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Determination of source parameters of the 2017 Mount Agung volcanic earthquake from moment-tensor inversion method using local broadband seismic waveforms

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Abstract. Monitoring of volcanoes has been an important issue for many purposes, particularly hazard mitigation. With regard to this, the aims of the present work are to estimate and analyse source parameters of a volcanic earthquake driven by recent magmatic events of Mount Agung in Bali island that occurred on September 28, 2017. The broadband seismogram data consisting of 3 local component waveforms were recorded by the IA network of 5 seismic stations: SRBI, DNP, BYJI, JAGI, and TWSI (managed by BMKG). These land-based observatories covered a full 4-quadrant region surrounding the epicenter. The methods used in the present study were seismic moment-tensor inversions, where the data were all analyzed to extract the parameters, namely moment magnitude, type of a volcanic earthquake indicated by percentages of seismic components: compensated linear vector dipole (CLVD), isotropic (ISO), double-couple (DC), and source depth. The results are given in the forms of variance reduction of 65%, a magnitude of M_w 3.6, a CLVD of 40%, an ISO of 33%, a DC of 27% and a centroid-depth of 9.7 km. These suggest that the unusual earthquake was dominated by a vertical CLVD component, implying the dominance of uplift motion of magmatic fluid flow inside the volcano.

1. Introduction

Indonesia is a country geographically located in the circumference of the Pacific ring of fire that leads to the presence of a series of active volcanoes along the Sunda arc in the country, and thus potential to earth-related disaster due to volcanic eruption. Efforts for minimising impacts and reducing risks of such a catastrophic disaster have been implemented by the government and non-governmental bodies, but much has not yet been achieved. In this context, monitoring of volcano activities has therefore been important for the development of knowledge in the discipline and hazard mitigation study [1].

We provide here a volcanic earthquake driven by recent magmatic events of Mount Agung, Bali that occurred on September 28, 2017 as a case study to consider. When magmatic processes naturally occurring in the deep down a volcano generate vertical movement of viscous fluids that passes through crustal rocks up to the caldera leading to an eruption, many phenomena associated with earthquakes of



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volcanic origin are possible to observe, such as cracks on the ground, lava flows, massive transports of mass and volume of volcanic materials, and volumetric changes inside the volcano [2,3,4].

Careful analysis of earthquakes of volcanic origin allows us to examine the dynamics of a magma and its complex geophysical and geochemical processes inside a volcano [5]. This is important in part to predict eruption that is possible to occur and estimate the possible impacts of such a volcanic hazard on the environment. Although most of these earthquakes are relatively small in magnitude and hence recorded by nearby stations of local network, in some circumstances such earthquakes may induce events with large magnitudes possibly observed by regional and global networks of observatories [6]. In many examples of these events, it has been found that the source shows anomalous behaviours, such as unusual patterns of seismic radiation or frequency content [7]. In addition, previous work on this topic [8] found that earthquakes of volcanic origin with magnitudes ~ 5 dominated by a vertical CLVD component were empirically identified within 6 volcanic zones around US and that after a time period of magma activities, the corresponding volcanic activities became weakening in intensity.

In the present work, we investigate an unusual earthquake observed from Mount Agung, Bali that occurred on September 28, 2017. We hypothesize such an earthquake as a vertical CLVD component. Vertical CLVD events have deviatoric moment-tensors with nondouble-couple (NDC) components are evidence-based seismic phenomena and are dominated by uplift motion of source deformation due to lateral compressions and vertical dilatations [9]. This type of earthquake is rare in nature but possible to occur and frequently associated with an active volcano. Thus, this study is of importance aimed at determining the source parameters of the earthquake effectively driven by recent underground events from Mount Agung magmatic activities.

2. Methods

Mount Agung is one of the two largest volcanoes in Bali island, geographically located at 8.29° S and 115.40° E with its elevation reaches to a 3,031 m high. This volcano has been recently in debate by many whether it would erupt since a sequence of unusual magma-driven earthquakes beginning from September 13, 2017 to date. The one we used in this study for determination of the source parameters is that to occur on September 28, 2017.

