# 42. *Ice Tremors Generated in the Floating Lake Ice (Part 1).*

By Syun'itiro OMOTE, Yoshio YAMAZAKI, Naoyoshi KOBAYASHI,

Earthquake Research Institute,

and Sadanori MURAUCHI,

National Science Museum.

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## 1. Introduction

We seismologists have long been paying keen attention to the phenomena seen in some floating lake ice. In some lakes, when a few days after the lake has frozen over it happens that the air temperature falls considerably, large fractures are formed at midnight in the ice sheet without any artificial cause, running from one shore to the other across the lake, and split the ice sheet into two or three parts. According to the inhabitants of the district, the formation of the fractures is often accompanied by such a severe shock that it awakens the sleeping people in areas around the lake. This phenomenon is of special interest to seismologists because of the elastic waves generated at the moment of formation of the fractures in the ice.

The opening thus made in the ice-sheet is soon filled up with new ice, but the new ice does not grow as thick as the older ice immediately, and the crack remains as a week line in the ice-sheet. Usually the weather is very fine on the day following such a cold night, so that the whole surface of the lake-ice is heated by the radiation from the sun, causing the expansion of the ice-sheet. As a result, the margins of the two ice-sheets bounded by the weak line are pushed up, and a peculiar ridge of ice is formed along the weak line. The ridge thus produced has been called "Omiwatari" (the sacred crossing) by the inabitants of the Suwa district from ancient times. Local tradition has it that the ridge of ice marks the path along which the God of the Suwa Shrine walked from the Upper Shrine where he lives to the Lower Shrine across the lake in which the Goddess lives. Lake Suwa is famous for this phenomenon of "Omiwatari." This phenomenon has attracted the lakeside people's attention since long ago, and the dates of the freezing over of the lake and the formation of "Omiwatari" have been recorded almost every year for about 500 years beginning in 1397. The record has been investigated by Fujiwara[1~3] and Arakawa in recent years as a very valuable material in the field of climatology.

The formation of a crack in the ice-sheet causes vibration of the ice-sheet. The significance of this vibration to us consists in that it is not generated by any artificial force but by a natural force. No doubt, vibrations are also to be generated by causing artificial explosions in the ice, but it is difficult to determine what similarity there is between the vibration caused by artificial method and that of earthquakes in their mode of occurrence. On the other hand, it may be safely assumed that vibrations caused by the formation of cracks in the ice-sheet closely resemble those of natural earthquakes in many respects.

By the contraction or expansion of the ice-sheet due to the variation of the air temperature, stress is accumulated in the ice-sheet until the strain overcomes the breaking strength of the material. When at last rupture is caused, the accumulated strain energy is converted into elastic waves.

Many theoretical and seismometrical studies on the mechanism of the occurrence of earthquakes have been carried out by good authorities[4~7], mainly on the basis of data obtained at seismological stations. However, the rapid progress of theoretical seismology makes it necessary to employ a much closer observation net in order to improve the seismometrical study on the mechanism of earthquake occurrence. However, chief difficulty in this direction consists in financial restrictions. Such being the case, it has been found necessary to introduce experimental methods to the study of seismology, and recent years seismic model experiments have been carried out by many investigators[8~14] to study the

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1) S. FUJIWHARA and H. ARAKAWA, *Jour. Meteorological Res.* (C.M.O.) (in Japanese) **6** (1955), 123.
2) H. ARAKAWA, *Jour. Meteorological Res.* (C.M.O.) **6** (1955), 584.
3) S. FUJIWHARA, *Geophys. Magazine*, **26** (1954), 1.
4) H. KAWASUMI, *Bull. Earthq. Res. Inst.*, **11** (1933), 403; **12** (1934), 660.
5) H. HONDA, *Geophys. Mag.*, **4** (1931), 185; **5** (1932), 69.
6) W. INOUE, *Bull. Earthq. Res. Inst.*, **14** (1936), 582; **15** (1937), 90, 674.
7) H. KAWASUMI and R. YOSHIYAMA, *Proc. Imp. Acad.* **10** (1934), 345.
8) K. KASAHARA, *Bull. Earthq. Res. Inst.*, **30** (1952), 259; **31** (1953), 71, 235, **32** (1954), 67.
9) Y. KATO and A. TAKAGI, *Sci. Rep. Tohoku Univ. Geophys.*, **7** (1955), 35.
10) T. D. NORTHWOOD and D. V. ANDERSON, *Bull. Seis. Soc. Amer.*, **43** (1953), 239.
11) J. OLIVER, F. PRESS and M. EWING, *Geophys.*, **19** (1954), 202. *ibid.* 388.
12) J. F. EVANS, C. H. HODLEY, J. D. EISLER and D. SILVERMAN, *Geophys.*, **19** (1954), 220.
13) F. K. LEVIN and H. C. HIBBARD, *Geophys.*, **20** (1955), 19.
14) PETER N. S. O'BRIEN, *Geophys.*, **20** (1955), 227.

generation and propagation of elastic waves. It is also along this line that our studies on the lake ice were planned and carried out, in the hope that the mode of occurrence of such tremors generated in the floating ice-sheet may serve as a model for that of the natural earthquake.

Our studies on the floating ice of Lake Suwa were begun in the winter of 1949/50. To record the vibration generated by such a great shock caused by the formation of Omiwatari, the great crack, would be easy enough in itself, for the vibration has a very large amplitude. But, from the standpoint of carring out observations, there arises the very difficult problem of how to catch without fail the rare phenomenon which occurs usually only one time in one winter. In order to preclude the possibility of missing the great chance that will not come around until next winter, it is necessary to record smaller tremors that occur much more frequently all through the winter in the ice-sheet. These tremors, however, are so small in their amplitudes, that they require much more sensitive seismometers than those used for the major tremors.

In the first year of our study we had great difficulties in the observation of ice tremors, as we had no knowledge beforhand of their amplitude range, of the frequency of the generation, or of the location of their occurrence. First of all, we had to know what sort of tremors were being generated in the floating ice. The first and second winters were spent on the preliminary experiment for the study of these subjects. In the third year detectors were installed in such disposition as shown in Fig. 1 and with these eleven detectors the observation of the tremors was carried out. By analysing the records obtained from the observations we learned that, although we were able to catch a large number of tremors, it was extremely difficult to locate the foci of the tremors that occurred in the area covered by our observation net. It was found that a great many of the tremors traced in our record were generated at points very near the lake shore, presumably by minor fractures in the ice-sheet near the shore line of the lake. Therefore in the next winter of 1953, our observation net was set up far into the lake, at a distance of some 500 meters from the shore, and

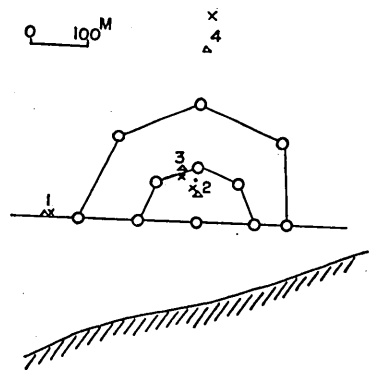

Fig. 1. Location of detectors on the ice-sheet in the winter of 1951/2.

in this same winter we used, in addition to the seismograph equipment, such other instruments as extensometers, thermocouples, etc.

## 2. Instruments used

Prior to the description of the phenomenon taking place in the ice-sheet, a brief sketch of the instruments used in the observation of ice tremors will be given.

a). Equipments for the recording of the ice tremors.

