Source Mechanisms of Volcanic Earthquakes at Some Volcanoes in Indonesia

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Abstract

Volcanological Survey of Indonesia has temporary seismic observations by installing data loggers stations whose timing system is calibrated by GPS at Guntur (December 1995-February 1996, October 1996-June 1997, August 1997-March 1998), Anak Krakatau (June 1997), Gede (August 1997), Sangeanapi (January-February 1997), Ili Lewotolo (June 1996), Slamet (March 1997) and Papandayan volcanoes (June-July 1998). (1) Volcanic earthquakes are concentrated or distributed in vertically elongated zone beneath the currently active crater or the crater of last eruption. (2) The depth of hypocenter are less than 8km, most of them are located shallower than 5km. (3) The mechanisms are normal or reverse faults beneath the craters. But as shown in Kamojang caldera, 5 km west of the Guntur crater, the volcanic earthquakes distant from the crater are located at rather deeper part and the mechanisms are strike-slip.

Keywords: Guntur, Anak Krakatau, Gede, Sangeanapi, Ili Lewotolo, Slamet, Papandayan, hypocenter distribution, focal mechanism

1. Introduction

Volcanological Survey of Indonesia (VSI) has monitored volcanic activity by a seismometer. When abnormal seismicity or increase in number of volcanic earthquakes were detected, temporary seismic observations in short-term have been repeated by installing several seismic stations in order to determine location of volcanic earthquakes. However it took a lot of time and labor to install several stations around volcano to transmit seismic signals to main observatory where the signals are recorded in common device, even though time to install should be reduced in case of crisis.

In the collaboration study between VSI and Sakurajima Volcanological Observatory, temporary observations were repeated around Guntur volcano by using data loggers (DATAMARK LS8000-SH) to supplement capability of hypocenter determination by the permanent stations (Iguchi et al., 1997; Suantika et al., 1998). The timing system of the data loggers is calibrated by GPS to keep precise timing for data acquisition (Morita and Hamaguchi, 1996).

Recently VSI has improved capability of hypocentral determination by using the data loggers at some volcanoes in Indonesia. Temporary seismic observations by installing data logger stations were conducted at Guntur, Anak Krakatau, Gede, Sangeanapi, Ili Lewotolo, Slamet and Papandayan volcanoes. In this paper, hypocenter distribution and focal mechanism are analyzed by using the data obtained by the devices, and common characteristics of hypocenters and their mechanism will be discussed.

2. Observation

We conducted seismic observations at

Table 1. Observation period and stations

Volcano	Period	Stations	Type of earthquakes
Guntur	December 1995-February 1996, October 1996-June 1997, August 1997-February 1998	6-11	A-type
Anak Krakatau	June 1997	3	A-type
Gede	August 1997	7	A-type
Sangeanapi	January-February 1997	4	A-type
Ili Lewotolo	June 1996	4	A-type
Slamet	March 1997	5	MP
Papandayan	June-August 1998	12	LF

Guntur (December 1995-February 1996, October 1996-June 1997, August 1997-February 1998), Anak Krakatau (June 1997), Gede (August 1997), Sangeanapi (January-February 1997), Ili Lewotolo (June 1996), Slamet (March 1997) and Papandayan volcanoes (June-August 1998). Krakatau volcano is situated in Sunda straight. Gede, Guntur and Papandayan volcanoes are located in West Java. Slamet is in Central Java. Sangeanapi and Ili Lewotolo volcanoes are located in the islands in Nusa Tenggara.

Krakatau volcano repeated explosive eruptions with effusion of lava since 1992 (Sutawidjaja, 1997). Eruption with lava flow occurred at Sangeanapi volcano from the end of January 1997 (Sulaeman, 1997). Observation was conducted immediately after the beginning of the eruption. The seismicity has been high at Ili Lewotolo volcano and more than 100 earthquakes occur per day (Sulaeman, 1997). The last eruption occurred at Slamet volcano, with lava dome formation in the summit in 1989 and earthquake swarm sometimes occurred. Monthly number exceeded 30,000 in March 1991 (Wildan, 1998). Guntur volcano has been quiet for about 150 years since the last eruption in 1847 (Sutawidjaja, 1998). Earthquake swarms has repeated at Gede volcano after the last eruption in 1957. Guntur and Gede volcanoes have rather long dormant period. At Papandayan volcano, volcano body was collapsed by the eruption in 1772. Recently minor mud eruptions were repeated at Kawah Mas crater where fumarolic activity continues. Seismicity gradually increased since October 1996.

At these volcanoes, several seismic stations were installed as shown in Table 1. The seismic stations were set up surrounding the active craters at the summits. The horizontal distances of the stations were less than 5 km from the summit crater. At Slamet volcano, small array consisting of 5 stations was installed 4km apart from the summit on the eastern flank. Each station at these volcanoes consists of vertical or 3-component short period seismometer (1 or 2 Hz), data logger and power supply system. The seismic signals from the seismometer are stored in data logger with sampling interval of 0.01 second and 16-bit resolution. The recording initiated by the trigger with a STA/LTA (ratio of short-term average to long-term average) algorithm. The internal clock in the data logger device is calibrated by GPS every 3 hours. The data logger has a memory of 20 Mbytes and can record 1000 events. The data stored in the data loggers are transferred to a PC via printer port.

