A Study on Ice Faulting and Icequake Activity in the Lake Suwa,(1) Preliminary Field Observations

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雑誌名	Science reports of the Tohoku University. Ser. 5, Geophysics
巻	24
号	1/2
ページ	43-54
発行年	1977-03
URL	http://hdl.handle.net/10097/44741

Sci. Rep. Tôhoku Univ., Ser. 5, Geophysics, Vol. 24, Nos. 1/2, pp. 43-54, 1977.

A Study on Ice Faulting and Icequake Activity in the Lake Suwa,
(1) *Preliminary Field Observations*

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(Received December 4, 1976)

Abstract: Ice faulting and icequake activity in the Lake Suwa, central Japan, were observed in 1975 and 1976 from the viewpoint that these phenomena give good simulations of natural earthquakes and of the plate tectonics. The phenomenological feature of the faultings is briefly described. The observations of ice-plate deformation and icequake activity were made in 1976. The main results are summarized as: I. The strain field of an ice plate in the morning and night is contraction in N-S direction, whereas it is E-W elongation in the afternoon. The amount of strain is calculated to be the order of 10^{-3}. II. A stationary slippage between two ice-plates was observed as well as many sudden slippages of stick-slip type. Icequake activity closely relates to the rate of the stick-slips. III. The peak activity of icequakes usually precedes to the occurrence of stick-slip at the ice-plate boundary by several minutes. Some physical interpretations of the observed phenomena are also given.

1. Introduction

It is a well-known phenomenon that the so-called *Omiwatari*, a large faulting of ice plate, occurs in the Lake Suwa, Nagano Prefecture, central Japan, when the lake is completely covered by an ice plate of thickness more than 10 cm.

There have been many documentary records of this phenomenon since the end of the fourteenth century. The records collected by Tanaka (1918) show that the large ice faulting across the whole lake has occurred in almost every cold winter with a preferred direction of fault strike. The faultings are usually accompanied with a rumbling sound.

Some Japanese seismologists have paid their attentions to this ice-plate fracture from the viewpoint that the phenomenon might be a model of seismic sources. Matuzawa (1953, 1964) stated in his thermodynamical theory on the earthquake occurrence that the development of the ice faulting in the Lake Suwa gives a good model of small scale for the volume increase in the horizotal direction by the intrusion of magma into cracks within the earth's crust. Kishinouye (1943) gave a brief explanation of the fracture mechanism of the ice plate, based on his measurement of linear expansion coefficient of the lake ice. He also studied the propagation of elastic waves generated by ice crackings and derived a dispersion curve of the waves, however, he mentioned that it was premature to discuss the physical property of the waves. Omote *et al.* (1955) made an extensive study on the ice tremors in connection with the temporal variations of strain within the ice plate and of temperatures in the air and ice plate. They demonstrated that the icequake activity in the evening was closely related to the contraction of the ice plate.

Although many efforts have been made by these authors, there has been no comprehensive interpretation on the mechanism of this phenomenon. This problem is certainly important in seismology, especially in the plate tectonics theory, because the ice plate and the water underneath it give a good model for lithosphere and athenosphere system in the actual earth and because the ice faulting corresponds to the cataclysmic event due to the interaction of plate motions which is thought to be the main cause of geophysical and geological processes.

The ice faulting in the Lake Suwa, in this sense, provides us with a very good field for experiments on the problem. The experiment may give us an accurate knowledge on stress, strain, and anelastic properties of the ice plate, as well as their interrelationships, which may be the key factors to solve the problem. Another favorite situation is that the deformation in this case develops very quickly in comparison with that in rocks because of low fracture strength and high ductility of ice. This is advantageous to observe the whole process within a very short period.

