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EVOLUTION OF UNDER-WATER SIDES OF ICE SHELVES AND ICEBERGS

by

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ABSTRACT

A systematic programme of side-scan sonar and plumb-line soundings was carried out in the Weddell Sea area in 1985 to measure the under-water sides of ice shelves and icebergs. From these observations the following model is suggested for the evolution of the ice front:

(1) Initial stage: fracturing of the ice shelves takes place along smooth, curvi-linear segments with vertical faces.

(2) Formative stage: the freshly formed vertical face is eroded both by wave and swell action around the water line, by small calvings from the undercut, overhanging subaerial face, and by submarine melting. The melting has a minimum at 50–100 m depth, and increases with depth to a rate of around 10 m a^{-1} at 200 m. This is about twice the rate of erosion at the water line. The variation in melting with depth results from a combination of summer melting by near-surface water, and year-round melting by water masses that are increasingly warmer than the pressure melting-point with depth.

(3) Mature stage: this stage is reached after a few years of exposure. The backward erosion of the face leads to a shape with a prominent under-water "nose" with a maximum projection to more than 50 m at 50–100 m depth. The ramp above this slopes upwards to meet the vertical wall about 5 m below the water line. The ice below the nose is melted back beyond the above-water face. There is no net buoyancy and ice shelves at this mature stage are generally *not* up-warped at the front.

INTRODUCTION

This paper discusses the evolution of the front of ice shelves and the sides of icebergs, with main emphasis on changes below the water line.

Ice shelves float, and are modified in contact with sea-water. A freshly calved tabular iceberg is a sample of the ice shelf, with the experimental advantage of including sides that have not been affected by the sea, and at least one side that has been exposed for some time.

The shapes and the physical dimensions of ice fronts tend to be similar around Antarctica. This, and the opportunity of recognizing ice fronts and icebergs recently calved, gives good conditions for systematic studies of the evolution of the free faces. Furthermore, ice fronts can sometimes be observed to have moved steadily outwards without undergoing large-scale calving. Such locations are especially attractive for investigation of changes with time.

A typical ice-shelf front is around 200 m high, of which 30–35 m is above water. The freeboard is greater than for pure ice because the ice shelves consist of firn in their upper layers. The elevation of the ice front generally varies little over short distances, except where grounding has taken place. Our typical measurements show a height of freeboard within 28 ± 4 m over a distance of several kilometres.

The map shape shown by the ice front is partly a question of scale. It will generally appear straight or slightly curved on a scale of a kilometre or less. The curved segments have the concave side to the sea, i.e. the fracture lines meet in cusps pointing away from the ice shelf. For present purposes, the ice front is considered constant in thickness and linear in map shape. Thus, we are only concerned with the changes in the profile at right-angles to the ice front.

This paper presents data on profiles at various stages. These are used to develop a model for the evolution of the free face, and determine which processes are most effective in forming the face. Practically all field data were collected on the Norwegian Antarctic Research Expedition (NARE) 1984–85, where part of the ship time was used for a dedicated study of the under-water ice. To my knowledge, no previous systematic studies have been conducted to determine the under-water shapes of ice shelves and tabular icebergs, apart from preliminary studies on NARE 1978–79 (Klepsvik and Fossum 1980).

OBSERVATION TECHNIQUES

(a) Side-scan sonar

The main part of the under-water data is based on sonographs obtained by a Klein model 400 side-scan sonar (SSS). The SSS system consisted of three units: an under-water unit (the "fish"), a combined data, power, and tow cable, and a dual-channel graphic printer. The fish is a streamlined, hydrodynamically balanced body containing two sets of transducers. These transmit a 0.1 ms ultrasonic sinusoidal pulse at 100 kHz and then change to a receiving mode for a time interval determined by the range.

Most of the pulse energy is concentrated in two beams with 40° openings. For these experiments, the fish was arranged so that both beams faced the ice wall, looking up and down from the horizontal. The beam width is 1° in the direction of travel. The resolution is determined both by graphic capability and range. It was typically 2–4 m in these studies.

The plotted image has a linear time-scale with zero at the centre, and each returning signal is plotted on the paper according to the time it is received after the outgoing pulse. As the fish moves through the water, the adjacent scans form an acoustic image with one scale determined by the speed of the fish. Strength of the return signal determines darkness of the plotted image. A strong signal appears black. For angles of incidence ≠ 90°, the strength of the return signal depends upon the roughness of the ice at scales comparable with the wavelength of the acoustic pulse (0.015 m) (Klepsvik and Fossum 1980).

