RELOCATION OF THE MACHAZE AND LACERDA EARTHQUAKES IN MOZAMBIQUE AND THE RUPTURE PROCESS OF THE 2006 Mw7.0 MACHAZE EARTHQUAKE

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ABSTRACT

In the present study, the 2006 Machaze earthquake (Mw7.0) and the 2006 Lacerda earthquake (Mw5.6) in Mozambique are relocated. The main purpose of the relocation is to determine fault planes related to those earthquakes. The result of the relocation of the Machaze earthquake indicates that the strike and dip of the fault plane is about 172° and 65° westward, respectively, and it represents a normal faulting. Analysis of the Lacerda cluster suggests that this is an earthquake swarm. The fault plane corresponding to the biggest event presents a strike and dip of about 350° and 40°, respectively, dipping to the east. The rupture process of the Machaze earthquake is also determined in the present study. The result of the slip inversion shows that two asperities characterize the Machaze earthquake. The maximum slip is 3.4 m located in the south asperity near the initial break point and the asperity in the north of the initial break point has a slip of about 2.5 m. The last asperity is located at surface and generated the most prominent offset observed at the surface. The aftershocks are located near the two asperities. Both analyses show a size of the fault plane corresponding to the mainshock about 50 km in length.

Key words: Mozambique earthquake, relocation, joint hypocenter determination, slip inversion.

INTRODUCTION

African continent is divided in two major tectonic blocks, Nubia and Somalia. The boundary between these blocks is along the East African Rift System (EARS). Mozambique is located in the boundary zone between Nubian plate and Somalia plate, at the southern end of the EARS. The seismicity in the eastern Africa is related to the tectonics of the region.

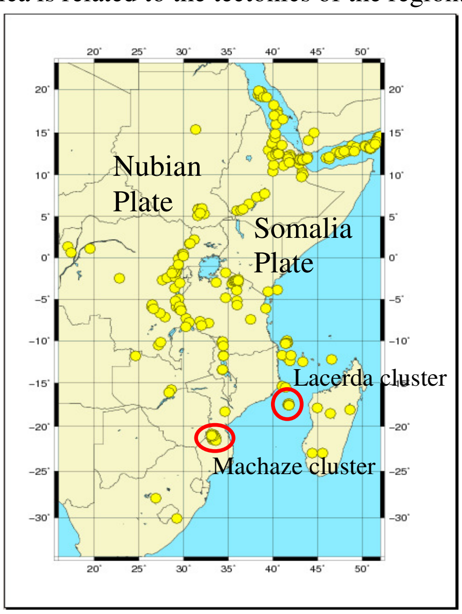

Figure 1. The seismicity map of eastern Africa region. The data used is from from Global CMT within the range from 1976 to 2007

The majority of events are located along the major tectonic lines, mainly along the EARS (Figure 1). The number of earthquakes occurring in the region, according to the historical recordings including the last strongest (Mw7.0) on February 22, 2006 at 22:19 UTC, with epicenter in Machaze, in the western province of Manica, denotes that earthquakes must be considered as one of the geohazards in the country. In the same year, on September 24, one event with magnitude Mw5.6 occurred in the offshore of Mozambique Channel. Both Machaze and Lacerda events are located in the south end of western and eastern branches of the EARS, respectively (circles in Figure 1). Precise earthquake locations play an important role in understanding earthquake source process and one of the most important parameters among the seismological ones on that strong motion estimation. The strong motion prediction is one of the key for earthquake disaster mitigation.

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In the present study the Machaze and Lacerda clusters are simultaneously relocated to determine the fault plane and seismic plane, respectively. Moment tensor inversion and Rupture process of the Machaze event are also determined in this study using the inversion technique developed by Yagi and Fukahata (2008).

METHODS

Three methods are used in the present study. The modified joint hypocenter determination (MJHD) method (Hurukawa and Imoto 1990, 1992) is used to determine the fault plane for the Machaze and the Lacerda earthquakes and two inversion methods are used to determine the moment tensor components and the rupture model for the Machaze earthquake, respectively. The MJHD technique is designed to minimize all travel-time residuals simultaneously and to find a common set of station corrections. This method removes the effect of horizontal heterogeneity of the earth through the introduction of station corrections. Due to the trade-off between station corrections and focal depth of earthquakes, the original JHD method becomes unstable and unreliable. The MJHD method introduced by Hurukawa and Imoto (1990, 1992) and Hurukawa (1995, 1998) overcome this problem by introducing the following priors. The station correction is independent of the distance and the azimuth from the center of the region to the station. This is very effective, especially in the case in which no earthquakes are observed clearly at all stations.

