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# SOURCE PARAMETER ESTIMATES OF THE 4 NOVEMBER 2016 $m_b$= 4.7 EARTHQUAKE NEAR LAWU MOUNTAIN IN EAST JAVA, INDONESIA

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**ABSTRACT**

Due to its geological conditions, Indonesia is home for a series of active volcanoes and fault zones spanning over the Sunda-arc in the country. With respect to possible volcano eruptions, earthquakes, and tsunamis, recent research development has therefore covered areas (previously not classified into areas vulnerable to potential threats)that are possibly suffering from tectonic movement. These include regions in the northern East Java, where Mount Lawu exists. This work aims to estimate source parameters of the 4 November 2016 earthquake with $m_b$= 4.7 that occurred in the region of interest. The methods were seismic data inversions using full moment tensors implemented in a MTINV software, where waveforms provided by 4 local stations from IA network: PCJI, UGM, SMRI, and KMMI were used. The results show a seismic moment of 5.03 x$10^{22}$ dyne cm, corresponding to a moment magnitude of $M_w$4.40, variance reduction of 60.8% with a 0.9% ISO component, a 73.8% CLVD component and 25.3%, DC component, and a centroid depth of 33 km. These suggest a complex fault interaction in the source mechanisms with the volcanoes earthquake is found to be complex interaction between fault about mountain Lawu and mountain Lawu.

## 1. INTRODUCTION

Identification of seismic signals produced by natural earthquakes of either tectonic or volcanic origin is of importance, in particular whenever there is a mountain situated nearby an active fault zone [1]. This problem drew particular attention to the community when an earthquake of $m_b$ = 4.7 occurred on Friday, November 4, 2016, at 05:08:12 UTC in a mountain located at Mount Lawu fault zone, stretching across the border of two provinces, the Central and East Java, in Indonesia [2]. As officially reported by The Indonesian Agency for Geophysics, Climatology, and Meteorology (BMKG), such an event was epicentered at 7.60 S and 111.30 E and mostly influenced surrounding cities, including Madiun, Trenggalek, Yogyakarta, Magetan, and Ngawi. Since then, a question of whether the quake is sourced from tectonics- or magma-driven activities has been raised with caution in that the affected regions along the northern part of Java island are not previously considered as regions vulnerable to seismic hazards, as opposed to most areas in the southern Java as part of the more active Sunda-Banda arc [3].

For a better understanding of Earth's crustal deformation processes in areas largely influenced by the Baribis-Mount Lawu thrust system that stretches across the northern Java island, a careful study [4] based on field measurements using Global Positioning System (GPS) has been performed. This study poses a question of whether the thrust system may extend to a more active fault zone in the Flores Sea. With respect to this, there is a need to examine events with relatively small to moderate magnitudes that occur in East Java, where Mount Lawu exists. This examination focuses on the determination of a seismic moment tensor, source parameters and corresponding mechanisms, and a focal centroid depth. Extraction of the source parameters from these earthquakes in the region of interest is of significance as they are too small to be detected by the Global Centroid Moment Tensor (CMT) solutions [5] and hence there have been so far no disseminations on this topic of research with a high local content. Further, the method of moment tensor inversion developed for the case considered in the present study serves as a useful tool for broad analyses of seismograms given by a local network of observatories. However, this method has also been applied to various cases using a regional network of stations [6] with the focus on examining the geological structure and seismicity in Egypt [7], exploring geothermal location in California, US [8], and characterizing nuclear explosions [9].

Within the context of seismic hazard assessment in the northern part of East Java, which includes Surabaya as the second largest city in Indonesia with a population of approximately 3 million people and considering that fault thrust passes through this crowded city and traverses a total distance of 300 km long in East Java, the main purpose of the present work is to estimate source parameters of the 4 November 2016 event with a recorded body wave magnitude of $m_b$ = 4.7 that propagated from the source region in the western Mount Lawu zone, East Java. In the process, we also solve focal and source mechanisms of the event under consideration. In the light of maximizing awareness of the science of disaster and minimizing disaster risks, the results obtained are used as a cornerstone for reassessing the level of seismic hazards in the regions of interest that include Surabaya and its neighboring cities.

