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Seismic Activity of Volcano-tectonic Earthquakes at Guntur Volcano, West Java, Indonesia During the Period from 1991 to 2005

Nurlia Sadikin[1)], Masato Iguchi[1)], Gede Suantika[2)] and Muhamad Hendrasto[2)]
[1)]Sakurajima Volcano Research Center, DPRI, Kyoto University,
Sakurajima-Yokoyama, Kagoshima, Japan
[2)]Center for Volcanology and Geological Hazard Mitigation, Bandung
e-mail : nurlia@svo.dpri.kyoto-u.ac.jp;   n.sadikin@gmail.com

Abstract

Volcano-tectonic earthquakes at Guntur volcano were analyzed. The hypocenters are distributed in 3 regions; around the summit area from Masigit volcano to Guntur volcano at depths <2km, Gandapura caldera at depths <3km and around Kamojang geothermal field at depths of 2-8km. The focal mechanisms are characterized by normal and reverse faults in the summit area and normal fault in Gandapura. The mechanism is dominated by strike-slip fault type in Kamojang. Although eruptivity of Guntur volcano has been dormant since 1847, VT earthquakes beneath the summit area and Gandapura may be related with intermittent intrusion of magma, considering focal mechanism of VT earthquakes and uplift of the ground around the summit area and Gandapura. However, the seismic energy release stayed at lower level than threshold preceding magmatic eruption.

Keywords: *Guntur volcano, seismicity, hypocenter distribution, focal mechanism, magma intrusion.*

1. Introduction

Volcano-tectonic (VT) earthquake is one the well-defined precursor to volcanic eruption. VT earthquakes occurred successively southwest off the Sakurajima volcano, Japan in March 1976. The hypocenter of the earthquakes migrated to the shallow part beneath the summit crater and the eruptive activity of Vulcanian style increased from May[1)]. Similar occurrence and migration of VT earthquakes were also detected at Unzen volcano, where dome growth and collapse generating pyroclastic flow repeated frequently during the period from May 1991 to 1995. Seismicity of the VT earthquakes began November 1989 at Chijiwa caldera, 10~15 km west of the volcano and the hypocenters migrated toward the volcano in July 1990[2)].

On the other hand, seismicity of VT earthquakes has not always been followed by volcanic eruptions. VT earthquakes swarmed southwest off the Sakurajima in November 2003 and the seismicity has not been followed by remarkable eruptions until now[3)]. Although earthquakes with M6.9 and M6.5 occurred in 1922 and earthquake swarm frequently repeated near the Unzen volcano, the seismicity did not lead to eruptive activity before phreactic eruption in 1990.

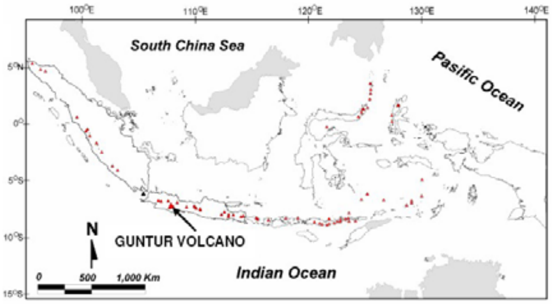
Guntur volcano is an andesitic volcano-complex in west Java, Indonesia. It consists of old and young cones groups. The old cones are Kamojang, Kancing, Gandapura, Gajah, Agung, Picung and Pasir Malang. The young cones consist of Masigit (highest peak, 2249 m), Paruhpuyan, Kabuyutan and Mt. Guntur, aligned from northwest to southeast direction. These young cones started eruptive activity 50,000 years ago. Geothermal area with fumaroles is located in the Kamojang caldera, 5 km west of the summit of Guntur. At Guntur volcano, 20 eruptions were recorded in the historic time from 1690 to 1847[4)]. The eruptions in 1690 and 1829 caused a lot of victims and destroyed several villages[4, 5)]. After the 1847 eruption, no eruptive activity has been recorded.

In contrast to the recent dormant eruptive activity for 160 years, seismicity of Guntur volcano is not quiet. VT earthquakes occurred at an average month number of 20 before 1998 and the seismicity sometimes increased in 1992, 1993 and 1997[6)]. Hypocenter of the VT earthquakes are located in the summit area and around Kamojang caldera, west of the summit[7,8)]. Considering the activity of VT earthquakes and the history of frequent eruptions in 17^{th} to 19^{th} century, Guntur volcano is regarded as a high-risk volcano.

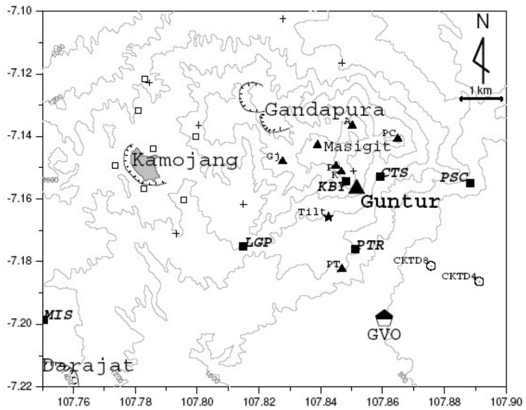
In this paper, hypocenters and focal mechanism of the VT earthquakes are determined by using seismic stations around Guntur volcano. The hypocenter distribution and the focal mechanism will be discussed in relation to intrusion of magma and surrounding tectonics by using ground deformation data of Guntur volcano and its geological setting. Finally, recent activity of Guntur volcano will be evaluated.

