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A Study on Ice Faulting and Icequake Activity in the Lake Suwa, (2) Temporal Variation of m–Value

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Abstract: Icequake activity and slippage of ice plate at ice faulting, the so-called *Omiwatari*, were observed in the Lake Suwa, Nagano Prefecture, Japan in the period from January 28 to February 1, 1976. The icequakes, faulting and slippage are considered to give a good simulation of the occurrence of earthquakes due to plate motion. The temporal variation of b-value (or m-value) is mainly discussed in this paper. The Gutenberg-Richter's relation holds well in the case of icequakes and b-value is found to be around 0.9. The variation of b-value with respect to time is proved to be significant with the confidence limit of 90%. An interdependent relationship between b-value and slip rate is found. The same relationship also exists in the Matsushiro Earthquake Swarm of 1965–1966 as well as in rock fracture. This suggests the temporal variation of b-value for natural earthquakes depends on the deformation rate in seismic region.

1. Introduction

A big ice faulting, the so-called *Omiwatari*, has occurred in almost every winter in the ice plate of the Lake Suwa, Nagano Prefecture, Japan. The faulting and the associated icequakes give a good simulation for the natural earthquakes and faulting in the Earth. The study of icequakes and ice faulting are advantageous in such points as; (1) The observations of displacement, strain, stress, temperature and cracking activity in ice plate can be made by simple methods and for short period of time, because the temporal variations of these quantities in ice plate are expected to be fairly large in their amplitudes. (2) The shape of ice plate is much simpler than that of the lithospheric plate. (3) The mechanical properties of ice such as elastic and plastic constants are well investigated in the field of ice physics.

The seismological observation of icequakes and the geodetic observation of ice faulting were carried out in the period from January 28 to February 1, 1976, after the preliminary field surveys on Jan. 14, Jan. 31 - Feb. 3 and Feb. 15 in 1975 and on Jan. 17, 1976. A preliminary result for the understanding of dynamic process in ice plate was reported by Hamaguchi *et al.* (1977), this paper being called "paper I" hereafter. The present study concerns mainly with the magnitude-frequency relation of icequakes as well as the relation between b-value, or m-value, and slip rate of ice plate.

The relation between magnitude and frequency for natural earthquakes is usually expressed by the well-known Gutenberg-Richter's (1954) formula. In some cases, especially for micro- and ultramicro-earthquakes, the so-called Ishimoto-Iida's (1939) formula is frequently used;

$$n(A)dA = kA^{-m}dA\ , \tag{1}$$

where A is the observed maximum amplitude, $n(A)$ is the number of earthquakes with the maximum amplitudes between A and $A+dA$, and k and m are numerical constants. The value of b in the Gutenberg-Richter's formula is connected with m-value in the Ishimoto-Iida's one as (Suzuki, 1959)

$$m = b+1\ . \tag{2}$$

This implies the constants m and b have essentially the same meaning. These relationships are recognized to hold well not only in many cases of natural earthquakes but also in fracture of rocks, glasses and other materials.

Some interpretations on the implication of m-value were given by Vinogradov (1962), Mogi (1962), Scholz (1968) and Suzuki and Hamaguchi (1966). According to them, m-value is much affected by heterogeneity and stress condition in material. It is of importance, therefore, to make the simultaneous observation of m-value and other parameters concerning stress, strain, heterogeneity, dilatancy and their time derivatives. This study is mainly engaged in the problem of m-value for icequakes and of its relation to ice plate deformation.

2. Observations

When we began the field observations on January 28, 1976, the Lake Suwa had completely been covered with ice plate and the ice faulting of about 4 km long had already taken place across the lake. The observations of icequake activity and displacement of ice plate were made at the south-eastern part of the lake, where the thickness of ice plate was about 13 cm. The index map of the observations was given in paper I.

(a) *Observation of icequake activity*; Two seismometers of vertical component with the natural frequencies of 4 and 10 Hz were set on the ice plate near the ice fault, about 100 m off the coast (see paper I, Fig. 3). In this paper, however, only the signals detected by the seismometer of 10 Hz were analyzed. The signals were fed to the amplifier with 70 Hz high pass filter and were recorded on a portable data-recorder. The replay of tape was made with the tape speed of 5 times as slow as the

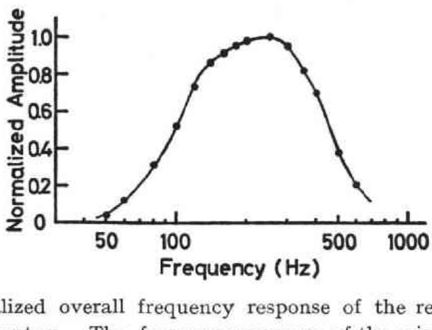


Fig. 1. Normalized overall frequency response of the record and play back system. The frequency response of the seismometer (f_0= 10 Hz) is assumed to be flat in the frequency range of 50–700 Hz.

