# Shallow Subsurface Structures of East Antarctic Ice Shelves

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# 東部南極におけるたな氷の表層部の構造

**要旨**：筆者は第8次日本南極観測隊の夏隊（1966～1967年）に参加してプリンスオラフ海岸を中心とする東部南極の卓状氷山の観察を行なった．これらの氷山から東部南極のたな氷の表層部について種々の考察を試みた．すなわち卓状氷山の側面に現われる層状構造から過去数10年にさかのぼって，気温や年間蓄積量の推定および長期変動について論じた．クレバス，スノーブリッジ，融水孔などについても過去の気候などとの関係について考察した．この地域の氷山に多くの横穴が見られたことから，数10年以前に東部南極の一部は暖かく降雪の多かったことを推論した．

## 1. Introduction

Mapping of large-scale surface forms of the Antarctic Continent has been accomplished by a few overland traverses and numerous airborne surveys. The region is so vast, however, that even in many of the more readily accessible coastal areas little is known of details of the smaller features, especially in three dimensions. Unusual opportunities to observe shallow subsurface structures apparently related to East Antarctic ice-shelf growth and to local climatic history were presented during the author's participation in the 8th Japanese Antarctic Research Expedition.

The expedition ship, icebreaker FUJI, left Perth, Australia at the end of December, 1966, working southwestward en route to Syowa Station. During much of the first half of January, FUJI proceeded through pack ice and then fast ice along Prince Olav Coast. Drifting with the floes of annual ice in the pack, and caught in the unbroken fast ice closer to shore, were many of the huge tabular icebergs so well known in Antarctic waters. When floating in their original horizontal attitudes, these icebergs have vertical sides that rise 30–50 m above water, and of course extend much deeper beneath the surface. Many of them are two or more kilometers in length. Probably at least most of these great flat-topped

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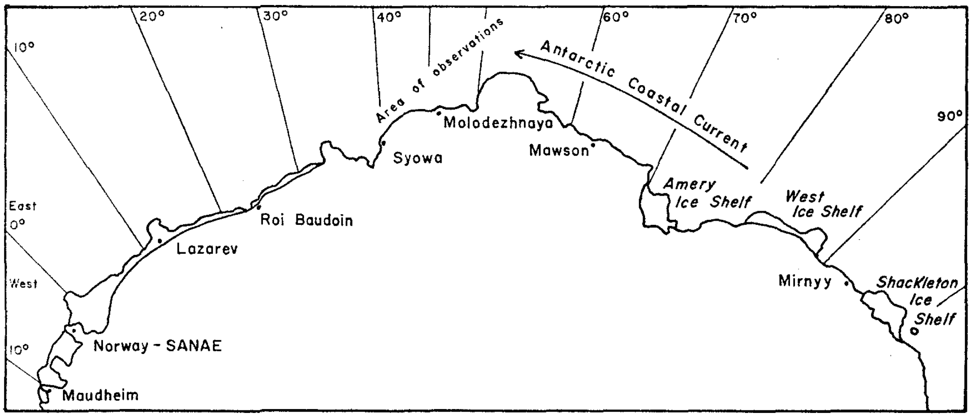


*Fig. 1. A portion of the coast of East Antarctica, showing the major ice shelves, the Antarctic Coastal Current, and the area in which observations were made while en route to Syowa Station.*

bergs have broken loose from the huge ice shelves located farther to the east, especially the Amery, West, and Shackleton ice shelves (Fig. 1). It is possible that some may come from glacier tongues in the same general rea, but ice masses produced by calving from active glaciers are more likely to have a rough surface and irregular shape unlike the typical flattopped tabular icebergs. After these icebergs have become separated from the parent ice shelf they are carried slowly westward by the Antarctic Coastal Current. Some are moved gradually seaward by offshore winds, but most remain within a few miles of the coast (LEDENEV, 1962).