During the observations, A-type earthquakes with clear P and S-waves were observed at Guntur, Krakatau, Gede and Sangeanapi volcanoes.

Observed volcanic earthquakes at Slamet volcano seem to be different from A-type earthquakes. The earthquakes was dominated by low frequency of 4-5 Hz and the first motions moved very emergently, however, as we expected, the seismic waveforms were similar to each other among the stations. The waveforms dominated by 4-5 Hz are similar to MP events at Merapi volcano (Ratdomopurbo, 1995). Here, we call this type of the earthquakes MP events. More than 400 MP events occurred every day during the observation and 2800 events were recorded in a week.

Earthquakes dominated by low frequency seismic waves increased at Papandayan volcano since June 1998. The frequency component of 2-5 Hz is dominated at the station closed to the crater. At more distant stations, the records have higher frequency content. This may be due to 2 Hz seismometer that is relatively insensitive to lower frequency. Here, we call this event merely low frequency event (LF).

3. Analysis

3.1 Hypocentral distribution

Hypocentral locations were calculated by using onset times of P-wave first motion, assuming homogeneous half space or 2-layered half space. Velocity models of underground structure are assumed as shown in Table 2. For volcanic earthquakes at Guntur, Gede, Sangeanapi, Ili Lewotolo and Papandayan volcanoes, more than 4 P-wave onset times were used. In Krakatau, only 3 stations were installed. Thus, S-P time interval was used to fix origin times of earthquakes.

To determine hypocenter, P-wave onset time is picked up, however, it is difficult to pick up P-wave onset time precisely for MP events at Slamet volcano. In order to increase in precision of P-wave time difference between seismic stations, coefficient of cross-correlation of waveforms between adjacent two stations were calculated. The shift time which gives maximum coefficient of cross correlation is arrival time difference of P-wave.

A small array was installed at eastern flank of Slamet volcano in order to estimate hypocenter locations of MP events. Multipartite method (Nishi, 1975) was applied to these events. Multipartite method is advanced from tripartite method, to determine azimuth and apparent velocity of seismic wave propagating through the array without assumption of P-wave velocity around the network on inclined volcano flank. By the method, azimuth and dip angle of propagating wave, and its velocity are calculated. Focal distances were calculated from S-P time interval. Detail of the procedure of calculation is described in Wildan (1998).

(1) Guntur volcano

Hypocenters are distributed vertically at depths of 0-5 km beneath the summit craters. In December 1995 – February 1996, most of the earthquakes are aligned from NE to SW (from Gandapura-Kamojang to Darajat caldera).

(2) Krakatau

Hypocenters are located at depth of 1-2 km beneath the summit. Some earthquakes are distributed at eastern part of the island.

(3) Gede

Most of the hypocenters were distributed beneath the summit crater. The depths of them range 2 –8 km below sea level. In preliminary study (Gede et al., 1997c), hypocenters were calculated in the area between Gede and Pangrango summits, shifting 2 km west from the results in this study. The seismic signals at some of the stations were recorded exactly 1 second earlier due to using old almanac data for time calibration by GPS. Correcting time shift by 1 second, hypocenters are located in the summit area.

(4) Sangeanapi

Hypocenters were vertically distributed at depths of 2-4 km beneath the summit crater.

(5) Ili Lewotolo

Epicenters were concentrated in the summit. The depths of the earthquake are less than 8 km below sea level. Some of the earthquakes are located at very shallow depth.

Table 2. P-wave velocity model for hypocenter determination

Volcano	Model	First layer	Second layer
Guntur	Homogeneous	Vp=2.75 km/s (Suantika et al., 1998)	-
Anak Krakatau	Homogeneous	Vp=2.5 km/s (Vp/Vs=1.7)	-
Gede	2 layers	Vp=2.5 km/s; h=3 km	Vp=5.9 km/s
Sangeanapi	Homogeneous	Vp=2.0 km/s	-
Ili Lewotolo	Homogeneous	Vp=3.0 km/s	-
Slamet	-	(Vp/Vs=1.7)	
Papandayan	2 layers	Vp=2.75 km/s; h=2 km	Vp=4.4 km/s

(6) Slamet

By the multipartite net calculation, azimuth and dip of propagation of seismic waves are determined N 240-260°E and 90-95°, respectively. Propagating velocity of P-wave is calculated to be around 3.8 km/s. Therefore hypocenters of MP events are estimated to be shallow depth (maybe <1 km) beneath the summit. Horizontal extension of focal zone is caused by ambiguity of S-P time interval. The results and similarity of MP events are interpreted that the hypocenters are concentrated at very shallow depth beneath the summit crater.

