# Recent 20 Years Activity at Satsuma-Iwojima Volcano Revealed by Seismic and Ground Deformation Observations

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## Introduction

Satsuma-Iwojima is an island volcano located on the northwestern rim of Kikai caldera, where a catastrophic eruption occurred 6,300 years ago. Submarine eruption began in September 1934 and a new islet, Showa-Iwojima was formed by lava extrusion from the sea bottom. In recent 1000 years, fumarolic activity has continued at the summit crater of Mt. Iwodake, located eastern part of the island and volcanic ash has been frequently emitted from the crater.

Volcano observation has been repeated at the volcano. Kamo(1976; 1977; 1978) conducted seismic observation installing a tripartite network at the northwestern flank and determined hypocenter location of volcanic earthquake at depth of 1km around Mt. Iwodake. Geological Survey of Japan has repeated observation of topographic changes of the summit crater, analysis of volcanic gas and temperature measurement of fumarolic gas (Geological Survey of Japan, 1997). Ohminato and Ereditato (1997) found long-period seismic pulse, which occur during the dormant period of volcanic tremor activity and inferred the long-period waves are related with magma convection in the volcanic conduit.

Continuous observation of volcanic earthquakes was conducted experimentally by Sakurajima Volcanological Observatory (SVO), Disaster Prevention Research Institute of Kyoto University by installing a 3-component seismometer and dial-up telemetering system with PC in 1988 (Iguchi, 1991), and the continuous observation was resumed in 1995 after 5 years-suspension of the observation at the station IWO at the NW flank of Mt. Iwodake. Most of the earthquakes observed at Satsuma-Iwojima volcano are unfelt micro-earthquakes around the Mt.Iwodake (Kamo, 1976;1977), however, an earthquake, which occurred on June 8, 1996, was felt one with M2.9. After occurrence of the earthquake, topographic change at the summit crater was found and ground deformation around the summit were detected by GPS measurement.

In this paper, we summarize and evaluate the activity of Satsuma-Iwojima volcano for recent four years from 1995 to 1998 comparing with seismicity in 1975-1977, and discuss significance of the felt earthquakes on June 8, 1996 by using seismic and ground deformation data at the volcano.

## Characteristics of volcanic earthquakes

The observed waveforms at Satsuma-Iwojima are classified into 4 types; A-type, B-type, C-type and volcanic tremor (Iguchi et al., 1999). A-type earthquake is high-frequency event with clear P and S-waves. B-type earthquakes are dominated by lower frequency seismic waves. C-type is a monochromatic

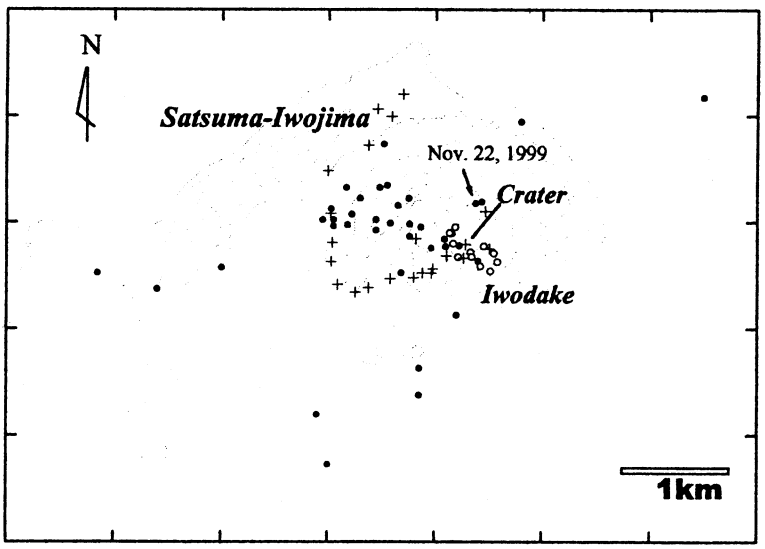


Figure 1. Epicenter distribution of A-type and B-type earthquakes. Solid and open circles represent A-type and B-type earthquakes, respectively. Epicenter distribution is compiled from this study, Kamo (1976; 1977) and Iguchi et al. (1999). The epicenter of earthquake at 01:01 on November 22, 1999 is indicated by arrow.

