Correspondence

The Editor,
Journal of Glaciology

SIR,

Fracturing and sediment deposition at the glacier surface by jökulhlaups: a common occurrence

Roberts and others (2000) reported jökulhlaups which generated basal water pressures in excess of ice overburden, thereby fracturing overlying ice and allowing sediment to be emplaced at high elevations within the glacier as water discharged through fractures onto the surface. Similar circumstances characterized drainage of the lake Kalvtjørna, at the glacier Austre Okstindbreen, Norway, on 5 August 1977 (Theakstone, 1978). Water, with a high sediment load, burst up through the glacier surface at a point 2 km from the lake basin, and fractures resembling low-angle thrusts were formed (Fig. 1). The emerging water covered a large area at the glacier surface, and sediments were deposited for a distance of > 100 m from the fracture zone (Fig. 2). Subsequent examination revealed that sediments had been deposited on the walls and roof of the 5 m high conduit immediately up-glacier of the point at which the water emerged through the glacier surface.

Short-lived events causing surface fracturing, water spouts at the glacier surface and related phenomena have been surprisingly widely reported over a long period (Table 1). When water flow beneath a glacier is interrupted, or when water is supplied to conduits more quickly than it can escape, high water pressures may develop. Because the resultant discharge of water through the glacier surface may be short-lived, the probability of its being observed is low, even if fieldwork is being conducted on the glacier.

George (1866, p. 123–125) described "a fountain of very considerable volume rising out of the ice" and published what probably was the first photograph of such a feature. He concluded that water "meeting with some obstacle in its subglacial course had forced its way to the surface through a fissure in the ice". Sturm and others (1986) reported that, during jökulhlaups at Drift Glacier, Alaska, U.S.A., water poured out from the base of a rock plug which projected through the lower glacier, and Lawson (1986) attributed water fountains discharging at an active glacier margin to an impermeable dam formed by frozen bed materials and stagnant ice. McKenzie (1969) described a sudden release of water from stagnant ice. Several accounts of water released from subglacial cavities penetrated by tunnels or boreholes have been published (Miller, 1952; Haefeli and Brentani, 1955; Fisher, 1963; Paterson and Savage, 1970).

Nordenskjöld (1881, p. 181) reported a column of water above the surface of a glacier, which "like a geysir ... rises to

Fig. 1. Water draining from the lake Kalvtjørna burst through the surface of the glacier Austre Okstindbreen on 5 August 1977. The glacier surface was fractured, and sediments were deposited by the emerging water.

Table 1. Observed events related to water bursting through a glacier surface

Glacier	*Event*	*Source*
Aargletscher, Switzerland	Water spout	George (1866)
Unnamed, Spitsbergen, Svalbard	Water spout	Nordenskjöld (1881)
West Ice, North East Land, Svalbard	Water spout	Glen (1941)
Sentinel Glacier, Canada	Fractures	Mathews (1949)
Von Postbreen, Spitsbergen, Svalbard	Water spout	Rucklidge (1956)
Martin River Glacier, Alaska	Fractures	Reid and Clayton (1963)
Aletschgletscher, Switzerland	Water spout	Wiseman (1963)
Britannia Gletscher, Greenland	Water spout	Wyllie (1965)
Kaskawulsh Glacier, Canada	Water spout	Ewing and others (1967)
Adams Inlet Glacier, Alaska	Water burst	McKenzie (1969)
Werenskioldbreen, Spitsbergen, Svalbard	Water spout	Baranowski (1973)
Austre Okstindbreen, Norway	Fractures	Theakstone (1978)
Storglaciären, Sweden	Fractures	Holmlund and Hooke (1983)
Triumvirate Glacier, Alaska	Upwelling	Sturm and Benson (1985)
Drift Glacier, Alaska	Upwelling	Sturm and others (1986)
Matanuska Glacier, Alaska	Fountains	Lawson (1986)
Law Dome, Antarctica	Fractures	Goodwin (1988)
Black Rapids Glacier, Alaska	Upwelling	Sturm and Cosgrove (1990)
Bas Glacier d'Arolla, Switzerland	Fractures	Warburton and Fenn (1994)
John Evans Glacier, Canada	Fractures and fountain	Skidmore and Sharp (1999)
Skeiðarárjökull and Sólheimajökull, Iceland	Fractures	Roberts and others (2000)

