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RADIO ECHO SOUNDINGS AND ICE-TEMPERATURE MEASUREMENTS IN A SURGE-TYPE GLACIER

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Abstract. Radio echo soundings on Rusty Glacier, a small surge-type glacier in Yukon Territory, reveal that the ice is considerably thicker than previously believed. A reinterpretation of deep ice-temperature measurements made in 1969 and 1970 suggests that a large zone of temperate basal ice exists. This result supports thermal instability as the surge mechanism for Rusty Glacier.

Résumé. *Sondages par écho-radio et mesures de températures de la glace dans un glacier de type "a crues".* Des sondages par écho-radio sur le Rusty Glacier, un petit glacier du type "à crues" dans le Yukon Territory, révèle que la glace est beaucoup plus épaisse qu'on ne le croyait autrefois. Une nouvelle interprétation des mesures profondes de la température de la glace faites en 1969 et 1970 laisse à penser qu'il existe une large zone de glace tempérée à la base. Ce résultat tend à faire penser que l'instabilité thermique serait le mécanisme de la crue pour le Rusty Glacier.

Zusammenfassung. *Radarecholotungen und Eistemperaturmessungen in einem Gletscher des "Surge-Typs".* Radarecholotungen am Rusty Glacier, einem kleinen Gletscher des "Surge-Typs" im Yukon Territory, zeigten, dass das Eis beträchtlich dicker ist als bisher angenommen. Eine Neuinterpretation der 1969 und 1970 angestellten Temperaturmessungen in der Tiefe des Eises deutet darauf hin, dass eine ausgedehnte Zone temperierten Eises am Untergrund existiert. Dieses Ergebnis unterstützt die Theorie eines auf thermischer Instabilität beruhenden Ausbruch-Mechanismus des Rusty Glacier.

Introduction

Rusty Glacier (lat. 61° 13′ N., long. 140° 18′ W.) in Yukon Territory, formerly known as "Fox Glacier" (Clarke and Crossley, 1972) is a small surge-type glacier in the Steele Creek drainage system (Collins, 1972). Temperature models based on a gravity survey to determine ice thickness (Crossley and Clarke, 1970) and deep ice-temperature measurements (Classen and Clarke, 1971, 1972) indicate a small zone of temperate basal ice. Radio soundings reveal that parts of the glacier are considerably thicker than previously believed. Basal ice temperatures calculated using this new information show that much of the bottom ice is at or near the pressure-melting point. This is consistent with the essential premise of thermal-instability surge theories: that surging glaciers are sub-polar glaciers with a basal temperature which oscillates near the melting point (Robin, 1955; Hoffmann and Clarke, 1973).

Radio echo soundings

Attempts in 1968 and 1969 to measure the thickness of Rusty Glacier by the conventional seismic reflection method and by radio echo sounding with a 35 MHz Mark II Scott Polar Research Institute radar set (Evans and Smith, 1969) positioned on the glacier surface were unsuccessful. Since a typical thickness for Rusty Glacier is 100 m, the transmitted radio and seismic pulses completely obscured the reflections, preventing depth determinations. Owing to the proximity of the valley walls, it was not thought that airborne soundings at 35 MHz would be fruitful, although Evans and Robin (1966) successfully used this method over wide valley glaciers. By removing the transmitter from the glacier surface they were able to increase the time between the transmitted and reflected pulses and as a consequence were able to measure depths over a thin ice cover. Using a 620 MHz high-resolution radio-sounding system developed for temperate glaciers (Goodman, 1970), depths as shallow as

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40 m could be measured from the glacier surface before the transmitted and received pulses were contiguous. The short wavelength (50 cm) and high spatial resolution (5.2° beam width between half-power points) of the equipment enabled the immediate analysis of the photographically recorded oscilloscope images. A more detailed description of the high-resolution radar system is presented in another paper (Goodman and others, 1975).

