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Earthquake Families Observed at Tarumai Volcano, Hokkaido, Japan, during January and February, 1988

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Abstract

An earthquake swarm mainly composed of 143 low-frequency (LF) earthquakes was observed during January and February, 1988 at Tarumai volcano, Hokkaido, Japan. The swarm consisted of many burstic activities of LF events, and the bursts occurred repeatedly with a strong 24-hour periodicity. The existence of twenty-one sets of "earthquake families" was another characteristics of this swarm. The families were identified by correlation analysis among the digital seismograms. The life time of each family ranges between 4 and 27 days. The peculiar phenomena were that the earthquakes making up each burst were classified into the different families without an exception. Since the source regions of the families are interpreted to be limited within several tens of meters, we conclude that this type of families are originated from the quasi-stable asperities which persist to survive throughout the repeated fault slidings. Similar conceptual model of family generation is also well-documented in the earthquake sequence associated with the cryptodome formation of Usu volcano from 1977 to 1982.

1. Introduction

Tarumai volcano is a truncated strato volcano located at the south-eastern rim of Shikotsu caldera, Hokkaido, Japan. The last large eruption occurred in 1909 when the present lava dome was formed at the summit. Thereafter, the volcanic activity has been characterized by some earthquake swarms, fumarolic activities and minor steam explosions (Umehara et al., 1981 ; Yamashita et al., 1984). The latest ash ejection occurred on February 27, 1981

An intensive earthquake swarm was observed during January and February, 1988 at Tarumai volcano. The swarm was mainly composed of the low-frequency (LF) earthquakes. "Earthquake families", certain earthquake groups characterized by similar waveforms at a given station, were found among the LF events. Recently, earthquake families were commonly observed either during the persistent volcanic earthquake swarms (Mizukoshi and Moriya, 1980 ; Okada et al., 1981 ; Fremont and Malone, 1987 ; Okada et al., 1988), or during the tectonic swarms (Hamaguchi and Hasegawa, 1975 ; Tsujiura, 1985 ; Ito, 1985 ; Motoya and Abe, 1985). Earthquake family is considered to be the most basic unit of the earthquake sequence because the family members have common spatial and dynamical characteristics (ex. Hamaguchi and Hasegawa, 1975).

In this paper, we investigate the time sequence of the 1988 seismic swarm of Tarumai volcano focusing on the activities of the earthquake families. Detailed study both on the waveform similarity and on the time series of the earthquake families give us an opportunity to investigate the generating process of these unusual earthquake sequences of volcanic origin.

2. Data

Since 1967, one seismic station, with three component displacement-type seismometers, has been operated at the northeastern flank of Tarumai volcano by the Japan Meteorological Agency (JMA). In January 1980, another four velocity type vertical seismographs were installed by the Usu Volcano Observatory (UVO), Hokkaido University. Locations of these seismic stations are shown in Fig. 1.

The seismic signals from these five stations are transmitted and centralized to UVO using radio telemetering system and recorded only on monitor pen-recorders. Seismic data of the vertical component from one summit station (WCR) are also telemetered to the Research Center of Earthquake Prediction of Hokkaido University (RCEP) at Sapporo via UVO using telephone lines. Those signals are stored continuously on magnetic tapes together with the signals from the routine regional seismic stations of RCEP in Hokkaido.

In the present study, we used those digital seismograms for the vertical component from one summit station WCR. The digital data were compiled with a sampling frequency of 92.3 Hz. Seismic data from another stations were not available, since they had been recorded only on pen-recorders.

3. Time sequence of the swarm

Figure 2 shows the monthly frequency of volcanic earthquakes detected by JMA since 1967 (after JMA). It reveals a gradual increase in seismicity to the