Under these considerations, we have planned a comprehensive observation of the

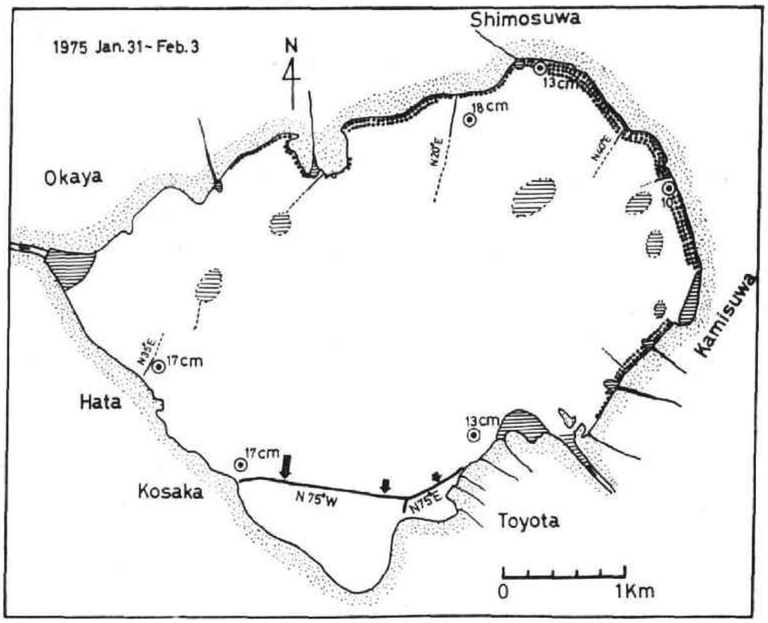

Fig. 1. Simplified index map of the observation in 1975 showing major fractures and ice condition during the period of Jan. 31 to Feb. 3. The thick solid lines indicate the main faulting with the strike of N75°W and N75°E. The northern large plate thrust onto the sourthern plate in the final stage of the fault development, as indicated by the arrows. The thin solid and dashed lines show large tensile fractures. The amount of thrust-up of the ice plate onto the coast is expressed qualitatively by thick dots on the coast. The numeral attached double circle shows the ice thickness mearsured in cm. The shaded portion in the lake indicates that the ice plate was melted by the small hot springs at the lake bottom or by artificial causes.

ice faulting and icequakes in the Lake Suwa. This paper reports the results of the first step of our program. The field surveys of the ice faulting have been made in the winters of 1975 and 1976. The preliminary results afforded us a phenomenological understanding of the dynamical process, such as the stress and strain accumulations and also the deformation and faulting within the ice plate.

2. Phenomenological Description of Ice Faulting

(1) *Field observations in 1975*

The surface of the Lake Suwa was completely covered by an ice plate on January 14, 1975 according to the Local Weather Station of J.M.A. at Suwa city. Our first observation in this year was carried out in the period of January 31 to February 3. The ice faulting had occurred before this time, forming a fault of about 2 km long off the coast of Kosaka in the western part of the lake (see Fig. 1). The second observation was made on February 15, when the faulting had developed into a distinct overthrust fault. Results of these observations are summarized in Fig. 1.

General strike of the main fault was N75°W in the western portion and N75°E in the eastern portion. Besides the main fault, there were several noticeable cracks of tensile type, as shown in Fig. 1 by thin solid and dashed lines. These tensile fractures were located at various places all over the lake. The thickness of ice plate in Fig. 1 shows the values measured during the first observation.

The ice plate had expanded onto the coast of the lake at some part of the lake as shown by dots in Fig. 1. The thrust-up of the ice plate onto the coast was more than 1 m along the northern and eastern coasts of the lake but it was scarcely seen in the southern and western parts.

In the first observation, the difference in the state of fracture was seen between the western and eastern portions of the main fault. In the eastern part of the main fracture, many number of small fragmental ice pieces were found between the boundary of two ice plates, the diameter of ice pieces being one to several centimeters. The two plates looked like pushing each other at the boundary with an upheaval of edges of the plates. In the western part, on the other hand, two ice plates was observed so as to be in direct contact, without fragmental ice-pieces, plate edges being slightly uplifted or subsided. The western part is considered to be in more advanced stage of faulting than that in the eastern part. In other words, passing through the stage observed in the eastern part, the fragmental pieces had been squeezed out from the fault planes by the pressure between two ice plates. Many acoustic emissions due to brittle crushings and crackings were observed by using seismometer around the fault. The pictures of the main fault taken at the first and second observations are seen in Photos. 1 and 2, which show well the above mentioned features.