In recording the ice tremors two systems of recording assemblies were used. Both systems were alike in that the detectors were placed on the ice-sheet, and that the recording equipments were installed in the Suwa Branch Station of CMO standing on the lake shore. They differed, however, in that one system had a very long recording time, longer than twelve hours, while the other had a very short recording time with a high paper speed, about 40 mm/sec. Also the latter was so constructed as to record the oscillation curves of the vibration of a single tremor caught by many detectors simultaneously side by side on a sheet of bromide paper.

i) Long recording system. This long recording time system consists, fundamentally, of detector—preamplifier—direct current amplifier—galvanometer of pen-writting type—and recording drum wrapped with smoked paper. The specifications of each unit are as follows—

Detector: A moving coil type electro-magnetic detector was employed in order to convert the mechanical energy due to the vibration of the ice into the electric one. The natural period of the detector was adjusted at 10 cps, and the sensitivity at this cycle was about 0.1 volt/kine.

Preamplifier and direct current amplifier: The overall frequency response of the tube amplifying units was about 90 db in the range from 1 to 50 cps. The details of the frequency characteristics of the preamplifier and the D.C. amplifier will be described elsewhere.

Pen-writing galvanometer: In order to have a visual recording, a pen-writing galvanometer recording tremors not on photographic paper but on smoked paper was used. This enabled us to record continuonsly for more than 12 hours with a paper speed of 4 mm/sec. In carrying out the observation, overall gains of the amplifying units were adjusted at such a sensitivity as the input of 100$\mu$V at the preamplifier produces a deflection of 1 mm at the end of the index of the galvanometer. Time markings were put on the record at every six seconds.

ii) Multi-channel recording system. This system consists, fundamentally, of—12 detectors—12 amplifiers—12 channel oscillograph—and a recording camera. In the operation of this system each of the 12 detectors was connected by a cable to the recording equipment which contained 12 low frequency amplifiers, one for each detector, and an oscillograph to record the ice tremors on a sheet of photographic paper. This multi-channel recording of the output from the twelve detectors was aided by the time-makings of light line across the paper placed at intervals of 10 milliseconds, making possible the picking up of the time of onset of energy to the nearest millisecond. The photographic recording paper was made to run through the oscillograph camera with the speed of 40 mm/sec and a role of bromide paper 25 meters long was consumed in 11 minutes.

b). Extensometer

Extensometers were used for the purpose of measuring the contraction and expansion of the ice-sheet. The construction of this instrument is as follows: One end of a bar about one meter long made of fused silica is fixed to a wooden plate frozen to the ice-sheet, and the other end is placed on a roller supported on a frame also fixed on the ice. The rotation of the roller is magnified by a bow—and—string mechanism and recorded automatically on a paper wrapped around a drum. In this manner the relative movement of the silica bar and the ice was recorded, magnified to $10^4$ times the actual amount. In the winter of 1952/3, extensometers were set in two different directions, making an angle $\pi/2$ to each other.

c). Temperature measurement

In the study of the phenomena in the ice-sheet, needless to say, temperature measurement is indispensable. Strictly speaking, it is desirable that the air temperature should be measured on the lake ice, but as the Suwa Branch Station of CMO, standing so near the lake shore, was kind enough to place its record of temperature measurement at our disposal, we used the temperatures measured at the station, to whose courtesy our heartfelt thanks are due. In order to know the temperature within the ice-sheet we used in the first year an underground thermometer and in the second year a thermometer of a thermojunction type.

### 3. Generation of the ice tremors

In order to show the general manner of the occurrence of the ice tremors, an example of the record obtained with the smoked paper seismograph is given in Fig. 2 (Plate). As is seen in the figure, sometimes many tremors take place one after another in a day, while on other days they occur only very rarely. We see from the figure that the

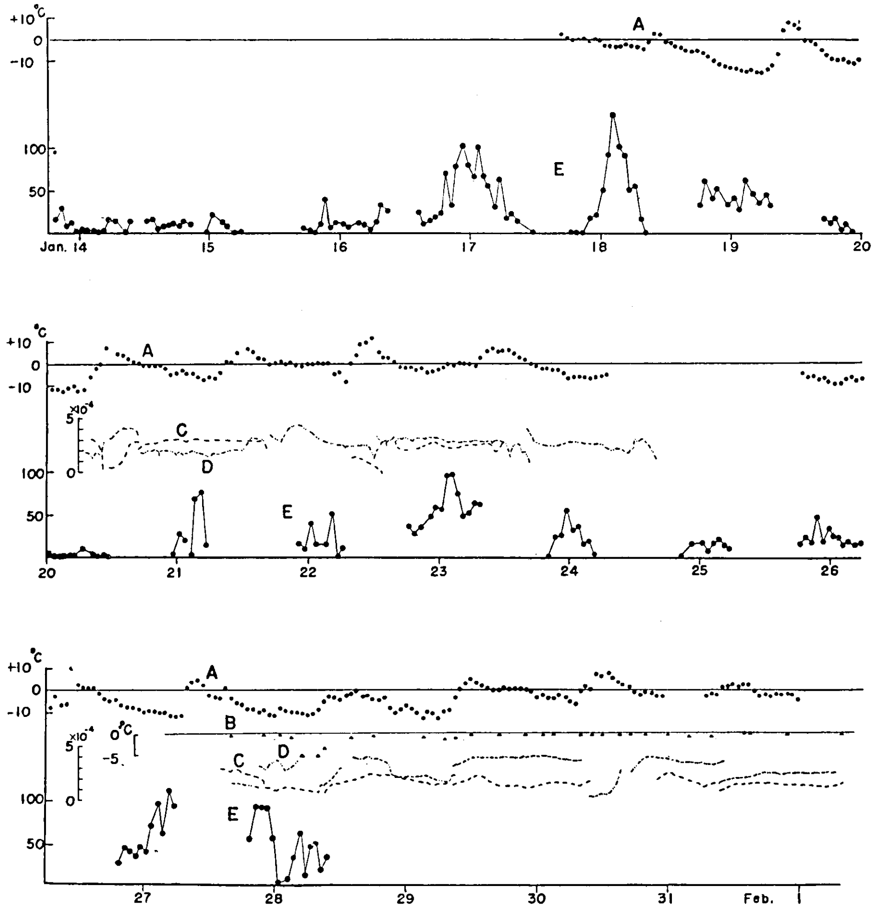


Fig. 3. Diagrams of frequency of ice tremors, contruction and expansion of ice-sheet, and the temperature in the ice and of the air.

tremors resemble more an earthquake in type than a microseism in that they can be counted one by one. From our observation it became clear that these tremors were taking place all day long, but since in the daytime there were too many man-made disturbances caused by skaters, anglers, etc., we gave up taking record of ice tremors until night, when, according to the custom of the district, and in view of the obvious danger, no one went out on the ice to affect our records. Our observation was therefore restricted to the time between nightfall and the dawn. Vicissitude of tremors observed in the winter of 1953 is shown in Fig. 3. The observation was kept from Jan. 13 to Feb. 1, and the number of tremors was counted every hour, which rose to more than one hundred in the most active period, but sank very low in some cases and there were whole nights when no tremor took place at all. In the

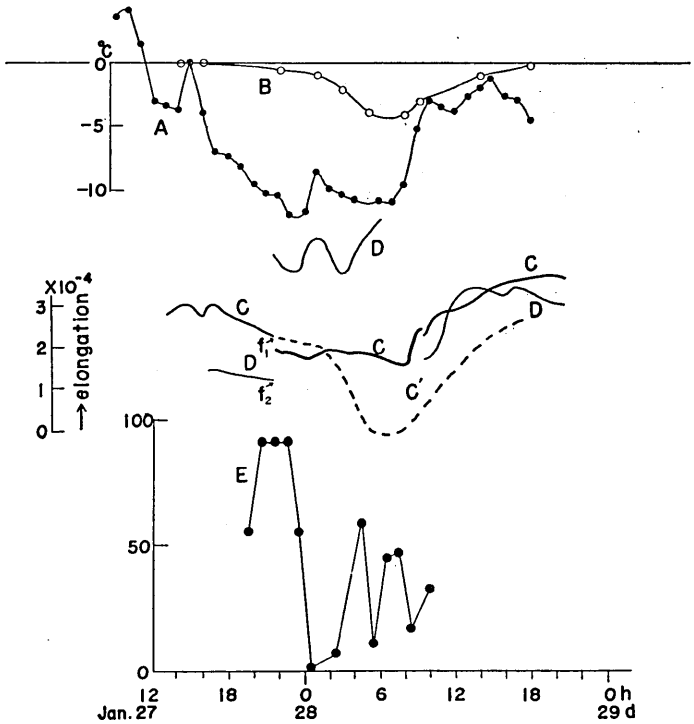


Fig. 4. An enlargement of part of the curves in Fig. 3, on Jan. 27 and 28. A is the air temperature, B is the temperature in the ice-sheet, C and D are records of extensometers and E is the frequency of ice tremors.

