IOS Note - 6

THICK CONGELATION SEA ICE

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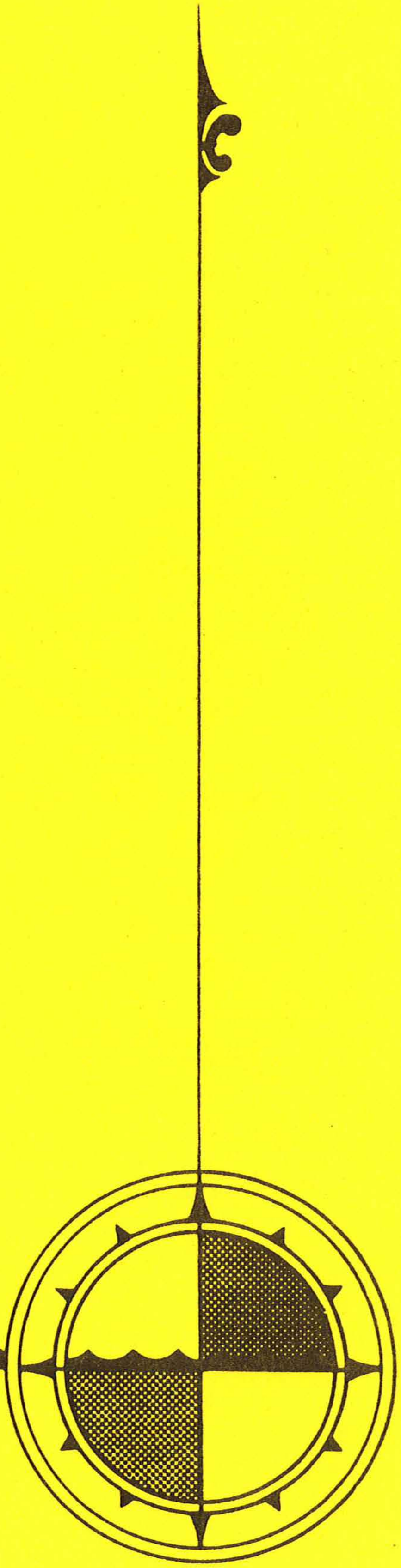
E. R. Walker



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Introduction

Thick sea ice can be formed by thermodynamic processes or by mechanical processes. With the present climate the equilibrium thickness of sea ice formed thermodynamically seems to be about three meters in north polar regions. There have been isolated reports of sea ice floes that have attained thicknesses of over ten meters, while retaining the crystal structure indicating purely thermodynamic growth (the congelation process). It is of interest to consider where and how this thick sea ice may have formed.

Sea Ice Formation

Most sea ice is formed by the congelation process, in which the surface heat budget is such as to cause the sea to freeze. After first formation the sea ice sheet thickens and the ice crystals at depths of perhaps 50 cm below the top of the sheet form a characteristic structure with the basal planes of the ice crystals vertical. The structures and characteristics of this type of sea ice are described by Pounder (1965) amongst many others.

In sea ice growing in very cold water a different crystal structure may result. Ice crystals formed in the very cold sea water below the ice sheet may freeze onto the bottom of the ice sheet. This as described by Cherepanov (1973) results in a more granular and disorganized crystal structure than that of the ice formed by the congelation process. Other freezing processes which result in crystal structure again different may occur when a sea ice sheet is flooded, with subsequent freezing, or when ice forms from snow which may fall on the ice sheet top in such quantities that it does not completely melt each summer. Old ice which has lasted through one or more summers may have lenses of relatively fresh water ice embedded caused by the freezing of summer melt water. Thick sea ice formed mechanically into ridges would have a crystal structure determined by the ice blocks making up the ridge-keel structure.

In the Antarctic winter sea ice thicknesses at high latitudes tend to be thicker than in the Arctic because of the colder climate in the south. In the Antarctic the adherence of ice crystals formed in very cold sea water below the congelation sheet is more common than in the Arctic presumably because the zonal circulation in the south prevents anything like the incursion of warm Atlantic water into the Arctic Ocean. Ice formed by deep snow and flooding on top of the congelation sheet is also reported as being more common in the Antarctic as compared to the Arctic.

Sea Ice Thickness

For the central Arctic Ocean winter ice thicknesses have several times been estimated from submarine traverses. Most of the thicker ice is found in the keels below pressure ridges. Wadhams, (private communication) in an under-ice cruise to the north pole, was able to distinguish only one possible 10 meter thick ice floe. Koerner (1973 - private communication) who trekked across the Arctic Ocean could not distinguish anv sizeable 10 meter thick floes.

