Journal of Glaciology, Vol. 39, No. 133, 1993

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The Editor,
Journal of Glaciology

SIR,

Most recent observations of the drainage of an ice-dammed lake at Russell Glacier, West Greenland, and a new hypothesis regarding mechanisms of drainage initiation

A series of papers in this journal and elsewhere has documented the sudden drainage of ice-dammed lakes along the northern flank of Russell Glacier, near Kangerlussuaq (Søndre Strømfjord), West Greenland (e.g. Sugden and others, 1985; Gordon, 1986; Scholz and others, 1988; Russell, 1989; Russell and deJong, 1988). Most recently, Russell and others (1990) and Russell (in press) described the drainage of a small unnamed lake in 1987, 1988 and 1990, and suggested a probable drainage mechanism. Since those observations were made, a further drainage event has occurred at the lake, and new observations made after this most recent drainage allow additional conclusions to be drawn. Here we identify seasonal lowering of the ice surface by ablation as a previously neglected factor that can affect lake drainage and suggest a model whereby drainage might occur due to different mechanisms in different years, making prediction difficult and having implications for the geomorphic effects of the drainage.

Observations

Our most recent observations of the lake were made between July and October 1991. As in previous years, the lake seems to have drained between mid-June and mid-July. When our observations were made, lake-bed sediments were still wet and fresh, shorelines were visible both on the ice front and on the vegetated off-glacier side of the basin, and a portal marking the presumed drainage route was intact. Two new observations are particularly important:

(i) The prominent shoreline on the ice front and around the off-glacier basin perimeter, which marks a level at which the lake depth must have been stable for some time prior to drainage, corresponds to the lake overspill at the glacier margin at the west end of the basin. In other words, the lake filled right up to its topographically controlled limit prior to drainage.

(ii) The shoreline and the overspill height correspond to 90% of the height of the ice cliff at the deepest part of the basin, directly above the drainage portal. This is equivalent to the theoretical water depth at which flotation of the ice dam is a feasible mechanism for initiating lake drainage (Thorarinsson, 1953).

Several points of interest arise from these observations.

First, the observations raise the question of whether drainage could have occurred by flotation of the dam. Because the lake drained from different levels in 1987 and 1988, Russell (in press) has for those drainage events rejected a simple flotation hypothesis in favour of drainage by connection with the glacier's internal drainage system, but the correspondence between the actual lake depth at the 1991 drainage and the theoretical flotation depth is remarkable. If the flotation hypothesis is invoked for the 1991 drainage, the question arises as to how the lake was able to persist at the same depth for long enough to produce a shoreline but without inducing flotation. We suggest that, while the water level was constant, the thickness of the ice dam decreased gradually as the ablation season progressed. Drainage might then be predicted to occur when the dam thickness fell to about 111% of the water depth. This hypothesis inverts the normal procedure of considering lake-depth increase as the mechanism for crossing the flotation threshold at 90% of the dam thickness.

A second point related to our observations is that, as the position of the ice front changes, the topographically limited maximum depth of the lake will change. At present the maximum possible lake depth is defined by the intersection of the ice margin with the sloping perimeter ridge at the western end of the lake basin. If the glacier continues to advance up the ridge, the maximum possible depth will increase until the lake overspills by a route at the head of the basin rather than by the ice-marginal overspill which it currently follows. After that time, glacier advance will have no effect on the maximum depth of the lake, and thickening of the dam will not be matched by deepening of the lake. In that situation, flotation will cease to be a possible drainage mechanism. We suggest that different drainage mechanisms may be feasible in different years. When the maximum lake depth is low in relation to the ice thickness, drainage occurs only when a connection is made with the main internal drainage system of the glacier. When the maximum lake depth is high relative to ice thickness, either because the spillway is at a high elevation or because the ice dam is thinned by ablation, we predict that drainage might be initiated by flotation of the ice barrier. In the latter case, the drainage might follow a route close to the glacier margin, and exit the glacier locally rather than connecting with the internal network. The implications for sediment supply to the

https://doi.org/10.3189/S0022143000016609 Published online by Cambridge University Press

glacier and geomorphic impact on the glacier margin would then be different.

