RELOCATION OF EARTHQUAKES IN MYANMAR BY MJHD METHOD: AFTERSHOCKS OF LARGE EARTHQUAKES AND SEISMICITY ALONG THE SAGAING FAULT

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ABSTRACT

To understand the seismicity in Myanmar, detailed analysis of hypocenters and fault planes determination are important. First, we relocated seven earthquakes of which magnitudes are $M_w \geq 6.0$, together with their aftershocks using modified joint hypocenter determination (MJHD) method and used P-wave arrival times from International Seismological Centre (ISC). We relocated aftershocks of one day, one week, or one month based on the aftershocks' occurrences. Target area is $\pm$ 1 degree from both the latitude and longitude from Global CMT for each large earthquake. After the relocations of the large earthquakes and their aftershocks, we could identify the fault plane of three earthquakes but some earthquakes are difficult to identify the fault plane due to aftershocks occurrences. Furthermore, we relocated earthquakes including the historical earthquakes to investigate the seismicity along the Sagaing fault. We used P-wave arrival times from ISC (1961 to March, 2007) and those for seven historical earthquakes from International Seismological Summary (ISS). Once the hypocenters relocated precisely, the earthquakes occurrence and seismic gap along the Sagaing fault would become clear. Some relocated epicenters are closer to the fault than those before relocation. We could determine the hypocenters of historical earthquakes and recent earthquakes on the five sub-regions. It means our results are consistent with the geological setting of this region and are useful for seismic hazard assessment in this region.

Keywords: Hypocenter relocation, Sagaing fault, Historical earthquakes

1. INTRODUCTION

Myanmar is located at a very active tectonic area, which includes the subduction zone and the active Sagaing fault. From seismological point of view, Myanmar is one of seismically active countries of the world. Shallow and intermediate earthquakes occur along the Burma subduction zone and shallow strong earthquakes occur along the Sagaing fault (Figure 1). The Sagaing fault is an active right lateral strike slip fault crossing from north to south through Myanmar. Most of historical earthquakes occurred along the fault. Fifteen large earthquakes (of $M \geq 7.0$) hit the country from 1912 to 2003 (Figure 2). The frequency of the occurrence of large earthquakes is around once in 12 to 16 years. According to the seismicity map, the northwestern part of Myanmar is one of strong earthquake sources of the world. The earthquakes are spreading all over the country except the southern coastal regions, which indicates orientation of active faults. In the present study, we relocate aftershocks of seven large earthquakes from 1988 to 2003 to determine the fault plane by MJHD method. In order to know the precise seismicity along the Sagaing fault, we relocated earthquakes along the Sagaing fault including events from 1961 to March, 2007 and historical earthquakes. We use the data from International Seismological Centre (ISC) and International Seismological Summary (ISS).

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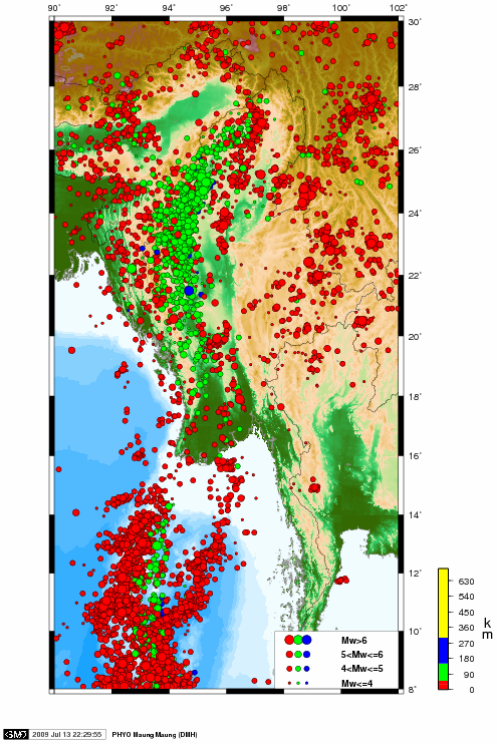


Figure 1. The epicenter distribution map of Myanmar is used USGS data from 1973 to 2009, March 31. The different size and color of symbols indicates the size and depth of earthquakes.