While the measurements above reveal few indications of sea ice floes 10 m thick, there are measurements which do indicate the presence of sea ice of such thickness. Most detailed are those reported by Cherepanov (1966). The Russian Arctic Ocean station NP-6 was, in 1955, situated on an ice floe of area 80 km^2, of thickness 10-12 m, and of crystal structure suggesting slow congelation growth. Cherepanov also remarks that floes of such thickness are rare, and usually are only about one kilometer across.Serson (1972) describes a 'plug' of multi-year old ice in Nansen Sound, Ellesmere Island, Canada. Some parts of this plug were 10 m thick. Using measurements of ablation (over one year apparently) and climatic data Serson estimated that the ice could have reached a thickness of 6 m over a growth period of forty years. From historical evidence Serson believed the plug may have been there since 1932 although it has broken up and moved out of Nansen Sound since 1971, when Serson studied it. Serson's note contains no details on the crystal structure which might allow discrimination between congelation ice, and that which may have been formed mechanically. Serson (1974) has also reported a plug of sea ice in Sverdrup Channel (80°N,98°W) about six meters in thickness. Milne (personal communication) encountered an ice floe 10-12 m thick on an icebreaker probe west of Prince Patrick Island in 1965.

Gow (1973) reports that the floating shelf-like tongue of the Koettlitz Glacier in McMurdo Sound, Antarctica is gradually transformed to sea ice as it progresses seaward, by accretion of congelation ice below and ablation of the original fresh water ice on top. Ablation and accretion, were estimated by Gow at about 0.4 m year $^{-1}$. Lyons et al (1971) report on the complicated structure of the Ward Hunt Ice Shelf off northern Ellesmere Island. A cross-section from their paper is shown in Figure 3(b). The ice shelf contains a wedge of sea ice some 20 meters thick, with brackish water ice and iced firn above and brackish water ice below the sea ice wedge for a total shelf thickness of 50 meters.

From the material quoted above a number of inferences can be drawn. Sea ice floes over 10 m thick can be formed by the congelation process. Such floes are rare so that they must be formed in rather special circumstances.

Thermodynamic Modelling

Models of ice growth have been formulated for many years although analytical solutions proved arduous. The advent of the computer allowed solutions to be obtained much more easily. The numerical model of Maykut and Untersteiner (1971) has recently appeared. It is a one-dimensional thermodynamic model including effects of snow cover, ice salinity, and internal heating due to penetration of solar radiation. Surface energy balances determine rate of ablation and accretion; diffusion equations govern heat transport within ice and snow. The incoming radiative and turbulent fluxes; heat oceanic heat flux, ice salinity, snow accumulation and surface albedo are specified as functions of time. Starting from an arbitrary initial condition the model is integrated numerically towards annual equilibrium in ice temperature and thickness. The main limitations of the model include the necessity of specification of quantities in the surface heat budget, details of heat transport from the melting snow, and treatment of the melt ponds.

Maykut tested his model by specifying best estimates of components of the surface heat balance. When annual values of incoming shortwave radiation of 75.4 kcal cm^{-2} (3.16 GJ m^{-2}), incoming long-wave radiation of 166.0 kcal cm^{-2} (6.95 GJ m^{-2}), flux of sensible heat 2.7 kcal cm^{-2} (0.11 GJ m^{-2}), loss of latent heat of 3.2 kcal cm^{-2} (0.13 GJ m^{-2}), flux of 1.5 kcal cm^{-2} (0.06 GJ m^{-2}) from water to ice, annual snowfall of 0.4 m, and summer ice albedo of 0.64 were chosen, the equilibrium thickness of sea ice was predicted at 3.14 m at the end of growth, 2.71 m at the end of ablation. The surface ablation was about 0.40 m, bottom ablation of about 0.05 m and bottom accretion of about 0.45 m in each year. These, and other values furnished by the model, agree fairly well with observations from the Arctic Ocean.

With specified parameters changed only in that the heat from the ocean was set to zero, Maykut found the ice reached an equilibrium thickness of 5.6 m, close to that reported by Serson (1972, 1974) in very old sea ice in the Canadian northern archipelago. Annual ablation was 0.39 meters at the surface, annual accretion 0.39 m on the ice bottom. With standard Maykut input but with increasing snowfall, ice thickness increased, reaching, at a value of annual snowfall of 1.2 m, an annual equilibrium of 7.02 m with annual ablation at the top of 0.005 m, ablation at the bottom of 0.021 m and accretion at the bottom of 0.026 m. When the annual snowfall was more than 1.2 m the specified parameters did not allow complete melting of the snow which then accumulated upon the top of the ice.