Icebreaker FUJI passed as close as 500 m to some of these icebergs; many were within a distance of 1–2 kilometers. Details of the sheer ice cliffs were observed by using hand-held 8-power binoculars and the ship's pedestal-mounted 20-power glasses. In this way, many features were clearly visible from the ship's bridge and crow's nest, offering vantage points well above the level of the sea. These forms could otherwise have been studied only with great difficulty and at few localities.

## 2. Firn and Ice Layering

All of the observed ice cliffs exposed well-developed bands that were parallel to the upper, flat, original surfaces of the icebergs and, therefore, of the ice shelves from which they had presumably broken loose. Exceptions to this horizontality of the banding were present only locally near crevasses and collapsed snow bridges and in icebergs that had tilted as a consequence of break-up or uneven melting. Because these bands were continuous on all observed sides of the icebergs, it was assumed that they represented the outcrops of layers that extended through the interior of each berg.

### 2.1. Field observations

Icebreaker FUJI paused for several hours at the approximate position 68° South, 42° East, providing an opportunity for prolonged study and measurement of the layers present in an iceberg situated at a distance of not more than 300 m from the ship. Measurements were made by use of an optical range-finder and a graduated scale in the field of the ship's pedestal-mounted 20-power binoculars.

This particular iceberg was tilted at an angle of approximately 30°. Its highest part was slightly more than 45 m above the surface of the surrounding fast ice. Therefore, the total true thickness of exposed ice layers was nearly 55 m. The internal stratification of the iceberg was clearly revealed on the ice cliff both by the presence of alternating lighter and darker bands and by a *bas-relief* pattern of projecting and indented layers that had been produced by differential melting. The repeated alternation of contrasting layers was interpreted as indicating the presence of a varve-like sequence of what might be loosely designated as "winter" and "summer" accumulation layers. These apparently have differing crystal size and bubble content and, therefore, density and resistance to melting. Each pair of layers, one projecting and one indented, would thus mark an annual increment of snowfall recrystallized into firn. It is not likely that layers so close to the snow surface had been metamorphosed into true glacial ice in this polar climate.

The thickness of almost all of the layers displayed a remarkable uniformity. Adjoining "winter" and "summer" layers, as revealed by color contrasts and *bas-relief* expression, were of equal thickness, within the limits of observation. Furthermore, aside from a few of the highest layers that are described below, there was no detectable difference in thickness of layers from the top to the bottom of the ice cliff. The weight of the overlying mass appeared to have caused no greater compaction of the deeper layers. Each pair of layers had a thickness of approximately 15 cm; the separation of the individual layers was too indistinct and the distance from the ship was too great to permit acceptably accurate measurement of the thickness of each half of the pair. A total of 315 pairs of layers were counted.

Near the top of the section there were five prominent layers distinctly one and one-half to two times as thick (about 25–30 cm) as the deeper layers (Fig. 2), and three leyers about six times as thick (90 cm). Each of these three thickest layers showed very indistinct internal banding, but the thicknesses of these subdivisions could

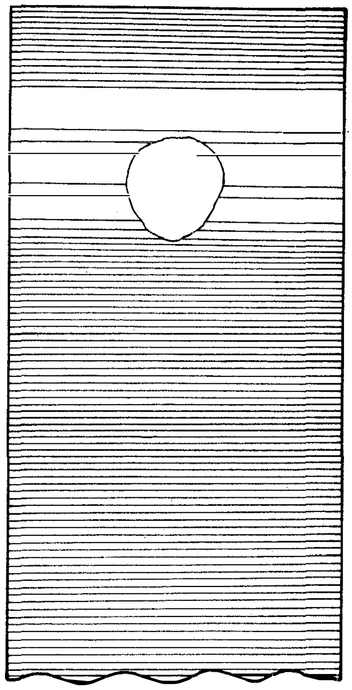

*Fig. 2. Typical stratigraphic section of firn and ice layers and the end of a tunnel as exposed in the faces of tabular ice bergs. Most of the layers are about 15 cm thick.*

not be determined with the facilities available. Above this general group of thicker layers, which aggregated about 3.5 m, were 13 more 15 cm-layers apparently the same as those constituting the lower part of the ice cliff. At the top was fresh snow.