2. Observation

Volcanological Survey of Indonesia (currently named Center for Volcanology and Geological Hazard Mitigation, CVGHM) started seismic monitoring with a vertical component seismometer (natural period T_o=1.0s, damping constant h=0.7) at station CTS in 1989. In October 1994, 3 permanent 3-component seismometers were installed at stations PSC, PTR and LGP to determine location of hypocenters of VT earthquakes. During the increase of seismicity in 1997, an additional station KBY was installed near the Guntur crater, and station PSC has been moved to station MIS since 2003 to increase the capability of earthquake detection west of the volcano. Locations of permanent seismic stations are summarized in Figure 1. The seismic signals from the seismometers are transmitted to Guntur Volcano Observatory by radio FM telemeters and are digitized by data logging device (DATAMARK LS8000-SH) with sampling interval of 0.01 second[7].



(a)



(b)

Figure 1. Seismic network at Guntur volcano. a) Location of Guntur volcano. b) Location of seismic stations. Solid squares indicate permanent stations. Temporary stations are shown by pluses for the period from December 1995 to February 1996, crosses for the period from October 1996 to June 1997 and open squares for the period from July to September 2001. A star shows a tiltmeter station and open circles are representative benchmarks for the leveling. GVO is Guntur Volcano Observatory as a recording site for the permanent stations. Triangles show volcanic cones; Gj: Gajah, A: Agung, PC: Picung, Pt: Gunung Putri, K: Kabuyutan and P: Paruhpuyan.

As the permanent stations are deviated at south and eastern part of the volcano, temporary seismic observations were conducted at the western and northern part of the volcano in three periods (December 20, 1995 to February 6, 1996, September 19, 1996 to June 4, 1997 and June 30 to September 20, 2001) to cover Guntur volcano-complex with the permanent and temporary stations. Vertical component seismometers (T_o=0.5s, h=0.7) were used for the temporary observations. Seismic signals were recorded in the data logging devices with the same sampling interval.

3. Seismic Activity

The events recorded around Guntur volcano are volcano-tectonic type with well-defined P and S-wave onset and dominant high-frequency component. Monthly numbers of volcanic earthquakes during the period from 1991 to 2005 are shown in Figure 2 with daily cumulative numbers. The numbers are counted, based on seismogram at station CTS for the event with maximum amplitude more than 10μm/s and S-P time interval shorter than 3s. During the period, 5827 events were detected and 32 events occurred in a month in average. The seismicity became active from May 1997. The monthly average number was 21 before April 1997. However, the monthly rate increased to 42 after May 1997. The monthly numbers sometimes exceeded 100 in October 1997, May 1999, November 2002 and June 2005.

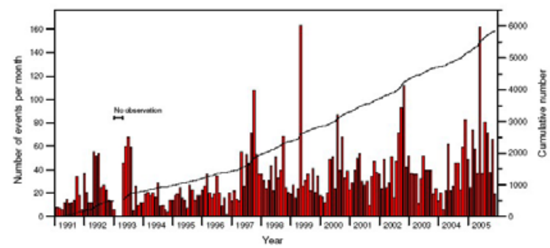


Figure 2. Seismic activity of VT earthquakes at Guntur volcano during the period from 1991 to 2005. Monthly numbers and the cumulative numbers are shown by histogram and lines, respectively.

The seismicity was rather quiet from September 1993 to April 1997. In May 1997, the monthly number suddenly increased to 55 and reached its peaks in October with 108 events. The seismicity increased again in May 1999. Two felt earthquakes occurred on May 6 and were followed by 60 after-shocks. The seismicity have been active since 2000, especially, 112 and 162 events were detected in November 2002 and June 2005, respectively.

In order to show the increase in seismicity quantitatively, seismic energy released by VT earthquakes is estimated by using seismograms at station CTS. Firstly magnitude is calculated using an empirical relationship[9] of magnitude (M) and duration (t_{F-P}) of the earthquake. The magnitudes ranged from -0.4 to 2.9 during the period from 1991 to 2005. Then, seismic energy is estimated using the Gutenberg and Richter formula[10]. Cumulative seismic energy released by VT earthquakes from the period of 1991 to 2005 is shown in Figure 3. Average seismic energy release rate was 1.5×10^{16} erg/year. The highest seismic activity was recorded in May 1999, releasing the energy of 2.8×10^{16} erg. During the period from October 1991 to August 1992, the seismic energy release rate was large and it gradually decreased until the seismicity in May 1999. The seismic activity immediately became quite low (0.4×10^{16} erg/year). After July 2000, the seismic energy release rate clearly increased to 1.3×10^{16}

erg/year. Steps of seismic energy release are found in August 2000 and May 2004.

