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# Internal Friction of Ice. III

## The Internal Friction of Natural Glacier Ice\*

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### Abstract

The internal friction of glacier ice was measured on specimens obtained from polar and temperate regions. Distinctively different curves were obtained for the specimens from various localities, and these differences can be attributed to; (1) environmental conditions at the time of formation, and (2) the environmental conditions that acted on the sample from the time of formation until the time of sampling. A reasonable explanation for the configuration of the glacier ice curves was easily made upon comparison with the experimental results from earlier work with pure and doped ice crystals (KUROIWA, 1964 a).

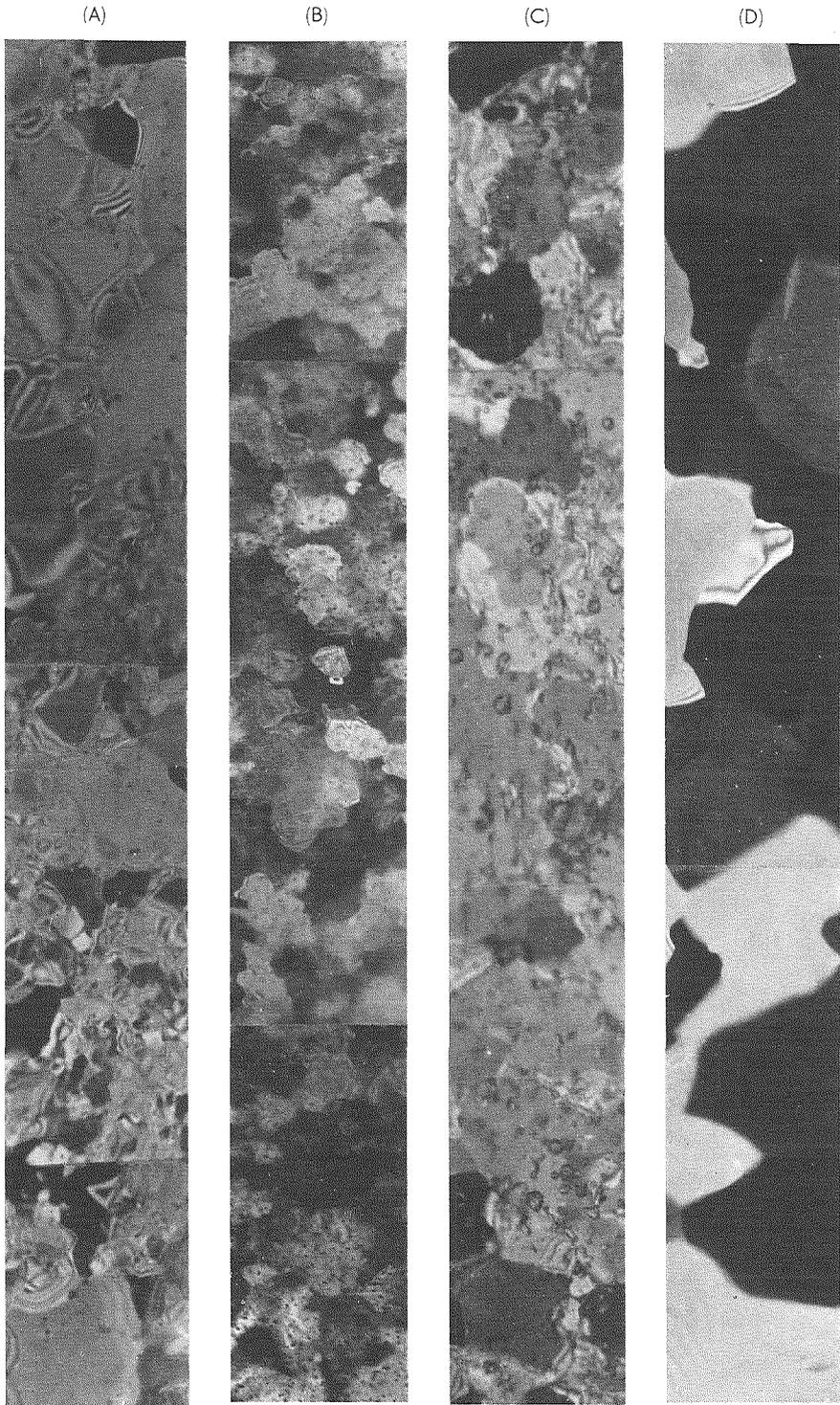
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### 1. Introduction

The formation of natural glacier ice is quite different from the formation processes of ordinary ice crystals grown from a melt. The ice of high polar glaciers is formed through densification of snow without ever being subjected to thawing. Snow crystals grow by sublimation of water vapor around tiny particles suspended in the air. While falling through the lower atmosphere the crystal surfaces become contaminated with various kinds of impurities. The main origin of the chemical impurities found in glacier ice are from the nuclei around which the snow crystal originally developed, and from the atmospheric aerosols captured by the snow flakes while falling to the ground. A very interesting problem arises when inquiring into how the impurities are distributed within glacier ice and how they exert their influences on mechanical damping. Since IGY (International Geophysical Year), the author has had

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**Fig. 1.** Photographs of the specimen of natural glacier ice. (A), (B), Greenland glacier ice. (C) Antarctic iceberg ice. (D) Le Conte Glacier ice

many chances to study the internal friction of glacier ice from Greenland, Antarctica, and Le Conte Glacier (West Coast of Canada). Their characteristic internal friction curves were explained well by the experimental results given in the preceding two papers (KUROIWA, 1964a, b). These specimens were obtained from the late Dr. NAKAYA (Greenland glacier ice), Mr. ONO, a member of the Japanese Antarctic Expedition Party (Antarctic iceberg ice), and Dr. HANAJIMA (Le Conte Glacier ice). The author wishes to express his sincere thanks for their offering these specimens. Figure 1 shows photographs of these specimens taken under the crossed polaroids.