Note: The photograph which has appeared on the cover of each issue of Antarctic Record since No. 31 is an excellent illustration of stratified firn. The thicknesses of the layers are the same as is shown in Fig. 2 of this report, except that there are present at the top a few additional thin layers and one thick layer.

### 2.2. Interpretation

As noted above, the two-part or paired layers observed in the cliffed sides of the tabular icebergs were interpreted in the field as being the result of combined "summer" and "winter" net additions of snow during a single accumulation year. To designate each individual layer as an annual increment would require that the character of the snow or resulting firn changed every second year, thereby producing the alternation of lighter and darker bands, a highly unlikely event. However, another possibility is that each pair of layers is the result of accumulation during a single storm, possibly one part formed by direct precipitation, the other by wind-driven snow.

The probable accuracy of these interpretations might be evaluated by reference to records of snow accumulation compiled at various Antarctic stations. Inasmuch as the layering was observed in icebergs believed to have calved from ice shelves, only accumulation records from coastal locations are applicable to this problem. Unfortunately, such records are scarce, and none comes from the region of the great ice shelves that are believed to have been the sources of the tabular icebergs.

Most of the observations of layering in icebergs were made between 45° and 40° East Longitude. The former Russian base as Lazarev Station was located on the Lazarev Ice Shelf at 13° East Longitude. The active zone of seasonal temperature changes in the snow and firn there extended to a depth of 14 m in 1959 (KRUCHININ, 1962a). Summer layers were 3–10 cm thick, autumn layers 12–25 cm, and winter layers 1–7 cm. These measurements suggest that annual net accumulation at this point on the Lazarev Ice Shelf might be 26–57 cm. Changes resulting from the weight of overlying layers and mass redistribution accompanying summer melting leave the upper part of each annual layer with a low density and coarse grains, whereas the lower part of the layer is characterized by extensive inclusions of secondary ice, an increased density, and finer grains. Thus, each annual layer of snow forms a firn layer having two more or less distinct parts. The thicknesses of apparent annual layers deposited from 1940 to 1959 averaged 45 cm; however, actual thicknesses ranged from 16 cm to 90 cm. Therefore, although the dual nature of each annual layer seems similar to the layers observed on the icebergs, neither the average thickness of layers not the constancy of thickness is duplicated at the site of Lazarev Station.

Records of snow accumulation from Lazarev, Maudheim, and Norway Stations suggest the existence of a marked 7-year periodicity of quantity, as well as a much lesser 11-year periodicity (PETROV and BARKOV, 1964). Annual accumulation at Norway Station and SANAE from 1913 to 1960, based on interpretation of a pit plus a core, averaged 38 g $cm^{-2}$, but actually ranged from 24.7 to 55.1 g $cm^{-2}$ with an apparent 11-year cycle and a gradual increase during the last 50 years (NEETHLING, 1970).

None of these records suggests a marked constancy of accumulation, especially through a period of more than 300 years. However, as noted by YEVTEYEV (1962), individual ice shelves, or even parts of a single ice shelf, may exhibit constrasting details of development, and the present writer does believe that the two-part layers observed in the icebergs are indeed annual accumulations.

The presence of the few thicker layers near the top of the ice cliff strongly suggested that a sequence of several years of abnormally great net accumulation of snow had occurred in the recent past. Whether this was the result of greater snowfall or less ablation or deflation could not, of course, be directly determined by distant observation.

If there were no years in which ablation equalled or exceeded accumulation, and if each two-part layer did indeed accumulate in a single year, and further, if the faint layering in the thickest units does indicate the presence of "summer" and "winter" layers that were the product of nearly uniform weather conditions and therefore lack the contrast seen throughout the rest of the section, then it follows that the period of heavy accumulation lasted approximately 22 years and began about 40 years before the iceberg was separated from its parent ice shelf. On the other hand, if the thick units are each the product of only a single season, and the faint layering records individual storms, then the heavy accumulation lasted approximately 8 years and began about 21 years before calving occurred.