To estimate ice growth and equilibrium thicknesses under conditions different from those in the Arctic Ocean the Maykut model standard input was changed, setting the oceanic heat flux to zero and the annual snowfall at 1.0 m. Other parameters were unchanged. When the model was run for 65 years sea ice of equilibrium thickness (3.0 m) increased in thickness to about 12 m (Figure 1). Annual surface ablation fell from about 0.09 m at the beginning to about 0.06 m after 65 years, while bottom accretion fell from about 0.40 m in 0.15 m in the same time. Projecting from the curves in Figure 1, one might estimate that equilibrium thickness might be reached in 200-300 years with an equilibrium thickness of about 20 m and annual ice top ablation and ice bottom accretion of about 0.05 m.

If ice of such thickness had formed, and then was exposed to the heat budget parameters suggested by Maykut and Untersteiner as typical of the present-day Beaufort Gyre, reduction in the thickness might be expected to occur relatively rapidly. To indicate this, ice of initial thickness of 12 m was used in Maykut's model with standard values of the heat budget parameters. The results are shown in Figure 2. In 45 years the thickness falls to about 3 m as ice-top ablation rises to 0.41 m while ice bottom growth increases to about 0.37 m (the model taking a year or two to 'settle down' at the beginning of the run). Extrapolation from the curves indicates that Maykut's standard equilibrium values should be reached within 100 years, although the vast majority of ice wastage occurs in the first 40 years.

Speculation

It has been demonstrated that in the present climate in locations of no oceanic heat flux and snowfall of annual snowfall of about one meter, congelation sea ice might reach equilibrium thicknesses of about 20 m. Those parts of the world where these conditions might obtain should be in high latitudes, probably in shallow bays where advection of oceanic heat is small. If annual snowfall should be less than one meter such locations may be subject to snow blown off nearby land. The most favorable locations should be where ice 'shelves' have been reported, between the islands of Severnaya Zemlya, between the islands of Franz Josef Land, in Svalbard off the southeast coast of Nordauslandet and off the east coast of Edgeoya, off the northeast coast of Greenland and along the north coast of Ellesmere Island.

While many of these ice shelves appear (from an inspection of a large scale chart) to have originated from glacier tongues,the formation of some appears more complicated. The Ward Hunt Ice Shelf in northern Ellesmere Island (83°N 75°W) (Lyons *et al* (1971)), seems to have a core of sea ice with firm and brackish ice above, brackish ice below. The consensus seems to suggest that the present shelf is the result of thickening, mainly over the climatic deterioration of the last millenium, of a floating ice shelf (of thick sea ice?) which grounded in the area. At present the mass balance of these Ellesmere shelves appears to be negative [Hattersley-Smith and Serson (1970)]and indeed parts have broken off to form ice islands.

Scores of ice islands or ice island pieces have been discovered in the last 30 years. If we choose an initial ice island thickness of 50 m we roughly calculate that in the Arctic Ocean, with surface ablation of 0.2-0.3 m annually, and little bottom accretion initially, the thickness would be reduced to 12 m in less than 200 years, after which the equilibrium thickness of 3 m would be approached as noted in Figure 2. Some of the ice islands described, (such as Arlis II), are horizontally inhomogeneous so that mechanical breakup may be expected to speed thermodynamic decay. So, as with thick congelation floes, the ice islands have a lifetime, in the Arctic Ocean, very brief compared to their existence in the areas in which they formed.

The Koettlitz glacier in McMurdo Sound, Antarctica (78°S, 165°E) appears an interesting example of a floating glacier ice tongue which is transformed into a shelf of sea ice. The area is shown in Figure 4 after Debenham (1965). Gow and collaborators have also reported upon this ice tongue (Gow *et al* 1965 Zotikov and Gow 1967, Gow 1973, Gow and Epstein 1972). The last report is particularly interesting in that it delineated the change from glacier ice to sea ice in a series of cores drilled in the shelf. The positions of the cores, and a schematic cross-section of the ice tongue are (after Gow and Epstein 1972) shown in Figures 5(a) and 5(b) respectively. The cores appear to be about 1 km, 9 km, 16 km, 23 km and 30 km from the ice edge and Gow mentions that the shelf is afloat for 20-30 km upstream of core 5. The thicknesses of ice measured were: core 1, 13 m, core 3, 13-15 m (sea water at 13 m), core 4, 15 m. As shown in Figure 5(b), cores 1, 3 and 4 were composed of sea ice. The top 7 m of core 5 (total depth not reported) was glacier ice. Speed of movement of the tongue was estimated at 5-10 m year^{-1} near the ice front, but in earlier references above, speed in the upper reaches of the tongue was (very tentatively) estimated at (as much as) 100 m year^{-1}. Ablation in the lower reaches of the tongue were observed to be about 0.4 m per year. Points of interest include the transformation of glacier ice to sea ice, and the maintenance of fairly uniform thickness in the lower part of the tongue.