There is some evidence that different drainage routes are taken by different events. Monitoring of the 1988 event showed no release of jökulhlaup water along the north flank of Russell Glacier, indicating that the water draining from the lake was either stored englacially or removed by a more deeply englacial route to the snout of the glacier which was unmonitored at the time. By contrast, after the 1990 event, a large cavity was observed in the north flank of the glacier about 250 m down-glacier and about 20 m lower in elevation than the draining lake. Although there was no surviving geomorphological evidence of high meltwater discharge downstream of the cavity, the cavity was morphologically indistinguishable from meltwater outlet portals observed elsewhere, and might represent a near-margin escape route for water from the draining lake, consistent with a drainage mechanism independent of the main glacier drainage system.

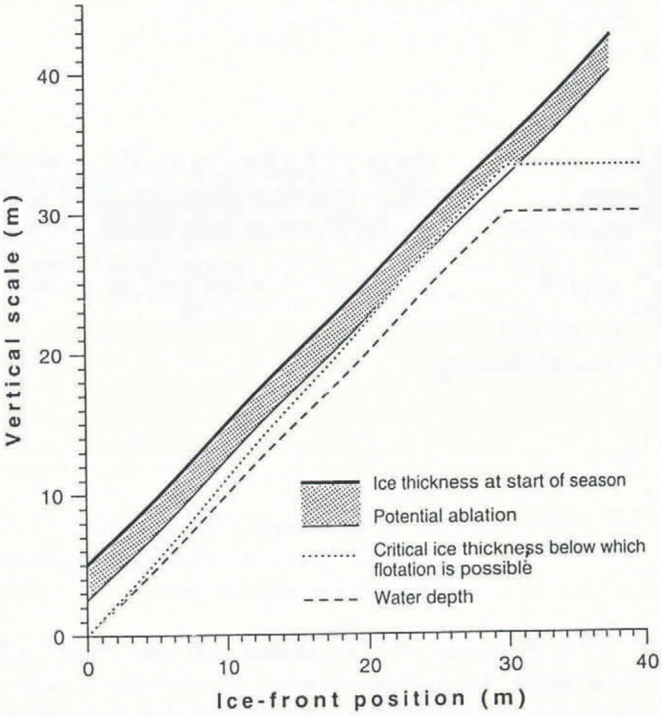

Fig. 2. For different ice-front positions, the graph indicates the thickness of ice at the ice margin in the lowest part of the basin at the start of the ablation season, the maximum lake depth which could be achieved before overspill occurs, the critical thickness to which the ice front would need to be reduced in order for flotation to occur, and (schematically) the amount of thinning that might occur due to seasonal ablation.

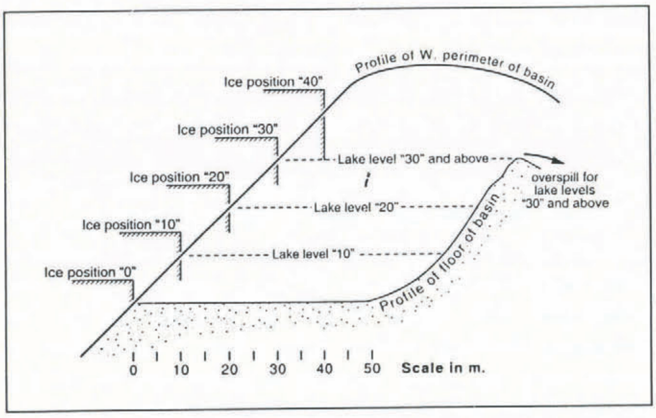

Fig. 1. Schematic cross-section of the lake basin showing various positions of the ice front at the western perimeter of the basin and the lake levels associated with them. For ice positions "0" to "30", the lake level is controlled by overspill at the level of the ice front at the basin perimeter. Beyond position "30", the lake level is limited by overspill at the head of the basin.

