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EARTH TIDE AND SEISMIC ACTIVITY IN THE VICINITY OF MOUNT EREBUS, ANTARCTICA

Yoshihiro IKEGAMI[1], Toru OUCHI[1] and Katsutada KAMINUMA[2]

[1]*Department of Earth Sciences, Faculty of Science, Kobe University, 1-1, Rokkodaicho, Nada-ku, Kobe 657*
[2]*National Institute of Polar Research, 9-10, Kaga 1-chome, Itabashi-ku, Tokyo 173*

Abstract: The relation between temporal variation of earthquake frequencies and the earth tide in the vicinity of Mount Erebus, Antarctica was investigated. No significant correlation was found between the earth tide and seismic activity. Interestingly, remarkable periodicities of about 2–4 days and 10–20 days were found by the spectral analysis of this seismic activity. These may be explained as peculiar rhythms of the seismic activity. The effect of the earth tide on the seismic activity seems very small, as Mount Erebus is located at a very high latitude of about 80°S. This enabled us to observe an intrinsic nature of the seismic activity and to reveal these periodicities.

1. Introduction

The correlation between the occurrence of earthquakes and the earth tide has been investigated by many seismologists since the Ito Earthquake Swarm occurred in 1930, in the Izu Peninsula, Japan. In the early period of this swarm, peaks in the burst-type activity occurred at the time of low tide (KISHINOUE, 1937). Since then various studies have been carried out to clarify the mechanism of tidal triggering for earthquakes as follows.

KNOPOFF (1964) studied 8614 earthquakes recorded at the Pasadena network, Southern California. He investigated cross correlations between tidal variations and real earthquake sequences. He also calculated cross correlations between tidal variations and random sequences generated artificially. Tidal variations were calculated theoretically. He found no significant differences in these two cross correlations. On the contrary, HEATON (1975) studied 107 world-wide earthquakes and suggested that shallow (<30 km) and larger magnitude ($M>5.0$) earthquakes of oblique-slip and dip-slip types are triggered by tidal stresses, while shallow earthquakes of strike-slip type and any other type of intermediate or deep earthquakes are not triggered. RYDELEK *et al.* (1988) showed that there are two predominant periodic cycles in earthquake swarms at Kilauea Volcano, Hawaii, which correspond to tidal phases (1 cycle/day and 2 cycles/day) through Fourier and regression analysis. OIKE and TANIGUCHI (1988) found good correlation between seismicity and the dilatational strains by the earth tide in four periods of the Matsushiro Earthquake Swarm. They further showed that the correlation was remarkable at the beginning of earthquake activity in less fractured areas. In the lunar seismicity, a very clear semimonthly periodicity was found (LAMMLEIN *et al.*, 1974).

As mentioned above, it is not always clear whether earthquakes are triggered by the earth tide or not. The triggering effect appears to depend on the individual situations of earthquakes like the stress or strain state of the epicentral region, etc. Thus the degree of its dependence changes from time to time and place to place. The triggering effect may be sensitive to the strength of the earth tide. In this regard, Antarctica is one of the most interesting places, as the effect of the earth tide is estimated very small and especially the semidiurnal components are quite small compared with low or middle latitude regions (MELCHIOR, 1966).

In this paper, we analyzed a seismic activity in the vicinity of Mount Erebus on Ross Island in the McMurdo Sound, Antarctica. Our purpose is to clarify whether we could find any periodicities due to the earth tide or not.

2. Observation and Seismicity in the Vicinity of Mount Erebus

Mount Erebus (3794 m) is located at 77.53°S, 167.15°E, on Ross Island in the McMurdo Sound, Antarctica. Since December 1980, seismic observation around Mount Erebus has been carried out by IMESS (International Mount Erebus Seismological Studies). Six seismic stations (Abbott Peak: ABB, Hooper's Shoulder: HOO, Summit Station: ERE, Bomb: BOM, Mount Terror: TER, Scott Base: SBS) were established in 1980, and two more stations (Fang Glacier: LFA, Three Sisters Cones: TSC) were added in January 1984 (Fig. 1). Each station is equipped with a vertical-component seismometer of one-second period. The output from these stations is transmitted continuously to Scott Base (TAKANAMI *et al.*, 1982).

