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Creep rupture at depth in a cold ice sheet

THE mechanism by which stress is released in intermediate and deep focus earthquakes and the physics of tectonic processes are of particular interest to Earth scientists. As a way of understanding such phenomena it would be valuable to have a relatively small scale tectonic system duplicating the processes taking place within the Earth. Several authors¹⁻³ have speculated that processes operating within glaciers and ice sheets are analogous to those in the Earth. Experimental evidence has not supported the hypothesis of an Earth glacier equivalence, especially in terms of identifying faulting at depth within glaciers. A seismic survey made of a valley glacier in Canada⁴ found no deep ice events. However, evidence of the existence of discrete shear planes within the Antarctic Ice Sheet⁵ and evidence described here relating to the Greenland Ice Sheet, indicate that faulting takes place at depth in cold ice sheets.

At great depths beneath the surface of the Earth (500-700 km) where the pressure is of the order of 10^{10} Pa and high homologous temperatures prevail, classical laws of brittle failure do not apply. As an alternative to stress release by brittle fracture, rupture of the material may result when creep is concentrated in very narrow bands subjected to shear stresses. Consideration of the creep rupture phenomenon and its associated stress drop have led to some current models of fault mechanisms for earthquakes⁶.

The mechanism by which stress is released in intermediate and deep focus earthquakes is of particular interest to seismologists and tectonophysicsists. Orowan¹ proposed that faulting at depth is initiated by the development of creep instabilities in shear layers in the Earth. The stress drop theory associated with Orowan's faulting mechanism serves as a partial base for models describing the seismic spectra from earthquakes.⁶ To verify his theory, Orowan¹ proposed that this faulting mechanism might also operate in temperate glaciers.

As a means of verifying the creep-rupture theory, Neave and Savage⁴ carried out a seismic investigation on the Athabasca Glacier in Canada. They aimed to detect shear faulting at depth within the glacier. After 390 h of seismic monitoring they concluded that creep instabilities which would be recorded as deep focus ice-quakes had not taken place in the Athabasca Glacier.

Field investigation of glaciers are generally conducted where simple flow regimes occur, so that research findings can be generalised⁷⁻⁹. However, recent drilling at the margin of the Greenland Ice Sheet^{10,11} in a peculiar area characterised by upslope flow of cold ice over geometrically complicated bedrock (see Fig. 1), has revealed the presence of a fracture at 240 m depth in the ice. The evidence for the fracture is threefold. First, although drilling was temporarily stopped at 250 m depth surface meltwater was observed to enter the liquid-filled hole, thus showing that the drilling fluid was running out of the hole at some depth. As no crevasses, moulins or englacial conduits are present in this area, this behaviour can only indicate the existence of an open fracture that intersects the hole between the surface and 250 m depth. The hole was then completed to bedrock at 299 m. Second, following drilling the saltwater used as a drill fluid was spontaneously flushed from the upper 240 m of the hole by surface meltwater whereas the lower 59 m of the hole retained the salty water, as shown by temperature measurements made periodically after the completion of drilling¹⁰. Third, calculated temperature profiles¹² for four other

holes in the same area are in excellent agreement with measured temperatures, but the calculated profile for the hole in question agrees equally well with the measured temperatures only if the ice is assumed to flow over an area of 'dead ice' as shown in the Fig. 1. Direct observations of dead ice have been made in valley glaciers but not in cold ice sheets.

As no evidence of a pre-existing fracture was obtained, it is possible that the excess hydrostatic pressure of the drilling fluid ($\sim 2.4 \times 10^5$ Pa) and the flow shear stress caused the formation of the fracture along a zone of weakness between the dead and moving ice. Whether or not there was a pre-existing fault at this depth, the excess hydrostatic pressure caused propagation and opening of the fracture sufficient to accept a large quantity of water; hence, it is likely that the fracture propagated to bedrock around the area of dead ice (the subglacial tills are permeable in this area¹⁰). The small excess hydrostatic pressure could not have caused fracture without an existing zone of creep-enhanced weakening at this depth.

Fig. 1 Ice thickness and bedrock profile (from a seismic survey) is shown along the flow line through the drill hole, Isua, Greenland.

The geometry shown in Fig. 1 suggests an area of dead ice overridden by the ice sheet while temperature and water flow observations clearly show a fracture in the ice at 59 m above the bed. This evidence for fracture at depth in the Greenland Ice Sheet leads us to reconsider the correspondence between flow and rupture at depth in the Earth and in cold ice sheets as suggested earlier^{1,2}. If seismic evidence of deep fracturing in cold ice sheets is found we will have a large-scale tectonic system available for the study of deep fractures associated with the underthrusting of cold lithospheric plates¹³. Direct investigations at depth in ice sheets are made with relative ease as compared to the nearly impossible task of direct measurements in the Earth's mantle.

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