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Analysis of swarm earthquakes around Mt. Agung Bali, Indonesia prior to November 2017 eruption using regional BMKG network

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Abstract

Mt. Agung, located in Karangasem-Bali, Indonesia, had a significant increase of swarm earthquakes from September 2017 until the recent eruption in November 2017. To analyze the seismic swarm and its correlation with the magmatic movement, we worked on the regional seismic data recorded by Agency for Meteorology, Climatology and Geophysics of Indonesia (BMKG) between September 14 to October 20, 2017. P-and S-wave phases of the swarm events had been manually picked. In total, 804 events in the time period of September 14 to October 20, 2017 were successfully determined. To improve the location precision, the double-difference relocation method was performed. We identified most of the events as Volcano-Tectonic type A (VT-A) earthquakes and located between Mt. Batur and Mt. Agung. Those events form a cluster striking in NE-SW direction at a depth between 2 and 20 km. Focal mechanism solutions for selected events below Mt. Agung show a thrust and strike-slip faulting regime. Interestingly, a trend of event propagation toward the summit of Mt. Agung was observed. The frequency of VT-A event occurrences is significantly increased at the later stage of the swarms. We concluded that the increased seismic activity in Mt. Agung was due to the migration of magma from the deep chamber to the shallow reservoir.

Keywords: Mt. Agung, Bali, Seismicity, BMKG regional seismic stations, Double-difference relocation, Focal mechanism

Introduction

Mt. Agung, located in Karangasem-Bali, is one of the 127 active volcanoes in Indonesia and the eruption type is explosive. Based on the record of the Center for Volcanology and Disaster Hazard Mitigation of Indonesia (CVGHM), Mt. Agung (3.142 m above the mean sea level) has erupted four times, i.e. in 1808, 1821, 1843, and 1963. The latest eruption in 1963 caused 1148 people to die, and 296 others were injured. Before the 1963 eruption (from February 18, 1963), an increase of earthquake activity was felt by a resident in Yeh Kori Village located 6 km southeast Mt. Agung, in the region of Tianyar-Tejakula, north coast of Bali (Zen and Hadikusumo 1964). In 1963, The first major explosion produced a widespread ash fall that dispersed west–northwestwards, with ash fall being reported as far away as Bandung and Jakarta in western Java, a distance of about 1000 km from the volcano (Self and Rampino 2012). The eruption occurred during the wet season in Bali, and the pyroclastic flow and tephra fall deposits rapidly generated hot and cold lahars by mixing with the torrential rainfalls that followed. Heavy rains on Agung began eroding the pyroclastic deposits immediately after the explosive phase, devastating the lowlands with lahars that reached all the way to the coast (Fig. 3). The eruption caused many casualties and destruction of villages, largely from the pyroclastic flows and ensuing lahars (Self and Rampino 2012).

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Considering the scale and impact of 1963 eruption, the Indonesian government began to intensively monitor the activity of the volcano to mitigate the negative impacts of the volcanic eruption (Kusumadinata 1964). In general, an increase of volcanic activity can be noticed by observing the physical and chemical changes, e.g. physical change of volcanic smog from the crater (as well as its chemical composition), an increase in temperature in the crater, volcano deformation, and an increase of microseismic activity recorded on seismographs (McGuire 1992).

In this study, an analysis of Mt. Agung swarm earthquakes 2 months prior to the November 2017 eruption was performed. The correlation between swarm earthquakes, tectonic and magmatic activity has been observed in many places, especially in Indonesian regions, e.g. Mt. Pandan (Santoso et al. 2018), Jailolo volcano (Nugraha et al. 2018a), Bekancan (Nugraha et al. 2018b), the southern part of Garut, West Java (Supendi et al. 2018), West Halmahera (Nugraha et al. 2017b) among many others. Albino et al. (2019) suggested that the dike intrusion between neighboring arc volcanoes was responsible for the Mt. Agung 2017 eruption. A dike intrusion might be the source of the seismic swarm recorded at Mt. Agung.

In September to October 2017, seismic activity around Mt. Agung reached hundreds of events, some of which were felt by the local population. The initial location of BMKG showed that these earthquakes are located at a depth less than 40 km. The aim of this study is to analyze the characteristics of VT events of Mt. Agung and its correlation with magma migration. An advanced analysis of sources relocation and their mechanism is performed in this study to improve the accuracy of the initial locations published by BMKG.

Data and methods

In the framework of Indonesian Tsunami Early Warning System (InaTEWS) operated by the Agency for Meteorology, Climatology and Geophysics of Indonesia (BMKG), there are 10-broadband seismic stations covering Mt. Agung (Fig. 1) with a sampling frequency of 40–100 Hz. The 3-component waveform data of those 10 stations were retrieved for the time period from September 14 to October 20, 2017. The selection of the time period was based on the occurrence of the seismic events observed at Mt. Agung.

