Micro-tilt changes preceding summit explosions at Semeru volcano, Indonesia

Kiyoshi Nishi[1*], Muhamad Hendrasto[2], Iyan Mulyana[2], Umar Rosadi[2], and Mas Atje Purbawinata[2]

[1]*Japan International Cooperation Agency (JICA), Indonesia Office, Jakarta, 10350, Indonesia*
[2]*Center of Volcanological and Geological Hazard Mitigation, Bandung 40122, Indonesia*

(Received August 31, 2006; Revised September 28, 2006; Accepted October 4, 2006; Online published March 23, 2007)

A two-axis tiltmeter installed at the summit of Semeru volcano, Indonesia, reveals two different modes of deformation, short-term and longer-term. The short-term variations are inflations precursory to the occurrence of summit explosions. The time intervals between the explosions range from several minutes to several tens of minutes, and the maximum precursory tilt change observed is about 0.1–0.2 μrad. This change in tilt is interpreted to reflect a shallow pressurization source, just beneath the active crater. The longer-term tilt changes are displayed over a period of several days to weeks, and a steady inflation during a period of nearly 2 weeks preceded the occurrence of pyroclastic flows on December 22, 2005. Both short-term and longer-term changes are confined to the radial tilt component, pointing toward the active crater and conduit. To explain both of these tilt changes we propose relatively shallow conduit pressurization, although at somewhat deeper levels in the case of longer-term deformation. The causative mechanisms involve gas exsolution, microlite crystallization, and rheological stiffening, which results in greater flow resistance and dynamic pressure in the upper conduit, thus causing the edifice tilts observed. The gas pore pressure in the magma builds until the threshold required to trigger explosive fragmentation is reached.

Key words: Semeru volcano, tilt observation, pressure source, precursory tilt, eruption monitoring.

1. Introduction

Semeru volcano is an andesitic stratovolcano located in East Java (Fig. 1). The peak's summit rises 3676 m above sea level, and its crater is about 300 m across. This volcano is the highest active volcano on the island of Java. Frequent explosions at the summit crater of Jonggring Seloko have been occurring continuously since 1941 (Kusumadinata, 1979), and during this period, frequent small vulcanian-type explosions have occurred, producing explosive plumes rising 400–1000 m above the summit. During active periods, lava flows, lava dome extrusions and pyroclastic flows have also been observed (Kusumadinata, 1979). In 2005, the frequency of the explosions averaged about 100 per day (Fig. 2).

To monitor the activity of this volcano, routine seismic observations have been carried out by the Indonesian Center of Volcanological and Geological Hazard Mitigation (CVGHM). More recently, a tiltmeter was installed at the summit with the aim of gaining a better understanding of the behaviour of this volcano from a different aspect, namely, ground deformation. The tiltmeter is a powerful tool for understanding and predicting volcanic activity (Ishihara, 1990; Dzurisin 1992; Voight *et al.*, 1998, 1999, 2000).

*Now at 24-2 Tanaka Higashi Hinokuchi, Sakyo, Kyoto city, Kyoto 606-8223, Japan.

2. Tiltmeter Installation

A bubble-type two-axis platform tiltmeter was installed about 500 m north of the active crater, at an elevation approximately 100 m above the crater. The orientation of one component (Y-axis) is radial to the active crater, and the other (X-axis) is perpendicular to the Y-axis (Fig. 3). A positive tilt on the Y-axis component indicates inflation of the crater area with respect to the tiltmeter site, i.e., a tilt down toward the north. A positive tilt on the X-axis component indicates a tilt down toward the west. We installed the tiltmeter in a shallow, 40-cm-deep pit with a concrete basement. The tiltmeter was covered with insulation and buried.

Data logger, wireless modem, and antennae systems were added, and power was provided by sealed batteries coupled to solar panels. Analog data from the tiltmeter were digitalized every second and averaged over 1 min, a relatively high frequency for tiltmetry (cf. Dzurisin, 1992; Voight *et al.*, 1998); the digitalized data were then stored with time stamps in the data logger at 1-min intervals at the summit site. Stored data were transmitted daily by wireless modem to the observatory receiving site and then relayed to a computer for data storage. The overall tilt resolution is 0.002 μrad. A diagram of the data acquisition system is shown in Fig. 4.