The seismicity in the vicinity of Mount Erebus was high during the year 1982–1984, and became very quiet since 1985. In this three years period, the mean fre-

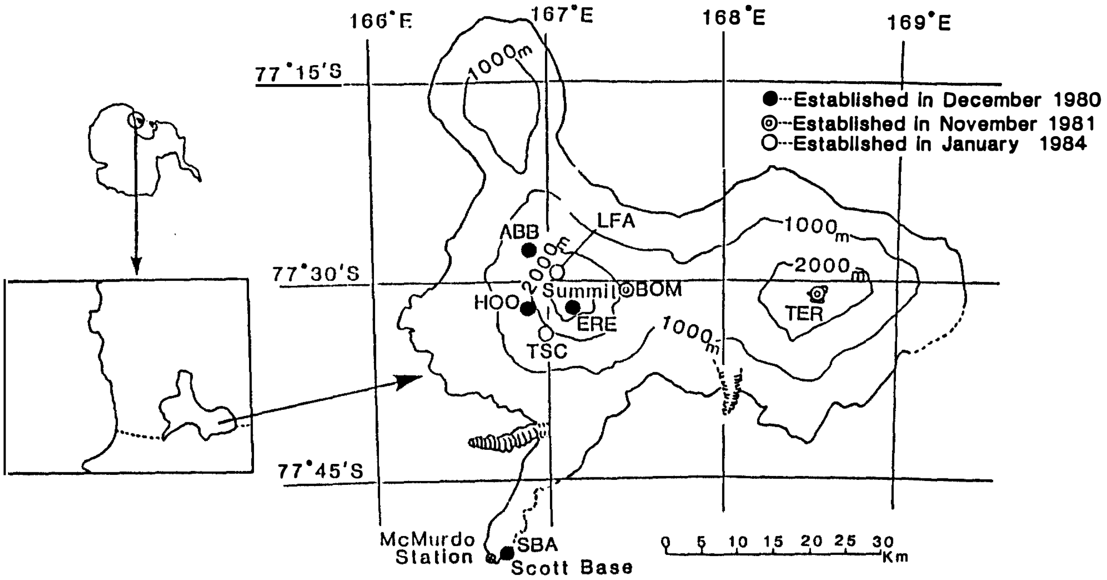

Fig. 1. Map of Mount Erebus and IMESS seismic network 1980–1984, after KAMINUMA et al. (1986).

quency of earthquakes recorded at Hooper's Shoulder was about 20 events per day, and sixteen earthquake swarms, which had more than 250 events per day, were observed by this seismic network. Many of the earthquakes occurred following Strombolian eruption at Mount Erebus summit lava lake. An aseismic zone measuring 3×5 km wide was found in the southwestern part of Mount Erebus. It is suggested that this zone indicates a magma reservoir (KAMINUMA *et al.*, 1984, 1986).

3. Data Selection

The data used in this study are supplied by National Institute of Polar Research. These data are daily and hourly frequencies of earthquakes recorded at Hooper's Shoulder during the years 1982–1984. We have not used the data obtained after 1985, because the seismic activity in this period was too low for the analysis.

In order to analyze seismic activity, we selected twelve data sets; four daily data sets (82y, 83y, 84ya and 84yb) and eight hourly data sets (83ha, 83hb, 83hc, 83hd, 84ha, 84hb, 84hc and 84hd) (Table 1). The formers are used to see longer periodic behavior (>10 days) and the latters are used to see shorter periodic one (<10 days), respectively. To study daily variation, we select the periods of longer than 100 days continuous recordings in which at least one event occurred per day. For hourly variation, we selected the periods of longer than 168 hours continuous recordings in which at least 70 events occurred per day. The events with maximum trace amplitude more than 5 mm were counted. Only the events with *S-P* times shorter than 10 seconds at Hooper's Shoulder are used, as other events are thought to be far from this area. We did not take account of the magnitudes of earthquakes and use the numbers of events only, because the triggering mechanism is likely to have no influence on the magnitude of the earthquakes (KNOPOFF, 1964). But the magnitude of all events is estimated at less than 2.0 (KAMINUMA *et al.*, 1986).

Table 1. Period of each data set and number of samples.