## II. The Temperature Dependence of Internal Friction in Ordinary Polycrystalline Ice

It is necessary to summarize the experimental results of internal friction on ordinary ice grown from a melt before describing the significance of the characteristic mechanical damping curves of natural glacier ice.

The following results have been obtained by the flexural vibration method. In Fig. 2 (A), solid curves depict schematically a typical temperature dependence of the internal friction  $\tan \delta$  of contaminated polycrystalline ice. Three remarkable variations in  $\tan \delta$  are seen in the temperature range between  $0^\circ\text{C}$  and  $-180^\circ\text{C}$  as indicated by G, P, and I. Both P and G shifted toward the high temperature range with an increase in the frequency, implying that they are caused by anelasticity due to proton movement and grain boundary viscosity, respectively. The mound-like damping I, observed only in contaminated specimens, decreased with an increase of the frequency and with long-time annealing, suggesting that this damping is produced by chemical impurities trapped locally within grains in an aggregated state. The relaxation curve of pure ice P', appeared in a higher temperature range than contaminated ice with a narrow width  $\Delta T$  (the temperature interval at  $\frac{1}{2}$  the height of the damping maximum)  $= 25^\circ\text{C}$  as illustrated by a broken line. In the contaminated ice,  $\Delta T$  was approximately  $40^\circ\text{C}$ . This broadness is due to chemical impurities trapped in the ice crystal lattice.

When the logarithms of relaxation time  $\tau$  (inverse of angular frequency at maximum damping) were plotted against the reciprocal of the absolute temperatures at which maximum damping occurs, the curve for pure ice appeared in the high temperature range with a steep slope, and its activation energy was  $Q=13.1$  kcal/mole. The curve for contaminated ice appeared in the low temperature range with a gentle slope, having an activation energy of  $Q=6$  kcal/mole, as illustrated in Fig. 2 (B).

In order to explain the complicated damping curve of the  $\text{NH}_4\text{F}$ -doped ice