figure, curve A represents the air temperature, curve B the temperature in the ice-sheet, curves C and D the records of the extensometers, and curve E the frequency of the tremors in the ice-sheet. In Fig. 3, these results have been put together. A glance at this figure makes it clear that on days when diurnal variation of the air temperature was small tremors were inactive in there occurrence, while on days when the temperature variation was conspicuous, a large number of ice tremors were generated. However, on looking over more carefully, we find that the relation of the two is not always so close. In order to study the relation between the two, we have to examine every part of Fig. 3 in greater detail. For this purpose we have reproduced in Fig. 4 a part of the former figure covering the period from Jan. 27 to 28, as in this period all cases are represented. In this figure we notice that although the air temperature begins to fall at about 15 o'clock, the temperature of the ice-sheet remains at the freezing point for some time, and only begins to fall, at about 20 o'clock, and that as soon as this fall begins the tremors also begin to occur more frequently. The curves of the extensometers show that there is no change in the length of the ice-sheet soon after the air temperature begins to fall below the freezing point, but two hours later since the air temperature becomes below the freezing point the extensometers begin to contract, and soon after the ice-sheet begins to contract the ice tremors also begin to occur. In the case of Fig. 4 (curves C and D), a small crack seems to have run under the silica bar in the course of its contraction and a sudden stepwise extension was recorded in one of the curves of the extensometer at a point denoted as $f_2$, and a sudden contraction in the other curve at $f_1$. Though this small crack is supposed to have been filled up with new ice soon, the curves of the extensometers look somewhat complicated after that points. Calculated contraction based on the temperature in the ice-sheet is shown by a broken line denoted as C′.

As is seen from Fig. 4, there exists a close relation among the generation of ice tremors, the temperatures of the air and the ice, and the contraction and expansion of the ice-sheet. The air temperature begins to fall rapidly after 16 o'clock and passes the freezing point, but on the surface of the ice-sheet there is still water remaining unfrozen in consequence of the warm temperature in the daytime, while the ice-sheet itself stays at 0°C. As the air temperature goes down lower and lower, this surface water on the ice finally begins to freeze. As soon as the surface water is converted into ice the surface temperature of the ice-sheet begins to fall below zero degree. It is just at this moment that ice tremors begin to take place. To sum up, as soon as the surface water is frozen, the surface of the ice-sheet comes into direct contact with the cold air, so that the ice-sheet is cooled and begins to contract, but because of the poor conductivity of heat of the ice, the lower part of the ice-sheet remains at 0°C for a little while, and the stress is accumulated in the ice and finally causes the formation of small crack. It should also be noticed in this figure that at about half past 23 o'clock, the approach of warm air mass caused the temperature to rise by about five degrees, and as if to correspond to this rise, the occurrence of tremors became inactive, until at last at one o'clock there were no tremors at all.

## 4. The frequency of the amplitude of the tremors

There is a well-known relation existing between the maximum amplitude of natural earthquakes and its frequency. The relation is:—

$$N(a)a^m = k$$ [15],

where $a$ is the observed maximum amplitude of an earthquake and $N(a)$ the number of earthquakes whose maximum amplitudes range from $a$ to $a+da$, and $m$ and $k$ are mumerical constants.

The values of the constant $m$ with respect to some earthquakes are given

| | |
|---|---|
| $m=1.92\pm0.04$ | Micro earthquakes of Fukui aftershocks[16] |
| $m=1.8\pm0.16$ | Micro earthquakes of Imaichi aftershocks[17] |
| $m=1.8\pm0.16$ | Aftershocks of the Tottori Earthquake[18]. |

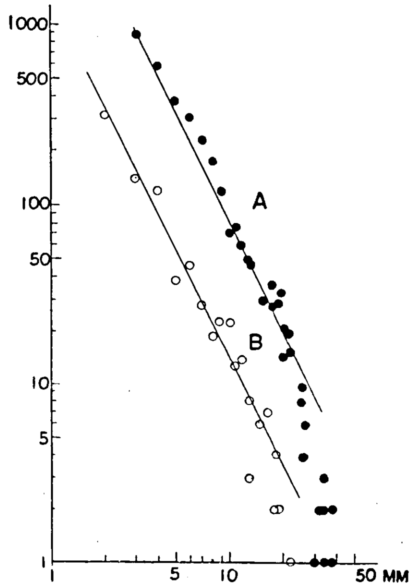


Fig. 5. Frequency distribution of maximum amplitude of the ice tremors. The data of the curve A are obtained from the detector installed at $D_1$ in Fig. 9, and of curve B from $D_2$.

The frequency diagram of the amplitude of ice tremors is shown in Fig. 5. From this figure the value of $m$ can be calculated as

$$m=1.8\pm0.2$$

15) M. ISHIMOTO and K. IIDA, *Bull. Earthq. Res. Inst.*, **17** (1939), 443.
16) T. ASADA, *Rep. Fukui Earthq.*, (1949), 58.
17) T. ASADA and Z. SUZUKI, *Bull. Earthq. Res. Inst.*, **28** (1950), 415.
18) S. OMOTE, *Bull. Earthq. Res. Inst.*, **33** (1956), 641.

This agrees well with the value of $m$ obtained with respect to natural earthquakes.

## 5. Velocity of the elastic waves in the ice-sheet

As to the velocity of elastic waves that propagate in the ice-sheet many authorities[19~26] have made many reports. We also made some study on the point, which will be roughly sketched below. A shock due to a small quantity of explosive caused to burst in ice was picked up by eleven detectors arranged along a straight line at intervals of fifty meters. The time distance curve deduced from the record of these detectors is given in Fig. 6. The first phase to arrive of the waves at had a velocity $V_1$=3200 m/s, the second phase a velocity $V_2$=1820 m/s, the third phase a velocity $V_3$=1460 m/s, and the fourth phase a velocity $V_4$ =330 m/s. It appears probable that the wave with the velocity of 3200 m/s was due to the $P$ wave, while the ratio of the two velocities $V_1$ and $V_2$ is $V_1/V_2$=1.78. Had the second wave been an $S$ wave (phases due to the shear waves), this ratio would have been about 2 in the ice-sheet, so that this velocity due to the second phase can hardly be accepted as that of $S$ waves. The third phase apparently is due to the waves that passed through the water

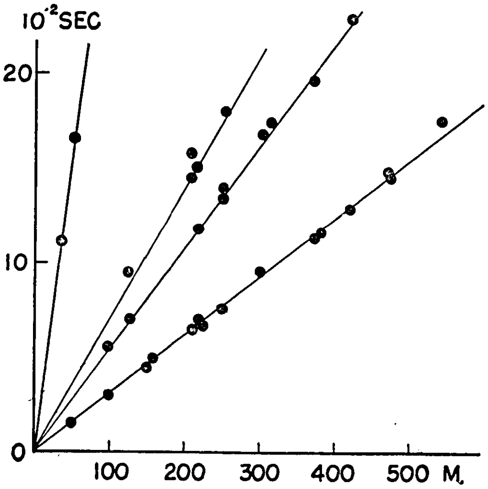


Fig. 6. Travel time curves for various event due to the detonation from the small charges measured on the ice.

