Tilt change recorded by broadband seismometer prior to small phreatic explosion of Meakan-dake volcano, Hokkaido, Japan

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[1] We discovered an anomalous very long period (VLP) signal (duration: about 60 s) in the broadband seismic record of the precursory swarm of a small phreatic explosion at the Meakan-dake volcano, Hokkaido, Japan, in 2006; this signal was masked by a short-period tremor in the original velocity waveform, but a considerable DC step appeared in the displacement trace. Since such a step results from a tilt change, we interpreted the observed trace as being a combination of rotational (tilt) and translational (displacement) motions. The apparent displacement step in the VLP signal indicates subsidence of the summit crater. Owing to limited data, we attempted deflating the Mogi source and simulating the seismic record including both motions. When only rotational motion is considered, the simulated waveform explains well the general features of the observed trace. However, the combined trace has incompatible phases, suggesting that a more complicated source process should be considered. **Citation:** Aoyama, H., and H. Oshima (2008), Tilt change recorded by broadband seismometer prior to small phreatic explosion of Meakan-dake volcano, Hokkaido, Japan, *Geophys. Res. Lett.*, *35*, L06307, doi:10.1029/2007GL032988.

1. Introduction

[2] Phreatic explosions are triggered by interactions between magma and ground water at shallow depths; they are widely observed at many volcanoes. However, despite the frequency of field observations of phreatic explosions, it is very difficult to measure the precursory phenomena of such small explosions using physical monitoring techniques. Moreover, whether the precursors of phreatic explosion are entirely nonexistent or too small to record has been the subject of considerable debate.

[3] Broadband seismic monitoring on and around active volcanoes has become popular in recent years. Furthermore, the high sensitivity of broadband seismometers has led to the frequent detection of anomalous very long period (VLP) signals around volcanoes [e.g., *Kawakatsu et al.*, 2000; *Kumagai et al.*, 2003; *Nishimura et al.*, 2002; *Chouet et al.*, 2003]. Some of these VLP signals have been recorded by using multiple seismometers, and waveform analyses has been attempted to reveal their excitation processes.

[4] Using a broadband seismometer, we monitored a small phreatic explosion that occurred at the Meakan-dake volcano on 21 March 2006. The explosion was associated with two precursory seismic swarms; we discovered an anomalous VLP signal in the data of the first swarm. In this report, we describe the VLP signal observed about one month prior to the phreatic explosion and discuss its implications as a precursor to the explosion.

2. Explosions of Meakan-Dake and Precursory Swarms

[5] The Meakan-dake volcano is an andesitic stratovolcano; it stands on the southwestern rim of Akan Caldera in eastern Hokkaido. Many fumaroles and hot springs are distributed on and around the volcano. The documented eruptions since 1957 have all been phreatic explosions that occurred at the Pon-machineshiri summit crater (Figure 1). The Meakan-dake volcano has produced four phreatic explosions in the last 20 years (Figure 2). On the occasion of the 1996 explosion, precursory seismic swarms similar to the 2006 activity were observed [*Okada et al.*, 1997]. The 1996 eruption opened a new small crater on the southern rim of the Pon-machineshiri crater but did not affect the neighboring fumarolic activity. In addition, an increase in seismic activity was also observed just before the 1988 eruption [*Okada et al.*, 1997].

[6] The small phreatic explosion that occurred in the early morning on 21 March 2006 caused the creation of new small pits around the northwestern perimeter of the Akanuma summit crater, which occupies the northern half of the Pon-machineshiri crater (Figure 1). Before the explosion, three separate earthquake swarms were observed by a continuous monitoring network: The first swarm continued for about five days from 18 to 22 February, comprising more than 1250 earthquakes; this swarm occurred after two years of seismic quiescence. About 20 days later, on 11 March, the second swarm began, and subsequently, the earthquakes increased in frequency once again one day prior to the phreatic explosion on 21 March.