(2) *Field observations in 1976*

The observation in 1976 was made on January 17 when the thickness of ice

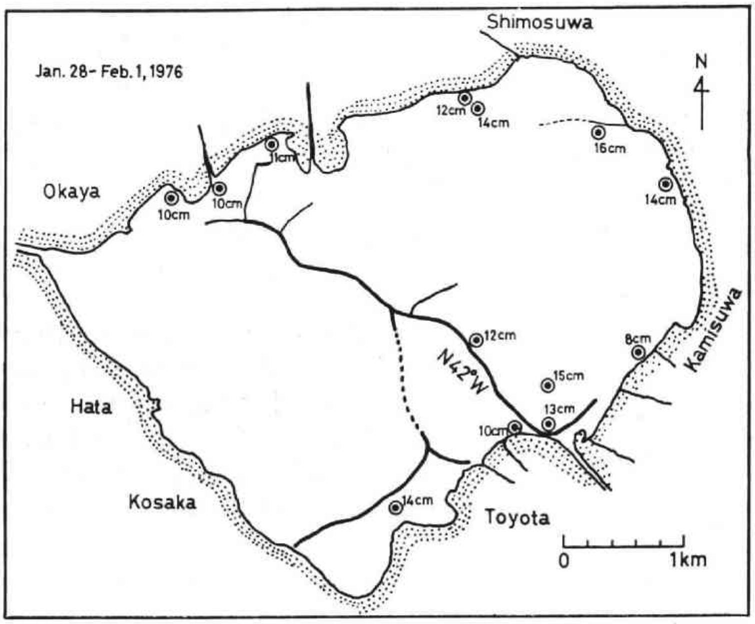

Fig. 2. Simplified index map of the observation in 1976. The main faulting across the lake shows the strike of N42°W. The geodetic and seismological observations were carried at the south-eastern portion of the main faulting. The information about the thrust-up onto the coast and the unfrozen portion are omitted in this map. The symbols used here are the same as those in Fig. 1.

plate was about 10 cm and no distinct fracture was found on the ice plate. The purpose of this observation was to search the state of ice plate and also to set up some bench marks for the survey carried out at the time of second observation. Several days after this observation, the ice plate was divided into many fragments owing to strong wind and rise of air temperature. Later the ice plate was rebuilt again on the lake.

Second observation was made in the period of January 28 to February 1, when the main faulting had occurred across the whole lake as seen in Fig. 2. Thickness of the ice plate was measured, the result being shown in Fig. 2. The strike of the main faulting was N42°W and sharply turned to N45°E at the southern end of the fault. The faulting in the north-western and south-eastern ends showed more active deformation and the large amount of dislocations than those in the central part. The thrust-up of ice plate onto the coast was also observed in this year, and the pattern of the thrust-up distribution was almost the same as that in 1975. There is a possibility that the non-uniform distribution of thrust-up, which means the anisotropic expansion of the ice plate, may be somehow related to the mechanism of the main faulting. However, there is no description about the thrust-up in old documents and it is difficult to make a detailed discussion at the present stage of this study.

3. Geodetic Measurement of Deformation in Ice Plate

Temporal variation of displacement field within the ice plate was observed at the

Photo. 1. The western part of the main fault on Feb. 1, 1975. It is clear that the two ice plates were directly in contact with each other and the fragmental pieces had been squeezed out from the fault boundary. The northern plate is in the left side in this photo.

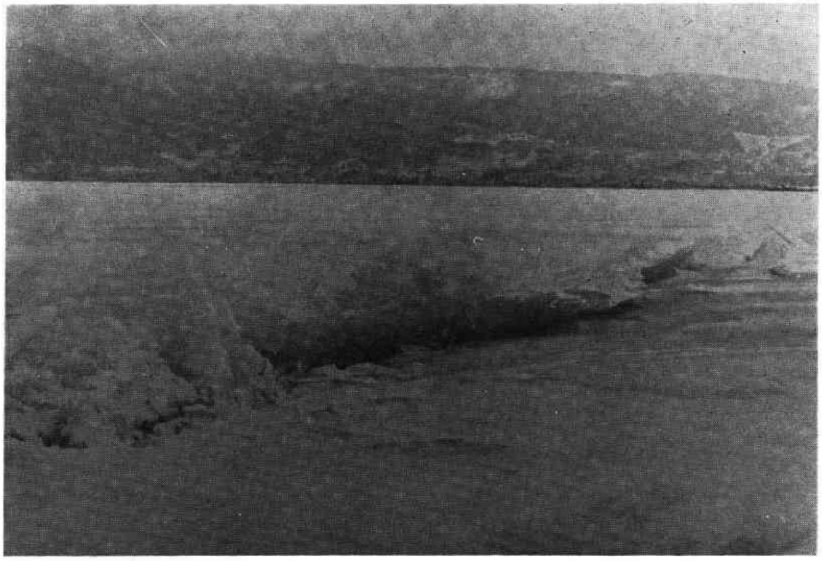

Photo. 2. The western part of the main fault on Feb. 15, 1975. The northern plate thrust onto the southern one. The amount of dislocation was about 2 m.