19) M. Ewing, A. P. CRARY and A. M. THORNE, *Physics*, **5** (1934), 165.
20) M. Ewing and A. P. CRARY, *do*, **5** (1934), 181.
21) F. PRESS, A. P. CRARY, J. OLIVER and S. KATZ, *Trans. Amer. Geophys. Uni.*, **32** (1951), 166.
22) F. PRESS and M. EWING, *Jour. Appl. Physics*, **22** (1951), 892.
23) A. JOSET et J. J. HOLTZSCHERER, *Ann. d. Géophys.*, **9** (1953), 330.
24) A. JOSET, *do.*, **9** (1953), 345.
25) F. KISHINOUYE, *Bull. Earthq. Res. Inst.*, **21** (1943), 298.
26) Y. SATÔ, *Bull. Earthq. Res. Inst.*, **29** (1951), 223.

beneath the ice-sheet. These three phases were followed up by still another wave with a definitly long period, of which the velocity was calculated as 330 m/s. These velocities here obtained, however, were by no means constant in all cases. For example, in Fig. 7 the values of $P$ waves observed at the same place every two hours are contrasted to the air temperature at which the observation of velocity was made. As is seen from the result, the velocity differs in the range from 2900 m/s to 3230 m/s. The velocity obtained from a single shot may be accepted as fairly accurate as the probable errors were small as shown in Fig. 7. This may indicate that the elastic constant of the ice-sheet itself has changed. In it will be noticed that the velocity increases as time goes on, in the same way as it increases as the temperature goes down. In the daytime, when the air temperature is 5°C and the ice is soft, waves with a velocity of 2900 m/s propagate in the ice, while as it becomes cold at night and the temperature is $-10$°C or so, the velocity is 3230 m/s.

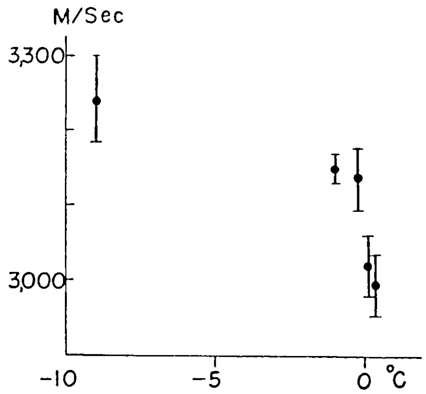


Fig. 7. Velocity of $p$ waves in the ice versus air temperature.

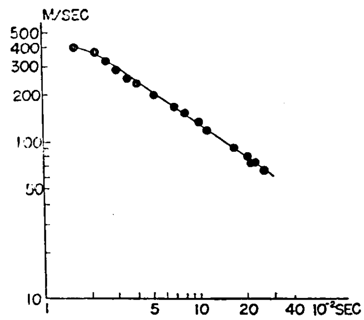


Fig. 8. Dispersion curve of flexural waves in the ice-sheet.

The fourth phase may be considered due to the flexural waves of the ice-sheet. Glancing at a record of this type we at once notice the dispersive nature of the waves. A dispersion curve will be shown in Fig. 8. As is well-known the thickness of the ice-sheet has a great bearing upon the velocity of the flexural wave, and so the measurement of the thickness of the ice-sheet was made once every day, we found from the measurement that the ice-sheet became thicker as days go on by 0.25 cm/day on the average.

## 6. Determination of epicenters of the ice tremors

As the ice tremors were known to be of the shock type in nature, we wished to know the point from which tremors originate[27]. For this purpose 12 detectors were distributed on the ice-sheet as is shown in Fig. 9 and the position of each detector was measured with great care by using the Wild theodolite and a steel tape 100 meters long. With

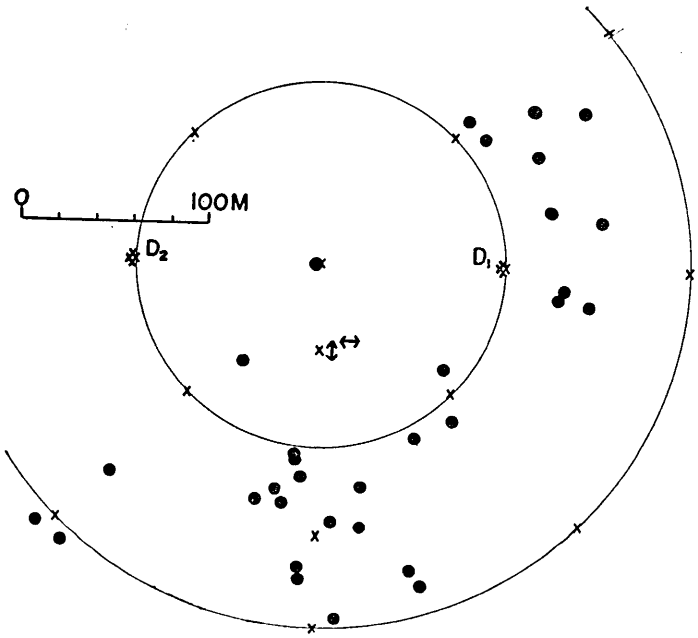


Fig. 9. Location of the origin points of the ice tremors.
× Location of detectors connected to the recording oscillograph.
※ Location of detectors connected to pen-galvanometer.
↔ Location of extensometers.
● Origin points of the ice tremors.

these twelve detectors the observations of the ice tremors were carried out. As is seen in Fig. 3, the occurrence of tremors is irregular, that is, under some conditions there take place so many tremors, while under others they are very few. While recording the tremors close attention was paid every night not to miss the time of the most active occurrence of tremors which lasted for one hour or so on the average.

27) A. P. CRARY, *Bull. Seis. Soc. Amer.*, **45** (1955), 1.

Vibrations due to an ice tremor picked up by the respective detectors were recorded side by side on a sheet of bromide paper. An example of the record of ice tremors is reproduced in Fig. 10 and Fig. 12 (Plate). By reading off the commencement time from these records the foci of tremors can be easily calculated. In order to obtain some measure on the accuraey of a focus of an ice tremor, a small amount of explosive was caused to burst at a known instant and at a known place. From the commencement times of vibrations caused by this explosion recorded at 12 points the location of this explosion point was determined. This calculated epicenter was compared with the actual spot of the explosion, and the result is tabulated in Table I. As is seen in the table, the two values, for the calculated and

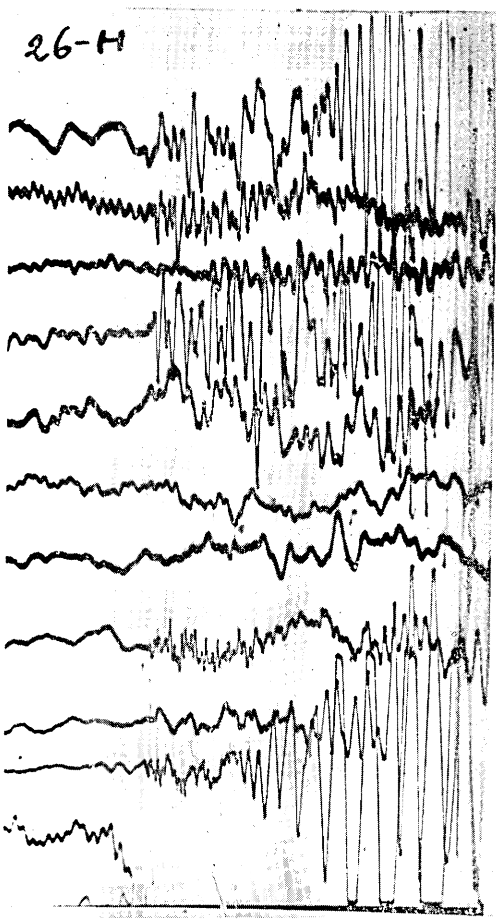


Fig. 10. An example of record of ice tremor on bromide paper.

