ICE RUMPLES ON RONNE ICE SHELF, ANTARCTICA

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ABSTRACT. Field studies have been made of ice rumples covering about 2300 km² between Korff and Henry ice rises on Ronne Ice Shelf, Antarctica. These are the most extensive ice rumples identified on any ice shelf. An ice flow velocity of 51 ± 4 m a^{-1} was determined, indicating a much reduced flow compared with the rest of Ronne Ice Shelf. Most, if not all the ice movement appears to be due to basal sliding. The ice rumples exhibit a simple grounding line geometry, which, together with their simple bedrock and surface topography, makes them a useful site for developing models of ice shelf flexure and basal sliding. Simple calculations suggest that the restraint exerted on the ice shelf by the ice rumples could be as important as that exerted by the adjacent Korff Ice Rise.

INTRODUCTION

The significance of grounded areas within ice shelves has long been recognized (Swithinbank, 1955). Ice rises form distinct topographic features, usually exhibiting well-defined margins, smooth, near-parabolic surface profiles (Martin and Sanderson, 1980) and independent flow regimes. In other places, the ice thickness and bedrock surface elevation are insufficient to produce an ice rise and the ice shelf is believed to slide over the bedrock while encountering some resistance at the base. This results in crevassing and surface undulations; hence the term ice rumples as defined by Armstrong and others (1977). Ice rumples may also have irregular and discontinuous outlines which may be difficult to define.

The criterion for distinguishing between ice rumples and an ice rise is the direction of ice movement. Ice may be deflected or even halted over ice rumples, but on an ice rise, movement is generally independent of that of the ice shelf and, being in the main radial, will in places oppose it. No known ice rumples rise more than 50 m above ice shelf level, whereas ice rises may be up to several hundred metres high.

Data have so far been published on two examples of ice rumples. The influence of McDonald Ice Rumples (Fig. 1) on Brunt Ice Shelf has been documented by Limbert (1964) and Thomas (1973*a*). Thomas calculated an ice flow velocity over the rumples of 50 m a^{-1}. This contrasts with about 400 m a^{-1} for the adjacent floating ice shelf. The McDonald Ice Rumples appear to divert the ice shelf flow from a northwesterly direction upstream of the rumples to an almost westerly direction downstream. Their position at the ice front suggests that they play an important part in determining the maximum seaward extent of the ice shelf.

Kershaw Ice Rumples on Ronne Ice Shelf were first observed in 1975 (Swithinbank, 1977) but have not been studied in detail. The record of a radio echo sounding flight across them is shown in Fig. 2. It reveals the steep-sided nature of this isolated bedrock obstruction and rapid thinning of the ice from 1100 m upstream to 600 m on the crest within a distance of about 3 km. In addition to chaotic crevassing over and around the rumples extensive crevassing extends downstream for at least 10 km.

While not as conspicuous as Kershaw or McDonald ice rumples, other ice rumples may play an important part in ice shelf dynamics. Surface undulations extending over an area of about 2300 km³ between Korff and Henry ice rises on Ronne Ice Shelf (Fig. 3),

Fig. 1. Aerial photograph of McDonald Ice Rumples taken from 8000 m. Ice flow is from bottom right towards the rumples. The long axis of the ice rumples is approximately 3 km. Photograph by US Navy for US Geological Survey (TMA 2068, F32, No. 167).