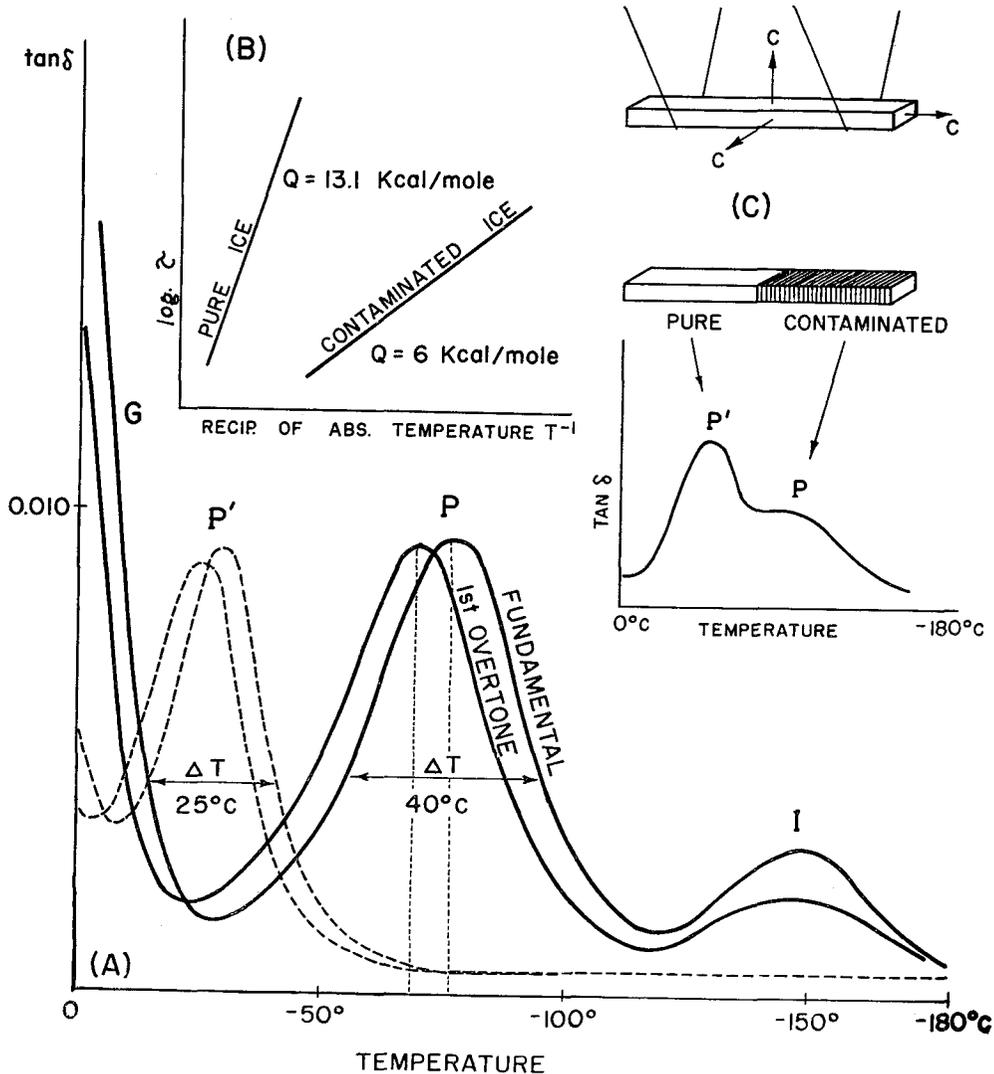


Fig. 2. Summarized temperature dependences of internal friction of ordinary polycrystalline and combined ice crystals

crystal, artificially combined crystals were made by welding together both pure and contaminated ice bars. The combined crystal showed a resultant bimodal curve which consists of a superposition of  $P$  and  $P'$  as depicted schematically in Fig. 2(C). Hence, if a bimodal relaxation curve is observed in a specimen, it can be concluded that the specimen may be composed of two component crystals which differ from each other in impurity content.

Anisotropy of the height of maximum damping was investigated by the use of a single ice crystal having different crystallographic orientations. The height of maximum damping of the specimens having c-axis parallel to the neutral line of the flexural vibration decreased to 1/5 of that of the specimen in which the c-axis was perpendicular to the neutral line.

These experimental facts provide very useful data for interpretation of the characteristic damping curve of natural glacier ice.

### III. Experimental Results

#### 1 *Internal Friction of Greenland Glacier Ice*

These ice samples were obtained by NAKAYA and BUTKOVITCH from an ice tunnel (1167 ft. long) excavated on the edge of the Ice Cap at TUTO about 15 miles east of Thule, Greenland. All specimens were removed carefully from the ice wall with the aid of a USA CRREL, 3 inches in diameter, coring auger. According to BUTKOVICH (1959), five types of ice were identified by differences in color, grain size, size and shape of entrapped air bubbles, and c-axis orientation. Among these specimens, the internal friction of the following two specimens are described.

Figure 3 illustrates the internal friction of an ice sample obtained from active glacier ice located 264 feet from the portal of the ice tunnel. The average grain size of the specimen was 7 mm, and it also contained elongated and aligned air bubbles. Its density was 0.905 and the electrical resistivity of this melted sample was 400 kohm cm. BUTKOVICH (1959) states that the c-axis of this specimen are randomly oriented as shown in the Schmidt diagram in Fig. 3. Two rectangular ice bars were cut from this ice core, parallel to the cylinder axis, and trimmed to the dimensions ; 173 mm  $\times$  19 mm  $\times$  5 mm and 182 mm  $\times$  18 mm  $\times$  3 mm. Their internal friction was measured at the fundamental and the first overtone oscillations. Their resonant frequencies at maximum damping are indicated on each curve. Both the steep rise of  $\tan \delta$  due to the grain boundaries and broad relaxation curves modified by impurities were observed, but no mound-like damping appeared in the low temperature range as was observed in ice crystals grown from a melt.

Figure 4 shows the internal friction of an ice specimen obtained 650 feet from the portal of the ice tunnel. The average grain size of this sample was 5 mm in diameter, and it contained homogeneously distributed spherical air bubbles less than 1 mm in diameter and also fine silt bands. Its density was 0.921 and the electrical resistivity of the melted sample was 185 kohm cm. Comparatively lower value for the electrical resistivity of this sample may be due to the silt bands. A petrofabric study of an ice plate cut perpendicularly