## 2. METHODS

The methodology used in the present work was given in details in [6]. Here, we provide the saline points of the moment tensor inversion method using broadband seismic signals from seismograms filtered by band-pass filter between 45 Hz and 69 Hz, and recorded at an IA network of 4 local stations managed by BMKG, in collaboration with GFZ. The use of seismic waves at low frequencies provides good estimates of earthquake source parameters as these waves are not much influenced by speed and density variations. A full moment tensor is normally decomposed into three components, namely the double-couple (DC), compensated linear vector dipole (CLVD), and volumetric (isotropic-ISO) components. For determination and examination of source parameters of the 4 November 2016 event, we used a MTINV 3.04 software to only apply a full moment tensor composition, instead of a full moment tensor, assuming that there are no other sources, such as explosions in the source region except natural earthquakes of either tectonic or volcanic origin. Keep in mind, the moment tensor inversions in this work were performed with almost a zero component of net volumetric change.

### 1. Data collection

The broadband seismic data were collected from the 4 local stations used in this study: PCJI, UGM, SMRI, and KMMI. These stations with their geographical positions relative to the source are listed in table 1 below. The data used in this study are available at http://202.90.198.100/webdc3/.

**Table 1**. Names of stations used in this study with their epicentral distances.

| Network code | Seismic station | Latitude | Longitude | Epicentral distance (km) |
|---|---|---|---|---|
| IA | PCJI | 8.19° S | 111.18° E | 67 |
| IA/GE | UGM | 7.91° S | 110.52° E | 92 |
| IA/GE | SMRI | 7.05° S | 110.44° E | 113 |
| IA | KMMI | 7.04° S | 113.92° E | 295 |

In accordance with the broadband data recorded, we applied a one dimensional model of velocity to the proposed method. In the model, speed variations of *P*- and *S*-waves with depth D, wave qualities $Q_P$ and $Q_S$ for each wave component, respectively, and the local density $\rho_L$ were provided, as seen in table 2. The wave qualities $Q_P$ and $Q_S$ are dimensionless, showing criteria of how good the model is. As discussed in [10], a threshold value of 500 for the *P*-wave speed distribution over the depth is provided, above which the corresponding *P*-waveforms from seismograms are assumed to be reliable owing to a minimum noise level and for the same reason a threshold value of 250 for the *S*-wave speed distribution is provided, above which the corresponding *S*-waveforms are reliable.

**Table 2**. Seismic velocity model for use of seismic data inversions.

| D (km) | $v_P$ (km/s) | $v_S$ (km/s) | $Q_P$ | $Q_S$ | $\rho_L$(g/cc) |
|---|---|---|---|---|---|
| 0.0 | 4.8 | 3.1 | 500 | 250 | 2.4 |
| 13.0 | 5.6 | 3.2 | 500 | 250 | 2.6 |
| 45.0 | 6.1 | 3.5 | 500 | 250 | 2.8 |
| 700 | 8.0 | 4.6 | 1000 | 500 | 3.2 |

### *2. **Data analysis***

Analysis of broadband seismogram data was performed by inverting 3 local waveform components obtained from 4 local stations used in this study to extract the source parameters and corresponding source mechanisms of the earthquake examined.Seismic moment tensor describing the earthquake intensity was decomposed into the full moment tensors component only and in turn this simple decomposition of the full moment tensors component into ISO, DC and CLVD components. This argument is supported by practical applications, where source mechanisms reported by almost all seismic surveillances for examining seismicity in particular areas as well as research findings reported in [8, 11] are primarily based on the decomposition of the full moment tensors component into an of ISO, DC and CLVD components.

