are determined for these events using data from the Malaysian National Seismic network, focal mechanisms have not been determined. In this study, we determined their focal mechanisms. We selected three crust structure models, and compared the observed travel time differences between P and S waves to those computed for these models. Although they agree relatively well for all of these models, model iasp91 explained the observations better. We analyzed four events that occurred in the Bukit Tinggi area for focal mechanism determination. We used three-component broadband waveform data recorded at stations IPM and KOM of the Malaysian National Seismic network. We determined their focal mechanisms using polarity data of the first motions of P and S waves and their amplitude ratios. We used iasp91 for take off angle calculations. We obtained relatively well-constrained solutions for all four events. The focal mechanisms of the largest 3.5mb event, which occurred on November 30, 2007 is a mostly strike slip with some dip slip mechanism, while those of three events are strike slip mechanisms. The maximum compressional (P) axes of the November 30, 2007 event is in the NNW-SSE direction, while those of three events are in the NW-SE direction. The minimum compressional (T) axes of the strike slip events are in the NE-SW direction. Since there is no surface trace of ruptures observed, this result is important to improve our understanding of these seismic activities.

Keywords: Focal Mechanism, Polarity, Bukit Tinggi fault.

1. INTRODUCTION

Malay Peninsula is considered as inactive earthquake zone since only induced earthquake activities around Kenyir Dam, Terengganu were recorded between 1984 and 1985, with magnitudes ranging from 2.4 to 4.6 on Richter scale. However, in November 2007 until January 2008, there were 13 tremors recorded in the Bukit Tinggi area, with magnitude up to 3.5. The Malay Peninsula seems to have its fair share of local earthquakes which generated weak motions when these Bukit Tinggi earthquakes have been continued occurring. As a result of these, the total number of events recorded in the Malay Peninsula increased to 30 until the end of 2010, including the newly recorded small earthquakes in Jerantut, Manjung and Kuala Pilah, which have occurred in March, April and November in 2009, respectively. Although hypocenters and magnitudes for these local earthquakes are determined by using data from the Malaysian National Seismic Network, solutions of the focal mechanisms have not been determined. The purpose of this paper is to determine their focal mechanism of these local earthquakes using polarities of the first motion of body waves and their amplitude ratios.

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2. THEORY AND METHODOLOGY

2.1. Focal Mechanism Solution using Polarities and Amplitude Ratios

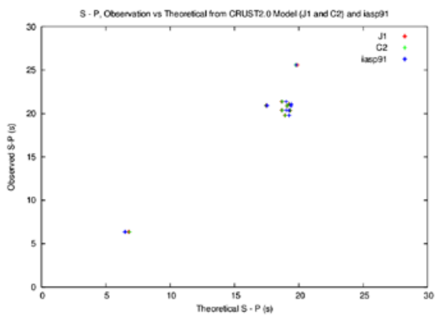
It is important to determine accurate focal mechanism solutions for earthquakes with small magnitudes or those recorded by a small number of seismometers. A method using the initial motion polarity of P and S waves, and their amplitude ratios is described below. We used the *FOCMEC* software package (Snoke 1984) from the Incorporated Research Institutions for Seismology (IRIS) which can be downloaded from http://www.iris.edu/software/downloads/processing/. This software package uses polarities of P and S waves (P, SV, SH) and amplitude ratios (SV/P, SH/P, SV/SH) as the input set for determination and display of earthquake focal mechanisms through its two main program, the *Focmec* and the *Focplt*. Directions of polarities in the *FOCMEC* package are considered in the position of observer facing the station with his/her back to the epicenter. Accordingly, the first motion of P arrival is either up or down, while the SH is either left or right, and upward or backward for SV. Using the Seismic Analysis Code (SAC), horizontal components of three-component seismographs are rotated into radial and transverse component to separate SV and SH. For crustal events recorded at local or regional distances, the first arrivals may be the refracted phases *Pn* and *Sn* and if the Poisson's ratio is constant in the crust and uppermost mantle, *Pn* and *Sn* will leave from the same point on the focal sphere and have identical travel paths. When choosing polarities and amplitudes for local mechanism determinations we must consider the fact that an SP arrival that comes in just before direct S affects the observed waveforms, particularly for SV incidence and also a low-velocity zone at the surface can complicate the waveforms (Booth and Crampin 1985).