3. Results

The data obtained from this observation system are shown in Fig. 5. As the tiltmeter is situated near the active crater and is highly sensitive, disturbances caused by explosions and local volcanic earthquakes caused large offsets or spikes in the tilt record; to aid data interpretation, these

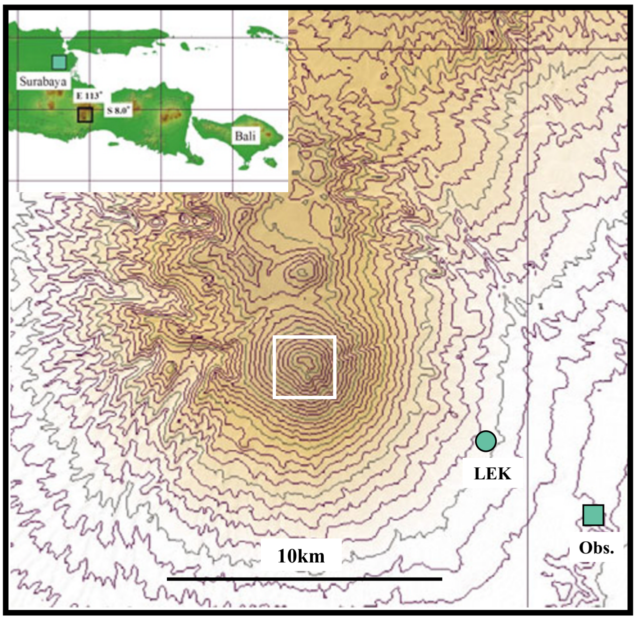

Fig. 1. Map of Semeru volcano and observation sites. Area within the white square is shown in detail in Fig. 3. *LEK* denotes the seismic station, and *Obs* is the local volcano observatory. Inset map shows the location of Semeru on Java island.

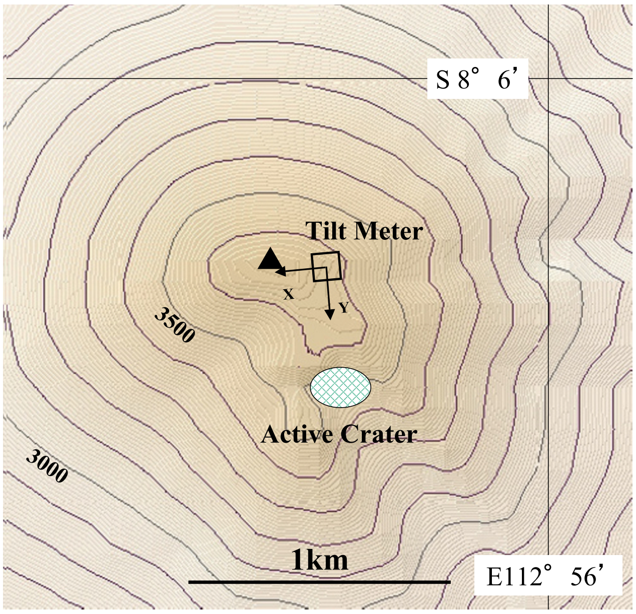

Fig. 3. Detailed topography of the summit area, Semeru volcano. Location of tiltmeter is shown, with directions of X and Y tilt axes. The Y-component of the tiltmeter is radial to the active crater.

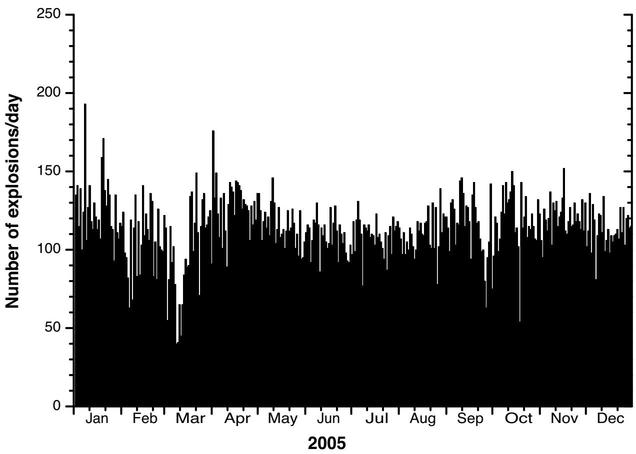

Fig. 2. Number of summit explosions per day at Semeru Volcano, for 2005.