Fig. 2. Sediments were deposited over a large area below the fracture zone at the surface of the glacier Austre Okstindbreen as water drained from the glacier-dammed lake.

a great height". Glen (1941) noted that water sometimes "attains such a high pressure that it literally bursts its way up through the ice, sending up a small water spout which may continue for as long as an hour". Wyllie (1965) reported water spouts which persisted for several days, whilst Rucklidge (1956) described one which lasted only a few seconds but was repeated six times at exactly 10 min intervals. Wiseman (1963) observed a water spout which rose rapidly to 5–7 m, and Ewing and others (1967) saw one which reached a maximum height of 4–5 m and issued for 7–10 s. Baranowski (1973) observed a series of water spouts, which occurred with striking regularity for an hour. Sturm and Cosgrove (1990) reported significant super-elevation of water discharging from a glacier pothole. Sturm and Benson (1985) noted that, during the early stage of a jökulhlaup, water flowed from under the ice at supraglacial pools.

Fracturing associated with the discharge of water through the glacier surface has been reported from many areas. Mathews (1949) described a 15–30 m diameter circular fracture in firn, and a trail of sediment deposited by the water which had burst through the surface. Reid and Clayton (1963) suggested that thrusting of ice blocks in the glacier marginal zone was responsible for the opening and closing of subglacial drainage. Holmlund and Hooke (1983) described surface fracturing induced by a rapid rise then fall of water pressures; cracking of the ice was heard before the rise of water level. Goodwin (1988) reported that, over a period of weeks before a jökulhlaup, fracturing of the ice was coupled to a dome-shaped uplift; chemical analyses suggested that the water, which erupted as a 1–2 m high water spout from the major crevasse, had been active in chemical erosion of the glacier bed. Warburton and Fenn (1994) noted arcuate post-event fractures associated with moulins, after water had flowed up them during "a highly unusual sequence of glacier flood events". Skidmore and Sharp (1999) reported that audible fracturing of the ice preceded the onset of upwelling of water at a glacier surface, and that longitudinal fracturing occurred in the vicinity of a fountain which rose 1–2 m above the surface. Bennett and others (2000) considered that fractures, opened during the 1991 surge of Skeiðarárjökull, Iceland, facilitated the escape of subglacial water to the glacier surface.

Roberts and others (2000) suggested that there is a continuum of glacier responses to sudden influxes of water to the bed, when the rate of water supply exceeds the rate at which it can escape. Ephemeral events involving water discharging through a glacier surface and depositing sediment there may be relatively common, although their short-lived nature means that they may be neither observed nor reported.

Department of Geography, WILFRED H. THEAKSTONE
University of Manchester,
Manchester M13 9PL, England

14 September 2001

REFERENCES

Baranowski, S. 1973. Geyser-like water spouts at Werenskioldbreen, Spitsbergen. *International Association of Scientific Hydrology Publication* 95 (Symposium at Cambridge 1969 — *Hydrology of Glaciers*), 131–133.

Bennett, M. R., D. Huddart and R. I. Waller. 2000. Glaciofluvial crevasse and conduit fills as indicators of supraglacial dewatering during a surge, Skeiðarárjökull, Iceland. *J. Glaciol.*, **46**(152), 25–34.

Ewing, K., S. Loomis and R. Lougeay. 1967. Correspondence. Water-spout on Kaskawulsh Glacier, Yukon Territory. *J. Glaciol.*, **6**(48), 956–959.

Fisher, J. E. 1963. Two tunnels in cold ice at 4,000 m on the Breithorn. *J. Glaciol.*, **4**(35), 513–520.

George, H. B. 1866. *The Oberland and its glaciers: explored and illustrated with ice-axe and camera.* London, Alfred W. Bennett.

