

## SHORT NOTES

### RIDGES ON ANTARCTIC ICE RISES

By P. J. MARTIN

(British Antarctic Survey, Cambridge CB3 0ET, England)

**ABSTRACT.** Satellite pictures have revealed the presence of ridges on the summits of ice rises in Antarctica. Because ice does not exhibit a critical stress it is concluded that these ridges must be produced by a snow accumulation process rather than by ice deformation. A sand-model analogue has been used to simulate this behaviour.

**RÉSUMÉ.** Ondulations sur le sommet de la calotte antarctique. Des photos de satellites ont révélé la présence d'ondulations sur les sommets des calottes de glace de l'Antarctique. Comme la glace ne subit pas d'effort critique en ces points, on conclut que ces ondulations proviennent d'un phénomène d'accumulation de neige plutôt que de déformation de la glace. Un modèle en sable a été utilisé pour simuler ce comportement.

**ZUSAMMENFASSUNG.** Rücken auf antarktischen Eiserhebungen. Aus Satellitenbildern ergab sich das Vorhandensein von Rücken auf den Scheiteln von Eiserhebungen in der Antarktis. Da das Eis keine kritische Spannung aufweist, wird angenommen, dass diese Rücken durch einen Prozess der Schneeeablagerung gebildet werden, nicht aber durch Eisdeformation. Zur Nachahmung dieses Verhaltens wurde ein analoges Sandmodell herangezogen.

AN ice rise consists of a mass of ice resting on rock and surrounded either by an ice shelf or partly by an ice shelf and partly by sea. No rock is exposed and it has been shown by radio-echo sounding that the bedrock may be below sea-level. Ice rises are of glaciological interest because they offer simple conditions for studies of the mechanism of ice deformation and the laws governing ice flow. Information obtained from these relatively simple systems can then be applied to larger ice sheets.

Observations of Antarctic ice rises have been made from the ground, from aircraft, and from satellites. Figures 1 and 2 are typical satellite images of ice rises in the Antarctic Peninsula. Although little can be deduced about the overall morphology, an interesting feature revealed by the pictures is the presence of a ridge running along the crest. Despite a near-zero surface slope in the region of the summit and a sun elevation in excess of  $20^\circ$ , a clear demarcation line can be seen.

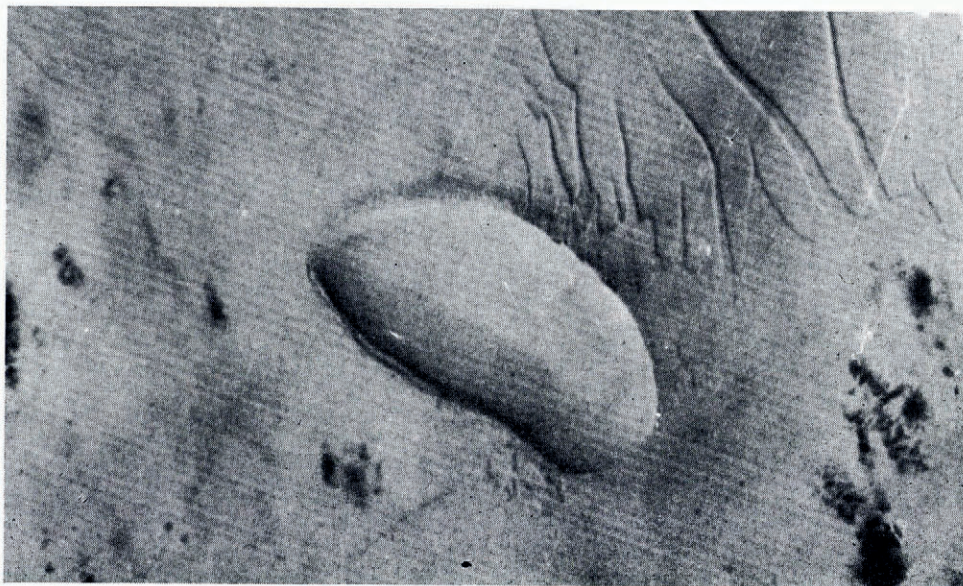


Fig. 1. Earth Resources Technology Satellite image of Gipps Ice Rise, Larsen Ice Shelf. Scale 3 cm = 10 km. (ERTS frame No. 1473-12051-7. Photograph by United States National Aeronautics and Space Administration.)