The present system was not equipped with a correcting device, the scales along the two axes of the sonograph were different, and the return times gave a non-linear representation of the object. The sonograph therefore needs careful analysis to give a correct image. The sonographs may also be distorted by phenomena such as: (a) cross-talk of various kinds between the channels, (b) deviating fish motions, (c) multiple reflections, and (d) focusing of the sound beams.

Further descriptions of the SSS can be found in Leenhardt (1974) and Flemming (1976). Information on this kind of SSS investigation of ice shapes has been given by Klepsvik and Fossum (1980). Their studies on NARE 1978–79 led to the present programme.

Two profiling techniques were used in the present study. Most of the data, altogether 130 line km, were

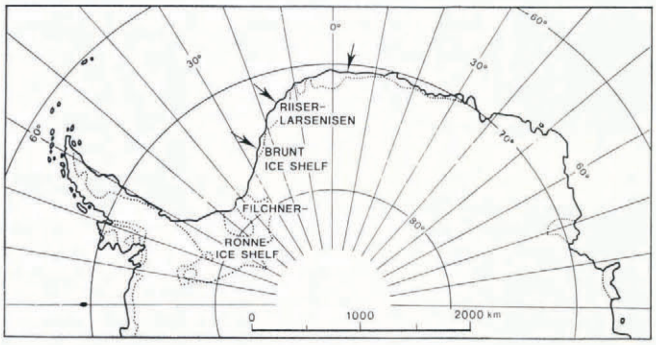

Fig.1. Index map showing location of side-scan studies.

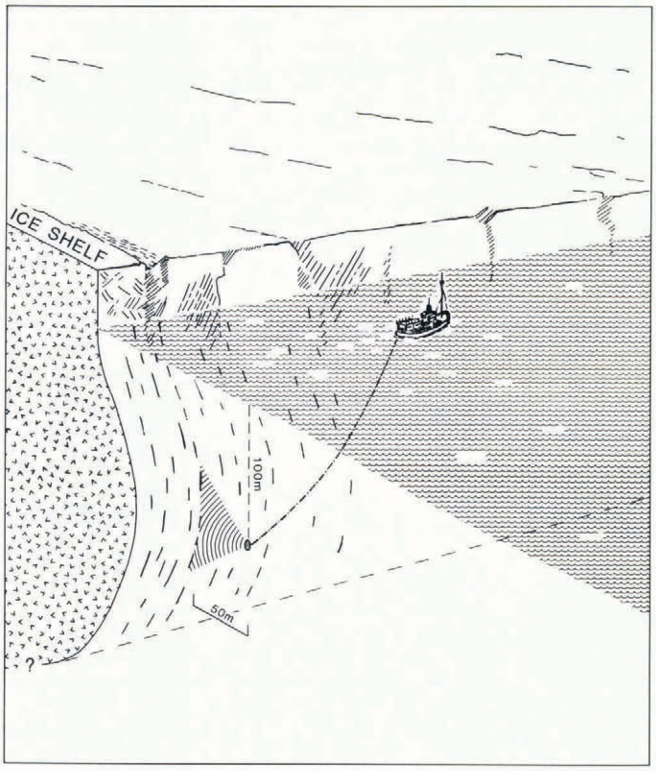

Fig.2. Principle of horizontal, under-water sounding. The figure does not show the whole sector covered by the sound beam.

collected by towing the fish behind the vessel, usually at around 50 m from the ice face (Figs 1 and 2). The best results were obtained by close profiling. However, navigating the vessel at a constant short distance from the ice face was not feasible because of reduced manoeuvrability at the profiling speed of 2–3 knots. We found it possible to profile as close as 30 m along straight sections.

The fish was towed at several depths at most locations. A major difference between the present study and that of Klepsvik and Fossum (1980) was that the present fish was now fitted with a depth sensor. This was read on board, and the depth controlled by adjusting cable length or vessel speed. More importantly, it became possible to combine different profiles to build three-dimensional images of the ice face. Such reconstructions are unfortunately labour intensive, because variations in scales caused by changes in speed and range meant that the assembly had to be done manually.