2.1. Data collection

The data used in this study were obtained from broadband seismic waves recorded by the IA network of local seismic stations officially operated by the Indonesian Agency for Geophysics, Climatology, and Meteorology (BMKG) which provides 5 seismic stations: SRBI, DNP, BYJI, JAGI, and TWSI. These stations with their geographical positions relative to the source covering a full 4-quadrant region surrounding the epicenter are listed in table 1 and schematically illustrated in figure 1. All of the data used are freely 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	SRBI	8.08° S	115.20° E	31
	DNP	8.68° S	115.21° E	48
	BYJI	8.21° S	114.36° E	115
	JAGI	8.47° S	114.15° E	139
	TWSI	8.74° S	116.88° E	170

2.2. Data analysis

For data analyses in the current study, we first used a seismic wave velocity model for providing variations of both P - and S -wave speeds with depth D and their corresponding wave qualities Q_P and Q_S

for each body wave component, respectively, as well as the local density ρ_L . All of these quantities, seen in table 2, were used for a seismic data inversion method. The wave qualities denoted by Q_P and Q_S are non-dimensional numbers showing measures of how reliable the model is (given in the forms of variations of the body wave speeds and the densities with depth for seismic data inversion techniques). As also used by [6], a lower limit value of 500 for the P -wave speed distribution over the depth is a threshold number, above which corresponding P -waveforms from recorded seismograms are reliable to analyse owing to a minimum level of noises and for the same reason a value of 250 for the depth-distributed S -wave speed is a threshold number, above which corresponding S -waveforms are reliable.

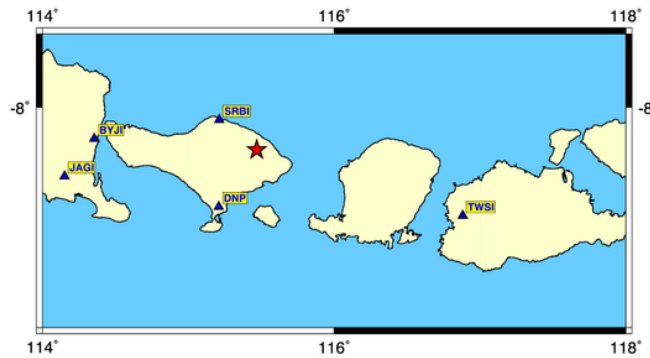


Figure 1. Map of the source (red star) and local stations (blue triangles) in this study.

Table 2. A seismic velocity model for use of seismic inversion method.

D (km)	v_P (km/s)	v_S (km/s)	Q_P	Q_S	ρ_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

The analysis of broadband signals from recorded seismograms with a low-pass filter at frequencies ranging from 0.054 to 0.072 Hz obtained from a network of 5 local seismic stations for determination of the source parameters was performed using a software package of MTINV 3.05 (used in this study with permission from Dr. Ichinose). The use of observed seismic signals at low frequencies is reliable for estimating source parameters as these signals are insensitive to the effects of lateral wave velocity and density variations inside the Earth [8].

3. Results and discussions

We used the moment-tensor inversion method using the local broadband seismograms to determine the source parameters of unusual events nearby Mount Agung that occurred on September 28, 2017. The method utilized a simple model of a one-dimensional seismic wave velocity profile. The results of seismic data inversions are then provided in the forms of three consecutive figures 2, 3, and 4, where each figure is correlated one to another to provide a complete description of the events.

Figure 2 describes waveform fitting from full moment-tensor inversions of the 28 September 2017 volcanic earthquake at and nearby Mount Agung recorded by 5 seismic stations listed in Table 1. In each seismic station, the 3 local components observed and synthetic displacement seismograms are symbolized as T for a tangential component, R for a radial component, and Z for a vertical component.

In all stations, black-colored waveforms represent observed waveforms while red-colored waveforms in stations SRBI, DNP, and JAGI are for synthetic waveforms as well as the blue ones in stations BYJI and TWSI.

