Subdivision of ice-wedge polygons, western Arctic coast

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ABSTRACT

Ice-wedge polygons are characteristic features of unconsolidated sediments in the continuous permafrost zone. They commonly have a well-defined surface expression in lowland basins, but are also ubiquitous on hill slopes. The polygons are outlined by a network of primary ice wedges, in places subdivided by secondary wedges, and even tertiary features. The evolution of ice-wedge networks was thought to be the result of winter climate variation. Three sets of observations suggest that, instead, the development of secondary and tertiary wedges may be due to growth of the primary ridges and troughs influencing snow depth. (1) J.R. Mackay showed that smaller, secondary wedges may crack more frequently than primary wedges. (2) Hill slope polygons are not characteristically subdivided by secondary ice wedges. (3) Thermal contraction cracks expand over winter, responding to cooling of the ground as the season progresses.

RÉSUMÉ

Les polygones à coins de glace sont communs dans les dépôts meubles de la zone de pergélisol continu. On les distingue aisément dans les basses-terres, où leur contour est bien défini, mais ils sont aussi omniprésents en terrains pentus. Les polygones sont délimités par un réseau de coins de glace primaires, et sont par endroits subdivisés par des coins secondaires ou tertiaires. On a cru que ces subdivisions étaient dues aux variations du climat hivernal, mais trois observations indiquent que les coins secondaires et tertiaires se développent parce que l'accumulation de neige dans les fosses des coins primaires inhibe le craquement de ceux-ci. (1) J.R. Mackay a démontré que les coins secondaires, plus petits, peuvent craquer plus fréquemment que les coins primaires. (2) Les polygones sur les pentes ne sont généralement pas subdivisés par des coins secondaires. (3) Les craques de contraction thermique s'élargissent au cours de l'hiver en réponse au refroidissement progressif du sol.

1 INTRODUCTION

Ice-wedge polygons are one of the most well-known geomorphological features of Arctic environments (Figure 1). They were a key research interest of J.R. Mackay, who published the most comprehensive field assessments of the development of both the polygons and their bounding ice wedges (e.g., Mackay 1974, 1993a, 2000). Ice wedges are amongst the few diagnostic features of permafrost terrain, and, as bodies of near-surface massive ice, may create considerable terrain sensitivity to changes in surface conditions or warming climate (e.g., Hayley 2015). Ice wedges themselves are useful as paleoenvironmental indicators, because truncated ice wedges may indicate the depth of a former active layer (e.g., Mackay 1975, 1978a; Burn et al. 1986; Burn 1997).

Ice-wedge polygons are commonly recognized in lowland settings (Figure 2), the environment in which Leffingwell (1915) developed the theory of ice-wedge origin by thermal contraction cracking. Leffingwell's (1915, 1919) work was the basis for Lachenbruch's (1962) magisterial quantitative model of thermal contraction leading to repeated cracking of the ground and development of the wedges. Ice wedges and their polygons were almost exclusively examined in lowlands until Mackay (1990, 1995) described anti-syngenetic ice wedges on hill slopes.

In lowland basins, the polygons are bounded by a network of primary ice wedges, and in some cases may be subdivided by secondary or tertiary features. At the first International Conference on Permafrost, Dostovalov and Popov (1966) provided a theory for subdivision of polygons that associated higher order wedges, which crack less frequently, with more extreme winter conditions. These authors recognized the ground temperature gradient as a prime factor in developing thermal stress. They stated: "(i)n relatively warm winters the temperature gradients are

Figure 1. Ice-wedge polygons in sedge tussock tundra of the Old Crow Flats, northern Yukon. Primary, secondary, and tertiary ice-wedge troughs are visible. Photo by C.R. Burn, July 2013.

small, and only fissures of low orders are formed; in cold winters (with great relative temperature) minimum temperature gradients are high, and cracking reaches higher orders of fissure generation." Dostovalov and Popov's understanding of thermal contraction cracking was consistent with Lachenbruch's (1962) model. The approach was the basis upon which Plug and Werner (2002) simulated the development of ice-wedge networks by using cellular automata. A fundamental assumption underlying the approach of Dostovolov and Popov (1966) and Plug and Werner (2002) is that changes to surface conditions due to continuing growth of ice wedges do not affect development of the thermal stress field. The purpose of this paper is to examine this assumption in light of the work of J.R. Mackay.