On 22 September 2017, the status of Mt. Agung was increased to level IV (warning) due to an increase of Volcano-Tectonic (VT) earthquakes intensity in the
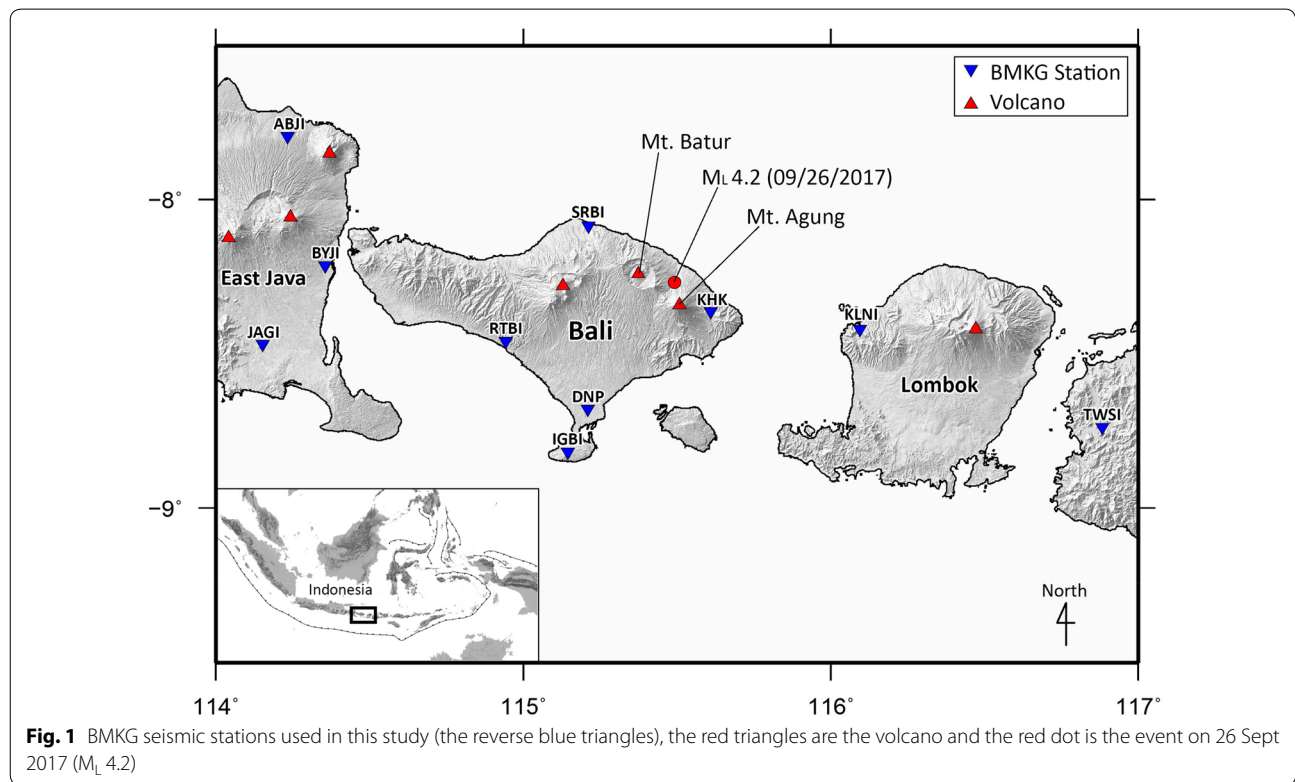

Fig. 1 BMKG seismic stations used in this study (the reverse blue triangles), the red triangles are the volcano and the red dot is the event on 26 Sept 2017 (M$_L$ 4.2)

Mt. Agung area. CVGHM produced Volcano Observatory Notice for Aviation (VONA) reports based on analysis of data from the agency's monitoring networks as well as from direct observations. VONA's alert levels are color-coded to indicate the different types of notifications addressing specific informative needs. VONA's alert consists of levels I (normal), level II (advisory), level III (watch), and level IV (warning). Level IV implies an intensive increase of seismicity, monitoring of other obvious volcanic changes, and visual observations including the crater.

We have utilized the regional seismic network surrounding Mt. Agung to analyze the swarm earthquakes for the time period of September 14 to October 20, 2017. A double-difference technique was applied to improve the accuracy of the initial hypocenter location obtained in this study. A significant improvement of the location accuracy was demonstrated. A further source mechanism analysis of the earthquake swarm sequence was obtained through focal mechanism inversion. Furthermore, the seismic swarms obtained in this study could also be further processed to infer the internal structure of the volcano (Nugraha et al. 2017a; Widiyantoro et al. 2018).