Data	Period	Number of samples
82y	Feb. 16–Jun. 29, 1982	134
83y	Feb. 15–Jun. 25, 1983	131
84ya	Jan. 09–Jul. 28, 1984	202
84yb	Sep. 16–Dec. 31, 1984	107
83ha	Mar. 05–Mar. 24, 1983	480
83hb	Apr. 01–Apr. 19, 1983	456
83hc	May. 31–Jun. 22, 1983	552
83hd	Jul. 08–Jul. 16, 1983	212
84ha	Mar. 24–Apr. 06, 1984	335
84hb	Apr. 08–Apr. 15, 1984	192
84hc	Jun. 19–Jun. 26, 1984	192
84hd	Jul. 09–Jul. 21, 1984	312

4. Fourier Analysis

As long-term trends are usually seen in the original data, it is necessary to remove them prior to Fourier analysis. For this purpose, we applied a band-pass filtering procedure to the data. We use a digital Chebyshev-Filter (ASHIDA and SAITO, 1970). The frequency response of the filter is nearly flat in the ranges of 3.3–25 days for daily

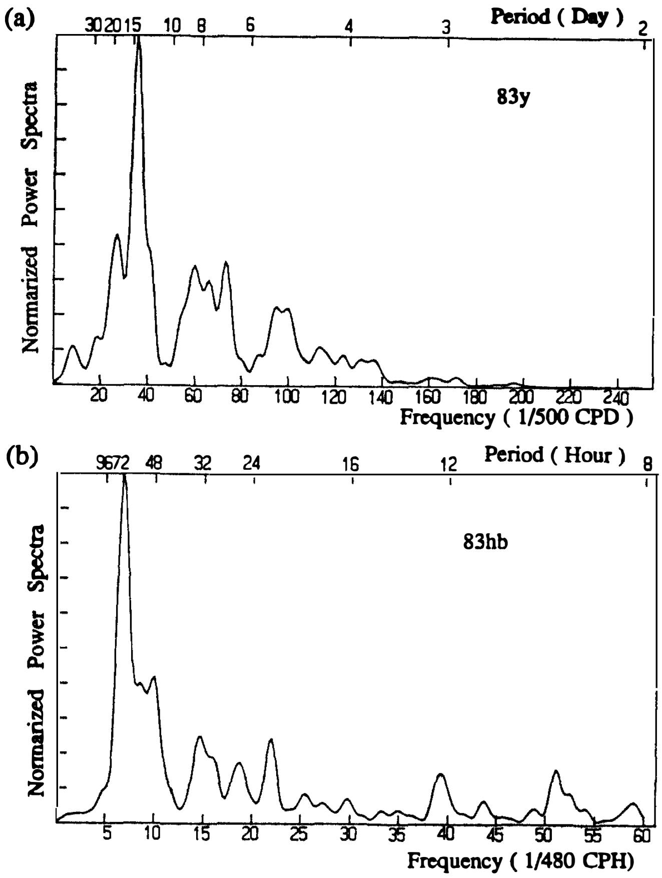

Fig. 2. Amplitude spectra. These figures show typical spectra for daily data (a) and hourly data (b).

Table 2. Predominant period and its significant level.

Data	Predominant period (days)	Significant level
82y	11.3	99%
83y	14.2	99%
84ya	20.8	95%
84yb	15.6	99%
83ha	3.8	99%
83hb	3.0	99%
83hc	3.8	99%
83hd	2.5	99%
84ha	3.5	99%
84hb	2.4	90%
84hc	2.7	90%
84hd	2.5	98%

data sets and 3.3–100 hours for hourly data sets. To obviate phase-shifts due to the filtering procedure, we operate this filter in both forward and backward directions.

After the band-pass filtering operation, we applied Fourier transformation to the data. All spectra are smoothed by Bartlett spectral window function. The smoothed power spectra are shown in Fig. 2 as an example. The predominant periods are summarized in Table 2.

5. Earth Tides and Triggering Mechanism

As the distance between the observation point on the Earth and the Sun or the Moon varies from time to time, the gravity potential on the earth due to the Sun or the Moon varies with time. Tidal potential can be computed separately for the Moon and the Sun (HARRISON, 1971). The lunar tides are about twice amplitude of the solar tides. The oscillation of this potential has many intrinsic periods determined by orbits of the Earth and the Moon or the rotation of the Earth. These are semi-diurnal, diurnal and fortnightly tidal components. Tidal acceleration, differentiation of this potential to a certain direction, also varies and generates variation of stress and strain on the earth. The closer the observation approaches to the equator, the larger the amplitude of the oscillation becomes.