## 3. RESULTS AND DISCUSSIONS

We have applied the full moment tensor inversions using broadband seismograms to estimate the source parameters of an earthquake nearby Madiun that occurred on Friday, November 4, 2016. The results of the data inversions are given in the forms of three correlated figures 1, 2, and 3.

Figure 1 describes curve fitting from both observations and simulations with the 3 local component micro-displacements are symbolized as T, R, and Z for tangential, radial, and vertical components, respectively. In all stations, black-colored curves show waveforms obtained from field observations whereas red-colored ones are for synthetic waveforms. The results of the moment tensor inversions for all the broadband seismograms recorded by 4 local stations can be seen on the top right of figure 1, where all numerical values characterizing the event, such as geographical locations in longitude and latitude degrees, a centroid depth in km, nodal planes (NP1 and NP2), a seismic moment ($M_o$), and all 6 components of the momen tensors($M_{xx}$, $M_{xy}$, $M_{xz}$, $M_{yy}$, $M_{yz}$, $M_{zz}$) with the other 3 components are given in a set of paired tensors $M_{yx} = -M_{xy}$, $M_{zx} = -M_{xz}$, and $M_{zy} = -M_{yz}$ as they are symmetric tensors.

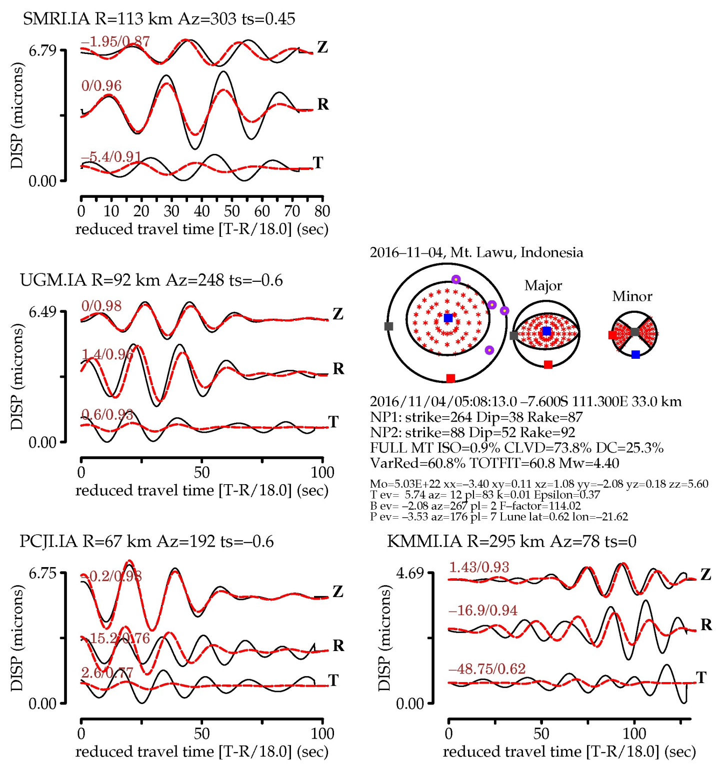


***Figure 1.*** *Broadband seismogram data with all the 3 local Z, R, and T waveform components from the 4 November 2016 event, showing curve fittings of observed and simulated waveforms obtained from the 4 local stations (PCJI, UGM, SMRI, KMMI) used in the present study, where black colors represent the observed waveforms and red colors represent the simulated waveforms. On the top right are the results of the moment tensor inversions for the full moment tensors component decomposition, where all computed values corresponding to the seismic source parameters are provided, including the source mechanisms and focal centroid depth. Numerical values above 3 waveform components recorded at each station denote epicentral distance R from the source, azimuthal location Az, and times ts at which the seismic inversion started to run.*