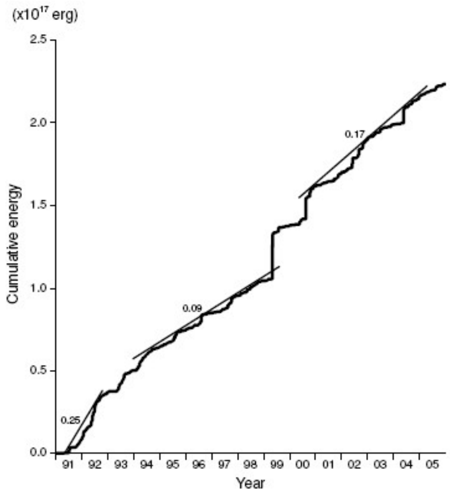


Figure 3. Cumulative seismic energy released by VT earthquakes during the period from 1991 to 2005.

4. Hypocenter Distribution

Hypocenters of VT earthquakes are determined by using more than 4 P-wave onset times, assuming P-wave velocity (V_p) dependent of depth (z) structure as;

V_p=2.76+3.3z (z <10 km),

taking V_p=2.76 km/s by Rasjid[11] into account. The software of "hypomh"[12] was used for determination of hypocenters. Clear S-wave onset times were added to the calculation, assuming V_p/V_s=1.73. Among the observed VT earthquakes, locations of 775 events were determined and they have mean nominal errors about 0.11 km for epicenter and 0.14 km for depth.

Figure 4 shows hypocenter distribution of VT earthquakes during the period from 1996 to 2005. Hypocenters are concentrated in elliptical zone extending from northwest to southeast and the seismic zone corresponds to the volcanoes from Masigit to Guntur at the summit. The depths are 0 - 2 km below sea level. No earthquakes were detected southeast of the Guntur crater. Some earthquakes are located around Gandapura caldera at depths of 0 - 3 km and around Kamojang geothermal area at depths of 2 - 8 km. Magnitude of VT events at the summit area is small, ranging from -0.4 to 1.3. Maximum magnitudes attained 2.9 and 2.1 at Gandapura and Kamojang, respectively. The determination of hypocenter within 2002-2004 by Nugraha *et al.*,[13] showed almost the same pattern of distribution regions, which are at Kamojang Caldera, Gandapura Caldera and Guntur volcano area. But, due to the difference of methods used, the hypocenter distributions of VT earthquakes were quiet difference.

Figure 4d shows an enlargement of epicenter distribution at the summit area. The hypocenters are distributed along alignment of the volcanoes of Masigit, Paruhpuyan, Kabuyutan and Guntur. The VT earthquakes with larger magnitude in this area (M=1) are distributed east of Masigit. VT earthquakes are also distributed around Gajah. An aseismic zone is recognized at an area west of Masigit and the seismicity gap can be seen in east-west cross-section of the hypocenter (Figure 4b).

5. Focal Mechanism

5.1 Method

Focal mechanisms of VT earthquakes were determined by using polarities and amplitude of P-wave first motions at more than 5 seismic stations. Displacement of P-wave at far-field is given by Aki and Richard[14] as follows,

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

where $U^P(r,t)$ = displacement of P-wave, R^P = radiation pattern of P-waves, r = distance from the hypocenter, $\mathbf{M}$ = moment rate function, α = propagation velocity of P-wave, ρ = density.

First derivative of equation (1) for particle velocity of P-wave is given as,

$$\dot{U}^P(r,t) = \frac{1}{4\pi\rho r\alpha^3} R^P \ddot{\mathbf{M}}\left(t - \frac{r}{\alpha}\right). \quad (2)$$

Here, double couple is assumed. Therefore, radiation pattern R^P is described as,

$$\begin{aligned} R^P &= \cos\lambda \sin\delta \sin^2 i_h \sin 2(\phi - \phi_s) \\ &\quad - \cos\lambda \cos\delta \sin 2i_h \cos(\phi - \phi_s) \\ &\quad + \sin\lambda \sin 2\delta\left(\cos^2 i_h - \sin^2 i_h \sin^2(\phi - \phi_s)\right) \\ &\quad + \sin\lambda \cos 2\delta \sin 2i_h \sin(\phi - \phi_s) \end{aligned}, \quad (3)$$

where λ, δ and ϕ_s are rake, dip and strike of faulting, respectively, and i_h and ϕ are take-off angle and azimuth of seismic wave departing from the source. In this study, polarity and amplitude of P-wave first motion are used. Neglecting the time term of equation (2), velocity amplitude of P-wave first motion at station $\mathbf{x}$ from the source $\mathbf{x}_0$ is given as follows,

$$\dot{U}^P(\mathbf{x}, \mathbf{x}_0, \lambda, \delta, \phi_s) = \frac{1}{4\pi\rho r\alpha^3} R^P(\mathbf{x}, \mathbf{x}_0, \lambda, \delta, \phi_s)\ddot{M}. \quad (4)$$

The source parameters of rake, dip and strike are obtained by grid search method so as to minimize RMS of residuals of the theoretical amplitudes from observed ones. Amplitude of P-wave first motion is corrected on local site effect and propagation path effect. For estimation of local site effect, 17 tectonic earthquakes were used and relative amplitudes in the frequency range between 4 Hz to 7 Hz, referred to station CTS were calculated. The relative amplitudes at stations PTR, PSC, LGP, KBY and MIS are 1.12, 0.11, 1.00, 0.17 and 2.60, respectively. The observed amplitudes were divided by the relative ones. Attenuation of seismic waves due to anelastic medium is taken into account, assuming Q=100 referred to Merapi volcano[15].