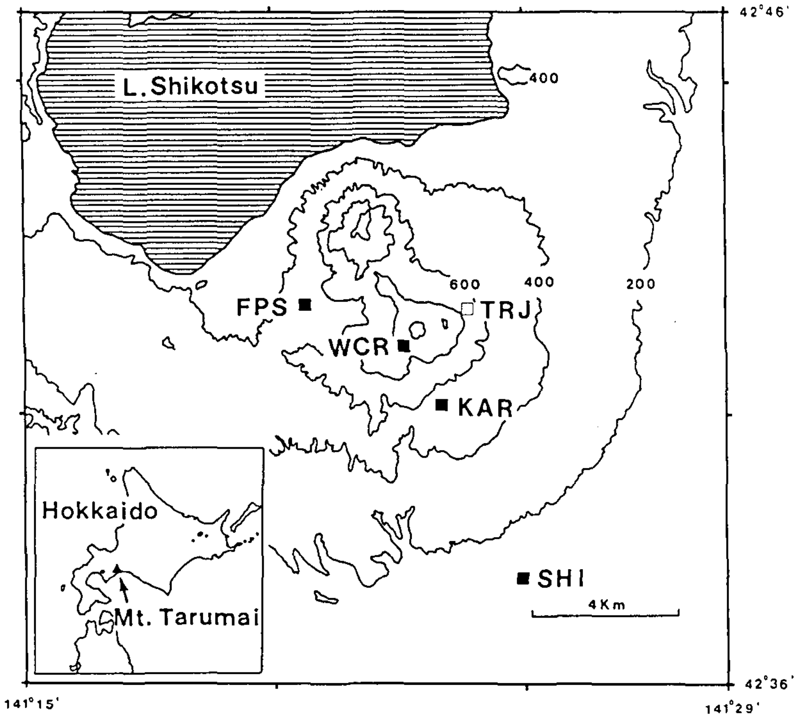

Fig. 1. Map showing Tarumai volcano and permanent seismic stations operated by UVO (solid boxes) and JMA (open box). The seismic data from those both stations are telemetered to UVO.

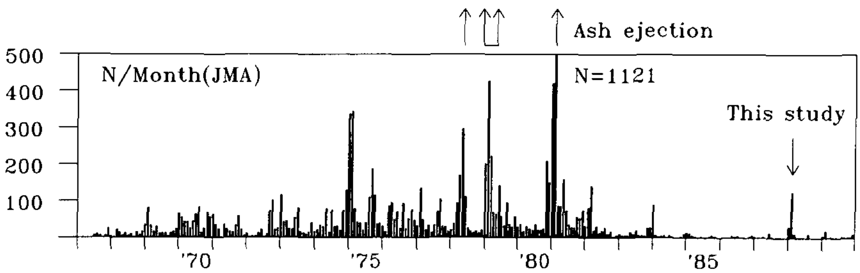

Fig. 2. Monthly frequency of volcanic earthquakes at Tarumai volcano observed by Japan Meteorological Agency (JMA).

notable peak activity during the recent minor eruptive period (1978-1981). Then, however, the seismicity turned to be declining continuously to the end of 1987. The 1988 swarm was occurred when the background seismicity had been in the lowest level since the start of the instrumental observation in 1967. Monthly frequency of earthquakes in January-February, 1988 was nearly the same level comparable to the active period during 1975 and 1981 in spite of its short life.

The 1988 swarm was mainly composed of the low-frequency earthquakes (LF). The dominant frequency was about 3 Hz at the summit seismic station, WCR. Figure 3 shows the amplitude-time diagram (upper) and the hourly frequency (middle) of the LF events. The first LF event occurred at 17 : 38 on January 24, 1988. This was the largest LF event in the series. F-P magnitude, which calculated from the duration time of seismogram at KAR (Umehara et al, 1981), was 1.8. Magnitude of the following LF events of this swarm ranged between 1.0 and 1.5. Those are relatively large LF events that have been observed at Tarumai volcano. The LF swarm continued sporadically to