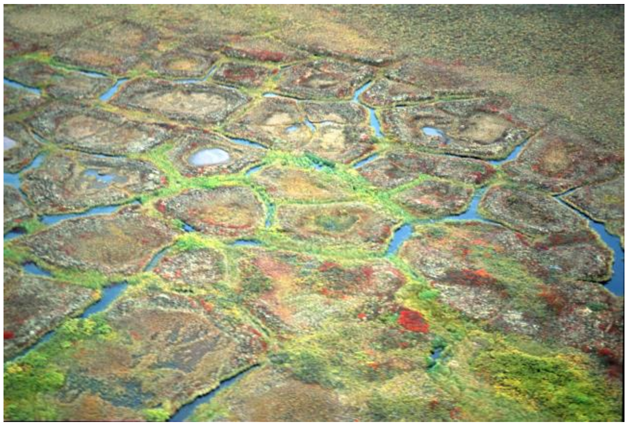

Figure 2. The ice-wedge polygons of site C at Garry Island, N.W.T. (Also known as the "Drinking Lake" site.) Photo by J.R. Mackay.

2 ICE-WEDGE SURFACE EXPRESSION

Ice wedge development leads to a characteristic morphology with ridges on each side of the wedge separated by a trough above the wedge (Burn 2004). "Single-ridge" morphology has been seen, at first inspection, above syngenetic ice wedges of the outer Mackenzie delta area, but upon closer examination, the characteristic morphology was apparent but muted (Morse and Burn 2013). At Garry Island, NWT (Figure 3), where Mackay conducted much of his research on ice wedges, the surface of troughs is characteristically ≤ 1 m below the ridges, and the separation of ridges is about 2 m. These values are characteristic of much of the western Arctic coastlands.

The development of ridges occurs due to displacement of ground by growing ice wedges and outward movement of soil from polygons towards the ice wedges (Mackay 1992, 2000). This is due to the confinement of soil within the polygons during thermal contraction, but accommodation of expansion in the troughs. Freshly growing ice wedges in recently drained lakes have little ridge development, although troughs may be observed after a few years (Figure 4). Growth of the ridges therefore occurs over time as the ice wedges develop.

In tundra regions, snow depth is partly controlled by snow fall, but also by accumulation in vegetation or in the lee of topographic obstacles (Morse et al. 2012). As ice wedges grow and displace soil upwards to form ridges, snow depth in troughs increases, and there is also potential for snow depth within polygons to increase. As a result, winter temperatures within a trough may increase, and the frequency of winter cracking may decline. Mackay (1978b) terminated ice-wedge cracking in a field experiment at Garry Island by erecting snow fences to increase snow depth. Sites unaffected by the experiment did not stop cracking.

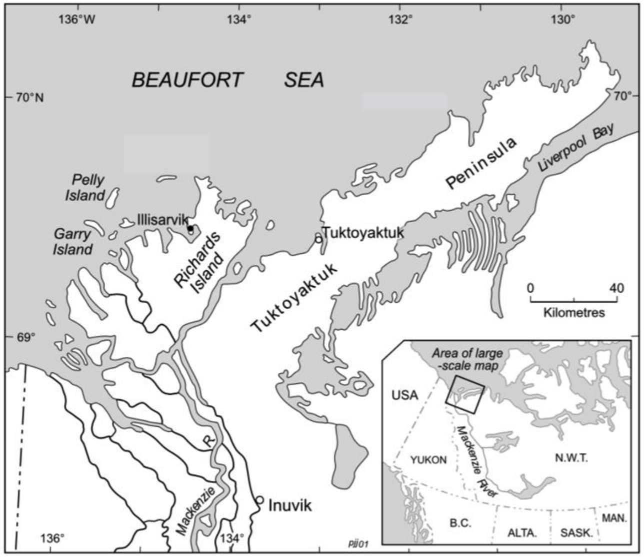

Figure 3. Location of Garry Island and Illisarvik, NWT.