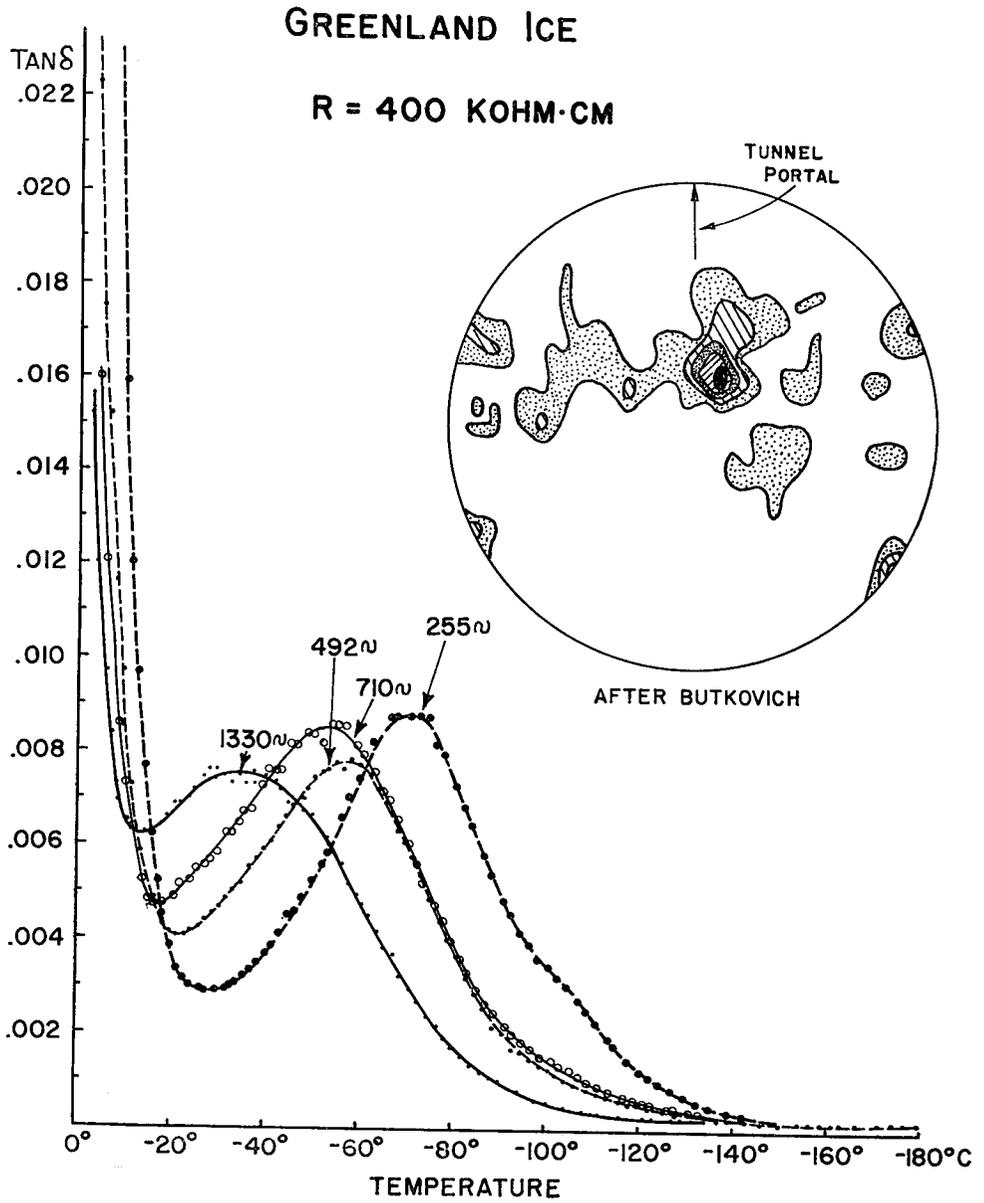


Fig. 3. Internal friction of randomly oriented Greenland glacier ice

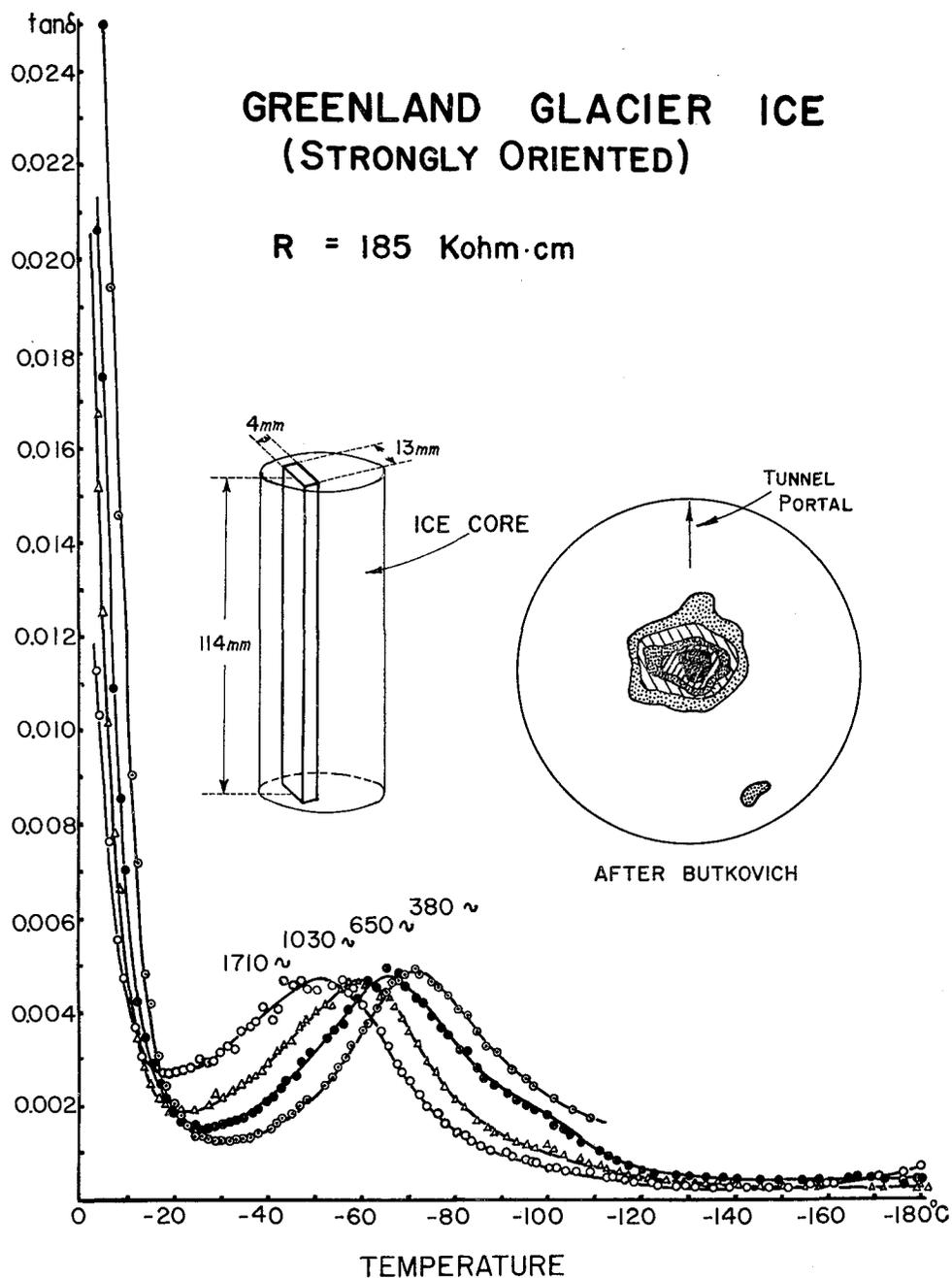


Fig. 4. Internal friction of strongly oriented Greenland glacier ice

to the core axis indicated a strong polar orientation of the *c*-axis (Fig. 4). A rectangular bar was cut parallel to the core axis, and trimmed to 114 mm × 13 mm × 4 mm, consequently the *c*-crystallographic axis and the bar axis are parallel. Lower value of maximum damping due to crystallographic orientation was observed as expected from the experimental data concerning anisotropy of the height of the damping maximum for single crystal ice. No mound-like damping in the low temperature range was observed in this sample, though a comparatively larger amount of chemical impurities were involved.

The relation between logarithmic plots of the relaxation time  $\tau$  of Greenland glacier ice and  $T^{-1}$  are given in Fig. 7, also the activation energy values are indicated for each curve. The values are quite similar to those of the contaminated ice crystals grown from a melt.

The broadness of the relaxation curve, the low value of activation energy, and no mound-like damping around  $-145^{\circ}\text{C}$  imply that chemical impurities in glacier ice can exist within grains in the atomic state but not in aggregates. Almost all chemical impurities found in glacier ice may have been derived from the sublimation nuclei of snow crystals and secondary contamination due to atmospheric suspensions or