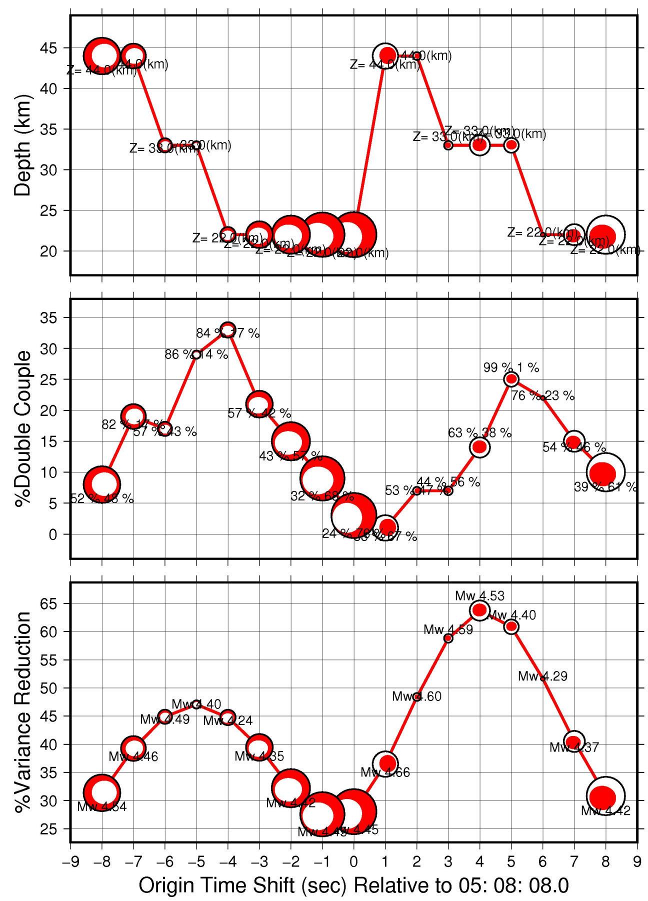


***Figure 2.*** *Visual graphics, showing cross-correlation of variance reduction, full moment tensors component, and centroid depth with respect to time taken for the moment tensor inversions. The variance reduction is at its peak of 60.8% corresponding to a seismic moment of $M_w$ 4.40 (bottom panel), which correlates to a 25.3% DC component (middle panel) and a 33 km centroid depth (top panel). This cross-correlation shows that the 4 November 2016 earthquake in the Mount Lawu fault zone is a seismic event caused by a complex interaction of both tectonic and volcanic forces, with the vertical CLVD component (73.8%) being the leading process in the source mechanisms.*

From statistical analysis of the data fitting, the moment tensor inversions yield variance reduction of 60.8% that corresponds to a seismic moment magnitude of $M_w$ 4.40, a 0.9% an ISO, 25.3% DC component and a 73.8% vertically oriented CLVD component, and a focal centroid depth of 33 km. The almost zero ISO component for a relatively shallow source in the present case is consistent with previous finding [11], where the isotropic component was reported as independently unresolved from the CLVD component for major deep earthquakes. These calculations demonstrate the relative importance of the presence of volcanic over pressure with almost no volumetric component observed in the source mechanisms, similar to the one discussed in [12] for the unusual 1996 Bardarbunga event that occurred in Iceland. These findings reflect unresolved, complicated processes in nature as claimed by previous work, see for example, [2, 4, 6].

The possible source for the 4 November 2016 earthquake seems to have dual mechanisms due to the complex interactions of the fault thrust and volcanic depression system, where the volcanic depression plays a greater role in regard to the larger CLVD component in percentage (73.8%), relative to the DC component (25.3%). This is consistent with the results of both primitive [3] and modern work [2, 4], claiming that areas of convergence based on geological and volcanic arc history are found along the fault lines across the border of Central and East Java. As conclusively noted by [2] based on the stratigraphic records of a volcanic eruption, Java is thus fundamentally a volcanic island with its recorded long history of arc volcanism.

