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High-frequency earthquake swarm associated with the May 1991 dome extrusion at Unzen Volcano, Japan

Kodo Umakoshi [a,*], Naoko Itasaka [b], Hiroshi Shimizu [c]

[a] Faculty of Environmental Studies, Nagasaki University, 1-14 Bunkyo-machi, Nagasaki 852-8521, Japan
[b] Graduate School of Science and Technology, Nagasaki University 1-14 Bunkyo-machi, Nagasaki 852-8521, Japan
[c] Institute of Seismology and Volcanology, Faculty of Sciences, Kyushu University, 2-5643-29 Shin-yama, Shimabara, Nagasaki 855-0843, Japan

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ABSTRACT

The 1990–1995 eruption of Unzen Volcano in southwestern Japan was characterized by the extrusion of a dacite lava dome and frequent pyroclastic flows during the dome growth. Associated with the dome emergence on May 20, 1991, an intense swarm of high-frequency (HF) microearthquakes occurred just beneath the crater at very shallow depths. We used data from FG3, a seismic station located 500 m SSW of the crater, to identify 29,401 HF earthquakes between May 11 and 31, 1991. The rate of HF earthquakes increased starting on May 12 and peaked on May 17. The high seismicity continued until May 26, then dropped sharply, coinciding with a marked decline in the swelling on the southern upper flank of the volcano. The seismicity increased and decreased repeatedly within a 1- to 2-h period, which was correlated with tilt cycles observed 680 m west of the crater in such a way that the seismicity increased during uplifting on the craterward side. Defining an earthquake group as a series of earthquakes with waveforms that are similar or vary only slightly over time, we identified 10 such groups, each containing more than 300 events. The largest group comprised 3,214 events over 18 days. Seismicity rates of eight groups, including the largest, increased and decreased repeatedly, correlated with the tilt cycles. As the waveform data from station FG3 were considerably clipped for relatively large events, we analyzed data from two additional stations, KRA and CJA, located 3.5 and 8.7 km from the crater, respectively, and identified a total of five new groups. The activity of two groups recorded at KRA was correlated with the tilt cycles, but those of three groups recorded at CJA did not always show such a correlation. Hypocenters for the groups recorded at KRA were distributed to the east side of the conduit and a focal mechanism suggested that the events in this area occurred due to compressional stress produced by the inflation of the conduit. The groups recorded at CJA occurred to the north side of the dike trending westward from the conduit. The focal mechanisms have P-axes roughly trending to the dike, which can be explained by the compressional stress generated by the increasing thickness of the dike.

1. Introduction

Unzen Volcano is located in the central part of the Shimabara Peninsula in southwestern Japan. The most recent eruption took place from 1990 to 1995 at Mt. Fugen (Fugendake), the main peak of Unzen Volcano. The volume of extruded lava during this eruption is estimated to be about 2×10^8 m^3 (Nagaoka et al., 1996), much larger than that extruded during the two previous eruptions (5×10^6 m^3 in 1663 and 2×10^7 m^3 in 1792) (Ohta, 1993). The 1990–1995 eruption extruded dacite lava from Jigokuato Crater, one of the summit craters and formed a lava dome, whereas the two previous eruptions ejected lava from the northern upper flank of Mt. Fugen and generated lava flows. Eruptions that form lava domes within the Myoken Caldera, where Mt. Fugen is located, occur every 4000 to 5000 years, including the 1990–1995 eruption (Nakada et al., 1999).