Since there was a dielectric in the near field of the antenna, the effects of lateral radiation resulting in wide-angle reflections from the valley walls could not be neglected. To discriminate between air-path valley-wall reflections and echoes from the glacier bottom, soundings were taken with the antenna in two orientations: longitudinal and transverse. The echograms (Fig. 1) show that some peaks change dramatically with antenna orientation while others are

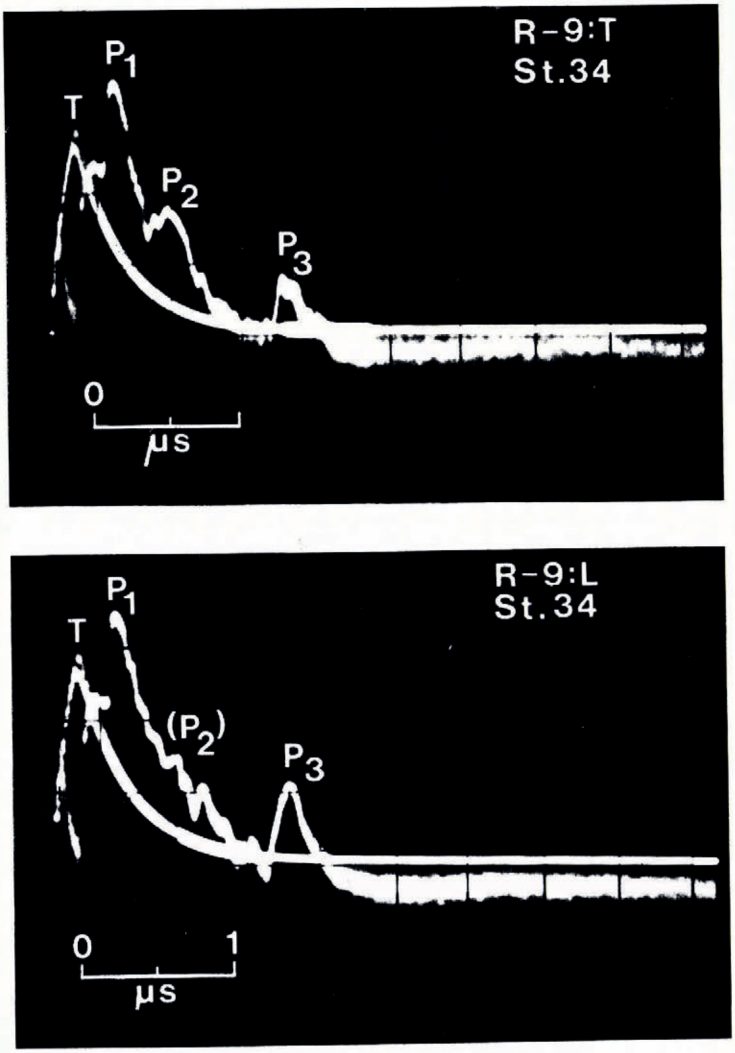

Fig. 1. Photographs showing effect of antenna orientation on radio reflections at the same site. P_1 is the return from the glacier surface; (P_2) is an orientation-dependent reflection from the valley walls or intra-glacier structure; P_3 is orientation independent and therefore interpreted as the bottom echo. T indicates the trigger pulse.

