SEISMIC ACTIVITY OF MOUNT EREBUS, ANTARCTICA IN 1982–1983

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Abstract: Mount Erebus is an active volcano with a persistent convecting lava lake at the summit crater, located on Ross Island, Antarctica. Since December 1980 the seismic activity of Mount Erebus has been continuously monitored using a radio-telemetered network of six seismic stations. A 50-day temporary seismic observation was also carried out in the 1982–1983 Antarctic field season. The following seismic activities were observed during this field season: 1) Explosion earthquakes accompanied with Strombolian eruptions from the lava lake occurred at a rate of 0–4 times per day which is slightly lower than the rate in the previous season; 2) an intense earthquake swarm, which is possibly related to the underground movement of magma, occurred in October 1982 near Abbott Peak, 10 km northwest of the summit; 3) there were other source regions of seismicity in Ross Island, fairly distant from Mount Erebus to the east.

1. Introduction

Mount Erebus (3794 m) is an active volcano located on Ross Island, Antarctica. Its volcanic activities such as eruptions and red glows have been occasionally observed since 1841 when the volcano was discovered by James Ross and his party (Ross, 1847). Mount Erebus is the only active volcano among four major volcanoes which form Ross Island, and is composed predominantly of anorthoclase phonolite lavas. At the summit, Mount Erebus has the oval main crater 600 m north-south and 160 m deep. The persistent convecting lava lake, which was first observed in December 1972, fills the bottom of a circular pit located at the north end of the main crater floor (KYLE *et al.*, 1982). The lava lake is 150 m east-west and 100 m north-south. The activity and the shape of the lava lake have remained constant over the last several years (KYLE and OTWAY, 1982).

Mount Erebus has aroused our interest not only because it has the persistent convecting lava lake but also because it is on the aseismic Antarctic plate. To reveal the mechanism of energy supply to the persistent lava lake and the tectonics of the active volcano on the aseismic plate, temporary seismological observations have been carried out since 1974. A continuous seismic observation with a radio-telemetry network started in December 1980 as part of the international cooperative program (International Mount Erebus Seismological Study: IMESS) of Japan, the United States and New Zealand (KIENLE *et al.*, 1981, 1982). The results of these observations show two kinds of seismic activities in Ross Island; one is the activity concentrated near the summit of Mount Erebus, and the other is spread through Mount Erebus and the surrounding area. The former is associated with Strombolian eruptions (KYLE *et al.*, 1982; SHIBUYA *et al.*, 1983; TAKANAMI *et al.*, 1983a, b).

The seismic activity observed in 1982–1983 was reported by KAMINUMA *et al.* (1984) with emphasis on an earthquake swarm. In this paper, the seismic activity in 1982–1983 will be compared with that in the preceding seasons.

2. Seismic Network and Data

The IMESS permanent seismic network consists of six seismometer stations (solid circles in Fig. 1). Each station has a vertical geophone of 1-s period, an ampli-

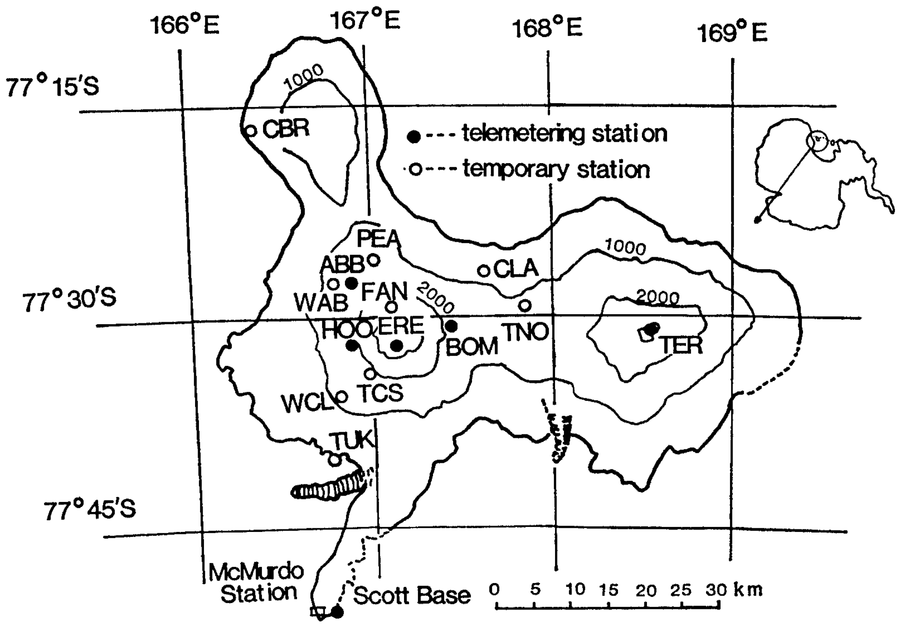


Fig. 1. Locations of seismic stations; both radio-telemetered stations (closed circles) and temporary stations with portable data recorder (open circles).

fier/VCO and a radio-telemetry transmitter. The power for the equipment at a station is supplied by batteries which are charged by a solar panel. The Erebus summit station (ERE) has two additional sensors; one is an infrasonic microphone to observe the air pressure change caused by eruptions, and the other is a magnetic induction loop. All signals of the stations are radio-telemetered to Scott Base and continuously recorded on a magnetic tape recorder (KIENLE *et al.*, 1982). The overall frequency response is nearly flat for ground velocity between 1.5 and 20 Hz (SHIBUYA *et al.*, 1983). Five stations out of six worked successfully throughout 1982, except for the months of July and August when the batteries were not sufficiently charged by solar panels as a result of no/weak sunshine in the austral winter. On the other hand, the summit station failed in the end of July 1982, and could not be repaired until December 1982.

