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Magma Supply System at Batur Volcano Inferred from Volcano-Tectonic Earthquakes and Their Focal Mechanism

Sistem Suplai Magma di Gunung Batur yang diduga dari Pemunculan Gempa VT dan Mekanisme Fokus

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Abstract

The Volcano-Tectonic (VT) earthquakes occurring during September - November 2009 were analyzed. The result shows that the epicentres aligning in NE- SW direction coincided with the weak zone of Batur Volcano Complex. The focal zone is located at the depth around 1.5 - 5.5 km beneath the summit. Migration of magma was detected by ground deformation measured by GPS and focal mechanism. Mechanism of VT earthquake shows mostly normal fault types during the swarm in November 2009.

Keywords: Batur Volcano, magma supply system, hypocentre, focal mechanism, pressure sources

Abstrak

Gempa VT yang muncul pada September - November dianalisis. Hasil analisis memperlihatkan episentrum berarah timur laut - barat daya yang berasosiasi dengan zona lemah Kompleks Gunung Batur. Kedalaman gempa VT terletak pada 1,5 - 5,5 km di bawah puncak. Perpindahan magma diketahui dari pengukuran deformasi dengan GPS dan mekanisme fokus. Mekanisme gempa VT menunjukkan tipe sesar normal pada November 2009.

Kata kunci: *Gunung Api Batur, sistem suplai magma, hiposentrum, mekanisme fokus, sumber tekanan*

Introduction

Batur Volcano (1717 m asl.) is one of the most active volcanoes in Indonesia, which is located at Panelokan Village, Kintamani, Bali. Batur is also well known as one of the most impressive calderas in the world. It is about 13.8 km x 10 km wide formed during the eruption of Bali Ignimbrite about 29,300 years ago (Sutawidjaja, 2009). Within the caldera there are Batur Volcano and a lake. The volcano rises 700 m above the lake surface, and it consists of a main cone with three summit craters (Figure 1).

The first eruption of Batur Volcano was noted in 1804 and the latest one was in 2000. There were 28 eruptions recorded with 1 - 37 years of repose period. Historical eruptions were characterized by mild-to-moderate explosive activities, sometimes accompanied by lava flows. Basaltic lava flows from both summit and flank vents reached the caldera floor and the shores of Lake Batur. The large eruption occurred in 1963-1964 producing a huge lava flow (Kusumadinata, 1979). Since 1922, the repose period has become 1 - 3 years shorter, except the eruption of 1963 and 1994 which occurred after the quiet period of about 37 and 20 years, respectively (Figure 2).

The eruption in 2000 was actually the continuation of the eruptive activity, which began in March 1999. During the year 1999 to 2000, some explo-

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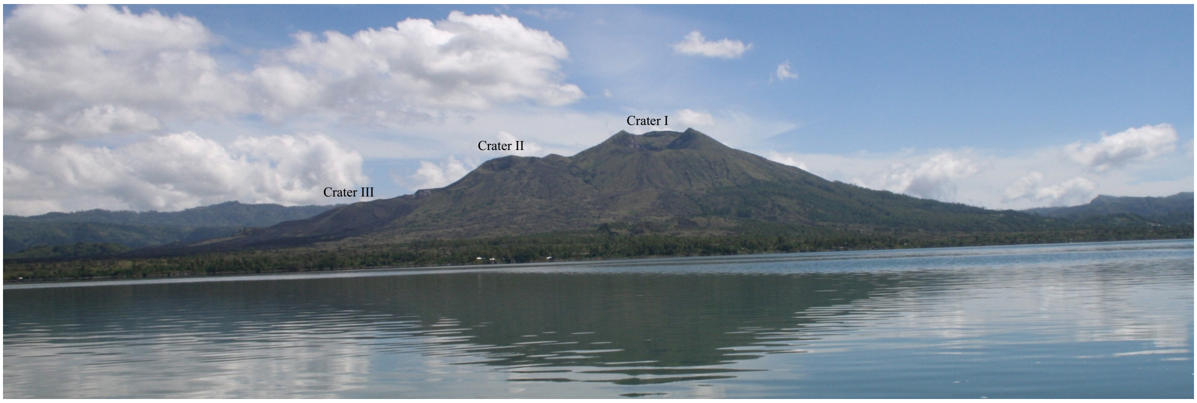

Figure1. Batur Volcano and its craters (picture courtesy of Akhmad Solikhin, CVGHM).