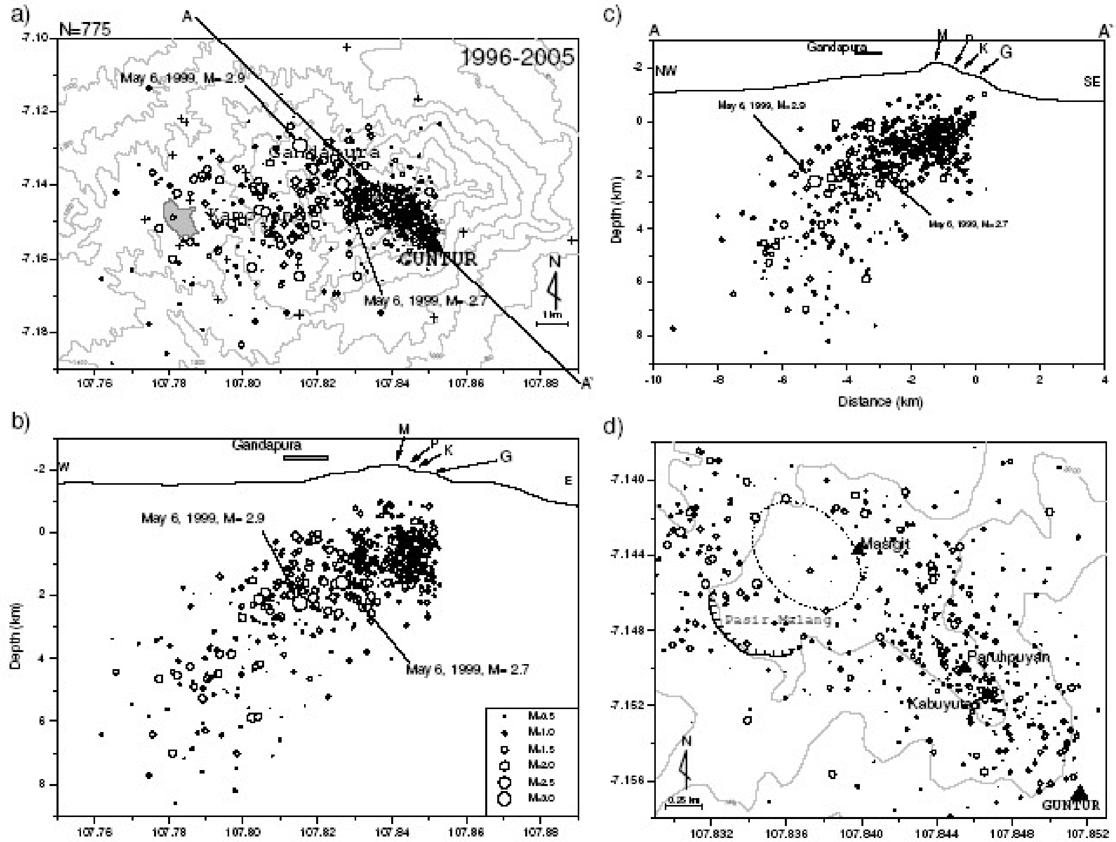


Figure 4. Hypocenter distribution of the VT earthquakes for 10 years from 1996. Hypocenters are indicated by open circles, and pluses are seismic stations. a) Epicenter distribution. b) Hypocenter distribution plotted on the vertical cross-section in east-west direction. M: Masigit, P: Paruhpuyan, K: Kabuyutan and G: Guntur. c) Hypocenter distribution plotted on the vertical cross-section in northwest- southeast direction (A-A'). d) Enlargement of epicenter distribution around the summit area from Masigit to Guntur. Dashed ellipsoid indicates an aseismic zone.