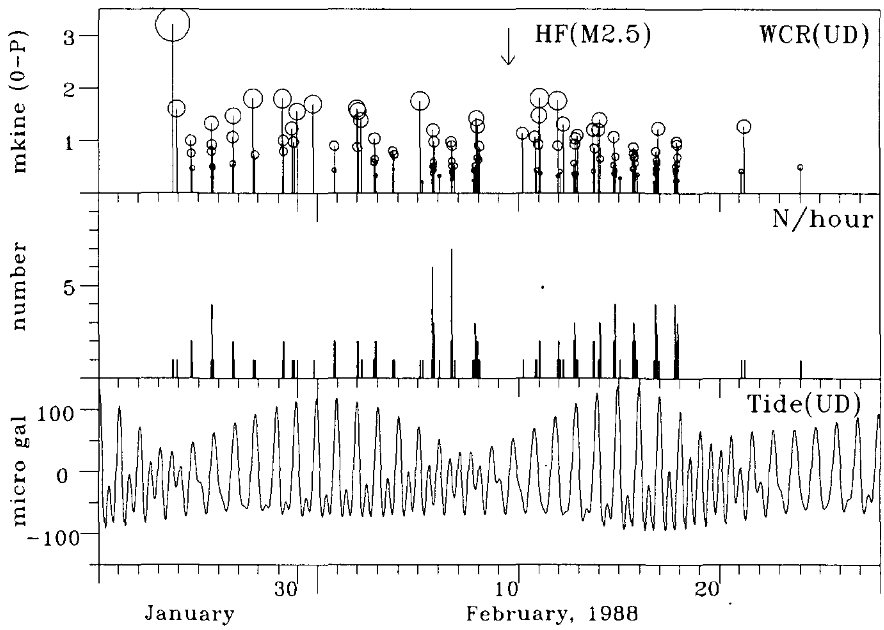

Fig. 3. Amplitude-time diagram for the 1988 low-frequency earthquake swarm (upper), hourly frequency of events (middle) and the vertical component of the tidal accerelation calculated for the summit of Tarumai volcano (bottom). Amplitude is the maximum zero-peak amplitude at WCR (UD component).

February 25, showing no distinct peak of the activity. During this period, the LF events amounted to 143.

Hypocenters of the LF events were inferred to be distributed in the small region at the shallow depth, less than 2 km below the sea level, beneath the summit crater (after UVO). This estimation was based on the careful comparison of the amplitude distributions among the seismic stations. Hypocenters are not determined, since the first arrivals and S-phases are not clear for the LF events.

There also observed five large high-frequency (HF) earthquakes before (18 : 14, January 12), during (11 : 59, February 10) and after (23 : 53, March 20, 04 : 35 and 16 : 28, March 21) the LF swarm. Their magnitude were estimated to be greater than 2. The HF event at 04 : 35 on 21 March was felt at JMA intensity 1 in the mountainside of Tarumai volcano. On the other hand, the earthquake at 16 : 28 on the same day was felt at JMA intensity 2 in the east of lake Shikotsu, 10 km NE of the volcano and was not felt close to the volcano. The epicenter of this event was estimated to be several km north of Tarumai volcano.

The time series of the 1988 swarm was characterized by many burstic activities of earthquakes, in which five to thirteen LF events occurred successively in several hours. The burstic activities clearly showed a strong 24-hour periodicity. There were almost no earthquakes observed between the bursts. This characteristics is most remarkable after the largest HF event with magnitude 2.5 on February 10 (arrow in Fig. 3). The burstic activities were well correlated with the pattern of the diurnal solid earth tide. The vertical tidal accerelation calculated for the summit of Tarumai volcano is shown in Fig. 3.

4. Earthquake family.

4.1 Classification

Well-developed activity of several different earthquake families is identified during the 1988 earthquake swarm of Tarumai volcano. To investigate how the families occur in the whole sequence of the swarm, we compared waveforms of all LF events focusing on their waveform similarity and classified them into families.

Classification of the earthquake families are at first made by the overlapping of their seismograms recorded at WCR. As the result, 136 (95%) of the LF events can be classified into 21 earthquake families. The families are named 'a' to 'u' in the order of their first appearance. The waveforms in each family