The offset of the fish causes problems both in field observations and later reconstructions. The fish trails behind the ship at cable lengths typically three times the depth, and will therefore only broadly follow the ship's course. It was difficult to get close to the ice at greater depths, because the fish had to be kept clear of the under-water "noses". (We did hit the ice with the fish and cable, without causing damage, which reflects on the smoothness of the under-water ice.) The increased offset, in combination with the back-sloping ice, unfortunately meant poor records from the greatest depths.

The fish was also used in a vertical mode, being lowered and raised by the cable. This technique had the advantage that it provided a direct visual representation of the face of the ice, which was readily interpreted. A disadvantage with our arrangement was that the fish hung freely. Thus, there could be gaps in the vertical records because the fish rotated around the cable so that both transducers faced away from the ice (Fig.3).

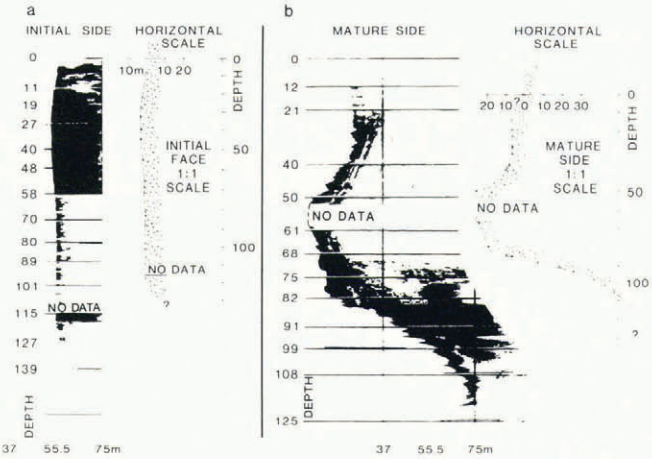

Fig.3a and b. Results of vertical sounding of two sides of iceberg Billie (B).
(a) Original record of initial (newly fractured) face, and rectified to a 1 : 1 scale.
(b) Original record of mature face, and rectified to a 1 : 1 scale. The spikes are not from the ice, but are probably caused by ship motion. Note vertical grooves at the side of the face, with the signal alternating between reflection and shadow. These are most noticeable between 21 m and 50 m depth.
Fig.3a and b show data from one channel. The fish rotated while being lowered and raised so that this channel did not always face the ice. For those sections where the other channel then faced the wall this recorded profile is shown. There are also gaps in the data where neither channel faced the ice.

(b) Direct soundings

Data on the under-water shapes were also collected by direct soundings. Most soundings were done from a small boat, using a plumb-line. This was not easy in rough seas. Soundings were also done by plumb-line from the bow of the expedition vessel, K/V *Andenes*, by nudging the ice front, but this was also a problematic procedure. We sounded all sections where we used the side-scan sonar. Altogether, 47 profiles were sounded. Typical examples of soundings are given in Fig.4.

FIELD LOCALITIES

The programme was aimed particularly at obtaining data from localities that could be identified as having been exposed to the open sea for specific time periods. How this was achieved requires explanation.

Any ice face exposed to the open sea will develop undercutting at the water line. Our observations show that an undercut typically extends a few metres inwards, and suggest that it takes a couple of weeks to develop a 1 m cut under "normal" sea states. Thus the criterion "lack of undercutting" was used to identify those faces that had not been exposed to the open sea.

Two types of such faces were observed. The first type,

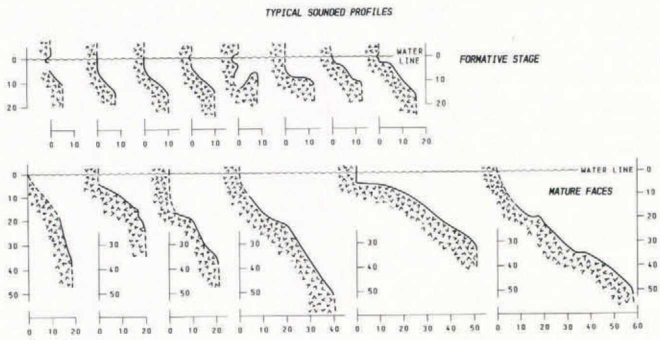

Fig.4. Examples of plumb-line soundings. The distance between each sounding was at 3–5 m, and the number of sounding points varies from 4–12 for the sections shown. The soundings were in all cases continued out to a vertical (or near-vertical) edge below which no bottom was encountered. All distances in meters.

noted especially in the early part of the season, was seen where the ice front had until recently been bounded by fast ice. Parts of the ice front would usually have a snow "foot" at the water line, i.e. snow adhering to the lower few metres of the ice front. (This snow would be the remnant of a snow bank formed on the fast ice, up against the ice front.) The under-water shape of this type could take a variety of forms.