Photo. 3. The southern part of the main fault on Jan. 28, 1976. The fault strike seen in this photo is N45°E.

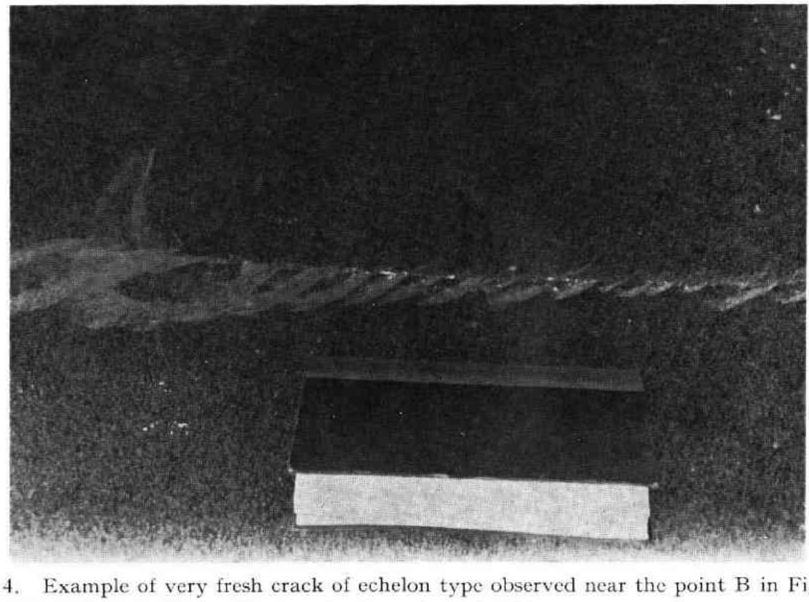

Photo. 4. Example of very fresh crack of echelon type observed near the point B in Fig. 3 at 9 o'clock on Feb. 1, 1976. The length of notebook is 16.3 cm.

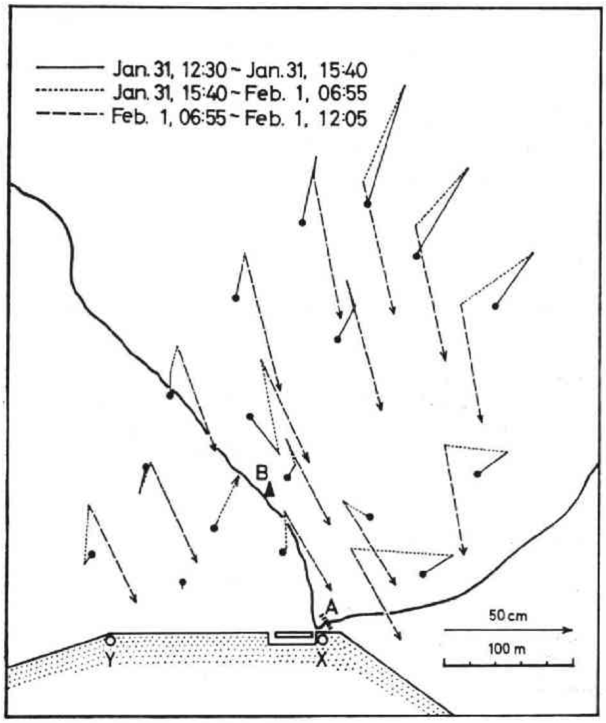

Fig. 3. The displacement vectors observed in 1976 for the three periods; (A) 'afternoon', (B) (B) 'night' and (C) 'morning'. The symbol marked by A indicates the place where the slip in the fault is measured and the triangle marked by B is the position of seismometers. The circles marked by X and Y are the fixed points on the coast for the geodetic measurement. The scales for displacement and for geography are given separately in the figure.

