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Self-levelling ice dams: a mechanism for bidirectional icing development

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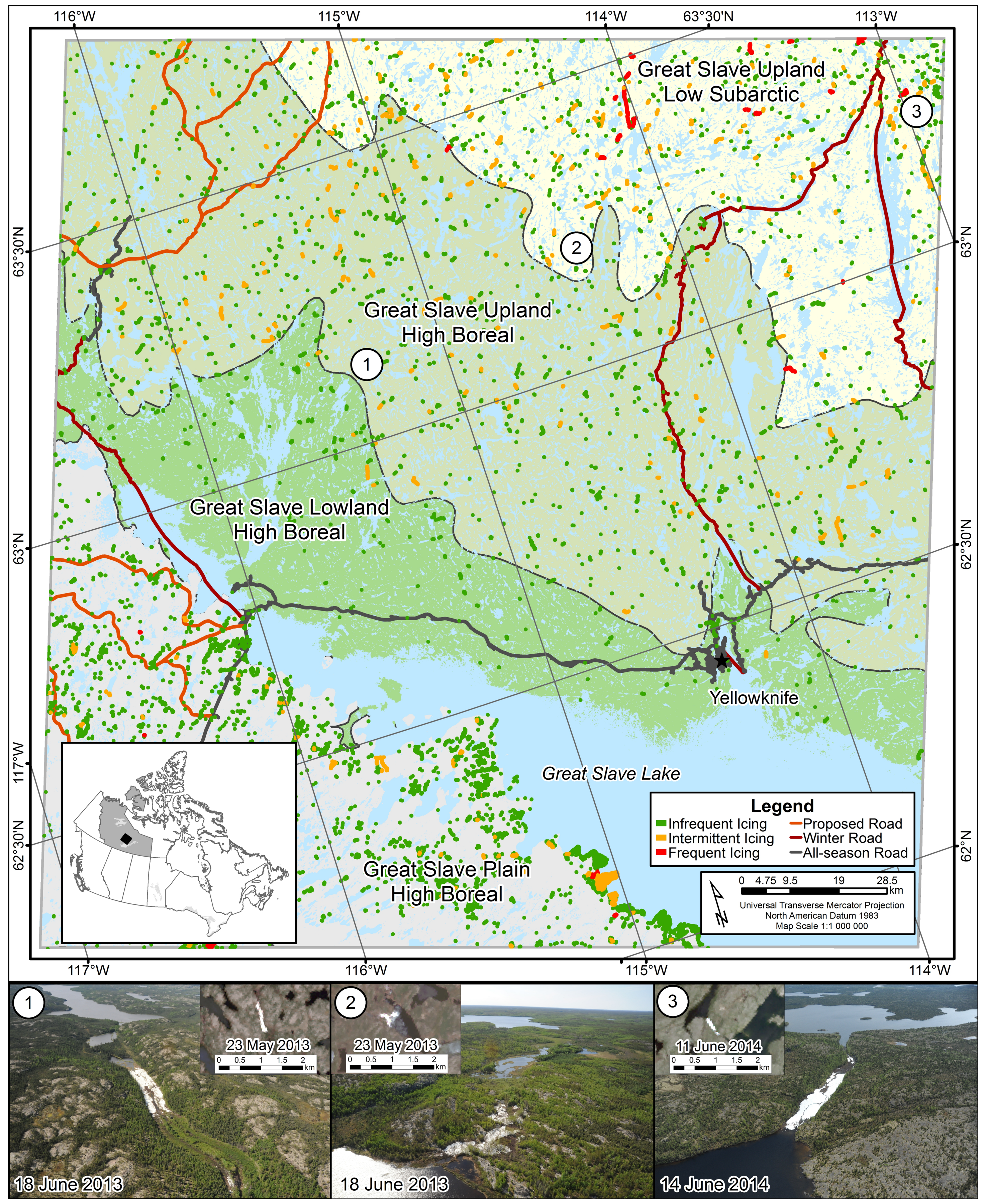

Figure 1. Icing deposits are widespread in the North Slave Region, NT (study area indicated by a black square in the inset map of Canada). Icings have been digitally mapped using Landsat data from 1985 to 2014. The distributions of infrequent (1–6 returns), intermittent (7–18 returns), and frequent (19–24 returns) icings are indicated. The numbered inset examples (locations indicated on the map) show oblique air photos of icings visible in Landsat data. Figure modified from Morse and Wolfe (Figures 1 and 4, 2015).