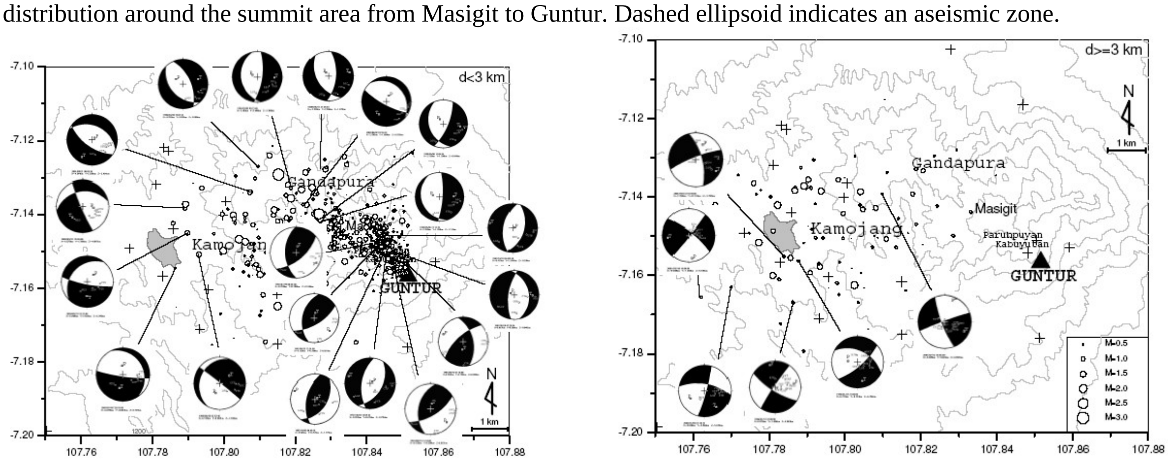


Figure 5. Focal mechanism of VT earthquakes at shallower than 3km (a) and deeper (b). Solid and open circles show compression and dilatation P-wave first motion, plotted on the upper hemisphere of the focal sphere by stereographic projection. Squares with "T" and "P" denote orientation of T-and P-axes.

5.2 Results

Polarities of P-wave first motion and obtained focal mechanism are plotted on upper-hemisphere of the focal sphere by stereographic projection as shown in Figure 5. Orientation of P- and T-axes is shown in Figure 6. Focal mechanisms of VT earthquakes at the summit area show normal and reverse faults with nodal lines in northeast-southwest direction (Figure 5a). Among the 31 events, whose mechanisms were determined, 22 are normal fault and 9 are reverse fault type. As the strike of nodal plane is directed to northeast-southwest, both T-axes of normal fault type and P-axes of reverse fault type are oriented to northwest-southeast direction (Figures 6a1 and a2). Around Gandapura caldera, the mechanisms of VT earthquakes are characterized by normal faults with nodal line striking in the direction of northwest-southeast (Figure 5a). T-axes are oriented nearly horizontal northwest-southeast direction and P-axes nearly vertical (Figure 6b). As the focal mechanisms are determined by amplitudes of P-waves in this study, the mechanisms of over-scaled two earthquakes with M2.9 and 2.7 could not be determined uniquely. However, the mechanisms are inferred to be normal fault from the polarity distribution at 11 stations including stations at Papandayan volcano and Bandung Basin. In Kamojang caldera, two types of focal mechanisms are found. Oblique normal fault type is obtained for the VT earthquakes at depths shallower than 3km (Figure 5a). The T-axes are oriented in north-south direction (Figure 6c1). At depths deeper than 3 km, the mechanisms are strike-slip faults with nodal lines in northeast-southwest and northwest-southeast directions (Figure 5b). T-axes are oriented to north-south or northwest-southeast direction and P-axes in northeast-southwest direction (Figure 6c2). The focal mechanisms around Guntur volcano-complex are clearly discriminated by focal depth; reverse or normal fault shallower than 3km, and strike slip-fault type deeper than 3km.

6. Discussions

Distribution pattern of hypocenters and focal mechanism are discussed with geological setting around Guntur volcano. Geological studies around Guntur volcano are summarized in "Geological map of Garut and Pameungpeuk"[16] and "Geological map of Guntur volcano"[17]. Hypocenter distribution and typical focal mechanisms are shown in Figure 7 with geological faults and volcanic cones. The geological maps show that volcanoes of Masigit, Paruhpuyan, Kabuyutan and Guntur are aligned from northwest to southeast and the volcanic zone is composed of several normal faults striking northeast-southwest direction (Figure 7b). The most dense hypocenter zone at the summit area corresponds to the alignment of volcanoes and the direction of strike coincides with that of geological faults. The VT earthquakes at the summit area occurred in the fracture zone, which was formed by the previous eruptions. Geological map also shows that Gandapura caldera is located northwest of the Masigit and a fault with vertical movement strikes southeastward from Gandapura caldera to Gajah. The VT earthquakes around Gandapura caldera seems to be related to the activity of the fault because the mechanism of the VT earthquakes is normal fault type and the strike direction of fault plane coincides with the direction of the geological fault. While the hypocenter zone around Kamojang caldera is elongated to the direction from northeast to southwest, and the direction coincides with the geological fault passing through the Kamojang caldera from southwest to east. T-axes and P-axes of the VT earthquakes in Kamojang caldera are oriented to north-south and east-west, respectively. The focal mechanism corresponds to the right-lateral strike-slip fault. They are affected by tectonic stress, because the T-axes in north-south direction and P-axes in east-west direction result from right-lateral strike-slip fault with northeast-southwest direction and the type of fault is dominant around Guntur volcano[16]. The focal mechanism at shallow part of Kamojang is oblique normal fault. Geothermal field was formed at the Kamojang caldera, and normal fault type of VT earthquakes is interpreted to be related with subsidence of the ground in the caldera due to emission of vapor. The VT earthquakes at a shallow part of Kamojang caldera may be triggered by hydrothermal activity and are affected by tectonic stress.