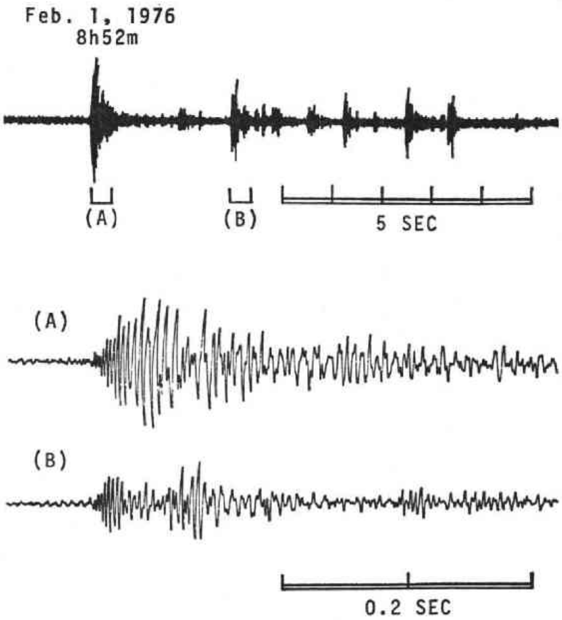


Fig. 2. The seismograms of icequakes around $8^h 52^m$ on February 1, 1976. The parts (A) and (B) in the upper seismogram are represented in the lower two seismograms with the time scale as long as 25 times.

recording speed through a 25 Hz high pass filter onto a pen-recorder; the cut-off frequency corresponding to 125 Hz in the original record. The frequency was chosen because the continuous background noise on ice plate was predominant at the frequency less than 125 Hz. The overall frequency response of the record and play back system is shown in Fig. 1, assuming that the frequency response of the seismometer is flat in the range of 50–700 Hz. Fig. 2 shows an example of icequake signals, which look quite similar to natural microearthquakes.

(b) *Observation of slip rate*; On the initial stage of faulting, two ice plates had clashed to each other at the fissure, as shown in Photo I in paper I, and later one plate have thrusted up on the other, as shown schematically in Fig. 3, where the plate X thrusted on the Y presumably in the forms continuous creep and/or spontaneous stick-slip. The displacement discontinuity across the fault finally amounted to about one meter.

The observation of slippage was performed at about 10 m off the coast on February 1, 1976 (see index map in paper I). The slippage between ice plate X and Y across the fault is schematically illustrated in Fig. 3. For the easiness of observation, some part of ice fragment between bench marks A and B (shown by dots in Fig. 3) were artificially scraped off in actual case. The distances $\overline{AB}$ and $\overline{CD}$ in Fig. 3 were measured using a handy type measure. While the distance $\overline{CD}$ did not vary within the accuracy of measurements, the distance $\overline{AB}$ markedly changed with respect to time. Therefore the plate Y was fixed to the coast and the plate X slipped towards Y. This is confirmed also by the triangulation surveying described in paper I. The initial distance between A and B was set to be about 8 meters, and the slippage of the

Table 1. Summary of basic data for temporal variation of distance between A and B in Fig. 3 on February 1, 1976.

Time	Distance	Slippage	Time	Distance	Slippage
7h 23m	7m 84cm 3mm	0.0cm	9h 10m	7m 66cm 0mm	18.3cm
25	82 1	2.2	13	64 8	19.5
35	81 6	2.7	17	63 0	21.3
40	81 2	3.1	20	61 8	22.5
45	80 9	3.4	25	61 0	23.3
50	80 4	3.9	31	60 0	24.3
55	79 7	4.6	39	58 4	25.9
57	79 0	5.3	43	56 2	28.1
8 02	78 4	5.9	50	51 6	32.7
08	77 3	7.0	57	48 5	35.8
10	77 0	7.3	10 06	44 4	39.9
17	76 1	8.2	15	43 5	40.8
18	75 8	8.5	41	42 7	41.6
23	74 9	9.4	55	42 3	42.0
30	73 6	10.7	11 10	42 0	42.3
38	72 3	12.0	25	41 8	42.5
46	70 6	13.7	43	41 6	42.7
53	69 6	14.7	12 00	41 5	42.8
56	69 0	15.3	35	41 3	43.0
9 01	67 6	16.7	13 15	41 5	42.8
09	67 2	17.1	14 03	41 1	43.2

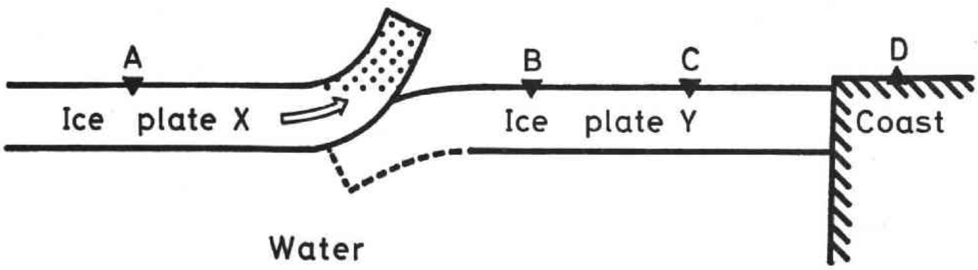


Fig. 3. Simplified sectional plan of ice plate at fault. A, B, C and D are the bench marks. The ice plate X is slipping towards the ice plate Y which is fixed to the coast. The ice fragment indicated by dotted part was actually scraped off when the distance between A and B was measured.

ice plate X was measured with time intervals between one to ten minutes depending on the slip activity. The amount of slippage during 7^h23^m to 14^h03^m are listed in Table 1. The total amount of slippage in the above period was 43.2 cm.