Fracture (earthquake) will occur on the fault plane when the shear stress applied exceeds the cohesive strength of the fault, which may depend upon the normal stress on the fault plane (YOUNG and ZÜRN, 1979). However, OIKE and TANIGUCHI (1988) suggested that the occurrence of earthquakes is more likely related to the dilatational strains by the earth tide than shear stress whose direction agrees with the fault motion, because the dilatational strains weaken the strength of rock in the source regions. The dilatational strains reduce the confining pressure and weaken the strength of rock that depends on the difference between the confining pressure and the pore pressure of rock. This pressure difference is named "effective pressure". In any case, earthquake triggered by the earth tide seems to take place only in the critical condition on the fault, because changing rates of the tidal stress are larger than tectonic ones by two order. According to this hypothesis, a large number of earthquakes and the peaks of seismic activity occur in a certain tidal phase. As long as the crust is in a state of critical condition, sequences of earthquakes will have same periodic cycles corresponding to the earth tide.

6. Correlation between Earthquakes and Earth Tides

If there is any correlation between earthquake sequences and the earth tide, some coefficients of cross correlation will predominate. These coefficients are given by the formula,

$$C(k)=\frac{\sum_{i=1}^{N} X_i * Y_{i+k}}{\left(\sum_{i=1}^{N} X_i^2 * \sum_{i=1}^{N} Y_{i+k}^2\right)^{1/2}}$$

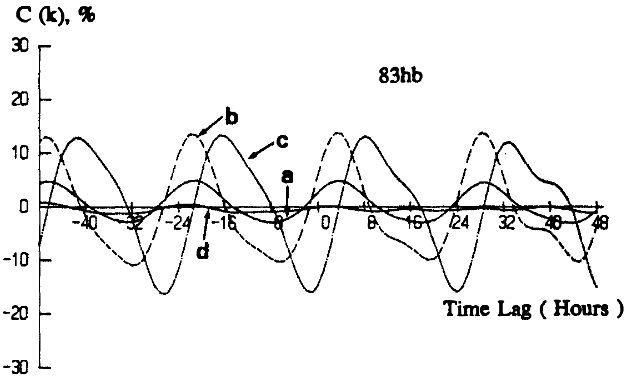

Fig. 3. Typical variation of the cross correlation coefficients between the hourly frequency of earthquakes and tidal accelerations, Up-Down (a), North-South (b), East-West (c) and total of these three components (d).

where X_i is the i-th earthquake data of N samples, Y_i is a tidal function computed theoretically at a certain time on an observation point, and k represents time lags for cross correlations, respectively.

We calculated four tidal accelerations which are East-West (positive to E), North-South (positive to N) and Up-Down (Positive to Up) components, and total of all components or summation of these three vectors. First three components are the differentiation of tidal potential to each direction. Cross correlation coefficients are calculated between the eight hourly data sets and tidal accelerations after the band-pass filtering.

The coefficients obtained from this estimation must lie in the range $-100\% \leqq C(k) \leqq 100\%$, and the extreme values of $\pm 100\%$ are obtained only when X_i and Y_{i+k} are linearly and inverse linearly related. The typical variation of the coefficients is shown in Fig. 3.

7. Results

From the spectral analysis, we found strong periodicity for each seismic data set. According to a table in NOWROOZI (1967), peaks for 84hb and 84hc are significant at higher than 90 percent level, and all other peaks are at higher than 95 percent level (Table 2). These values seem to concentrate in the range of 10–20 days and 2–4 days that do not agree with the periodicities of the earth tide of semidiurnal and diurnal components.

The cross correlation coefficients for our eight smoothed hourly frequency of earthquakes and four accelerative tidal components have some positive and negative peaks. These peaks may come from a frequency difference between each tidal acceleration and earthquake activity. However, the time lags, that correspond to peaks of cross coefficients, differ from data to data. Hence, we conclude from this statistical analysis that there exists no significant effect of the "Triggering Mechanism for Earthquakes" in the vicinity of Mount Erebus.