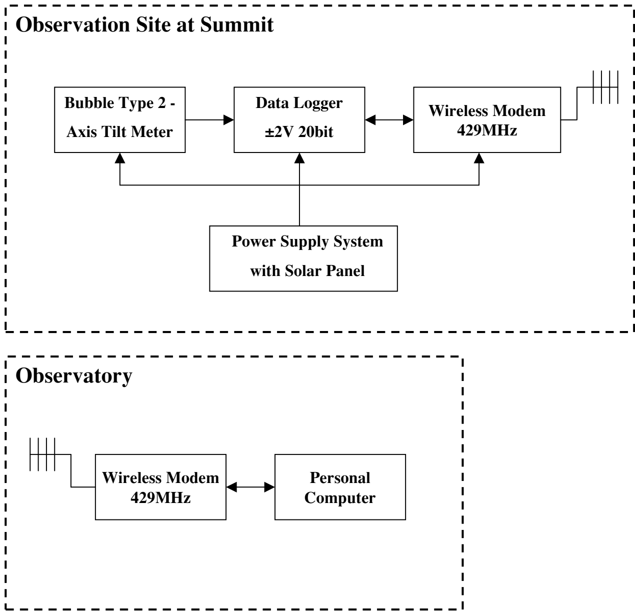

Fig. 4. Flow diagram of tiltmeter observation system, showing components for the summit station and the observatory data acquisition system.

large disturbances were removed. The resulting data pattern is complex and shows systematic changes (particularly in the Y-component) that extend over several weeks, overlain by a diurnal pattern that reflects temperature changes (Fig. 5); when examined in further detail, clear systematic changes are shown each day, on the timescale of a few tens of minutes (Fig. 6). These patterns are discussed below.

3.1 Short-term, minute, tilt changes preceding explosions

To examine the data in more detail, the circled portions of Fig. 5 are shown in Fig. 6(a) and (b), as an expansion of the time and amplitude axes for the Y-axis and X-axis tilt components, respectively. These data are representative of the short-term patterns, with each dot representing data at 1-min intervals. In Fig. 6(a), which represents the component radial to the crater, the dots generate about 28 discrete steeply-inclined segments over a 12-h period. The gradients of each of these segments are steeper than the mean trend of all data shown by the dashed line, and the resulting pattern is saw-toothed, with the teeth spaced at about 10- to 30-min intervals. The saw-toothed pattern correlates with repetitive explosions from the summit crater.

In Fig. 6(b), data for the component tangential to the crater show some local changes in pattern but nothing that correlates to the repeated saw-tooth segments of Fig. 6(a). This is consistent with the hypothesis that processes associated with the summit explosions principally cause radial

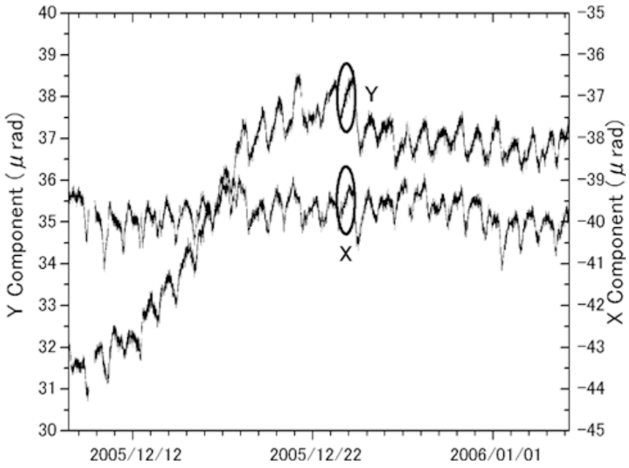

Fig. 5. The original time-series records from the tiltmeter, beginning 8 December 2005. Spikes and offset noise have been removed. The data interval is one minute. Circled portions are detailed in Fig. 6(a) and (b). Y component is radial to the crater, and X component is tangential.