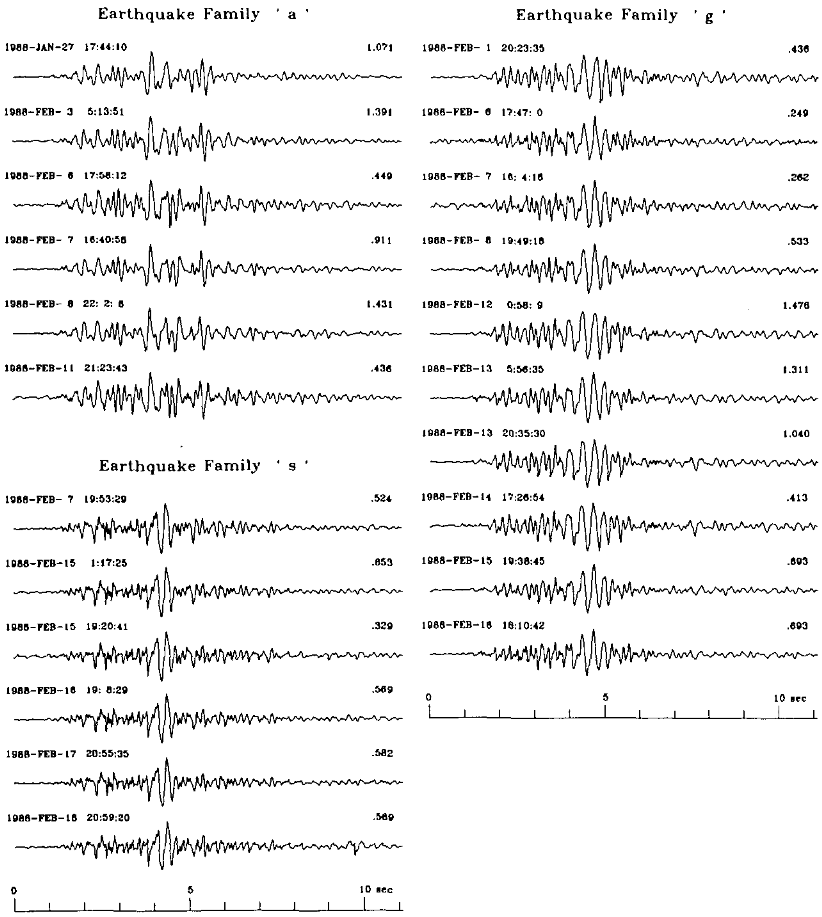

Fig. 4. Examples of the digital seismograms for three earthquake families ('a', 'g' and 's') recorded at the summit station WCR.

resemble each other in detail from the onset to the coda. The WCR seismograms belonging to three earthquake families are shown in Fig. 4.

Since the digital seismograms at the summit station WCR were available, the classification was also made by comparing the maximum cross-correlation functions among the seismograms. Cross-correlation is a simple and useful tool to evaluate waveform similarity when digital seismograms are available (Pechmann and Kanamori, 1982; Motoya, 1984; Motoya and Abe, 1985). In this study, maximum cross-correlation functions were calculated for all possible pairs of the WCR digital seismograms of 143 LF events. Time windows for the

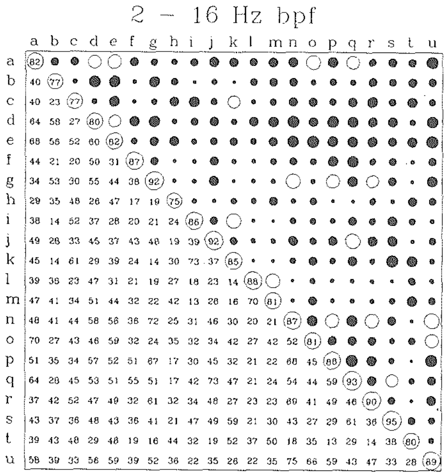

Fig. 5. Cross-correlation score for the earthquake families 'a' to 'u'. The mean of the maximum cross-correlations for all possible pairs of two set of the families is displayed corresponding to its position in the matrix. The cross-correlations are calculated by using the 2-16 Hz bandpass filtered seismograms. The circle size (upper-right half) is proportional to the cross-correlation values which are shown in the lower-left half in percent. Open circles in the upper-right half represent the correlation values greater than 0.6.

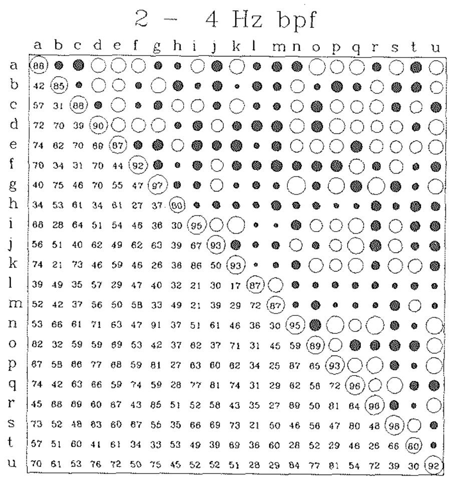

Fig. 6. (a) Same as Figure 7 except that the cross-correlations are calculated for the 2-4 Hz bandpass filtered seismograms.