Problem

Icings are widespread in the northern hemisphere and particularly in the North Slave Region, but processes leading to their seasonal development remain poorly understood (Figure 1). Icing (also known as aufeis, naled, or overflow ice) development occurs in winter where successive overflows of groundwater freeze on the surface, creating a sheet-like mass of ice (Carey 1973; Kane 1981; Figure 2). Their formation affects groundwater discharge, water storage, spring freshet diversion, and winter geohazard development (Figure 3). An icing grows upward as ice-layers accumulate and outward as water flows across the frozen surface. At saline springs, new snow cover facilitates the development of pipes and channels, allowing water to flow several hundred metres from the source (Heldmann et al. 2005). Here we present field observations from the North Slave Region, NT, of water redistribution leading to horizontal and vertical icing expansion related to ice dams that form in the snow cover near the icing.

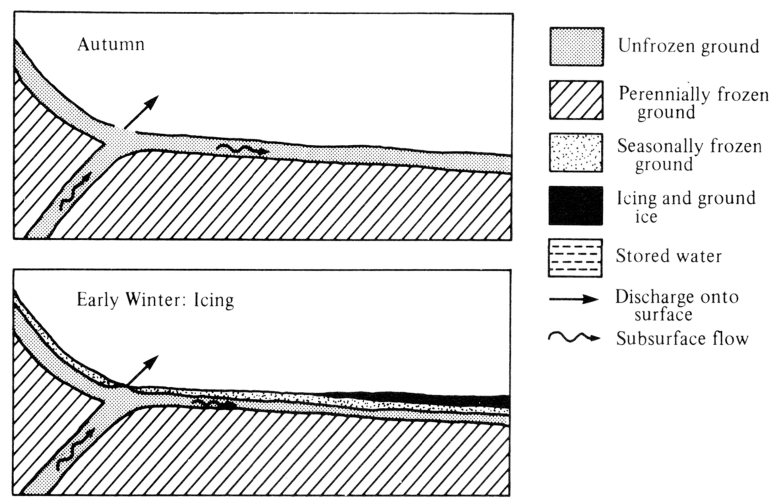

Figure 2. Schematic diagram oriented down-valley of icing development due to groundwater flow restriction as the active layer freezes back (from van Everdingen 1978).

Figure 3. Icing mitigation at a 500 m long section of the Dempster Highway south of Inuvik, NT, 17 March 2018.

North Slave Region

The subarctic North Slave Region, defined by the Slave Geological Province, has gently undulating terrain with local relief of about 10 to 30 m. Till, till veneer, and glacofluvial deposits predominate amongst bedrock outcrops (Kerr and Wilson 2000). Glaciolacustrine and lacustrine sediments are widely distributed throughout the Great Slave Lowland High Boreal (Figure 1), deposited by Glacial Lake McConnell (12,700 to 9,500 cal BP) and the receding ancestral Great Slave Lake (Lemmen et al. 1994). The region is in the extensive discontinuous permafrost zone (Heginbottom et al. 1995), and permafrost occurs beneath peatlands and woodlands on fine-grained sediments (Morse et al. 2016). The climate is subarctic and continental, with long cold winters (-25.6°C January mean temperature), and short warm summers (17.0°C July mean temperature).

Figure 4. Examples of ice dams with horizontal crests observed at the margins of 3 different icings during 2 different winters. Dissolved solids in the source water can colour the ice. Note the distinct break in slope from the ice accumulating on the valley floor to the ice dam created by saturation of the existing snow cover by ground water and subsequent freezing. Photographs in panels from left to right were taken 10 March 2015, 18 February 2014, and 24 February 2014, respectively.