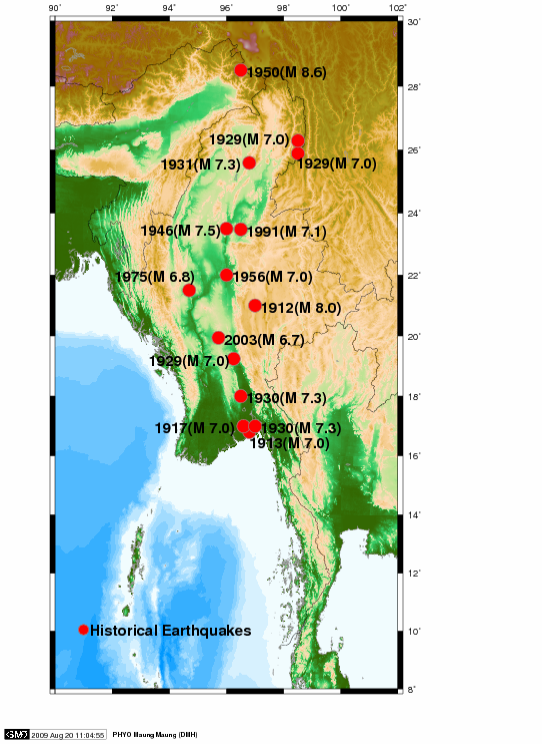


Figure 2. The epicenter distribution map of historical earthquakes in Myanmar occurred from 1912 to 2003 and data from Department of Meteorology and Hydrology (DMH).

2. METHOD

In this study, we used the Modified Joint Hypocenter Determination (MJHD) method developed by Hurukawa and Imoto (1990, 1992) for the determination of hypocenters and fault planes in Myanmar. The equation shown as follows;

$$(O-C)_{ij} = (t_{ij} - To_j) - T_{ij} = \frac{\partial t_{ij}}{\partial \lambda_j} d\lambda_j + \frac{\partial t_{ij}}{\partial \varphi_j} d\varphi_j + \frac{\partial t_{ij}}{\partial z_j} dz_j + dTo_j + dS_i \quad \ldots\ldots\ldots\ldots (1)$$

where t_{ij} is arrival time of j^{th} event at i^{th} station, T_{ij} is the calculated travel time of the j^{th} event at the i^{th} station, dS_i is the station correction at the i^{th} station, To_j is the origin time, O is the observed travel time, C is the calculated travel time, $(O\text{-}C)_{ij}$ is the travel time residual of j^{th} event at i^{th} station, $d\lambda_j$, $d\varphi_j$, dz_j and dTo_j are correction of trial hypocenter of j^{th} event.

Due to the heterogeneous earth's structure, when the station coverage is not good, the JHD solutions become unstable and unreliable because of the trade–off between station corrections and focal depths of earthquakes. For this reason, Hurukawa and Imoto (1990, 1992) developed using the constraints below.

$$\sum_{i=1}^{n} S_i D_i = 0 \quad \sum_{i=1}^{n} S_i \cos\theta_i = 0 \quad \sum_{i=1}^{n} S_i \sin\theta_i = 0 \quad \sum_{i=1}^{n} S_i = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where S_i is the station correction at i^{th} station, D_i is the distance between the ith station and the center of the region, θ_i is the azimuth of the i^{th} station from the center of the region and n is the number of stations.

3. DATA

3.1 Aftershock relocation and its fault plane

Foreshocks, a mainshock and its aftershocks are relocated in this study by using P-wave arrival times from International Seismological Centre (ISC) in order to determine the fault plane. Then, the corresponding fault plane is determined based on the obtained aftershock distribution. We relocated seven large earthquakes from 1988 to 2003 with $M_w \geq 6.0$ with data taken from Global CMT catalog.