VT earthquakes of a volcano are classified into VT type A (VT-A) and VT type B (VT-B) (McCausland et al. 2017; Iguchi et al. 2011). Stress accumulation is caused by magma intrusion to the surface, which might trigger slip on the nodal plane of the fault around the volcano. The mechanism and waveform signatures of this event are almost identical to that of a tectonic earthquake (McNutt 2002), therefore, we called it VT-A. These VT-A events have typical depths of more than 2 km, high-frequency content (more than 5 Hz), and clear time onsets of P-and S-waves. On the other hand, VT-B earthquakes typically occurred at a shallower depth (1–2 km) and had a lower frequency content (1–5 Hz), and the onset time of S-waves on seismogram mostly is unclear it arrives almost at the same time with the onset of P-waves (Wassermann 2012). The Seismic zone of VT-A and VT-B is commonly assumed as a manifestation of a small magma chamber, i.e. where the magma is stored temporarily before exploded to the surface (Wassermann 2012).

We manually picked carefully for P- and S-wave was used for arrival times of 3-component waveforms using Seisgram2K (Lomax and Michelini 2009) based on kurtosis and STA/LTA. An example of the P-and S-wave arrival times is presented in Fig. 2. Using the updated arrival times, the earthquake hypocenters were then determined using the Hypoellipse code (Lahr 1979). A 1-D seismic velocity model of AK135 (Kennett et al. 1995) was used in this study. Afterward, the HypoDD program (Waldhauser 2001) was used with arrival times data to implement the double-difference method (Waldhauser and Ellsworth 2000) for relocating the initial hypocenter locations. To ensure the quality of the dataset, only events with a minimum of six phases of arrival time (P- and S-waves) were selected from the initial hypocenter locations. The distance of each event to the seismic station was selected to be no more than 5 degrees to diminish the effect of earth curvature as this study used the Cartesian coordinate system.

The focal mechanism was then inverted for selected events below Mt. Agung. A moment tensor inversion scheme developed by Kuge (1999) was applied in this study. We applied some data processing to our waveform data as follows. First, the instrument responses had to be corrected. Then, windowing was calculated in the length of 20 s and followed by band-pass filtering from 0.1 to 0.3 Hz. The optimum moment tensor solution was achieved by fitting and synthesizing observational waveforms through the inversion process. The synthetic waveforms calculation used in this study was an extended reflectivity method developed by Kohketsu (1985).

Result and discussion

In the first step of hypocenter location determination, we successfully located 804 events in the vicinity of Mt. Agung and Mt. Batur (Fig. 3a). To check the reliability of the hypocenter solutions, a Wadati diagram of the arrival time was plotted (Fig. 4). In general, a Vp/Vs ratio of 1.74 was obtained, this value is close to the global average of Vp/Vs data, i.e., 1.73 (Stein and Wysession 2003), indicating that our P and S wave arrival time picking should be close to the actual arrival time.

We have relocated 682 out of 804 events which shows more precise locations (Fig. 3b). The improvement of the travel time residuals before and after double-difference hypocenter relocation is shown in Fig. 5. Furthermore, the problem of fixed depth from the initial locations was also solved (Fig. 6). After relocation, we can see that the events are clustered between Mt. Agung and Mt. Batur with a general strike of NE-SW. The events mainly concentrated at depths of 0–20 km (below sea level) and showed to move shallow beneath Mt Agung.