2.2. Seismic Velocity Model for Malay Peninsula

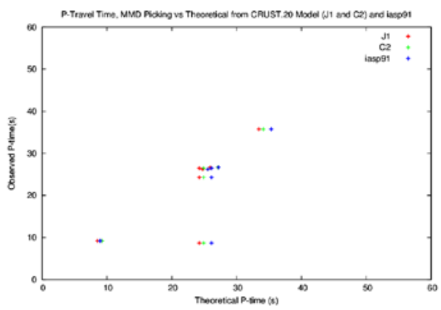
We checked the effect of the three velocity models available for Malay Peninsula (J1 and C2 from CRUST2.0, and iasp91) on the travel-time differences between P and S waves and on the P-phase arrivals picked up by the MMD (Figure 1). The calculation was performed using the TauP Toolkit (Crotwell 1999). The following root mean square (RMS) is calculated for the comparison between the observed and the theoretical S - P travel time, and P-phase arrival,

$$\mathrm{RMS} = \sqrt{\frac{\sum_{\mathrm{i}=1}^{\mathrm{n}}(obs_{\mathrm{i}} - cal_{\mathrm{i}})^2}{\mathrm{n}}}$$

where obs_{i} is the *i*-th observed value, and cal_{i} is the *i*-th calculated value and n is the total number of values. Although the differences of the RMS among three velocity models, J1, C2 and iasp91, are not so large, the lowest values are consistently obtained by iasp91. These results suggest that model iasp91 predicts the behavior of the seismic velocity in the Malay Peninsula better than the models from CRUST2.0. This is also consistent with results obtained by Din (2011) who suggests that the crustal thickness beneath IPM station is similar to the thickness of iasp91 (35km). Thus we used a velocity model from iasp91 for the calculation of take off angles; for epicentral distances of Moho headwave the calculation of take off angle will be robust since the crustal waves travelling along the Moho discontinuity have the same take off angles.



(a)



(b)

Figure 1. (a) Comparison of the observed and the theoretical (calculated) S-P using data from IPM station (b) Comparison of the observed and the theoretical (calculated) P-phase arrival using data from IPM station.

3. DATA

Table 1.List of the Bukit Tinggi events analyzed for focal mechanism determination.

YEAR	MONTH	DAY	TIME (UTC)	EPICENTER		DEPTH (KM)	MAGNITUDE
				LAT	LONG		
2007	Nov	30	02:13	3.36°N	101.80°E	2.3	3.5 mb
2007	Nov	30	12:42	3.31°N	101.84°E	6.7	3.2 mb
2007	Dec	12	10:01	3.47°N	101.79°E	10.0	3.2 mb
2008	Jan	10	15:38	3.39°N	101.73°E	3.0	3.0 mb

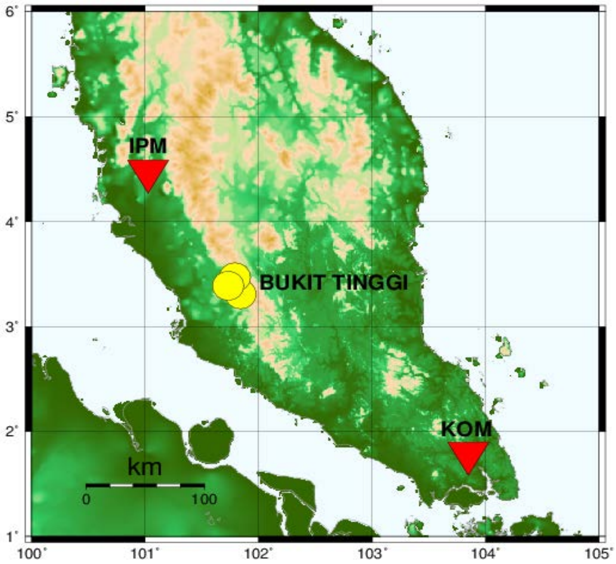


Figure 2. Locations of the broadband stations (IPM and KOM) and the events used for determination of focal mechanisms. Inverted triangles and circles denote stations and events of Bukit Tinggi, respectively.