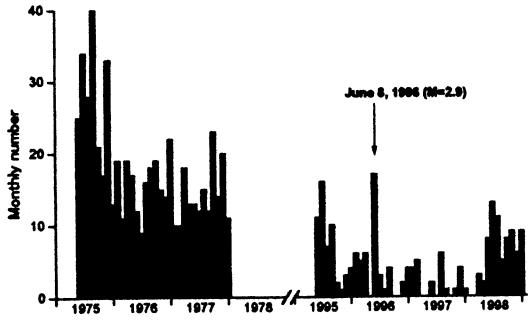


Figure 2. Monthly number of volcanic earthquakes at the station IWO. The earthquakes with maximum amplitude of >16μm/s are counted. The numbers during the period from 1975 to 1978 are corrected, taking into account of attenuation of seismic waveform due to geometric spreading.

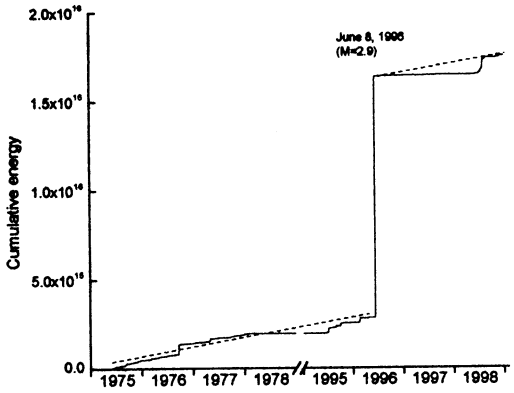


Figure 3. Cumulative of seismic energy released by the A-type earthquakes originating at Satsuma-Iwojima during the periods in 1975-1978 and 1995-1998. Dashed lines denote seismic energy release rate of $7\times10^{14}$ erg/year.

event with peak frequency of 6.5 Hz. C-type events have two patterns of envelope of waveforms; spindle-shape and long coda part similar to T-type at Asama volcano (Hamada et al., 1975).

Epicenters of A-type and B-type earthquakes are shown in Figure 1. The distributions of epicenters of earthquakes obtained by Kamo (1976; 1977) and Iguchi et al. (1999) are added to Figure 1. Hypocenters of A-type earthquakes were distributed around volcanoes, especially northwestern flank of Mt.Iwodake at depth of 1km. In contrast, the epicenters of B-type earthquakes were concentrated in the summit crater of Mt.Iwodake. Focal depths of the B-type earthquakes were determined in the range from 0 to 4 km. Scattered range of focal depth is due to emergent onset of B-type earthquakes. Particle motion diagram based on the velocity waveforms of 3-compoent shows that P-wave first motion moved nearly horizontally (Iguchi et al., 1999). This fact suggests the source of B-type earthquakes is located very shallow depth, maybe, above sea level.

Focal mechanism of A-type earthquakes is determined from the push-pull pattern of the P-wave first motion. Push-pull pattern of the P-wave first motion is a quadrantal type, as usual tectonic earthquake. In contrast, B-type earthquake has a different focal mechanism. The first motions of B-type earthquake were observed as "push" at all the stations. The distribution pattern of the first motion suggests volume expansion at the source. Moment tensor inversion (Kikuchi and Kanamori, 1991) for P-wave first motion shows that dominance of three diagonal components of moment tensor, and it is thought that B-type earthquake is initiated by volumetric expansion of the source (Iguchi et al., 1999).

**Comparison of seismic activity in 1995-1998 with that in 1976-1978**

We count number of volcanic earthquakes with maximum amplitude of larger than 16μm/s at the station IWO. The larger earthquakes were categorized into A-type. After June 1995, 10-20 volcanic earthquakes occurred every month (Figure 2). The seismicity in 1995-1998 is compared with that during the period from June 1975 to January 1978. Volcanic earthquakes with maximum amplitude of >10μm/s and S-P time interval of < 2s were counted in 1975-1978, and the earthquakes were also classified into A-type (Kamo, 1976; 1977; 1978). Although the monthly number of volcanic earthquakes sometimes reached more than 80, 10-30 volcanic earthquakes were observed in a month for most of the observation periods. The seismic station used for count of number of volcanic earthquakes in 1975-1978 was more closed to the summit of Mt.Iwodake than station IWO. Here, we try to recount number by correcting the amplitude of volcanic earthquakes, considering attenuation of seismic waves due to geometric spreading. Monthly numbers of A-type earthquakes during the period from 1975 to 1978 and from 1995 to 1998 are shown in Figure 2. Monthly numbers of A-type earthquakes were 20-40 in 1975 and 10-20 in 1976 and 1977. After June 1995, 10-20 volcanic A-type earthquakes also occurred in a month. The seismicity during 1995-1998 did not change from that 20 years before.