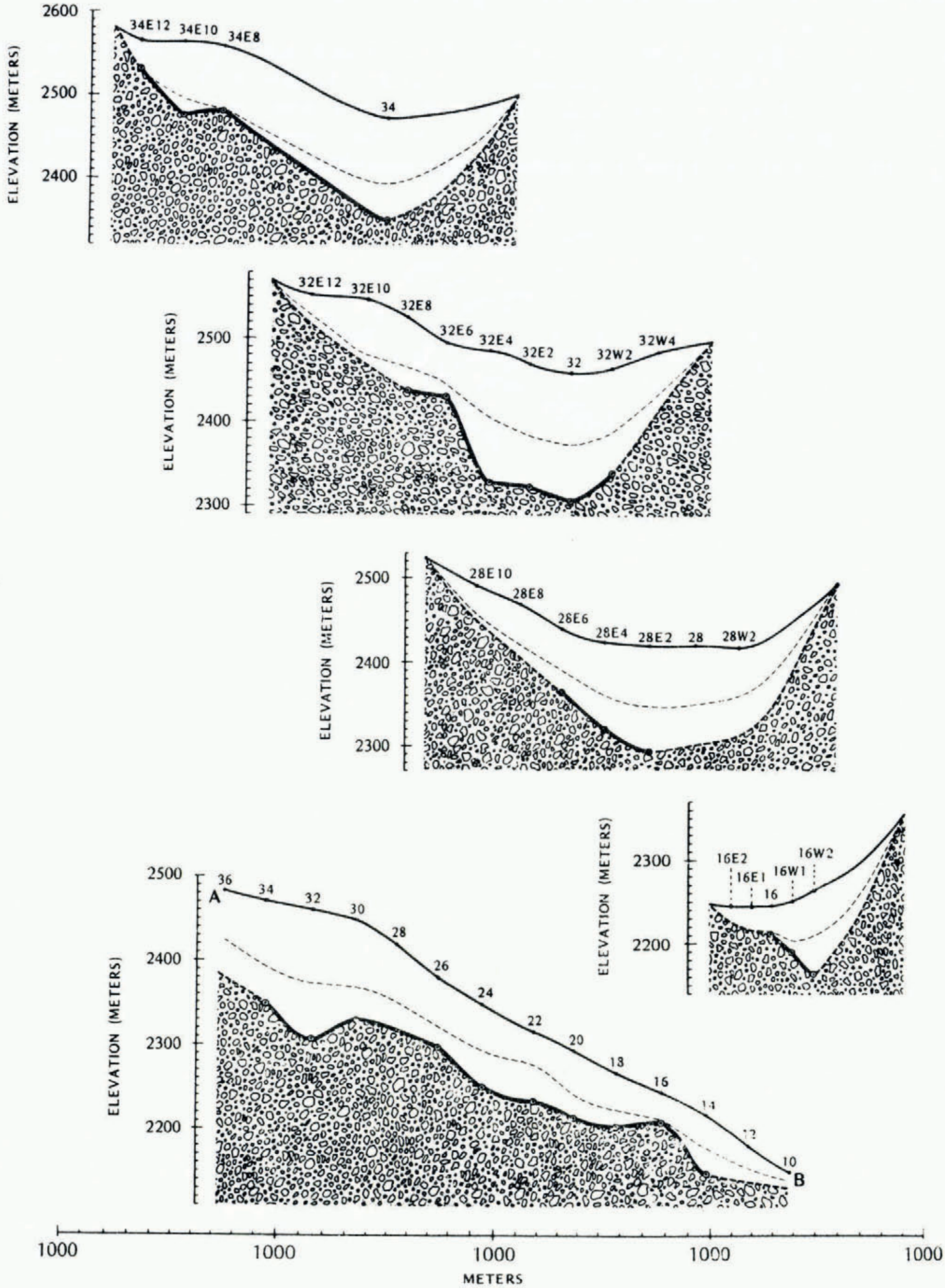

Fig. 2. Cross-sections of Rusty Glacier as determined by radio echo soundings. The gravity results of Crossley and Clarke (dashed line) consistently underestimate the ice thickness.

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unaffected; the latter peaks are interpreted as from the glacier bottom. Internal time delays were calibrated using a crystal-controlled pulse generator, and depths were calculated using a velocity of 176 m/μs.

The internal equipment delays were calibrated in the field and a preliminary value of 130 ns was obtained. This value was subtracted from the arrival time of the echo before depth was computed. A subsequent detailed analysis of internal time delays performed in the laboratory gave a final value of 80 ± 20 ns. Since the 130 ns delay was used for all calculations in this paper, the ice thickness is probably systematically underestimated by approximately 5 m.