3. Results

The data of the icequake activity and the slippage of ice plate are analyzed in special reference to their relation. Fig. 4 shows the frequency of icequakes and the slip rate of the ice plate X during the period of 7^h25^m to 12^h00^m on February 1, 1976. Since the observation of slippage was carried out at unequally interval of time, as mentioned previously, the Chebyshev's polynomial of seventy four degrees is used to interporate the observed values. The slip rate is obtained as the time derivative of thus calculated values. The counted number of icequakes with trace amplitude larger than 2.5 mm were also smoothed by applying the Chebyshev's polynomial. The icequake activity began to increase at about 7^h45^m and the maximum was during 9^h30^m to 9^h40^m. As many as 109 events/min. were detected at 9^h37^m. It decreased sharply at about 10^h00^m. The total number of icequakes during 7^h25^m to 12^h00^m was 3201. The slip rate increased gradually at about 7^h50^m and the maximum was seen during 9^h40^m to 10^h00^m. It decreased sharply at about 10^h10^m. There is a good correlation with some time lag between the frequency of icequakes and the slip rate.

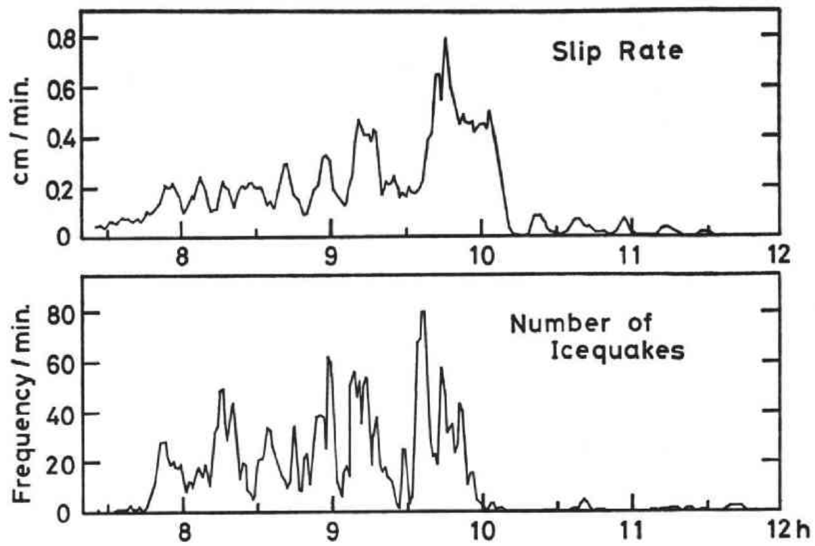


Fig. 4. The frequency of icequakes per minute and the slip rate of ice plate X during 7^h25^m to 12^h00^m on February 1, 1976 (redrafted from paper I). These values are obtained by using the interporation scheme by the use of the Chebyshev's polynomial. It is noticeable that there is a good correlation between icequake activity and slip rate.

The period from 7^h25^m to 12^h00^m on February 1 was divided into fifteen sub-periods with time interval of 10 minutes except for the sub-periods from 7^h25^m to 7^h50^m and from 10^h10^m to 12^h00^m, when the icequake activities were very low. The icequake activity in the sub-period from 10^h00^m to 10^h10^m was also very low, however this sub-period was remained in order to investigate the tendency with time as mentioned later. The events in each sub-period are classified according to their trace amplitude as listed in Table 2.

When the amplitude-frequency distribution is expressed by Eq. (1), the m-value is estimated by the following equation (Utsu, 1965);

$$m = \frac{N \log e}{\sum_{i=1}^{N} \log A_i - N \log A_{min}} + 1\,, \tag{3}$$

where A_i is the amplitude of the i-th event, N is the number of icequakes with the

Table 2. Summary of icequake activity on February 1, 1976. Icequakes are divided into fifteen sub-periods and classified according to their trace amplitudes. The lack at the period from 8^h30^m to 8^h40^m is due to the exchange of magnetic tape.