The results of the full seismic data inversions for all the broadband seismograms from the 5 stations can be seen on the top right of figure 2. The seismic inversion method yields a variance reduction of 65.2% from statistical analysis of the data fitting that corresponds to an earthquake of M_w 3.64 in size, a vertically oriented compensated linear vertical dipole (CLVD) component of 39.9%, an isotropic (ISO) component of 33.1%, a double-couple (DC) component of only 26.9%, and a centroid-depth of 9.7 km below the sea surface level. These features, to some extent, confirm the relative importance of vertical magmatic movement inside the volcano in the presence of highly viscous, magmatic fluid flow under the influence of uplift volcanic pressure. This geophysical process is complicated in nature as claimed by [5, 6] for the 2000 Miyakejima unusual swarms. As is the case discussed by [4], this study also finds that the relative dominance of uplift motion indicated by a major of a vertically oriented CLVD component, following a weak DC source mechanism, is accompanied by volumetric change inside the volcano. This finding is different from that reported by [10], in which unusual earthquakes that occurred in the Bardarbunga, Iceland in 1996 were to occur with no net volumetric component in the source mechanism.

Figure 3 shows a simple description of 3 interconnected graphics on the cross correlation between variance reduction and a double-couple (DC) source mechanism (given in per cent), and a centroid-depth (given in km). It is clear that the 28 September 2017 Mount Agung unusual events with a 65.2% variance reduction of magnitude 3.64 were visibly accompanied by many anomalous earthquakes with relatively large nondouble-couple (NDC) components of approximately 73%, in oppose to almost 27% double-couple source mechanism. Natural earthquake sources with a net volumetric component are commonly modeled using a DC source mechanism [5, 6] but it does not work for the case of the 2017 Mount Agung events. Although in a particular example, such as the 1996 Bardarbunga earthquake, volumetric component was absent [10], the present case clearly shows the relative importance of NDC components with a compensated linear vector dipole (CLVD) component is measured slightly greater, in percentage, than an isotropic (ISO) component. It suggests that the full moment-tensor inversions as well as the cross correlation between the corresponding source parameters in the present study reveal magmatic motion of viscous fluid flow in the vertical direction [7, 8] all the way up to the caldera before eruption to occur.

We have modeled broadband seismograms from the IA network of the 5 stations surrounding Mount Agung. The local broadband seismograms extracted from the occurrence of 28 September 2017 yield a vertically oriented CLVD component, a relatively dominant feature in the source mechanisms (as seen in figure 4) as a result of seismic moment-tensor inversions, the same method as utilized by [7, 8]. This suggests that vertically directed motion of magmatic fluid flow inside the volcano with a net volumetric change, as implied by [4, 5, 6], is a leading uplift force although it is not yet clear why the volcano remains active with no eruption. However, the full moment-tensor inversions give a better result in terms of a centroid-depth instead of depth determined by other methods of depth estimation, in particular when dealing with active volcanoes. Knowledge of the source process and its component dominance is directly derived from examining and analyzing differences in percentage of CLVD, ISO, and DC components (see figures 2 and 3).

It is interesting to make direct comparison of all aspects of focal and source mechanisms between this study and previous work [10]. The case considered here applied different broadband seismograms in comparison to those used in [10]. While a local network of seismic stations were provided by BMKG for use of the 2017 Mount Agung earthquake, regional broadband waveforms were used in [10] although the full moment-tensor inversions were applied in both. The results for these studies were nondouble-couple (NDC) source mechanisms. However, [10] found a volumetric change to be absent in the dominance of a vertically linear vector dipole (CLVD) component. In contrast, the present study has a clear (isotropic) net volumetric component that is comparable to the vertical CLVD component. The

fact that the vertical CLVD component (39.9%) is not much greater than the ISO component (33.1%) is likely to be the cause for Mount Agung being active with no eruption.