To estimate seismicity more quantitatively, seismic energy released by the A-type earthquake was calculated. The stations equipped with seismometers of the same frequency response are located at west-northwestern flank of Satsuma-Iwojima, and the relation of duration ($T$) of earthquake and magnitude ($M$) is obtained empirically as follows;

$$M = 4.25\log_{10}T - 0.4.$$

The seismic energy released by the earthquakes was calculated by Gutenberg-Richter formulae. The magnitude and seismic energy release estimated for the earthquakes in the periods of 1975-1978 and 1995-1998 are shown in Figure 3. Magnitudes of the earthquakes

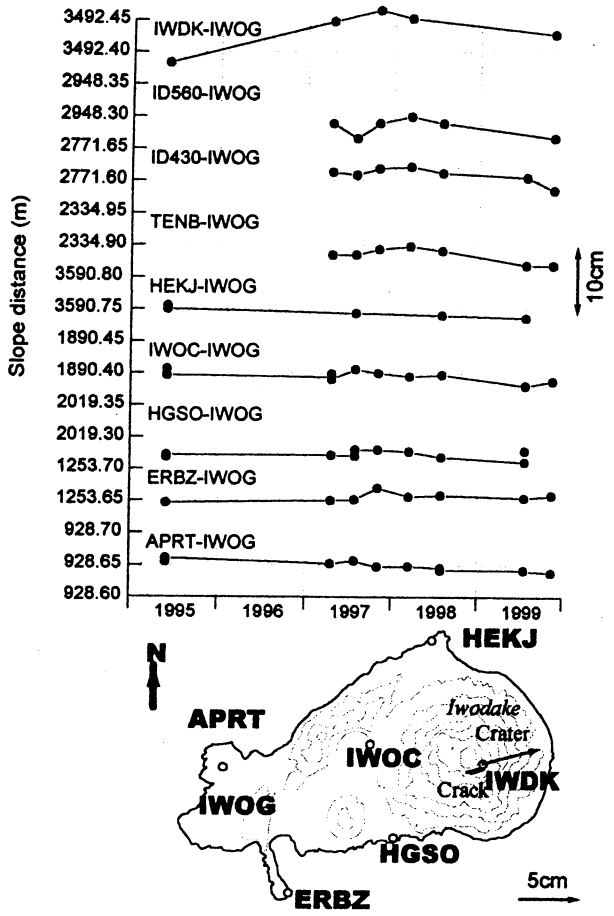


Figure 4. Changes in slope distances measured by GPS (top). Displacement vector at IWDK site during the period from June 1995 to April 1997 is shown at the bottom.

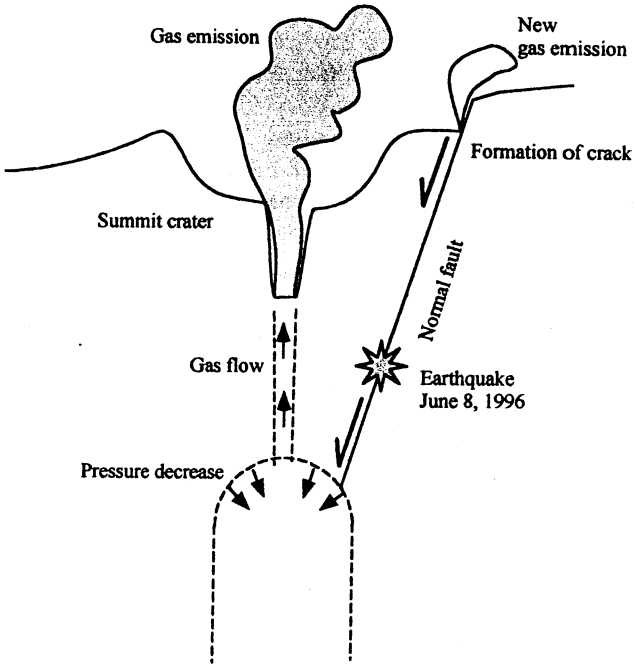


Figure 5. A probable model for occurrence of earthquake on June 8, 1996 and formation of crack. The crack was found at southeastern rim of the summit crater in October 1996, after the earthquake occurred. The pressure beneath the crater decreased by emission of volcanic gas. The ground in the crater subsided due to the pressure decrease, generating the normal fault earthquake. Volcanic gas was newly emitted through the fault and crack.

were less than 2, except the earthquakes on June 8, 1996. Most of the earthquakes have magnitude of <1. Seismic energy release rates were nearly $7\times10^{14}$ erg/year in both of the periods of 1975-1978 and 1995-1998, except the seismic energy increase by the earthquake on June 8, 1996. It was not reported that felt earthquakes with hypocenter beneath Satsuma-Iwojima volcano occurred during the gap of observation during the period from February 1978 to May 1995. Nearly constant seismicity has continued for at least 20 years.