Table I. Comparison of the calculated and the true origin points due to explosion of small charges.

| No. | Co-ordinate of the true origin point | | Co-ordinate of the calculated origin point | | Calculated origin time | Calculated velocity |
|---|---|---|---|---|---|---|
| | $X_0$ | $Y_0$ | $X$ | $Y$ | $T_0$ | $V$ |
| | m | m | m | m | $\times 10^{-2}$ sec | m/S |
| 1 | 0 | 0 | 4.9±1.1 | −2.8±1.2 | −1.4±0.1 | 3290±70 |
| 2 | 0 | 0 | −4.5±5.1 | −0.5±4.7 | +1.5±0.5 | 3360±170 |
| 3 | 0 | 0 | −3.9±2.8 | +4.4±2.9 | +1.1±0.1 | 3306±106 |

given locations, are in good accord with each other.

Attempts at the determination of sourse points of tremors was carried out every night from Jan. 25 to Feb. 1, 1953. Thus we have succeeded in recording a great many tremors, of which, however, the foci of only about 30 tremors could de located. In the calculation of a

Table II.

| No. | Date | Observed time | $T$* | Epicenter $X_0$ | Epicenter $Y_0$ | Velocity | Number of obs. point |
|---|---|---|---|---|---|---|---|
| | | h m | $T$°C | m | m | Km/sec | |
| F-1 | Jan. 21 | 20 10∼20 | −2.1 | 71.9± 1.5 | − 82.1± 8.8 | 2.62 ±0.03 | 10 |
| F-2 | 23 | 18 12∼20 | −2.7 | 11.9± 7.4 | −192.1±31.0 | 3.45 ±0.13 | 10 |
| F-3 | 27 | 23 57∼09 | −3.8 | − 40.0±59.0 | − 53.1±29.0 | 3.24 ±02.0 | 10 |
| F-4 | 28 | 0 15∼25 | −4.0 | 57.4± 5.8 | −172.2± 8.0 | 2.90 ±0.07 | 9 |
| F-5 | 〃 | 〃 | 〃 | − 8.4±22.9 | −114.5±32.3 | 2.95 ±0.15 | 9 |
| F-6 | 〃 | 〃 | 〃 | − 68.9±30.0 | − 57.9±36.0 | 3.01 ±0.27 | 9 |
| F-7 | 〃 | 〃 | 〃 | 24.0±12.0 | −141.9±18.0 | 3.05 ±0.03 | 10 |
| F-8 | 〃 | 〃 | 〃 | 121.3± 6.7 | 30.1± 2.8 | 3.05 ±0.37 | 9 |
| F-9 | 〃 | 〃 | 〃 | − 66.0±13.0 | −129.0±23.0 | 2.84 ±0.11 | 10 |
| F-10 | 〃 | 1 10∼20 | −4.6 | − 12.0± 1.0 | −105.0±18.0 | 2.99 ±0.23 | 8 |
| F-11 | 〃 | 〃 | 〃 | 23.0± 0.9 | −119.3± 3.8 | 2.85 ±0.04 | 11 |
| F-12 | 〃 | 1 21∼31 | −4.8 | 8.3± 2.1 | −209.3± 6.5 | 2.90 ±0.09 | 10 |
| F-13 | 〃 | 1 49∼2 00 | −5.3 | 137.0±22.8 | 8.4±12.1 | 2.50 ±0.09 | 12 |
| F-14 | 〃 | 〃 | 〃 | 66.2± 7.1 | − 55.7± 5.3 | 3.38 ±0.20 | 11 |
| F-15 | 〃 | 2 04∼15 | −5.5 | 191.0±14.2 | − 77.6± 7.3 | 2.52 ±0.04 | 9 |
| F-16 | 〃 | 〃 | 〃 | − 19.4± 4.4 | −126.8± 7.5 | 2.85 ±0.24 | 10 |
| F-17 | 〃 | 〃 | 〃 | −149.7±14.7 | −141.0±11.1 | 3.14 ±0.07 | 12 |
| F-18 | 〃 | 〃 | 〃 | 75.5±19.0 | 98.3±11.0 | 2.83 ±0.18 | 10 |
| F-19 | 〃 | 〃 | 〃 | 147.0±13.0 | 26.0± 5.0 | 2.85 ±0.11 | 10 |
| F-20 | 〃 | 〃 | 〃 | −135.3±20.0 | −151.6±19.0 | 3.19 ±0.30 | 11 |
| F-21 | 〃 | 6 17∼23 | −2.2 | 7.6± 4.0 | −139.3± 9.1 | 2.87 ±0.03 | 11 |
| F-22 | 〃 | 6 30∼33 | 〃 | 113.0±28.0 | 59.0±18.0 | 2.69 ±0.16 | 10 |
| F-23 | 〃 | 〃 | 〃 | 149.8±14.8 | − 21.4± 6.9 | 2.80 ±0.09 | 7 |
| F-24 | 〃 | 7 07∼10 | −2.1 | 9.5± 4.9 | −165.5±14.0 | 3.05 ±0.08 | 10 |
| F-25 | 〃 | 0 15∼25 | −4.0 | 17.2± 3.7 | −169.1± 8.1 | 3.08 ±0.25 | 9 |
| F-26 | Feb. 1 | 20 14∼17 | 〃 | 48.0± 1.5 | 100.0±30.0 | 2.65 ±0.01 | 7 |

* $T$: Air temperature.

focus its depth was assumed to be zero as the thickness of the ice-sheet was not more than only 19 or 20 cm. Accordingly in calculating the focus of a tremor we had only four unknowns, namely, the coordinates of the focus, $x$ and $y$; the velocity $V$ of the elastic wave that propagates in the ice; and the origin time $T_0$. In this case of the observation, 12 detectors were used, and we were able to determine those four unknown quantities by means of the least square method. In Table II the results of calculation are shown. The diversity of the calculated values of velocity is about 10 percent. Some noticeable foci are reproduced in Fig. 9.

It has a great significance that we could determine the epicenters of these ice tremors.

Among these 30, three shocks, F–4, 5 and F–6, in Table II are especially interesting. These three shocks, as is seen in the table, took place successively in the interval of about 100 milliseconds. As is seen in Fig. 11, the distance between F–4 and F–5 is 80 m and the time interval between the two is 63 milliseconds, while the distance and the time interval between F–5 and F–6 are 120 m and 215 milliseconds respectively. These facts may indicate that a crack that started from the focus of F–4 proceeded to F–5 and then to F–6, It will be seen from this example that a crack generated at one point in the ice-sheet sends out elastic waves from its origin point and at the same time the crack itself goes forward with some finite velocity smaller than the commpressional elastic $P$ waves in the ice, and in the course of its progress releases a strain energy in the ice-sheet in the form of elastic waves. The progressive velocity of a crack will be given as 1270 m/s and 560 m/s from the curve $F_4$–$F_5$–$F_6$ in Fig. 11. These numerical values may not be highly accurate as the speed of progress of a crack, but the tendency of the speed of the earlier stage to be greater than that of the latter stage seems to have some meaning, because in the formation of a crack, a large amount of strain energy will be released and converted into elastic waves by the first shock, and lesser part of the energy is due to the second shock, and

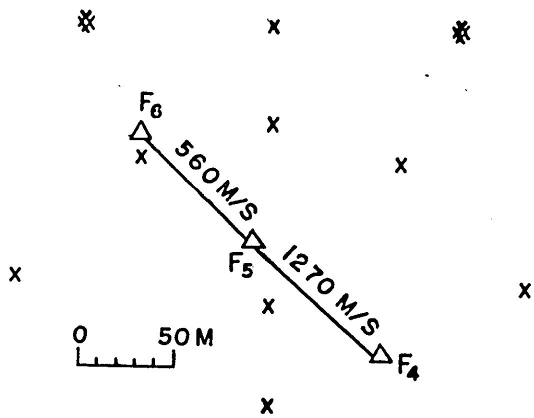

Fig. 11. Progress of a fracture in the ice-sheet.

when a less strained field of stress energy is released, the speed of the progress of a crack will be retarded.