south-eastern portion of the main fault by measuring the distances among bench marks in the period from the noon of January 31 to the noon of February 1, 1976. The picture of the main fault near the point A in Fig. 3 is seen in Photo. 3. Seventeen bench marks were set in the area of approximately 350×300 m^2 and the position of bench marks was measured from the two fixed points on the coast. The period of observations is divided into three parts; 12^h30^m–15^h40^m ('afternoon') 15^h40^m–06^h55^m ('night'), and 06^h55^m–12^h05^m ('morning'). The loci of observed displacement are seen in Fig. 3 in addition to the locations of bench marks and the fixed points on the coast.

The displacement vector of each bench mark in the period of 'morning' is almost the same one another in its direction as well as in magnitude. The movement of the plate looks like to be pushed off from the center of the lake to the coast. The amount of displacement is about 40 cm near the coast and about 55 cm off the coast.

The vectors in the 'night' show more complicated pattern in comparison with those in the 'morning'. The distribution of displacements represents the tendency of clockwise rotation though the amount of displacements is not uniform. The displacement field in the 'afternoon' is also complicated, but there is a systematic tendency that the displacement in NE-SW direction is somewhat predominant.

Based on the observational data, the dilatation, rotation, maximum shear, principal strain, and principal axes of strain can be calculated under the assumption of two-dimensional problem. The average values of dilatations, rotations, and maximum shears for triangles are listed in Table 1 for the periods of 'morning', 'afternoon', and 'night'. The distribution of principal axes is seen in Fig. 4. The amount of maximum principal strain is estimated to be the order of 10^{-3} in every period, however, the strain

Table 1. Summary of the average strain components for the three periods; 'afternoon', 'night' and 'morning'.

	12:30-15:40 Jan. 31	15:40-06:55 Jan. 31∼Feb. 1	06:55-12:05 Feb. 1
Areal Dilatation	2.04×10^{-3}	-2.56×10^{-3}	-1.01×10^{-3}
Rotation	0.13	−0.51	0.04
Maximum Shear	2.09	2.87	1.00