Even at a speed of 100 m per year the glacier ice after becoming afloat would take at least 200 years to reach the position of core 5. If ablation in the upper reaches were 0.4 m per year then 80 m of glacier ice would be ablated. Estimates of cooling of ice tongues by Wexler (1960), and Chikovskii (1973) indicate loss of most 'cold' in less than 200 years for a shelf 100 m thick. Very rough calculations, warming an ice sheet originally everywhere at -20°C, to -2°C at the bottom, with a linear gradient to -20°C at the top would indicate ice accretion at the bottom of about 4 m for an ice sheet originally 100 m thick. Another mechanism which would add sea ice to the bottom of the upper reaches might be ice formation in very cold water circulating from McMurdo Sound. Figure 5(b) indicates that Gow considers this latter mechanism unimportant. Certainly the result reported at core 5 would indicate comparatively little sea ice there, if the total ice thickness agrees with the schematics of Figure 5(b).

How does the lower reach of the ice tongue maintain a relatively uniform thickness over many years? With a top surface ablation of 0.4 m per year, the same amount must be accreted to the bottom. Annual values of the heat budget parameters for McMurdo Sound (78°S 165°E) were estimated as 90.0 kcal cm^{-2} (3.77 GJ m^{-2}) for incoming solar radiation, 158.1 kcal cm^{-2} (6.62 GJ m^{-2}) for incoming long wave radiation, a sensible heat loss of 4.6 kcal cm^{-2} (0.19 GJ m^{-2}), a latent heat loss of 1.6 kcal cm^{-2} (0.07 GJ m^{-2}), no heat flux from the water, annual snowfall of 0.305 m, and a summer ice albedo of 0.64. When these values were put in the model of Maykut and Untersteiner the equilibrium ice thickness was 11-12 m with annual ablation/accretion of about 0.32 m year^{-1}. These values are close to those reported by Gow (1973), so the lower reaches of the Koettlitz Glacier are probably close to equilibrium thickness.

Conclusion

It has been demonstrated that congelation sea ice could grow in the north polar regions to thicknesses of at least 12 m under present large scale climatic conditions in localities exhibiting annual snowfall of around 1 meter and little or no oceanic heat flux. The most favorable localities appear to occur in bays or channels of islands in very high latitudes. Once sea ice of thickness of 12 m is released into the Arctic Ocean it should in a few score years be reduced to the thermodynamic equilibrium thickness of three meters. Under conditions postulated the equilibrium sea ice thickness is at least 20 m. A sea ice layer of this thickness forms the core of the Ward Hunt Ice Shelf, although this core, and indeed the whole shelf may have formed under colder climatic conditions during the last millenium. No examples of glacier ice shelves being transformed to sea ice, documented for the Koettlitz glacier in Antarctica, have been noted in the Arctic.

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Figure Captions

Figure 1 Ice thickness (m) and ablation and accretion rates (m year^{-1}) from the model of Maykut and Untersteiner (1971) using standard parameters, an initial ice thickness of 3 meters, one meter of snowfall annually and no water heat flux. The dashed extrapolations indicate an equilibrium thickness of about 20 meters with an ablation/accretion rate of about 0.05 m year^{-1}.

Figure 2 Ice thickness (m) and ablation and accretion rates (m year^{-1}) from the model of Maykut and Untersteiner (1971) using standard parameters and an initial ice thickness of 12 meters.