The apparent equality of thicknesses of the layers exposed throughout the remainder of the section in turn suggests that there had not occurred a similar sequence of abnormally heavy snow accumulations during the preceding 300 or so years. Data are not now available to permit a meaningful estimate of the length of time during which this and other icebergs have slowly drifted from the points of calving to the locations at which they were observed in 1967. Certainly this movement has not been continuous, for they are often held immobile in the fast ice, and it may at no time have been rapid. The true age of the thick layers cannot be determined until their remnants are observed in place in the source ice shelf.

The occurrence of outstandingly thick accumulation layers in a single iceberg would constitute merely a curiosity. However, the writer was able to view a considerable number of large icebergs of the tabular variety while travelling along Prince Olav Coast from 45° to 40° East Longitude. Throughout this region, a notably high percentage, certainly more than half, of these bergs showed a similar development of a few relatively thick accumulation layers a few meters from the top of the cliff face, but no such abnormal layers were seen at greater depths in the faces of any bergs.

It therefore seems certain that unusually thick layers of snow accumulated on an ice shelf or shelves in East Antarctica in the relatively recent past, but not during the preceding three centuries. It has been suggested by several researchers that a rise above the present mean annual temperature in Antarctica would result in greater snowfall. Such a "warm" interval may have occurred, at least locally, in East Antarctica. Which ice shelf or shelves were thus affected, and whether such a potentially important climatic event occurred over a larger area can be determined only by tracing these icebergs back to their source. The charts of iceberg distribution presented by LEDENEV (1962) suggest that icebergs calved from the Shackleton, West, and Amery Ice Shelves might all move along Prince Olav Coast.

## 3. Subsurface Openings

The ice-cliff faces of many of the tabular icebergs seen along Prince Olav Coast during January, 1967, were marked by scattered openings of various sizes, shapes, and locations. They can be grouped conveniently into four categories:

1. Sea caves
2. Open crevasses
3. Brigded crevasses
4. Tunnels

### 3.1. Sea caves

Many of the icebergs studied from icebreaker FUJI were surrounded by fast ice far from the open sea both in early January (mid-summer in Antarctica) and in early February. They seemed to be locked fast in an unchanging environment. However, all of these icebergs have from time to time drifted freely in pack ice or open water. Only in this way could they have been moved by wind and ocean currents to their present location from their apparent source areas along the fronts of the great ice shelves. Therefore, all have been subjected to at least some modification caused by action of ocean waves.

In many instances, the consequences of wave attack have been negligible, often resulting only in the formation of a wave-cut or wave-melted platform a few meters below water line. However, some of the icebergs have been more exposed to powerful waves that have succeeded in etching out weak spots in the ice. Once an opening has formed, wave splash is concentrated there and enlargement proceeds at an increasing rate. In this way, sea caves are formed that may be as much as 50 m across, extend 10–20 m above water level and perhaps half as far below, and penetrate into the ice for several tens of meters (Figs. 3 and 4). Occasionally, if the situation is favorable, arches or stacks may form as on a rocky coast; sometimes these forms are subsequently raised above water level, forming a sloping terrace on a tilted berg.

### 3.2. Open crevasses

Inasmuch as the tabular icebergs are calved from an ice shelf and then gradually break up themselves, many of them are riven by open crevasses. These cracks may extend downward only a few meters from the top surface, or they may reach below water line. They are generally short-lived features, in effect