Nine seismic stations were temporarily operated around Mount Erebus for 50 days in November and December 1982 by the Japanese party (open circles in Fig. 1). The station was equipped with a vertical geophone having a 2-Hz natural frequency and a slow-speed tape recorder which is of the same model as those used in the preceding seasons (TAKANAMI *et al.*, 1983a). The clocks installed in the tape recorders were calibrated three times during the observation referring to the clock at Scott Base by using a portable crystal clock.

3. Seismicity in 1982–1983

3.1. Number of earthquakes

The daily number of earthquakes counted at the Abbott Peak station (ABB) is given in Fig. 2 for the period from September 1982 to February 1983. Only the events with S-P time not greater than 10 s were picked from the continuous monitoring record. Teleseisms and local earthquakes which occurred far from Ross Island were counted out. The events which had characteristic wave form of higher frequency and shorter duration time were recognized as icequakes (KAMINUMA and HANEDA, 1979), and they were also counted out. The daily variations of the number of the earthquakes recorded at the Hoopers Shoulder (HOO) and Bomb (BOM) stations are very similar to that at the Abbott Peak station. The average number of the earthquakes observed at the Abbott Peak station for this field season was 76 per day. This value is comparable to that for the 1980–1981 field season (Fig. 2 in TAKANAMI *et al.*, 1983a). The seismicity for the period from December 1980 to February 1982 was summarized by SHIBUYA *et al.* (1983). Their counts included icequakes and their threshold level of count was different from ours, thus the seismicity in 1980–1982 cannot be compared directly with that for this field season. Nevertheless, we see no evident change in the seismicity in the Mount Erebus region throughout the period from December 1980 to February 1983, except an earthquake swarm on October 8–9, 1982, which will be described in detail later.

The daily number of earthquakes seems to show a quasi-periodic change of 1.5 or 2-month occurrence interval, as is already pointed out for the preceding period (SHIBUYA *et al.*, 1983; TAKANAMI *et al.*, 1983b). Even though the count of events can be affected by the level of microseisms or ground noise caused by wind, the increased level of noise cannot last so long as one month. Consequently, the quasi-periodic change of the daily number of events is probably real, not an apparent one. The daily number of events with maximum trace amplitude more than 10 mm (M>*ca.* 0.5) is shown by solid bar in the lower part of Fig. 2. The seismicity of these larger events does not appear to change quasi-periodically and appears to be rather constant throughout this field season except during the swarm in October 1982. Thus, it seems that only the number of smaller earthquakes changes quasi-periodically.

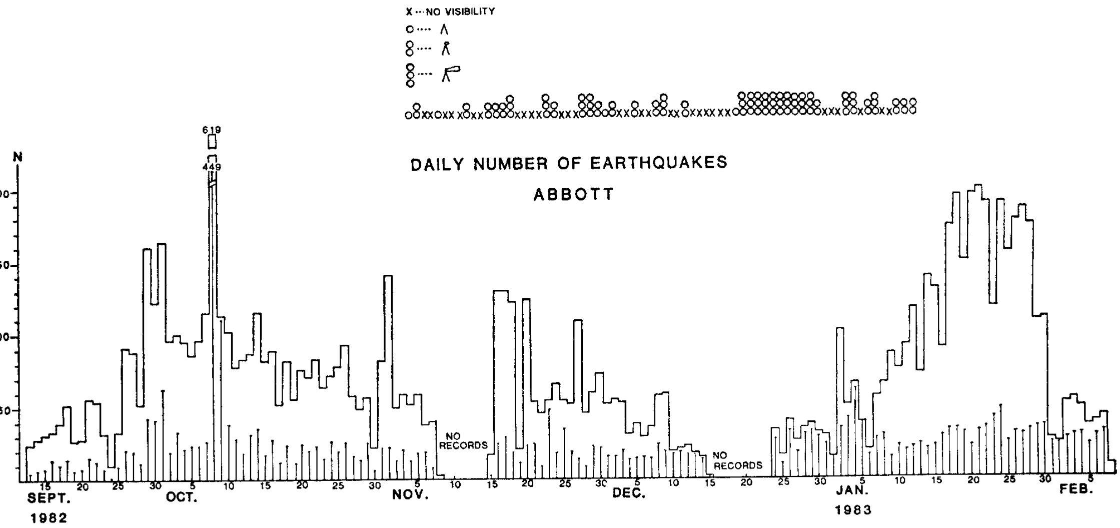


Fig. 2. Bottom: Daily number of earthquakes at the Abbott Peak station. Solid bar denotes the daily number of the earthquakes with A_{max}>10 mm on chart. Top: Quantity of plume observed at McMurdo Station.