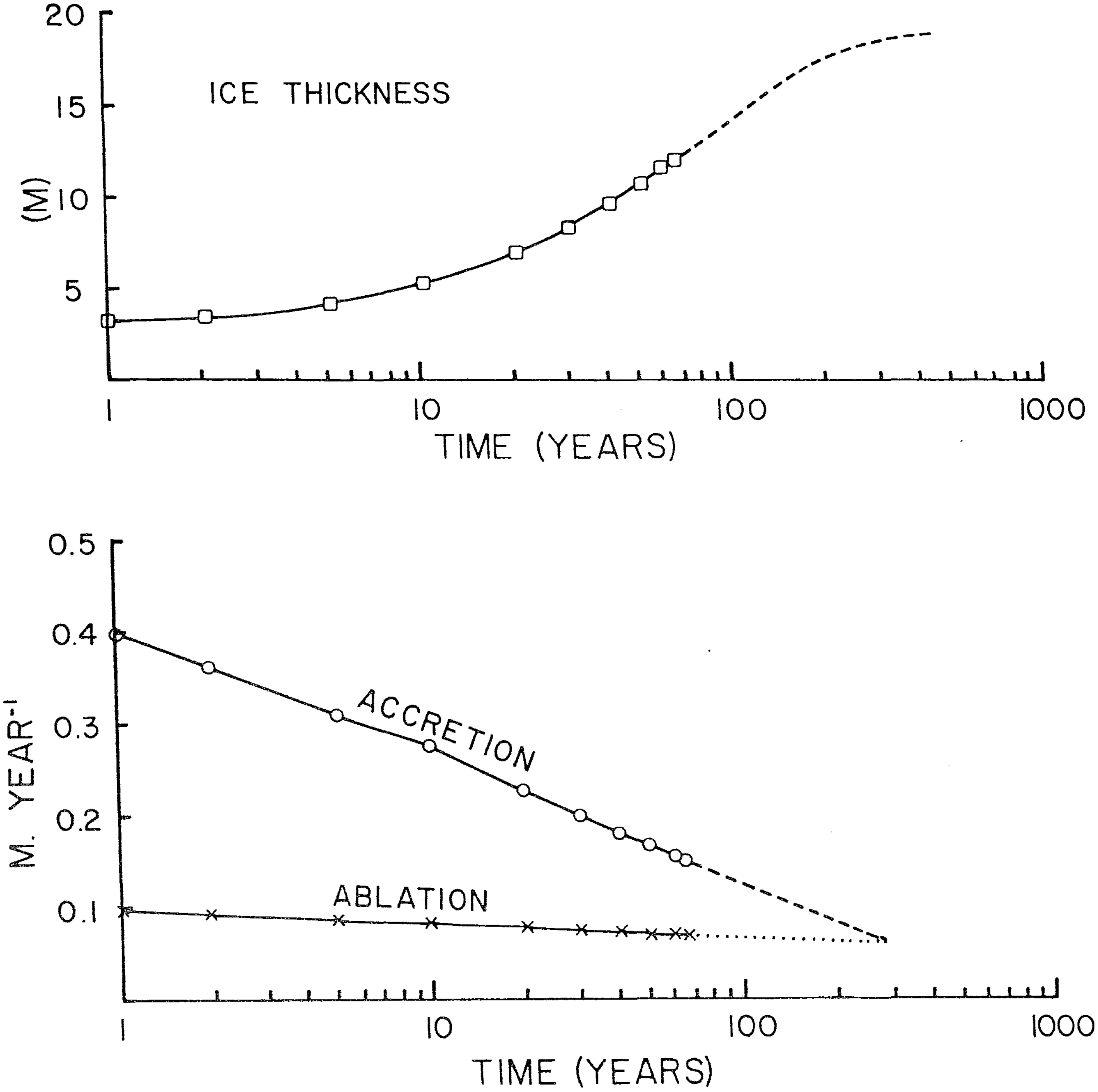
Figure 3(a) Map of Ward Hunt Ice Shelf and adjacent ice rises. Ice types identified partly by field and laboratory study, and partly by aerial photography. (From Lyons *et al* 1971)

3(b) Interpretation of stratigraphy of part of Ward Hunt Ice Shelf, based on drill-core and laboratory studies. See Figure 3(a) for location of holes A and B. Ward Hunt ice rise towards right side of section; trough of syncline between Ward Hunt and Ellesmere Islands to left of section. (From Lyons *et al* 1971)

Figure 4 Map of McMurdo Ice Shelf and surrounding areas. Flecking shows the extent of shelly moraine based on observations by the author in 1911 (northern part) and reports in diaries of Koettlitz and Bernacchi on sledge journeys made in 1902-03. Approximate heights of ice surface above sea-level in metres are shown. Figures underlined are from the author's observations, those ringed are deduced from barometric recordings of other sledgers. The ice front is very variable, especially on the Koettlitz Glacier side. The average depth of McMurdo Sound is around 400-500 m except for one sounding shown on the map. (From Debenham 1965)

Figure 5(a) Map of McMurdo Sound region showing locations of drill holes on the Koettlitz glacier tongue. (From Gow and Epstein 1972)

5(b) Schematic cross section of Koettlitz glacier tongue depicting processes involved in its formation. (From Gow and Epstein 1972).