Fig. 2. Earth Resources Technology Satellite image of Spaatz Island (lat.  $73^{\circ}$  S., long.  $75^{\circ}$  W.). Scale  $1.3\text{ cm} = 10\text{ km}$ . (ERTS frame No. 1190-12374-7. The Newton's rings are due to photo-copying and are not a real feature. Photograph by United States National Aeronautics and Space Administration.)

The formation of a ridge on the summit of an ice rise indicates that, in the region of the crest, some process must be occurring in addition to the expected deformation behaviour. In predicting the theoretical profile of a typical ice rise, Nye (1959) made the assumption that all the shear takes place at the base and that contributions from differential shear motion within the bulk of the ice can be neglected. The steady-state profile will then be of the form:

$$(h/H)^{2+1/m} + (x/L)^{1+1/m} = 1 \quad (1)$$

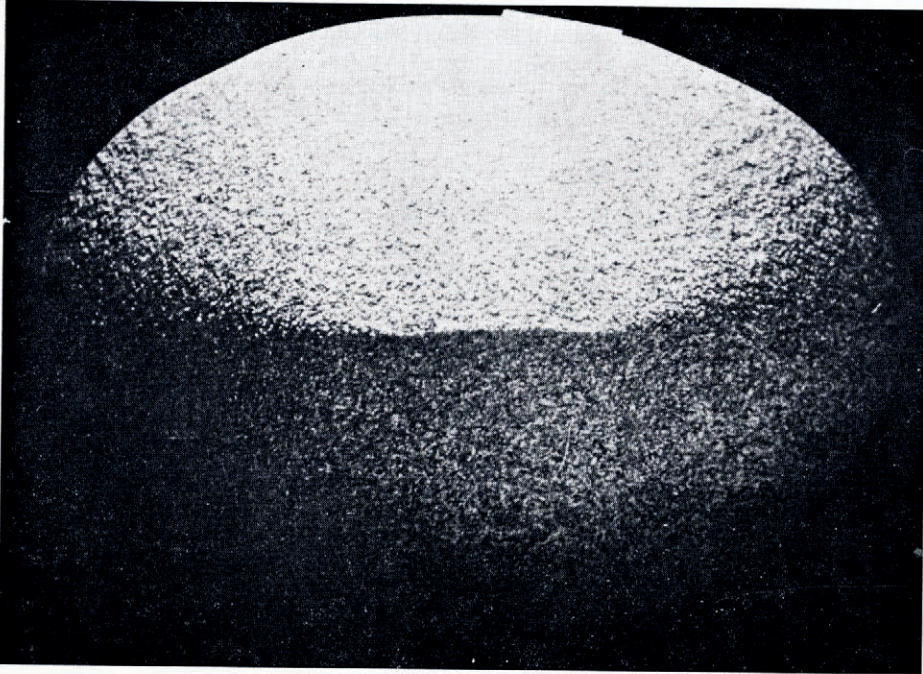
where  $h$  is the height of the upper surface at a distance  $x$  from the centre,  $H$  is the thickness at the centre and  $L$  is the distance from the centre to the edge of the ice rise. The constant  $m$  would take a value of 2 if the flow law relating strain-rate  $\dot{\epsilon}$  to stress  $\tau$  is assumed to be