3.2 Historical earthquakes relocation

We relocate seven historical earthquakes using data from International Seismological Summery (ISS). These are the January 19th, 1929 (M=7.0), August 8th, 1929 (M=7.0), May 5th, 1930 (M=7.3), December 3rd, 1930 (M=7.3), January 27th, 1931 (M=7.3), September 12th, 1946 (M=7.3) and July 16th, 1956 (M=7.0) earthquakes. In addition, we relocated the earthquakes to know the precise seismicity and to determine hypocenter on the five sub-regions along the Sagaing fault using International Seismological Center (ISC) from 1961 to March, 2007.

4. RESULTS

4.1 Aftershock relocation and its fault plane

It is difficult to determine the fault plane of the mainshock using only ISC hypocenter distribution due to insufficient accuracy. Therefore, we analyzed the earthquakes to determine the fault plane using MJHD method. In order to determine the fault plane of the August 6th, 1988 earthquake, we relocated the aftershocks from August 6th, 1988 to August 21st, 1988. We cannot determine the fault plane of the mainshock using International Seismological Centre (ISC) hypocenter distribution map in Figure 3.

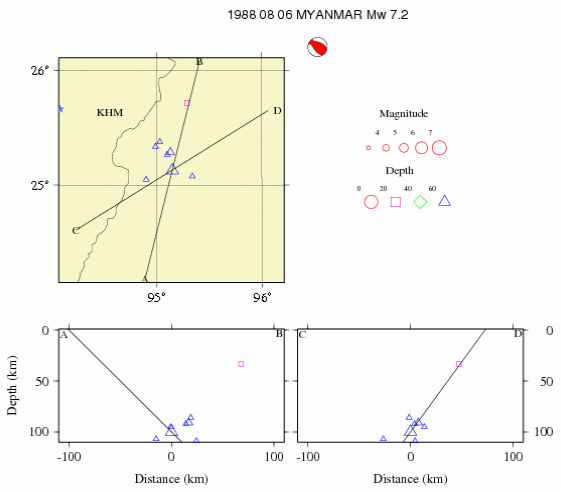


Figure 3. Hypocenter distribution of the August 6th, 1988 earthquake and its aftershocks by ISC. The size of symbols represents the magnitude of the events. The color and shape of the symbols denote the depth range of the events.

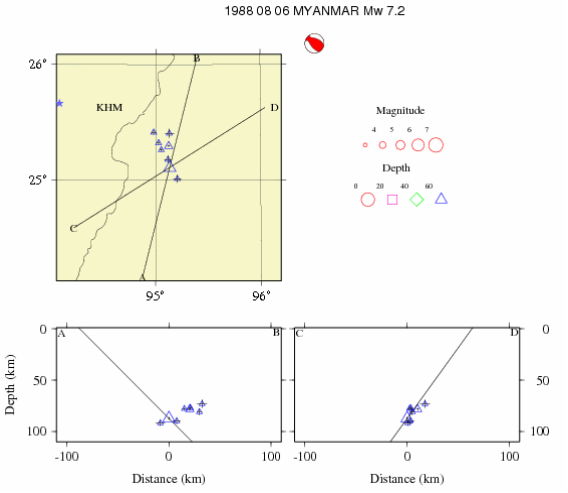


Figure 4. MJHD hypocenter of the August 6th, 1988 earthquake and its aftershocks. Symbols are same as in Figure 3. The A-B and C-D lines are two nodal planes shown by solid lines in cross sections. The moment tensor solution is taken from Global CMT catalog.

We identified 236 stations worldwide and phase data with travel time residuals (O-C) $\geq$ 2.0 seconds were excluded. The mainshock and its aftershocks are relocated to identify the fault plane using MJHD method in Figure 4. The hypocenter distribution of this event suggests the nodal plane shown in cross section C-D could be the fault plane related to that event as shown in Figure 4, because the mainshock and all aftershocks were located along this nodal plane. The strike and dip of the fault plane are 148° and 54° determined by Global CMT.