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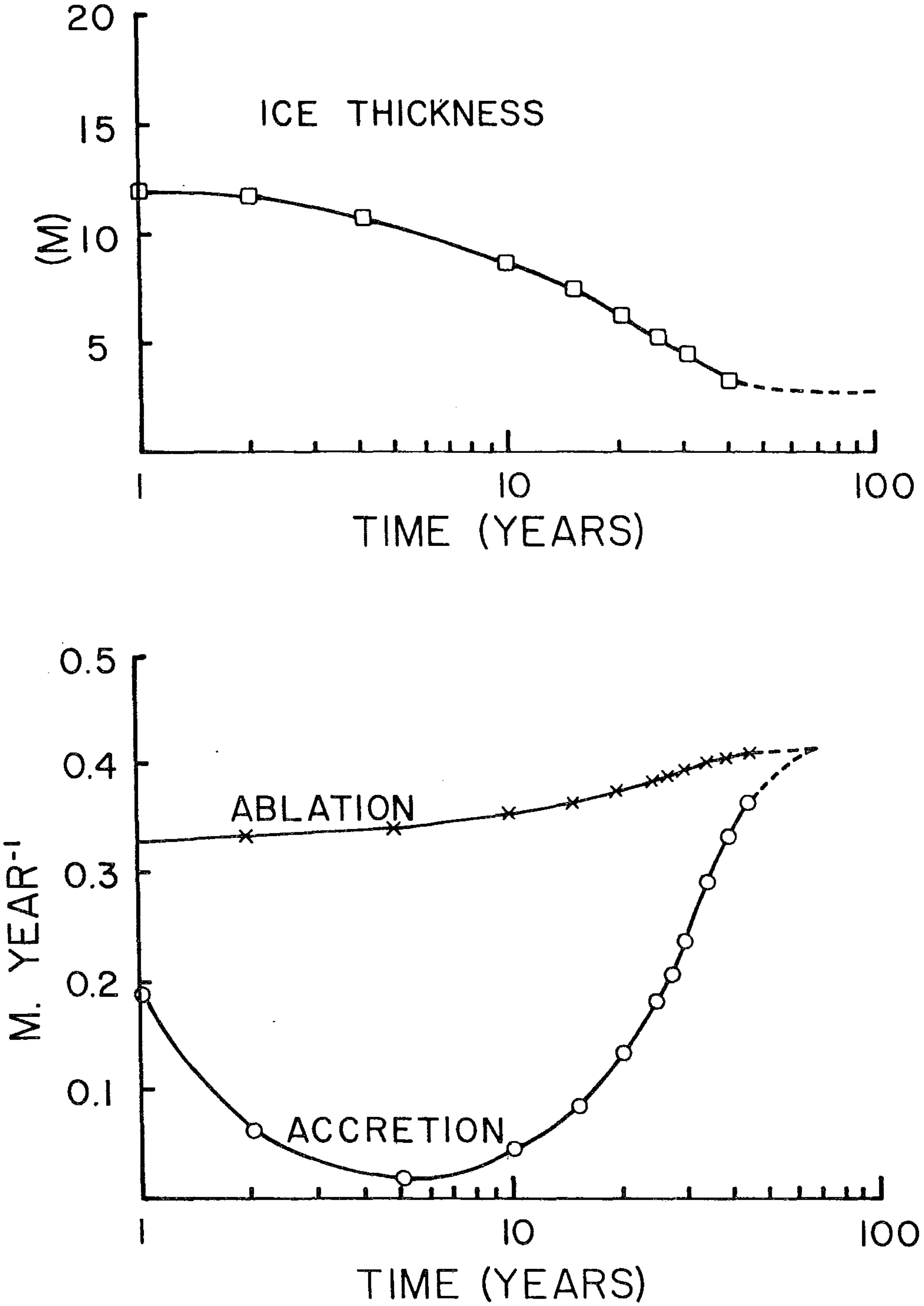