[7] Institute of Seismology and Volcanology (ISV), Hokkaido University, operates a few seismic stations at the western foot of the Meakan-dake volcano (Figure 1). During the active period in 2006, a Guralp CMG-40T (0.033–50 Hz) was installed at the Nonaka Onsen spa (hereinafter, MEA), which is about 2.0 km west-northwest of the Akanuma crater. The sensor outputs were digitized by a Hakusan LT8500 data converter (22-bit precision) oper-

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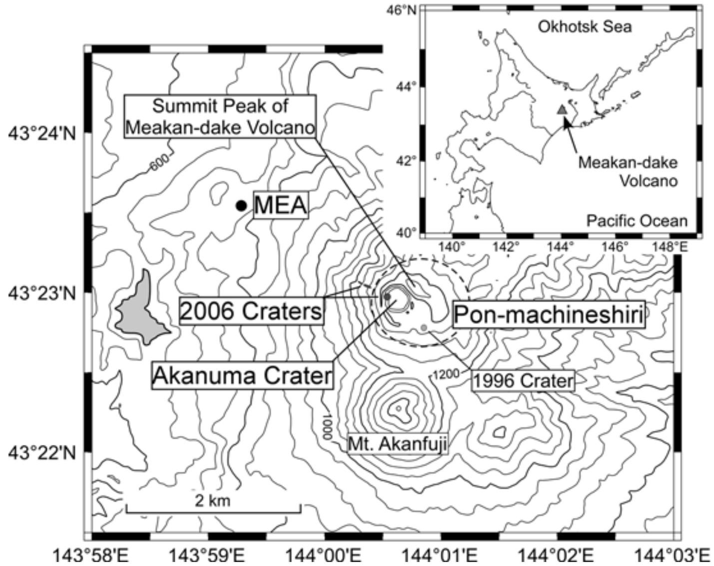

Figure 1. Contour map of Meakan-dake volcano showing location of seismic station (black circle). Contours represent 50-m elevation intervals. Dark and light gray spots are crater areas made by the 2006 and 1996 explosions, respectively. Inset shows location of Meakan-dake volcano.

ating in continuous mode at 200 samples s^{-1}, and were then transmitted to ISV thorough a telephone line.

3. Tremor Overlapped With VLP Signal and Earthquake

[8] The first swarm comprised small earthquakes and two volcanic tremors. The volcanic tremors occurred at around 0552, 19 February, and at 0550, 20 February. The largest earthquake during this swarm overlapped with the first tremor, and soon after the first tremor, the number of earthquakes began to decrease.

[9] We discovered an anomalous VLP signal in the seismic trace of the first tremor observed at MEA. Since the velocity amplitude of the earthquake was about 4 times larger than that of the tremor, this earthquake is remarkable in the original data (Figure 3a). On the other hand, the displacement waveforms obtained by time integration obviously show different features (Figure 3b): a large step appears in both horizontal components; moreover, the offset in the east-west component is about twice as large as that in the north-south component. This VLP signal continues for about 60 s, and the remarkable offset remains in the displacement waveforms. Since the pass-band frequency of the CMG-40T at MEA is restricted to above 0.033 Hz, this long-period offset does not reflect the actual displacement.

4. Estimation of Tilt Change From Seismogram

[10] When a seismometer leans slowly, it is expected that a VLP signal is recorded in its horizontal components due to the effects of gravitational acceleration. *Rodgers* [1968] analyzed the pendulum response of a traditional inertial seismometer to a tilt change and obtained the relation between the displacement response and tilt response as a function of the angular frequency of the input signal. Recently, *Graizer* [2006] described the complete equation of motion for pendulums and summarized the results of shaking tests on accelerographs. These reports suggest that the VLP signal observed by the CMG-40T seismometer in the present study is quite likely to be the pendulum response to a tilt change.

[11] The gravitational force experienced due to a tilt change acts as additional acceleration on pendulums [*Graizer*, 2006]. When the tilt change is small, the additional acceleration can be approximated by $g\psi$, where g is the gravitational acceleration and ψ is the tilt angle. Therefore we can expect the following relationship to hold between the tilt step response function $C_T(\omega)$ and the velocity impulse response function $C_v(\omega)$ for the CMG-40T:

$$C_T(\omega) = \frac{g\psi}{-\omega^2} C_v(\omega), \qquad (1)$$

where ω is the angular frequency of the input signal. $C_v(\omega)$ can be calculated using the distribution of poles and zeros, p_i, z_i (i = 1 $\sim$ 3), for the CMG-40T as,

$$C_v(\omega) = -0.314 \frac{(i\omega - z_1)(i\omega - z_2)(i\omega - z_3)}{(i\omega - p_1)(i\omega - p_2)(i\omega - p_3)}. \qquad (2)$$