Figure 4. New ice wedge trough at Illisarvik that initially developed between 1980 and 1989. The ice wedge has been rejuvenated by cutting vegetation to reduce snow depth (site 3 of Mackay and Burn, 2002).

Mackay (1992) presented a remarkable set of data on the cracking frequency of ice wedges at Garry Island.

These data were collected over each of 21 years at 32 ice-wedge sections of site C (Figures 2, 5).

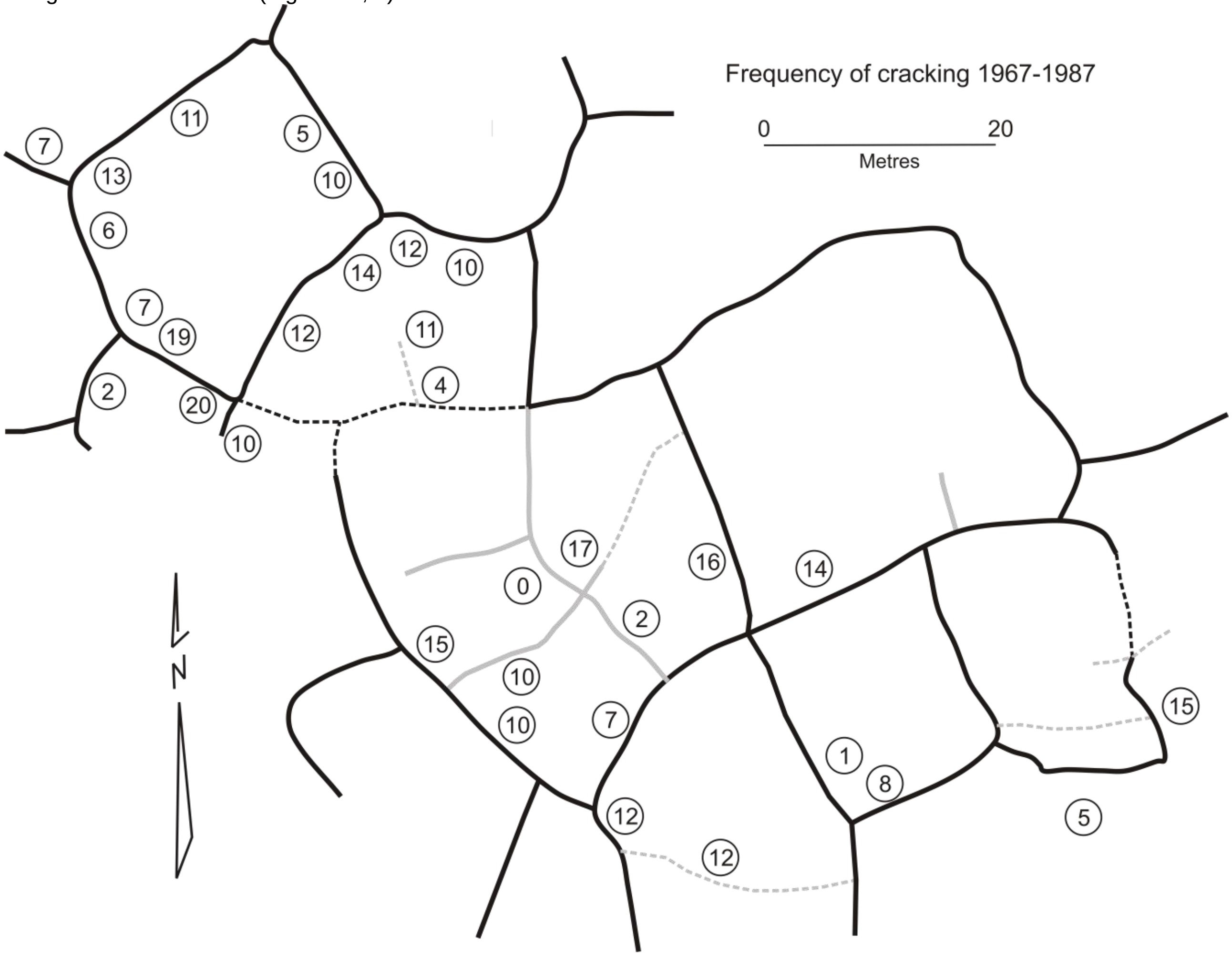

Figure 5. The ice wedge network and crack frequency, 1967-87, at site C, Garry Island (after Mackay 1992, Fig. 6). Secondary wedges are in grey. Troughs obscured by growth of peat are shown with dashed lines.

These ice-wedge sections included both primary and secondary features. The primary wedges ranged in crack frequency from 20 out 21 years to 0 out of 21 years. The secondary wedges showed a similar range in crack frequency, of between 17 and 0 years out of 21. In other words, the secondary wedges cracked as frequently as their primary counterparts. These data do not suggest that secondary cracking only occurs in relatively cold winters, because, if this were so, cracking of secondary ice wedges would be less frequent than of primary ice wedges.

3 OPENING OF CONTRACTION CRACKS

At the western Arctic coast, Mackay (1993a) determined that most thermal contraction cracks open between mid-January and late March. The length, width, and depth of cracks varies between ice wedges that crack in any given year and from year to year (Mackay 1974). The initial cracking event may be sudden, producing a report like that of a rifle (Mackay 1993b), or, alternatively, cracking may be slow. Mackay (1993b) found that, in general, crack propagation at Garry Island was several orders of magnitude slower than the 200 m/s required for an audible report. Nevertheless, the data indicate that once initiated, cracks may grow. Mackay (1993b) reported horizontal propagation, but he had noted earlier that cracks may widen after they open (Mackay 1989, p. 366). We might assume that cracks may also deepen after they have been initiated.

Crack widths and depths have been measured during field visits, but, to our knowledge, sequential measurements of crack depth following initiation have not been presented. Variation in crack width may be inferred with data presented by Allard and Kasper (1998), who reported that electrical cables across ice wedges were strained, but not necessarily broken during two years of measurements at Salluit, QC.