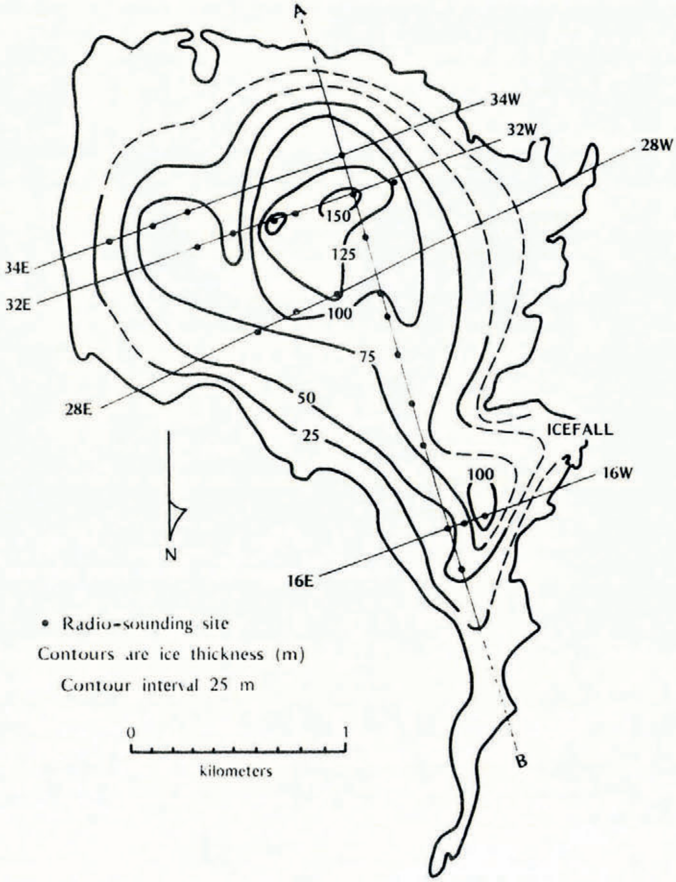

Fig. 3. Rusty Glacier ice-thickness map based on radio-sounding and gravity results. The contour interval is 25 m. The solid dots indicate sounding sites.

Glacier cross-sections based on the radio soundings show that the gravity-depth interpretation of Crossley and Clarke (1970) is consistently shallower than the sounding depth (Fig. 2). This is a well-known characteristic of the infinite slab approximation which they used. A contour map of ice thickness was constructed using the sounding data in combination with the gravity data (Fig. 3).

Basal ice-temperature model

Deep ice-temperature measurements in thermally drilled holes at seven sites on Rusty Glacier have been reported by Classen and Clarke (1971, 1972); their data are presented in

Figures 4 and 5. The radio soundings indicate that few of the thermally drilled holes are close to the bed. Only hole 7 shows the presence of ice at the pressure-melting point. The temperature gradient, as determined from the lowest two thermistors in each hole, was used to predict the basal ice temperatures. When the predicted ice temperature exceeded the melting point, temperate ice was assumed to exist. On this basis warm ice is thought to underlie holes 1 and 2.