aerosols. Since high polar glacier ice has never been subjected to melting, it is believed that incorporation of these chemical impurities within the ice crystal lattice may have been achieved through densification processes and long annealing under high pressure.

## 2 *Internal Friction of Antarctic Iceberg Ice*

This sample was obtained from a grounded iceberg near Showa Base ( $39^{\circ}31'\text{E}$ ,  $69^{\circ}02'\text{S}$ ), Antarctica. Although the true age of this iceberg is not known, it is supposed that it has been subjected to erosion by wind and melt water for a long time. Many aligned air bubbles and healing interfaces of thermal cracks were observed. The density of this specimen was 0.86. The electrical resistivity of the melted sample was 230 kohm cm.

The internal friction of two specimens, one cut vertically and one horizontally from the same block of ice, is shown in Fig. 5. The relaxation curves of both samples are very broad and have obvious shoulders on the low temperature side of the curves. These shoulders can be considered to be a resultant of the two imaginary dotted curves depicted in Fig. 5. In actuality, these dotted curves probably represent the internal friction of ice crystals containing different concentrations of chemical impurities, which may occur through repeated thawing and freezing during the summer season. The only justification for these assumptions is the experimental results obtained from a combined crystal composed of both pure and contaminated ice bars (KUROIWA, 1964 a. Fig. 21).

