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SHORT NOTES

TRACING PARTICLE PATHS IN THE ANTARCTIC ICE SHEET

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ABSTRACT. A layer of moraine within the Antarctic ice sheet has been detected in the course of airborne radar ice soundings. The moraine was injected at the margin of the ice and can serve as a tracer to pick out a particle path within the ice. When combined with surface measurements, the ability to trace particle paths should allow detailed modelling of the dynamic behaviour in limited areas.

RÉSUMÉ. *Itinéraire de transit de matériaux à travers la calotte glaciaire de l'Antarctique.* Une campagne de sondages aériens par radar a permis de détecter un niveau de moraine à l'intérieur de la calotte glaciaire de l'Antarctique. La moraine était insérée en bordure de la glace et peut servir de traceur pour mettre en évidence un itinéraire de transit des matériaux à l'intérieur de la glace. Combinée avec des mesures de surface, cette possibilité de reconstituer l'itinéraire de sédiments devrait permettre une représentation détaillée du comportement dynamique de la glace dans des zones limitées.

ZUSAMMENFASSUNG. *Die Verfolgung von Partikeln in der antarktischen Eisdecke.* Im Zuge von Radar-Echolotungen aus dem Flugzeug wurde eine Schicht mit Moränenmaterial innerhalb der antarktischen Eisdecke festgestellt. Die Moräne wurde am Eisrand vereinnahmt; sie kann als Trägerschicht zur Verfolgung des Weges eines Partikels im Eis dienen. Durch Kombination mit Messungen an der Oberfläche sollte sich die Möglichkeit zu detaillierten Modellvorstellungen über das dynamische Verhalten in begrenzten Gebieten eröffnen.

FLOW at depth in ice sheets is normally deduced from surface measurements. Drilling is expensive and time consuming and is therefore only suitable for the investigation of relatively shallow glaciers. It is well known that in polar regions radio echo records often show an internal layering structure (Robin and others, 1969). Although the reasons for these internal reflections are not completely understood, it is likely that they are associated with relatively small changes in physical or electrical properties of the ice (Paren and Robin, 1975; Keliher and Ackley, 1978). It is also not known whether a reflection corresponds to a single discontinuity in the ice or whether it is integrated over the wavelength or pulse length of the radar (commonly used pulse lengths are around 0.2 μs with carrier frequencies between 30 and 300 MHz). However it is usually assumed that these layers are sedimentary features related to former surfaces and are therefore isochronous. This fact has been used in conjunction with surface measurements of accumulation and strain-rates to suggest that the existing flow regime of the West Antarctic ice sheet has been stable for the last 10 000 years (Whillans, 1976).

Another way of investigating internal flow would be to study particle paths. These are not normally visible using remote-sensing techniques. However, Figure 1 shows data recorded in January 1975 while on an airborne radio echo survey around the Ellsworth Mountains, Antarctica (Fig. 2), which suggest that a reflecting horizon was seen corresponding to a moraine layer injected into the ice and thus tracing out a particle path.

The unusual feature in Figure 1 is the presence of a strong reflecting layer at a varying distance above, but distinct from, the bedrock echo. The layer begins and ends at definite horizontal positions, has a well defined depth, and shows a lengthening of the echo that is characteristic of a reflection from a rough surface (the equipment used had a radio wavelength in ice of about 3 m). These features distinguish the layer from the common type of internal layering which generally consists of a large number of weakly reflecting (< -50 dB), closely spaced layers which are extensive in area and decrease in strength with depth (Keliher and Ackley, 1978). Internal layering was recorded close to, but not at, the site where the strong reflecting layer was seen and could easily be distinguished from it. Although no quantitative echo-strength measurements were made, it can be seen that the layer and the bedrock have similar reflection strengths. If an average reflection coefficient for bedrock is taken as -20 dB (Robin and others, 1969), then a single reflecting layer which also has this value will cause very little attenuation