Similarly, we could determine the fault plane of the November 6th, 1988 earthquake with M_w 7.0 occurred in the China-Myanmar border region as shown in Figure 5. The largest aftershock followed with M_w 6.9 within 12 minutes after the mainshock and some nine aftershocks followed on the same day with $M_w \geq 4.5$. From the MJHD hypocenters distribution map, we can clearly find the fault plane of the earthquake after relocation from two nodal planes. The nodal plane shown in the cross section A-B is the fault plane because aftershocks concentrated along this plane. The strike and dip angle of this fault plane are 333° and 78° as determined by Global CMT. And also, we could determine the fault plane of the September 21st, 2003 earthquake as shown in Figure 6. The nodal plane, which is shown in cross section C-D could be the fault plane of the event. Aftershocks are concentrated along this nodal plane and all earthquakes are around 20 to 50 km depths. The strike and dip of the fault plane are 100° and 83° determined by Global CMT.

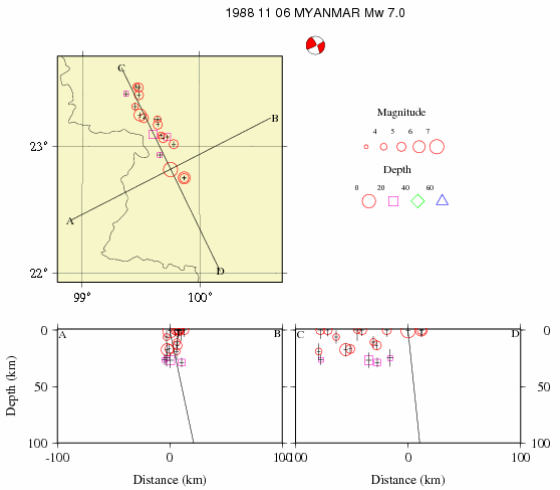


Figure 5. MJHD hypocenters of the November 6th, 1988 Earthquake and its aftershocks. Symbols are same as in Figure 4.

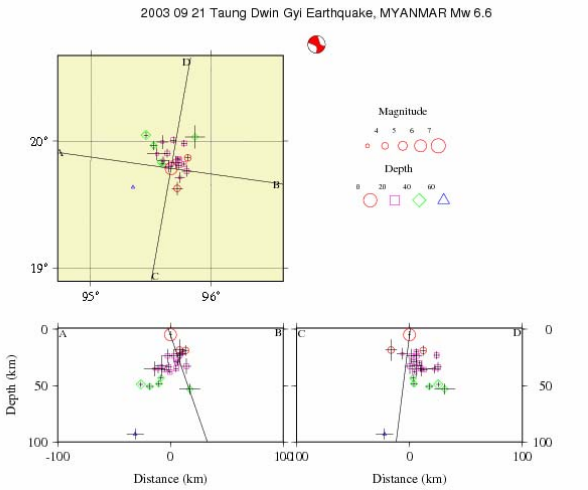


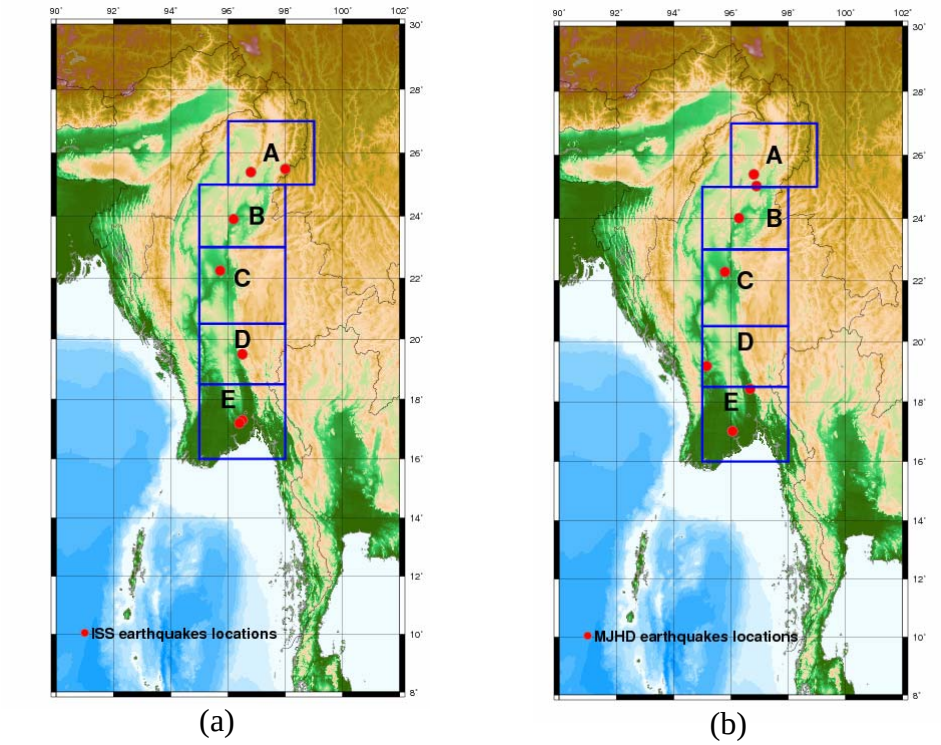
Figure 6. MJHD hypocenters of the September 21st, 2003 Earthquake and its aftershocks. Symbols are same as in Figure 4.