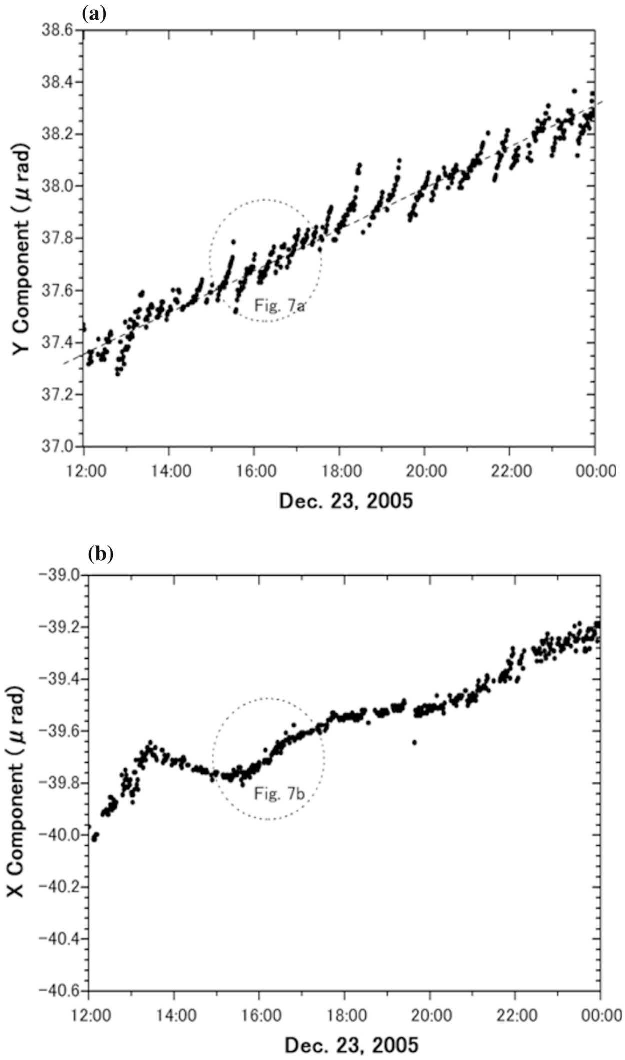

Fig. 6. Tiltmeter records, Semeru, December 23, 2005. (a) Detail of the circled portion of the radial Y-component in Fig. 5. Note frequent episodes (<30 min) en-echelon to baseline trend. Each episode culminated in an explosion. (b) Detail of the circled portion of the tangential X-component in Fig. 5. Individual episodes (<30 min) are not clear, although some linear patterns of several hours' duration occur. Circles show data detailed further in Fig. 7.

deformations, with the tangential components being small or negligible.

To examine these tilt changes in even more detail and to clarify the correlation between the tilt patterns and the explosions, the circled portion of Fig. 6(a) is presented at a higher magnification in Fig. 7(a). In this figure the mean data trend (the inclined dashed-line of Fig. 6(a)) has been subtracted out.

Figure 7(a) reveals the distinct relation between the inflationary tilt and the occurrence of explosions, as indicated by arrows at the top of the figure. The bars at the bottom of the figure show the relative energy release of the explosion seismic signals. The pattern suggests a generally steady and (commonly) slightly accelerating build-up of inflation over ten to several tens of minutes to a peak value, at which point one or—more rarely—two explosions occur that are associated with a rapid deflation. The next inflation begins immediately without any evident pause, and the cycle repeats itself. The amplitudes of the precursory tilt changes are minute, only 0.1–0.2 μrad. This Semeru pattern appears to be approximately similar to precursory tilts recorded on the Sakurajima (Ishihara, 1990; Fig. 7), Montserrat (Voight *et al.*, 1998; Fig. 5), and Suwanosejima volcanoes (Iguchi *et al.*, 2004) prior to explosions of the vulcanian or vulcanian-strombolian type, with different time-scales and deformation amplitudes.

In Fig. 7(b), the tangential tilts (X-components) are shown, with the mean data trends removed as in Fig. 7(a). The tangential tilt changes show no systematic changes, such as those evident in the radial (Y) component and, accordingly, show no relation between precursory tilt changes and the occurrence of explosions. Likewise there is no evidence for deflationary changes in tangential tilt following the explosions.

3.2 Longer-term tilt changes

To examine the long-term behavior of tilt changes, daily averages of recorded tilt are plotted versus time in Fig. 8 (cf. Fig. 5). On December 22, 2005, three pyroclastic flows occurred, with runouts as far as 2500 m. Prior to the pyroclastic flows, an inflationary tilt of approximately 7 μrad was observed in the radial (Y) component during a 13-day period.

This inflationary tilt ceased with the occurrence of the pyroclastic flows, and a deflation of approximately 1 μrad occurred over the next few days. On January 5 and 7, 2006, five pyroclastic flows in total occurred after approximately 1 μrad inflationary tilt over a 3-day period. We did not observe any significant tilt changes either before or after the occurrence of the pyroclastic flows in the tangential (X) component.