In order to understand the fault rupture process, waveform modeling is one of the most powerful tools available. The method developed by Yagi and Fukahata (2008) is used, in which covariance components in analysis of densely sampled observed data are considered. The source depth and source time function are determined using a grid search method. Assuming that those parameters are known, the moment tensor components were determined by inversion technique. For the slip inversion, the seismic fault is gridded into many sub-faults. Then the whole rupture process is considered to be the summation of all these sub-events, which are considered point source, respectively. The unknown parameters include the amount, direction and temporal change of slip at each grid point. The result of the inversion which gives the amount of slip at each grid point is obtained using least square fitting. From this inversion the initial depth can be corrected, hypocenter can be relatively accurate located, the initial rupture time, and the moment tensor can be obtained.

DATA AND RESULTS OF RELOCATION

The data used for relocation of both Machaze cluster and Lacerda swarm consist of P-arrival times from International Seismological Centre (ISC) and National Earthquake Information Center (NEIC) operated by United States Geological Survey (USGS). From ISC, the data was retrieved within the period between January 1, 1964 and December 31, 2004 and from NEIC the data ranges between January 1, 2005 and December 31, 2007.

Machaze cluster

The criterion used for station and events selection is MSTN (minimum number of stations which record the event) is 15 and for the MEVN (minimum number of events recorded by each station) is also 15. By using this criterion initially 69 stations were selected worldwide to locate 103 events. Figure 2 shows the hypocenters distribution determined by ISC and NEIC-USGS. The fault mechanism used is obtained from Global CMT catalog. Since depths of hypocenters were fixed at 10 km, it is difficult to identify the fault plane of the mainshock. The MJHD method is used to relocate the Machaze event. In these analyses only hypocenters with travel time residuals less than 2.0 seconds are relocated.

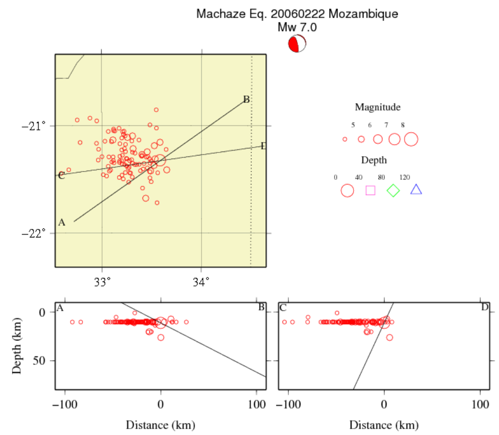

Figure 2. The epicentral distribution and two vertical cross sections along A-B and C-D lines, which are perpendicular to the strikes of the two nodal planes of the Glonbal CMT, are illustrated. The size of symbols represents the magnitude of the event and the shapes and the colors of the symbols denote the depth.

Observing the cross sections in Figure 3, it seems to be clear that the nodal plane shown in the cross section C-D is the fault plane of the Machaze earthquake. Figure 4 shows only immediate aftershoks.

Although there is some scatter in hypocenter distribution in horizontal direction, it still clear that the nodal plane shown in the cross section C-D in Figure 4 is the fault plane of the Machaze event. The strike and dip of this fault are 172° and 65°, respectively. The length of fault plane is estimated to be approximately 50 km and the epicenter is located near the center of the fault. This event has only one immediate foreshock observed in the relocated results and the epicenter is located less than 1 km from the mainshock. The time difference between the foreshock and mainshock is approximately 27 hours and 8 minutes.