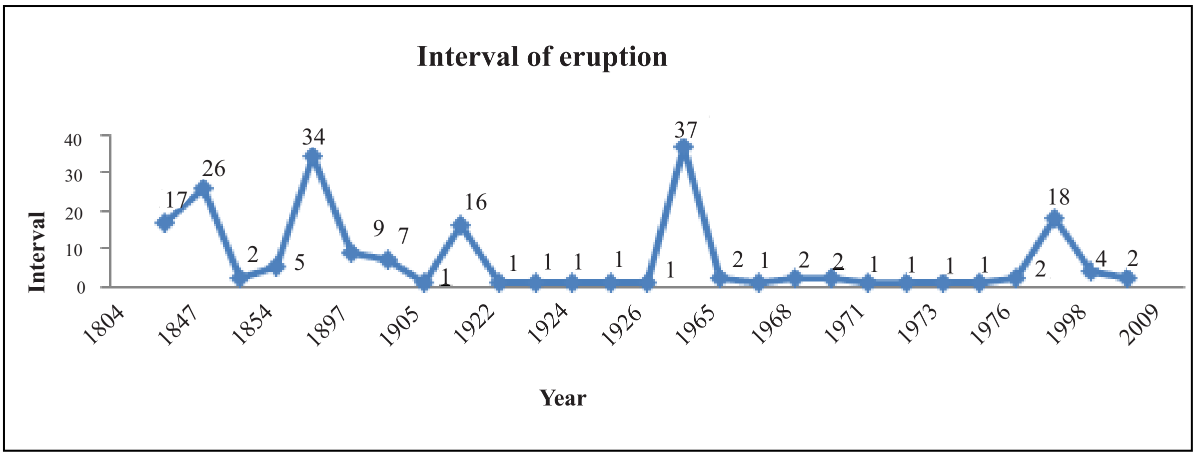

Figure 2. Eruption interval of Batur Volcano.

sions produced incandescent materials, which fell around the crater and killed two persons, a German couple (Purbawinata, 2001). Ash emission sometimes reached a height of 300 m above the summit and it continued until April 2000. After the eruption in 2000, the volcano shows no significant activities, except solfatara emission within the craters.

After nine years of quiescence, the Batur Volcano showed an increasing activity in September 2009 when the number of Volcano-Tectonic (VT) earthquakes gradually increased. The number of VT earthquakes significantly increased during October until the first week of November and the VT swarmed on November 8th 2009. The increase of VT usually indicates the beginning of an unrest stage, as observed previously at Merapi Volcano (Ratdomopurbo and Poupinet, 2000; Hidayati *et al.*, 2008), Sakurajima Volcano (Hidayati *et al.*, 2007), and Kelud Volcano (Hidayati *et al.*, 2009). The sudden increase of VT earthquakes in November 2009 might be an indication of the magma migration from the deeper part to the shallower one. In order to describe the magma migration, the characteristic of the VT, their hypocentre, and focal mechanism will be discussed.

Methodology

Centre for Volcanology and Geological Hazard Mitigation (CVGHM) monitored the Batur Volcano using four seismometers, one tiltmeter, and Electronic Distance Measurement (EDM). The seismic stations were BTR, MPH, SGN, and DNU, all were located at the craters (Table 1 and Figure 3). All seismic and tilt data were telemetered to Batur Volcano Observatory, Kintamani, using radio waves. Moreover, all of the data were also sent to the head office in Bandung via Very Small Aperture Terminal (VSAT). Meanwhile, EDM measurement was conducted daily from the observatory, at the location close to the lake, to three reflectors placed on each slope of the craters.

Tabel 1. Location of Seismic Station

No	Station Code	Longitude	Latitude	Elevation
1	BTR	115°22.578’	-8°14.712’	1363
2	MPH	115°20.748’	-8°14.521’	1125
3	SGN	115°23.298’	-8°13.788’	1277
4	DNU	115°23.136’	-8°16.158’	1054