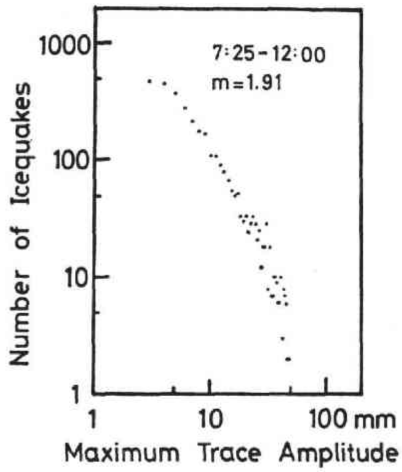
Amplitude (mm)	7:25 ~ 7:50	7:50 ~ 8:00	8:00 ~ 8:10	8:10 ~ 8:20	8:20 ~ 8:30	8:40 ~ 8:50	8:50 ~ 9:00	9:00 ~ 9:10	9:10 ~ 9:20	9:20 ~ 9:30	9:30 ~ 9:40	9:40 ~ 9:50	9:50 ~ 10:00	10:00 ~ 10:10	10:10 ~ 12:00
2.5~ 3.4	20	46	26	42	19	24	47	31	51	28	41	45	30	3	16
3.5~ 4.4	18	39	26	47	31	12	49	36	41	17	46	46	31	1	12
4.5~ 5.4	7	32	26	41	22	25	27	30	40	14	44	36	24	2	5
5.5~ 6.4	4	15	11	32	15	18	30	28	30	9	40	30	10	1	3
6.5~ 7.4	4	15	7	23	20	10	18	17	29	12	32	17	11	0	2
7.5~ 8.4	3	11	4	17	6	10	24	19	20	6	25	21	9	1	2
8.5~ 9.4	2	12	5	24	8	6	15	14	19	4	32	20	10	0	1
9.5~10.4	0	4	3	13	7	9	10	12	21	1	16	8	4	1	1
10.5~11.4	5	9	4	10	2	5	15	13	19	3	13	4	5	0	2
11.5~12.4	2	6	2	12	2	6	12	6	9	3	17	8	5	0	0
12.5~13.4	0	3	2	7	5	5	13	1	13	5	11	9	3	0	1
13.5~14.4	1	1	1	4	3	4	5	6	11	2	11	13	4	0	0
14.5~15.4	0	4	1	6	2	2	6	5	9	0	10	7	2	1	0
15.5~16.4	0	3	3	3	0	4	5	1	4	2	12	5	6	0	1
16.5~17.4	1	2	1	6	4	1	5	5	8	1	10	6	2	0	0
17.5~18.4	0	3	0	1	1	0	6	3	2	3	7	5	1	0	1
18.5~19.4	0	2	1	1	0	5	9	0	4	1	3	2	2	0	0
19.5~20.4	0	4	4	2	1	2	2	0	6	0	8	2	2	0	0
20.5~21.4	0	1	1	4	1	2	5	0	1	1	5	2	0	0	1
21.5~22.4	0	2	0	5	1	4	5	0	5	1	3	2	1	0	0
22.5~23.4	2	2	0	1	0	3	7	3	7	1	1	6	0	0	0
23.5~24.4	0	0	0	3	2	2	5	2	5	0	6	1	2	0	1
24.5~25.4	0	0	0	0	0	2	6	2	5	0	3	3	0	0	0
25.5~26.4	1	1	1	3	1	2	4	1	1	1	3	5	1	0	0
26.5~27.4	0	0	0	1	1	0	1	1	3	1	4	0	0	0	0
27.5~28.4	1	0	0	1	1	1	2	0	2	1	3	3	3	0	0
28.5~29.4	0	1	0	4	0	1	3	1	1	1	3	2	1	0	0
29.5~30.4	1	1	1	3	1	2	7	0	2	0	4	4	3	0	0
30.5~31.4	0	2	0	1	0	1	1	0	1	0	1	0	0	1	0
31.5~32.4	0	1	0	0	2	3	5	1	1	0	1	1	3	0	0
32.5~33.4	0	0	0	0	0	0	2	1	2	0	1	1	0	0	0
33.5~34.4	0	0	0	0	0	1	0	1	2	1	1	1	0	0	0
34.5~35.4	0	1	1	1	0	0	1	2	1	1	1	0	0	1	0
35.5~36.4	1	0	1	1	1	2	2	1	1	0	0	0	0	0	0
36.5~37.4	0	0	0	0	0	0	2	1	0	1	3	1	1	0	0
37.5~38.4	0	0	0	0	0	0	1	0	1	1	3	0	0	0	0
38.5~39.4	0	0	0	0	0	0	1	0	2	0	2	1	0	0	0
39.5~40.4	0	0	0	1	0	0	2	1	0	2	2	0	2	0	0
40.5~41.4	0	0	0	0	0	0	0	0	2	0	0	0	1	0	0
41.5~42.4	0	0	0	0	1	0	1	3	1	0	2	0	0	0	0
42.5~43.4	0	0	0	0	0	3	0	1	0	0	0	2	1	0	0
43.5~44.4	0	0	1	0	0	0	0	1	2	0	0	2	0	0	0
44.5~45.4	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
45.5~46.4	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0
Total Number	73	223	133	320	160	177	361	250	384	125	431	322	181	12	49

trace amplitudes larger than or equal to the smallest amplitude A_{min}, which is taken to be 2.5 mm in this study. The m-values obtained by Eq. (3) for the total period and for each sub-period are listed in Table 3, although the m-value for the sub-period from $8^h 30^m$ to $8^h 40^m$ on February 1 is not listed because it was the time of exchange of magnetic tape. The slip rate and the number of icequakes in each sub-period are also given in