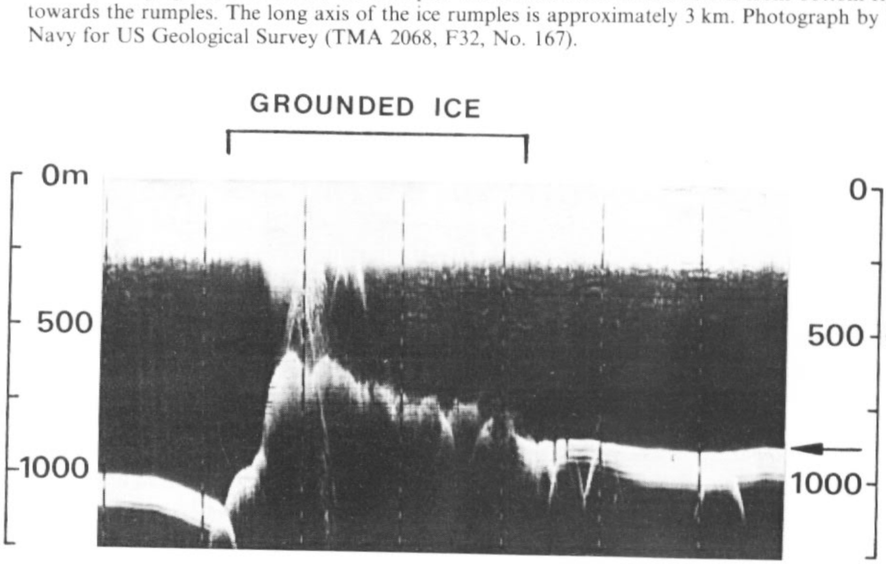

Fig. 2. Radio-echo sounding record over Kershaw Ice Rumples. The arrow marks the reflection from the bottom of the ice. Ice flow is from left to right. Hyperbolas below the bottom reflection to the right of the figure represent bottom crevasses.

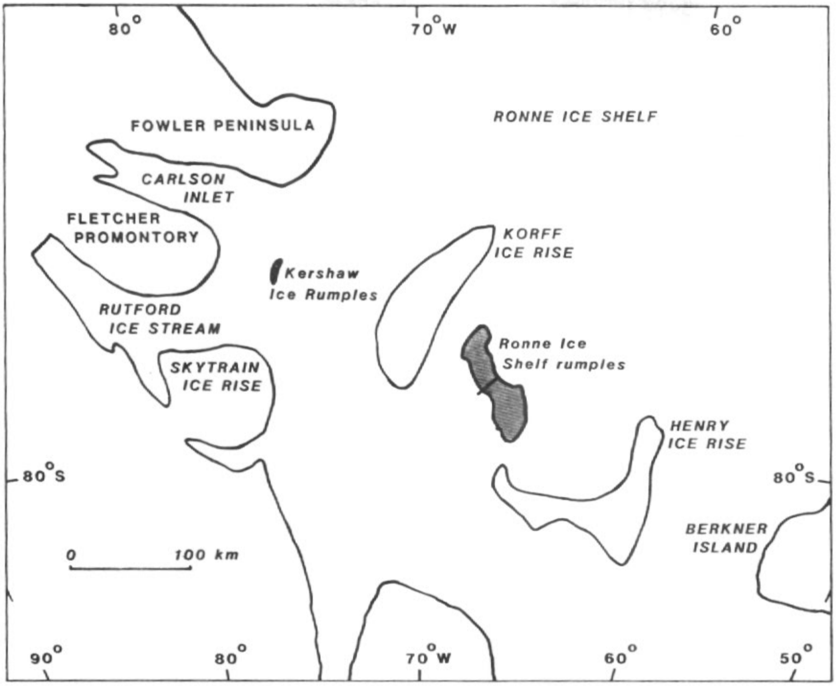

Fig. 3. Map showing part of Ronne Ice Shelf. Ice rumples are shaded. The line across the Ronne Ice Shelf rumples marks the position of the stake scheme.

were first seen on Landsat images (Crabtree and Doake, 1980). Together with results from airborne radio-echo sounding, the surface topography was believed to indicate that here the ice shelf was grounded. The ice flow and tidal flexure over this area have recently been investigated.