The second type occurred when the ice front or iceberg had recently calved so that undercutting had not yet developed. Identification of this initial stage in the evolution of the ice face was particularly important to this study, e.g. iceberg Billie (B). This iceberg had clearly calved recently. It had well-developed undercutting on one side which extended round the corners to the two adjacent sides, but elsewhere showed no undercutting. Fig.3a and b are from two opposite sides of the iceberg. Horizontal profiling at different depths confirmed that the undercutting criterion distinguished between different developments. The sections without undercutting were smooth, while the mature side had a "rough" appearance.

Data were also required from sections that had been exposed to the sea for known periods. Studies were done of the fronts of Riiser-Larsenisen and Brunt Ice Shelf, where in both cases information on the calving history was available.

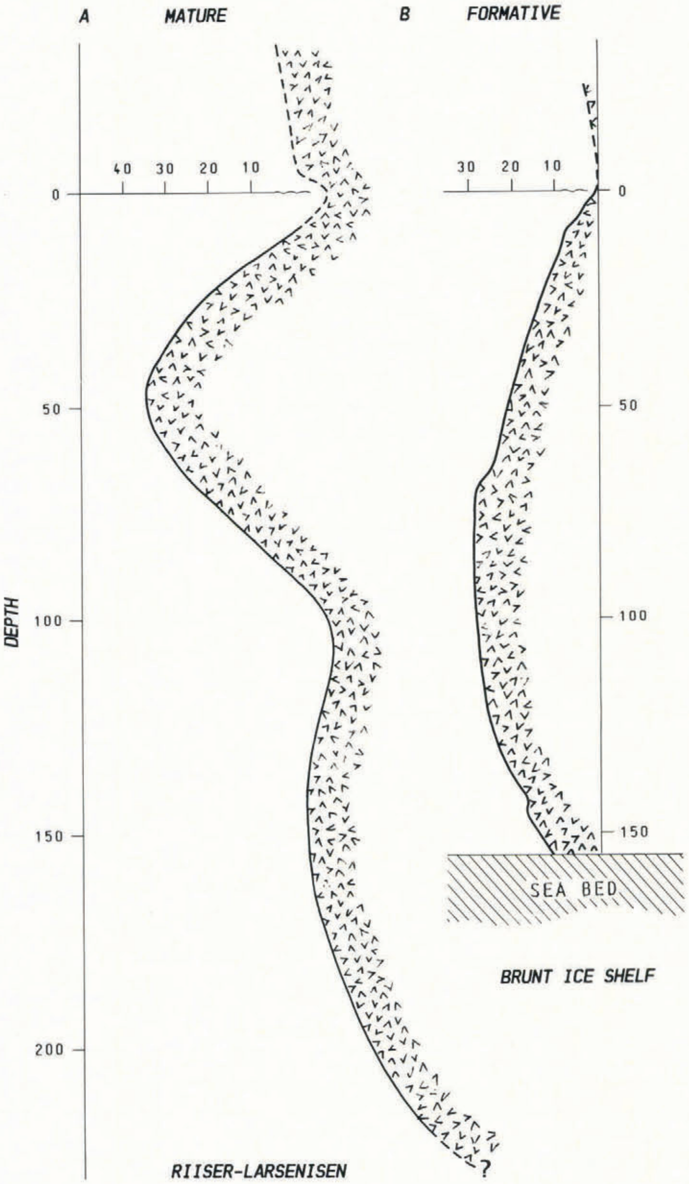

Fig.5. Rectified under-water profiles of (a) mature stage (Riiser-Larsenisen), and (b) formative stage (Brunt Ice Shelf). All distances in metres.

The most comprehensive studies were at Riiser-Larsenisen, where a detailed survey was done of a 4.8 km section from long. 16°07'W. to 16°16'W. Our surveys of Riiser-Larsenisen in 1977, 1979, and 1985 showed that this section of the ice shelf retreated due to major calving between 1977 and 1979. The ice front had thereafter advanced 450 m between 1979 and 1985. Our velocity measurements at the ice shelf indicate an outflow rate of around 100 m a^{-1}, suggesting no major calving during this period. Recognition of characteristic features in soundings both in 1979 and 1985 (see below) also indicated no major calving. Thus, this ice front could be taken as an approximately 7-year-old, "mature" face.