Glen, A. R. 1941. A sub-Arctic glacier cap: the west ice of North East Land. *Geogr. J.*, **98**(2), 65–76.

Goodwin, I. D. 1988. The nature and origin of a jökulhlaup near Casey Station, Antarctica. *J. Glaciol.*, **34**(116), 95–101.

Haefeli, R. and F. Brentani. 1955. Observations in a cold ice cap. Part I. *J. Glaciol.*, **2**(18), 571–581.

Holmlund, P. and R. LeB. Hooke. 1983. High water-pressure events in moulins, Storglaciären, Sweden. *Geogr. Ann.*, **65A**(1–2), 19–25.

Lawson, D. E. 1986. Observations on hydraulic and thermal conditions at the bed of Matanuska Glacier, Alaska. *In Hydraulic Effects at the Glacier Bed and Related Phenomena, International Workshop, 16–19 September 1985, Interlaken, Switzerland.* Zürich, ETH. Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, 69–71. (Mitteilungen 90.)

Mathews, W. H. 1949. Correspondence. Subglacial streams and extrusion flow. *J. Glaciol.*, **1**(5), 284/282.

McKenzie, G. D. 1969. Observations on a collapsing kame terrace in Glacier Bay National Monument, south-eastern Alaska. *J. Glaciol.*, **8**(54), 413–425.

Miller, M. M. 1952. Correspondence. Glacier tunnel observations in Alaska. *J. Glaciol.*, **2**(11), 69–70.

Nordenskjöld, A. E. 1881. *The voyage of the Vega around Asia and Europe. Vol. 1.* London, Macmillan and Company.

Paterson, W. S. B. and J. C. Savage. 1970. Excess pressure observed in a water-filled cavity in Athabasca Glacier, Canada. *J. Glaciol.*, **9**(55), 103–107.

Reid, J. R. and L. Clayton. 1963. Correspondence. Observations of rapid water-level fluctuations in ice sink-hole lakes, Martin River Glacier, Alaska. *J. Glaciol.*, **4**(35), 650–652.

Roberts, M. J., A. J. Russell, F. S. Tweed and Ó. Knudsen. 2000. Correspondence. Rapid sediment entrainment and englacial deposition during jökulhlaups. *J. Glaciol.*, **46**(153), 349–351.

Rucklidge, M. A. 1956. A glacier water-spout in Spitsbergen. *J. Glaciol.*, **2**(19), 637–639.

Skidmore, M. L. and M. J. Sharp. 1999. Drainage system behaviour of a High-Arctic polythermal glacier. *Ann. Glaciol.*, **28**, 209–215.

Sturm, M. and C. S. Benson. 1985. A history of jökulhlaups from Strandline Lake, Alaska, U.S.A. *J. Glaciol.*, **31**(109), 272–280.

Sturm, M. and D. M. Cosgrove. 1990. Correspondence. An unusual jökulhlaup involving potholes on Black Rapids Glacier, Alaska Range, Alaska, U.S.A. *J. Glaciol.*, **36**(122), 125–126.

Sturm, M., C. Benson and P. MacKeith. 1986. Effects of the 1966–68 eruptions of Mount Redoubt on the flow of Drift Glacier, Alaska, U.S.A. *J. Glaciol.*, **32**(112), 355–362.

Theakstone, W. H. 1978. The 1977 drainage of the Austre Okstindbreen ice-dammed lake, its cause and consequences. *Nor. Geogr. Tidsskr.*, **32**(4), 159–171.

Warburton, J. and C. R. Fenn. 1994. Unusual flood events from an Alpine glacier: observations and deductions on generating mechanisms. *J. Glaciol.*, **40**(134), 176–186.

Wiseman, M. L. 1963. Correspondence. Water-spout on the Aletsch Glacier. *J. Glaciol.*, **4**(35), 647–648.

Wyllie, P. J. 1965. Correspondence. Water-spouts on the Britannia Gletscher, north-east Greenland. *J. Glaciol.*, **5**(40), 521–523.