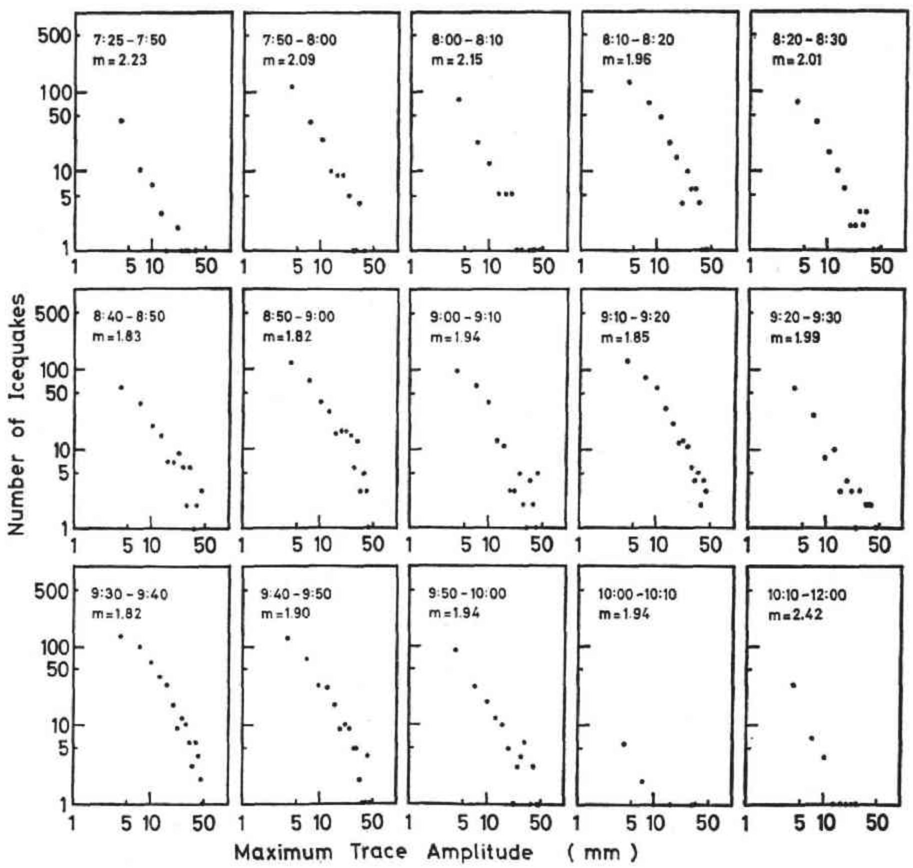
Table 3. The amplitude-frequency distribution is plotted on a diagram in doubly logarithmic scale as shown in Figs. 5 (a) and (b). It is clear that every amplitude-frequency distribution can be approximated by a straight line on the diagram. Fig. 6 shows the temporal variations in m-value (open circle) and slip rate (solid circle). Error bars for m-values are the ranges with the confidence limit of 90%. On February 1, the m-value was estimated to be 2.23 ± 0.24 in the period from $7^h 25^m$ to $7^h 50^m$, and it decreased gradually with time lapse until the minimum value of 1.82 ± 0.08 in the period from $8^h 50^m$ to $9^h 00^m$. After it slightly increased for about half hour, the minimum m-value appeared once more between $9^h 30^m$ to $9^h 40^m$ and later the m-value increased again, the m-value of the last sub-period from $10^h 10^m$ to $12^h 00^m$ was 2.42 ± 0.33. Some variation of m-value is significant with the confidence limit of 90% although it is not always so when the limit of 95% is adopted. The change in m-value on January 30 is seen in Table 3 and Fig. 6. It is clear that the temporal variation of m-value on

Table 3. Calculated m-values and slip rates for total and each sub-period on January 30 and February 1, 1976. N is the number of icequakes.