With this relation, we can calculate the theoretical amplitude of the response to a tilt step change of 1 μrad, $|C_T(\omega)|$, as shown in Figure 4a. As shown, a constant amplitude response is expected in the frequency range below 0.033 Hz, which is the natural frequency of the CMG-40T. The lower frequency limit in equation (2) gives us a theoretical value of 0.223 mm/μrad (= 4.48 μrad/mm). This amplitude can be used as a transfer factor between the apparent displacement due to tilting and the angle of tilt change. Equation (1) has the same implication at that of equation (41) from *Rodgers* [1968].

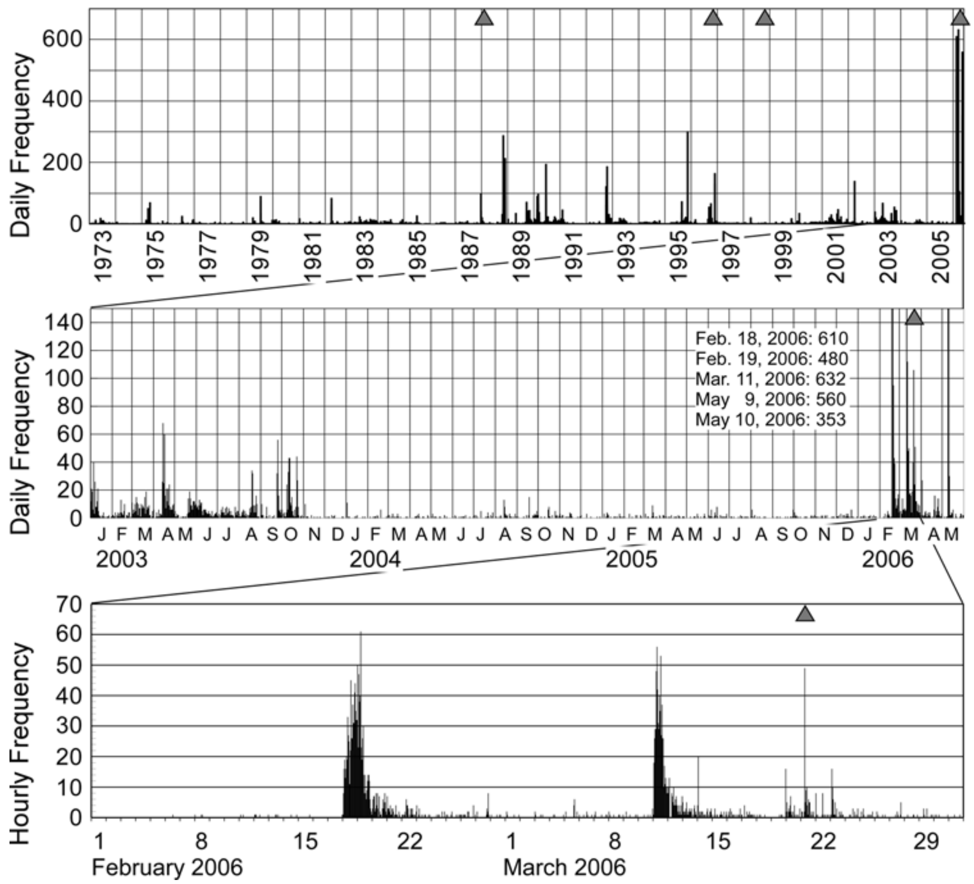

Figure 2. Bar graphs indicating number of earthquakes counted by JMA Sapporo: (top) daily frequency since 1973; (middle) daily frequency since 2003; (bottom) hourly frequency during February–March 2006. Triangles indicate occurrence of explosions.

[12] Thus, to confirm the actual tilt response of the CMG-40T as expressed in equation (1) and the transfer factor, we performed a simple test on the tilt response of the seismometer [*Aoyama*, 2008]. A seismometer and tiltmeter are set up together on the same thick metal plate, which is placed on a thin spacer. With this setup, when the spacer under the edge of the plate is pulled out, an instantaneous tilt change occurs for the metal plate, with negligible associated translational motion; thus this test affords the tilt step response of the instruments. For this test, we used a Model 701-2 biaxial tiltmeter (Applied Geomechanics Inc.) to monitor the absolute value of the applied tilt change.