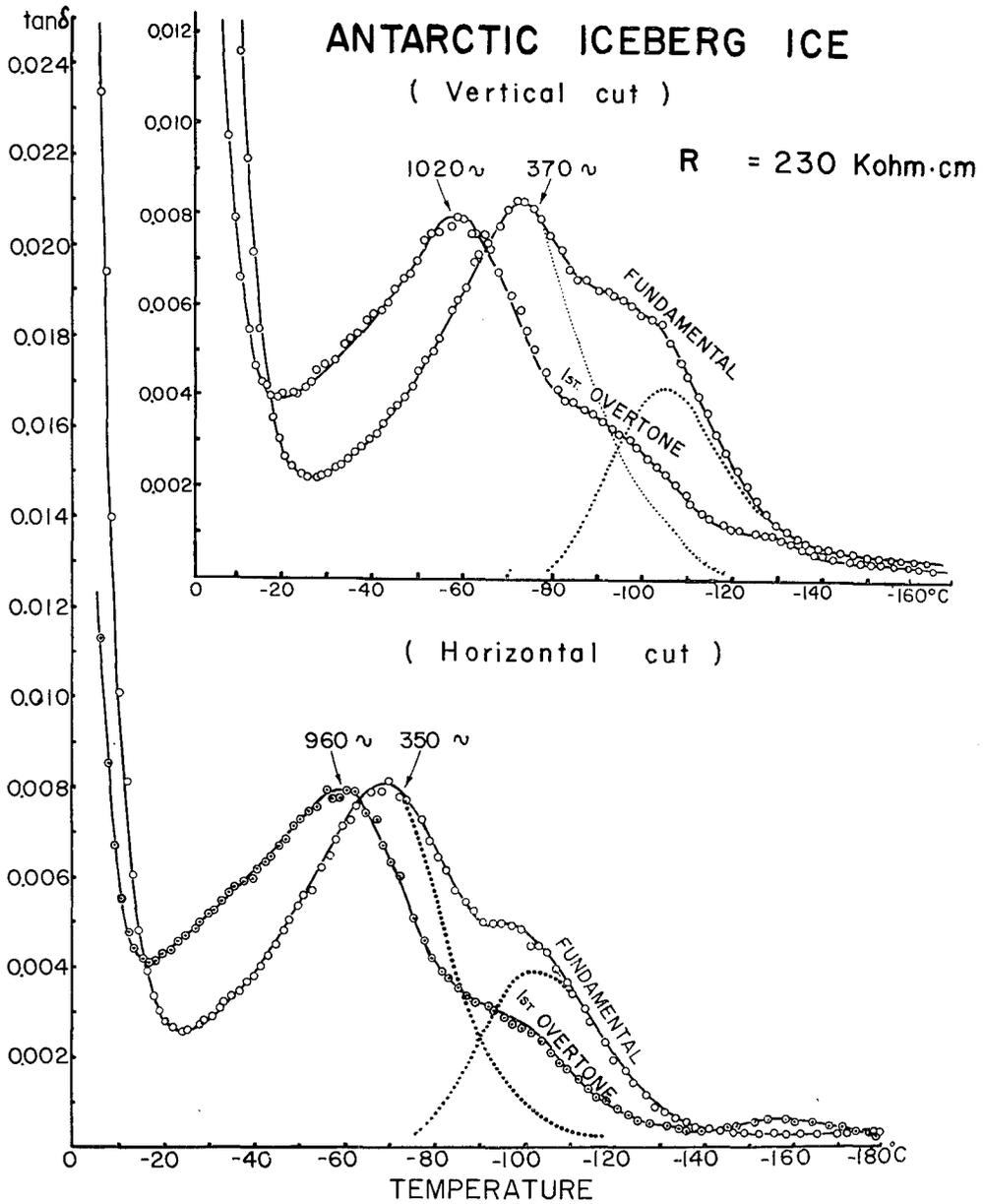


Fig. 5. Characteristic curves of  $\tan \delta$  for Antarctic iceberg ice

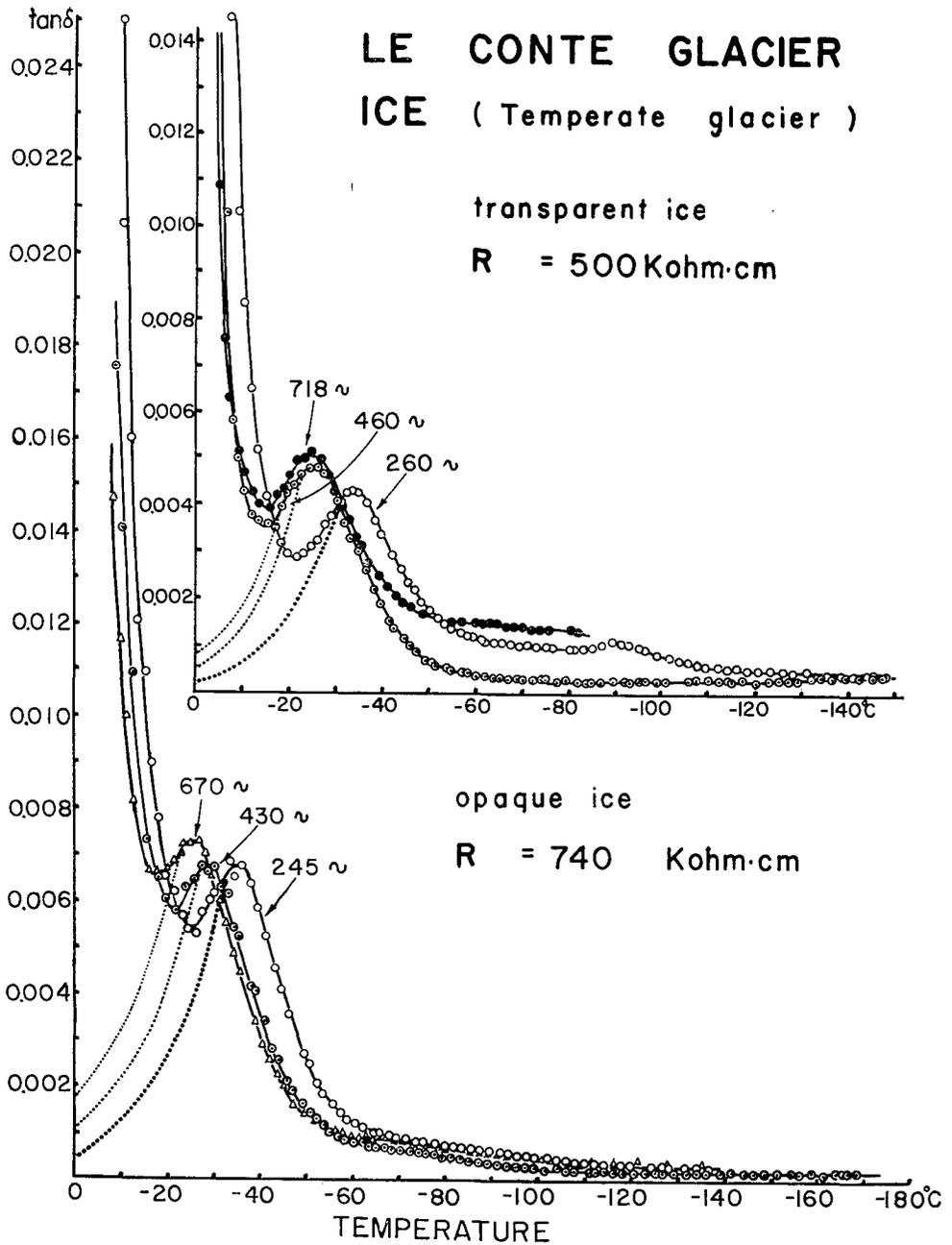


Fig. 6. Temperature dependence of  $\tan \delta$  for Le Conte Glacier ice

The combined crystals exhibited a bimodal curve which was made by the superposition of two relaxation curves.

The logarithmic plots for the relaxation time of Antarctic iceberg ice vs.  $T^{-1}$  are illustrated in Fig. 7.

### 3 Internal Friction of Le Conte Glacier Ice

Le Conte Glacier is located  $56^{\circ}45'N$  and  $130^{\circ}30'W$  (West coast of Canada). The ice samples from this glacier were initially obtained by a Japanese crew who took aboard several floating ice blocks that had calved from the terminal portion of the glacier. Two kinds of ice were identified by differences in grain