No.	Time	Slip rate (cm/min.)	m-value	Confidence limit 90%	N
	Jan. 30, 1976				
	7:50-10:30	—	1.95	1.93-1.96	3876
a	7:50- 8:00	—	2.48	2.35-2.62	212
b	8:00- 8:10	—	1.95	1.79-2.11	70
c	8:10- 8:20	—	2.23	1.81-2.65	24
d	8:20- 8:30	—	1.97	1.89-2.05	256
e	8:30- 8:40	—	2.31	2.04-2.58	53
f	8:40- 8:50	—	2.33	2.13-2.53	93
g	8:50- 9:00	—	1.80	1.75-1.85	467
h	9:00- 9:10	—	1.80	1.76-1.84	875
i	9:10- 9:20	—	1.81	1.78-1.84	965
j	9:20- 9:27	—	2.10	2.00-2.20	190
k	9:50-10:00	—	2.34	2.20-2.48	180
l	10:00-10:10	—	2.42	2.24-2.60	121
m	10:10-10:20	—	2.46	2.18-2.74	60
n	10:20-10:30	—	2.62	2.50-2.74	310
	Feb. 1, 1976				
	7:25-12:00	0.15	1.91	1.87-1.94	3201
1	7:25- 7:50	0.07	2.23	2.00-2.47	73
2	7:50- 8:00	0.18	2.09	1.98-2.21	223
3	8:00- 8:10	0.17	2.15	1.98-2.31	133
4	8:10- 8:20	0.15	1.96	1.87-2.05	320
5	8:20- 8:30	0.18	2.01	1.88-2.15	160
	8:30- 8:40	0.16	—	—	—
6	8:40- 8:50	0.19	1.83	1.72-1.93	177
7	8:50- 9:00	0.23	1.82	1.74-1.89	361
8	9:00- 9:10	0.18	1.94	1.84-2.04	250
9	9:10- 9:20	0.40	1.85	1.78-1.92	384
10	9:20- 9:30	0.19	1.99	1.84-2.14	125
11	9:30- 9:40	0.24	1.82	1.75-1.88	431
12	9:40- 9:50	0.61	1.90	1.81-1.98	322
13	9:50-10:00	0.45	1.94	1.83-2.06	181
14	10:00-10:10	0.35	1.94	1.47-2.41	12
15	10:10-12:00	0.02	2.42	2.09-2.75	49



(a)



(b)

Fig. 5. The amplitude-frequency distribution of icequakes on February 1, 1976. (a) For the total period (from $7^h 25^m$ to $12^h 00^m$). (b) For the fifteen sub-periods given in Table 2. The interval of trace amplitude is taken as 3 mm.

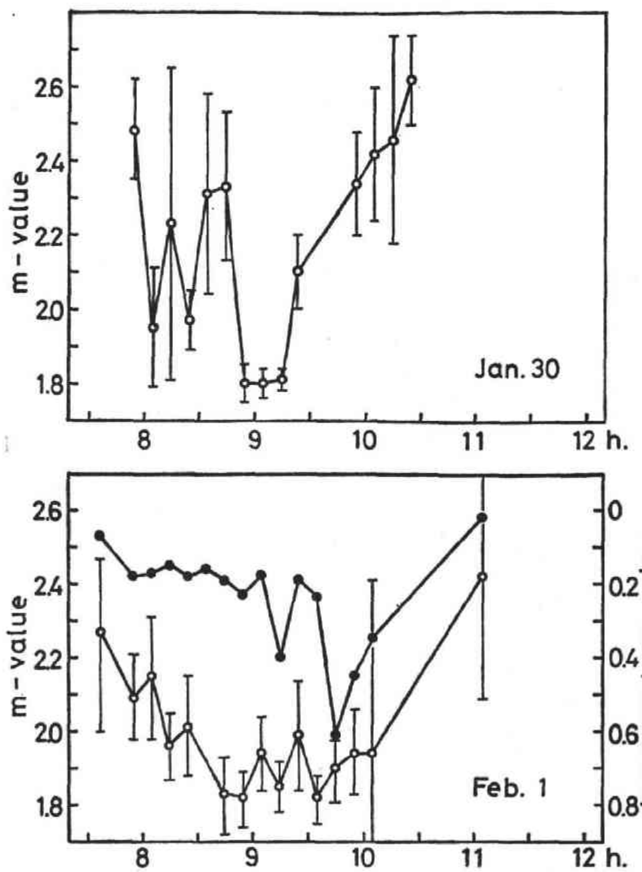


Fig. 6. Temporal variation of *m*-values (open circle) and slip rate (solid circle). Error bars of *m*-value indicate the range with 90% of confidence limit. Upper graph; On January 30, 1976, in which no observation of slippage made. Lower graph; On February 1, 1976. It is clear that the temporal variation of *m*-value has a fairly good correlation with slip rate.

January 30 is similar to that on February 1. It may be safely concluded with 90% of confidence limit that the *m*-value of icequakes varies with a characteristic aspect of decrease and increase within a short period of time. The slip rate also shows a temporal variation as seen in Figs. 4 and 6. Two sudden increases in slip rate are recognized in the periods from $9^h 10^m$ to $9^h 20^m$ and from $9^h 40^m$ to $9^h 50^m$ on February 1. Fig. 6 indicates interesting facts that there is a fairly good correlation between *m*-value and slip rate and that the time of occurrence of high slip rate is preceded by the minimum *m*-value.

The *m*-value plotted versus slip rate in abscissa is shown in the middle part of Fig. 7, the numeral aside each point being the sub-period's number in Table 3. The time sequence of the relation between *m*-value and slip rate is indicated by the numerals in the figure. An interdependent relationship between *m*-value and slip rate is clearly seen in this figure, too. The slip rate is small when the *m*-value is large, and it increases gradually as the m-value decreases. After m-value becomes the minimum one, the slip rate increases in spite of almost constant m-value. This hysteresis phenomenon of m-value found for icequakes is very interesting and it may be worthwhile to compare it with the results in fracture experiments and natural earthquakes.

