Tidal influence on the 2000 Miyake-jima eruption and its implications for hydrothermal activity and volcanism

By Junzo Kasahara,1) Shigeru Nakao, and Kazuki Koketsu

Earthquake Research Institute, The University of Tokyo, 1-1-1, Yayoi, Bunkyo-ku, Tokyo 113-0032
(Communicated by Yoshihumi Tomoda, M. J. A., June 12, 2001)

Abstract: During the 2000 Miyake-jima volcanic activities, forty-six steps on tilt meters and earthquake bursts in Miyake-jima were observed over a 40-day period. These tilt steps and earthquake bursts seem to have a diurnal or semi-diurnal periodicity. Earthquake bursts were high around tilt steps. The correlation of tilt steps and calculated shear strain components of tidal force was examined. If we consider some scatter of direction, shear strain components of tidal deformation show good coincidence with tilt steps. The coincidence is best in the N45°E-N70°E directions. A model to explain tilt steps by tidal triggering is proposed. According to this model, the tidal force triggered or accelerated the opening of gaps between volcanic conduit and capped-rock near the summit. The shear movements in the N45°E-N70°E directions might effectively act to open gaps between conduit and capped-rock and/or existing cracks. Vapor, sulfur dioxide, and/or carbon dioxide are candidates for the pressure source in the volcano conduit. If the tidal effect on volcanism in Miyake-jima can be applied to other cases, many similar observations can be explained.

Key words: Tidal force; tilt steps; volcanic swarm; Miyake-jima eruption; ocean tide; earth tide.

Introduction. There are many studies discussing the effects of ocean tide and earth tide on earthquake occurrence and volcanism. Tidal force has diurnal and semi-diurnal periodicity due to forces exerted by moon, sun and planets. Scientists noticed the presence of diurnal or semi-diurnal variations in the number of earthquake sequences and timing of volcanic eruptions. However, relations among earthquakes, volcanism and tides seem very diverse.1) The major reasons are short appearance of phenomena and diverse relations of tides with earthquakes and volcanisms.

Miyake-jima is an island of active volcano 9 km-long × 7 km-wide, and is located 180 km south of Tokyo (Fig. 1). It is a part of the Izu-Bonin Arc, which is on the Philippine Sea Plate. Miyake-jima experienced repeated strong eruptions in 1874, 1940, 1962, and 1983. The eruption in 1983 occurred from the SW flank of Mt. Oyama in Miyake-jima in October 4.2) It was found from OBS observations that volcanic earthquake activities during the 1983 Miyake-jima eruption had a good correlation with sea-level changes at Ako port.3)4) Peaks and troughs in the number of volcanic earthquakes varied with sea-level changes at Ako port. In addition to this correlation, the fissure eruption in 1983 started at low tide, but the following earthquakes felt in Miyake-jima before the OBS observations occurred at high tides.

From June 2000, strong earthquake activities occurred in and around Miyake-jima, and volcanic eruptions occurred in Miyake-jima.5)6) During the volcanic activities in Miyake-jima, tilt meters, seismometers, and electrical field measurement observed notable phenomena. In this paper, the authors interpret these phenomena in terms of tide.

The 2000 Miyake-jima volcanism. The volcanism of the 2000 Miyake-jima eruption is summarized as having three major stages (Fig. 2). Fig. 3 shows earthquake epicenter distributions during the 2000 Miyake-jima eruption.6) Fig. 4 shows hourly number of earthquakes and tilt measurements from July 6 to July 18.7)8) Tilt meters show gradual increases and sudden decreases called tilt steps. Each step shows a sharp change with approximately 1-2 minute durations. The tilt-steps were as large as a few micro-radians. The earthquake activities in Miyake-jima during this period showed burst-like activi-
ties, and the seismic bursts seem to be diurnal or semi-
diurnal. The seismic bursts resemble tilt steps in
appearance, but the peaks are not as sharp as tilt steps.
Forty-six tilt steps between July 8 and August 18
(Stage-2) were observed by tilt meters in Miyake-
shima (Fig. 5). The first step was observed during the
steam eruption at 18:41 on July 8. The last tilt-step was
observed on August 18, 2000. Earthquake activities and tilt-steps
show nearly diurnal and/or semi-diurnal variations during this
period. The number of earthquakes peaks at the tilt step, but
they are not as sharp as tilt steps.

Fig. 1. Location map of Miyake-jima and bathmetry.

Fig. 3. Earthquake hypocenters during June 26 and December 31,
2000 (after Sakai et al.15).

Fig. 2. Summary of volcanism during 2000 Miyake-jima eruption.

Fig. 4. (a) Map of Miyake-jima tilt-meters (after Ukawa et al.8).
(b) Top: hourly number of earthquakes between July 6 and July
18, 2000 obtained by JMA (unauthorized data) and bottom: tilt
steps between July 8 and July 18, obtained by NEID (Ukawa
personal communication). Earthquake activities and tilt-steps
show nearly diurnal and/or semi-diurnal variations during this
period. The number of earthquakes peaks at the tilt step, but
they are not as sharp as tilt steps.
observed at 18:09 on August 18. The tilt steps are interpreted as volumetric expansions of summit region of Mt. Oyama.