(7) Papandayan

Hypocenters of LF-type earthquakes were determined in vertically elongated zone of 2-5 km deep beneath fumarolic area (Kawah Mas crater).

3.2 Focal mechanism

Mechanisms of the earthquakes were determined using polarity of P-wave first motions assuming quadrantal pattern of P-wave push-pull by the method of try-and-error. For some earthquakes, it is difficult to obtain unique solution of the mechanism. Possible solutions of mechanisms are examined for Krakatau, Gede, Sangeanapi, Ili Lewotolo and Papandayan volcanoes. Obtained focal mechanisms at Guntur volcano are shown in Gede et al. (1998). The P-wave first motions are projected on the upper hemisphere of the focal sphere. All plots are equal-area projection. Composite focal mechanisms were obtained for the earthquakes at Krakatau, Sangeanapi, Ili Lewotolo due to small number of seismic stations.

(1) Guntur

Focal mechanisms of most of the events around Kamojang Caldera, 5 km west of the summit crater, are generally strike-slip fault with the fault plane direction of NE-SW and NW-SE. In contrast, in the summit area, mechanisms are normal fault and reverse fault type. No strike slip solution was obtained.

(2) Krakatau

Composite mechanism shows oblique normal fault for the earthquakes beneath the summit.

(3) Gede

Most of the solutions of the mechanisms are reverse fault type. A few earthquakes have normal fault mechanism. No strike slip fault was obtained.

(4) Sangeanapi

By combining into composite mechanism, reverse fault mechanism was obtained.

(5) Ili Lewotolo

Composite mechanisms were obtained. The earthquakes in western part of the summit area have normal fault. In the eastern area, nodal plane vertically oriented.

(6) Papandayan

Most of LF events have normal fault mechanism.

The hypocenter locations and typical focal mechanisms are summarized in Table 3.

4. Discussions

It is commonly recognized as;

(1) Volcanic earthquakes are concentrated or distributed in vertically elongated zone beneath

Table 3. Summary of hypocenter distribution and focal mechanism

Volcano	Epicenter	Depth (km)	Typical mechanism	Type of earthquakes
Guntur	Beneath summit crater (Guntur)	<5	Normal or Reverse	A-type
	Kamojang	5-10	Strike slip	A-type
Anak Krakatau	Beneath active crater East of the volcano	<2.5	Normal	A-type
Gede	Beneath summit crater	4-8	Reverse	A-type
Sangeanapi	Beneath summit crater	2-4	Reverse	A-type
Ili Lewotolo	Beneath summit	<8	Normal or reverse	A-type
Slamet	Beneath summit crater	<1	-	MP
Papandayan	Beneath active crater	2-5	Normal	LF

the summit.

(2) Volcanic earthquakes are located at depths less than 8km, most of them are shallower than 5km.

(3) The mechanisms are normal or reverse faults beneath the craters.

Concentration of hypocenters in vertically elongated zone is found at other volcanoes in Indonesia, as Merapi (Ratdomopurbo, 1995) and Lokon volcano (Solihin, 1996). In Japan,, A-type earthquakes are located 1-4 km beneath the summit crater at Sakurajima volcano(Ishihara, 1990) and earthquakes at Asama volcano show similar pattern (Sawada, 1994). Pattern of concentration beneath the summit crater is commonly found in andesitic or dacitic volcanoes where central eruptions occur. The hypocenters of A-type earthquakes surround volcanic conduit of Sakurajima volcano (Iguchi, 1994). At volcanoes treated in this study, the hypocenters are located beneath the crater currently active or active in the last eruption. The hypocenters beneath the summit crater at these volcanoes are corresponded to currently active conduit or conduit formed by previous eruptions. Volcanic earthquakes with the mechanism of normal or reverse fault occur beneath the summit crater. This means that compression or tension axes are vertically oriented and may be related with vertical elongation of volcanic conduit.

As shown in Kamojang caldera in Guntur area, 5 km west of the Guntur crater, the volcanic earthquakes are located at rather deeper part (5-10 km) and mechanisms are strike-slip. The characteristics of the earthquakes are rather similar to shallow inland earthquakes in tectonic region. Around Guntur volcano, most of the fault strikes from NE to SW (Alzwar et al., 1992). The earthquakes in Kamojang area are generated by slip of the fault.

5. Conclusions

Common features of volcanic earthquakes in this study can be pointed out as follows;

(1) Volcanic earthquakes are concentrated or distributed in vertically elongated zone beneath the currently active crater or the crater of last eruption.

(2) The depth of hypocenter are less than 8km, most of them are located shallower than 5km.

(3) The mechanisms are normal or reverse faults beneath the craters. But as shown in Kamojang caldera, 5 km west of the Guntur crater, the volcanic earthquakes distant from the crater are located at rather deeper part and mechanisms are strike-slip.

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