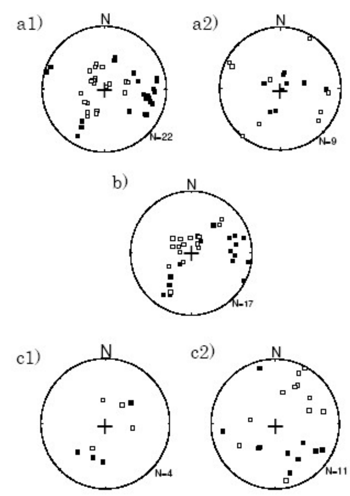
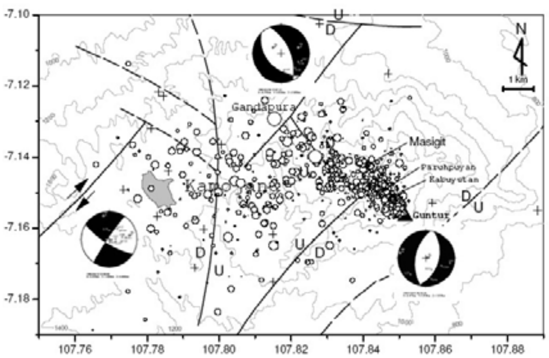
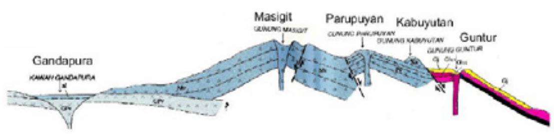


Figure 6. Orientation of P- and T- axes for VT earthquakes. P- and T-axes are plotted on the upper-hemisphere of the focal sphere by stereographic projection and are indicated by open and solid squares. (a1) Normal fault type and (a2) reverse fault type at the summit area, (b) around Gandapura caldera, and (c1) normal fault type and (c2) reverse fault type around Kamojang caldera.



(a)



(b)

Figure 7. a) Distribution of epicenters of VT earthquakes with their typical focal mechanisms, geological faults15) and volcanic cones[16]. b) Geological structure of Guntur volcano-complex in northwest-southeast cross-section[15].

The number of VT earthquakes increased from May 1997 and the activity continued to November 1997. The increase in seismicity was accompanied with ground deformation. Figure 8 shows tilt change in radial component at a station 2 km south of the Guntur crater. When the number of VT earthquakes began to increase, upward tilt toward the Guntur crater started. The upward tilt suggests a minor inflation of the summit area[18]. Then, the upward tilt continued to November and stopped when the seismicity returned to normal level in December, 1997. The uplift of the ground around the summit area during the period was confirmed by precise leveling survey during the period from August 1996 to November 1997 at the south flank[19] as shown in Figure 9. As the VT earthquakes occurred at the summit area of Masigit to Guntur and west Masigit during the period from May to October, it is suggested that the seismic activity is related to uplift around the summit area and/or Gandapura. The simultaneous occurrence of increase in seismicity and uplifting ground around the summit area repeated in 1999, 2000 and 2002 (Figure 9). The location of the pressure source inducing the deformation is estimated to be located at a depth of 2.5 km beneath the summit area[19]. Compared with the hypocenter distribution (Figure 4), the pressure source is located in the aseismic portion immediately beneath the cluster of VT earthquakes at the summit area or Gandapura caldera. Therefore, it is possible that the VT earthquakes at Gandapura and the summit area of Guntur volcano are related with intrusion of magma. In addition, eruption rate at Guntur volcano was high as shown by frequent historic eruptions from 1690 to 1847. It is reasonable that the increases in seismicity were caused by stress changes beneath the Gandapura and the summit area due to intrusion of magma. Relationship of VT earthquakes at Guntur volcano-complex with magma intrusion and surrounding tectonics is illustrated in Figure 10.

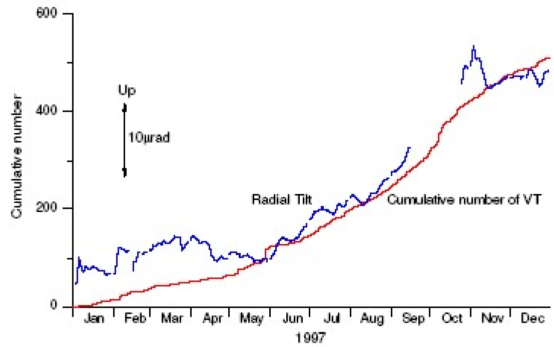


Figure 8. Relation of cumulative number of VT earthquake with tilt change in the increase in seismicity in 1997. Tilt change in radial component is shown. "Up" indicate that the ground of Guntur crater side is uplifted.

If magma chamber was located beneath the Gandapura caldera and/or the summit area and magma was supplied to the reservoir, the pressure of magma reservoir would increase and the stress field above it would be tensional. The normal fault VT earthquakes maybe occur due to the tensional stress field along the fault. The summit area from Masigit to Guntur is also affected by the increase in pressure of the magma reservoir because normal fault type is dominant.

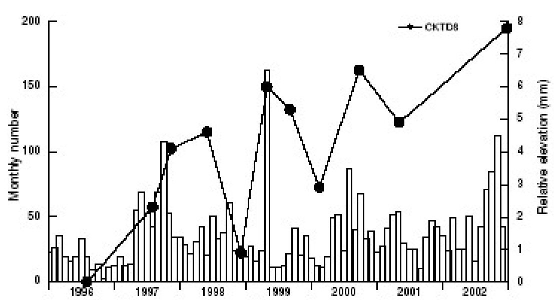


Figure 9. Relative elevation change at BM. CKTD8 referred to BM.CKTD4 (See locations of benchmarks in Figure 1b). Monthly numbers are shown by histogram.