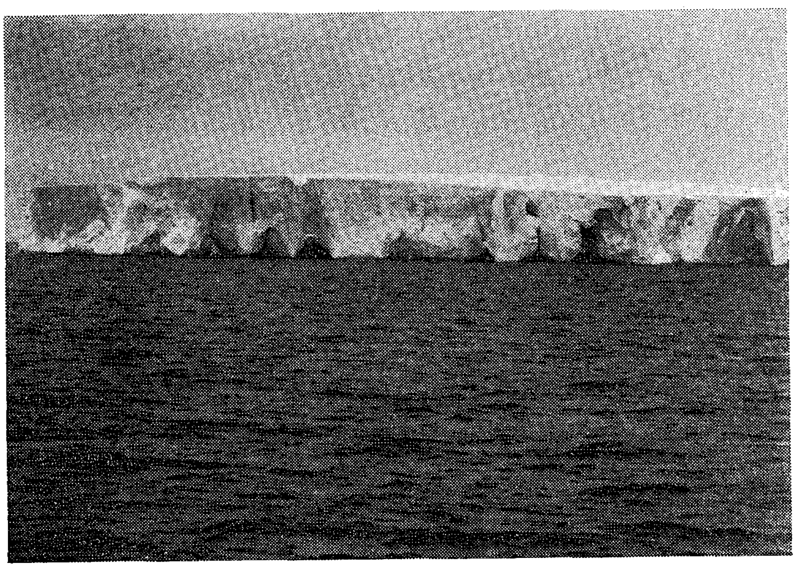

*Fig. 3. Sea caves forming along the face of a tabular ice berg.*

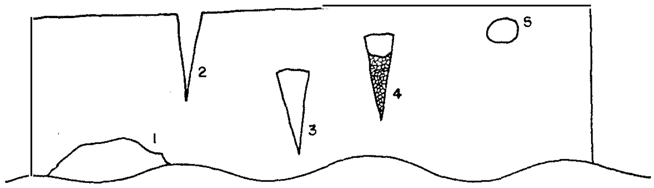


*Fig. 4. Diagrammatic representations of typical occurrences of openings in the face of a tabular ice berg.* (1) *sea cave,* (2) *open crevasse,* (3) *bridged crevasse covered by later firn and snow,* (4) *bridged crevasse largely filled with ice breccia formed by collapse of earlier snow bridges* (5) *tunnel formed by meltwater stream.*

disappearing when the ice block on one side falls away from that on the other side. They are not, however, subject to compressional healing, as are crevasses in a moving glacier. The separation of the two walls at the top of the crevasse may be a few tens of centimeters or a few meters, depending on the time of observation in relation to the moment of final collapse.

### 3.3. Bridged crevasses

As a consequence of tensional forces set up by uneven flow of glacial ice, crevasses may open in ice shelves or glacier tongues. Often, with continued flow, these crevasses close and, as the two sides freeze together again, the fracture is healed. When this happens, there may be no readily discernible evidence of its former presence. In contrast, some crevasses will remain open more or less permanently if no subsequent compressional forces affect that particular part of the ice mass.

If a crevasse does remain open, wind-blown snow soon begins to form a cornice overhanging from the upwind side. With continued accretion, this cornice may eventually be built completely across the crevasse and so form a snow bridge. The bridge may collapse during the next ablation season, and then form again the following year, or it may become permanent and be covered by the accumulating snow of succeeding seasons (Figs. 4 and 5).

Exposed in the sides of many of the icebergs observed off Prince Olav Coast were crevasses that had been bridged and subsequently covered by snow that accumulated for many years. The tops of some of these crevasses were as much as 25 m below the upper surface of the berg. Visual detection of the presence of such deeply buried crevasses would have been impossible from above.

The long-term preservation of these open crevasses indicates that the ice mass had been essentially static for at least the length of time required for accumulation of the snow that covered the original cornice bridge; any movement would probably