[13] Example waveforms obtained from the CMG-40T and tiltmeter in this test are shown in Figure 4b. Figure 4b confirms that the test actually generated a step change in the tilt angle. The resultant velocity amplitude spectra of the horizontal component seismograms are shown in Figure 4a. Except for the noisy frequency range above 1 Hz, the experimental spectra and theoretical response are quite similar. In the frequency band below 0.003 Hz, the amplitude is independent of the frequency, while above this value, it is proportional to ω^{-2}. The transfer factor experimentally determined from the measured tilt angle and apparent displacement is 4.01 μrad/mm for this example. We repeated this test eight times using different step amplitudes for the tilt change and obtained an average transfer factor of 4.3 μrad/mm with standard deviation of 0.25 μrad/mm, which corresponds well to the theoretically expected value of 4.48 μrad/mm. This result confirms that the angle of tilt change can be estimated from the seismogram by a CMG-40T insofar as the inclination of the seismometer is small.

[14] In Figure 3b, the apparent amplitudes of displacement offset, dN and dE, are about 0.08 mm and -0.19 mm, respectively, and therefore the amplitude ratio between the north-south and east-west components is $dN/dE \sim -0.42$. This means that the downward dipping vector is approximately toward east-southeast (Figure 3c). The summit crater is located about 2.0 km east-southeast of MEA. The offset in the displacement seismogram can be regard as subsidence around the summit area during the first tremor. By using the theoretical transfer factor of 4.48 μrad/mm, the final tilt change is calculated to be 0.94 μrad from the apparent amplitude (0.21 mm) of the displacement offset.

5. Discussion

[15] What occurred beneath the volcano before the explosion is intriguing problem, both in terms of volcano research and explosion forecasting. Although the data we now have are very limited in the number of components

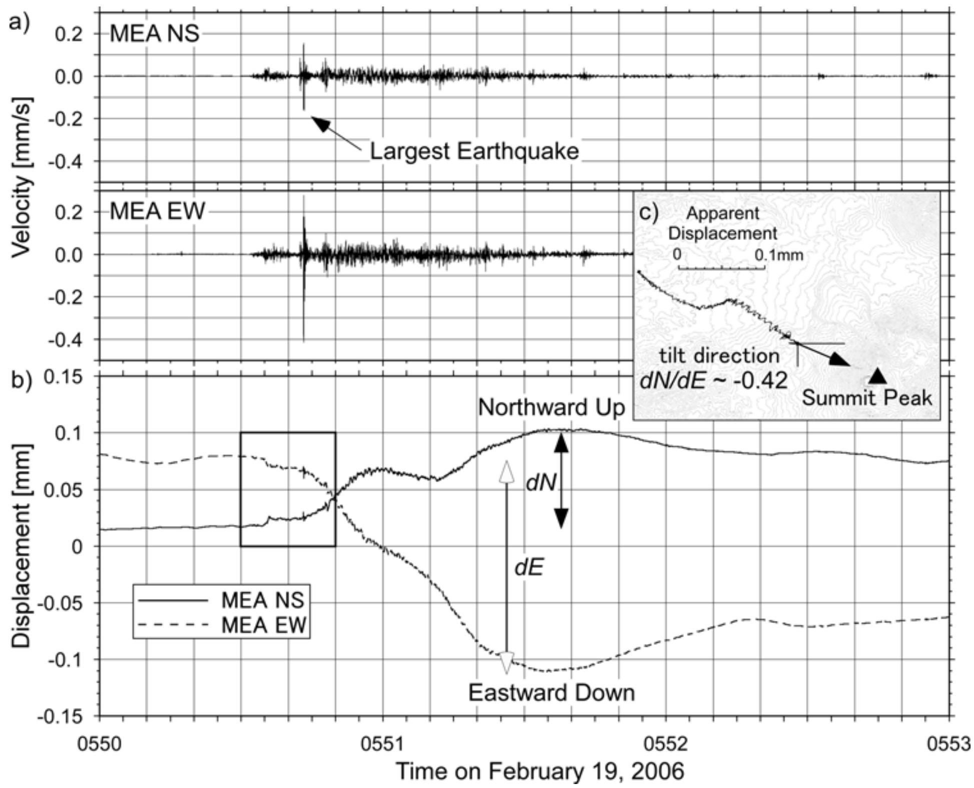

Figure 3. (a) Horizontal ground velocity at MEA. (b) Displacement traces obtained by simple integration. (c) Maximum downward tilt direction estimated from displacement traces.

measured at one station, the seismic data does suggest subsidence of the volcano during the volcanic tremor.