Plotted in figure 2, visual graphics as a result of the seismic moment tensor inversions. The plots show cross-correlation of statistical variance reduction (in percent), an ISO, DC, CLVD component (in percent), and a centroid depth (in km). The 4 November 2016 event fits with a peak of variance reduction at 60.8%, corresponding to a seismic moment magnitude of $M_w$ 4.40, accompanied by many earthquakes with portions of ISO, DC) and CLVD components are somewhat in balance where the NDC component is dominated by the vertical CLVD. As with natural earthquakes having almost a zero volumetric (ISO) component, the source mechanism is commonly modeled using a combined (DC + CLVD) source mechanism, as also discussed in [8, 11]. This combination, as in most cases, places the DC component in a major role but in a particular example, such as the 1996 Bardarbunga earthquake [12], the volumetric (ISO) component was insignificant, making the CLVD component to be the dominant part and hence a less role in the DC component. These, together with the results of both moment tensor inversions (figure 1) and cross-correlation (figure 2), yield the same centroid depth of 30 km, suggesting an uplift magma-driven motion of fluid flow under the influence of high pressure inside a mountain chamber [6], as oppose to the processes characterizing underground explosions with domination of the apparent isotropic component [9].

In summary, we have utilized the broadband seismogram data from the 4 local seismic stations (within the IA network) surrounding the epicenter of the 4 November 2016 event of $m_b$ = 4.7 that occurred in the potential active Mount Lawu fault zone in East Java. The moment tensor inversions applied to the broadband data result in a vertically oriented CLVD component as a relatively dominant feature in the source mechanisms with almost no isotropic component (figure 3). This suggests that depression inside Mount Lawu mountain is a leading uplift force although it is not yet clear why there exists somewhat a dynamic balance between the DC (25.3%) and CLVD components (73.8%). However, the moment tensor inversions give better resolution in determining a focal centroid depth for the source than other methods of depth estimation, particularly when dealing with potential an complex interaction a mountain situated nearby an active mountain Lawu as is the case in the present work.

In addition, determination of earthquake source parameters using the moment tensor inversion method is of importance as the method is likely to be able to reveal the dominant factor of the source. It follows that using this method accurate identification of seismic source characteristics whether it is of tectonic or volcanic origin, or due to underground explosions or surface landslides is relatively easy to handle [5, 7]. As pointed out by [1], the identified source parameters and focal mechanisms can also be used to determine whether the earthquake is classified intraplate (when the centroid location is at or nearby the source region) or extrapolate (when the centroid is located at relatively far from the source).