Our results show that the seismicity recorded by regional seismic stations have a significantly increased from September 20 to October 19, 2017, with an average of 40 events per day (Fig. 7). This increase of the seismicity is probably related to the migration of magma from deep into shallow magma storage. An interesting feature was observed from October 19 to 21, 2017, in which only four VT events were recorded and located. Syahbana et al. (2019) showed using local
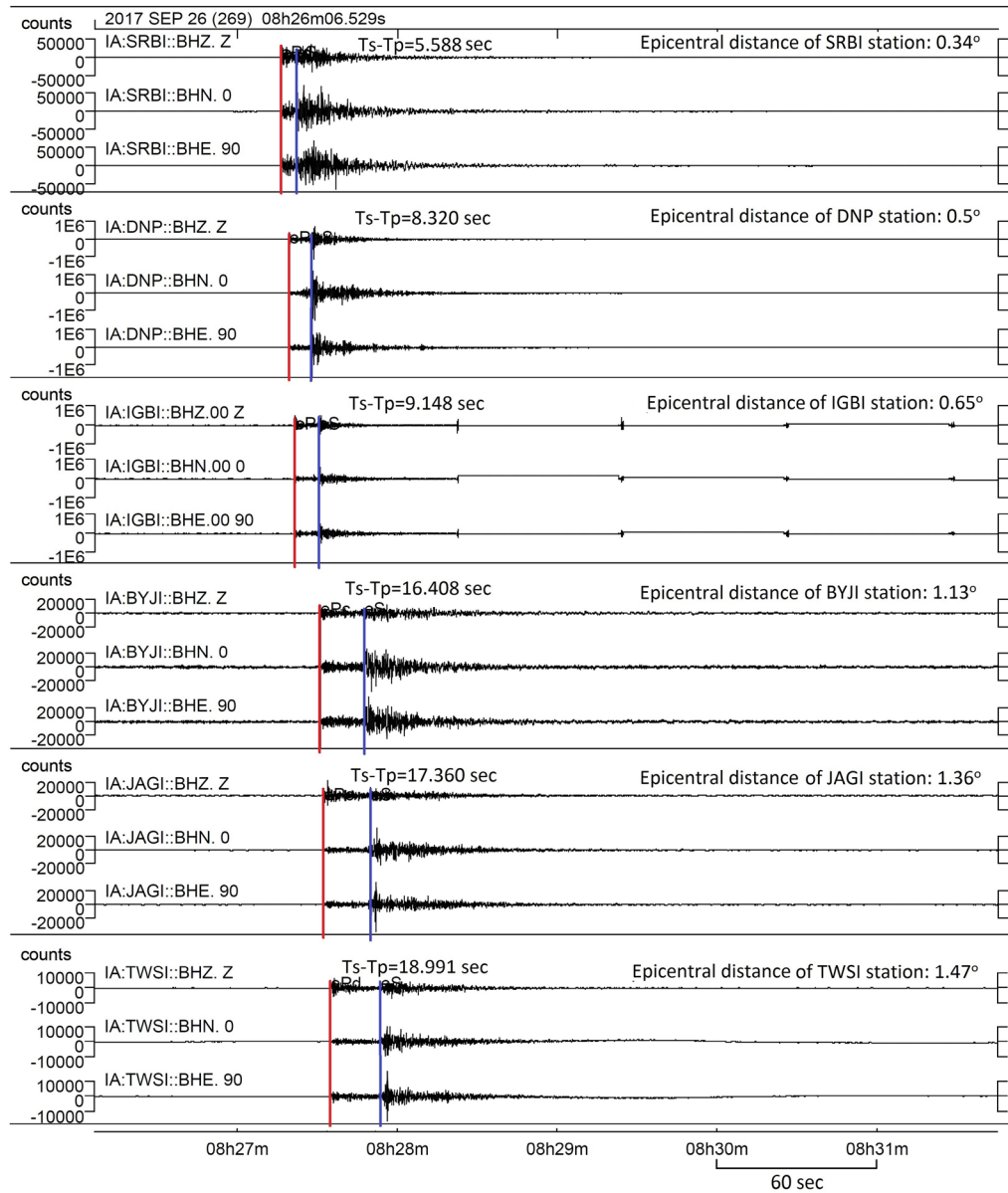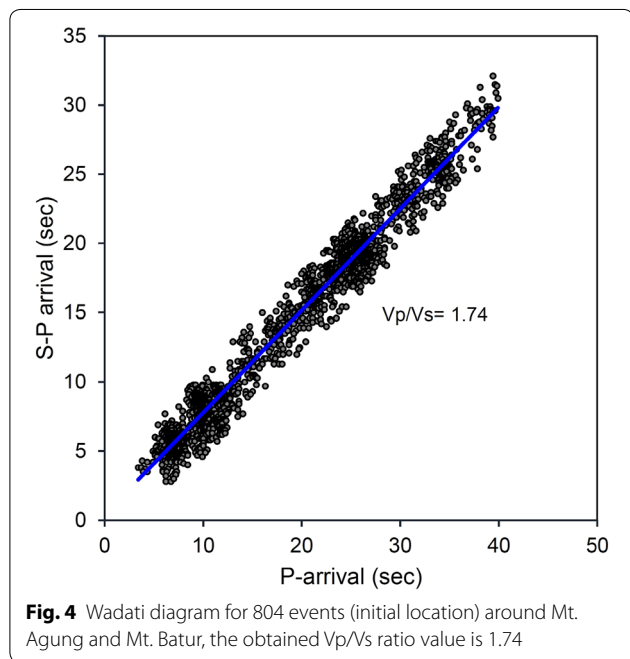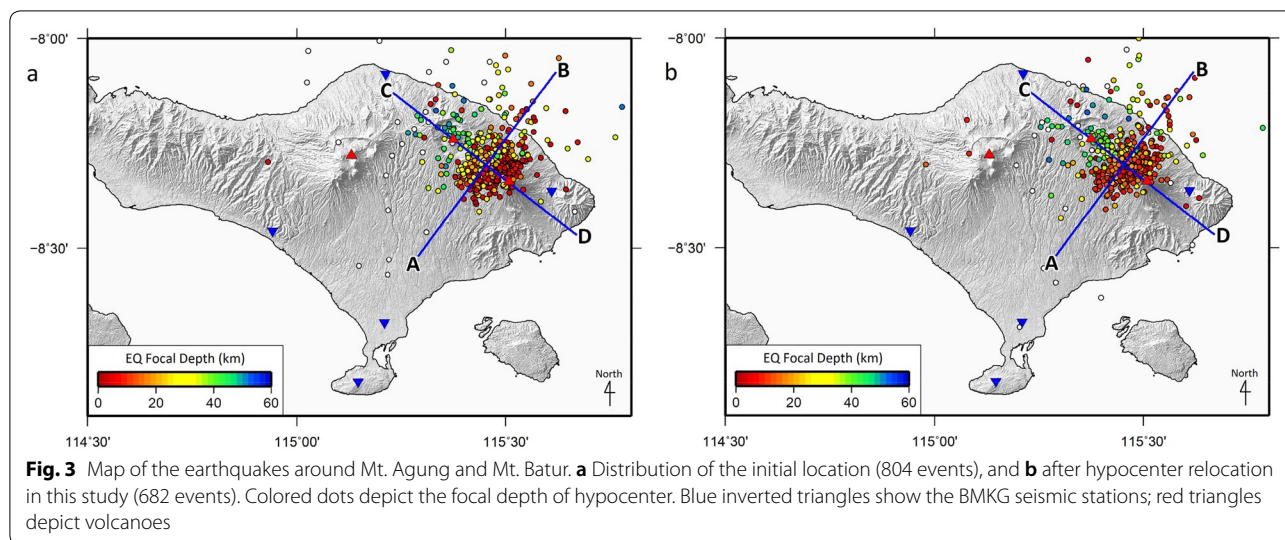
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Fig. 2 Example of picked of P and S onset arrival time of the September 26, 2017 event (M_L 4.2) on BMKG seismic network. Red and blue lines indicate pick of P-and S-wave arrival times, respectively