A word will be added on the determination of the epicenter. We have a few foci which were determined by means of the commencement times of the flexural waves. The beginning of the flexural waves is not so distinct as that of the initial *P* waves, but not so indistinct as the beginning of the surface waves of natural earthquakes.

The probable errors of the foci thus determined from the flexural waves are of course somewhat large as compared with those due to the errors in the *P* waves. Seeing from the facts that the two foci are quite near in their positions, and the probable errors of the respective locations of these two foci are so small it will not be too much to say that the two waves, the compressional wave and the flexural wave, started from the same point at the same instance.

In our coming paper more detailed description on the nature of the ice tremors will be attempted.

## Acknowledgement

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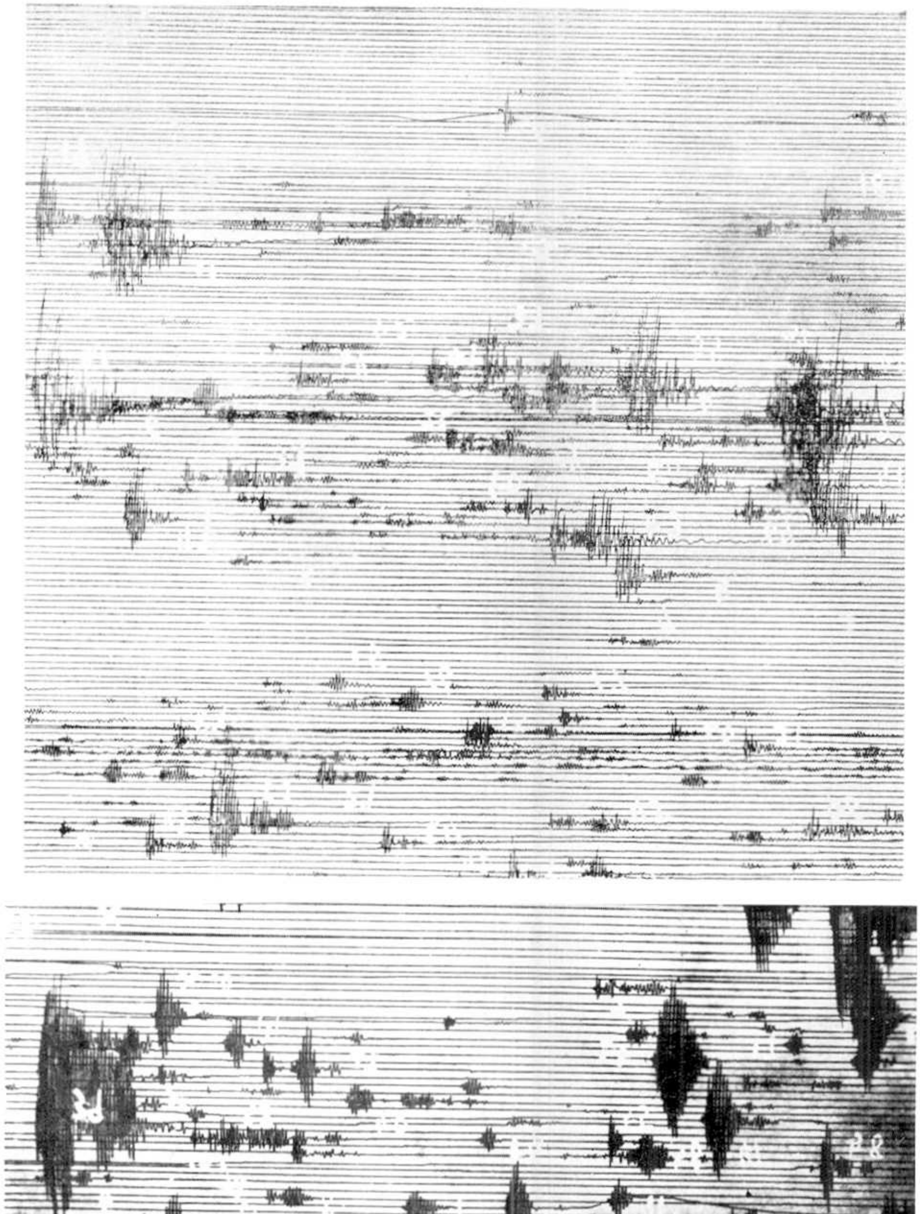

Fig. 2. Record of ice tremors by pen-galvanometers (full size).

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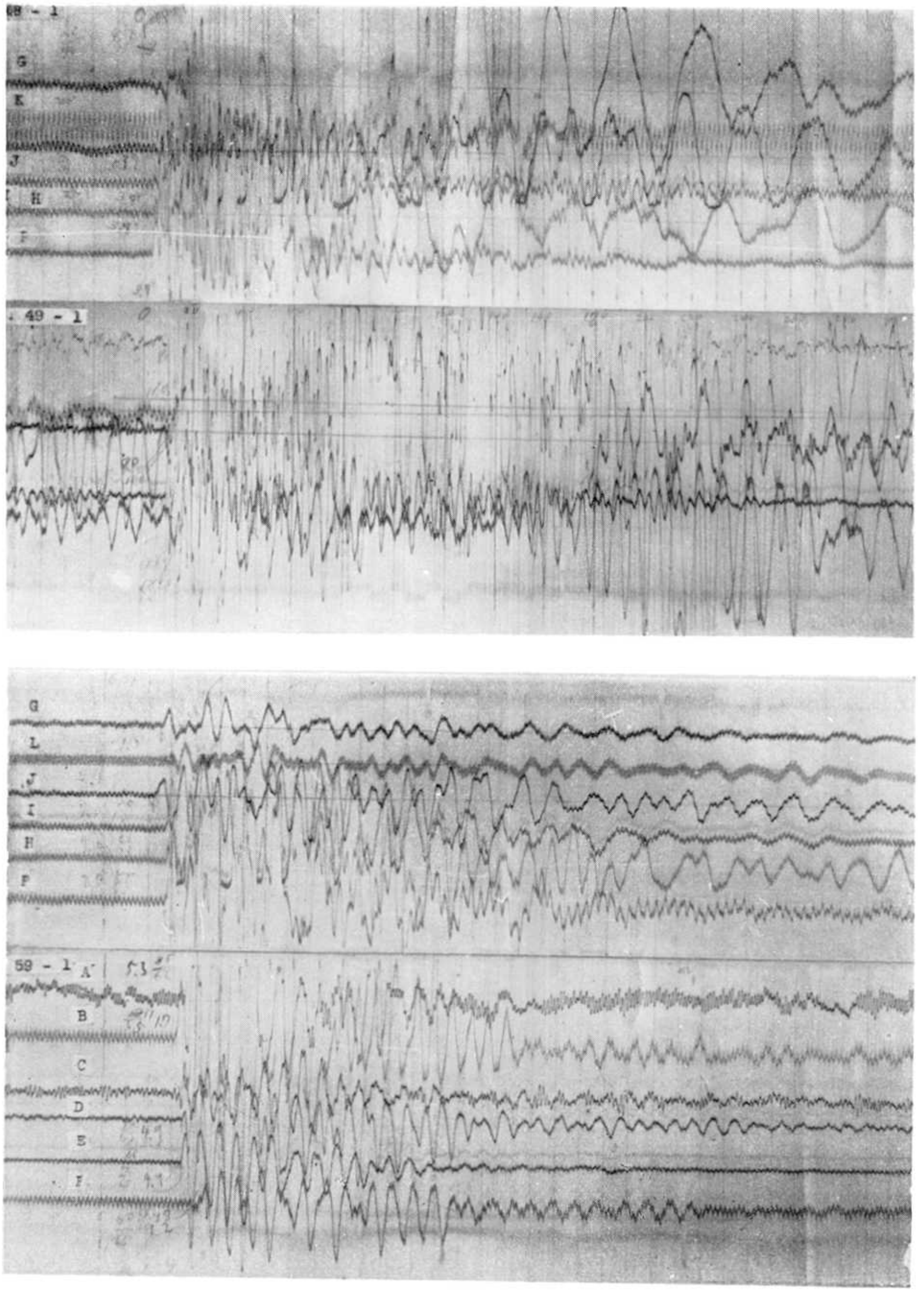