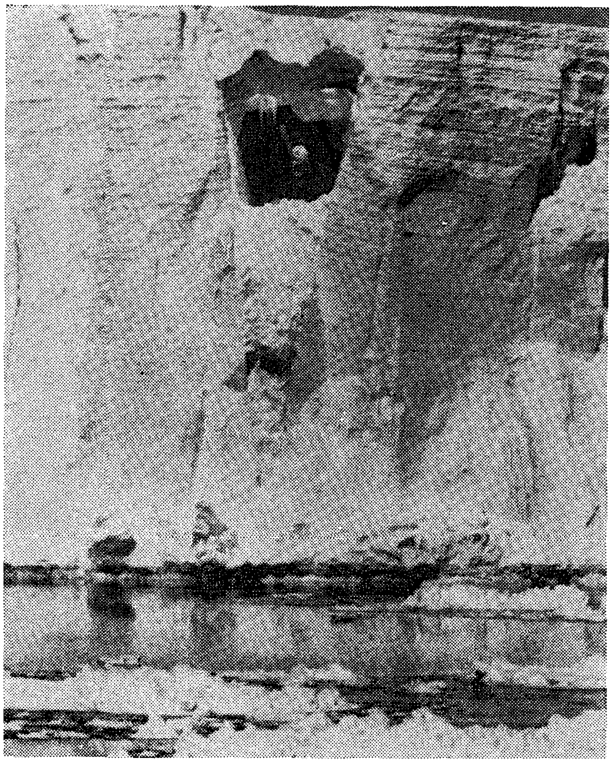

*Fig. 5. Crevasse capped by a snow bridge that has partially collapsed. The lower part of the crevasse is filled with ice breccia formed by collapse of earlier bridges. Note the near-horizontality and even thickness of the firn layers.*

have resulted in a closing of the crevasse even though it was bridged. This in turn suggests that the ice shelf or shelves from which these particular icebergs broke off are now in a major period of wastage by calving without compensating flow from inland sources, therefore appearing to have a negative budget. This tentative conclusion is strengthened by the fact that the limits of a number of ice tongues and ice shelves in the more accurately mapped parts of Antarctica are known to have retreated in recent years.

### 3.4. Tunnels

If a snow bridge collapses into a crevasse and is later replaced by a new bridge, a cross section of the remaining open space will have a roughly circular outline. However, the shape of the pre-existing crevasse will still be readily apparent when seen in the side of an iceberg. The deeper, narrower parts of the original V shape will be filled with a chaotic ice-block breccia which clearly interrupts the regular horizontal layering of the ice (or firn) on each side. Entirely different are circular openings that do not have any associated breccia. For the purposes of the present discussion, these latter features are categorized as tunnels, a term that does not in itself imply a specific origin.

Tunnels of this type that were observed in the cliffed sides of icebergs passed by icebreaker FUJI along Prince Olav Coast had sharp boundaries; there was no ice breccia below or at the sides (Figs. 4 and 6). They were circular, or nearly so, in cross section, with diameters ranging from as little as 1 or 2 meters to perhaps as much as 10 m. The average seemed to be about 5 m. They were more numerous than either open or bridged crevasses, being present in more of the icebergs, and in greater numbers in each of the largest bergs.

It does not appear possible that these round forms originated as bridged crevasses that would have had narrow V shapes preserved below the snow bridge. A more likely explanation is that these were meltwater channels. They might have been formed by surface streams eroding (by melting) channels that were later roofed by snow bridges, or alternatively, they might have been developed by shallow subsurface flow within an especially permeable layer of firn.

It was observed that there was no consistent relationship between the occurrence of tunnels in the tabular icebergs and the presence of the unusually thick, near-surface layers of ice or firn. Some icebergs had tunnels but no detectable thick layers; others showed the development of thick layers but no tunnels. However, in all instances where the two features were present in a single iceberg, the tunnels were always located within the zone of thicker accumulation layers, although the bottoms of a few tunnels had penetrated 2–3 of the thin layers beneath.