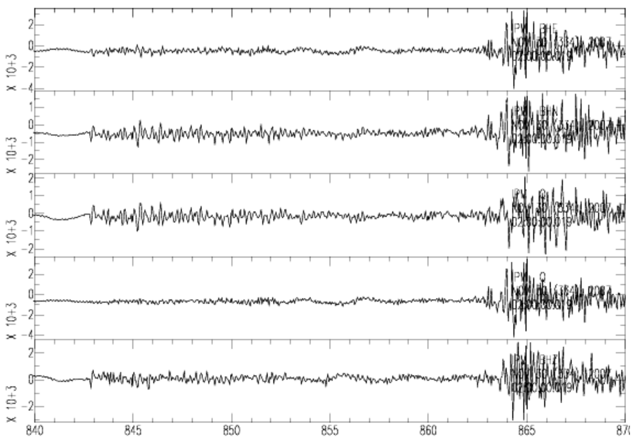


Figure 3. Observing polarities of the largest Nov 30, 2007 Bukit Tinggi event. Five traces from up to bottom are the E-W, N-S, Radial, Transverse and Vertical component of data recorded at IPM station.

We used polarity and amplitude ratio from three-component broadband data from two stations, IPM and KOM; the locations of the stations and the events are shown in Figure 2. Table 1 shows information of the events. Data were retrieved through BREQ_FAST Request by electronically mailing a specially formatted file to breq_fast@iris.washington.edu. The horizontal components were rotated into radial and transverse components to separate SV and SH waves. The polarities in the FOCMEC package are designated by the directions with respect to an observer facing the station with his/her back to the epicenter. We used the Seismic Analysis Code (SAC) (Goldstein et al. 2007) for seismic waveform data analysis. Figure 3 shows the component for the P and the S arrivals at IPM station for the 02:13UTC, November 30, 2007 Bukit Tinggi event. The basis for the polarity choices for IPM station for *Focmec* input file is D (down on vertical) for P arrival and as for S arrival, F (up on radial and vertical) for SV, and L (down on transverse). We made corrections for amplitudes assuming Q_α as 600 and Q_β as 300. The *Focmec* program output all acceptable solutions ("possible" mechanisms) based on input parameters (station identifiers, azimuths, take off angles at the source, polarities and amplitude ratios from among P, SV, and SH arrivals). As for selection criteria, no error is allowed. The maximum number of solutions is set to 100,000. We allowed 0.1 for the maximum log10 of ratio, and selected 0.01 and 0.02 for lower bound (cutoff value) of P and S radiation factor, respectively. The ratio was indeterminate when both calculated values were less than the chosen cutoff values.

4. RESULTS AND DISCUSSION

4.1. Bukit Tinggi, November 30, 2007 (02:13 UTC) 3.5 mb

We obtained a relatively well-constrained solution for the largest 3.5mb event which occurred at 02:13 UTC, November 30, 2007. The focal mechanism of this event is a mostly strike slip with some dip slip and the maximum compressional (P) axes are in the NNW-SSE direction (Figure 4). We obtained 58 acceptable solutions, for which the dip, strike and rake of one nodal plane fall in the range of 45° to 75°, 10° to 60°, and 20° to 50° respectively, while for the second nodal plane they fall in the range of 50° to 70°, 270° to 310°, and 130° to 170°, respectively.

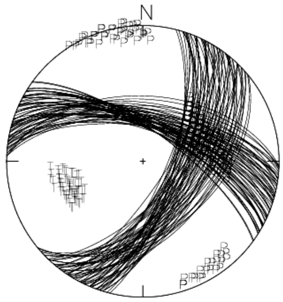


Figure 4. Lower-hemisphere projections of the focal sphere for the November 30, 2007, 02:13 UTC Bukit Tinggi event .

4.2. Bukit Tinggi, November 30, 2007 (12:42 UTC) 3.2 mb

The solutions of the November 30, 2007, 12:42 UTC Bukit Tinggi event are well-constrained; we obtained a strike slip faulting with the P axes distributions in the NW-SE direction and the T axes distributions in the NE-SW direction (Figure 5). We obtained 10 acceptable solutions for which the dip and rake angles of the first nodal plane fall within the range of 72° to 85° and of -40° to 0°, respectively while for the second nodal plane, the dip and rake angles fall within the range of 58° to 82° and -180° to -160°. The strike angles, falling in two ranges, between 170° and 190°, and between 340° and 360° for the first nodal plane, and between 80° and 100°, and between 270° and 280° for the second nodal plane.