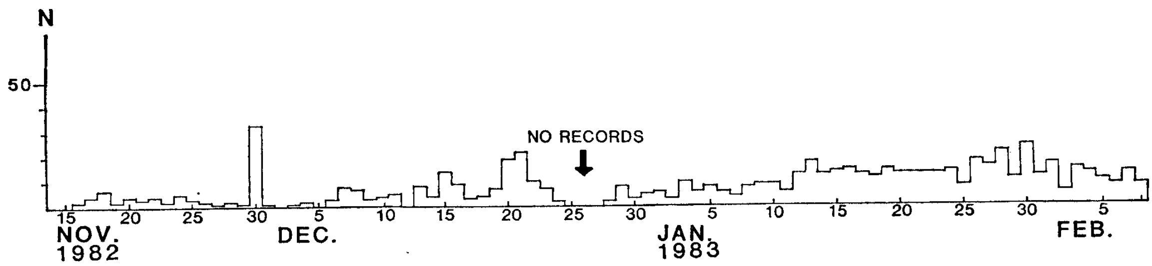


Fig. 3. Daily number of earthquakes at the Mount Terror station.

The diagram of the daily number of the earthquakes observed at the Mount Terror station (TER) (Fig. 3) shows some peaks of activity which were not recognized at ABB. An example of this sort of activity is the swarm on November 30, 1982. The earthquakes belonging to this sort of activity were observed at TER and BOM or just at TER with larger amplitude than at other stations. Their focal area is thought to be separated from the major focal area around Mount Erebus to the east.

The quantity of the plume rising from the Erebus summit is shown in the upper part of Fig. 2. This plume activity was observed from McMurdo Station (38 km south of the summit) during our stay. One circle in Fig. 2 indicates that no plume was seen throughout the day, two circles signify a small amount of plume and three circles indicate an extended plume streaming away from the summit. A cross denotes that the summit could not be seen. From this observation no correlation is recognized between the number of earthquakes and the quantity of plume, but the data is not enough to draw any final conclusion at the moment.

3.2. Hypocenter distribution

The hypocenters of the earthquakes were calculated for the period from September 13, 1982 to January 29, 1983. The velocity structure of the Mount Erebus region was assumed to be horizontally multi-layered. The *P*-wave velocity of the part higher than 1 km above sea level was assumed to be 2 km/s (SHIBUYA *et al.*, 1983). The velocity model revealed by explosion seismology at the McMurdo Sound (WILSON

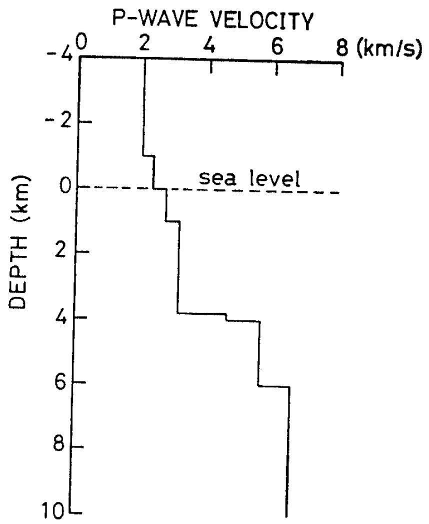


Fig. 4. P-wave velocity model for the determination of hypocenters.

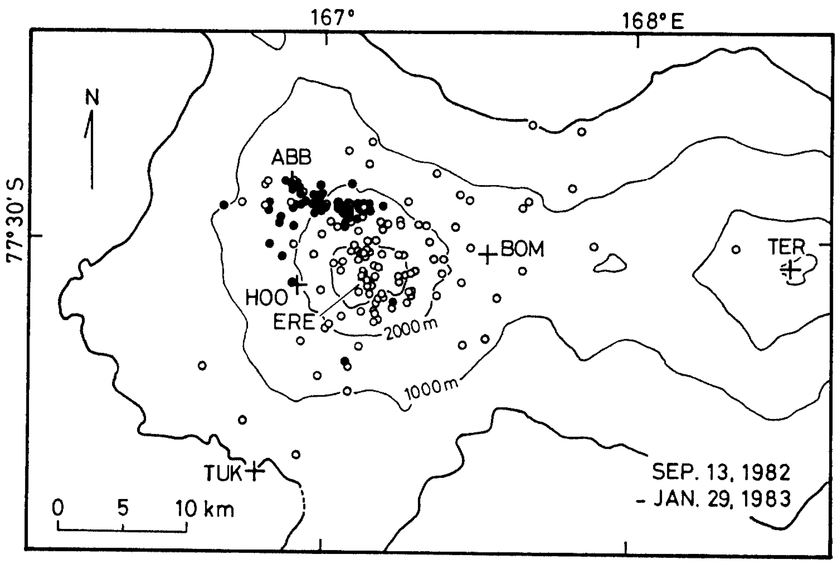


Fig. 5. Epicenter locations of Ross Island earthquakes (September 13, 1982 to January 29, 1983). Solid circles denote the earthquakes which occurred on October 8–9, 1982.

et al., 1981) was adopted for the part deeper than 1 km below sea level. Between higher and deeper parts, two layers with intermediate velocities were assumed (Fig. 4). The value of V_p/V_s was assumed to be 1.78 (TAKANAMI *et al.*, 1983a). Arrival times of P and S waves at three or more stations were used for the hypocenter calculation.