In spite of frequent increases in seismicity of VT earthquakes, eruption has not taken place yet since 1847. Yokoyama[20] obtained an empirical threshold level of cumulative seismic energy release preceding magmatic eruptions based on seismicity before the eruption at Bezymianny volcano and Shiveluch volcano in Kamchatka, Tokachi volcano in Japan, la Soufriere La Guadeloupe in France and El Chichon volcano in Mexico. The results generally indicate that the cumulative seismic energy released from the precursory earthquake swarms exceed 10^{17} to 10^{18} ergs before the eruptions. At Guntur volcano, the seismic energy increased in 1999, 2000 and 2004, however, the seismic energy release in each increase in seismicity stayed at an order of 10^{16} ergs (Figure 3). The largest earthquake (M2.9) in recent 10 years occurred on May 6, 1999, and the seismic energy release associated with the seismicity including after-shocks was 2.8×10^{16} ergs. The seismic energy release is still lower than the threshold preceding magmatic eruption obtained by Yokoyama[20]. Kagiyama[21] pointed out importance of knowledge for accumulation of magma or suspend to rise up of magma, for prediction of volcanic eruption. It is inferred that magma is storing or stopped to rise up at deeper than 2 km beneath the summit area and/or Gandapura caldera of Guntur volcano-complex.

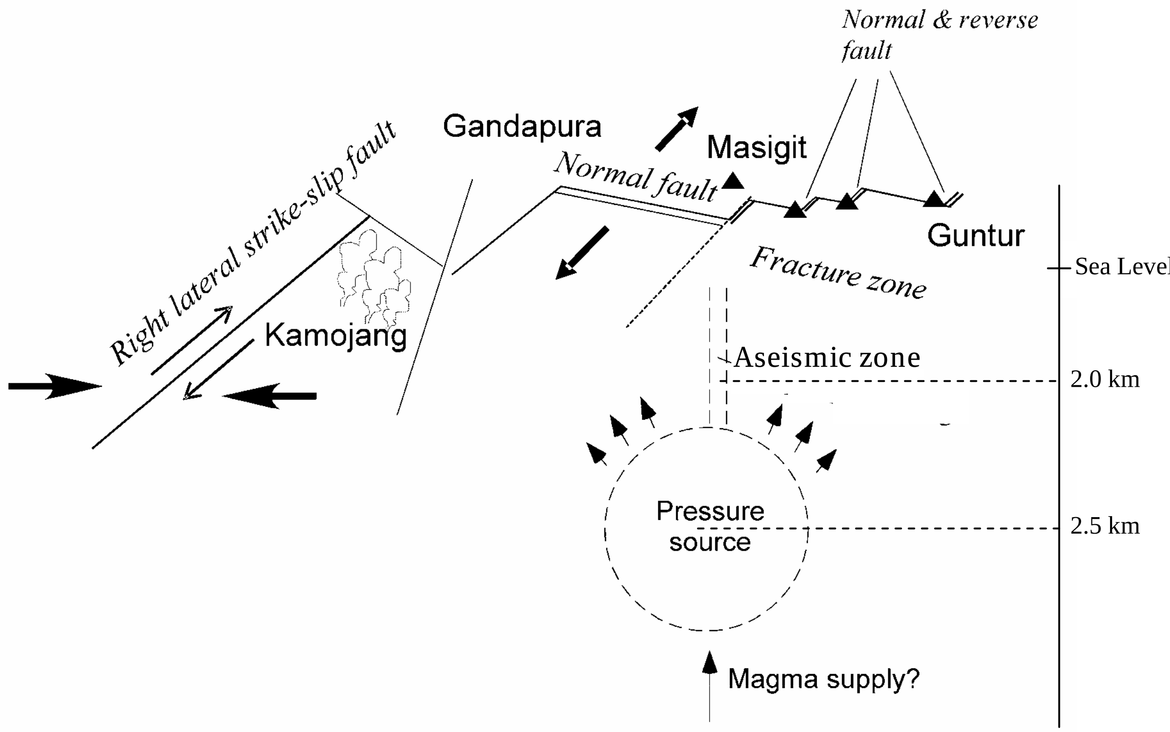


Figure 10. Schematic figure for relationship of seismicity of VT earthquakes with pressure source and tectonic stress. Hatched areas indicate hypocenter zone of VT earthquakes.

7. Conclusions

The activity of VT earthquakes increased at Guntur volcano during the observation period from 1991 to 2005. By analyzed the hypocenter location and focal mechanisms, we could obtain several results.

The distributions of VT earthquakes showed that hypocenters were located at 3 regions. They are aligned along direction of the volcanoes, from southeast to northwest, at depths of 0-2 km below sea level beneath the summit area of Masigit to Guntur. The VT earthquakes are also distributed around Gandapura caldera at depths of 0 – 3km. In Kamojang geothermal area, west of the summit, they were located at depths of 2 –8 km. The determination of focal mechanisms showed differences from among the regions. The mechanisms are mixed with normal fault and reverse fault at the summit area. In Gandapura caldera and shallower part (<3 km) of Kamojang, only normal fault events were found. Right-lateral strike-slip fault type is predominant at deeper part of Kamojang. The mechanism of earthquakes in Kamojang caldera is controlled by tectonic stress and triggered by geothermal activity. Whereas, the VT earthquakes at Gandapura and the summit area may be related with intermittent intrusion of magma. Normal fault earthquakes are caused by tension field above the inflation magma reservoir.