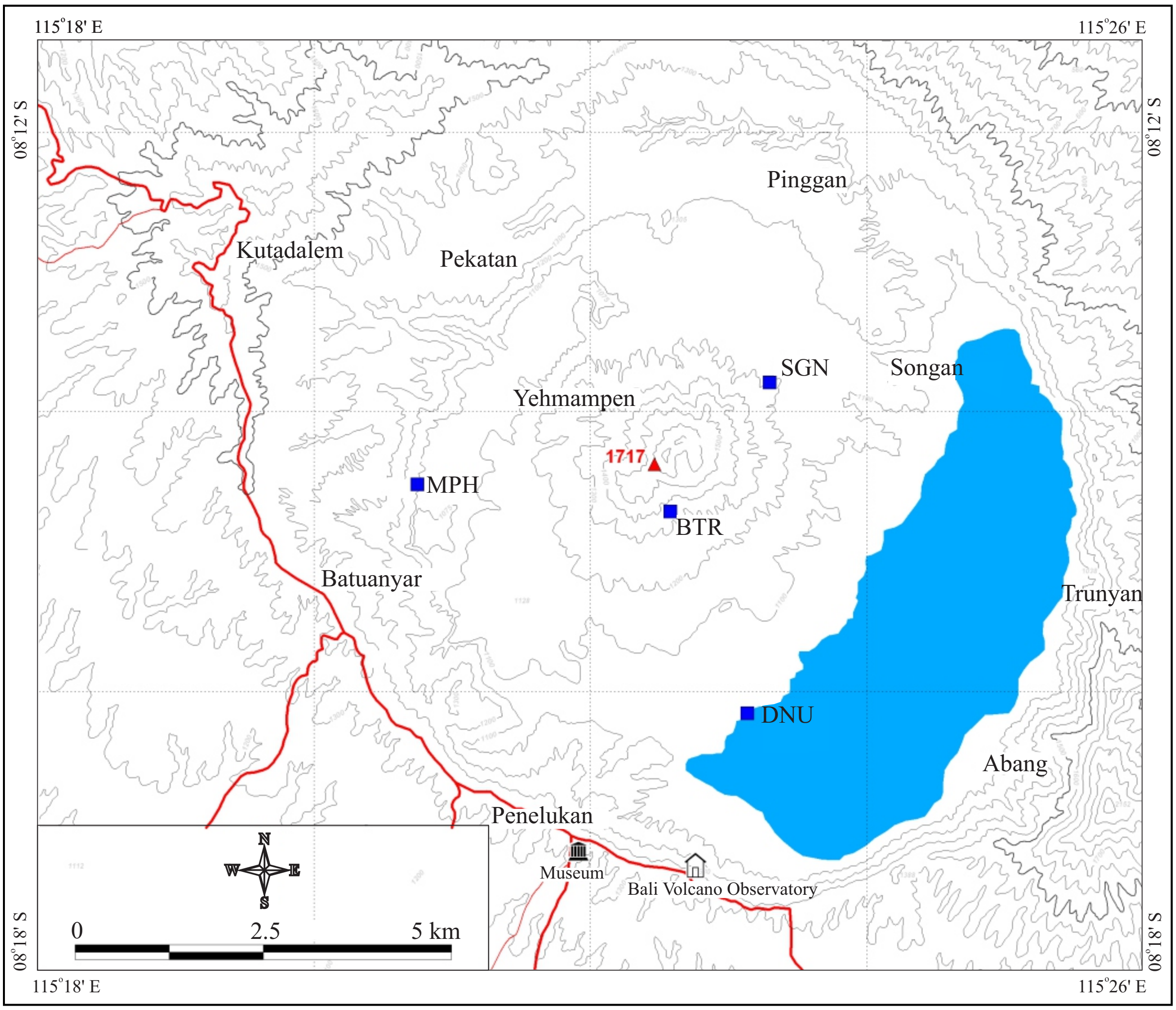

Figure 3. Permanent seismic network of Batur Volcano operated by CVGHM. Triangle and solid squares indicate the highest peak of the volcano and seismic stations, respectively.

VT earthquake of the Batur Volcano is characterized by a sharp onset of P-waves arrival time at all stations and the frequency dominant at 3 - 7 Hz, as shown in Figure 4. Determination of those hypocentres were performed using 4 P-wave arrival times recorded at each station and assumption of a homogeneous isotropic medium with Vp = 2.7 km/s, and Vp/Vs = 1.73. During daytime DNU station could not be used since it was noisy due to on-going construction. Therefore, there were only twenty well-located VT events.

A focal mechanism of VT earthquake is determined in order to get a better understanding of magma migration. As mentioned above that seismicity of the Batur Volcano is monitored using four seismic stations and equipped with a single component (vertical), so it is difficult to estimate the focal mechanism from polarities of the first arrivals. Therefore, to get more stable and better constrained solution, a grid search method using the polarities and amplitude of P-wave first motion by assuming double couple mechanism and homogenous half space will be used (Hidayati *et al.*, 2008). The following equation is used to determine the focal mechanism which was developed by Aki and Richard (1980) for far-field displacement of P-wave from a point double-couple source with standard fault orientation parameters ϕ (azimuth), ϕ_s(strike), δ (dip), λ (rake), and source take off angle (i_h). The equation is as follows:

$$U^P(r,t) = \frac{1}{4\pi\rho \ r\alpha^3} R^P \dot{M}\left(t - \frac{r}{\alpha}\right)$$

Where:

$U^P(r;t)$ = far-field displacement for P-wave,
R^P = radiation pattern for P waves
r = geometrical spreading
$\dot{M}$ = seismic moment
α = velocity of P-waves
ρ = density

The amplitude of P-wave first motion and its polarity take an important role in determining the mechanism as well as calculating the radiation pattern. To avoid ambiguity of determination of focal mechanism, VT earthquake with M>1 was used for analysis.