Figure 5 shows the epicentral distribution and Fig. 6 shows the focal depth distribution projected onto vertical cross sections oriented E-W and N-S. Plotted are the earthquakes of which the horizontal error is less than 5 km and the vertical error is less than 10 km. The cluster of solid circles near the Abbott Peak station is associated with the October 1982 earthquake swarm. Another concentration of epicenters is in the summit area of Mount Erebus. The focal depth of the greater part of earthquakes is shallower than 6 km below sea level. This means that most of the

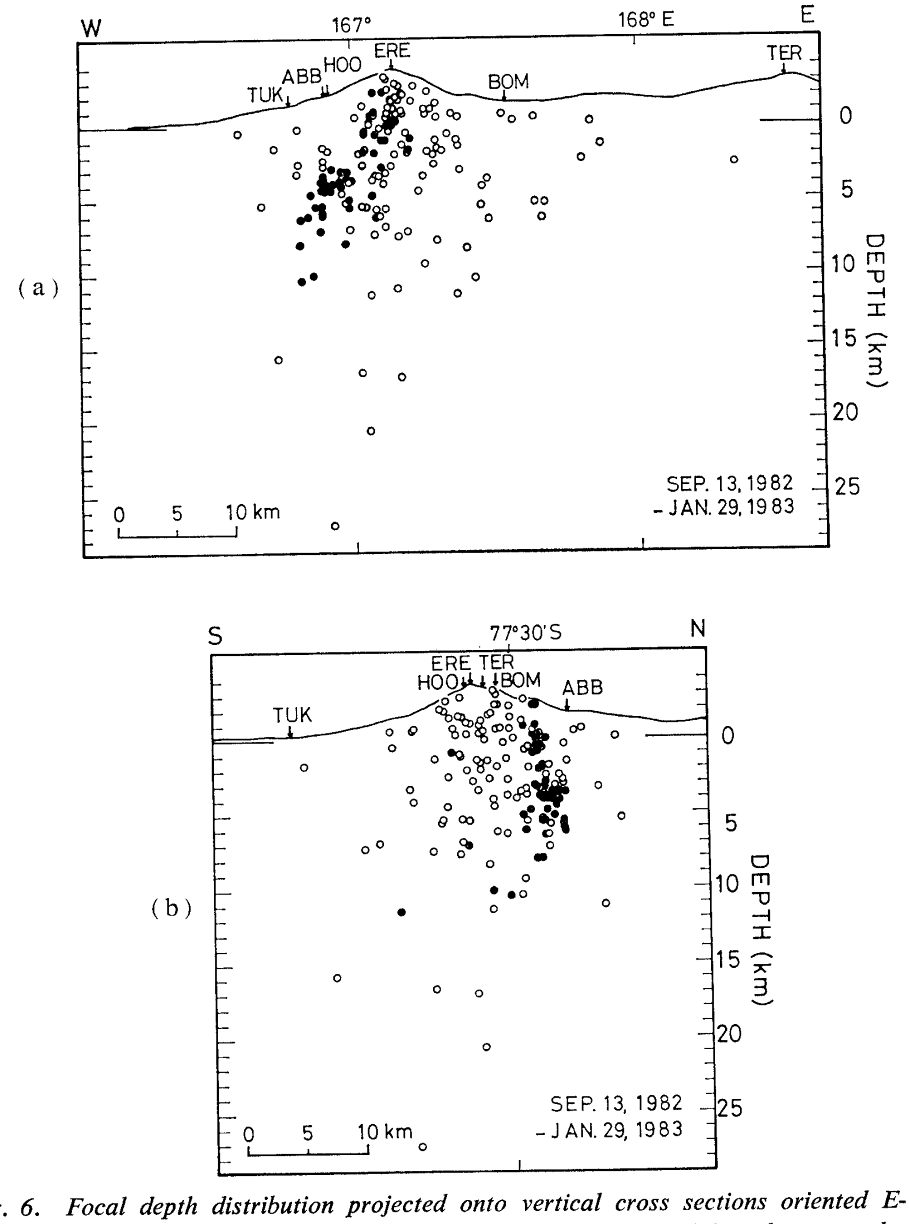


Fig. 6. Focal depth distribution projected onto vertical cross sections oriented E-W (a) and N-S (b) (September 13, 1982 to January 29, 1983). Solid circle means the same as in Fig. 5.