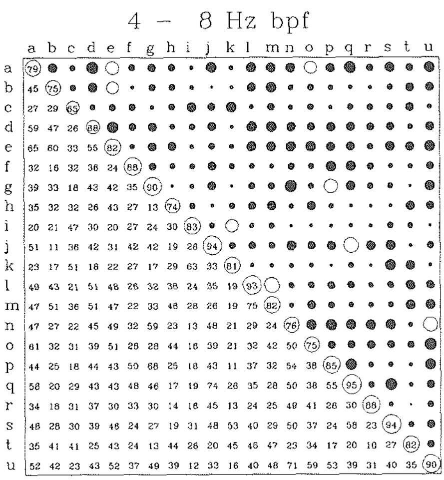

Fig. 6. (b) Same as Figure 7 except that the cross-correlations are calculated for the 4-8 Hz bandpass filtered seismograms.

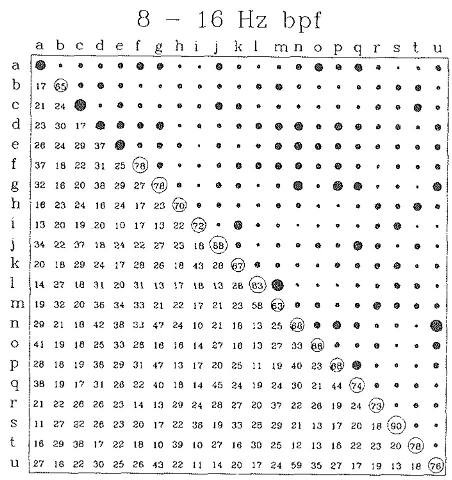

Fig. 6. (c) Same as Figure 7 except that the cross-correlations are calculated for the 8-16 Hz bandpass filtered seismograms.

calculation were about 11 sec (1024 points) covering the entire waveforms.

Cross-correlation score for the 21 earthquake families are shown in Fig. 5. First, using the 2-16 Hz bandpass filtered seismograms, the maximum cross-correlations were calculated for all possible earthquake pairs from two set of families. The mean values of these correlations are shown corresponding to its position in the matrix of Fig. 5. It is clear that the correlations among any pair of members for the same families are systematically high, almost greater than 0.8 (diagonals of the matrix). On the other hand, the correlations among the different set of families are significantly lower, mostly less than 0.6.

4.2 Estimation of the source dimensions

Hypocenter distribution of members of an earthquake family had been suggested to be in a small limited region (Ito, 1985 ; Fremont and Malone, 1987 ; Nishigami, 1987). Ito (1985) and Fremont and Malone (1987) applied the cross-spectral analysis method to determine the relative locations of family members precisely. They concluded that the events in the family distribute closely in space with a linear dimension of about 50 m.

Cross-correlations of filtered seismograms can be used to make constraints on relative locations of earthquakes. Geller and Mueller (1980) hypothesized that earthquakes producing nearly identical waveforms occur within a distance of one-quarter of the shortest wavelength to which the similarity extends. Thorbjarnardottir and Pechmann (1987) tested this hypothesis by the cross-correlating bandpass filtered seismograms of the explosion data. They demonstrated that the cross-correlation matrices give a good indication of the relative locations of the similar waveform events.

On the basis of these arguments, the linear source dimensions of the earthquake families of Tarumai volcano can be estimated by using only one set of digital seismograms. Figure 6(a)-(c) show the cross-correlation scores for WCR seismograms filtered in passband of 2-4 Hz, 4-8 Hz and 8-16 Hz, respectively. Assuming a P-wave velocity of 3.0 km/sec, the one-quarter wavelength distances corresponding to cut-off frequencies of 4, 8, 16 Hz are 188, 94, 47 m, respectively.

As shown in Fig. 6-(c), within the 8-16 Hz passband, the correlation values among the members in the same families are almost greater than 0.6, except for the families 'a', 'c', 'd' and 'e'. That is, the well correlated earthquakes within such a family take place within a region less than 50 m in linear dimension. This estimation coincide well with the source size of families in various regions which determined directly by using the cross-spectral analysis method (Ito, 1985 ; Fremont and Malone, 1987).