Broadband seismometers and strong motion seismometers around Japan also recorded long-period events, not resembling ordinal earthquakes. The largest event was observed 1,400km from Miyake-jima. The typical duration of these events is 50 seconds. Electrical field measurements in Miyake-jima also showed exactly the same waveforms as seismic records.

Comparison of tilt-steps and tidal changes.

Considering the tidal correlation of earthquake occurrence found during the previous eruption in 1983, we examined the correlation between tilt steps and tidal change. As seen in Fig. 4, earthquake activities in Miyake-jima show similar peaks as tilt steps, and a comparison was made only for tilt-step and tidal variation.

The shear strain components of tidal force were calculated using the ocean model and the program developed by Matsumoto et al. The reference point was placed on the summit of Mt. Oyama (34.85°N, 139.22°E). On islands such as Miyake-jima, ocean tide components have a larger contribution than earth tide on tidal deformation. To examine the accuracy of their ocean model, the tide level measurements at Ako port in Miyake-jima were compared to calculated values, and both agreed well. Approximately twenty-one peaks and troughs of high tides and low tide are correlated with tilt steps, but the fit is not as good as matches observed during the 1983 Miyake-jima eruption. Fig. 6 shows shear strain components of tidal deformation from N45°E to N80°E directions. The solid circle shows the best match and open circle shows the second best. Thirty-three tilt steps were among forty-six occurring at peaks or troughs of tidal shear components. For example, #31 and #32 tilt steps for two days are in exact agreement with shear strain components for the N75°E directions seen in Fig. 6 (c). However, the best fitting directions vary over time. Initial tilt steps occurred in the N45°E-N50°E directions and later ones show extensive directional scatter. Although 13 tilt steps do not have good correlations with tidal peaks/troughs, the correlation might suggest that the tilt steps were controlled by tidal shear components. Sea-levels and linear strain components show poorer relations than shear strain components of N45°E to N80°E directions. The N5°E-N45°E directions of shear strain components of tidal deformation also have poorer relations than those for N45°E to N80°E. The coincidence is best in the N45°E-N70°E directions (Figs. 6 and 7). Considering directional dependence, the sensitive directions of tilt steps against tidal forces have a few degrees of directional range. The N45°E-N70°E directions might suggest dominated cracks generated during the summit collapse, and these directions are also similar to the fissure directions in 1983.

Explanation model of 2000 Miyake-jima volcanic process. In the previous section, we found a strong correlation between tidal shear deformation and tilt steps. As seen in Fig. 4, seismic activities in Miyake-jima for stage two (Fig. 2) are strongly correlated. At each tilt step, earthquake activities show peaks. Broadband seismometers and electrical field measurements show that each event has a characteristic period of one minute. The deformation at a tilt step was a sudden inflation and the land surface shows subsidence as a relaxation process. Considering the above evidence, we propose a model to explain the volcanic process at tilt steps during the 2000 Miyake-jima volcanism.

a) Upward movement of magma generated a volcanic swarm around 18:00 on June 26, 2000, and on June 27, hypocenters migrated to NW due to migration of magma body.

b) Following a large steam eruption at 18:41 on July 8, 2000, subsidence of the summit region occurred and sliding blocks shielded the volcanic conduit forming capped-rocks.

c) Because the capped-rock shielded the volcanic conduit, vapor (and/or gas such as carbon dioxide and sulfur dioxide) in the conduit column could not easily escape into the air. This increased the vapor (gas) pressure in the volcanic conduit. The shape and the
size of the conduit remained the same during stage two.

d) The stress caused by high vapor pressure, which acted to open gaps, generated earthquake bursts. The vapor pressure was especially high just before the opening of gaps between the capped-rock and the conduit wall.

e) The shear stress component of the earth tide assisted the opening of gaps between the capped-rock and conduit wall, or fracture zones. The magnitudes of tidal strains are small (order of $2-3 \times 10^{-8}$) and they effectively assist to create pathways from conduit to air. The main force opening gaps might be vapor (or gas) pressure in the conduit. When the vapor pressure is high enough to be critical for opening, the tidal forces might show tilt steps. Due to some directional
scatter of gaps (or cracks), the periodicity of tilt steps was imperfect.

f) The sudden release of vapor by the opening of gaps generated a single tilt-step, and earthquake bursts ceased with the sudden release of vapor. The time constant, namely one minute, might be determined from the duration of escaping vapor, and it was fairly stable due to the constant capacity of the conduit column and the continuous water supply to the magma head.

g) The vapor pressure increased due to contact between magma head and seawater or groundwater. The processes c)-g) were repeated until August 18 when the capped-rock subsided again.

h) Due to the generation of large gaps, vapor, sulfur dioxide, and carbon dioxide gases easily escaped into the air.