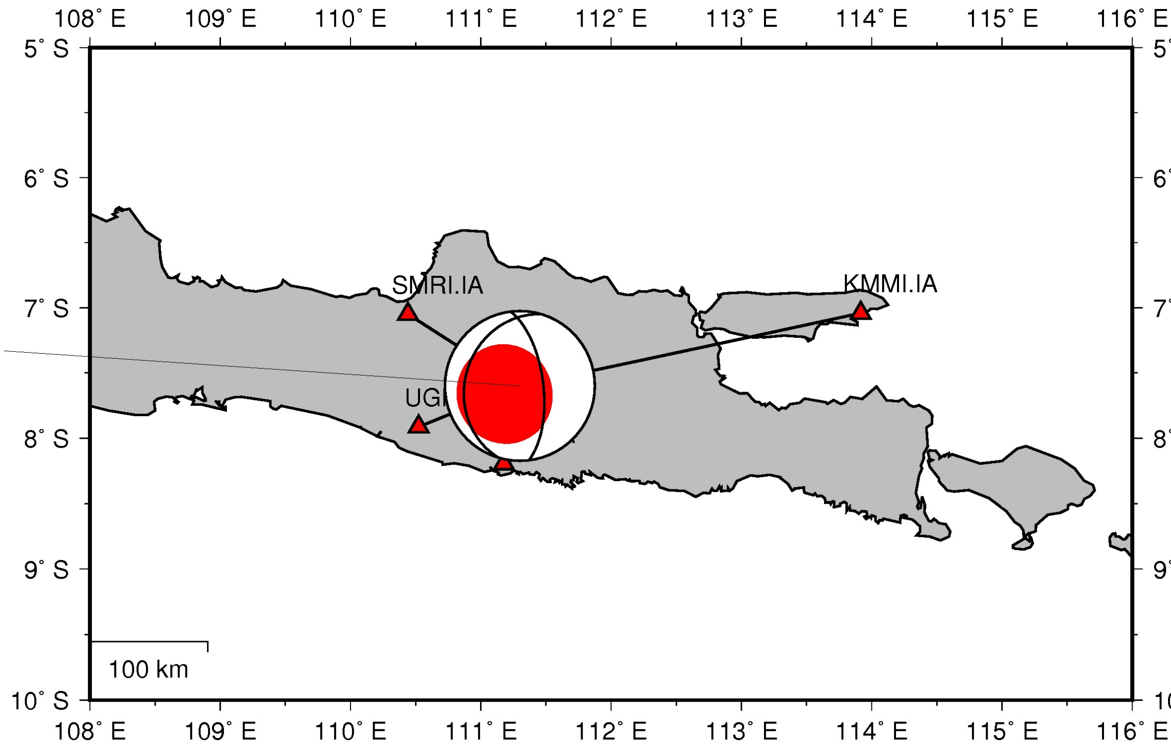


*Figure 3. A simple map, showing type of source mechanisms for the 4 November 2016 earthquake (given in the form of a beach-ball slightly dominated by vertical CLVD component, relative to the DC component) with all of the 4 local seismic stations (PCJI station is unseen due to an excessive size of the beach-ball) used in the present study. The focal mechanism is vertical-P of CLVD. The vertical-P focal mechanisms indicate that the earthquakes are associated with a documented episode of volcanic unrest at a nearby volcano [13], where unrest is not soon followed by an eruption [14].*

## 4. CONCLUSIONS

We have performed the full moment tensor inversions for the 4 November 2016 earthquake of $m_b$ = 4.7 that occurred about mountain Lawu zone, East Java, Indonesia. This event raises a crucial question whether such an event was mainly triggered by seismo-tectonic forces or induced by magma-driven activities. Using the data from broadband waveforms recorded at local stations within an IA network, the method of the moment tensor inversions reveals surprising results, providing a new insight into the source and focal mechanisms of the quake under consideration. The results indicate the dominance of the ISO component (0.9%), compensated linear vector dipole (CLVD) component (73.8%) relative to the double-couple (DC) component (25.3%), suggesting no net volumetric-isotropic (ISO) component, which is a puzzling result from a volcanic point of view [12]. Together with a measured seismic moment of 5.03 $x10^{22}$ dyne cm corresponding to $M_w$ 4.40 (an intermediate earthquake in size) and a relatively shallow, centroid depth of 33 km, we conclude from the relative dominance of the CLVD component over DC component that the 4 November 2016 event is not merely related to the active mountain Lawu zone. Instead, the event is primarily driven by complex internal interactions between active faults and volcanic systems of depression, normally characterizing intraplate earthquakes nearby the mountain Lawu zone.

However, the main finding in the current study raises a possibility for crustal deformation to occur in the eastern Sunda-Banda arc owing to earthquakes (with and with no tsunamis generated) in areas in the northern Central and East Java, previously not considered as regions vulnerable to either tectonic or volcanic earthquakes. As suggested by [4], potential active crustal structures beneath the island of Java and hence the presence of active fault zones particularly in the northern part of Java may induce several devastating ruptures in the past times. Thus, much concern with care about the importance of considering crustal deformation and fault activity in East Java, as a region of interest, is necessary for minimizing disaster risks, highlighting the need for reconsidering the level of seismic hazards as part of future seismic analysis and assessment in the surrounding regions.


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