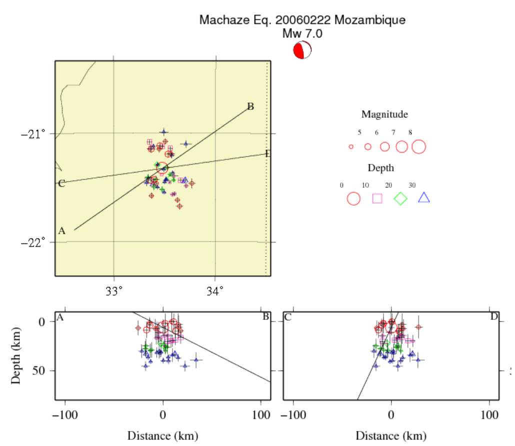

Figure 3. Relocated hypocenters. The bars in the circles represent the standard deviation. The sym,bols are the same as in Figure 2

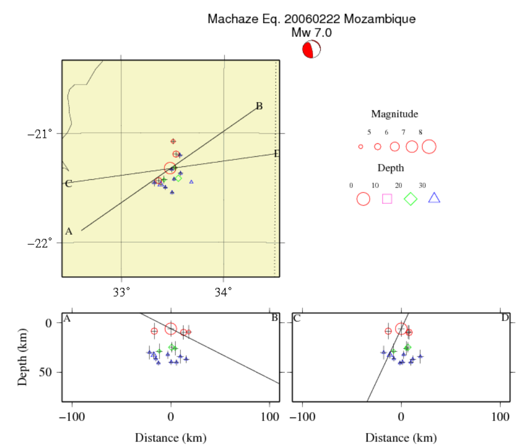

Figure 4. Immediate aftershocks within a week after the mainshock of the Machaze earthquake. The symbols are the same as in Figure 3.

Lacerda cluster

For the case of the Lacerda cluster the criteria used is as follows: MSTN is 12 and MEVN is also 12. In this relocation 21 stations were used to locate 15 events. Figure 5 shows the epicentral distribution determined using data from NEIC-USGS. Analyses of the relocated events shows that this cluster is composed by events with magnitude ranging between Mw4.0 and Mw5.6 and the biggest event (Mw5.6) is one of the last in the cluster, which suggest that the cluster can be considered an earthquake swarm. The fault mecanism used is obtained from Global CMT catalog, considering the biggest event.

The focal depth is fixed at 10 km, it is impossible to identify the fault plane. Figure 6 shows the results of relocation. It is clear that all events follow the N-S lineament, which is consistent with the tectonic lineament of the Lacerda graben. Although the scatter is large, the hypocenter distribution of these events suggests that the nodal plane shown in cross section A-B could be the fault plane related to the major event. The strike and dip of the fault plane determined by the Global CMT is 350° and 40°, respectively. This fault plane dips to the east.

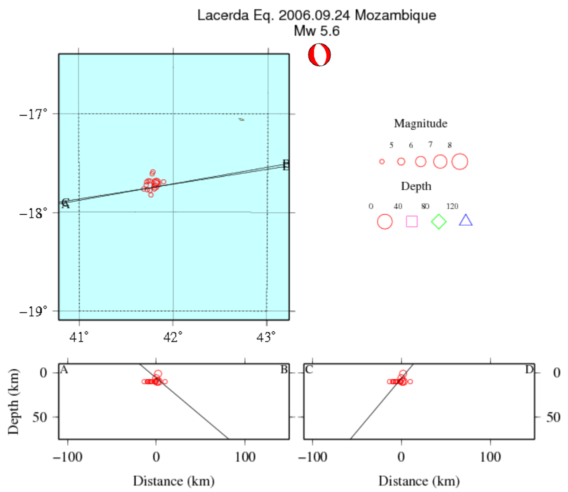

Figure 5. Epicentral distribution map using data from NEIC-USGS. The mechanism of the event considered is from Global CMT. The symbols are as in Figure 2.

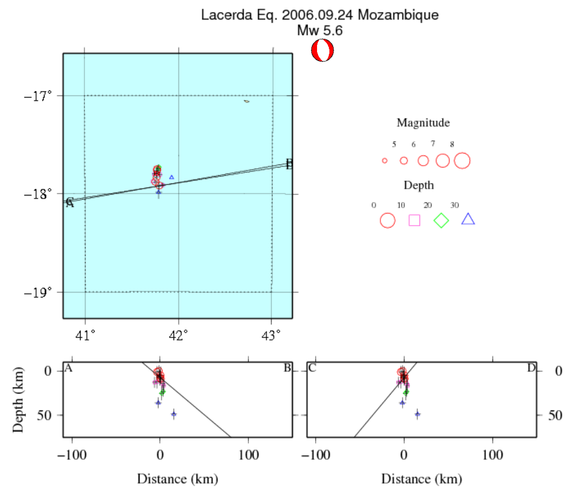

Figure 6. Relocated events from Lacerda cluster. The symbols are as in Figure 3.