[16] Volcanic uplift and subsidence are often explained by volumetric changes in a chamber under the volcano. One of the simplest and the most conventional models for determining the volume change associated with volcanic activity is the Mogi model [*Mogi*, 1958; *Yamashina*, 1986].

[17] The expected tilt change γ due to volume change in the ground is given by,

$$\gamma = -\frac{9}{4}\frac{Dr}{\pi(D^2 + r^2)^{2.5}}\Delta V, \tag{3}$$

where ΔV is the volumetric change at the source; D, the source depth relative to the station; and r, the horizontal distance between the source and station. According to the hypocenter relocation analysis performed by Sapporo District Meteorological Observatory, Japan Meteorological Agency (JMA Sapporo), the source area of the first swarm is located under the western perimeter of the Akanuma crater at a depth around 800 m below sea level (J. Funasaki et al., unpublished data, 2006). Here we assume D to be 1500 m and r to be 2000 m and let γ be 0.94 μrad; then, the volume decrease required to cause the subsidence of the volcano during the tremor is estimated to be about $4.3 \times 10^4 m^3$.

[18] However, when such deflation occurs, both tilt change and translational motion are caused. The expected radial displacement u_r due to a Mogi source is given by,

$$u_r = \frac{3}{4}\frac{r}{\pi(D^2 + r^2)^{1.5}}\Delta V. \tag{4}$$

The volume decrease produces a translational motion of -1.3 mm. It is expected that the seismometer also recorded this translational motion.

[19] Here we simulate the combined waveform, considering both translational and rotational motion. The assumed time function for the volume change at the source is shown in Figure 5a. Then, the tilt change and radial displacement can be expressed as shown in Figures 5b and 5e, respectively. For rotational motion, the apparent displacement due to tilt change with the CMG-40T tilt response is shown in Figure 5c; its time derivative yields the apparent velocity trace shown in Figure 5d. For translational motion, Figure 5f shows the radial ground velocity, and Figure 5g shows the velocity output from the CMG-40T. The combined velocity waveform (Figure 5h) can be obtained by summing Figures 5d and 5g; integrating this combined waveform yields the simulated displacement waveform shown in Figure 5i. When only rotational motion is considered, the simulated waveform (Figure 5c) explains well the general features of the observed trace (Figure 3b). On the other hand, the combined displacement trace in Figure 5i has incompatible phases when compared with Figure 3b. However, a more complicated source model such as crack deflation or volume change of dual sources may be able to better explain this phenomenon.

