hopefully encourage students to develop a further interest in studying glaciology and glacial sedimentary processes.

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SIR,

Ice blisters and ice dolines

In a recent letter to the Editor of *Journal of Glaciology*, Kovacs (1992a) gave a very comprehensive review of observations and morphology of ice blisters on glaciers, sea ice and rivers. Kovacs (1992a, b) gave many examples of ice blisters from Alaska and Antarctica, where they are generally observed in association with the ready availability of liquid water (Fig. 1). Ice blisters are usually 5–20 m across and 1–3 m high, although Echelmeyer and others (1991) estimated that some of the examples they observed on Jakobshavns Isbræ, West Greenland, were up to 8 m high. Kovacs (1992b) discussed their formation by the freezing of water trapped within ice which expands and forces up the ice cover, in an analogous way to the cream on top of a frozen bottle of milk. Many ice blisters are hollow inside with evidence for the release of water provided by the presence of refrozen water-icings around the ice blister. The drilling of many blisters reveals the presence of liquid water in their core.

Fig. 1. Ice blister in a melt pool on the Koettlitz Glacier Ice Tongue (McMurdo Sound, Antarctica) surrounded by summer meltwater. The ice blister is about 12 m across and 0.5 m high. (Photograph by courtesy of A. Kovacs, CRREL.)

I should like to draw attention to a class of features, ice dolines (sometimes known as ice calderas) that appear to be very similar to ice blisters, except that they are much larger, being of the order of kilometres in diameter and perhaps tens of metres deep. Mellor (1960) suggested the term doline for the features from their similarity to subsidences which occur in karst country after the collapse of underground chambers. Several examples of this type of feature were seen on George VI Sound, West Antarctica, in 1936 during the British Graham Land Expedition. Stephenson and Fleming (1940) described the largest doline as being a bowl "nearly a mile across, bordered by ice cliffs 100 ft high"; they suggested the term "ice caldera" for the feature (Fig. 2). The bottom of the bowl contained piles of angular ice blocks up to 12 m high. Fleming and others (1938) described the mounds of material in the caldera as consisting of "slabs of radially cracked ice tilted upwards to meet in a point". Stephenson and Fleming (1940) stated that "it looked as if there had been an enormous hollow dome that has suddenly collapsed". Similar features were also seen in that area by Byrd (1947), who suggested that they may have formed by the explosion of gas trapped within the ice. There is no generally agreed explanation for the origin of ice dolines, one explanation being that they are impact craters, another that they are melt lakes that drain intermittently to the sea beneath the ice shelf (Swithinbank, 1988). The ice shelf in the area near the doline is about 175 m thick (Crabtree, 1983), if the bottom of the doline was about 30 m below the surrounding ice shelf as has been suggested by the observations of Stephenson and Fleming (1940), then assuming the ice shelf is in hydrostatic equilibrium, the bottom of the doline would have been below sea level, allowing for drainage through basal fractures. Reynolds (1983) believed that the largest doline on George VI Ice Shelf described by Stephenson and Fleming (1940) was mapped in 1949 (Searle, 1960) and was roughly circular with a diameter of 1.5 km. Further observations of this feature in the 1960s and 1970s showed a gradual deterioration of surface definition and, by 1979, only the outline of the doline was clearly visible

Fig. 2. The large ice doline (also called the ice caldera) on George VI Sound, Antarctica, taken from the air in January 1967. The doline is about 1.5 km in diameter. Uranus Glacier at top left and Eros Glacier from the upper right are shown entering the ice shelf. The dark streaks are meltwater lakes. Notice the similarity in shape to the ice blister in Figure 1 but the great difference in size. (Photograph by courtesy of C. W. M. Swithinbank.)

(Reynolds, 1983). The area near the doline has very low net accumulation, being in the precipitation shadow of Alexander Island, and is also associated with many meltwater lakes. This means that the feature survived for at least 44 years without being buried, which is consistent with the low or possibly negative net accumulation rate in the area (Reynolds, 1983).

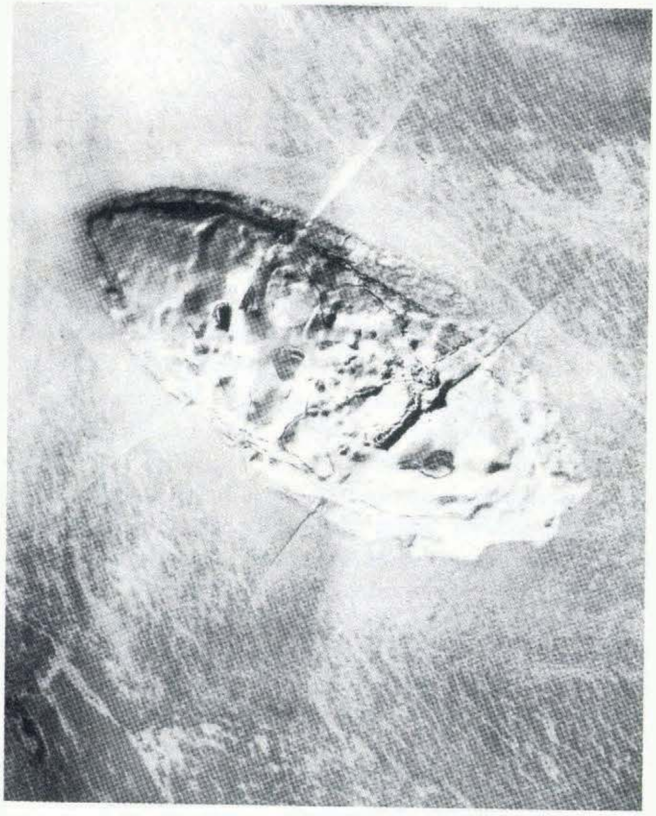

Fig. 3. Vertical air photograph of an ice doline at 71°20′ S, 68°40′ E near the southern edge of the Amery Ice Shelf, Antarctica. The doline is about 3 km long by 1.3 km wide and stereo-pair photography gives a depth for the doline of 80 m below the surrounding ice surface (Mellor and McKinnon, 1960). (Photograph by courtesy of ANARE.)