Results

In a normal state, the occurrence of VT earthquake in Batur Volcano is about 10 events per month. Visually, the volcano emitted white smoke from solfatara field at the summit craters. The increases in seismicity were detected in September 2009, when about 32 VT events were recorded. In October 2009, there were 48 VT earthquakes, as seen in Figure 5. At the beginning of November 2009, there were 19 of VT earthquakes recorded. On November 8th, VT earthquakes swarmed and reached 69 events (Figures 5 and 6). The following day, on November 9th, the number decreased to 30. Since November 10th, the occurrence of VT earthquake seemed to decrease by 1 event in a day.

Hypocentral distribution of VT earthquakes recorded during September - November 2009 were plotted as shown in Figure 7. The epicentres align

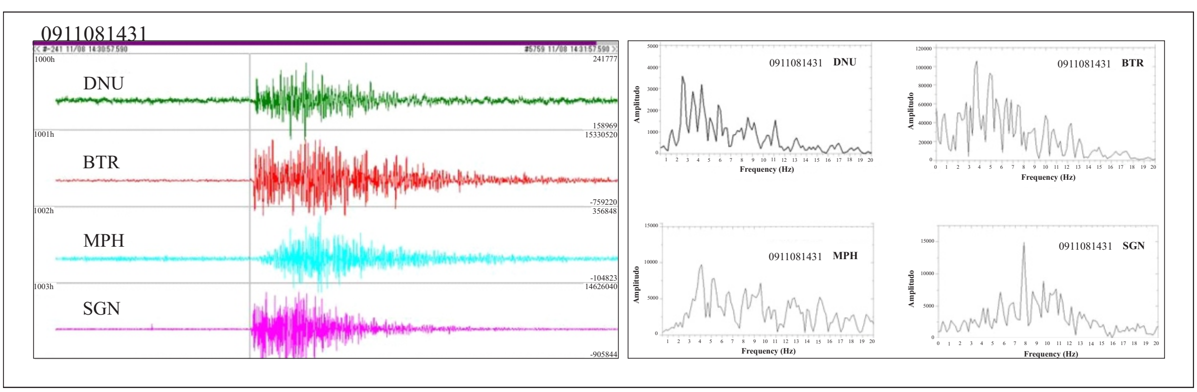

Figure 4. Seismogram and frequency dominant of VT earthquake recorded at four seismic stations (BTR, MPH, SGN, and DNU). This VT was recorded on November 8th, 2009, at 14:31 WITA.