size, transparency, and entrapped air bubbles. One of them was transparent ice, containing no air bubbles and consisting of fairly large grains from 20 mm to 30 mm in diameter. (Fig. 1D). The electrical resistivity of this melted specimen was 500 kohm cm. Another specimen consisted of opaque ice

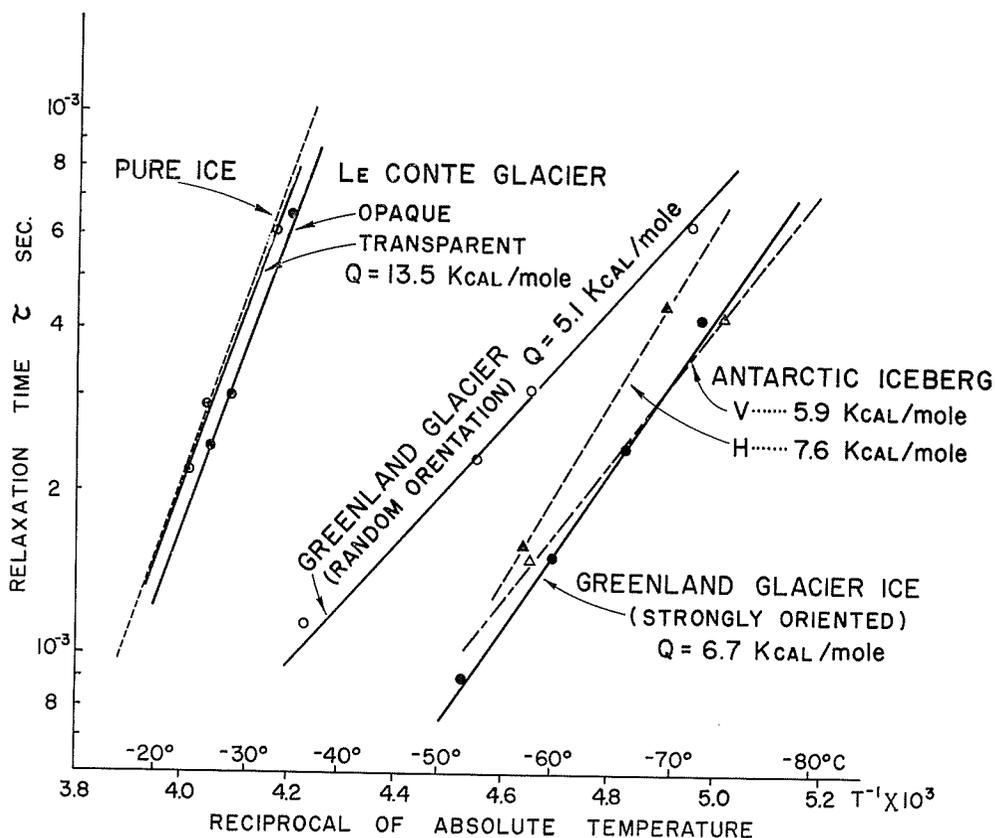


Fig. 7. Relation between  $\log \tau$  and  $T^{-1}$  for ice specimens with a wide geographic distribution

made up of many small grains containing tiny air bubbles. The electrical resistivity of this melted specimen was 700 kohm cm. It is not known how much time elapsed after these ice blocks calved into the sea, but it is no doubt that they have been subjected to annealing at the melting point for a long period of time. The internal friction curves for these specimens are illustrated in Fig. 6.