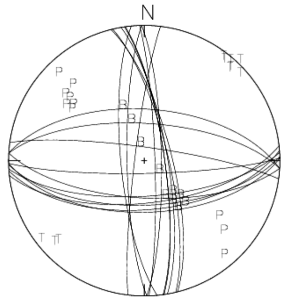


Figure 5. Lower-hemisphere projections of the focal sphere for the November 30, 2007, 12:42 UTC Bukit Tinggi event .

4.3. Bukit Tinggi, December 12, 2007 (10:01 UTC) 3.2 mb

As for the Bukit Tinggi event that occurred at 10:01 UTC, December 12, 2007, the results are close with those of Bukit Tinggi, 12:42 UTC, November 30, 2007 event in that the focal mechanism of this event is strike slip. P axes distributions are in the NW-SE direction and the T axes distributions are in the NE-SW direction (Figure 6). We obtained 6 acceptable solutions with a range of 70° to 82° for dip angles, and -40° to -10° for rake angles while strike angles fall in two ranges, of 160° to 180° and of 330° to 360° for the first nodal plane and 55° to 80° for dip angles, -180° to -150° for rake angles, while strike angles fall in two ranges, of 70° to 90° and 260° to 280° for the second nodal plane.

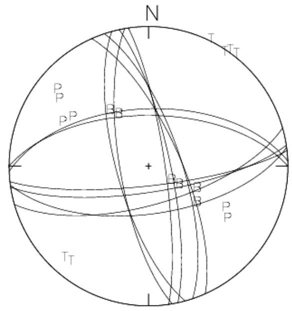


Figure 6. Lower-hemisphere projections of the focal sphere for the December 12, 2007, 10:01 UTC Bukit Tinggi event .

4.4. Bukit Tinggi, January 10, 2008 (15:38 UTC) 3.0mb

The focal mechanism of the January 10, 2008, 15:38 UTC Bukit Tinggi event shows similar results with the previous two Bukit Tinggi events (the 12:42 UTC, November 30, 2007, and the 10:01 UTC, December 12, 2007 Bukit Tinggi event) in which the obtained focal mechanism is of strike slip faulting with P and T axes distributed in the NW-SE and NE-SW, respectively (Figure 7). We obtained 2 acceptable solutions with a range of 80° to 85°, 0° to 10° and 170° to 180°, and -20° to -10° for the distributions of dip, strike, and rake angles, respectively, for the first fault plane. As for the second fault plane, the dip and the rake fall in the range of 75° to 80° and -180° to -170°, respectively, while the strike fall in two ranges, 90° to 100° and 260° to 270°.

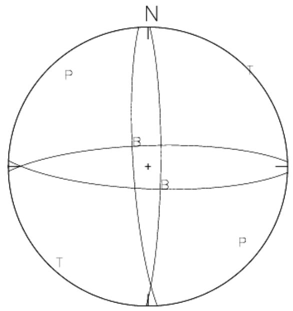


Figure 7. Lower-hemisphere projections of the focal sphere for the January 10, 2008, 15:38 UTC Bukit Tinggi event.

4.5 Comparison of the Orientation of P and T axes, and the Observed Polarities

The P axes of the largest 3.5mb Bukit Tinggi event are in the NNW-SSE direction while those of the three strike slip events are consistently in the NW-SE direction. The T axes for the three strike slip events are also consistent; in the NE-SW direction. We also compared the polarity of the first motions of P-phases for six Bukit Tinggi events, of which four are events described earlier while two others are events that occurred on December 9, 2007 and March 15, 2008. The consistent dilatational first motions of P waves observed for all events recorded at IPM station imply that the mechanisms of the events are similar. Hardebeck (2002) suggests that the observed polarity at a given station should be the same for each event in a cluster.