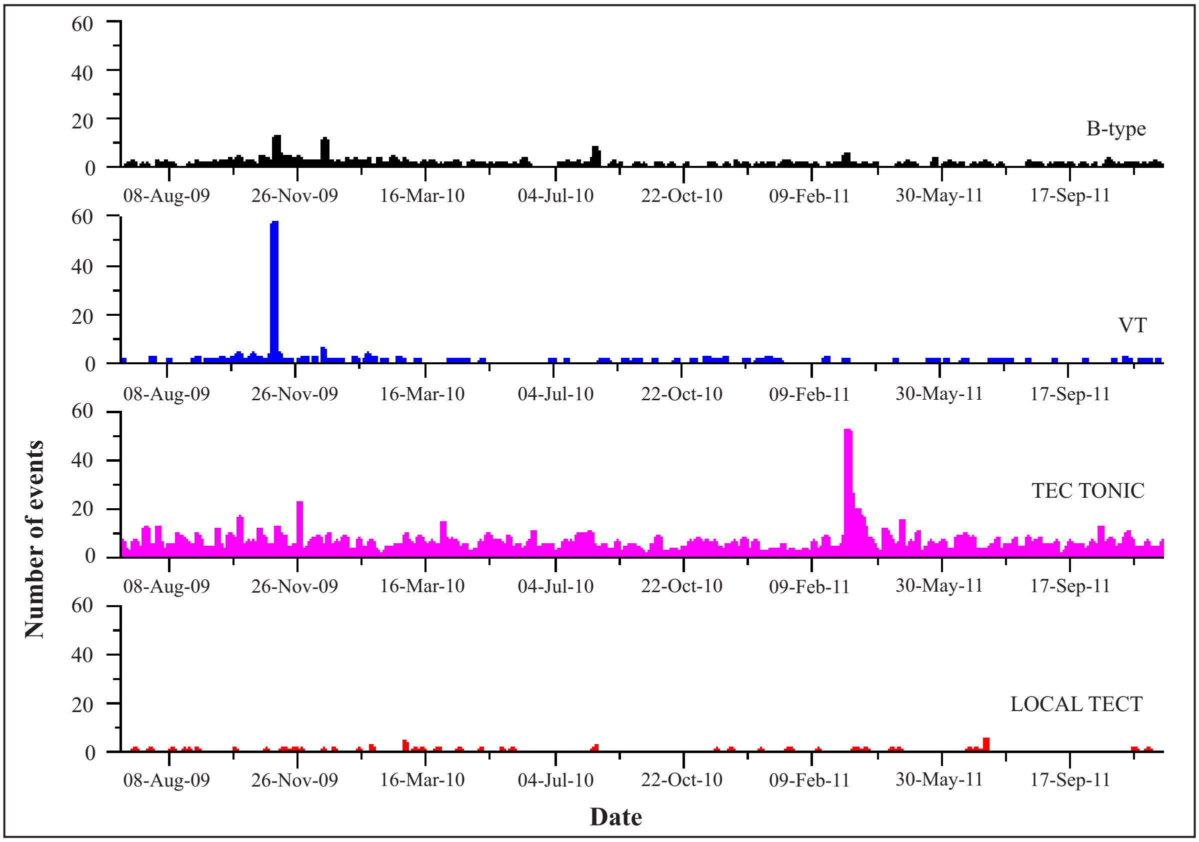

Figure 5. Daily number of seismic events originated at the Batur Volcano during period January 2009 - October 2011. The swarm of VT earthquakes occurred at November 8th, 2009.

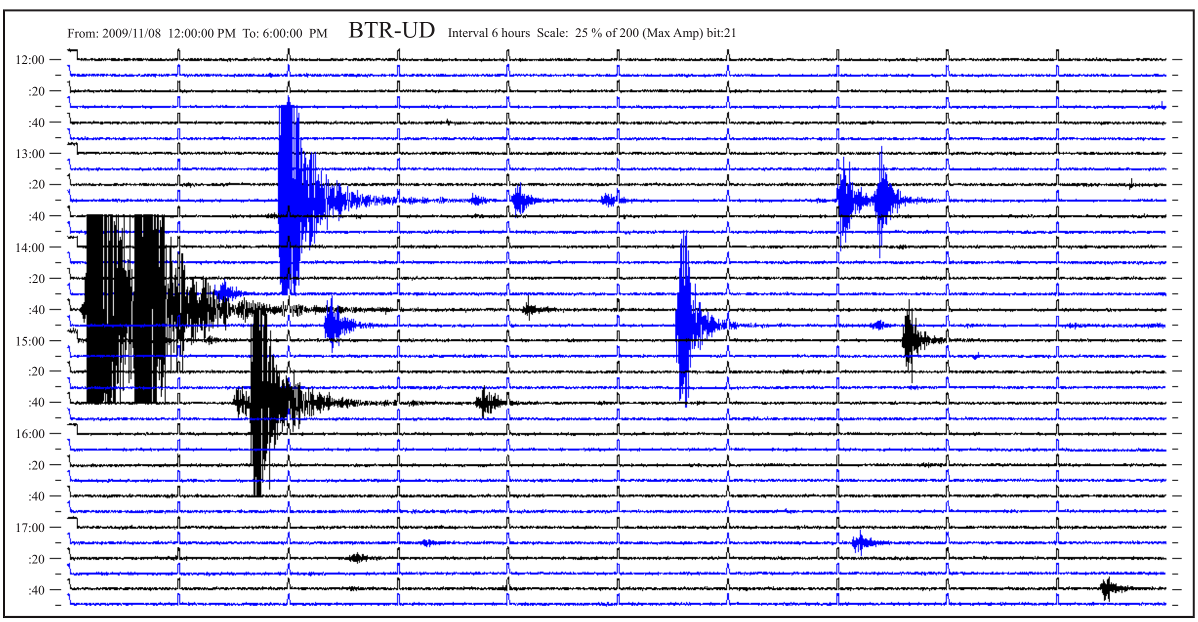

Figure 6. Seismogram of VT earthquakes during the swarm at 13:00 - 17:00 WITA (local time: GMT+8) on November 8th, 2009.