The fact that the tunnels were without exception present at no level other than in the zone of thicker layers strongly suggested a common causal relationship. As was discussed above, it is believed that the thicker layers resulted from unusually heavy annual snowfall which in turn was the result of an interval of warmer mean annual temperature. This is in keeping with evidence from other parts of Antarctica, particularly Southern Victoria Land, that at least the local

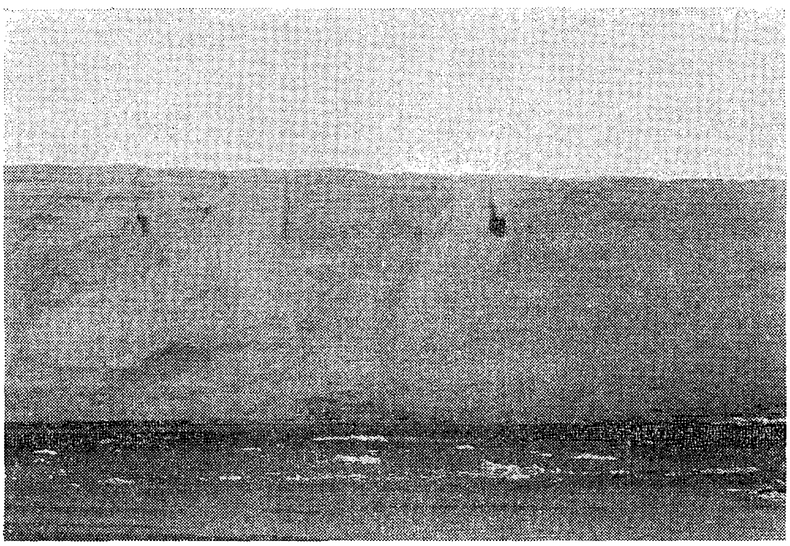

*Fig. 6. End of two meltwater tunnels exposed in the face of a tabular iceberg.*

mountain glaciers now have negative budgets resulting from lack of precipitation and that this lack is caused by excessively low temperatures (DORT, 1968; 1970). If this is correct, a general rise in temperature would cause an increase in available atmospheric moisture and, therefore, greater precipitation and accumulation. It might further be expected that during such a period of higher temperatures there would be increased meltwater runoff in absolute terms even though greater depths of snow remained through each season and therefore accumulated year after year. As a consequence, surface stream channels would tend to form in the first thick "warm weather" accumulation layer to be deposited.

Renewal of meltwater flow in succeeding years would serve to maintain the existence of these surface channels and, in especially large channels carrying relatively great volumes of water, might permit melt-erosion short distances into the underlying thinner accumulation layers. Not all meltwater channels would develop at the same time, however, so the floors of some would be at a slightly higher level than the others. Furthermore, flow in some channels might be diverted, as often happens during the evolution of a system of consequent rills on a new land surface, and these channels would become roofed by permanent snow bridges in the same manner as crevasses, and would thus be preserved as tunnels. Other channels might remain open until the end of the interval of warmer climate and would, therefore, be roofed at a somewhat higher level. That a running stream can occupy such a tunnel, at least in an intermontane valley locale, was demonstrated by the discovery of such a feature in the Obruchev Hills (D. S., 1964).

The presence of numerous tunnels in icebergs observed along Prince Olav Coast thus appears to strengthen the suggestion that a few decades ago there was an interval of higher temperatures and greater snowfall that affected some coastal portion of East Antarctica. It may have been effective over an even greater area.

## 4. Surface Furrows

While on a helicopter reconnaissance flight, the author noticed that the flat surfaces of some of the large tabular icebergs were marked by shallow furrows that were neraly straight and parallel. Views of the cliffed faces of these bergs showed that some of these furrows marked the locations of old crevasses partly filled with snow (Fig. 7), but other furrows were located directly above the subsurface tunnels (Fig. 8). By later close observation of a few of the same icebergs from shipboard, it was seen that the overlying accumulation layers had sagged slightly into the tunnels, thereby forming the furrows at the surface. There was thus provided added support to the concept that the tunnels were originally the open channels of surficial meltwater streams whose courses were straight and parallel, consequent on the slope of the ice surface, and were subsequently covered by snow bridges.

## 5. Conclusion

Firn layers and meltwater tunnels exposed in the vertical sides of tabular ice bergs observed during the 8th Japanese Antarctic Research Expedition are believed to record brief variations in the mean annual temperature and the annual net accumulation of snow for a portion of the coast of East Antarctica at some time within the past few decades. Interpretations reported here would be strengthened if samples of the supposed annual layers could be collected and subjected to laboratory analyses and if the actual source or sources of the tabular ice bergs could be determined through additional regional exploration.