Similar tilt patterns in association with pyroclastic flows have been observed at Merapi volcano (Young *et al.*, 1994; Voight *et al.*, 2000).

4. Discussion

Tilt changes in the radial (Y) component to the crater, as shown in detail in Figs. 7(a) and 8, are expressed schemat-

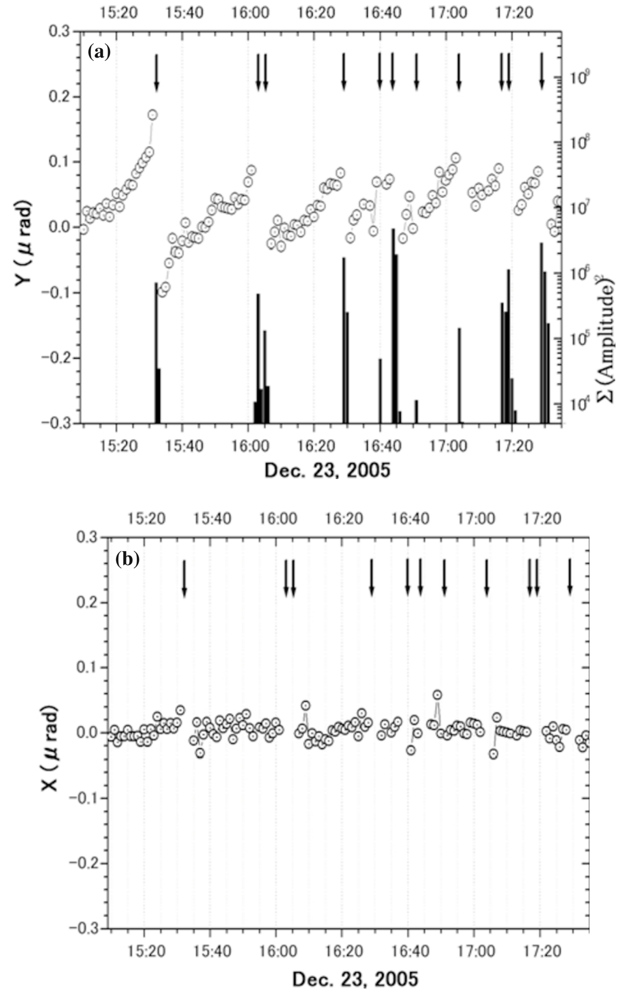

Fig. 7. Tiltmeter records, Semeru, December 23, 2005. (a) Detail of circled portion of the Y-component in Fig. 6(a) and the relationship between tilt changes and the occurrence of explosions. Arrows at the top indicate the time of explosions. Bars at the bottom indicate the sum of square amplitudes per minute for explosion earthquakes recorded at LEK station, in arbitrary units. (b) Details of circled portion of the X-component in Fig. 6(b). Arrows indicate explosions. No relation is found between tilt changes of the X-component and the occurrence of explosions.

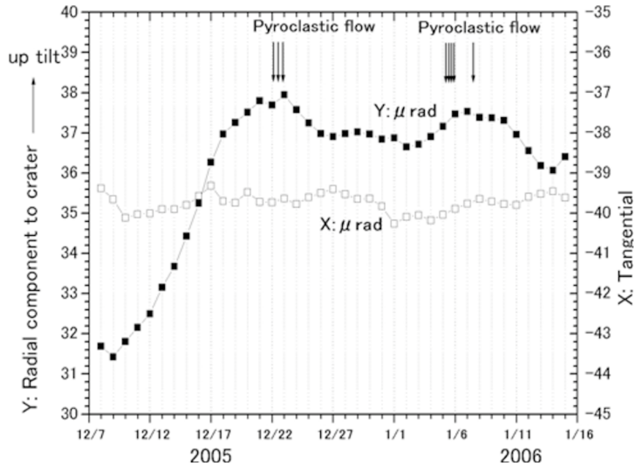

Fig. 8. Longer-term tilt changes. Dots (Y-component) and open squares (X-component) are the averaged daily values from original data that were taken each minute (cf. Fig. 5). The plot is concave-upward prior to December 16, and concave-downward from December 16 to 23. After the pyroclastic flows occurred, the inflation ceased. The X-component shows no systematic changes with respect to inflation, but there are some minor changes that might reflect environmental influences.

ically in Fig. 9. Variations due to thermal noise have been removed by using the daily average. The radial tilt changes are thus expressed by the superposition of frequent short-term changes (rapid mode) and gradual longer-term changes (slow mode).