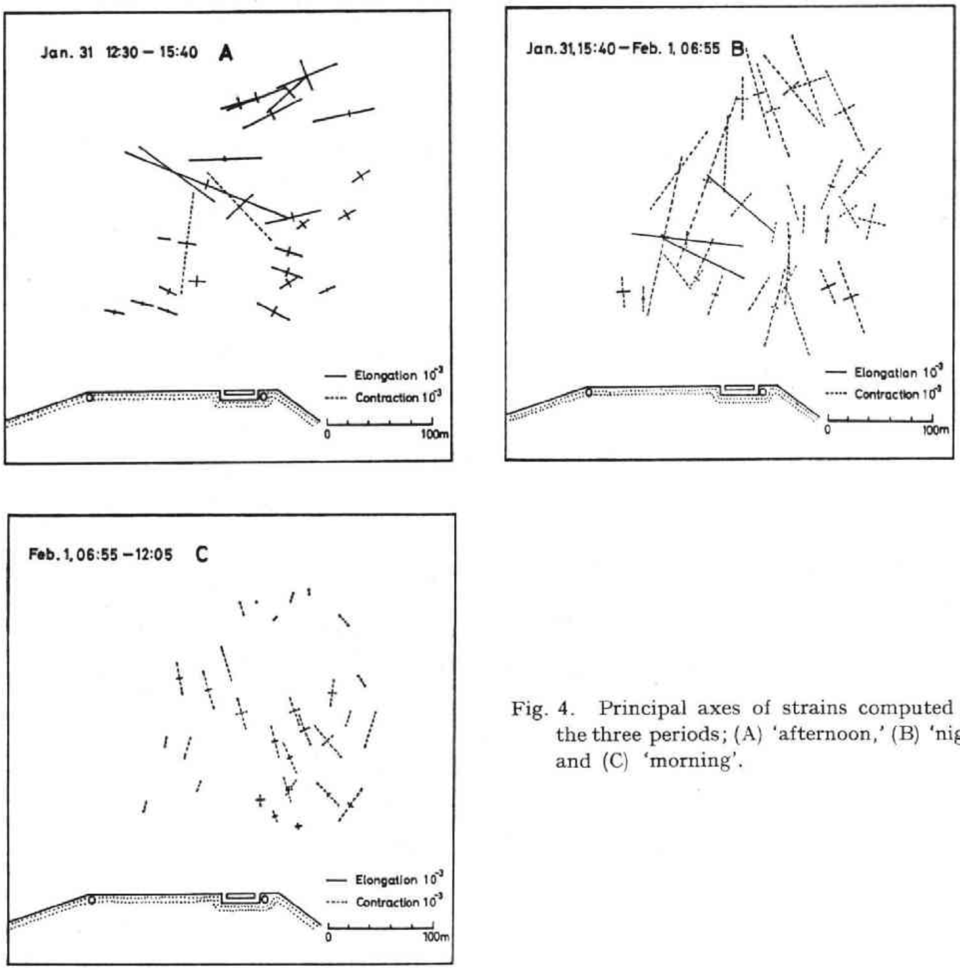

Fig. 4. Principal axes of strains computed for the three periods; (A) 'afternoon,' (B) 'night' and (C) 'morning'.

state is the contraction in N-S direction during the periods of 'morning' and 'night', whereas it is the elongation in E-W direction during the period of 'afternoon'. The maximum value in the strain appeared in the period of 'night'.

4. Observation of Icequakes and Slips across the Fault

The icequake activity was measured on February 1, 1976, by two seismometers of vertical component; the natural frequencies being 4 and 10 Hz. The two seismometers are set at the same point marked by B in Fig. 3. The signals were recorded on a magnetic tape and played back later onto a visible recorder. The number of events with trace amplitudes larger than 2.5 mm is counted, and the number of events within the time-interval of one minute is taken as the measure of icequake activity. The total number of events thus counted was about 3,400 during the period of about 4.5 hours from 07^h25^m to 12^h00^m.

The change in the activity with respect to time is seen in Fig. 5, which indicates a clear onset of high activity at 07^h45^m. After several active periods, the activity

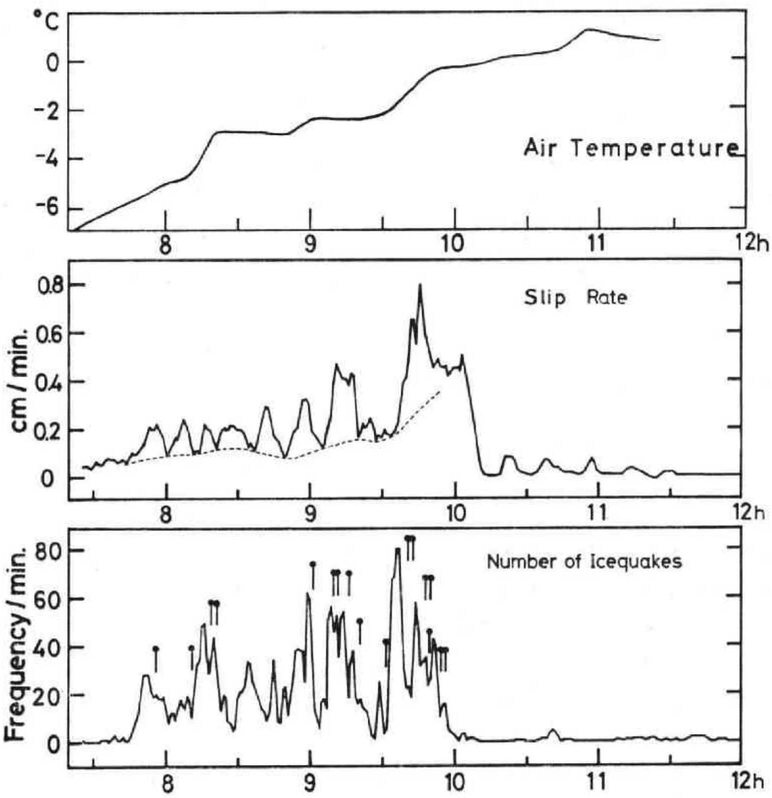

Fig. 5. Number of icequakes per minute, slip rate on the fault and air temperature versus time. The observations were carried on Feb. 1, 1976 at the south-eastern portion of faulting. The air temperature was measured at 30 cm above the ice surface. The vertical bars with solid dot indicate the occurrence of stick-slip movement (see text).

gradually became quiet at around 10^h00^m. The highest activity appeared at the time of 9^h30^m–9^h40^m.