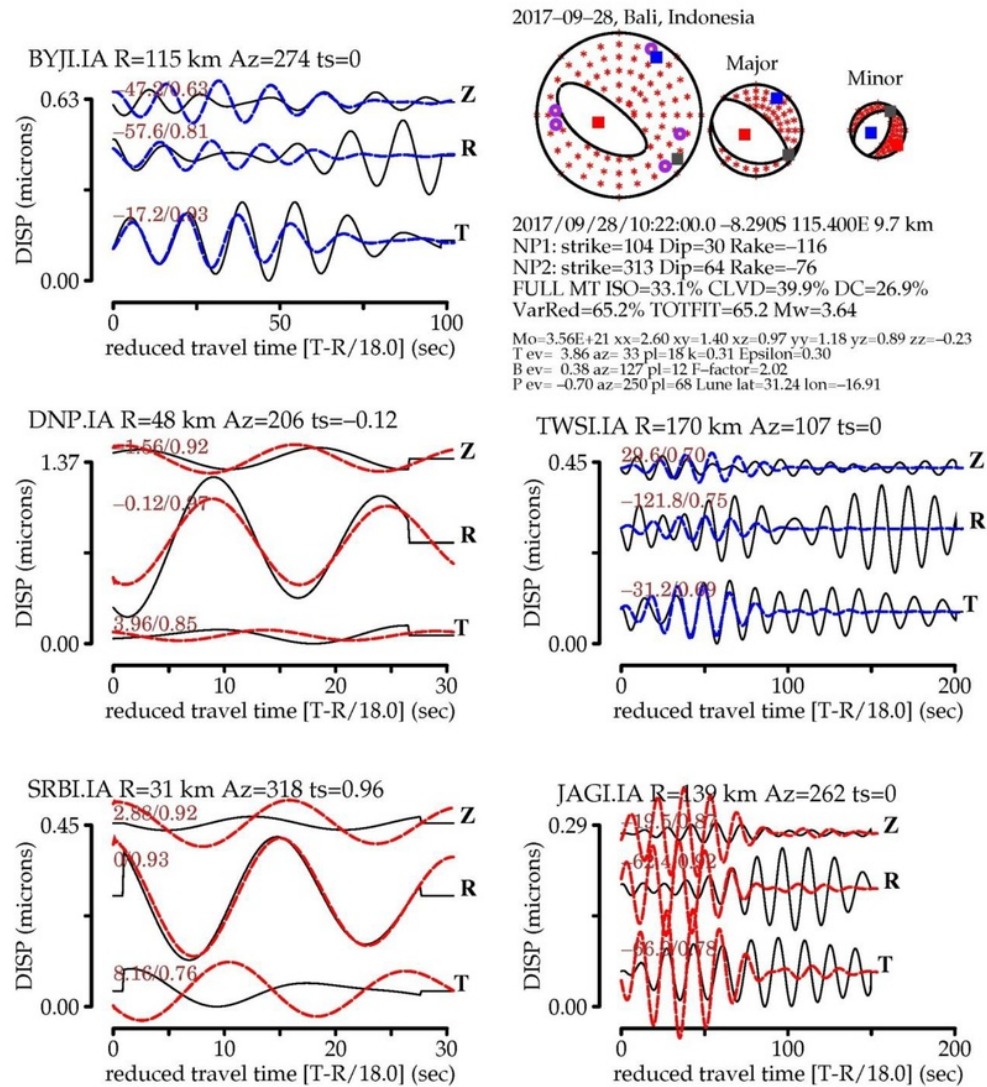


Figure 2. Broadband seismogram data with the 3 local Z, R, and T components showing fittings of observed and synthetic waveforms from the network of 5 local stations (SRBI, DNP, BYJI, JAGI, and TWSI) used in this study, where black colors denote observed waveforms and both red and blue colors represent synthetic waveforms. On the top right are the results of full seismic moment-tensor inversions, where all the computed source parameters, including source mechanisms are provided.