Judging from the difference between short-term and longer-term tilt changes in rate and amplitude, each tilt change may be caused by a different pressure source. Moreover, since both short-term and longer-term changes are restricted to the radial tilt component pointing toward the active crater and conduit, the plausible location of both pressure sources may be in the conduit at different depths.

4.1 Upper pressure source related to the short-term tilt changes

The short-term patterns are qualitatively similar to precursory tilts recorded on Montserrat prior to vulcanian explosions in August 1997 (Voight *et al.*, 1998), but with quite different time-scales and deformation amplitudes. Although the tiltmeters were located at similar distances from the crater in both cases, the amplitudes of tilt change were on the order of 0.1 μrad for Semeru and approximately 10 μrad for Montserrat, a difference of approximately 100×. Likewise, the cyclic time-scales were of the order of 10 min for Semeru and 10 h for Montserrat, a difference of approximately 60×. The mechanisms involved in the two cases may be generally similar, with the differences caused by bulk magma chemistry, melt chemistry, and initial volatile content. At Montserrat, a partly crystalline andesitic magma (60 wt% SiO_2, with initial viscosity 10^7 Pa·s at 850°C and approx. 5 wt% dissolved water) erupted (Voight *et al.*, 1999; Melnik and Sparks, 2002). At Semeru, the magma is more mafic (56–57% SiO_2,, basaltic andesite), and viscosity could be of order of 10^5 Pa·s, suggesting that it is plausible to consider the mechanisms as being similar with the several orders-of-magnitude scaling differences supported by differences in viscosity and other dynamic parameters. However, these parameters have not been studied thus far for Semeru.

In the Suwanosejima volcano (56–60% SiO_2), Japan, similar precursory events were recorded by tilt plus broadband seismic observations (Iguchi *et al.*, 2004). Precursory upward displacement of the active crater of 8–17 μm was observed prior to the frequent summit explosions at 3- to 5-min intervals. The cycle time of upward displacement is somewhat shorter than Semeru's short-term tilt changes, but it is likely that a similar mechanism was observed by the different instruments, the broadband seismometer and tiltmeter. Tameguri *et al.* (2003) pointed out the similarity of explosion phenomena between the Suwanosejima and Semeru volcanoes based on observations by broadband seismometers and infrasonic microphones.

Based on the interpretations of the cyclic tilt changes for Montserrat (Voight *et al.*, 1998; Voight *et al.*, 1999) and cyclic displacements for Suwanosejima (Iguchi *et al.*, 2004), we interpret the Semeru short-term patterns as follows. Starting with an explosion of a gas-tephra mixture,

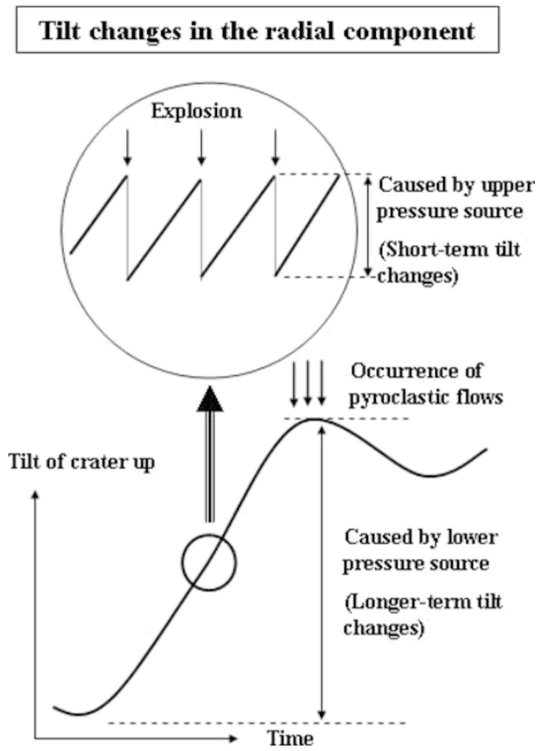

Fig. 9. Schematic expression of tilt changes of the radial component.