A cursory glance at these figures will show that the relaxation curves of Le Conte Glacier ice are quite different from those of both Greenland and Antarctic glacier ice. The damping maxima (curves on the high temperature side are depicted by dotted lines) due to proton movement appeared very close to the steep rise of  $\tan \delta$  produced at the grain boundaries. When the relaxation time of these specimens were plotted logarithmically against  $T^{-1}$ , they appeared in the same temperature range as those of pure ice crystals as represented in Fig. 7. The activation energy of Le Conte Glacier ice is equal to

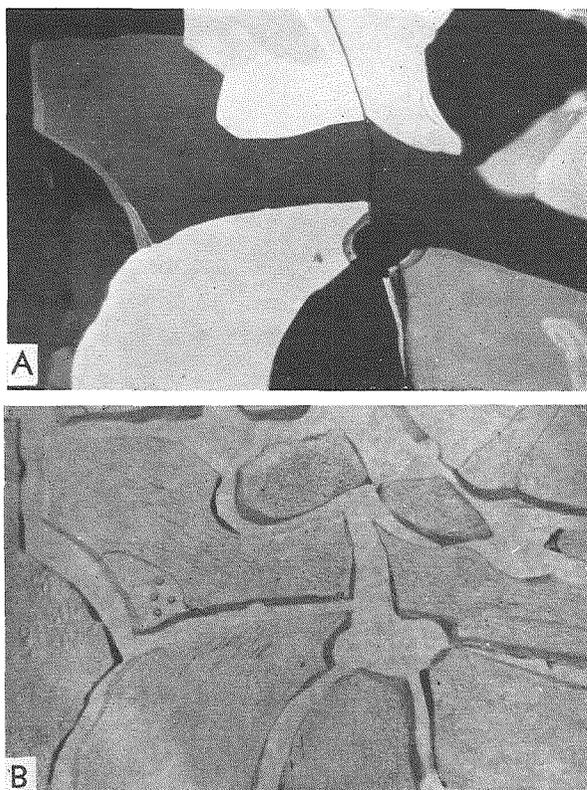


Fig. 8. Separation of ice grains due to irradiation of heat ray. (A) before irradiation. Pattern indicates the grain structure. (B) after irradiation

that of pure ice, even though it is contaminated with chemical impurities. It is difficult to understand why these conditions exist, since glacier ice from Greenland and Antarctica or doped ice crystals have an activation energy of approximately 6 kcal/mole. This peculiar behavior of Le Conte Glacier ice can be explained if we recognize that almost all chemical impurities have diffused from within the grains to the grain boundaries, due to long annealing near the melting point.

ANDRÉ RENAUD (1951) found that Z'Mutt Glacier (temperate glacier in Switzerland) consisted of pure ice grains surrounded by a concentrated saline film. After RENAUD's experiment, the following examination was carried out. A specimen of Le Conte Glacier ice (transparent ice as shown in Fig. 1D) was exposed to a strong infrared lamp. Separation of the grains occurred easily because of rapid melting of the grain boundaries as shown in Fig. 8. A thin surface layer from each grain was melted and collected in a glass bottle, then the center portion of the grains were melted in order to measure their electrical resistivities separately. The values for the electrical resistivity of the melted grain boundaries and for the center of the grains were found to be 88 kohm cm, and 800 kohm cm, respectively. The lower resistivity at grain boundaries is enough to substantiate the above statements.

#### IV. Activation Energy for Grain Boundary Viscosity of Glacier Ice

The activation energy for grain boundary viscosity of glacier ice was estimated by the approximate method used in the previous paper (KUROIWA, 1964 b). The results are:

Greenland glacier ice-

randomly oriented grains ( $R = 400$  kohm cm) ..... 36.5 kcal/mole

strongly oriented grains ( $R = 185$  kohm cm) ..... 38.0 kcal/mole

Antarctic iceberg ice-

horizontal cut specimen ( $R = 230$  kohm cm) ..... 34.0 kcal/mole

vertical cut specimen ( $R = 230$  kohm cm) ..... 35.0 kcal/mole

Le Conte Glacier ice-

transparent, large grains ( $R = 500$  kohm cm) ..... 36.0 kcal/mole

opaque, small grains ( $R = 700$  kohm cm) ..... 35.0 kcal/mole

These values were quite similar to those obtained in commercial or contaminated polycrystalline ice.

#### V. Conclusions

The internal friction of glacier ice obtained from Greenland, Antarctica,

and Le Conte Glacier was measured between  $0^{\circ}\text{C}$  and  $-180^{\circ}\text{C}$ . The nature of the characteristic curves observed in glacier ice was explained by the environmental conditions that acted on the ice samples.

Greenland glacier ice and ordinary ice grown from a melt exhibited similar relaxation curves. The broad relaxation curves of glacier ice indicate that some chemical impurities are incorporated into ice grains through the densification process of snow. The mound-like damping curve observed in ordinary ice around  $-145^{\circ}\text{C}$  has never been observed in glacier ice, suggesting that chemical impurities exist in an atomic state rather than in an aggregated state within the grains. Bimodal relaxation curves observed in Antarctic iceberg ice can be explained by assuming that the ice consists of two types of crystals containing different concentrations of chemical impurities, which might develop through repeated thawing and freezing. The narrow relaxation curve found in Le Conte Glacier ice suggests that all chemical impurities diffused from within the grains to the crystal boundaries during long annealing at the melting point. This was supported by the fact that the electrical resistivity of the melted boundary zone is much lower than that of the melted central portion of the grains.

#### Acknowledgement

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