Ronne Ice Shelf Rumples

A stake scheme 20 km in length was established over the Ronne Ice Shelf rumples in December 1983 (Fig. 3). Ice surface and bottom profiles along the stake scheme are shown in Fig. 4. These were determined by optical levelling and ground based radio-echo sounding. Bedrock depth beneath floating ice was determined by seismic sounding. Monitoring of tidal flexing using tiltmeters helped to define the position of the upstream grounding line. Doppler satellite surveying provided absolute values of surface elevation and repeated position measurements gave a velocity of 51 ± 4 m a^{-1} over the grounded area. The error value has been calculated from the standard deviations for each position measurement. These are based on the difference between positions calculated from individual satellite passes and the final position calculated from all available satellite pass data. This velocity contrasts with an estimated value of 730 ± 250 m a^{-1} to the west of Korff Ice Rise at a comparable distance from the ice front (Doake, in press). A radio-echo sounding fading-pattern technique similar to that described by Doake (1975) was used to estimate the difference in velocity between the ice surface and the reflecting layer producing the radio echoes. Over 20 days no difference in velocity was detected. The upper limit of

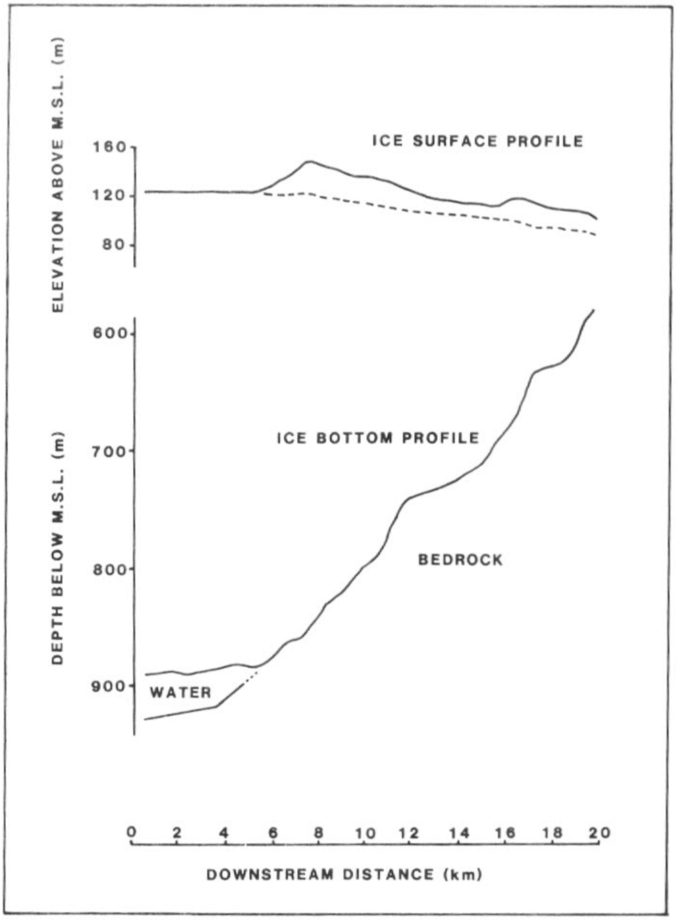

Fig. 4. Ice surface and bottom profiles over the Ronne Ice Shelf rumples. Ice flow is from left to right. Dashed line below ice surface shows surface profile necessary for ice to be fully supported by buoyancy forces.

this velocity difference is therefore presumed to equal the accuracy with which any difference could be measured, in this case 10 m a^{-1}. If the reflecting layer is presumed to be close to the base of the ice shelf this suggests that ice flow over the ice rumples is dominated by basal sliding with little internal creep deformation. Grounded ice flowing over the ice rumples was found to be not more than 30 m thicker than that required for hydrostatic equilibrium (Fig. 4).

Ice thickness was found to decrease from 1000 to 700 m over a distance of less than 15 km along the stake scheme (Fig. 4). Airborne radio-echo sounding showed that further downstream the ice, at that point freely floating, had thinned to 450 m at a distance of only 30 km from the upstream grounding line. Ice from this area appears to continue to the ice front 500 km away as a region nearly 100 km wide and approximately 200 m thick compared with ice about twice as thick on either side (Robin and others, 1983). It may be underlain by a layer of saline ice frozen from seawater (Robin and others, 1983). If it is, the thickness of this layer is uncertain (Thyssen, 1985; Crabtree and Doake, in press). Korff and Henry ice rises act as major obstructions to ice flow and the further restriction caused by the ice rumples between them forces a large proportion of the ice flowing into Ronne Ice Shelf to be diverted to the west of Korff Ice Rise or to the east of Henry Ice Rise.