8. Discussion

By the Fourier and the cross correlation analyses, we found that there is no significant triggering effect by the earth tide on earthquakes in the vicinity of Mount Erebus. Although the remarkable periodicities about 15 days in the data sets of 83y and 84yb are close to the tidal fortnightly component, we think that these periodicities are attributed rather to the seismic rhythm in this region than to the tidal effect, because this tidal component is much smaller than other components. However, these do not indicate that there is no triggering effect on the earthquakes in this region. Some earthquakes may be affected by earth tides, but we can not find significant triggering effect by the cross correlation analysis. This situation seems to be the same as the case of the Matsushiro Earthquake Swarm. KLEIN (1976) showed also that there is no notable correlation between the 6678 earthquakes during the whole period of the swarm and the semidiurnal tidal component by the statistical study. On the contrary, OIKE and TANIGUCHI (1988) found the four periods in which good correlation is observed between seismicity and dilatational strains due to earth tides for the case of the Matsushiro Earthquake Swarm.

In our spectral calculation, we find prominent frequencies for each data set. These periodicities vary from case to case, but are mostly in the same ranges of 2–4 day for hourly data sets and 10–20 day for daily data sets. These periodicities seem to reflect the seismic rhythms in this region, as the strength of the earth tide is thought to be small compared with low or middle latitude regions. On the other hand,

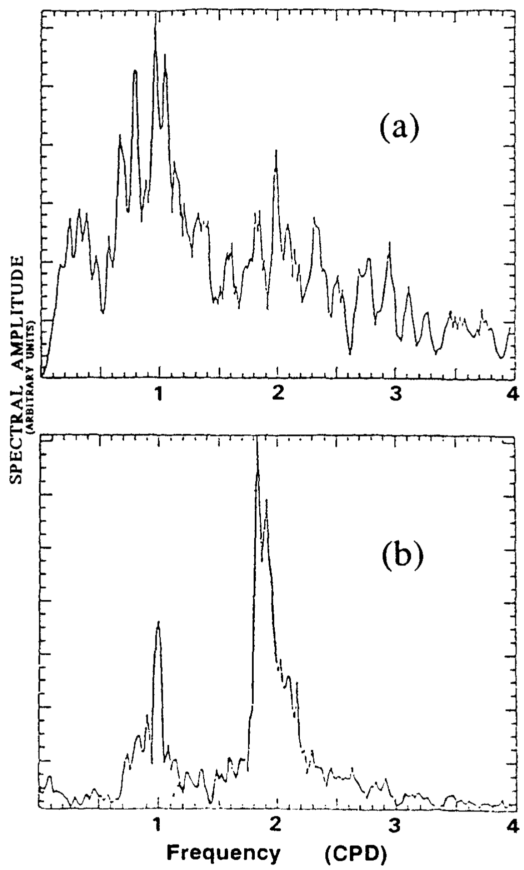

Fig. 4. Amplitude spectra of a swarm at Kilauea Volcano (upper) and the corresponding theoretical dilatational tidal strain (lower), after REYDELEK et al. (1988).

RYDELEK *et al.* (1988) suggested that there are two predominant peaks corresponding to diurnal and semidiurnal tidal components in the earthquake swarms of Kilauea Volcano, Hawaii (Fig. 4). They also suggested that these swarms are triggered by the earth tide. How should we explain this situation? Apparently, the triggering effect depends on the strength of the earth tide and thus the weak tidal effect reveals the intrinsic rhythms of seismic activity in our case.

9. Conclusion

We applied Fourier analysis to investigate variations of seismic activity around Mount Erebus during the period of 1982–1984 and calculated the cross correlations between the hourly frequency of earthquakes in this region and the three components of tidal acceleration and total of them. The results are:

1) Earth tide effects are not clear for the seismic activity in the vicinity of Mount Erebus.

2) The seismic activity in this region shows prominent periodic behaviors of about 2–4 days and 10–20 days. These periodic behaviors appear to be intrinsic seismic rhythm in the vicinity of Mount Erebus.

3) The small effect of tide seems to have revealed these periodicities or intrinsic pattern of seismic activity around Mount Erebus.

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