The relative slippage of the fault plane was also observed at the point A in Fig. 3 using a handy tape measure for the period from 07^h25^m to 12^h00^m. The time interval between successive measurements was varied according to the state of faulting. The Chebychev's polynomial of seventy four degrees is adopted to represent the observed slippage with respect to time, and the displacements and slip rates are numerically calculated as a function of time. The calculated slip rates are plotted in Fig. 5 versus time in abscissa. This figure demonstrates that there are two kinds of slips, i.e., continuous creeps and spontaneous stick-slips. We may assume that the line connecting every trough in the slip rate, shown by dashed line in Fig. 5, corresponds to the stable creep of the fault increasing monotonously with time. The other type of slips is considered to be stick-slips because the slips were accompanied with felt shocks and audible sounds and because a sudden increase in displacement discontinuity across the fault was clearly observed. If this standpoint is valid, we can separate the fault displacement into stable creep and stick-slips. Then the amount of stable creep is about 25 cm out of total dislocation of 40 cm. The peaks in the slip rate mostly correspond to the occurrence of big stick-slips on the fault, as seen in Fig. 5. The biggest stick-slip occurred at 09^h40^m and it caused the slip of 1 cm on the fault with six successive stick-slips. The total dislocation of the seven slips amounted to 5 cm during 20 minutes.

Figure 5 also demonstrates some other interesting facts: First, the peak of icequake activity usually preceded to the peak of slip rate by several minutes. This means that all the big stick-slips on the fault plane occurred after the peak of the icequake activity. Second, the icequake activity sharply fell down after the occurrence of stick-slips on the fault. It may be considered natural that the stick-slip motion causes a large stress drop within the ice plate. The experiment by Brace *et al.* (1966) shows that the activity of microfracturings falls down immediately after the occurrence of stick-slip. Third, three big stepwise increases of air temperature were observed during the period of observation, as seen in Fig. 5. The rate of the increases is 1.8°C in 10 min. at 08^h10^m, 0.8°C in 12 min. at 08^h50^m and 1.9°C in 20 min. at 09^h20^m. The last two are closely associated with the onsets of high icequake activities and sharp increases in slip rate. Gold (1963) stated in his report of laboratory experiment on shocks in ice that many thermal icequakes, called 'cold thermal quakes', occurred by sudden cooling. Takahashi and Wakahama (1975), however, reported that no 'hot thermal quake' by sudden heating was observed even when the heating rate was as high as 1.0°C/min. The heating rate of about 0.1°C/min. in the present cases may be too low to initiate thermal icequakes, according to their result. However, the ice plate in our case was prestressed before the occurrence of icequakes, so that the low rate of heating might act as a trigger. The comparison between the slip rate and the icequake activity is of some meaning, because the occurrence of many small icequakes, even when they take place outside of the fault plane, gives a change in stress state within the ice plates

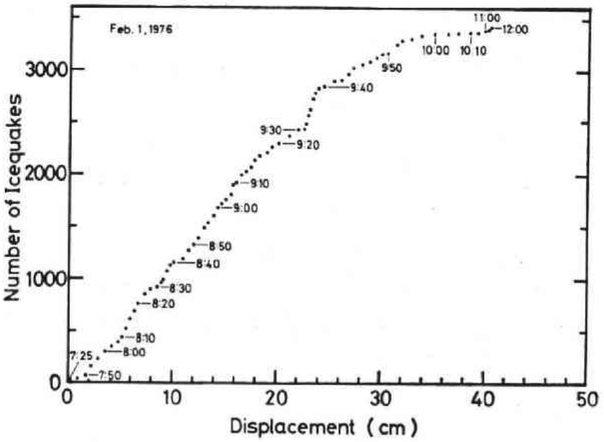

Fig. 6. The relation between the cumulative number of icequakes and displacement on the fault. The numerals in the figure indicate the hour and minutes on Feb. 1, 1976. After the occurrence of the biggest stick-slip at 9^h40^m, the displacement increased quickly, however, the icequake activity did not; the both ceased at noon.

causing another stick-slip of the fault plane. This is justified by the fact that there were many fresh cracks of tensile type within the ice plate at the time of high activity of icequakes. As a matter of fact, very fresh cracks of echelon type and many tensile crackings were observed at about 9 o'clock (see Photo. 4) though they had not been found before 8 o'clock.