Shield Hydrology

Permafrost extent and geological setting constrain the regional hydrology, which is dominated by surface water and 'fill-and-spill' runoff generation processes (Spence and Woo 2003). There is little snowfall, which generally accumulates from late-September to March. The normal end of season snow cover is 0.37 m thick. About 76% of the 290 mm annual precipitation falls from May to November, with 58% as rain. Since 1997, there has often been a delay in the onset of snow resulting in increased autumn rainfall (Spence et al. 2011, 2014). In years when autumn rainfall is persistent, early-winter runoff events can be greater in magnitude than the spring freshet (Spence et al. 2011). Consequently, regional icing distribution and activity are closely linked to runoff generation, as high autumn rainfall and periods of warm winter (air) temperatures drive overflows and icing development (Morse and Wolfe 2015).

Figure 5. Excavations and probing behind dams during active overflow revealed saturated snow to the level of the crest and a zone of moist snow above the water table. Photos: 24-25 February 2014.

Observations

Ice dams with horizontal crests were observed at multiple valley margins in multiple winters, induced by natural and anthropogenic water flow (Figure 4). During active icing development, we observed saturated snow behind the dam and level with the crest, and moist snow above the crest (Figure 5). Lateral diversion behind the dam apparently allows groundwater redistribution far from the source before overflow occurs (Figure 6). Counterintuitively, ice damming may also facilitate up-slope redistribution of water on valley sides; apparent vertical migration of the dam was indicated at several sites by the ice surface following the contour and vertical profile of the snow pack, closure of overflow points below the crest, flow from points near or at the crest, and parallel horizontal lineations in the ice (Figure 7).

Figure 6. Example of an icing with ground water diverted along the valley margins by ice dams before overflowing onto the valley floor. Note the source outlet is located in the upper left portion of the photograph, but overflow occurs down valley from the source. Overflow from the ice dam to the right is shown in the left panel of Figure 4. Photo: 10 March 2015.

Figure 7. Indicators of apparent up-slope migration of the open-system, self-levelling ice dam: (a) parallel lineations in the ice surface that are perpendicular to the fall-line (lineation are not to be confused with snowmobile tracks visible in the lower portion of the photograph); (b) closure of an earlier overflow point (to the right) and active flow from the dam crest (to the left). Photos: 24 February 2014.