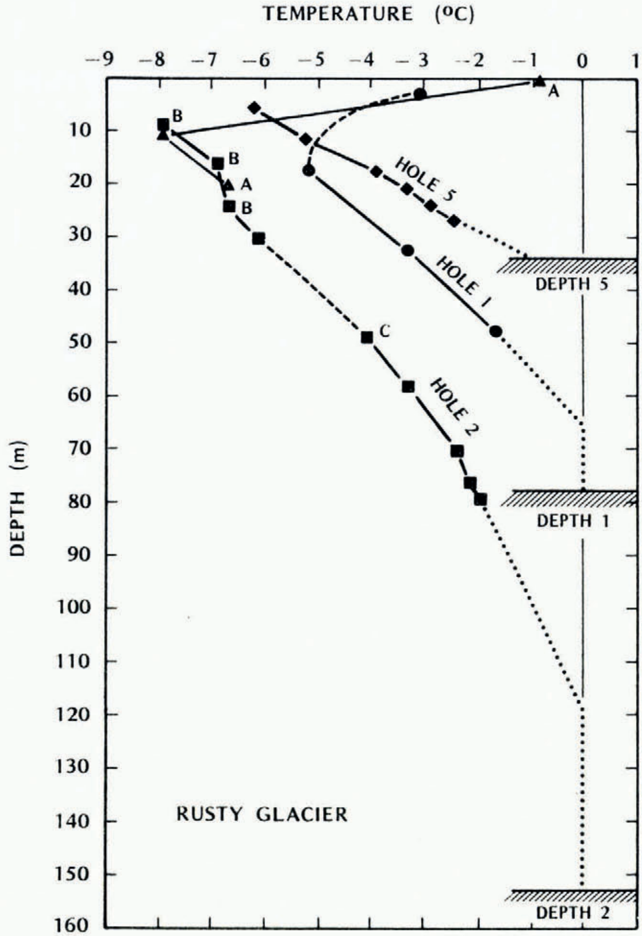

Fig. 4. Ice-temperature profiles for drilling sites 1, 2 and 5. Holes 2A, 2B and 2C are different holes at the same site. All the depths were determined by radio soundings with the exception of hole 5 where the depth was found by gravity measurements.

A predicted ice-temperature map using the radio sounding and ice-temperature data was constructed in the following manner. 10 m temperatures for the entire glacier were calculated using a least-squares fit to the bore-hole data (Classen and Clarke, 1972). The glacier was subdivided into six zones, one for each hole. The characteristic ice-temperature gradient within each zone was estimated using the fitted 10 m temperatures and the depth at which the temperature was predicted to reach 0° C. The latter prediction was made with the same extrapolation as was used to estimate the basal ice temperature. Finally, the temperature gradients were adjusted to give a smooth variation across zone boundaries. Using these

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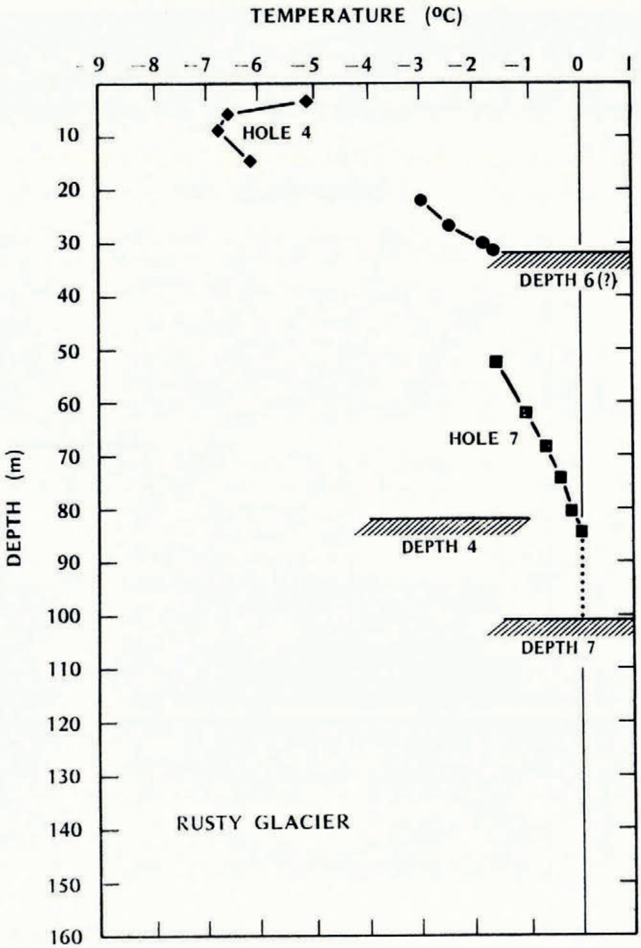

Fig. 5. Ice-temperature profiles for drilling sites 4, 6 and 7. The data from hole 7 show temperate ice near the bed.

temperature gradients, linear extrapolation of the 10 m temperatures to the glacier bed predicts basal temperature (Fig. 6). According to these results much of the deep ice is at or near the pressure melting point.