Fig. 12. Record of ice tremors. (full size)

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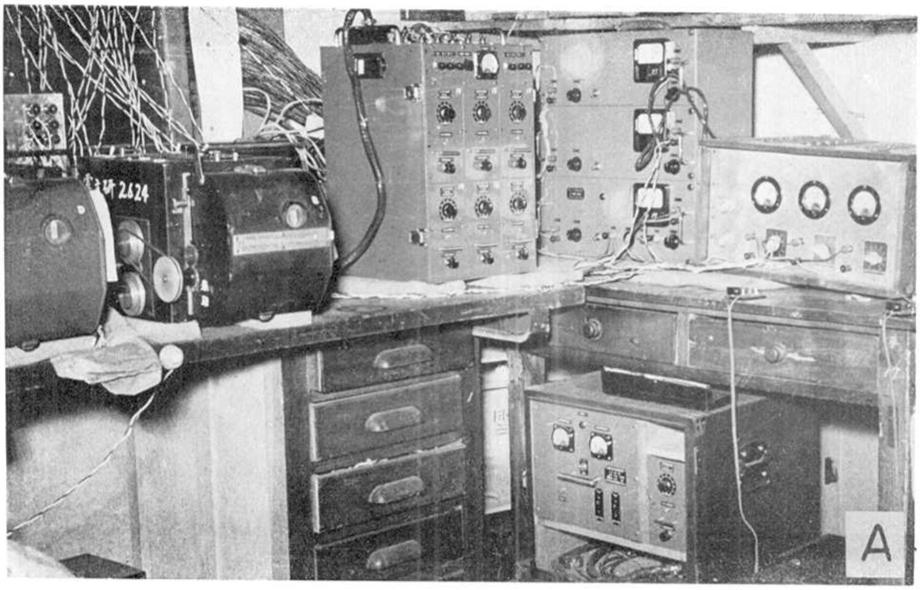
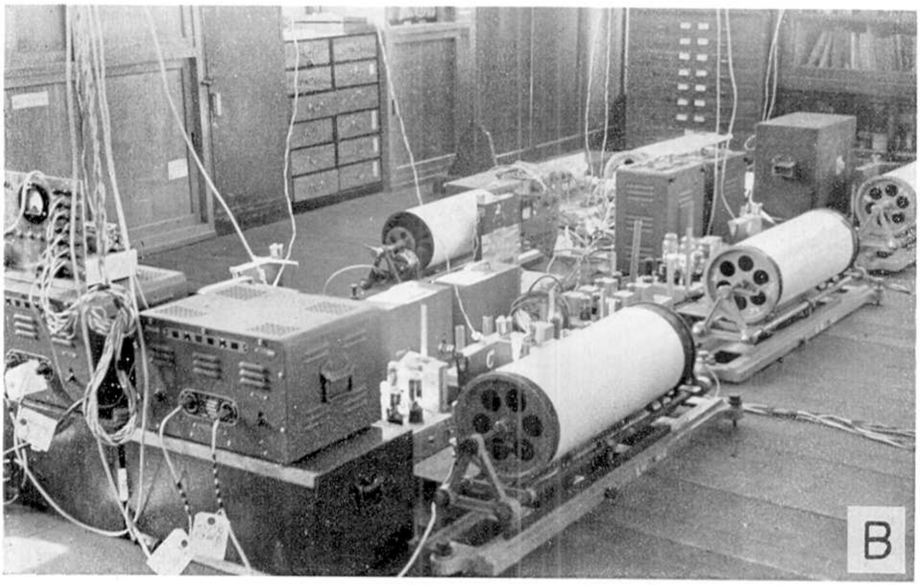
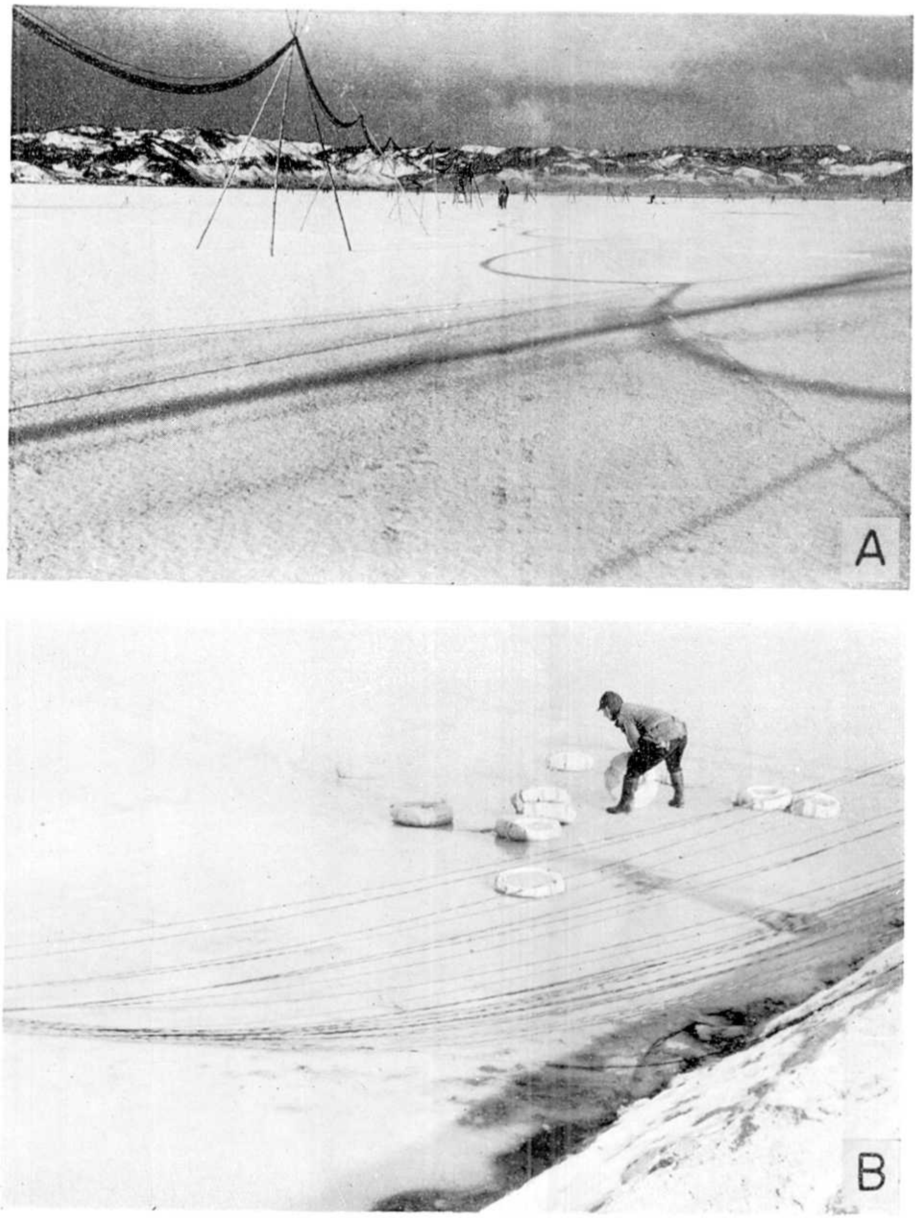



Assemblage of recording instruments.

A: Amplifiers and oscillographs.