there is an immediate relaxation of pressure within the conduit, and this is reflected by a deflation at the summit tiltmeter. The loss of pressure triggers a new round of vesiculation within the conduit and, in turn, degassing effectively undercools the melt and causes microlite crystallization. The increase in pressure can occur both by gas exsolution and by rheological stiffening, which results in greater resistance and dynamic pressure in the upper conduit (Sparks, 1997; Voight *et al.*, 1999). Thus, the gas pore pressure in the magma continues to build until the threshold required to trigger explosive fragmentation is reached, this threshold being related to the critical tensile strength of the magma and column cap resistance. This inflation process was observed by the tiltmeter as upward tilt changes to the crater. The explosion occurs, conduit pressure drops, and the tiltmeter records a deflation. The cycle continues to repeat itself, on a time scale on the order of 10 min. Taking data on Montserrat (Voight *et al.*, 1998; Voight *et al.*, 1999) and Suwanosejima (Iguchi *et al.*, 2004) into consideration, we interpret this process as mainly involving the upper part of the conduit.

4.2 Lower pressure source related to the longer-term tilt changes

Judging from the relative slowness of tilt changes at Semeru, and the tilt amplitude, the longer-term pressure source is likely to generate a greater force than that associated with the cyclic short-term changes. A plausible model is as follows. In addition to the very shallow cyclic exsolution and conduit pressurization processes that result in small explosions and dominate the short-term deformation, it is also possible to consider the presence of a gradual stiffening and pressurization build-up of conduit magma in the region of middle to lower part of conduit. The same processes may be involved, i.e., bubble nucleation and growth, and crystal nucleation, and growth, but such processes can have residual effects that carry over from one short-term cycle to the next, and they likely also extend to deeper levels in the conduit. The result of this process is an increase in the baseline of pressurization and vesicularity over a period of days to weeks, with the short-term cyclic changes superimposed on this base level. The summit tiltmeter displays this gradual increase in longer-term, base-level pressurization, with the center of pressure likely somewhat deeper than that for the short-term changes. Ultimately, the baseline increases in vesicularity and pressurization can be interrupted by one or several larger-than-average explosions that cause greater-than-average drawdown in the conduit magma level. The result can be a cessation of the longer-term inflation and perhaps partial deflation.

An alternative model for the lower pressure source is a magma chamber. However, in this case, it is speculative whether chamber expansion could cause the summit inflation observed in such a steep cone rather than a half-space. Further, the resultant deformations for both short-term and longer-term data are precisely aligned to the position of the conduit. This observation is consistent with a shallow, conduit source for pressurization, but it is not consistent with a deep source of uncertain geometry and location. The addition of several tiltmeters at different radii from the source, or a tiltmeter network, would probably enable the location and quantification of pressure sources (Mogi, 1958; Voight *et al.*, 1998).

Finally, we note that the empirical data and models provide forecasting possibilities. The short-term trends clearly indicate impending explosions. The longer-term trend indicates the possibility of larger-than-average explosions. The threshold values for forecasting may be assessed from a continued study of tiltmeter data.

5. Conclusions

We summarize our results as follows:

- A two-axis tiltmeter with frequent data recording was installed at the summit of Semeru volcano; this tiltmeter shows two different modes of deformation, short-term and longer-term.
- The short-term variations are inflations precursory to frequent small vulcanian explosions, with a rapid deflation simultaneously accompanying each explosion. The time intervals between explosions range from several minutes to several tens of minutes, and the precursory tilt changes in each episode are 0.1–0.2 μrad. These remarkable data were recoverable because of the relatively high frequency of measurements.
- The longer-term tilt changes are displayed over a period of several days to weeks, as exemplified by a steady inflation in the tilt over a 13-day period that preceded the occurrence of pyroclastic flows on December 22, 2005.
- Both short-term and longer-term changes are restricted to the radial tilt component pointing toward the active crater and conduit. We propose shallow conduit

pressurization as an explanation for the tilts observed, with the causative mechanisms involving gas exsolution, microlite crystallization, and rheological stiffening. These mechanisms result in greater flow resistance and dynamic pressure in the upper conduit, causing the observed edifice tilt. The gas pressure in the bubbly magma builds until the threshold required to trigger explosive fragmentation is reached.

- The same processes affect the longer-term deformation, but these have residual pressure effects that carry over from one short-term cycle to the next and, consequently, the base-line pressurization is gradually increased. The center of pressure for longer-term deformation extends deeper into the conduit. A larger-than-average eruption with deeper drawdown can interrupt the longer-term inflation.
- Both short-term and longer-term trends have clear implications for event forecasting. The hazard of a dangerous event is suggested by a longer-term inflation, and during such periods caution should be advised for summit expeditions, including volcano monitoring work.