DATA AND RESULT OF SLIP INVERSION

The rupture model of Machaze earthquake is determined in the present study using the inversion method by Yagi and Fukahata (2008). The data used was retrieved from Data Management Center (DMC) of Incorporated Research Institute of Seismology (IRIS). Fifteen vertical components from broadband seismograph stations are used to pick P-arrivals. To retrieve the source information the stations were selected within the epicentral distance between 30° and 90°.

For slip distribution waveforms are inverted for both nodal planes. For the nodal plane I, 13x10 grid points with spacing of 4 km was adopted. For the nodal plane II, grid points with 13x13 and spacing of 4 km was adopted. The fault models are determined for both nodal planes. The hypocenter is determined by grid search method varying the depth for every 2.0 km for both fault models. According to Figure 7, the differences between the variances of the strike, dip and rake of both fault models are small, but the fault model I present slightly smaller variances. Using the result from aftershock distribution it is assumed that fault model I is the actual fault plane. The spatio-temporal slip distribution is presented in the Figure 8d.

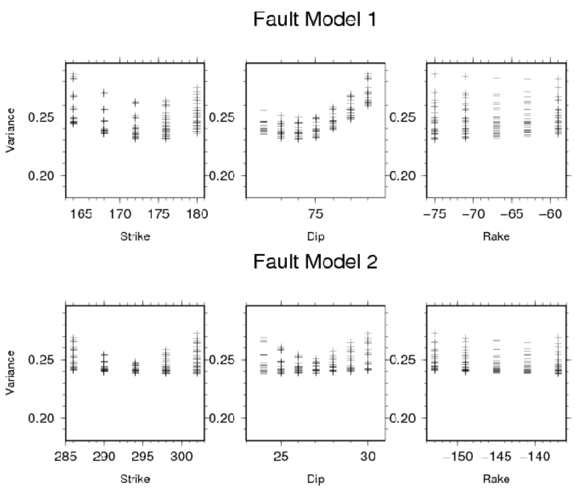

Figure 7. Comparison of the variances obtained for fault model I and fault model II.

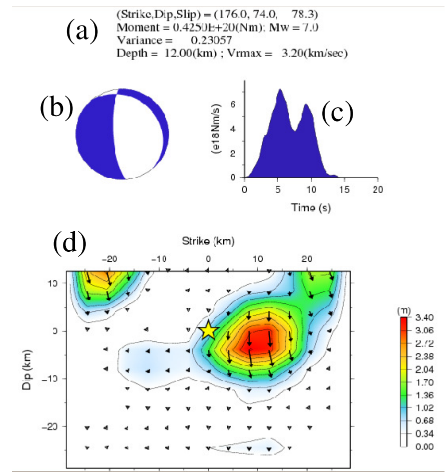

Figure 8. (a) Source parameters, (b) fault mode I mechanism of the event, (c) source time function, (d) amount of slip in each grid point. The arrows indicate the slip direction of the hangingwall.

The final source parameters of the Machaze earthquake determined in the present study can be summarized as follows: Strike, dip and rake, 176, 74 and -78.3, respectively; the initial break point is located at 12.0 km depth; the source duration is 13 seconds (Figure 8c); there are two asperities, the maximum slip is 3.4 m located in the south asperity near the initial break point and the asperity in the north of initial break point has a slip of about 2.5 m. The length of the fault plane is approximately 50 km.