Few glaciers are known to have a cold surface and temperate bed; this thermal regime may be characteristic of many surge-type glaciers. Surges could arise in the following manner: when a large fraction of the glacier bed reaches the melting point, sliding becomes significant, causing the enhanced flow velocities associated with a surge. Downward advection of cold surface ice during the surge conducts heat away from the bed, eventually diminishing the zone of temperate basal ice and stopping the surge. A quantitative version of this simple model developed by Hoffmann and Clarke (1973), and subsequent unpublished computer modelling by Clarke and Jarvis, show that a periodic cycle of advance and retreat can result. It is interesting to note that the tongue of Rusty Glacier appears to be frozen to the bed so that a thermal dam to basal water flow may exist. A stress-induced dam playing a similar role has been postulated as the cause of surge behavior in temperate glaciers (Robin and Weertman, 1973).

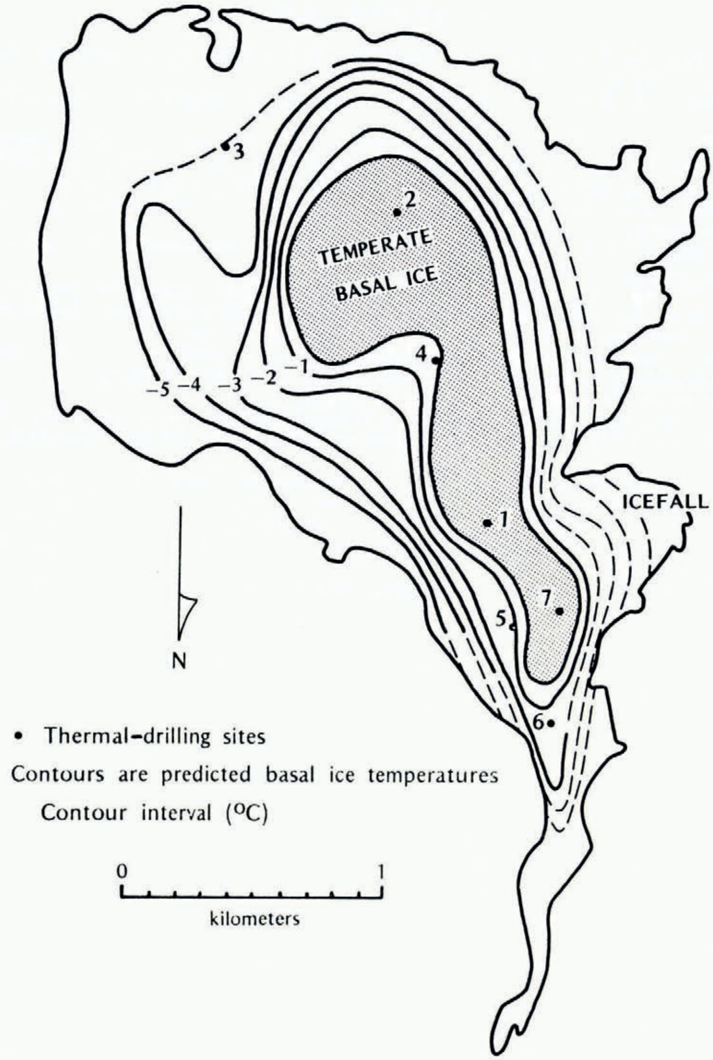

Fig. 6. Contour map of predicted basal temperatures for Rusty Glacier. The shaded zone indicates the extent of the basal hotspot. Thermal-drilling sites are numbered 1 through 7; site 3 was near a crevasse and the data were considered unreliable.

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