At the Illisarvik experimentally drained lake, we have recently installed several TinyTag shock loggers at the suggestion of H.H. Christiansen. These have been used with a thermistor cable attached to a data logger, to determine the time of ground cracking. The miniature shock loggers are cubic, with sides of approximately 3 cm. They are placed firmly into the active layer in the side of an ice-wedge trough at the end of summer. The accelerometer senses ground shocks and the logger stores them every 20 min. The thermistor cable has been laid across the permafrost table of the same trough, within 2 m of the shock loggers. It has been attached to a HOBO HTEA miniature logger, recording five times each day (every 4 hr 48 min). The ground temperature reading defaults to -37 °C when the thermistor cable breaks, and then remains constant. The shock loggers and thermistor cables have been installed at ice wedge #3 of Mackay and Burn (2002), which has been rejuvenated by annually cutting vegetation and hence reducing the snow cover (Figure 4). The annual thermal contraction crack has been seen in March or April each year. All shock loggers have measured one and only one ground movement in winter, in late January or February. The thermistor cable has broken, but considerably later in winter, commonly in late March. We interpret the delay between ground shock and rupture of the cable as due to expansion of the thermal contraction crack, as the ground continues to cool during winter.

For the purposes of this paper, this interpretation implies that increased thermal stress after initial crack opening may be relieved in extant cracks by their growth, rather than necessarily by opening of new cracks.

4 HILLSLOPE ICE-WEDGE POLYGONS

Ice wedges are widespread on hill slopes near the western Arctic coast (Mackay 1990, 1995). The wedges form polygons, as in lowlands (Mackay 1995). However, the polygons tend to be larger on hillslopes (Figure 6). In a comparative study of upland and lowland ice wedge polygons using aerial photographs from Garry and Richards islands, LeCompte (2004) digitized and measured over 3400 polygons near the northern point of Richards Island and on NW Garry Island. He found that the average size of upland polygons was 796 m^2 (n = 1480) and of lowland polygons 309 m^2 (n = 1998). A histogram of the distribution of upland and lowland polygons is presented in Figure 7.