Nine profiles of the front of Riiser-Larsenisen were collected at controlled depths, spaced ≈40 m apart, during a 24 h period. Precision navigation was achieved by use of Motorola Miniranger transponders positioned on the ice shelf, together with the ship's own composite navigation systems. The distance from the ship to the ice front was recorded at frequent intervals. A second repeated profile was obtained 1 month later.

Part of this section was also covered by side-scan sonar studies during NARE 1978–79 (Klepsvik and Fossum 1980). These revealed, in map view, a 1 km section of distinctive waves, with amplitude of 10–15 m and wavelength of 30–100 m. The surveys repeated after 6 years showed that the waves were still present but the amplitudes had been reduced to 3–7 m.

The studies of Brunt Ice Shelf were done near Mobster Creek, the landing ramp for the British station Halley, and where station personnel informed us that various calvings had taken place over the recent few years. Thus, those sections were taken as examples of the young, formative stage, perhaps 1–3 years old.

OBSERVATIONS – LARGE FEATURES

Initial stage

(a) The *subaerial* face. As explained earlier, freshly fractured faces were recognized in the open sea by the absence of the effects of wave-action. The profile of such newly ruptured faces appears approximately vertical and smooth on a scale of metres.

(b) The *submarine* face. The initial under-water profile is essentially vertical, and appears smooth at our resolution of a few metres. Fig.3a shows the profile of a freshly formed face.

Formative (young) stage, 0.1–≈3 years

(a) The *subaerial* face. High ice fronts are generally overhanging, often accentuated by snow-drift cornices. Crevasses are often seen in the ice shelf a few metres in from the edge. The undercut at the water line typically extends 2–3 m inwards, and 0.5–1 m up into the ice (firn).

(b) The *submarine* face. The upper part of the face is in the form of an approximately plane ramp sloping at high angles, usually >45°. The size of the ramp depends upon age. It extends from a few metres to a few tens of metres. The ramp starts about 5 m below the water line, and the maximum depth varies from 5–10 m to a few tens of metres. Below the ramp, the face is nearly vertical for a considerable depth, before sloping backwards below 100–150 m depth (Figs 4 and 5b).

Mature stage, several years old

(a) The *subaerial* face is like the formative stage described above.

(b) The *submarine* face has an under-water ramp observed at Riiser-Larsenisen up to 60 m from the ice front. This corresponds to an average melt rate of about 10 m a^{-1}, from the time of calving at this locality (higher if the melt rate at the nose is large). The slopes may be plane, concave, or convex, and are generally less steep than at the formative stage. The face has a prominent "nose" at around 50 m water depth, and below this the ice face slopes backwards at angles around 30°–>45° (Figs 3b, 4 and 5a). Limited data from one locality suggest that the face is smoothed in the direction along the front, i.e. that the under-water back-melting is greatest on what were originally protruding cusps. This smoothing seems to increase with depth.

OBSERVATIONS – SMALL FEATURES

It is beyond the scope of this paper to discuss in detail the various smaller features that can be observed in the side-scan sonar. However, some aspects relevant to the discussion of processes should be noted.

(1) The mature face appears "rough", and includes isolated areas, especially at less than 100 m water depth, which do not reflect the sound waves (Fig.6). These have different shapes, vary from 2.5 m to 10 m in extent, and may be caused by protruding knobs or by depressions in the ice surface, in the latter case presumably reflecting where blocks of ice had "calved" in a submarine environment. An example of a sounded hollow is seen in Fig.4.