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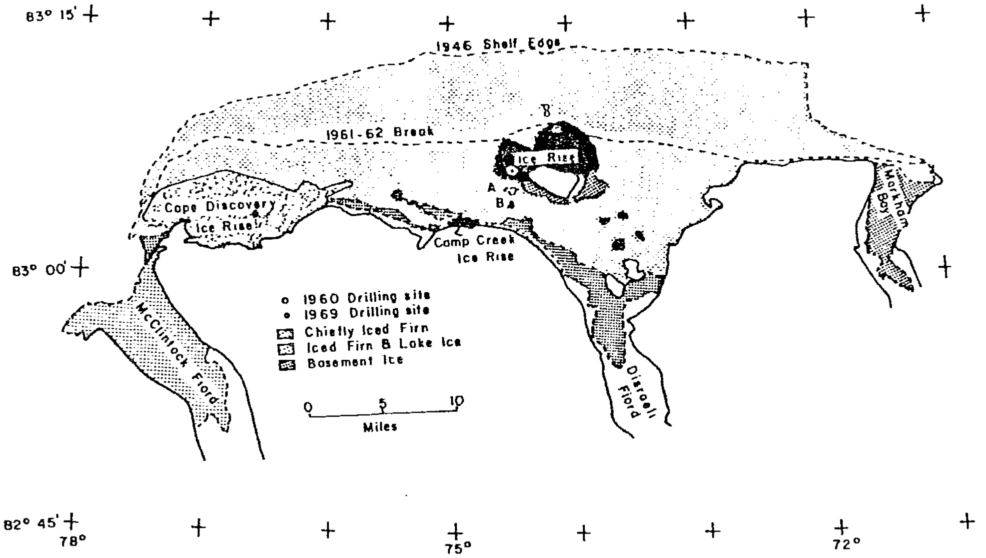

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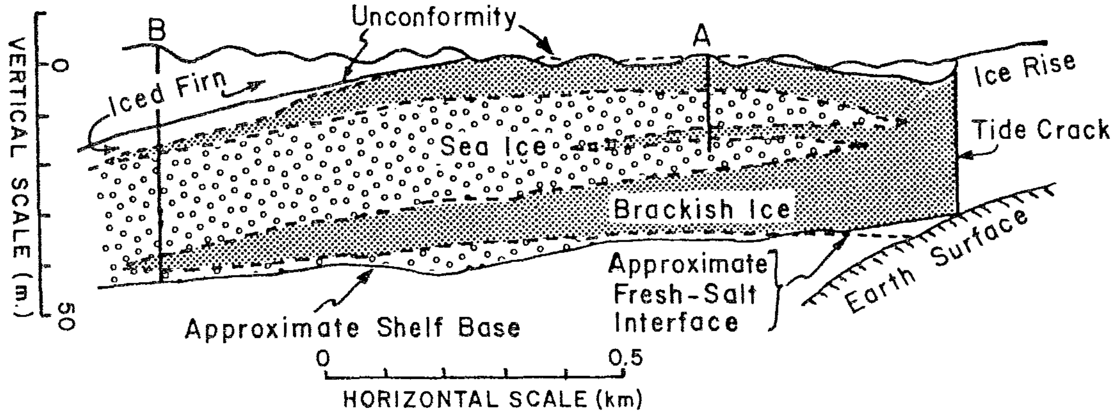