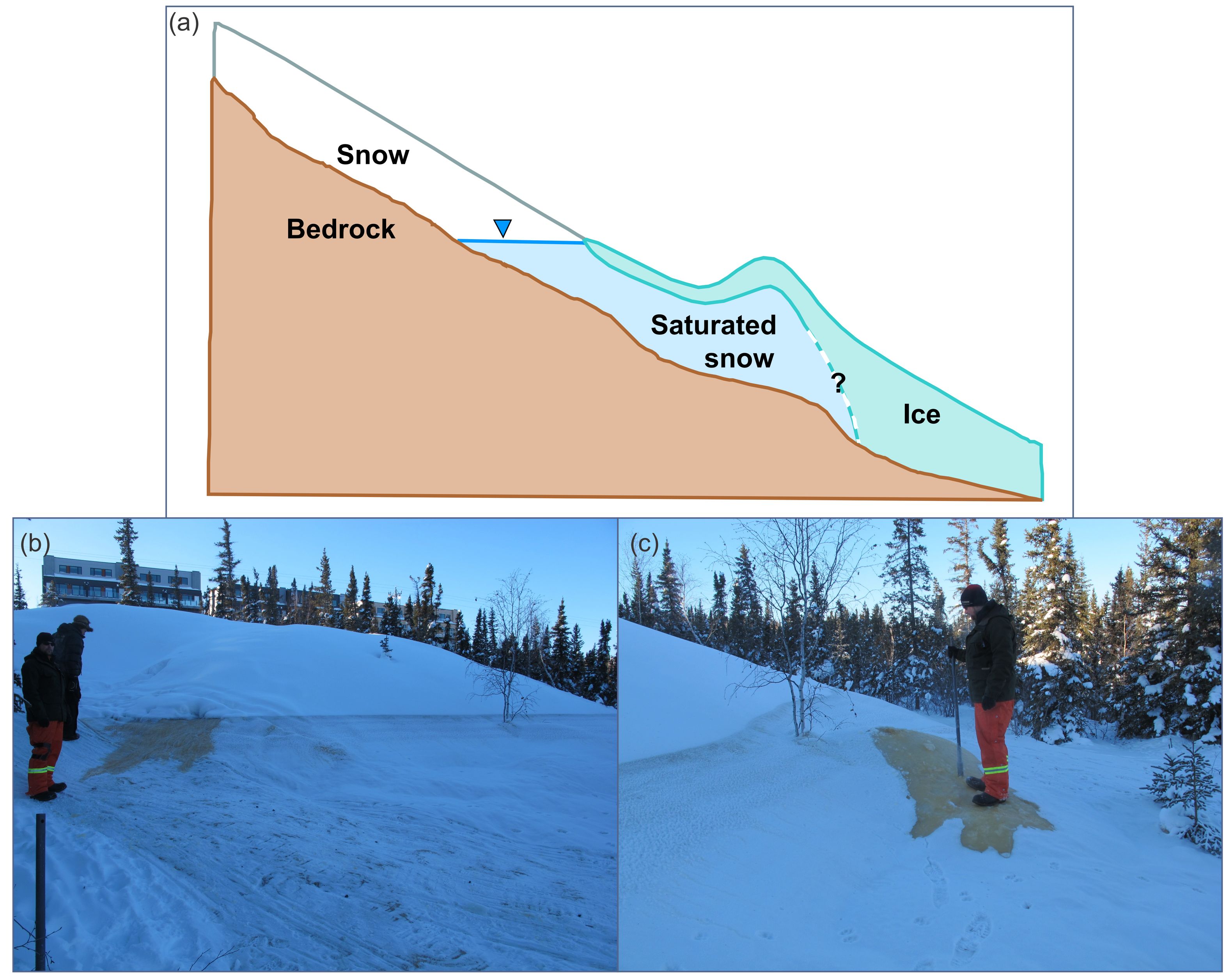

Figure 8. (a) Schematic diagram of an ice dam oriented perpendicular to the fall-line of the slope at the icing margin based on location shown in (b) and (c), and examples of (b) overflow at the crest and (c) at a previously closed overflow point below the crest. A broken water main artificially induced this icing, but features and processes are analogous to natural examples.

Discussion

Based on our observations, we hypothesize that moist snow surface freezes in contact with cold air, increasing the level of the dam's freeboard and thereby raising the hydrostatic potential (Figure 8).). With subsequent water flow into the snow pack, this capillary-rise mechanism likely allows the dam crest to migrate upslope. These observations imply that water can migrate well beyond the spring outlet to grow the icing outward and upward without the need for new snow (Figure 6), a common prerequisite for extensive down-slope icing development from high-Arctic saline springs (Heldmann et al. 2005). The observations also have implications for estimations of icing volume based on remote sensing techniques that frequently assume the maximum icing area and thickness are related (Sokolov 1978). At locations where the ice margin may migrate upslope over time, the thickness of the icing in the valley floor is unrelated to the horizontal extent of ice in plan view and the estimated icing volume would be exaggerated under this assumption.

Conclusions

Observations of ice dams at the margins of icings suggest an apparent upslope migration of a self-levelling dam crest. These dams also allow water to flow through the existing snow pack and become distributed well beyond the source, without the need for new snow on the icing itself. In this region of sparse snowfall, this mechanism allows the icing to develop in horizontal extent while minimizing the absolute thickness of the icing. The mechanism hypothesised herein is likely widespread in the North Slave Region where shield hydrological conditions, which constrain ground water flow, prevail.

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