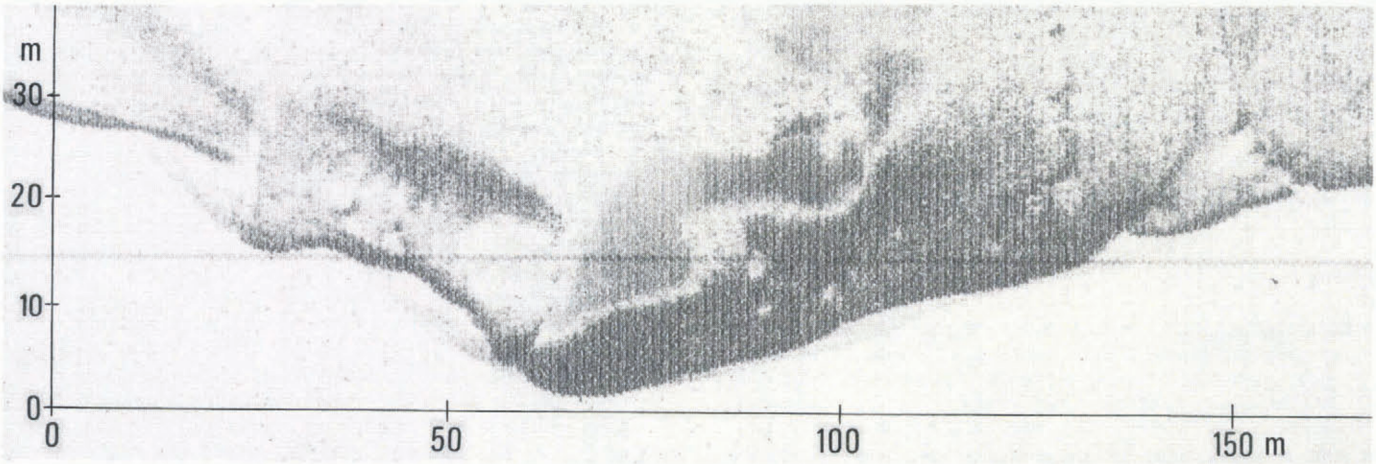

Fig.6. Sonograph looking up from 90 m water depth at a mature face. Note the difference in scale along the face and towards the face. The latter scale is converted from the return time of the sound waves, and later echoes are from higher on the ice face. The variation in strength of the return signal is related to varying angle of incidence and to the roughness of the face. Note step-like features and hollows or protruding knobs.

(2) Vertical grooves, with a regular spacing of a few metres, were seen during vertical profiling (Fig.3b). Such shapes would not be recorded by horizontal profiling, and it is not known whether they are common. However, these grooves were observed in partly successful under-water photography along Riiser-Larsenisen, and they have been seen in overturned icebergs (Fig.7). I believe these grooves result from upward-flowing sea-water, and hence demonstrate vertical circulation along the ice front.

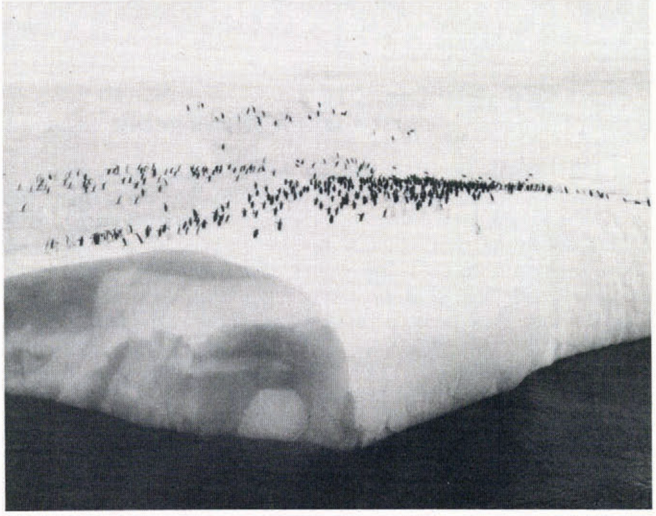

Fig.7. Submarine vertical grooves and wave-cut platform exposed in iceberg tilted on its side. Photograph: January 1981 in northern Weddell Sea. Scale of grooves can be judged from Adélie penguins; the grooves are similar in size to those shown in Fig.3b.

EVOLUTION OF THE ICE FRONT: PROCESSES AND MODEL

The above observations lead to a description of the evolution of the ice front with the following main components (see Fig.8).

(1) Initial stage: fracturing of the ice shelves takes place along smooth, curvi-linear segments with vertical faces.

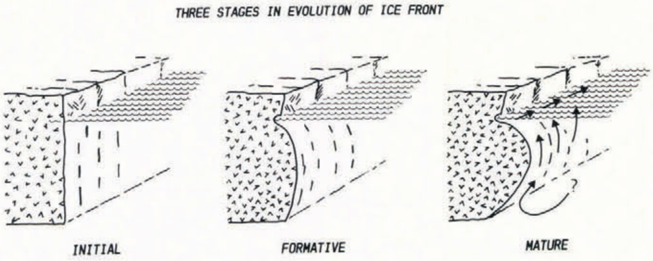

Fig.8. The three stages in the evolution of a "typical" ice front.