There is no family pair which shows good correlation in the 8-16 Hz passband, so the maximum separation distance among families should be more than 50 m one another. On the other hand, for the 4-8 Hz passband (Fig. 6-(b)) there seem to be some pair of families showing good correlations. And, for the 2-4 Hz passband (Fig. 6-(a)), the number of such family pairs increase significantly. The results of the cross-correlation calculations for the filtered data show that source regions of the certain set of families are also distributed in a small region with a linear dimension of about several hundred meters or so. It is consistent with the observational fact that the all of LF events at Tarumai volcano was expected to be originated at a small limited region (less than several hundreds meters) below the active crater of Tarumai volcano.

4.3 *Time series*

The amplitude-time distributions for the twenty-one earthquake families

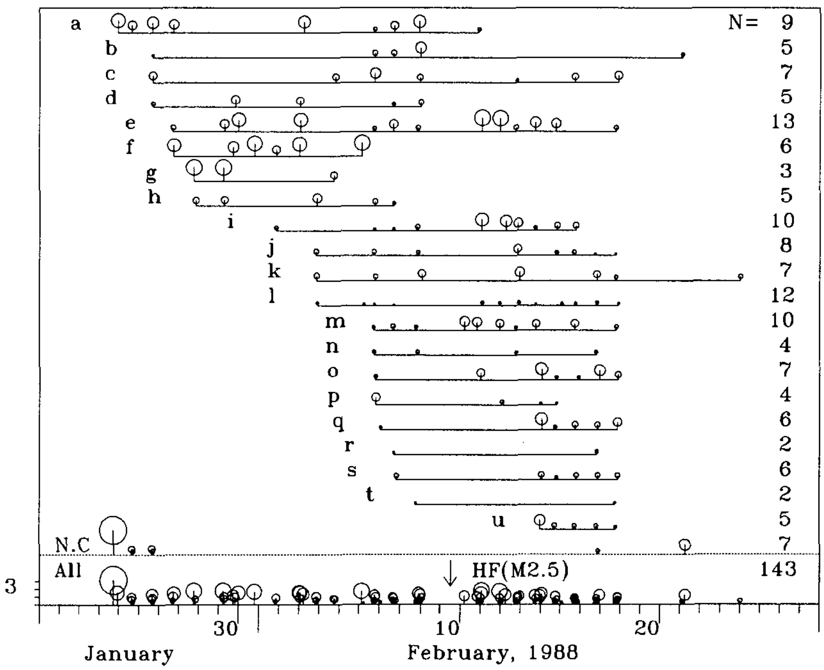

Fig. 7. Amplitude-time diagrams of twenty-one earthquake families. Family 'a' to family 'u' are named in the order of their first appearance. N.C. shows the activity of the non-classified events.

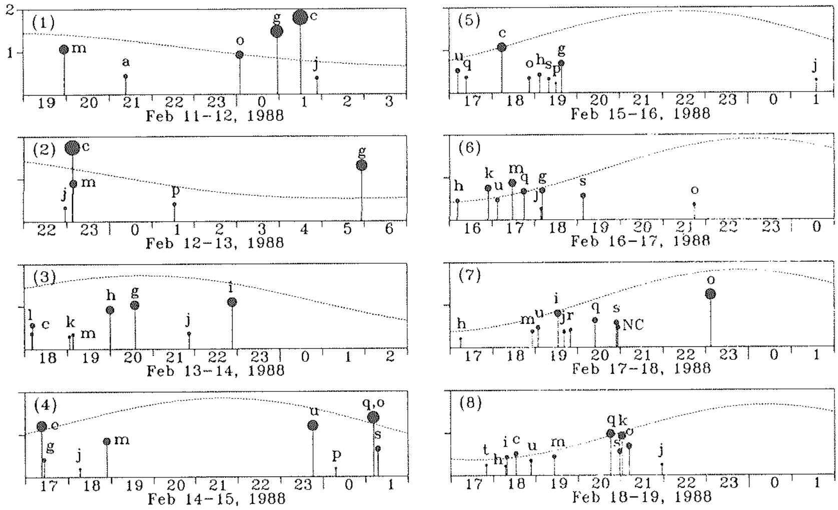

Fig. 8. Detailed time sequence of the earthquake occurrence in the eight burstic activities after the M 2.5 high-frequency event. The smooth curve indicates the vertical component of the solid earth tide. Family names of each event are attached. No systematic order of the family occurrence is recognized.

and the non-classified events (N.C.) are shown in Fig. 7. The families are characterized by their long life times in the whole time sequence of the swarm ; the life time of each family ranges between 4 days (family 'u') and 27 days (family 'b'). There is no earthquake family which persist to survive throughout the entire period of the 1988 swarm. Five of seven non-classified events, including the first largest LF event, occurred in the first 3 days of the swarm.