4. Discussions

The relation between amplitude and frequency is expressed by Eq. (1) in the case of icequakes in the Lake Suwa. The obtained m-values for the whole periods on January 30 and on February 1, 1976 are 1.95 ± 0.02 and 1.91 ± 0.04, respectively. Omote *et al.* (1955), who observed ice tremors in the same lake, reported that the m-value of the tremor is 1.8 ± 0.2. Present results agree well with their m-value, in spite of the big difference in sensitivity and in frequency range of the recording instrument between the two cases. It is also interesting that the m-value of 1.8 to 2.0 for icequakes coincides with the common m-value for natural earthquakes.

The temporal variation of m-value has been reported in some cases of natural earthquakes. For examples, in the case of Matsushiro Earthquake Swarm, the Party for Seismographic Observation of Matsushiro Earthquakes and the Seismometrical Section, Earthquake Research Institute (1967) and Hamada (1968) obtained the m-values for one month and every ten-day intervals, respectively. VanWormer *et al.* (1975) obtained the m-values for about one day interval in the small earthquakes near Fairbanks, Alaska. Watanabe (1976) also obtained the m-values for about four-hour interval at Amagi Earthquake Swarm accompanied the Izu Earthquake of 1974. These results reported that the m-value changed during a short period of time from several months to several hours depending on the magnitude of the principal shock in earthquake swarm or aftershock sequence and that the minimum m-value appeared before the occurrence of main shock or peak activity. The duration time of increase in m-value for natural earthquakes mentioned above seems to be shorter than that of decrease. Our results for icequakes show that m-value changes only within four hours and that two minima at $8^h 50^m$ and $9^h 30^m$ on February 1 correspond to two peaks of icequake activity and precede to two high slip rates by several minutes. The duration time of increase in m-value is about equal to that of the decrease.

The sudden increase in slip rate across the fault, which were accompanied felt shocks and audible sounds, causes a large stress drop within ice plate. The stress state in ice plate due to the thermal volumetric expansion under some boundary conditions is high immediately before the occurrence of large slippage. Fig. 6 means that the smaller m-value recognized before the large slip rate correspond to the higher stress state in plate and that the decrease in m-value during $7^h 25^m$ to $9^h 00^m$ corresponds to the increase in stress due to temperature rising. The large m-value and the small number of icequakes during $10^h 10^m$ to $12^h 00^m$ are due to the stress relaxation at the grain boundary of ice, because the surface temperature of ice plate is nearly 0°C after 10 a.m. (see paper I, Fig. 5).

Vinogradov (1962) reported in his paper on rock fracture experiment that a relation exists between the rate of deformation and the coefficient γ, which appears in the energy-frequency relation; $\log n(K)=\delta+\gamma K$, where $K=\log E$. The m-value in Eq. (1) relates to the γ-value as $m=\beta\gamma+1$ through the relation between energy E and magnitude M for an earthquake; $\log E=a+\beta M$. His experimental results for limestones and gypsums with sand are shown in the upper part in Fig. 7. The similar relation obtained in the present case is shown in the middle part. The relation between m-value and strain rate obtained for Matsushiro Earthquake Swarm in the period from