earthquakes in Ross Island occur in the upper crust where the *P*-wave velocity is thought to be less than 6 km/s. Figure 5 also shows that some earthquakes took place in the regions near Mount Terror and around Mount Terra Nova, which is located between Mount Terror and Mount Erebus. These regions are considered to be the focal area of the earthquakes observed at TER and BOM with larger amplitude than at other stations. The seismic observation at TER was started in November 1981, but no event near TER was detected in the 1981–1982 field season (SHIBUYA *et al.*, 1983). The seismic activity in the regions around Mount Terra Nova and Mount Terror was found for the first time in this field season. This observation revealed that the seismic activities in Ross Island were not restricted within the region near the active volcano Erebus.

Figure 5 shows also that the seismic activity is very low in the western flank of Mount Erebus. It is interesting that no earthquake was located within a distance of 1 km from the summit of Mount Erebus (Fig. 6).

4. Explosion Earthquakes

Strombolian eruptions and gas discharges usually occur several times a day from active vents adjacent to the lava lake or from the lava lake itself (KYLE *et al.*, 1982). SHIBUYA *et al.* (1983) showed that the earthquake accompanied by an infrasonic signal can be recognized as an explosion earthquake. Figure 7 is an example of the seismo-

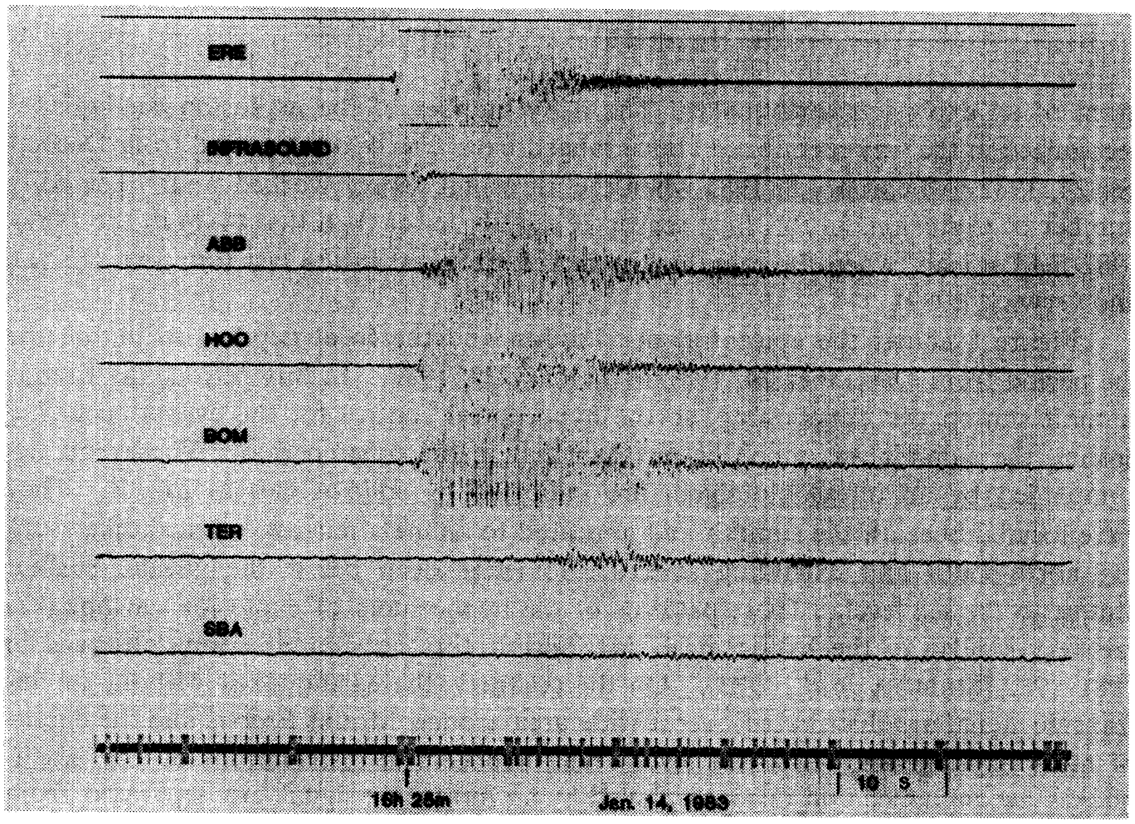
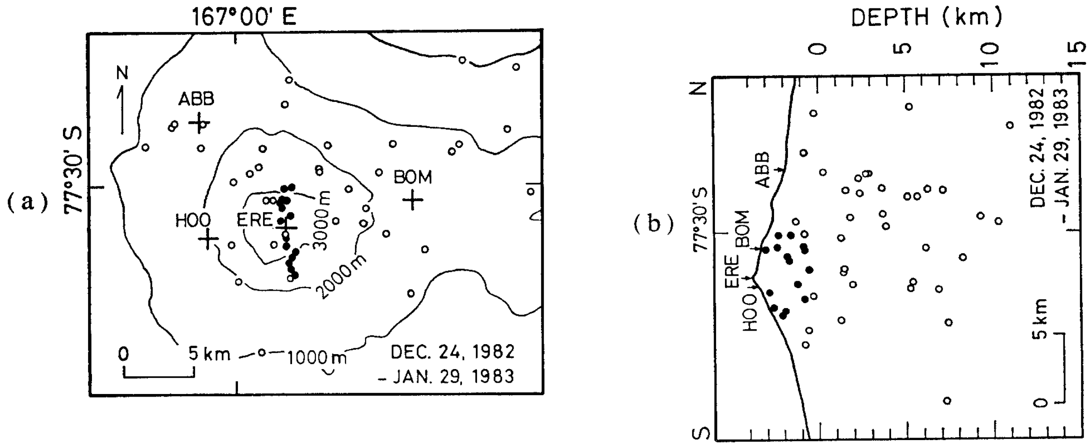