In order to compare the restraint exerted on an ice shelf by ice rises and ice rumples, Sanderson (1979) considered a simple model in which the ice flowing round the perimeter of an ice rise encounters a limiting compressive stress (C) on the upstream face and a limiting shear stress (T) along the sides. The total upstream force is then given by

$$F_a = H(2LT + WC),$$

where H is the ice shelf thickness, L is the ice rise length and W is the ice rise width. A model used by Thomas (1973*b*) for the upstream force (F_b) exerted by McDonald Ice Rumples assumed that

$$F_b = AS,$$

where A is the grounded area and S is the basal shear stress. Sanderson used values for T, C and S of 90 kPa to show that the restraint caused by 27 km² of ice rumples was equivalent to four ice rises each with an effective perimeter ($2L + W$) equal to 30 km in an ice shelf 225 m thick.

However, a similar calculation to compare Korff Ice Rise and the Ronne Ice Shelf rumples suggests that the resulting restraining force exerted by the rumples is unrealistically high. This is probably because the basal shear stress over ice rumples could be significantly less than 90 kPa. Ice will not necessarily fill bedrock hollows and some shear may be sustained by a soft, poorly competent bedrock. Basal shear stress will be lower when the ice is largely supported by buoyancy forces than when flow is virtually halted. The following values may be assumed for Korff Ice Rise and the ice rumples in the simple models described here; $T = C = 90$ kPa, $L = 162$ km, $W = 45$ km, $H = 1000$ m and $A = 2300$ km². These suggest that an average basal shear stress on only 14 kPa over the ice rumples would give a similar restraining force to that produced by Korff Ice Rise. The restraining force per unit width across the ice rumples estimated by Doake (in press) using a mass balance argument is also consistent with an average basal shear stress of around 10 kPa. It appears therefore that the restraint exerted by the ice rumples is likely to be as important to the ice shelf regime as that exerted by Korff Ice Rise.

Discussion and Conclusions

The ice rumples discussed in this paper appear to fall into two main categories. Firstly, Kershaw and McDonald ice rumples are caused by isolated bedrock peaks with steeply dipping sides (around 14 ° upstream of Kershaw Ice Rumples), and small surface area (approximately 70 km² for Kershaw Ice Rumples). Extensive crevassing occurs on, around and downstream of them. Secondly, Ronne Ice Shelf rumples represent larger areas of grounding in which bedrock dip is shallower. The bedrock slope of about 1 ° over the Ronne Ice Shelf rumples has been shown from seismic records to continue upstream for at least 40 km (L. D. B. Herrod, personal communication). Soft, water-saturated sediments have been suggested for large areas of grounding (Crabtree and Doake, 1980; Drewry and others, 1980) and this is consistent with a low value for the basal shear stress. Crevassing may occur downstream but it is not severe.

Studies of ice rumples can help in understanding ice shelf flexure and basal sliding. The former is important to studies of ice shelf grounding lines, the latter to studies of ice stream flow. Ice rumples exhibiting simple topography and grounding line geometry can be used to develop theoretical models which may then be applicable to more complex areas. For example, features on Landsat images of Antarctic outlet glaciers appear similar to ice rumples. This suggests that common processes may control ice flow and points to the importance of basal sliding, particularly at the heads of outlet glaciers (McIntyre, 1985).

All ice rumples will be sensitive to certain environmental changes. Differences in bedrock lithology, topography and surface elevation will affect resistance to basal sliding. A change in resistance with time could be caused by changes in ice shelf thickness, in sea level or in sea floor elevation. This would favour the growth of an ice rise or the decay of ice rumples which in turn would affect the flow of the ice shelf. The restraint exerted upon an ice shelf by ice rumples can be an important part of the total force controlling its flow. Thus they may affect the seaward extent of ice shelves and the equilibrium state of the Antarctic ice sheet.

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