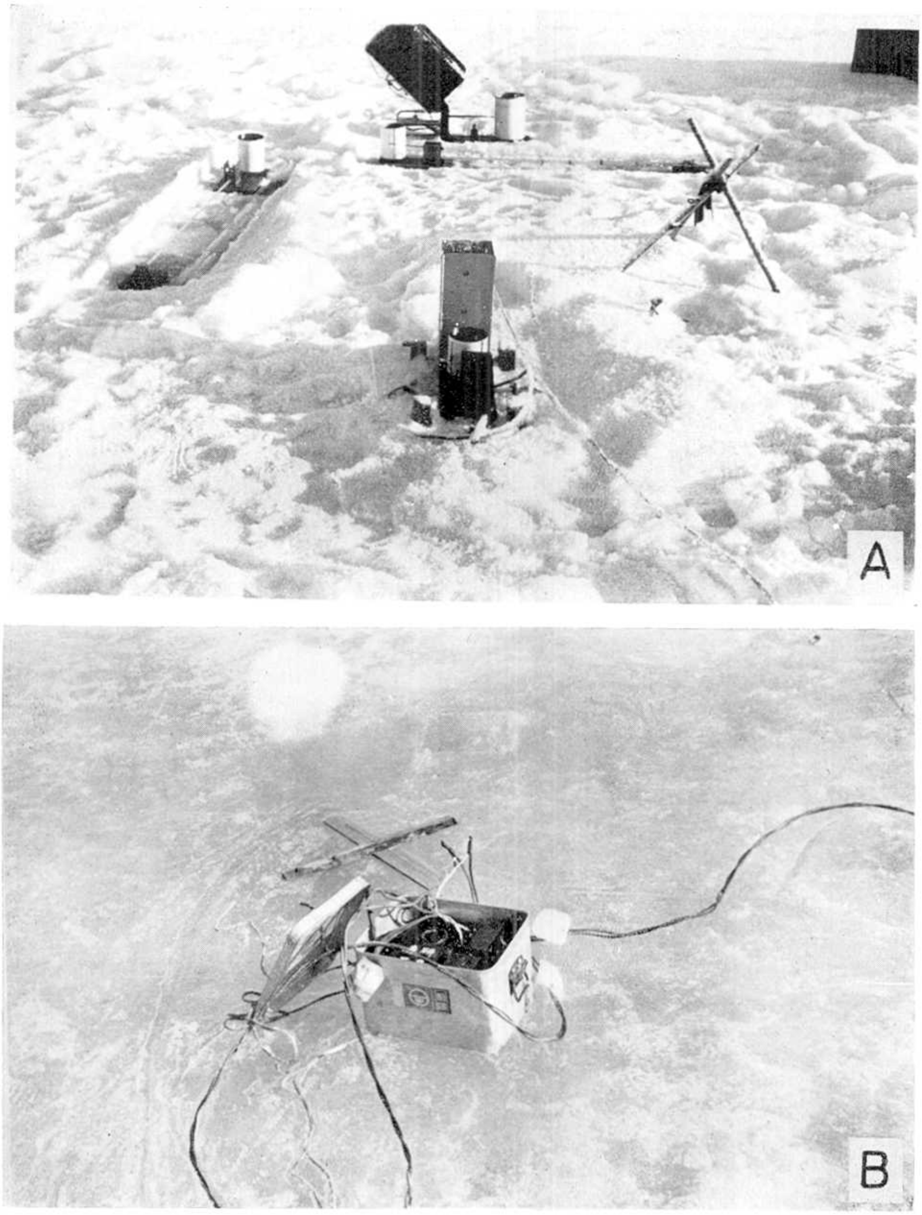
B: Long recording time system.




Cables that connect detectors to the recording equipments.

A: Cables mounted on bamboo poles.

B: Getting cables ready.




Instruments set up on ice.

A: Extensometers and thermo-couples.

B: Detectors.

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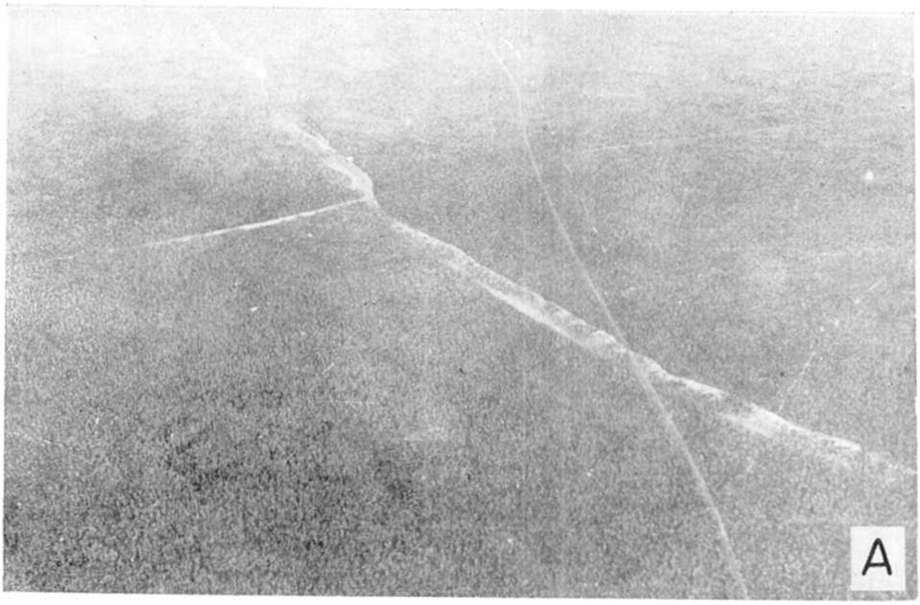



Fractures in the ice-sheet.

A: Small cracks.

B: *Omiwatari* of a small scale.

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# 42. 湖氷中に発生する自然震動の研究 (第 1 報)

地震研究所 表 俊 一 郎 / 山 崎 良 雄 / 小 林 直 吉

国立科学博物館 村 内 必 典

冬に湖水が全面結氷した後，夜間の冷えこみ，昼間の日光直射等により湖氷が収縮，膨脹を行うに際し氷の中に自然に割目が生じそれに伴つて可なり大きな音がきかれることが気付かれていた．長野県諏訪湖の有名な「御神渡」はこのような現象の顕著なものと考へられる．氷自身の収縮膨脹により氷の中に歪が蓄積せられ遂いに自然に破壊が起つて弾性波を送り出すという機構は地震の研究を行つている者に特別な注意を呼びおこすものである．最近地震の波の発生について model seismology の分野にめざましい発展がなされつつあるが，我々も諏訪湖の湖氷上に換震器を設置して氷の中に起る自然震動—氷震—の観測を行い，これを 1 つの地震の model と考えて氷震発生の機構を研究してみようと試みた．

氷震の発生と，気温，氷中温度，氷の伸縮等との間には第 3, 4 図に示されているように密接な関係が見られる．気温が 0°C 以下に降下して後 2 時間位遅くれて氷中温度も 0°C 以下に下り始め同時に氷の収縮が始まり，ほとんどこれと同時に氷震も起り始めるのが見られる．これらの氷震は，例えば第 2 図又は第 10 図の記録に見られるようにいわば shock type であるので氷震の震央をもとめることが出来る．氷の厚さが僅か十数糎であるので深さは $O$ として普通の地震の場合のように震央の座標 $X$, $Y$, 発震時 $T_0$, 波の速度 $V$ を未知数として 10 ケ位の観測点の発震時を用いて最少自乗法によつて計算を行つた結果は第 II 表及び第 9 図に示されている．これらの図及び表から見るように氷の上に見られる割目は長く延びているけれども割目の始めの所は点としてその origin をきめることが出来ることが知られた．このようにして発生する氷震の振幅の頻度分布について石本飯田の係数 $m$ をもとめた結果は普通の地震の場合に得られている値とほとんど一致していることが知られた．

氷の中をつたはる波の速さについては多くの人々の研究がある．我々もこれについて 2, 3 の測定を行つたので，氷震による初動の押し引きの問題と共に第 2 報において詳述することとしたい．