Based on our tilt observations and analysis, we have provided a new approach to improve understanding of the present volcanic activity at the Semeru volcano that includes a forecasting capability for hazardous events.

Acknowledgments. We wish to express our thanks to the Japan International Cooperation Agency (JICA) for providing us with the instruments used in this investigation. Dr. Iguchi of Kyoto University provided advice on the design of the tiltmeter system, and we express our gratitude to him for this help. Professor B. Voight of Pennsylvania State University provided constructive suggestions. We express our thanks for his courtesy. Dr. Murase of Nagoya University gave us very helpful comments. Our thanks also go to the staff of Sawur Observatory of Semeru volcano, and the staff of the Center of Volcanological and Geological Hazard Mitigation, for their help.

References

Dzurisin, D., Electronic tiltmeters for volcano monitoring: lessons from Mount St. Helens, *U.S. Geol. Surv. Bull.*, **1966**, 69–83, 1992.

Iguchi, M., T. Tameguri, and H. Yakiwara, Very-long period seismic pulses associated with small-scale eruptions at Suwanosejima volcano, Japan, *Eos. Trans. AGU*, **85**(28), West. Pac. Geophys. Meet. Suppl., Abstract V23A-76, 2004.

Ishihara, K., Pressure sources and induced ground deformation associated with explosive eruptions at an andesitic volcano: Sakurajima volcano, Japan, in *Magma Transport and Storage*, edited by M. P. Ryan, 335 pp., John Wiley & Sons Ltd, 1990.

Kusumadinata, K., Catalogue of References on Indonesian Volcanoes with Eruptions in Historical Time, 304 pp., Volcanological Survey of Indonesia, 1979.

Melnik, O. and R. S. J. Sparks, Modelling of conduit flow dynamics during explosive activity at Soufriere Hills Volcano, Montserrat, *Geol. Soc. London, Mem.*, **21**, 307–317, 2002.

Mogi, K., Relations between the eruptions of various volcanoes and the deformations of the ground surfaces around them, *Bull. Earthq. Res. Inst. Univ. Tokyo*, **36**, 99–134, 1958.

Sparks, S., Causes and consequences of pressurization in lava dome eruptions, *Earth Planet. Sci. Lett.*, **350**, 177–189, 1997.

Tameguri, T., M. Iguchi, H. Triastuty, I. Mulyana, M. Hendrasto, and A. D. Wirakusumah, Observation of eruption and air-shocks accompanied with small explosive eruptions at Semeru volcano, East Java, Indonesia, *Annu. Disaster Prev. Res. Inst., Kyoto Univ.*,**46B**, 779–786, 2003.

Voight, B., R. P. Hoblitt, A. B. Clarke, A. B. Lockhart, A. D. Miller, L. Lynch, and J. McMahon, Remarkable cyclic ground deformation monitored in real-time on Montserrat, and its use in eruption forecasting, *Geophys. Res. Lett.*, **25**, 3405–3408, 1998.

Voight, B., R. S. J. Sparks, A. D. Miller, R. C. Stewart, R. P. Hoblitt, *et al.*, Magma flow instability and cyclic activity at Soufriere Hills Volcano, Montserrat, *Science*, **283**, 1138–1142, 1999.

Voight, B., K. D. Young, D. Hidayat, Subandrio, M. A. Purbawinata, A. Ratdomopurbo, Suharna, Panut, D. S. Sayudi, R. LaHusen, J. Marso, T. L. Murray, M. Dejean, M. Iguchi, and K. Ishiharta, Deformation and seismic precursors to dome-collapse and fountain-collapse nuees ardentes at Merapi Volcano, Java, Indonesia, 1994–1998, *J. Volcanol. Geotherm. Res.*, **100**, 261–287, 2000.

Young, K. D., B. Voight, Subandrio, Sajiman, Miswanto, R. W. LaHusen, and J. Marso, Tilt monitoring, lava dome growth, and pyroclastic flow generation at Merapi Volcano, Java, Indonesia, *Geol. Soc. Am. Annu. Meet. 26*, **483**, 1994.

K. Nishi (e-mail: west@da2.so-net.ne.jp), M. Hendrasto, I. Mulyana, U. Rosadi, and M. A. Purbawinata