(2) Formative stage: the freshly formed vertical face is eroded (a) by wave and swell action around the water line, (b) by small calvings from the undercut, overhanging subaerial face, and (c) by submarine melting. The melting increases with depth to ≈10 m a^{-1} at 200 m, which is about twice the rate of erosion around the water line.

(3) Mature stage: erosion continues, with a maximum rate at around 50 m water depth, where the under-water "nose" has its maximum projection, observed extending up to 60 m.

Processes governing the formation of the undercut face

Our observations indicate that ice fronts with a freeboard >20 m were practically always overhanging. The main reason must be undercutting at the water line and related crevassing of the ice shelf.

Three processes can contribute to the undercutting:

(1) Higher local water velocities produced by waves and swell action cause higher effective heat-transfer rates between the ice and the near-surface waters, heated by short-wave radiation in the "summer". Martin and others (1978) showed that this was a very effective process, producing a 3 m wave cut in 1 day in ≈+2°C water.

(2) Calved pieces of ice moved by the turbulent water cause mechanical erosion.

(3) Ice and firn is wetted by splashing, causing lower albedos and hence under appropriate conditions more absorbed solar radiation.

These are mainly "summer" processes. Most of the year the sea ice effectively prevents turbulent motion, and in the winter the surface waters are also at freezing temperatures.

Only the first of these three processes can contribute to the deeper erosion of the submarine ramp observed in the formative and mature stages. The heat transfer seems to be very effective to 5 m depth. Below this the efficiency falls rapidly with depth.

Processes governing back erosion at greater depths

The observations indicate varying degrees of melting with depth, with a minimum around 50–100 m depth, and a maximum annual melt of ≈10 m at 200 m depth. The heat transfer to the ice front depends upon the water temperature, and mixing coefficient and small-scale boundary-layer dynamics.

Field observations on the water temperatures show two phenomena:

(1) In the summer, the upper ≈70 m of the water in contact with Riiser-Larsenisen are heated to about 0.5°C above the pressure melting-point (Foldvik and others 1985[a], Fig.15), with highest temperatures at the surface. Correspondingly, the above-freezing temperatures extend to 30–50 m depth along the Filchner–Ronne Ice Shelf (Foldvik and others 1985[b], Figs 14 and 15). In the winter, the upper waters are at pressure melting-point. Hence, this condition leads to back melting to such depths in summer.

(2) Foldvik and Kvinge (1974, 1977) observed that the melting potential of water masses in contact with the Filchner Ice Shelf increases with depth, because the pressure melting-point decreases with depth (Fig.9). Temperatures were about 0.2°C above the pressure melting-point at 200 m depth. This condition should lead to melting which increases with depth from a minimum around 100 m, and takes place year-round.

We therefore see that the combination of these temperature observations explains qualitatively the observed shapes as resulting from annual melting rates with a minimum around 50–100 m depth, and with greater annual melting at 200 m depth than near the surface.

Melting of vertical ice walls in the ocean has been discussed by Gill (1973), Martin and Kauffman (1977), Gade (1979), Greisman (1979), Huppert (1980), and Russell-Head (1980). These give a range of melt-rates which bracket the rates presented here. The present observations give a melt-rate of 10 m a^{-1} for a temperature difference (ΔT) above pressure melting-point of 0.2°C at 200 m depth, and a rate of 20 m a^{-1} for a ΔT of 0.5°C, the latter derived from the observed rate of ≈5 m a^{-1}, and taking this to apply only for the summer period of 1/4 year. The differences between the various melt-rates proposed by the above authors are related to varying models for heat transfer to the ice face and are outside the theme of the present discussion.