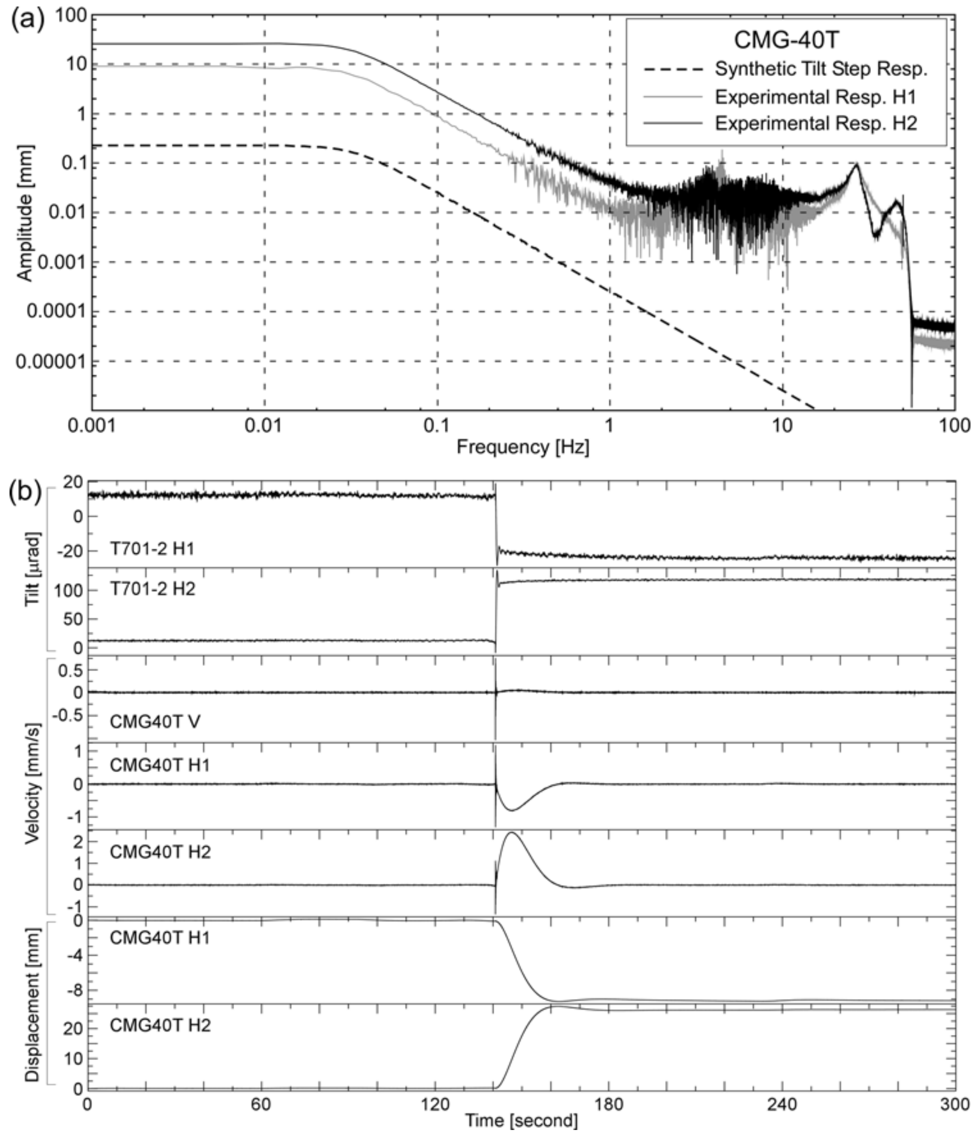

Figure 4. (a) Amplitude response curve of CMG-40T. Broken line is tilt step response to 1 μrad. Solid lines express velocity amplitude spectra calculated from tilt step experiment data. (b) Waveform examples from the tilt test: (top) outputs of the biaxial tiltmeter; (middle) velocity outputs of CMG-40T; (bottom) displacements of the horizontal components calculated from the velocity traces.

[20] Finally, to interpret what went on under the volcano during the tremor, we return to the original displacement waveform of the CMG-40T. Just after the beginning of the tremor, a small step about 0.01 mm can be seen in both horizontal components. Since the duration of this step is on the order of a few seconds, it may correspond to the translational displacement at MEA. However, despite the low-cut frequency response of the CMG-40T, a DC component remains in the displacement trace after the small step. This suggests that the tilt change began right after the small step. Then about 10 s later, the largest earthquake occurred, and soon after, the VLP signal appeared. These processes suggest the following chain of events: an initial rapid pressure disturbance in a fluid chamber induced the large earthquake close to the chamber, and then the large volumetric change began. Phase change of the volcanic fluid and fluid migration may be candidates for the volumetric change estimated here.

6. Summary

[21] A small phreatic explosion occurred at the Meakandake volcano on 21 March 2006, accompanied precursory earthquake swarms. We discovered an anomalous VLP signal in a seismogram obtained at the foot of the volcano during a tremor in the first swarm, which occurred about one month before the explosion. The VLP signal could be interpreted as a tilt change due to the subsidence of the volcano. The offset in the displacement trace could be explained by an isotropic chamber deflation of about 4.3×10^4 m^3. Then, we simulated the seismogram of the CMG-40T, considering both rotational and translational motions. However, the inconsistency between the simulated