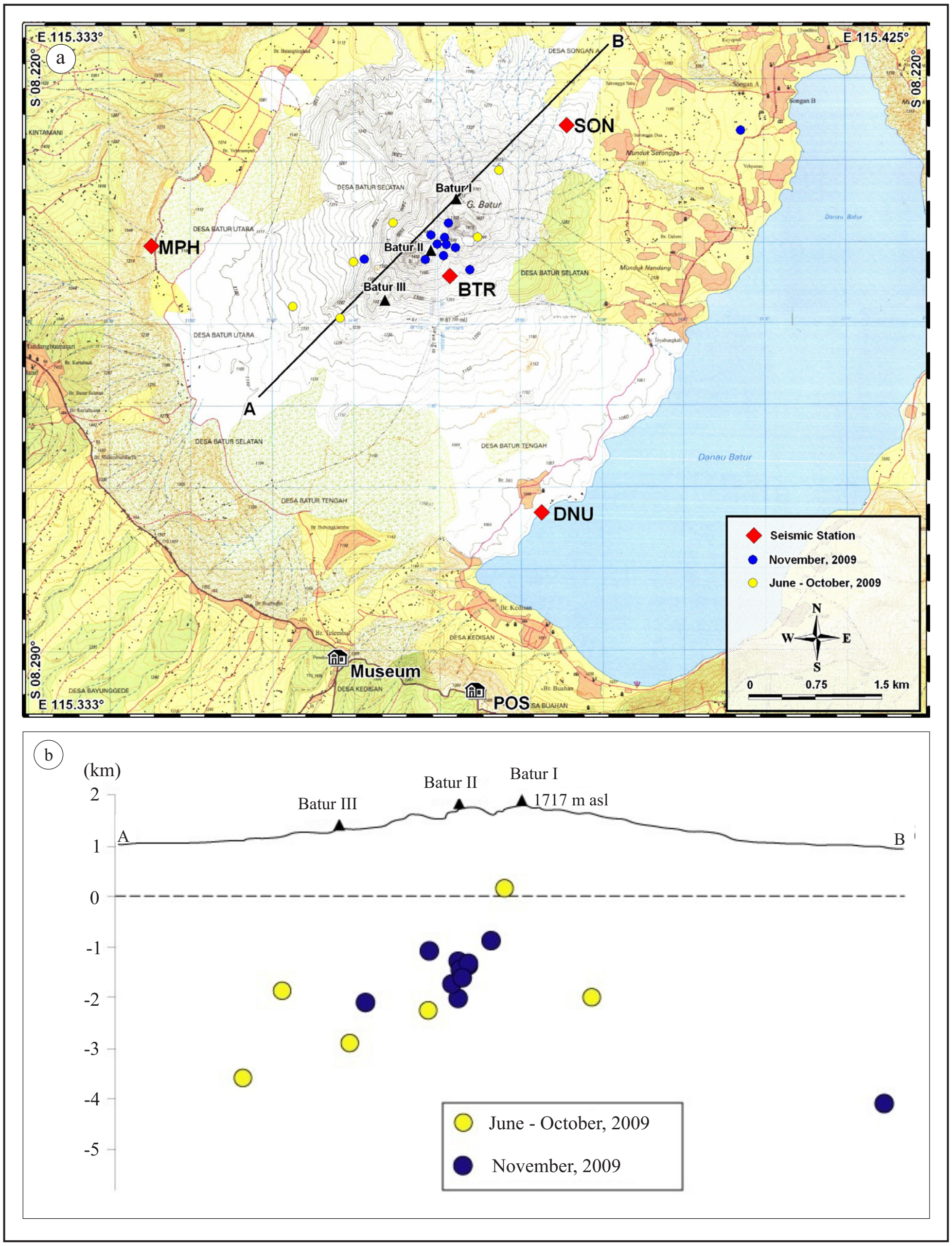

Figure 7. Hypocentral distribution of VT earthquakes of the Batur Volcano recorded during period of September - November 2009. (a). Epicentre distribution of VT earthquakes. (b) Hypocentres are plotted on the vertical cross section of A-B. Yellow and blue solid circles represent VT event occurred on June-October 2009 and November 2009, respectively.

in NNE - SSW direction and it seemed to coincide with the weak zone in Batur Volcano Complex (Figure 7a). Furthermore, the focal zones of VT earthquakes were located at the depth of 1.5 - 5.5 km below the summit as seen in Figure 7b. During period of September - October 2009, the focal zones ranged at the depth of 2.5 - 5.5 km and spread around southwest region of the volcano. While in November, especially on November 8th, 2009, hypocentres were concentrated around the summit area between Crater II and III with the depth of 2.5 - 3.0 km. This suggests the possibility of migration of magma was from the deeper part to the shallower depth and stopped at a depth of 2.0 - 5.0 km from the summit.