The observed vertical ripples suggest vertically moving water and may confirm upwelling. Such processes, at various scales, have been proposed, e.g. by Neshyba (1977) and Josberger (1980), and would enhance melt-rates by their

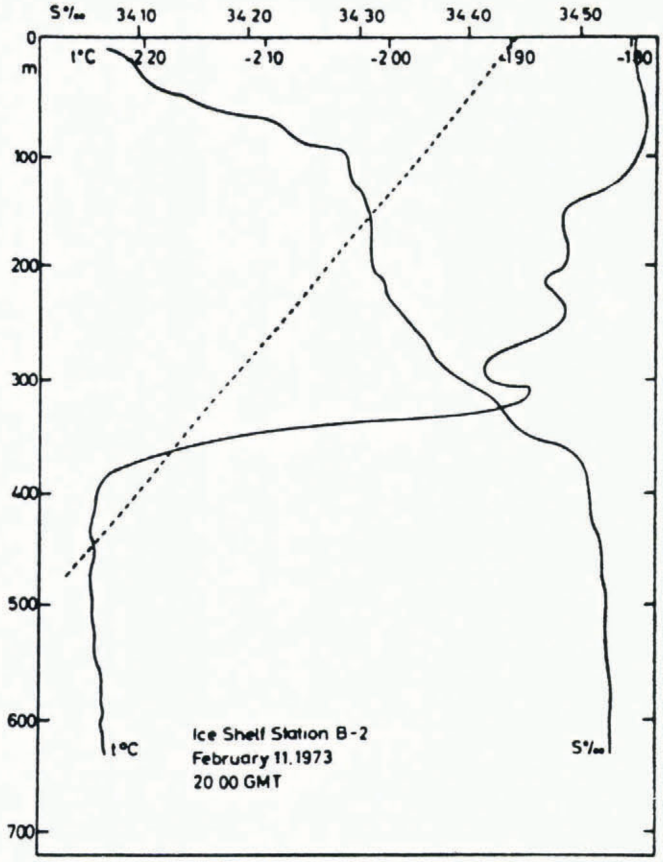

Fig.9. Temperature and salinity of water near the Filchner Ice Shelf (lat. 77°44'S., long. 41°44'W.). The dashed line shows the change in pressure melting-point with depth for water of the salinity at lower levels. (From Foldvik and Kvinge 1977.)

effect on the boundary-layer dynamics.

Observations from the closest comparable field situation are those of Holdsworth (1982). He calculated a lateral melt-rate of 6–10 m a^{-1} in −1.3°C water for the Erebus Glacier tongue, based on repeated mapping and calculated lateral creep spreading.

Many of the field observations presented here were anticipated by Robin (1979), who used the work of Foldvik and Kvinge (1974, 1977) in a theoretical discussion of melting/freezing under, and in front of, ice shelves. He recognized the potential for increased melting with depth, and that this process could take place year-round, and he suggested a melt-rate at depth on the order of 10 m a^{-1}.

Buoyancy effects

As noted, even at the mature stage, the ice shelves are not generally up-warped at the front. Calculations show that profiles such as Figs 3b and 5 are essentially in balanced buoyancy, because the effect of the "nose" is compensated by the ice removed at greater depths.

Indeed, down-sloping towards the front is more commonly observed, and this is indirect confirmation of back-melting at depth, as recognized by Robin (1979). Such bending from the effect of extensive melting of the lowest ice could also increase the depth of the ramp.

Buoyancy probably accounts for the rough appearance of the mature face, causing large and small pieces of ice to "calve" off along faults and inhomogeneities (Fig.6). The face seems roughest at shallow depths and such calving is presumably assisted by wave and swell action.

Under-water plastic deformation

A protruding under-water "nose" will experience deformation as a result of the buoyancy stresses. Taking as a first approximation that the ice will begin to deform rapidly at a shear stress of 100 kPa (1 bar), we see that the shape of a "nose" extending 50 m as in Fig.3b or Fig.5a will be determined by the melt-rates, as these shapes will have maximum shear stresses less than 50 kPa at the line of the vertical wall. The shear stress increases with extension of the nose, and a 100 m nose could experience rapid plastic deformation. Thus plastic flow will limit the extension of the nose to approximately 100 m.

CONCLUDING REMARKS

The preceding results are based on field data which have been consistent, and are therefore used as the foundation for a model. However, some words of caution are needed. As mentioned earlier, the records are poorer for the deeper part of the ice front, and in particular for the mature case. In many cases, no records were obtained because the ice retreated and was out of range for the sonar. Thus, we know that the ice was sloping backwards, but not its exact shape. The records are also from a small part of the Antarctic ice shelves, and possibly the Riiser-Larsenisen locality is one where water enters beneath the ice shelf to circulate around the ice rise Kvitkuven. For this reason, the melting-rates at depth here for the mature case may be abnormally high, and it is likely that there is less melting of ice shelves further south. Further data are needed from different ice shelves, and in different oceanographic environments, to test whether these observations are typical and the model is universal.

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