The major force opening gaps might be vapor pressure and/or gas pressure. Heating of ground water by magma body could produce vapor. The magma body itself also emits vapor and/or gas such as carbon dioxide or sulfur dioxide. If vapor or gas pressure increases, it might generate earthquakes and act to open gaps.

Discussion. There are some other studies on the correlation between tidal change and earthquake activities, volcanic eruptions, and hydrothermal venting. Among the many cases, Ito-earthquake swarm is the most well known. Swarm earthquake activity in March 1930 in the area off Ito in Izu Peninsula, Japan, showed a diurnal change in the number of earthquakes compared to tide gauge records at a distance of c.a. 20 km.\(^\text{16}\) In the Ito swarms, earthquake activity was high at low tide levels. Earthquake swarms off Ito in another year also showed good correlations with tidal variations.\(^\text{17,18}\) Just after the earthquake swarm off Ito in 1989, a submarine volcano erupted in the swarm region, suggesting that the swarm activities off Ito had been controlled by a volcanic source (e. g., ref. 17)). There are some studies on the correlation between eruptions and tides for Pavlof volcano in Alaska\(^\text{19}\) and Hawaiian volcanoes.\(^\text{20,22}\)

Hydrothermal venting activities at oceanic ridges and rifts in back-arc basins might be controlled by heat supplied from magmatic sources. Seismic observations using OBS (Ocean Bottom Seismometers) near hydrothermal vents in the south Mariana Trough,\(^\text{23,24}\) TAG (Trans Atlantic Geotraverse) in the Mid-Atlantic Ridge\(^\text{25}\) and Okinawa Trough\(^\text{26}\) showed good correlations between hydrothermal activities and tidal changes. However, the correlations are not the same for the three cases.

If the tidal effects on tilt steps and earthquake activity during 2000 Miyake-jima eruption can be applied to other volcanic cases, tidal force acts to trigger or assist the opening of cracks or fissures. The major force might be vapor pressure generated by heat supplied by the magma body. Vapor can be generated when magma body rises to the ground water level. Alternatively, vapor or gas such as sulfur dioxide and carbon dioxide emitted by the magma body acts as a wedge penetrating the fractures. Scatter in the directions of gaps between conduit and capped-rock or cracks can explain the directional dependence seen in this study, or the diversity in the relation with fracture alignment existing in the volcanic field. From the diversity of the pre-existing fracture directions, some phenomena might relate to high ocean tides, and other case might relate to low tides. In volcanoes, the directions of fractures might be distributed with some directional distribution and they might not show a simple relation.

Another objection to tidal contribution is the short appearance of diurnal / semi-diurnal change. This can be explained by the nature of tidal effects. Strains generated by tidal forces are in the order of \(10^{-8}\) and the amount seems too small to open fractures as the main force. If tidal force acts as a minor factor and the major force is another force such as vapor (or gas) pressure, the appearance of the short duration can be explained, because high vapor (gas) pressure can be obtained only when the magma body is sufficiently shallow and a water supply to magma or vapor or gas supply from magma is necessary. Carbon dioxide is a major component of gases of magmatic origin. Sulfur dioxide is also another candidate for the gas phase released from magma. In many cases, diurnal/semi-diurnal variations of
earthquake activity were seen only for shallow hypocenters (e. g., 4 km for the 1989 swarm just before the submarine eruption with diurnal change\cite{ERI(1990)}, suggesting the presence of a magma body or an intrusion of a vapor (gases) wedge at a shallow depth.

**Conclusions.** During the 2000 Miyake-jima volcanic activities, forty-six tilt steps with intense volcanic seismicity were observed between July 8 and August 18. Tilt steps and earthquake bursts on Miyake-jima seem to occur nearly diurnally or semi-diurnally. The calculated tidal shear strain components were compared to tilt steps. The shear strain components for N45°E-N70°E directions show a better fit than linear strain components and sea level changes. It is concluded that the calculated tidal shear strain components coincided well with tilt steps, if some directional scatters is considered. The N45°E-N70°E directions might suggest dominated directions of gaps between conduit and capped-rock generated at the summit collapse, and/or existing cracks.

Based on the above result, a model explaining tidal triggered tilt steps is proposed. Vapor pressure in the volcanic conduit increased from one tilt step to the next tilt step. The tidal force might trigger or accelerate the opening of gaps between volcanic conduit and capped-rock near the summit. After August 18, 2000, permanent gaps connecting conduit and air were formed by a large subsidence, and no more tilt steps were observed since the day. Vapor, sulfur dioxide, and/or carbon dioxide are candidates for the pressure source in the volcano conduit.

If the tidal effect on volcanism in Miyake-jima can be applied to other cases, many similar observations can be explained. The short appearance of diurnal/semi-diurnal occurrence might be caused by the depth of magma or vapor (gases) wedge. Some scatter of fracture directions can explain the imperfectness of periodicity.

**Acknowledgement.** The authors would like to thank Dr. Y. Tomoda, M. J. A., for his advice and assistance in preparing this article.

**References**
9) JMA (2000).