CVGHM stations that VT event rates decreased significantly in late October to early November 2017. This anomaly might indicate that the position of magma had been approaching the shallow magma storage and could potentially trigger an eruption. The relocation events in this study (Fig. 6b line C-D) are in good agreement with the Model 2 of the magma plumbing system beneath Mt. Agung from Syahbana et al. (2019) which concluded uplift as well as the VT events.

To have a better understanding of the magma source mechanism of intrusion, a focal mechanism inversion of selected events was conducted. In total, 11 events were successfully identified for their mechanism (Fig. 8) with the best waveform fitting. Those 11 events have a local magnitude of greater than M_L 3. Out of those 11 events, 3 clusters were selected according to their location and mechanism.
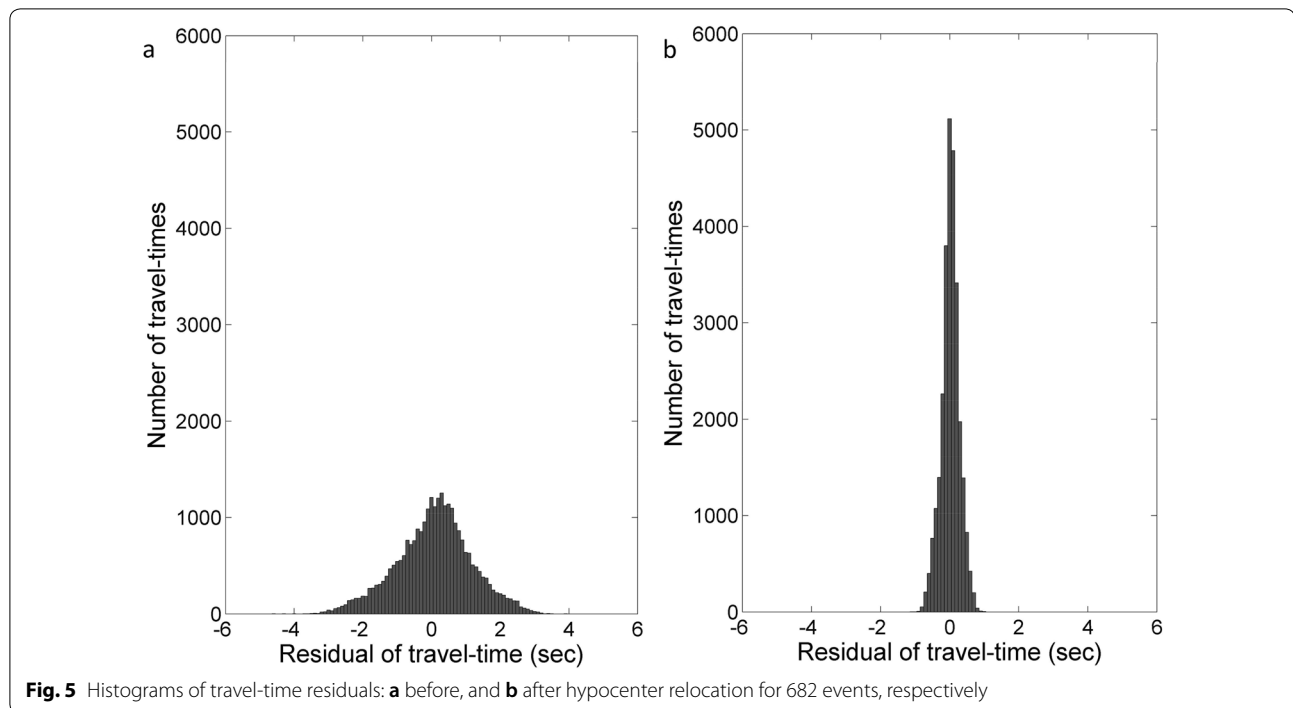
Fig. 3 Map of the earthquakes around Mt. Agung and Mt. Batur. **a** Distribution of the initial location (804 events), and **b** after hypocenter relocation in this study (682 events). Colored dots depict the focal depth of hypocenter. Blue inverted triangles show the BMKG seismic stations; red triangles depict volcanoes