Fig. 7. A sample seismogram of an explosion earthquake associated with a Strombolian eruption. Infrasonic signal is shown on the second trace.



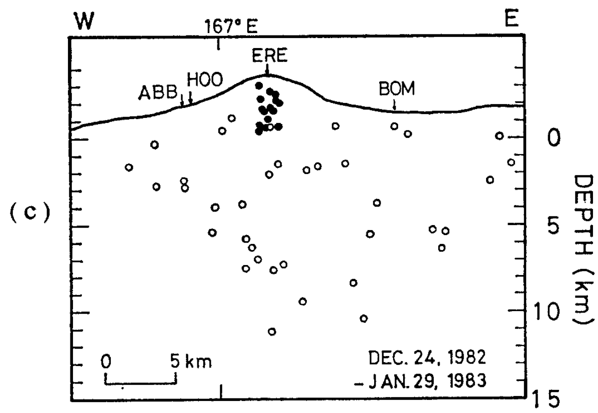


Fig. 8. Epicenter distribution (a) and hypocenter distribution projected onto vertical planes oriented N-S (b) and E-W (c) for the period from December 24, 1982 to January 29, 1983. Solid circle and open circle denote an earthquake with an infrasonic signal and the event without infrasonic signal, respectively.

gram of an explosion earthquake. The daily number of the explosion earthquakes recognized in the way mentioned above ranged from 0 to 4 in the period from December 24, 1982 to February 8, 1983 when the infrasonic sensor worked well. The daily number of explosions in this field season is slightly fewer than that (4–6) in the 1981–1982 field season, when the eruptions were the strongest in the last four years (KYLE and OTWAY, 1982).

Figure 8 shows the epicentral distribution and the focal depth distribution for the period from December 24, 1982 to January 29, 1983. In this period, the Erebus summit station was functioning, so the hypocentral control for the events occurring around the summit was much better than that in the other period. The events accompanied by an infrasonic signal are indicated by solid circles in Fig. 8. They were located beneath the summit and appeared to define a narrow, vertical dike striking north-south and extending several kilometers deep below the ground surface almost to the sea level. These patterns of the hypocenters of explosion earthquakes are very similar to the hypocentral distribution for the summit events observed in 1981–1982 (SHIBUYA *et al.*, 1983). On the contrary, the earthquakes without an infrasonic signal are distributed over a wide area around Mount Erebus and the depths of most of them are below sea level. The hypocentral distributions of the earthquakes accompanied and unaccompanied by an infrasonic signal are separated from each other.

It is now clear that the explosion earthquakes occur in a narrow vertical zone beneath the lava lake and their depths are shallower than sea level, but the details of the focal zone are not clear yet. The epicentral distribution elongated in the N-S direction is probably affected by the shape of the station network elongated in the E-W direction. No earthquake was located within 1 km from the summit station. This aseismic region is possibly an apparent one caused by the discrepancy between the assumed velocity model and the real structure. To solve the problems, an intensive seismic station network in the summit area is needed, and development of a new method to determine the focal depth and/or the origin time of explosion earthquakes, for example by using the arrival time of infrasonic signal, is also needed.

5. October 1982 Swarm

An earthquake swarm occurred on October 8–9, 1982 in the vicinity of the Abbott Peak station (KAMINUMA *et al.*, 1984). Earthquake swarms have been observed frequently around Mount Erebus. This swarm, however, was remarkable indeed. More than 600 earthquakes were recorded in a day. This value is the largest daily number of earthquakes ever observed in Antarctica.