$$\dot{\epsilon} = A\tau^3. \quad (2)$$

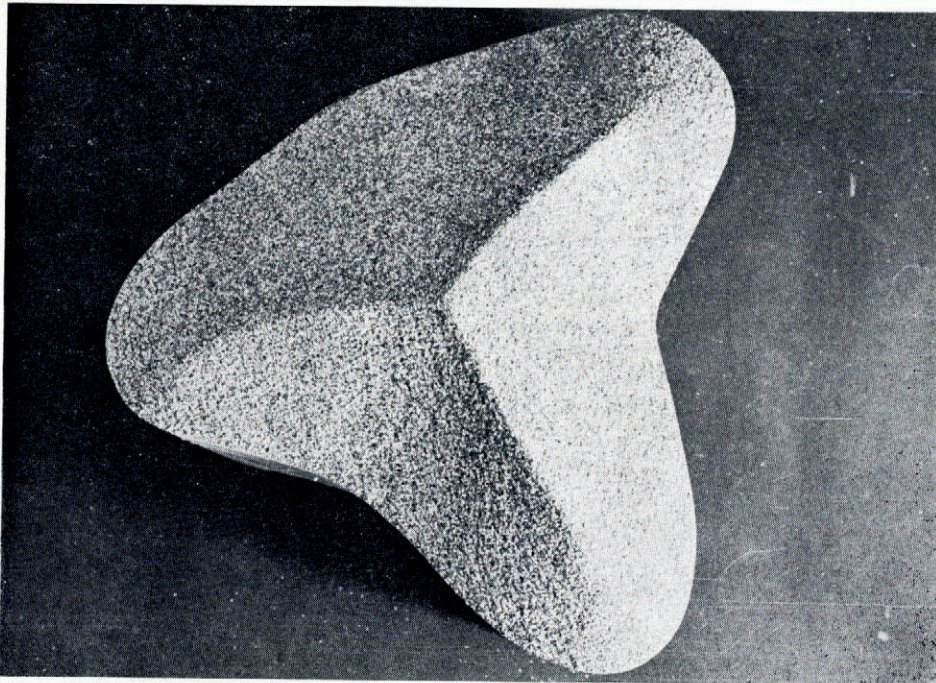
The predicted form of the ice rise, with a surface slope close to zero in the vicinity of the crest and increasing uniformly to a maximum at the edge, has been found to agree well with measured profiles (Paterson, 1969, p. 153; Clapp, 1965).

It was shown by Nye (1959) that if  $m$  becomes infinite in Equation (1), a sharp ridge will appear at  $x = 0$ . This would imply that the ice is behaving as a perfectly plastic material in which the strain-rate is zero up to a critical stress, above which it can take any value. The treatment of ice as a perfectly plastic medium was discussed by Nye (1952) in an earlier paper in which he successfully used this approximation to predict ice thickness on the basis of the surface slope of an ice sheet. On the other hand Hawkes and Mellor (1972) determined the stress-strain curves of large specimens of randomly oriented polycrystalline ice and reported no indication of a critical stress.

In view of the general evidence (Paterson, 1969, p. 82) that polycrystalline ice does not exhibit critical stress behaviour, it seems probable that the ridges found on the ice rises are created by an accumulation process. In the initial stages of snow densification, deformation occurs by shearing of grain contact areas without deformation of individual grains (Bader and Kuroiwa, 1962, p. 9). In such a system where grains have a high degree of mobility, critical-state behaviour could arise. A model of this process can be made by heaping sand into a mound. This analogue has been used to simulate a variety of critical-state phenomena (Campbell and Evetts, 1972). In this situation a build-up of sand occurs until a critical surface slope is reached, thereafter small displacements, or avalanches, occur to



*Fig. 3. Sand model showing ridge formation. One-quarter full size.*



*Fig. 4. Sand model of a more complex shape showing ridge formation. One-third full size.*

produce a mound with a constant maximum slope. Two examples are shown in Figures 3 and 4. There is a close similarity between the ridges formed by this process and those shown in Figures 1 and 2.

The existence of a ridge on an ice rise will produce an increase in the shear stress below it, which in turn will tend to flatten the surface profile. Thus, unlike the sand model, the normal flow behaviour of the ice will tend to spread the surface ridge, so producing the very shallow slopes observed.

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