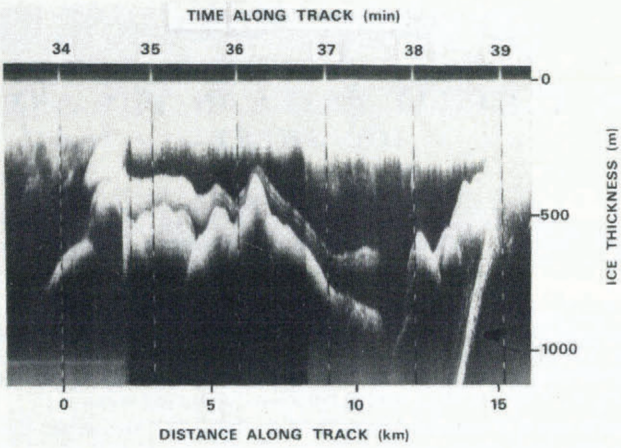

Fig. 1. Print of radio echo record showing a strong reflecting layer within the ice but at some distance above bedrock. (Note that the ice-thickness scale refers to times after 34.7 min, where there is a change of vertical scale.)

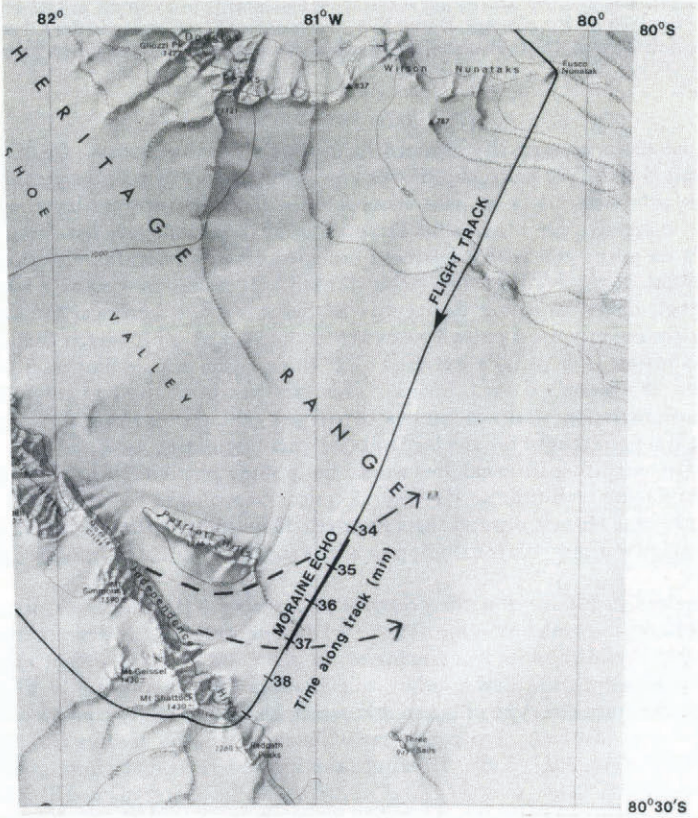

Fig. 2. Map showing flight track and extent of internal echo. The dotted lines indicate possible flow lines. (Liberty Hills, Antarctica, 1 : 250 000 reconnaissance series, U.S. Geological Survey.)

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of the transmitted wave, so allowing the bottom echo to be detected. It is obvious from Figure 3 that the depth of the layer in Figure 1 is not a constant proportion of the ice thickness. There is therefore no possibility that the echo is caused by some multiple-reflection phenomenon. The aircraft was too far from any nunataks for the reflection to be a side echo from exposed rock and there is unlikely to be a subglacial scarp parallel to the flight-track but perpendicular to the dominant structural trend of the mountains (Fig. 2) which might give an oblique echo.