The earthquake swarm started abruptly at 0207 (UT) on October 8, 1982 and the frequency of earthquakes increased rapidly (Fig. 9). The earthquakes had rather clear *P*- and *S*-phases (Fig. 10). At the peak of activity, about 150 events were counted at the Abbott Peak station during one hour from 03 to 04 on the same day. Afterwards, the frequency of events decreased gradually. The swarm finally ceased by midday of October 9. Short-period tremor (Fig. 11a) began to be recorded at the Abbott Peak and Hoopers Shoulder stations at 03 on October 8 and continued for more than 30 hours while varying its amplitude. Furthermore, long-period tremor (Fig. 11b) was recorded from 2200 to 2303 on October 8. Both of the tremors had wave forms different from microseisms (Fig. 11c). The predominant period of the short-period tremor is about 0.1 s. The seismogram of the short-period tremor

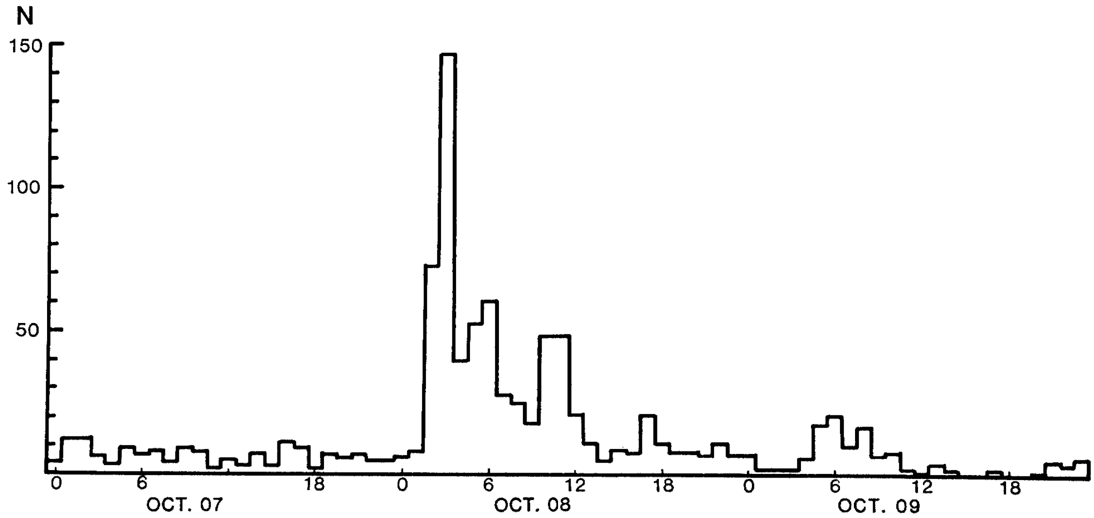


Fig. 9. Hourly number of earthquakes during the October 1982 earthquake swarm counted at the Abbott Peak station.

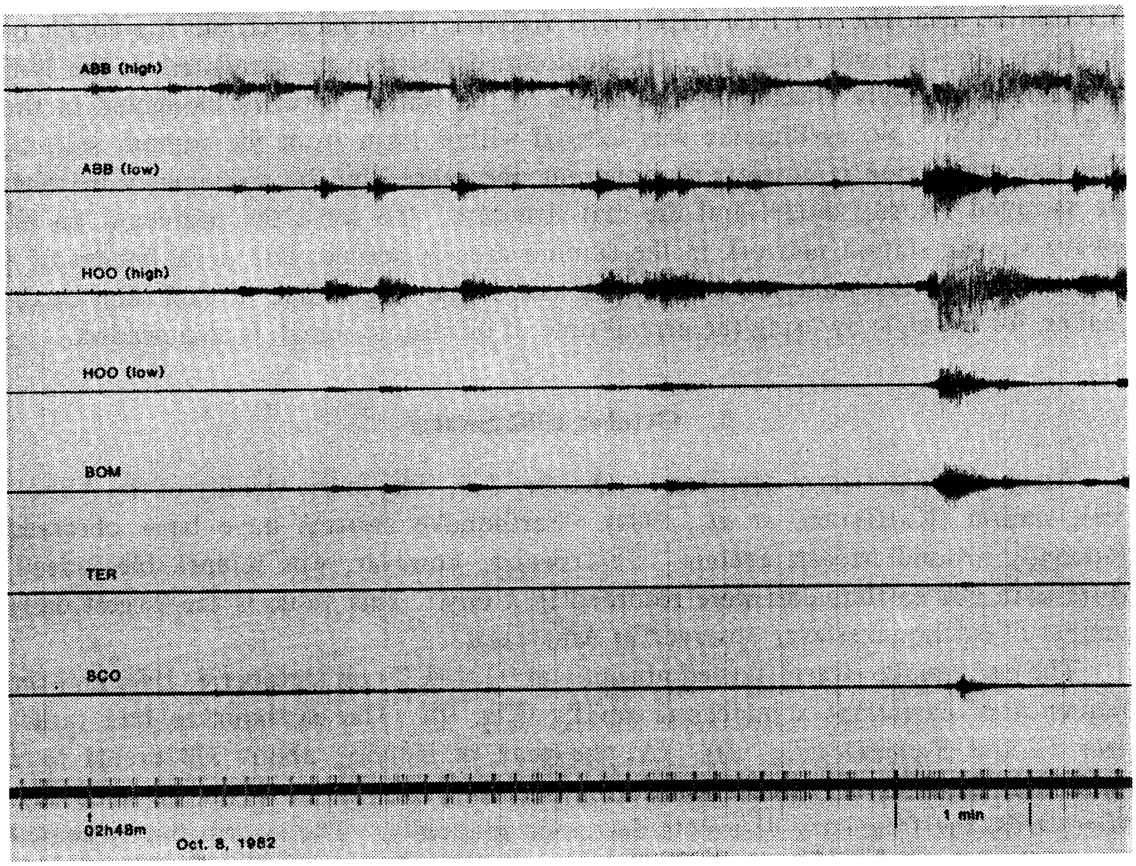


Fig. 10. Seismogram of a part of the onset of the October 1982 earthquake swarm.