Fig. 4 Wadati diagram for 804 events (initial location) around Mt. Agung and Mt. Batur, the obtained Vp/Vs ratio value is 1.74

We divided the events into three clusters, based on the similarity of focal mechanism types and hypocenter distribution. Cluster I comprises four VT events dominated by strike-slip faulting. The VT distribution of this cluster corresponds to the position of the surface fault observed in the northwestern of Mt. Agung. The source mechanisms of earthquakes in the cluster I indicate a

sinistral strike-slip movement, with the strike ranging from N237.0° E to N257.9° E and dip from 63.47° to 87.54°. Cluster II consists of six VT events dominated by thrusting. In this cluster, earthquakes occurred at the medial and distal facies. The thrusting fault mechanism probably depicts magma intrusion activity. The intrusion caused lateral forces which could have triggered the development of thrust fault and concentric faulting around the volcano (Bronto 2006). Cluster III shows that normal faulting dominates the eastern area of Mt. Agung. We suspected that this event was positioned at the proximal facies triggered by the combination of gravitational effect and slope topography.

Based on the source mechanism analysis from 11 events, we suggest that the swarm events in the vicinity of Mt. Agung probably were probably triggered by magma intrusion. Magma pushes rock upward, causing inflation and uplift, resulting in tilting at the surface. The largest tilting occurs at the peak and the upper slope, and then decreases downslope. Conversely, when intruded magma eventually cools it reduces its volume and results in deflation, the volcano slope will be inclining inward (Bronto 2006).