The lava dome associated with the 1990–1995 eruption emerged on May 20, 1991, about 6 months after the first phreatic eruption on November 17, 1990. As various observations had been made since the first eruption (e.g., Geophysical Party, Joint University Research Group, 1992), some marked changes in the data were detected for about 2 weeks around the beginning of the dome extrusion. On May 12, high-frequency (HF) microearthquakes began to occur at very shallow depths just beneath the crater, and the seismicity continued to intensify. On May 13, inflation of the southern upper flank of Mt. Fugen was detected by electron-optical distance measurements (EDM) (Saito et al., 1993). In addition, remarkable changes were observed in the total geomagnetic field near the crater (Tanaka et al., 1994) and in ground tilt 680 m west of the crater (Yamashina and Shimizu, 1999). Furthermore, many WNW–ESE cracks were developed on the surface near the crater. Using

* Corresponding author. Tel./fax: +81 95 819 2766.
E-mail address: umakoshi@nagasaki-u.ac.jp (K. Umakoshi).

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photogrammetric analysis, Yasuda et al. (1993) revealed that a WNW-ESE trending graben about 250 m width and 300 m long had formed in this area.

Several studies of one of these phenomena, the HF earthquake swarm, have been conducted. Sudo et al. (1992) installed a seismic station 2 km SSW from the crater and detected a group of earthquakes with similar waveforms. This activity continued from May 14 until the end of May, with the waveforms progressively varying slowly over time. A similar study was carried out by Umakoshi et al. (2008), who used cross-correlation analysis to examine waveforms recorded at station FG3 (Fig. 1) and detected many earthquake groups within the swarm. Shimizu et al. (1997) determined hypocenters for relatively large events via the master event method using data from six seismic stations FG1, FG2, FG3, TKE, FKE, and KRA (Fig. 1). They demonstrated that in May 1991, the hypocenters were concentrated in two areas beneath the crater at depths ranging from 600 to 1000 m above sea level (Fig. 2).

Despite this research, the HF earthquake swarm in May 1991 has not yet been fully studied. For example, the temporal variation of the seismicity rate has not been investigated in detail, making it difficult to compare the swarm activity with other data. In addition, the characteristics of the earthquake groups detected by Umakoshi et al. (2008) have yet to be investigated. In this paper, we reveal the characteristics of this swarm, analyze earthquake groups, and discuss the relationship between the swarm activity and ground deformation data (Yamashina and Shimizu, 1999) to infer the process generating the swarm associated with the lava dome extrusion at Unzen Volcano in May 1991.

2. Data

Fig. 1 shows the locations of seismograph stations in the central part of the Shimabara Peninsula that were installed by the Shimabara Earthquake and Volcano Observatory (SEVO) (now known as the Institute of Seismology and Volcanology) of Kyushu University. Signals were telemetered to SEVO and were recorded continuously on digital audiotapes with a sampling rate of 100 Hz (Shimizu et al., 1992). We used waveform data from FG3, a seismic station located 500 m SSW of the crater. We also used data from stations KRA and CJA, located 3.5 and 8.7 km from the crater, respectively, to analyze relatively large events, for which waveforms recorded at FG3 were considerably clipped. Each station had a 1-Hz vertical-component seismometer.

In this study, we analyzed seismic data for the period between May 11 and 31, 1991. Although Umakoshi et al. (2008) have created a data set of P-wave arrival times at FG3, we improved the data by checking continuous seismograms visually and obtained a revised data set consisting of 32,914 events with maximum amplitudes $\geq 1.0\times10^{-5}$ m/s. Of these, we classified 29,401 events as HF earthquakes, defined as those with waveforms that have abundant spectral components higher than 5 Hz. The remaining 3513 events were classified as low-frequency (LF) earthquakes. This classification was generated automatically by spectral analysis using fast Fourier transforms (FFT) with a window length of 2.56 s starting 0.25 s before the onset.

P-wave arrival time data for KRA and CJA were created by selecting events with maximum amplitudes $\geq 3\times10^{-6}$ m/s for each station on the basis of the P-wave arrival time data at FG3. There are 2044 and 182 selected events for KRA and CJA, respectively. No waveform data were recorded at KRA from 11:52 to 17:50 on May 16. We determined magnitudes for the 182 events selected at CJA using the formula given by Watanabe (1971). In the calculation, we used maximum amplitudes of the vertical component recorded at seismic stations in and around the Shimabara Peninsula. Magnitudes determined by this method have been shown to be roughly consistent with those determined by the Japan Meteorological Agency (JMA) (Umakoshi et al., 2001).