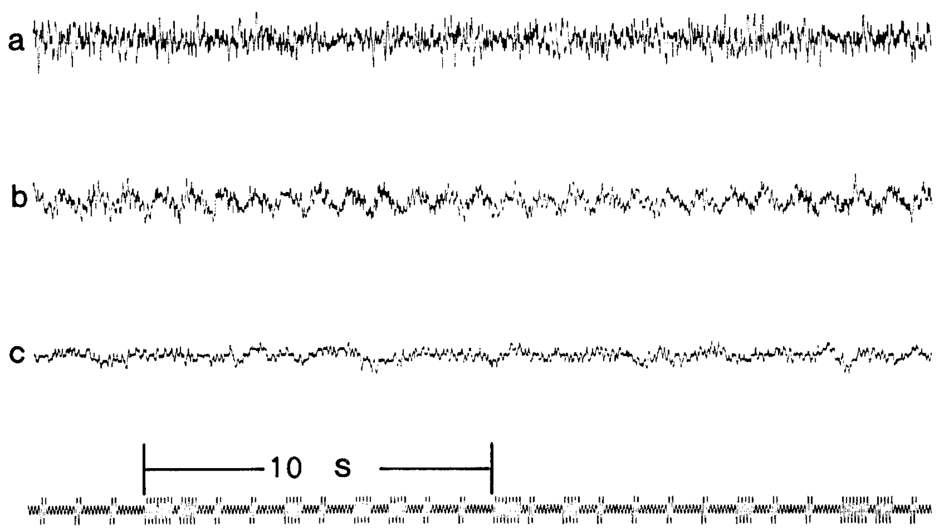


Fig. 11. Example of the record of short-period tremor (a), long-period tremor (b) and micro-seisms (c).

is very similar to the noise which is frequently observed on a stormy day. Therefore, the short-period tremor observed on October 8 and 9 was likely caused by winds and ocean waves. On the contrary, long-period tremor is rarely observed at Mount

Erebus. The long-period tremor recorded on October 8 was characterized by monotone oscillation of 0.9-s period. The period and the mode of oscillation are similar to those of volcanic tremor observed at many other volcanoes (*e.g.* KUBOTERA, 1974). Consequently, the long-period tremor observed on October 8 was probably a volcanic one.

Solid circles in Figs. 5 and 6 show the epicentral distribution of the earthquakes observed on October 8 and 9 and their focal depth distribution, respectively. The focal depths spread from 1 km above sea level to 10 km below sea level with a concentration around a depth of 5 km. It appears that the hypocenters are distributed in a zone steeply inclining west-northwestward. The earthquake swarm took place at the northwest margin of the seismic area around Mount Erebus. The epicenters are located some 10 km northwest of the Erebus summit. The epicentral distance from the summit seems long enough to indicate that the swarm had no direct relation to the activity of the phonolitic magma in the lava lake. In fact, no unusual volcanic activity at the summit was observed either from McMurdo Station or from Scott Base in October 1982, nor unusual number of fresh bombs were found lying on the crater rim in December when we visited the summit. The focal depth distribution and the occurrence of the long-period tremor rather suggest that the earthquake swarm was associated with underground movement of a new batch of magma. No volcanic phenomenon is seen in the epicentral area at the present time. It is interesting, however, to note that in 1908 a hydrothermal eruptive activity was observed in the immediate vicinity of the epicentral area by the members of Shackleton Party at Cape Royds (SHACKLETON, 1909).

6. Conclusion

This paper summarizes the seismic activity observed around Mount Erebus during the 1982–1983 field season with the following results:

(1) There were two major seismic activities; one is the ordinary activity known since 1980 near the summit of Mount Erebus and the other is an earthquake swarm in the northwestern flank of Mount Erebus in October 1982.

(2) Centrally located earthquakes in the summit area map out a nearly vertical, narrow dike-like seismic zone beneath the lava lake extending down to a depth of several kilometers.

(3) Infrasonic signals show that Strombolian eruptions continued frequently in the lava lake at a rate of 0–4 times per day. The rate is slightly lower than that in the last season.

(4) The intense earthquake swarm occurred in October 1982 near the Abbott Peak, 10 km northwest of the Erebus summit. The focal distribution and the appearance of the tremor of 0.9-s period suggest the underground movement of magma in the swarm area.

(5) There are other source regions of seismicity in Ross Island, fairly distant from Mount Erebus to the east.

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