From January 6 to February 18, the burstic activities are always composed by the activities of more than two different families. And, the peculiar phenomena were that the earthquakes making up each burst were classified into the different families without an exception. For example, thirteen LF events occurred within three hours on February 6-7 : each one was a member of the different families.

Families which appeared in one burst varied among each burst. Figure 8 shows time sequences of the earthquake occurrence in the eight burstic activities after the M 2.5 HF event. It should be noticed that the order of the family appearance showed no regularity, but also varied among each burst.

5. Discussion

There are two conceptual models to explain source mechanism of earthquake families (Aki, 1984). In one of them, an earthquake family may be attributed to a stable asperity. This type of family was typically observed at Mt. Usu in the 1977-1978 eruption series (Mizukoshi and Moriya, 1980 ; Okada et al, 1981). The earthquakes characterized by similar waveforms have been repeatedly produced during the continuous upheaval of the dacite dome. Because the strength associated with the asperity as well as the dynamic friction is nearly constant, the family has an optical magnitude. Aki (1984) called this type of family as the "asperity-type earthquake family".

In the other conceptual model, family members may be attributed to each patches on a same fault plane. So earthquakes consisting one family occur successively in a short time while one fault plane is broken heterogeneously. The activity of this type of family is characterized by short life-time and relatively wide range of their magnitude distribution. Tsujiura (1983), Ito (1985) and Fremont and Malone (1987) reported the activities of this type of family in Izu, Tochigi prefecture, and Mt. St. Helens, respectively.

Earthquake families observed at Tarumai volcano are considered to be typical ones of the asperity-type earthquake family. In this case, twenty-one quasi-stable asperities persist to survive more than several days. The periodical occurrence of the burstic activity of earthquakes belong to the different families indicate that the stress release have been accomplished almost simultaneously for the various families.

Since the stress release occurred with a strong 24-hours periodicity, tidal stress acting on the volcano is one of the plausible trigger force of the family generation. The correlation between the solid earth tide and seismic or volcanic phenomena has been reported in various volcanic regions (Hamilton, 1973 ; Johnson and Mauk, 1972 ; Mauk and Johnson, 1973 ; Mauk and Kienle, 1973 ; Filson et al., 1973 ; Colombek and Carr, 1978 ; McNutt and Beavan, 1981, 1984 ; Rydelek et al., 1988 ; Mitsunami and Yamazaki, 1990). These observations suggest that small changing tidal stress loads may trigger the earthquakes or eruptions when the deformation system of the volcano is under the delicate balance.

Tidal correlating activity of the asperity-type earthquake family was observed with the caldera collapse of Fernandina in the Galapagos Islands during June of 1968 (Filson et al., 1973). In this case, large events with similar waveforms occurred only at 6-hour intervals coinciding with extremes in the ocean and earth tides.

In both case of Fernandina and Usu, however, volcanic activity is very high, and large scale continuous crustal deformations have been observed with the activity of earthquake families. In contrast, Tarumai volcano shows no anomalous surface activities nor crustal deformations in the early period of 1988. Seismic activity is also in their lowest level since 1967 when instrumental observation started by JMA. So, in the case of the 1988 Tarumai swarm, unusual but minor stress regime was inferred to be established temporarily at the shallow limited region beneath the summit crater, which probably originated by the magmatic activity or the geothermal activity.

6. Conclusion

We examined an earthquake swarm at Tarumai volcano, Hokkaido, Japan, during January and February, 1988. The results are as follows:

1. One hundred and forty-three low-frequency earthquakes occurred from January 24 to February 25, 1988 at Tarumai volcano.
2. The swarm consisted of the burstic activities of earthquakes which occurred with a strong 24-hour periodicity.
3. There exist twenty-one earthquake families persisting over some burstic activities of earthquakes.
4. Hypocenter distributions of each family are estimated to be in the small limited regions; mostly with a linear dimension of less than 50 m.
5. The life times of the families distribute in the range of 4 to 27 days. The burstic activities are always composed of each one member from the different families.
6. The activity of this type of families support a conceptual model that families are originated from the stable asperities which persist to survive throughout the repeated faultings.

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