3. Seismicity

Table 1 shows the daily number of HF and LF earthquakes and pyroclastic flows. Pyroclastic flow data were obtained from the Fukuoka District Meteorological Observatory (1996). During the study period, HF seismicity rates were much higher than LF seismicity rates. Fig. 3(a) shows the number of HF earthquakes in 6-h intervals from May 11 to 31, 1991. The black and gray bars indicate the number of events with maximum amplitudes $\geq 3\times10^{-5}$ m/s and between 1×10^{-5} and 3×10^{-5} m/s, respectively. Small closed circles above the bars indicate periods when the seismograms were disturbed by debris flows due to heavy rainfall and the observed seismicity rates were consequently reduced. After May 24, pyroclastic flow signals prevented identification of earthquakes for 1 to 3 h per day. Earthquake counts increased beginning during the 00:00 to 06:00 interval on May 12 and peaked in the 18:00 to 24:00 interval on May 17, about 2 days before the dome emergence. The high seismicity was steady until the counts dropped suddenly after the 12:00 to 18:00 interval on May 26. Although debris flows occurred on May 26 and pyroclastic flows increased markedly on

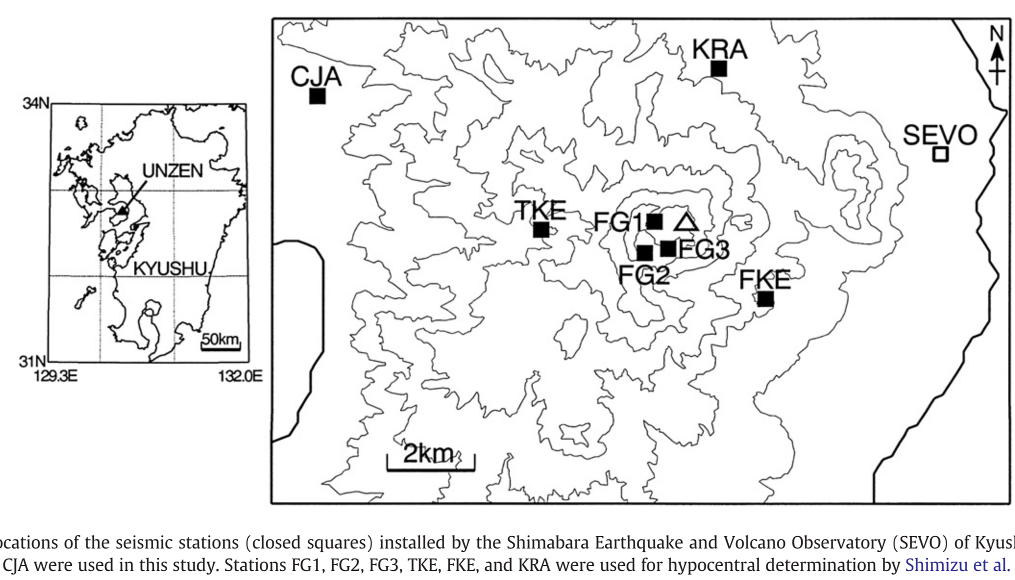

Fig. 1. Map showing locations of the seismic stations (closed squares) installed by the Shimabara Earthquake and Volcano Observatory (SEVO) of Kyushu University. Data from stations FG3, KRA, and CJA were used in this study. Stations FG1, FG2, FG3, TKE, FKE, and KRA were used for hypocentral determination by Shimizu et al. (1997). The open square denotes the location of SEVO. The open triangle indicates the location of Jigokuato Crater, where the lava dome emerged on May 20, 1991. The contour interval is 200 m.