4.6 Relationship between Focal Mechanism Obtained and the Existing Faults

Figure 8 shows the epicenter of the four events that we analysed, their focal mechanisms and the faults in the study area, namely the Bukit Tinggi fault and the Kuala Lumpur fault. Comparing the fault orientations and the strike of the nodal planes, the relationship between these two faults and the focal mechanisms obtained is not clear. The difference in the movement rate between the west and the east based on the GPS data observed in the Southeast Asia within a ten-year span (between 27 November 1994 and 25 December 2004), may cause some pushing that could release energy to trigger movement on any weak plane, such as in the Bukit Tinggi fault zone (Lat 2009). The stress regime for this area inferred from GPS data within a ten-year span (between 27 November 1994 and 25 December 2004) indicates that the force in play is compressional in the NE-SW direction (Simons et al. 2007). This is contradict with the orientation of compressional axes obtained from the determination of focal mechanisms , in which in the NW-SE and NNW-SSE direction. One possible explanation to these Bukit Tinggi earthquakes is that

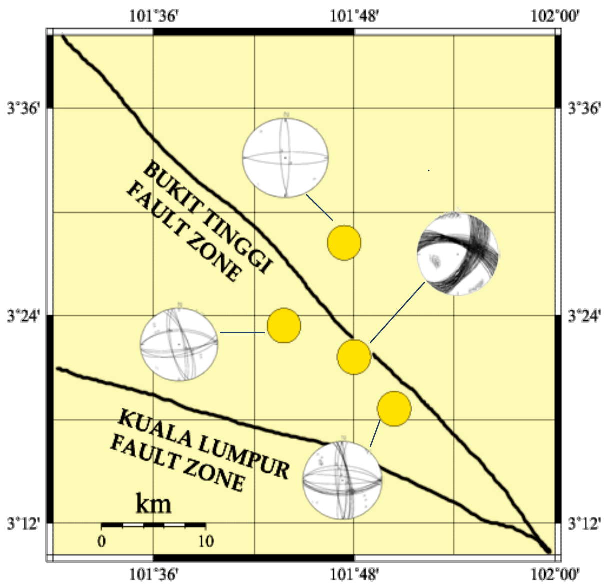


Figure 8. Map showing locations of four Bukit Tinggi events (yellow circles), focal mechanisms obtained and the existing ancient and inactive faults, namely the Bukit Tinggi fault and the Kuala Lumpur fault.

they are due to the weak-zone-normal extension mechanisms (Hurukawa and Imoto 1992). Fatt et al. (2011) conducted a relocation study of local earthquakes in the Malay Peninsula and showed that hypocenters of these events are better improved by using a method of modified joint hypocenter determination (MJHD) developed by Hurukawa and Imoto (1990), and HYPOCENTER program (Lienert and Havskov 1995). The MJHD program shows that epicenters are scattered along the Bukit Tinggi fault (striking NW-SE directions and dipping toward NE) and Kuala Lumpur fault (striking NW-SE directions and dipping toward SW) with depth between 6 and 30 km. The HYPOCENTER program shows that the epicenters are scattered at the Bukit Tinggi fault with depth between 0 to 10 km with similar orientation of nodal plane to the MJHD program. Their study however, did not relocate the four Bukit Tinggi events that we analysed. Thus, relocation of these earthquakes will be effective to improve the accuracy of the results of this study in future works.

5. CONCLUSION

We determined focal mechanisms for four Bukit Tinggi events that occurred in 2007 and 2008 using the polarity data of the first motions of P and S waves, and their amplitude ratios from three-component broadband waveform data recorded at stations of IPM and KOM. Although constraint for dip angles is weaker for two Bukit Tinggi events on November 30, 2007 (12:42UTC) and on December 12, 2007 (10:01UTC), we obtained relatively well-constrained solutions for these four events; three events have strike slip faulting while one (and the largest) has a mostly strike slip with some dip slip. The T axes of the strike slip events are in the NE-SW direction while their maximum P axes are in the NW-SE direction. The P axes of the largest event are in the NNW-SSE direction. The consistency of the first motion polarity of P-waves observed for all Bukit Tinggi events together with relatively well-constrained P and T axes direction, suggest that these earthquakes might have similar mechanisms. This fits the characteristics of cluster earthquakes or earthquake swarms (Lat 2009). The validity of the relative motion of the strike slip mechanism, unfortunately, cannot be confirmed geologically since these Bukit Tinggi earthquakes share significant similarities with other intraplate earthquakes in that there are lack of surface ruptures (Shuib 2009). Due to an absence of this surface movement, the result of this study serves for an important basis in ascertaining the focal mechanisms of the earthquakes near Bukit Tinggi area, and will improve an understanding of seismic activities in the Malay Peninsula.

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