The relation between the cumulative number of icequakes and the cumulative slip on the fault is given in Fig. 6, in which some undulations of the slope were seen during 07^h50^m to 09^h40^m. This situation can be explained from the fact that the onset of icequake activity preceded several minutes to that of slip movement, as stated previously.

5. Discussions

Gold (1960) has made an experiment on the creep of multigrained ice at −10°C under a constant compression. He stated that no crack was observed under the stress lower than 9 bars. The number of cracks, which were observed under higher stress, was proportional to creep strain. He also mentioned that the increase of volume of the specimen was about 3% when the applied stress was 17 bars.

The thermal volumetric expansion of the ice plate in the present case is the stress that causes thrusting of a plate over another. The observed amount of slip, therefore, is in proportion to the volumetric strain of the ice plate. Except for the final aseismic creep-stage, the linear relation between number of icequakes and amount of slips is compatible with that of Gold's experiment.

It is interesting that this is coincident also with the result of rock fracture experiment (Scholz; 1968), though there are marked differences in material properties and sample sizes between rocks and ice plates.

As seen in Fig. 6, there is a period of high slip rate without icequake occurrences at about 10 o'clock. The reason of this final stage may be explained as follows: The crack may be due to the tensile stress acting across the grain boundary, which is mostly perpendicular to the free surface in the case of ice plate. It is expected that the crack develops in vertical direction and, if the crack eventually reaches the base of the ice plate, the water comes into the void space produced by tensile crack and friction at the grain boundary decreases. Therefore, after many cracks take place, the ice plate shows a ductile feature as a whole. This may give an explanation of the final stage of high slip rate without occurrence of icequakes. There may be another possibility that the air temperature near the melting point (0°C) around 10 o'clock (see Fig. 5) affects the creep rate to great extent, as seen in the experiments by Glen (1955).

Acknowledgements: We express our hearty thanks to Prof. A. Takagi for his valuable advices and continuous encouragements and also to Prof. T. Hirasawa for his critical reading the manuscript and for kind discussions. We used the computer program prepared by Dr. H. Ishii, to whom we are indebted. Our hearty thanks are also due to the members of Suwa Weather Station of J.M.A., for providing us with the documents and the information about ice conditions on the Lake Suwa. The finance of this study is partly supported by Grant No. 174112 in Aid of Scientific Research, the Ministry of Education.

References

Brace, W.F., B.W. Paulding, and C. Scholz, 1966: Dilatancy in the fracture of crystalline rocks, J. Geophys. Res., **71**, 3939–3953.

Glen, J.W., 1955: The creep of polycrystalline ice, Proc. Roy. Soc. London, A, **228**, 519–538.

Gold, L.W., 1960: The cracking activity in ice during creep, Can. J. Phys., **38**, 1137–1148.

Gold, L.W., 1963: Crack formation in ice plates by thermal shock, Can. J. Phys., **41**, 1712–1728.

Kishinouye, F., 1943: Studies on lake-ice, Bull. Earthq. Res. Inst., **21**, 298–306 (in Japanese with English summary).

Matuzawa, T., 1953: Feldtheorie der erdbeben, Bull. Earthq. Res. Inst., **31**, 179–201.

Matuzawa, T., 1964: *Study of Earthquakes*, Uno Shoten, Tokyo, Japan, 181–202.

Omote, S., Y. Yamazaki, N. Kobayashi and S. Murauchi, 1955: Ice tremours generated in the floating lake ice (Part 1), Bull. Earthq. Res. Inst., **33**, 663–679.

Scholz, C.H., 1968: Microfracturing and the inelastic deformation of rock in compression, J. Geophys. Res., **73**, 1417–1432.

Takahashi, T., and G. Wakahama, 1975: A study on thermal stress in ice, Low Temperature Science, Ser. **A**, **33**, 29–37 (in Japanese with English summary).

Tanaka, A., 1918: Suwako no Kenkyu, Vol. 1, Iwanami Shoten, Tokyo, Japan, 725–772 (in Japanese).