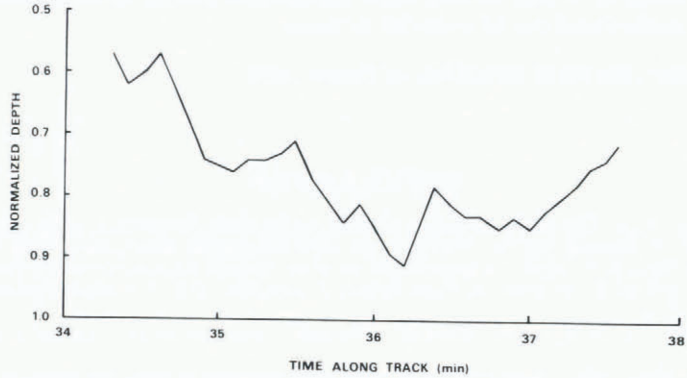

Fig. 3. Plot of normalized depth of echo (layer depth divided by total ice thickness) against time along flight track. The most recently injected moraine occurs furthest along the flight line.

The most plausible explanation is that the echo comes from a thin layer of moraine. Study of the map in Figure 2 and of an oblique air photograph of the area (Fig. 4) reveals a large area of scree and lateral moraine in Independence Hills which could be the source of material. If the flight track had followed a flowline on the ice the layer would have traced out a particle path within the ice sheet. The actual track appears to have crossed the flow obliquely. Ice presumably flows in a generally eastward direction past Independence Hills, turning slightly north once it has passed Patriot Hills. It should be noted that the shaded ice surface features on the USGS map have been interpreted from aerial photography (e.g. Fig. 4) and do not necessarily represent flow directions. Figure 3 shows however that there is no simple, or even monotonic, relationship between normalized layer depth and age as would be expected if vertical strain-rates were constant over the area (Crary and others, 1962). Of special interest is the way in which the layer approaches the bottom when flowing over the bedrock protuberance at time

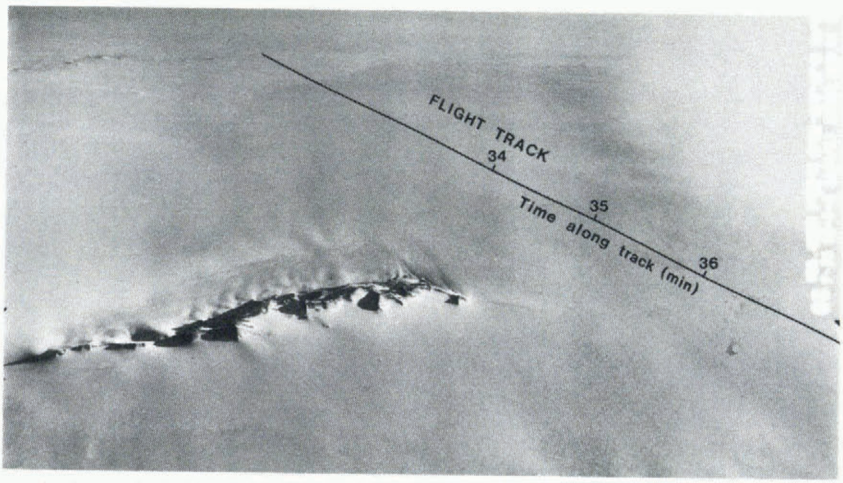

Fig. 4. Oblique air photograph, looking north-east over Independence Hills, a likely source of moraine. Photograph: U.S. Navy for U.S. Geological Survey.

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36.2 min. The surface altitude was measured during the flight and shows that there is no local ice divide at this point. Without measurements of accumulation, velocity, or strain-rate, little can be deduced about the internal flow regime other than that it appears to respond to the bedrock topography, especially close to the bed.

The ability to trace particle paths in an ice sheet should allow detailed modelling of ice flow with the possibility of checking any variation in flow parameters over the time period covered by the age of the particles. A bonus would be to find an area where isochronous internal layering could be detected in addition to particle paths traced out by englacial moraine.

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