But, it is difficult of determine the fault plane of the January 5th, 1991 earthquake due to the lack of aftershocks. However, we think that the nodal plane shown in the cross section A-B might be the fault plane because aftershocks occurred near the nodal plane. We could determine the accurate hypocenters but we could not determine the fault plane by using MJHD method alone. For the April 23rd, 1992, July 11th, 1995 and June 7th, 2000 earthquakes, we could not determine the fault plane due to lack of aftershocks even though earthquakes occurred in the shallow depth.

4.2 Historical earthquakes relocation

In order to understand the precise seismicity along the Sagaing fault, we relocate hypocenters of historical large earthquakes from 1929 to 1956 using data from International Seismological Summary (ISS). Combining historical earthquakes and recent earthquakes from 1961 to March, 2007 using the data from International Seismological Centre (ISC), we relocated them simultaneously in order to improve accuracy of historical earthquakes location by MJHD method (Hurukawa et al. 2008).

Figure 7 (a) shows location of the five sub-regions and locations of seven historical earthquakes by ISS data and Figure 7 (b) shows the relocation results by MJHD method. Only P-wave first arrivals are used in this hypocenters relocation because the reading accuracy of S-wave arrival times is worse than P-wave arrivals.



(a) (b)

Figure 7. Comparison between before and after relocations on the five sub-regions. (a) ISS locations and (b) MJHD locations. The rectangles with blue color (A-E) indicate the five sub-regions for relocation of earthquakes along the Sagaing fault and red circles indicate the epicenters of historical earthquakes.

In the region (A), we relocated the 223 earthquakes from 1961 to March, 2007 and two historical recorded earthquakes: the January 19th, 1929 (M 7.0) and January 27th, 1931 (M 7.3). We selected earthquakes that had occurred in the rectangle between 25.00°N-27.00°N latitude and 96.00°E-99.00°E longitude. Phase data with travel time residuals (O-C) $\geq$ 2.0 seconds were excluded. After the relocation by MJHD method, we can see clearly that the earthquakes concentrate along the active Sagaing fault and depths of the shallow earthquakes are around 10-40 km. Two historical earthquakes are moved closer to the Sagaing fault with focal depths of around 0-20 km as shown in Figure 8, while some of earthquakes are occurred at 40-50 km depth. The difference of location for the January 19th,1929 (M 7.0) earthquake is 0.47°N in latitude and 1.10°E in longitude and depth is 20.4 km. We could determine the hypocenter of historical earthquakes with accuracy because the errors of the hypocenters are not so large. Epicentral distribution and E-W and N-S cross section along A-B and C-D lines are shown in Figure 8 and cross bar in the circles represent the standard errors of the hypocenters.