From the VT earthquake recorded at 2009 focal mechanism of 15 VT events out of 20 well-located ones could be determined. Fault plane solution of the VT is shown in Figure 8. Polarities of P-wave first motion are plotted on upper hemisphere of the focal sphere by stereographic projection. The plane solution shows strike slip, normal and reverse fault types. The strike-slip fault type is dominantly the mechanism with 7 out of 14 events. Meanwhile, reverse fault and normal fault types are 5 and 3 out of 14 events, respectively.

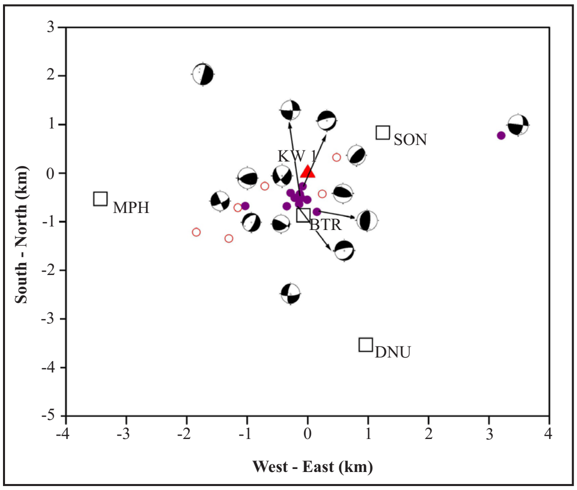

Figure 8. The result of focal mechanism of VT earthquakes. The red open circles, purple solid circles, open squares, and solid triangle represent hypocentre during September-October 2009, hypocentre during the swarm on November 2009, seismic station, and main crater, respectively.

Discussion

Focal Mechanism

A sharp decline in number of VT earthquakes after November 8th, 2009 swarm can be interpreted as a period of *aseismic,* though there were still the possibility of magma supply from a deeper part to a shallower one. No VT earthquakes as shown on the seismograms might interpret that the upward movement of magma did not require much effort. In some volcanoes, a period of *aseismic* in many cases was followed by an eruption.

The normal fault type mechanism occurred during the swarm on November 2009. Ground deformation measured by GPS showed the inflation during this period. It might indicate a magma supply from a deeper part. Magma migrates to a shallow part may cause an increase in the horizontal tension around the conduit and normal fault of VT events could be generated. Furthermore, the reverse fault type might associate with the horizontal compression by a pressure decrease. The occurrence of VT in both normal and reverse fault types during November 2009 might indicate that the Batur Volcano is under a complicated state.

The strike-slip fault type mechanism occurred with the orientation mostly in NE-SW direction. It might coincide with the geological structure around the Batur Volcano Complex showing weak zones within the caldera as indicated by the fissure system where the craters of Batur I, II, and III aligned in NE-SW direction (Figure 7).

Deformation

GPS campaign was carried out in November 2009 at ten benchmarks around the edifice of Batur Volcano. This work was a continuation of previous measurement in 2008. The result (Sulaeman *et al.*, 2008) of the 2008 measurement was compared to the result of 2009 which showed the vertical and horizontal displacements (Figures 9 and 10). Horizontal displacement was observed at stations located in down slopes (DB12, TABU, DB5, DB6, PJ5, DB17, DB10, and DB19) of the volcano with vector lines directed toward the crater. While the stations KW1 and KW2 located at the upper slope and closer to the crater, showed a displacement outward from the crater.

The displacement pattern indicated that there might be two magma pockets located beneath the Batur Volcano craters, the deep and the shallow one. When the pressure source of deep magma pocket decreased, the ground deflated at the downslope, which was indicated by the vector lines directed toward the crater. The shallow magma pocket, on the other hand, showed an increase pressure and caused the ground inflation demonstrated by the vector lines directed outward the crater. Increasing pressure at the shallow magma pocket (inflation) was expressed by the occurrence of VT earthquakes in early November 2009. However, due to lack of