**Felt earthquake on June 8, 1996**

During the period of 1995-1998 with stable seismicity, the felt earthquake occurring at 21:06, on June 8, 1996 is remarkable event. The seismic intensity of the earthquake was 2 at a village 3km apart from Mt.Iwodake in Satsuma-Iwojima Island and M2.9 is larger than the other A-type earthquakes (Figure 3). Hypocenter location was estimated to be around Satsuma-Iwojima Island by using P and S arrival times at stations of larger seismic network in southern part of Kyushu assuming a standard velocity structure model (Nishi and Iguchi, 1983). S-P time interval of 0.5 s of the earthquake at the station IWO is the same as those of the earthquakes, which were located beneath Mt.Iwodake, and the particle motion of the first motion showed seismic waves propagated from east. These facts show that the event occurred around Mt.Iwodake. Focal mechanism of the event was judged as normal fault type, which is dominant at Satsuma-Iwojima volcano.

It is inferred that the earthquake on June 8, 1996 was related with topographic change and deformation around the summit crater of Mt.Iwodake. GSJ has repeated observation of topographic change in and around the summit crater and change in fumarolic activity (Geological Survey of Japan, 1997). In 1990, fumaroles with high temperature were distributed at the slope near the rim of the summit crater. Fumaroles near the bottom of the crater have become active since 1994 and the activity around the slope of rim declined, and a new pit crater ejecting jet sound was found. In October 1996, a new crack with the length of 100 m was found at the southeastern rim.

Changes in slope distances are shown in Figure 4 for baselines between IWOG stations and several benchmarks at the summit and the flank. The slope distances of benchmarks at the flank from station IWOG have been stable since June 1995, however, slope distance between IWDK and IWOG increased 6 cm in the period from June 1995 and April 1997. The benchmark IWDK is estimates to move to east-northeast by 6 cm, by fixing IWOG stations (Figure 4). IWDK is closed to the crack at southeastern rim of the summit crater, and no remarkable changes were observed after

April 1997. The displacement of the IWDK was caused by formation of the southeastern crack. During the period from 1995 to 1998, the earthquake on June 8, 1996 was the largest one with M2.9. Considering that the earthquake occurred in June 1996, 4 months before finding of new crack at southeastern rim in October, it is inferred that the event is related with formation of crack. The ground of the crater-side of the crack was subsided (Geological Survey of Japan, 1997) and the subsiding deformation of the crack is reflected by normal fault type focal mechanism of the event. It is reported the event occurred with sound (per. comm. with Mr. Orita, habitant in the island). It is possible the sound associated with the earthquakes was generated by fracture zone reaching ground surface beside the southeastern rim of the crater. A probable model is shown in Figure 5. Shinohara et al. (2000) interpreted that increase in $SO_2$ flux, highest temperature and equilibrium temperature of gas from the summit crater in mid 1990's were caused by ascent of magma column. Pressure beneath the crater increased by ascent of magma column temporarily, however the pressure maybe decreased after a large amount of volcanic gas was emitted. The normal fault earthquake may be generated by subsidence of the ground of the crater due to pressure decrease beneath the crater bottom, and the fault reached the ground surface. As the result, crack was formed at southeastern rim of the summit crater and volcanic gas was also emitted through the fault, expanding the crack.

Except one earthquake with M2.9, seismicity during the period from 1995 to 1998 was almost stable. The seismicity of the period was not so different from that in 1975-1978. The seismicity at the volcano has been stable for recent more than 20 years. The stable seismicity at Satsuma-Iwojima volcano coincides with stable volcanic activity estimated by analysis volcanic gas and temperature measurement of fumarolic gas (Shinohara et al., 2000).

**Conclusion**

Seismic observation shows almost stable activity at Satsuma Iwojima volcano in recent 20 years. The felt earthquake with M2.9 on June 8, 1996 was generated by minor increase in volcanic activity within the stable activity for more than 20 years. The earthquake occurred due to decrease in pressure beneath the crater and formed a crack at the southeastern rim of the crater.

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