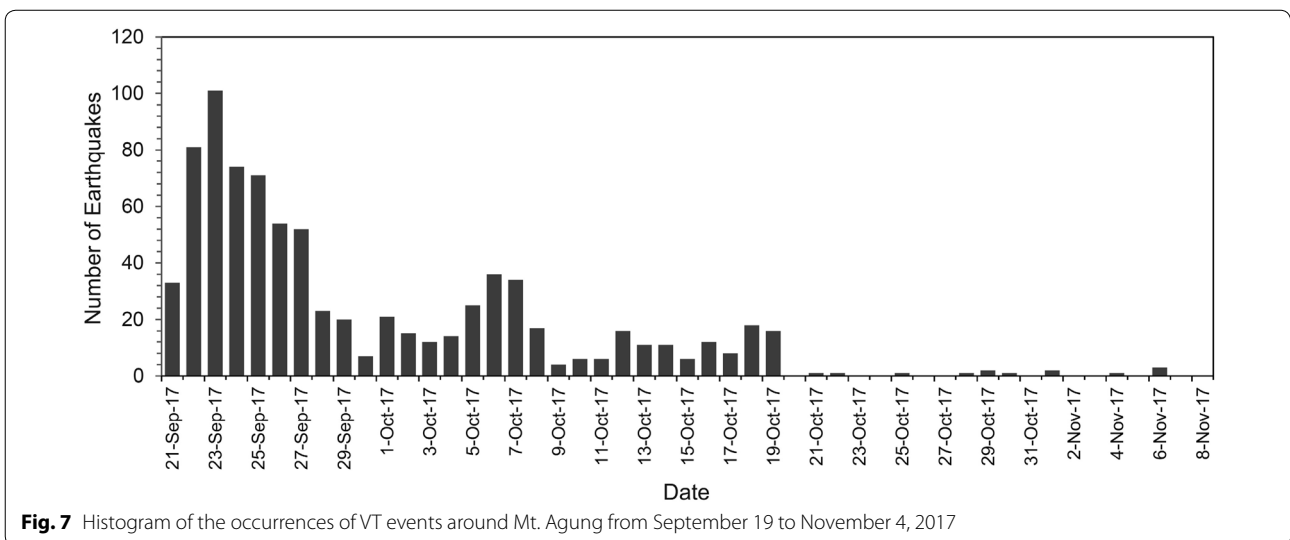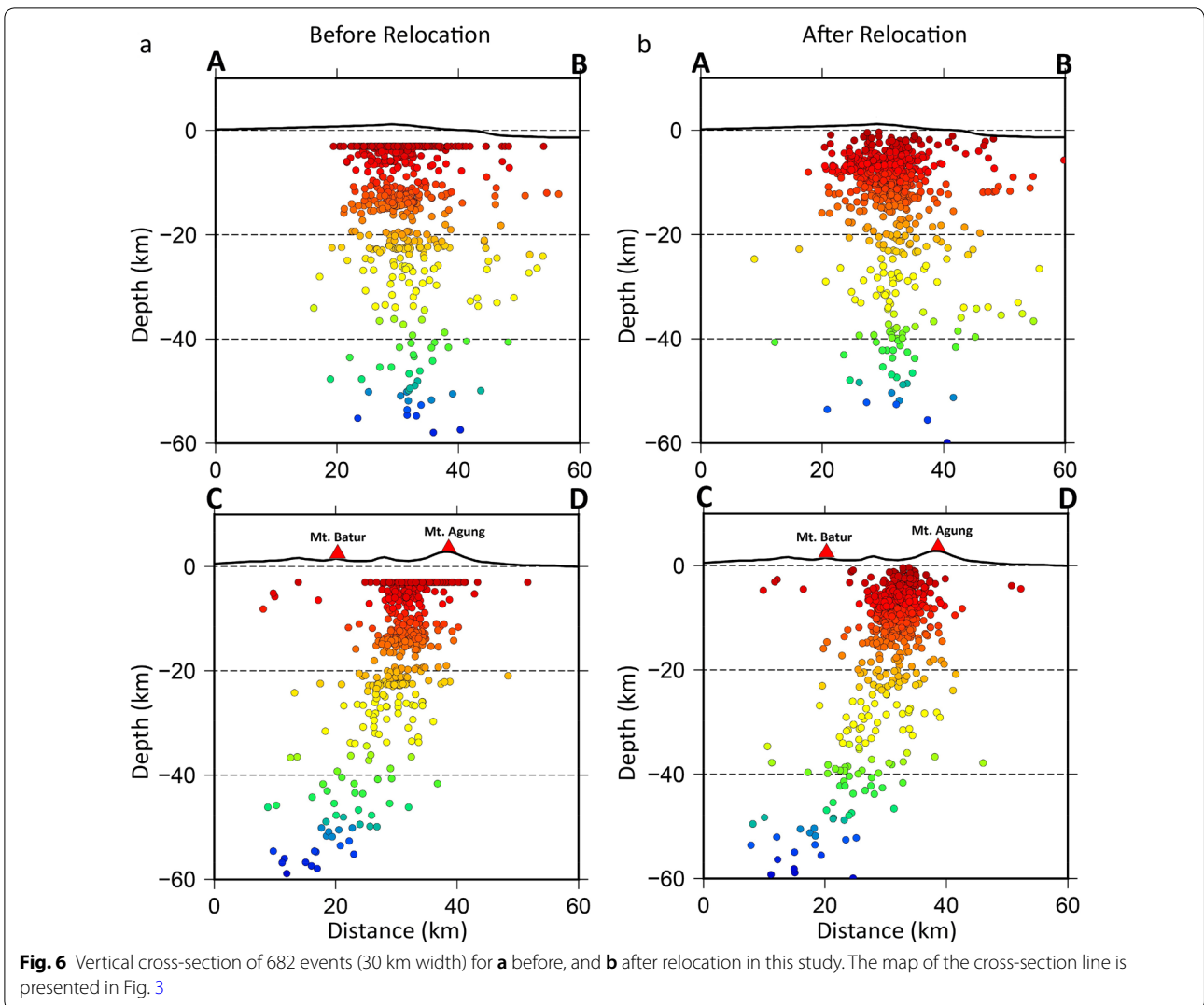
Our results from this study give tangible credence to the hypothesis of magma migration underneath Mt. Agung being responsible for the observed seismic swarms observed between September 14 and October 20, 2017, eventually leading up to the November 2017 eruption. A further study of geodetic GPS could be performed to confirm and refine this analysis.

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Fig. 5 Histograms of travel-time residuals: **a** before, and **b** after hypocenter relocation for 682 events, respectively

Conclusion

After we carefully identified and relocated the swarm events and inverted their mechanisms, we could draw the conclusion that magma intrusion was responsible for the observed seismic swarms, especially on VT events. This analysis and interpretation of the volcano's activity were possible due to the high precision hypocenter locations obtained in this study, using the double-difference technique. A significant improvement in the hypocenter location was demonstrated in terms of residual time. In general, the events are located between Mt. Agung and Mt. Batur striking toward NE-SW direction. The occurrence and absence of VT events might be used as an indicator of the presence of magma migration from the deep magma chamber to the shallow magma storage. Focal mechanism solutions further support the impact of