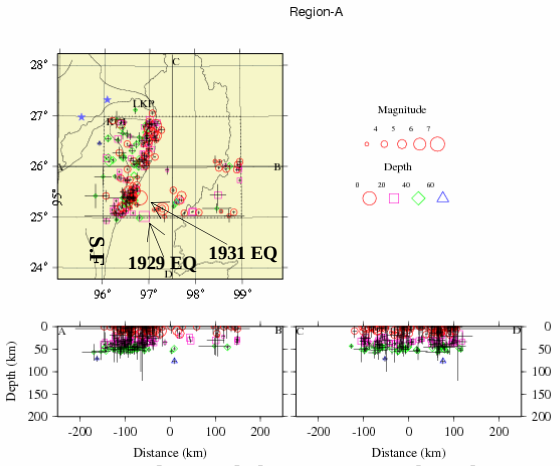


Figure 8. Relocated hypocenters by the MJHD method in region A. Symbols are same as in Figure 3. S.F is the Sagaing fault.

One historical earthquake (M=7.3) occurred on September 12th, 1946 in the region (B). The deeper earthquakes occurred outside of the Sagaing fault. According to the relocation result, the location of the 1946 historical earthquake moved to the north and depth is still shallow. We relocated the July 16th, 1956 historical earthquake in the region (C). We think that the hypocenter would be mislocated because we relocate this earthquake using few stations data and stations are far from the epicenter. We relocate the earthquakes from 1961 to March, 2007 and the August 8th, 1929 historical earthquake in the region (D). The earthquake cluster occurred between the Sagaing fault and other small fault from epicenter distribution map. About the historical earthquake, we think that the hypocenter would be mislocated because we used few stations data and the stations are far from the epicenter. In the region (E), we relocated 61 earthquakes during from 1961 to March, 2007 including the two historical earthquakes that occurred on the May 5th, 1930 and December 3rd, 1930. After relocation, we could determine the focal depth of the historical earthquakes to be around 5-40 km.

5. DISCUSSION AND CONCLUSION

We relocated the seven earthquakes from 1988 to 2003 with $M_w \geq 6.0$ and their aftershocks to determine the fault plane using Modified Joint Hypocenter Determination (MJHD) method developed by Hurukawa and Imoto (1992). We obtained high accuracy hypocenters of the earthquakes and our results are more reliable than hypocenters of International Seismological Centre (ISC) catalog. We could determine the fault plane of the August 6th, 1988 earthquake, November 6th, 1988 earthquake and September 21st, 2003 earthquake. However, we could not determine the fault plane of some earthquakes which are the January 1st, 1991 earthquake, April 23rd, 1992 earthquake, July 11th, 1995 and June 7th, 2000 earthquake. These results indicate that we cannot determine the fault plane of small earthquakes. Moreover, we noticed the deep and shallow earthquakes have aftershocks with different behavior. Large shallow earthquakes are likely to be followed by aftershocks more than deep earthquake. This MJHD method is very useful for determining the accurate hypocenter of the earthquake.

In addition, we relocated the earthquakes along the Sagaing fault using ISC data from 1961 to March 2007 and ISS data for historical earthquakes from 1929 to 1956. We used the only P-wave arrival times and determined the hypocenters of earthquakes during 47 years and the historical earthquakes using the MJHD method. We determined the depths of the January 19th, 1929 (M 7.0) and January 27th, 1931 (M 7.3) historical earthquakes are 5 to 30 km in region (A). The 1946 historical earthquake epicenter is on the Sagaing fault before relocation. After the relocation, the earthquake moves to the north although depth is still shallow. We could determine the hypocenters of the December 3rd, 1930 (M=7.3) earthquake that moved to the north and May 5th, 1930 (M=7.3) earthquake that moved to the west. The depths of earthquakes are around 10-50 km. Before relocation, these two earthquakes are located on the same place according to the ISS data. We think that the July 16th, 1956 and August 8th, 1929 earthquakes were mislocated due to the poor azimuth coverage and low quality of data from ISS. Therefore, we concluded that the azimuth coverage, nearby stations and reading data are important in order to relocate hypocenter using MJHD method. We have to be careful for the input parameters for relocations and the data to get accurate and reliable results. Finally, we expect that the results of this study will be useful for the future seismological study in Myanmar.

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