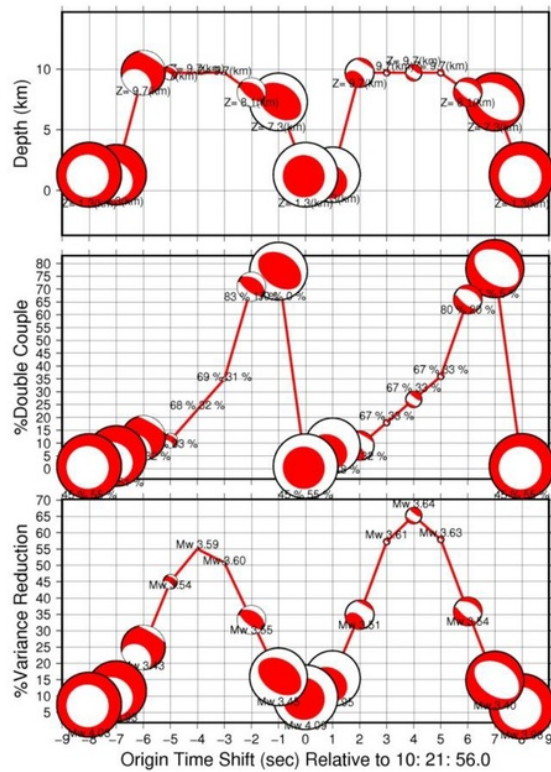


Figure 3. Three graphics in one, describing a simple cross correlation of variance reduction, double-couple component, and centroid-depth with respect to time taken for the full seismic moment-tensor data inversions. The variance reduction reaches the highest value at almost 65% corresponding to an unusual earthquake with a magnitude of M_w 3.64 (bottom). This relates to a 27% DC component (middle) and then a 9.7 km centroid-depth (top). The cross correlation shows that all the inter-correlated 'beach-balls' for the 2017 Mount Agung events are dominated by nondouble-couple source mechanisms.

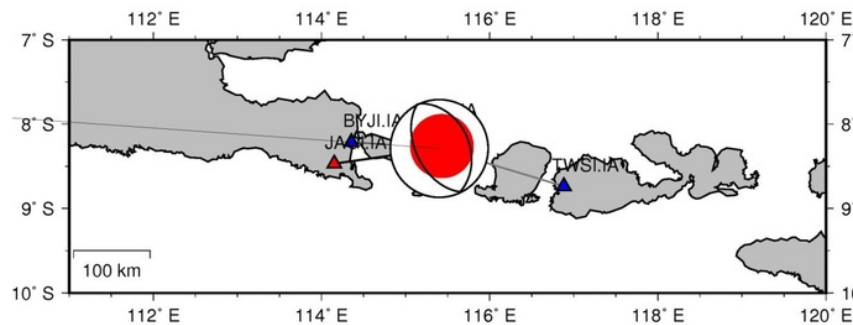


Figure 4. A simple map, showing a type of the Mount Agung unusual earthquakes (given in the form of a beach-ball dominated by NDC source mechanisms) that occurred on September 28, 2017 with all of the 5 local seismic stations (some stations are unseen due to an excessive size of the beach-ball) used for recording local broadband seismogram data are positioned located nearby the epicenter.

4. Conclusions

We have used seismic moment-tensor inversions for examining an unusual, magma-driven earthquake of Mount Agung, Bali that occurred on September 28, 2017 to determine the source parameters involved. The model of a one-dimensional velocity structure used in this study fits the local broadband data with

statistical analysis of the 65.2% variance reduction that corresponds to the earthquake size of M_w 3.64, where the earthquake is found to be primarily characterized by the 39.9% vertical CLVD component as well as a less dominant part, the 33.1% isotropic (ISO) component and the relatively unimportant 26.9% DC component, and the hypocenter at a centroid-depth of 9.7 km, suggesting that such an earthquake is of a nondouble-couple source mechanism. The results indicate that the volcanic earthquake under consideration is dominated by uplift motion of magmatic fluid flow accompanied by a volumetric change inside the volcano. These two features are in common for volcanic earthquakes before eruption. Knowledge of which seismic component is dominant is necessary for decision making about volcano alert status. Because the vertical CLVD component (~40%) is not too large relative to the ISO component (~33%), we therefore speculate for this case that the volcano has not yet erupted although it remains active. However, as Indonesia is a country vulnerable to geophysical hazards, such as volcanic eruption, monitoring of volcanoes is of fundamental significance to prevent community from disastrous events. The methods developed are possibly evaluated for a wide range of applications to similar cases with different source mechanisms, for example, detection and characterization of nuclear explosions and natural tectonic earthquakes, as also discussed in [11, 12], for future work.

Acknowledgments

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PAGE 1

PAGE 2

PAGE 3

PAGE 4

PAGE 5

PAGE 6

PAGE 7

PAGE 8