Seismicity sometimes increased at Guntur volcano, however, seismic energy release stays at lower than those preceding magmatic eruptions.

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References

1. K. Kamo, Some Phenomena Before the Summit Eruptions at Sakura-zima Volcano, *Bull. Volcanol. Soc. Japan*, **23,** 53-64, 1978. (Japanese with English abstract).
2. K. Umakoshi, H. Shimizu and N. Matsuwo, Magma Ascension path in the 1990-94 Eruption of Fugendake, Unzen Volcano, as Inferred from Precisely Determined Hypocentral Distribution, *Bull. Volcanol. Soc. Japan,* **39,** 223-235, 1994. (Japanese with English abstract).
3. S. Hidayati, K. Ishihara and M. Iguchi, Volcano-tectonic Earthquakes During the Stage of Magma Accumulation at the Aira Caldera, Southern Kyushu, *Japan, Bull. Volcanol. Soc. Japan* (submitted), 2007.
4. K. Kusumadinata, Data Dasar Gunungapi Indonesia, *Direktorat Vulkanologi*, 1979. (in Indonesia).
5. S. Wikartadipura *et al.*, Volcanic Hazard Map of Guntur Volcano, West Java, Indonesia, *Volcanological Survey of Indonesia*, 1993. (in Indonesia).
6. M. Iguchi *et al.*, Evaluation of the 1997 Activity at Guntur Volcano, West Java, Indonesia, *Symposium of Japan-Indonesia IDNDR Project,* Bandung Indonesia, 1998.
7. M. Iguchi *et al.,* Seismic Activity at Guntur Volcano, West Jawa, Indonesia, *Ann. Dist. Prev. Res. Inst., Kyoto Univ., Japan,* **39**, B-1, 1-11, 1996. (In Japanese, abstract in English).
8. Suantika, *et al.,* Hypocentral Distribution and Focal Mechanism Around Guntur Volcano, West Java, Indonesia, *Ann. Dist. Prev. Res. Inst., Kyoto Univ., Japan,* **40**, 5-11, 1997.
9. Suantika *et al.,* Characteristics of Volcanic Earthquakes Around Guntur Volcano, West Java, Indonesia – Hypocenter and Focal Mechanism from 1994 to 1998, *Proceeding of the symposium on Japan-Indonesia IDNDR project*, Indonesia, 71-80, 1998.
10. B. Gutenberg and C. F. Richter, Magnitude and Energy of Earthquakes, *Ann. Geofis.,* **9,** 1-15, 1956.
11. S. A. Rasjid, Kusma and Samid, Laporan Penyelidikan Kegempaan Komplek Vulkanik G. Guntur-Papandayan, Januari – Maret 1989, *Proyek penyelidikan Gunungapi dan Panasbumi*, Direktorat Vulkanologi, 1989 (in Indonesia).
12. N. Hirata and M. Matsu'ura, Maximum- likelihood Estimation of Hypocenter with Origin Time Eliminated Using Nonlinear Inversion Technique. *Phys. Earth Planet. Int.*, **47,** 50-61, 1987.
13. A. D. Nugraha, S. Gede and W. Sri, Relokasi Hiposenter Gempa Vulkanik Gunung Guntur Menggunakan Model Kecepatan Tiga Dimensi, *Jurnal Geofisika*, **2,** 20-26, 2006 (In Indonesia).
14. K. Aki and P. G. Richards, Quantitative Seismology, W.H. Freeman and Company, San Francisco, 1980.
15. C. Friedrich and U. Wegler, Localization of Seismic Coda at Merapi Volcano (Indonesia), *Geophys. Res. Lett.*, **32,** L14312, doi:10.1029/2005GL023111, 2005.
16. M. Alzwar, N. Akbar, and S. Bachri, Geological Map of the Garut and Pameungpeuk Quadrangle, Jawa, *Geological Research and Development Center*, Indonesia, 1992.
17. M. Surmayadi *et al.*, Geological Map of Guntur Volcano, West Java, *Volcanological Survey of Indonesia*, Indonesia, 1998.
18. O. K. Suganda *et al.,* Strain Component and Tilt Vector Changes at Guntur Volcano, During the Increasing of Seismic Activity in 1997, *Proceeding of the symposium on Japan-Indonesia IDNDR project*, Indonesia, 81-93, 1998.
19. M. Hendrasto *et al.*, Ground Deformation at Guntur Volcano as Revealed by Precise Leveling Survey, *Proceeding of the symposium on Japan-Indonesia IDNDR project,* Indonesia, 95-105, 1998.
20. I. Yokoyama, Seismic Energy Release from Volcanoes, *Bulletin of Volcanology,* **50,** 1-13, 1988.
21. T. Kagiyama, Future View of the Research on Prediction of Volcanic Eruptions and Structure of Volcano, *Butsuri-Tansa*, **62,** 2007 (in press, in Japanese with English abstract).