Mellor and McKinnon (1960) reported a number of ice dolines at the southern edge of the Amery Ice Shelf in East Antarctica, and also smaller features about 200 m across on glaciers in Greenland. One example discussed by Mellor and McKinnon (1960) on the Amery Ice Shelf was an oval depression 3 km by 1.3 km, with its bottom about 80 m below the surrounding ice surface (Fig. 3). Mellor and McKinnon (1960) suggested that the doline formed by the filling of depressions with meltwater which freezes more rapidly at the top surface than at the bottom where conduction of heat is slow. Melt lakes are observed upstream of the feature which show the availability of liquid water in the area. The presence of apparent icing features around the doline supports the hypothesis that they contained liquid water.

Swithinbank (1988) presented features interpreted as dolines in satellite images of the northern part of the Larsen Ice Shelf (Antarctic Peninsula) and the Lazarev Ice Shelf (Dronning Maud Land). Additionally, a Landsat 5 image (50719-12504; 18 February 1986; path 220, row 110) of the Wilkins Ice Shelf (Antarctic Peninsula) shows many melt lakes and possible dolines (personal communication from D. G. Vaughan). The Amery Ice Shelf has a mean annual temperature of about −10°C, similar to the areas with dolines of George VI Ice Shelf and Larsen Ice Shelf (Reynolds, 1981), and Lazarev Ice Shelf (Solopov, 1969). All three ice shelves have extensive melt lakes in the area of the dolines. Drainage via hydraulic connection to the sea is possible either by direct penetration of meltwater through the ice shelf or by brine flowing to the doline laterally through the permeable firn of the ice shelf from rifts or the ice edge. Lazarev, Larsen and Wilkins Ice Shelves all have tidal lakes or the open sea within 30 km of their dolines and lateral penetration of brine may be responsible for creating paths for drainage; lateral brine infiltration has been observed several kilometres from open rifts (Thomas, 1975) in the Brunt Ice Shelf, and extensive brine layers covering tens of kilometres observed in the Larsen and Wilkins Ice Shelves (Smith, 1972). Penetration of meltwater to more than 200 m depth in ice shelves has been suggested (personal communication from A. Jenkins) as the explanation for isolated spikes in the $\delta^{18}O$ profile of an ice core from the Amery Ice Shelf (presented by Robin (1983)), that are similar to near-surface $\delta^{18}O$ values. Therefore, direct meltwater penetration may account for drainage of the Amery Ice Shelf dolines.

There is no evidence of current features on George VI Ice Shelf that could be called dolines, though there are certainly many lakes. George VI Ice Shelf was rather colder in the 1940s and probably also in the earlier decades of the century than the present day (Jones, 1990). Warmer years are mainly a result of mild winters, the summer temperatures being close to 0°C. In warmer times, it is likely that much thinner surface covers of ice would form above the melt lakes, not allowing the accommodation of significant pressure from expansion of water during freezing. The water would tend to seep away gently rather than drain catastrophically, and we should expect no roof collapse or a doline feature to form.

The occurrence of dolines on ice shelves in areas where there are substantial supplies of meltwater strongly supports the theory that dolines are melt lakes that freeze over and then suffer drainage, causing the unsupported roof to collapse. Unlike ice blisters, which usually drain through cracking of the roof of the blister forming icings, dolines probably drain through fractures in their base to the sea beneath the ice shelf.

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SIR,

There is direct evidence for Pleistocene collapse of the West Antarctic ice sheet

Diatom fossils, the siliceous shells of microscopic marine planktonic algae, have been identified in glacial till recovered from beneath Ice Stream B near the Upstream B camp (UpB) in West Antarctica (Engelhardt and others, 1990; Scherer, 1991). Most of the diatoms identified in these sediments are Miocene, older than 5 Ma and represent marine conditions in the West Antarctic interior. Most of the Pliocene and Pleistocene is not represented due to glacial erosion and non-deposition during glaciated intervals. Rare post-Miocene diatoms are present in the UpB 1988–89 sediment matrix. Scherer (1991) suggested that most of these diatoms are likely to be less than ~600 000 years old and may represent remnants of the most recent deglaciation in West Antarctica.

If these findings and interpretations are correct, then they provide the first direct evidence of Pleistocene collapse of the West Antarctic ice sheet. Mercer (1978) first suggested that the West Antarctic ice sheet might have collapsed during a Pleistocene interglacial. Based on independent proxy records, including the deep-sea sediment record (e.g. Howard and Prell, 1992; Hodell, 1993), sea-level history (e.g. Cronin, 1981; Wornardt and Vail, 1991; Brigham-Grette and Carter, 1992) and

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