magma migration to the seismicity pattern. VT events in Mt. Agung are dominated by thrust faulting at the medial and distal facies, normal fault in proximal facies, and shear fault in the northwestern sector of Mt. Agung. The phenomenon of VT earthquakes at Mt. Agung is significant for volcano observatory operations, to understand the migration of magma toward the crater and as an indicator to determine the status of a volcano in the context of volcano disaster mitigation. Using event locations and their source mechanism, we investigated if the magma intrusion led to the Mt. Agung eruption and its impact on seismicity. More detailed investigations combining data from denser seismic station networks, deformation (GPS), petrology, geochemistry, as well as remote sensing data analysis would lead toward a better understanding of the magmatic plumbing system of Mt. Agung.
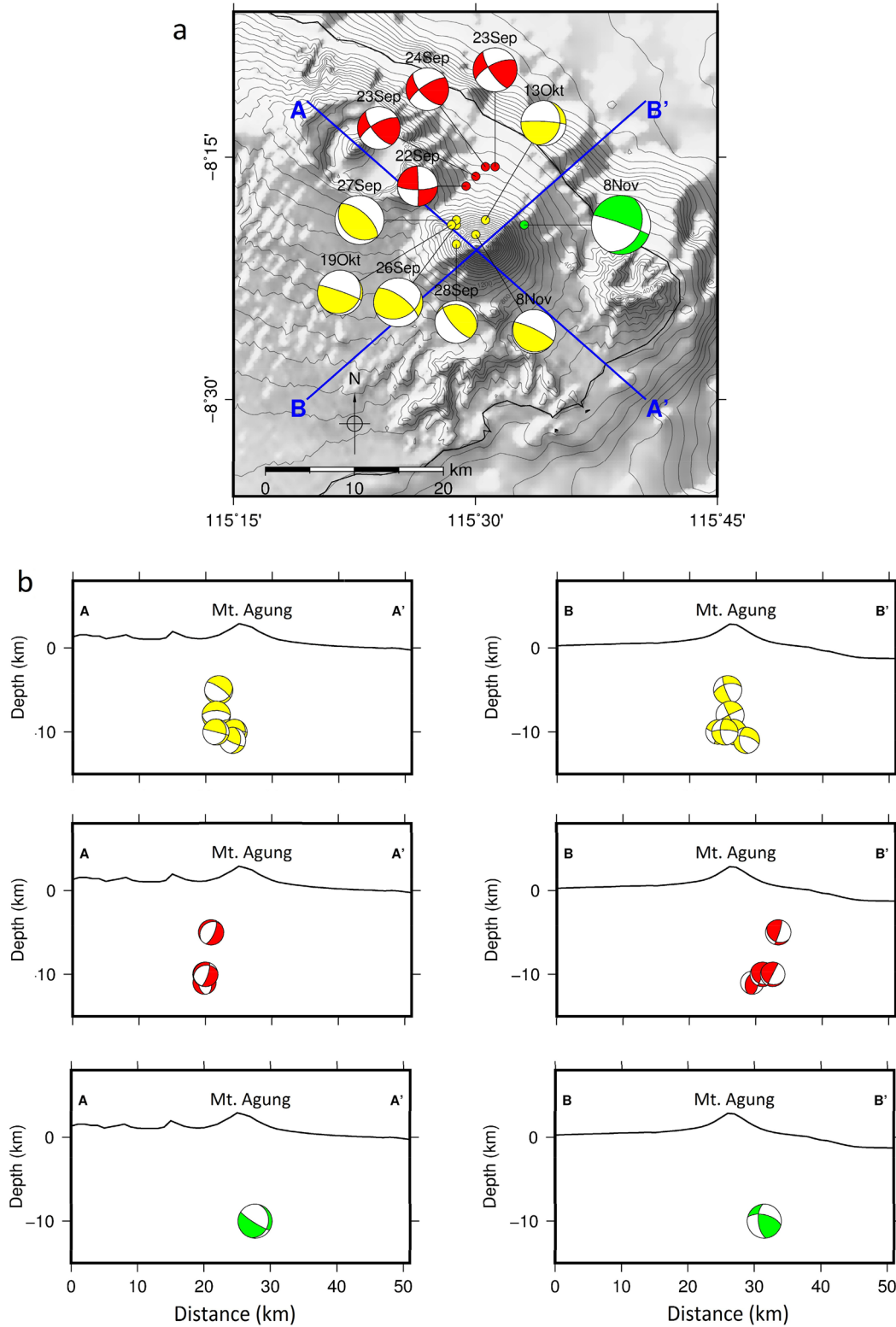
Fig. 6 Vertical cross-section of 682 events (30 km width) for **a** before, and **b** after relocation in this study. The map of the cross-section line is presented in Fig. 3

Fig. 7 Histogram of the occurrences of VT events around Mt. Agung from September 19 to November 4, 2017

Fig. 8 **a** Map of focal mechanism of selected VTA earthquakes below Mt. Agung. **b** Cross-section in northwest–southeast and southwest–northeast directions. The red, yellow and green color indicates the strike-slip, thrust, and normal faulting regime, respectively

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