Model

We can therefore propose the following model for the evolving drainage habit of this lake, as shown in Figures 1 and 2. The dimensions used in the model are schematic and are not surveyed values for this basin. Assuming that the overall morphology of the ice front remains similar from year to year, as suggested by our observations since 1986, the height of the ice ramp directly above the overspill point at the western edge of the basin remains constant as the ice front migrates up (or down) the hillside. Figure 1 shows that for successively more advanced positions of the snout, the maximum possible lake depth defined by the height of the spillway represents a progressively increasing fraction of the total height of the ice front at the deepest part of the basin. Taking into account that the thickness of the ice decreases as the ablation season progresses (Knight, 1992), Figure 2 shows that for flotation to occur at ice position "10" would require about 3.9 m of ice-surface lowering during the ablation season. At position "20", 2.8 m of lowering would be required; at position "30", 1.7 m and so on. Marked on Figure 2 is a schematic indication of the amount of surface lowering that might be expected during the ablation season. Van de Wal and Russell (personal communication; submitted to *Global and Planetary Change*) provide more detailed ablation measurements appropriate to the site. The figure indicates that flotation is only possible for a limited range of snout positions but that, within all but the last part of that range, the more advanced the glacier the less surface lowering is required before flotation can occur. For progressively more advanced positions, flotation could thus occur progressively earlier in the ablation season. Our previous observations suggest that drainage often occurs by linkage with the glacier-drainage system by mid-July anyway, so that the question of flotation later than that is irrelevant. If we apply our model to the Russell Glacier case, we can argue that the glacier has advanced to a point where surface lowering by ablation to the critical flotation threshold of 111% of the lake depth can occur before the lake drains by linkage to the glacier-drainage network. If the glacier continues to advance, the model predicts that drainage could occur progressively earlier in the year. However, if the glacier advances beyond position "30", the maximum lake depth will be controlled by a different overspill, continued advance will have no effect on lake depth, and the ratio of lake depth to ice thickness will begin to fall, so that the

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drainage by flotation will occur progressively later and, by the time the glacier reaches position "31", flotation will once again be impossible with the amount of ablation shown on the model. Thus, we identify that the likely mechanism of drainage depends on the position of the glacier, and as such may vary through time with fluctuations in the position of the ice. We can postulate that, up to and including 1988, drainage occurred by linkage of the lake with the internal drainage of the glacier as described by Russell (in press) but that in 1990 and 1991 drainage by flotation occurred first, because the lake depth was closer to the critical flotation threshold which was crossed by thinning of the ice due to ablation.

Conclusions

1. The topographically controlled lake depth is variable over time as a function of the changing positon of the ice front on the hillside forming the western margin of the lake basin. As the glacier advances, so the maximum possible lake depth increases. This means that, as the glacier advances or retreats, different drainage mechanisms related to different water depths and water pressures may become relevant.

2. Flotation of the ice dam by a depth of water equivalent to 90% of the thickness of the ice-wall margin of the lake is a possibility for the 1991 drainage. If this mechanism does apply, then the timing of the drainage event depends on the rate of seasonal thinning of the ice over the seal rather than on the increasing depth of the lake, which is topographically limited each season.

3. Depending on the position and height of the spillway between the ice and the hillside, which determines the depth which the lake can reach and the relationship between lake depth and ice thickness, different drainage mechanisms might be feasible in different years, with significant implications for the timing, and the geomorphological and glaciological consequences of the drainage.

Acknowledgements

P.G.K.'s field work in Greenland was funded by an Overseas Field Research Grant from the Royal Society and assisted by D. Knight. A.J.R. made observations in 1990 and 1991 as a participant in the GIMEX expeditions. Research was carried out with the permission of the Danish Polar Centre. The figures were drawn by A. Lawrence at Keele University.

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17 July 1992

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The accuracy of references in the text and in this list is the responsibility of the authors, to whom queries should be addressed.

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Aqueous ethanol as an ice-drilling fluid

Since the publication of our paper on the use of butyl acetate as an ice-drilling fluid (Gosink and others, 1991), we have received numerous inquiries about the use of ethylene glycol and aqueous ethanol which have an appreciable history of glaciological application (e.g. Ueda and Garfield, 1969; Zagorodnov, 1989). This letter expresses our reasons for choosing butyl acetate over aqueous ethanol.

The principal factors we considered were: minor yet chemically significant corrosion to the ice sample and to the drill (leading to contamination of the core), solvent penetration of the ice core, density, viscosity, safety and cost.

Aqueous alcohol can rapidly attack ice if either temperature or concentration equilibrium conditions are not met. Non-equilibrium conditions will lead to partial destruction of the all-important core sample or inordinate production of slush which can jam the hole. Since the internal temperature of the borehole varies with depth (generally colder at the top), the ratio of water to alcohol in deep holes must be monitored and changed with depth. Addition of heat will keep the hole open (e.g. Ueda and Garfield, 1969) but it is potentially destructive of the core for sensitive chemical measurements and, unless heat is maintained throughout the operation, severe slush formation or refreezing will occur (Humphrey and

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