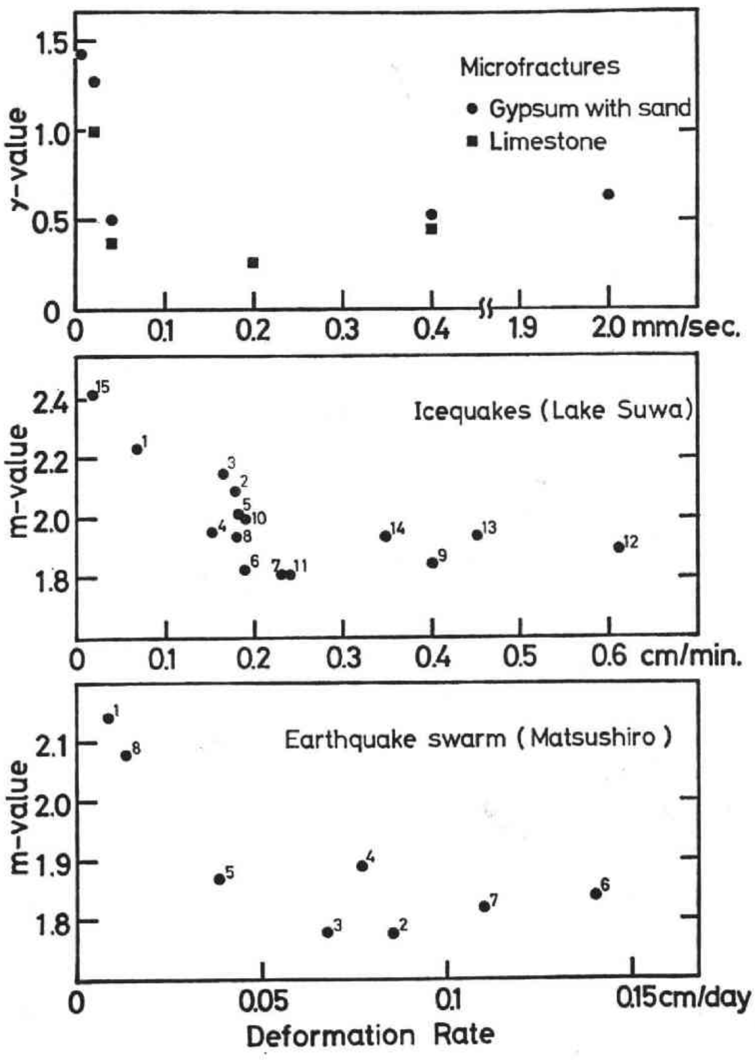


Fig. 7. The interdependent relation between m- or γ-value and deformation rate. Upper; For the experiment of rock fracture after Vinogradov (1962). Middle; For the icequakes on February 1, 1976. The numeral aside each plot corresponds to the number of sub-period given in Table 3. Lower; For Matsushiro Earthquake Swarm during December 9, 1965 to November 12, 1966. The numerals indicate the following periods; (1) Dec. 9∼Mar. 2, (2) Mar. 2 ∼ Apr. 12, (3) Apr. 13 ∼ Apr. 18, (4) Apr. 18 ∼ May 5, (5) May 6 ∼ July 3, (6) July 3 ∼ Sep. 7, (7) Sep. 8 ∼ Oct. 13, (8) Oct. 14 ∼ Nov. 12.

December, 1965 to November, 1966 is seen in the lower part in Fig. 7, of which diagram is complied from the seismic and geodetic observation data at Zozan station. The m-values are taken from the report by the Party for the Seismographic Observation of Matsushiro Earthquakes and the Seismometrical Section, Earthquake Research Institute (1967) and the strain rates are calculated from the report by Kasahara *et al.* (1967). It is of interest that the same relationship between m-value and strain or slip rate can be found in three cases irrespective of the wide difference in media and dimensions. This close correlation suggests that some common process controls both size distribution of fracturing and strain rate, and the study of icequakes is useful for the understanding of the physical basis in magnitude statistics and other problems related to seismicity.

In contrast to the present results, McGarr (1976) who studied the magnitude statistics of mine tremors and deformation associated with the enlargement of excavations concluded that the b $(=m-1)$ value is independent of the rate of aseismic tilt deformation and that stress change by some hundreds bars does not cause any measurable effect on b-value. However, this different dependency on deformation rate between the present results and McGarr's one can be naturally understood when we evaluate the order of tilt deformation rate at the mine. The observed deformation rate of the order of 10^{-5} radian/day (McGarr, 1976) is very large in comparison with that of rock in natural seismic active region; for example, the maximum tilt rate recorded at the Matsushiro Earthquake Swarm on August 1966 is, at the most, 1.5×10^{-5} radian/month or 5×10^{-7} radian/day (J.M.A., 1968). It is considered, therefore, that the relationship of b-value versus tilt deformation rate obtained by McGarr shows only the portion in a high deformation rate within a wide range of relationship, where b-value is almost stable in spite of different deformation rate as shown in Fig. 7. It appears to be sound that b- or m-value is dependent on the rate of seismic deformation, especially on lower level of deformation rate, as in the present case.

Recently Hirasawa *et al.* (1977) showed that the m-value decreases with increases in volumetric strain but the change in m-value depends also on the history of rock deformation, based on the uniaxial compression test of rock specimen. The above study implies that the change of m-value of natural earthquakes, icequakes and rock fracturings must be investigated in connected with deformation process.

5. Conclusions

The icequake activity and the slip rate of ice plate were observed in the Lake Suwa, Nagano Prefecture, Japan. The amplitude-frequency relation and the dependency of m-value on slip rate are discussed in this paper based on the data of January 30 and February 1, 1976 and the following results are obtained;

(1) The relationship between amplitude and frequency of icequakes is expressed by Eq. (1).

(2) The m-value in Eq. (1) for icequakes is estimated to be $m=1.95\pm0.02$ on January 30 and $m=1.91\pm0.04$ on February 1 with 90% of confidence limit. These values agree well with the common value for natural earthquakes.

(3) The *m*-value varies significantly with time if 90% of confidence limit is adopted. It is noticeable that the *m*-value decreases gradually with increasing icequake activity and that the minimum value appears at the time of the highest icequake activity preceding to high slip rate.

(4) The relationship between *m*-value and deformation rate, which is originally argued by Vinogradov (1962), is applicable to the present case as well as to the case of Matsushiro Earthquake Swarm in the period from 1965 to 1966.

(5) The *m*-value depends upon the deformation rate in the seismic region.

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