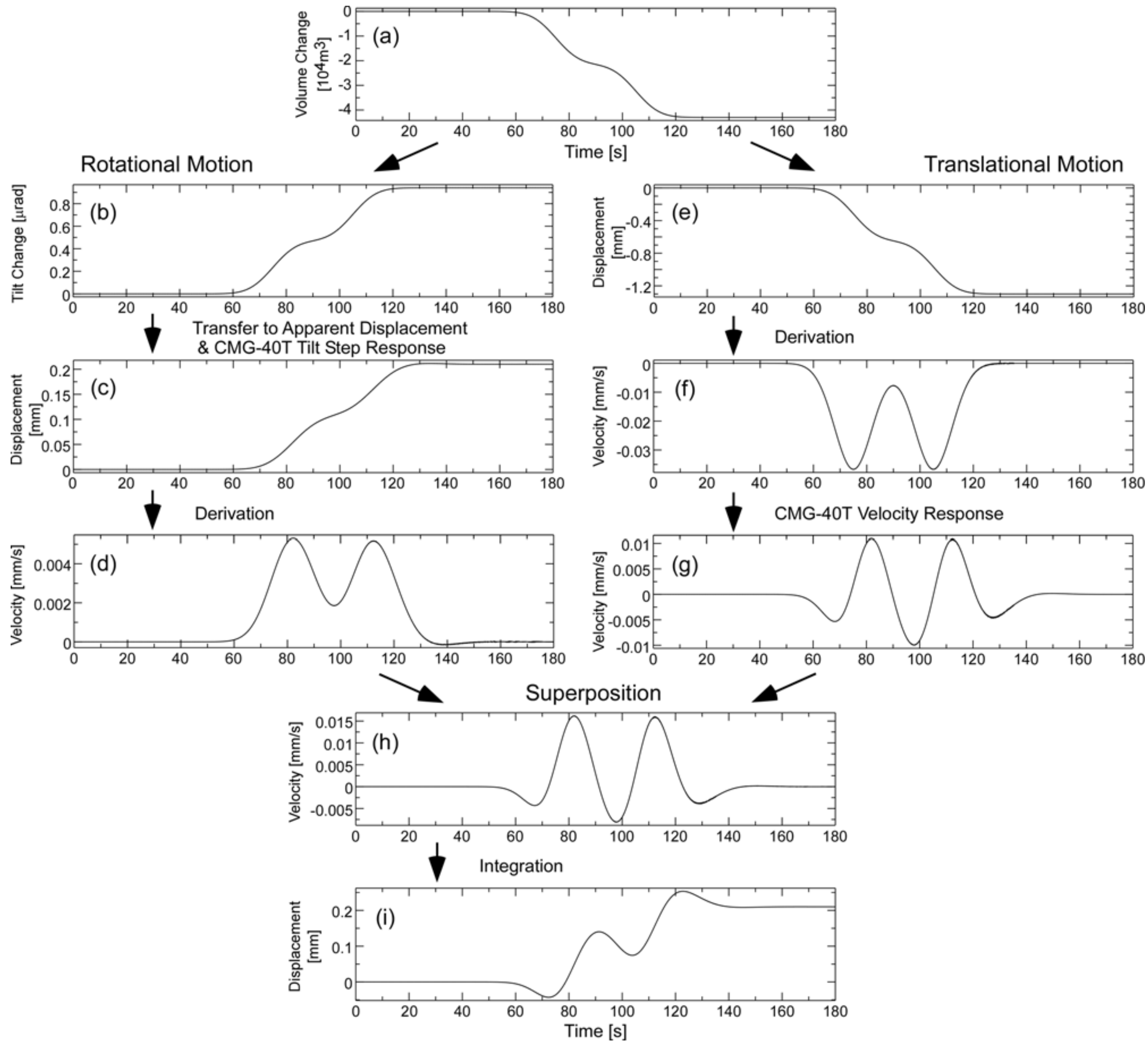

Figure 5. Simulation procedure for synthetic seismogram: (a) assumed volume change of the source; (b) tilt change at the station; (c) apparent displacement due to tilt change considering tilt response of CMG-40T; (d) apparent velocity waveform; (e) translational displacement; (f) translational velocity; (g) velocity waveform considering velocity response of CMG-40T; (h) superposed velocity waveform; (i) simulated displacement seismogram.

and observed waveforms suggests that a more complicated source model should be considered.

[22] It should be emphasized that the seismic data before the small phreatic explosion suggests the existence of precursory activity of volcanic fluid. Broadband seismic observation is very useful not only for studies on source processes but also for precise monitoring of volcanic activity. However, the data presented herein warns of the possibility of contamination due to tilt change, especially for long-period signals.

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