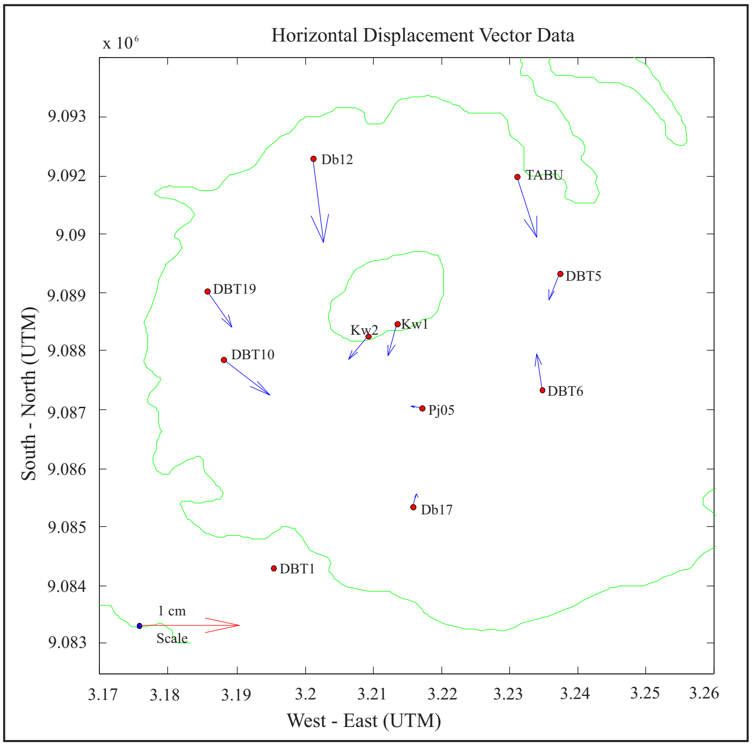

Figure 9. Horizontal displacement November 2009 - October 2008.

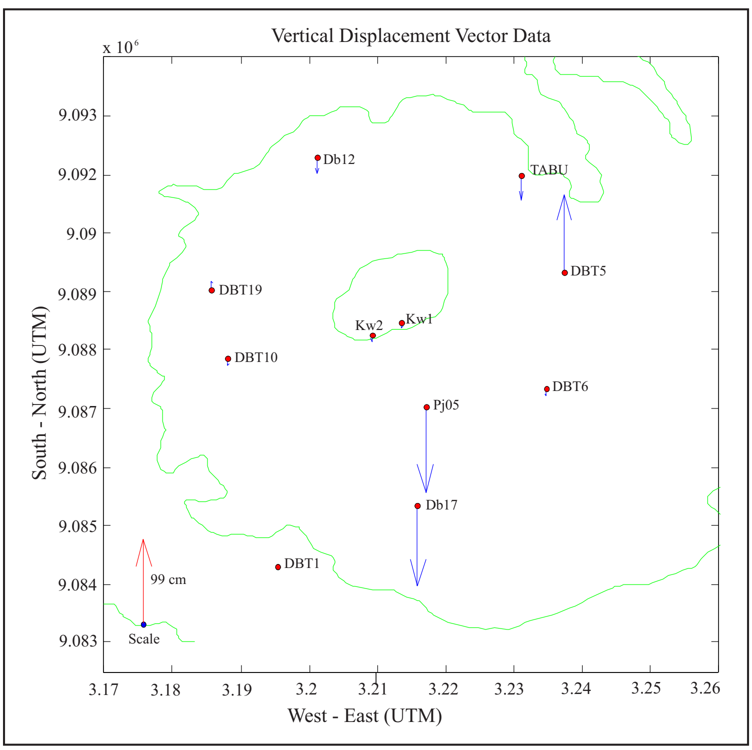

Figure 10. Vertical displacement November 2009 - October 2008.

GPS data the interpretation of the occurrence of two magma pockets is very weak. Suganda (2008) found that the pressure sources are located at 1.8 to 2.1 km.

The pattern of vertical displacement mostly showed downward vector lines, except at DB5 (Figure 10). The largest vector lines occurred at DB17 and PJ5 attaining a distance of about 1 m. However, the vertical displacement measured by GPS was not accurate enough compared to the horizontal measurement. Therefore, it could not be used.

Conclusion

Increasing activity of the Batur Volcano began in September 2009 and escalated in November 2009. It peaked on November 8^{th}, 2009 when the VT earthquakes swarmed. Hypocentral distribution of the earthquakes during September - November 2009 showed a migration of magma from the deep part to the shallow one. This interpretation was supported by GPS analysis where the horizontal displacement oriented towards the crater in the distance benchmark measurement. Outward direction (away from the crater) as shown by benchmarks, which were located close to the crater, might imply the pressure increase. Moreover, the epicentre of VT earthquake distributes in NE - SW direction which was coincident with the weak zone on Batur Volcano Complex.

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