**Acknowledgements**

All of the observations reported in this paper were made during the period that I had the privilege of being a member of the 8th Japanese Antarctic Research Expedition. I am greatly indebted to Dr. Tetsuya Torii who, as Leader of JARE-8, made possible my active participation in the scientific program and to Captain Mitsutoshi Matsuura, Captain of icebreaker Fuji, who generously made available to me the facilities of his ship. Discussions held with Dr. Yoshio

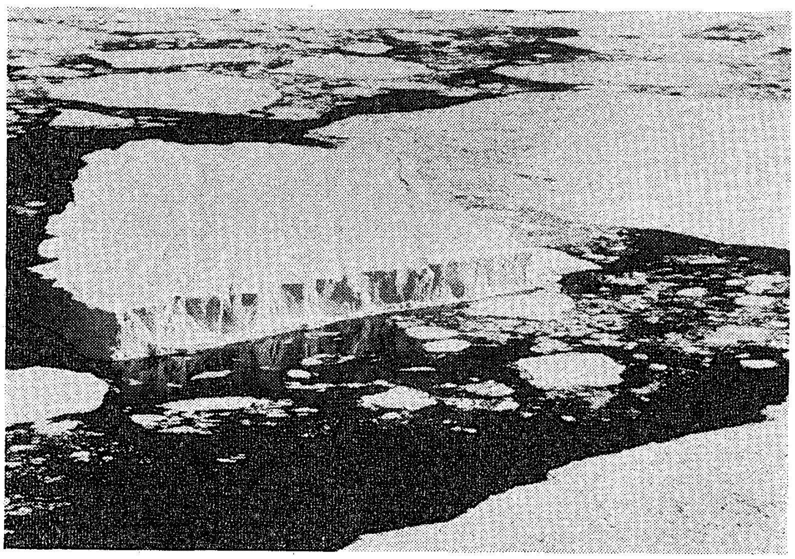

*Fig. 7. Surface furrows formed by collapse of snow bridges into crevasses.*

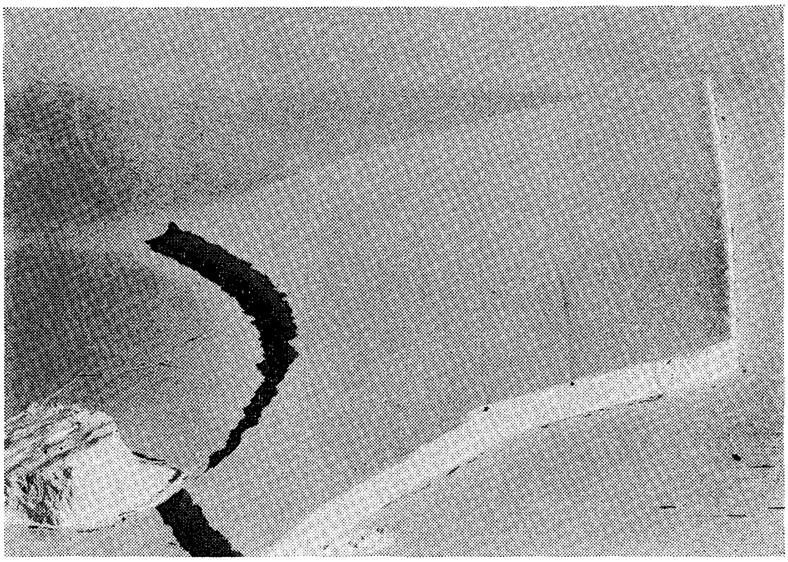

*Fig. 8. Surface furrows formed by partial collapse of snow bridges over meltwater tunnels. Compare size and shape with those in Fig. 7.*

YOSHIDA during the voyage were extremely helpful. Portions of the research were supported by Grants GA-688, 1685, and 16037, received from the National Science Foundation of the United States.

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(*Received April 30, 1971*)