DISCUSSION

The Machaze fault plane determined using the MJHD method dips to the west. It is normal fault and the strike, dip and rake (172°, 65° and -78°) of the determined fault plane are adopted from Global CMT. The result based on relocated aftershock distribution is consistent with the field observations by Fenton and Bommer (2006). Those authors observed that the Machaze fault strikes N10-20°W, and the linear trace of the fault indicates that the fault plane is relatively steep, which displacement is normal, down-to-the-west on a west-dipping fault plane. In the rupture process determination, there are two asperities observed. One of them is located at the surface, 15 to 25 km on the north of the initial break point. Source time function (Figure 8c) shows two peaks corresponding to two observed asperities. The second peak occurs five seconds after the first peak which means that the second major slip was observed at the surface five seconds after the major slip. The slip inversion showed also that other than the dominant dip slip offset, there are a small left-lateral offset (Figure 8). This result is consistent with the observations presented by Fenton and Bommer (2006). Aftershock distribution as observed in Figure 9 points that events in the northern side of the mainshock are shallower and in the southern side are deeper. That aftershocks distribution is consistent with the observed asperities from slip inversion. From slip inversion it is observed that the asperity located in the north of the initial break point is shallower and the southern one is deeper. In Figure 9 the fault plane is projected assuming the result of fault plane model determined from the slip inversion. This Figure shows a steeper fault plane (dipping 74°) and it fits well the aftershock distribution reducing the scatter observed when the orientation of fault plane determined by Global CMT is adopted.

Hashimoto *at el.,* (2007) observed from the analyses of ENVISAT images that the source fault is elongated in both north and south directions from the surface rupture, but they couldn't observe clearly the extent in the north of rupture area. In the fault slip distribution presented in this study, it's clear that there is no extension of slip distribution in the north of surface rupture area, related to coseismic rupture.

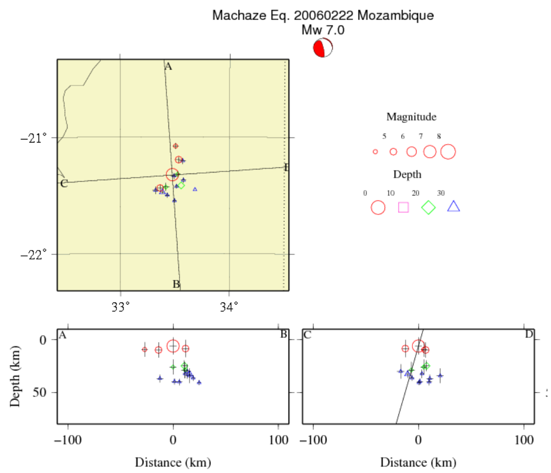

Figure 9. Aftershock distribution of Machaze event adopting the mechanism determined from slip inversion. The symbols are as in Figure 4.

The surface offset determined from the slip inversion in the present study is about 2.5 meters and that obtained by Hashimoto *at el.*, (2007) is about 2.0 ~ 2.7 meters. Those results are consistent each other. The fault length interpreted by Hashimoto *et al.*, (2007) is about 50 km.

The result from aftershock distribution suggests a fault length of approximately 50 km which is the same obtained from slip inversion. Furthermore, all analyses indicate bilateral rupture of the earthquake. The fault plane of the biggest event of Lacerda dip to the east and the strike is approximately N-S, which is consistent with the general strike of the Lacerda graben. Hypocenter distribution of this swarm shows that all of events lie along the same line suggesting that they belong to the same seismic plane.

CONCLUSIONS

Using the MJHD technique, a foreshock, the mainshock and aftershocks of the 2006 Machaze earthquake are accurately relocated in the present study. The fault plane dips to the west with a steep angle. The length of the aftershocks area is approximately 50 km. This study revealed also that the Lacerda cluster is an earthquake swarm. Although it should be an earthquake swarm, all events lie along the same line suggesting that they belong to the same seismic plane which dips to the east. Analyzing the orientation of both Machaze fault plane and Lacerda fault plane determined in this study and relating them with the tectonics of the area where they are located, it can be concluded that they are related to the progressive continental break-up, and intra-continental tectonism related to EARS. From the slip inversion analyze of the Machaze fault, it can be concluded that the Machaze earthquake had two main asperities, one of them located on the surface, which originated an offset of 2.5 meters. The initial break point was not the point of major slip of the fault. The fault slip confirmed that the fault was mainly normal faulting, but there is a small left-lateral slip along the fault plane. The length of the rupture zone is about 50 km and is consistent with the length of aftershock area.

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