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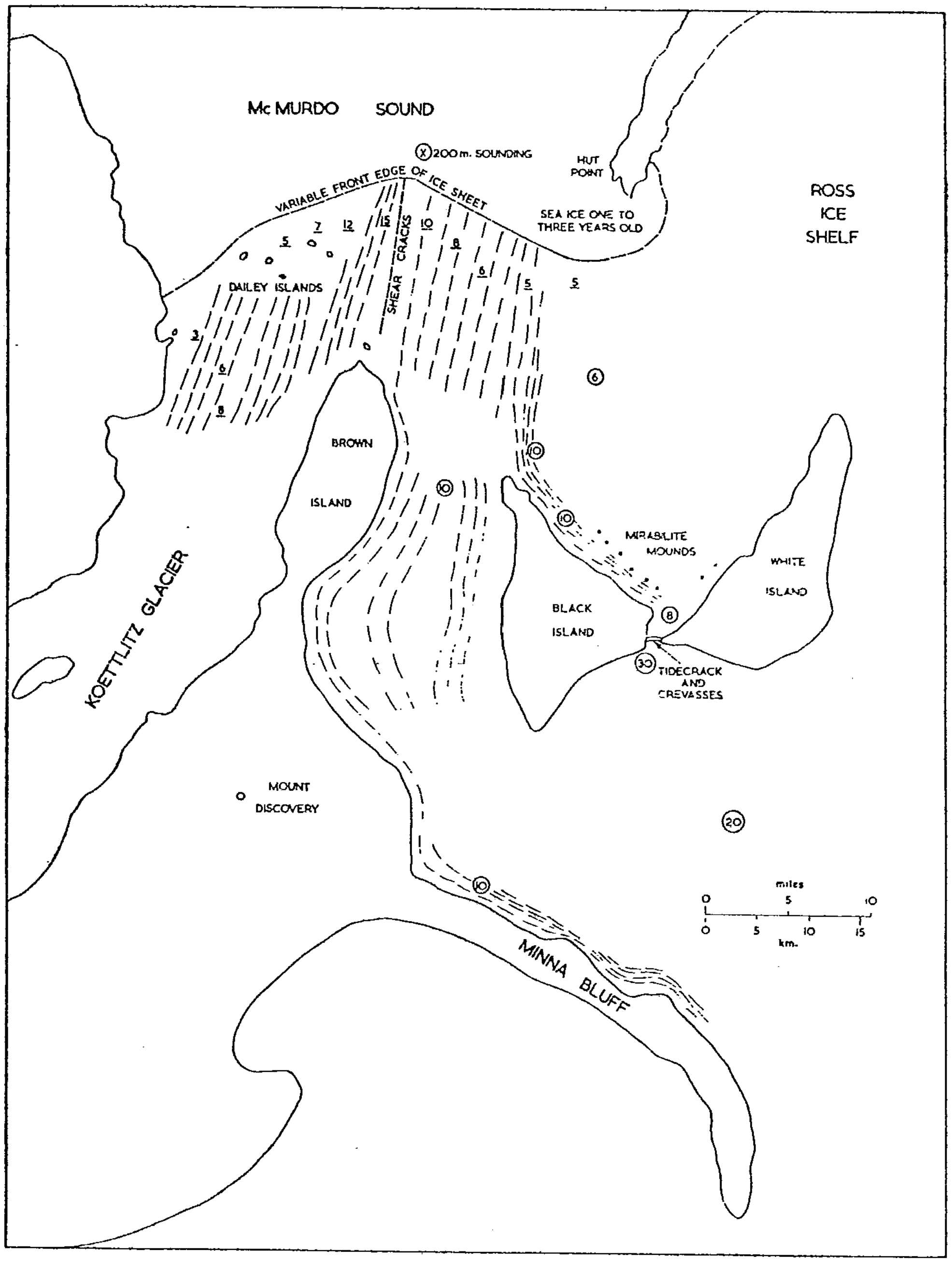

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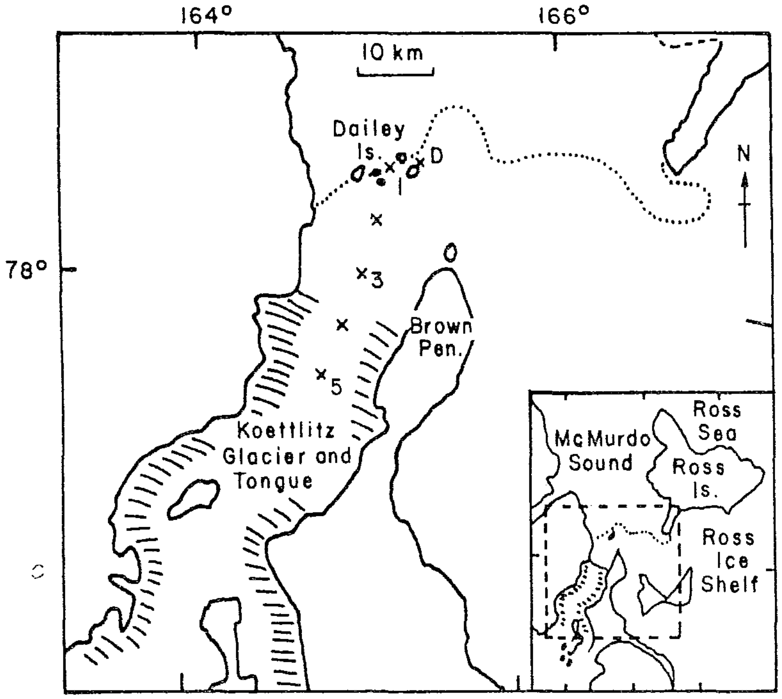

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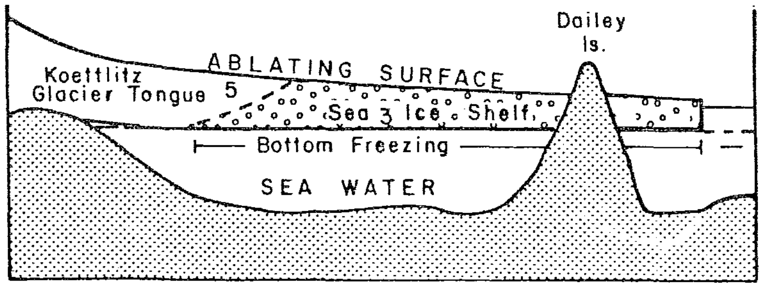

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