In part the difference in size is due to the reduced thermal contraction coefficient of mineral materials in comparison with ice. Anderson and Ladanyi (2004, p.53) indicate the coefficient is approximately 5×10^{-5} °C^{-1} for ice, and $\leq 2 \times 10^{-5}$ °C^{-1} for mineral soil materials. Therefore, if the ice content of near-surface permafrost is less on well-drained hillslopes than in wet lowlands, we might expect larger distances between ice wedges. In addition, upland polygons rarely appear to be subdivided, but rather the ice wedge networks are dominated by primary features.

Ice-wedge troughs are discernable on hill slopes, but are difficult to see unless degradation of the ice wedge has occurred. In many cases, the ridges are eroded by slope movement, which may also fill in the troughs. As a result, the ridge-trough-ridge morphology of lowland ice wedges is replaced by a smoother surface on hill slopes.

Figure 6. Lowland and upland ice-wedge polygons at Garry Island. The images are at the same scale. The lowland is site C. X marks the same location in each image.

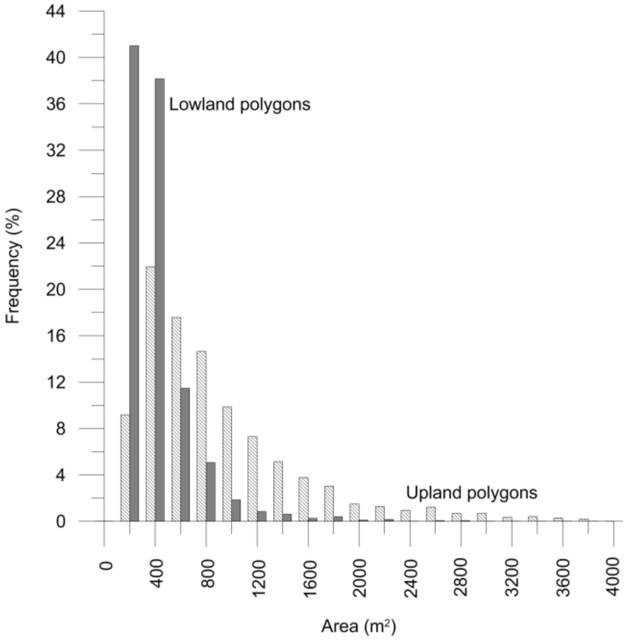

Figure 7. Relative frequency of ice-wedge polygons from a sample of 3478 in uplands and lowlands on the basis of polygon area. After LaCompte (2004, Fig.3.2).

5 ICE-WEDGE DEVELOPMENT AND POLYGON EVOLUTION

Dostovalov and Popov's (1966) account of polygon evolution in response to climate variation may be reconsidered in light of J.R. Mackay's subsequent field observations of thermal contraction cracking and polygon development at Garry Island and Illisarvik. The most important observation is the similar contraction crack frequency distribution for primary and secondary wedges at Garry Island site C (Mackay (1992). In greater detail, Mackay (1992, p. 246) also noted that "(s)econdary wedges in topographically well-defined polygons tend to crack more frequently than those in less well-defined polygons." Given that ice wedges crack in response to thermal stress, we may infer from the last observation that primary ice wedges with well-developed topographic expression experience less thermal stress than those with lower ridges. As a result, the thermal stress within the polygons is relieved by cracking of secondary ice wedges. A physical hypothesis to account for this observation is that the development of ridge-trough-ridge topography at the edges of polygons alters snow accumulation patterns sufficiently to affect the locus of maximum thermal stress. If primary ice wedges do crack, then increasing thermal stress may be relieved by expansion of the cracks rather than initiation of new cracks within a polygon.

The hypothesis accounts for the relatively rare subdivision of polygons on hill slopes, because the primary wedges are not shielded from thermal stress by snow accumulation in troughs. Ridge-trough-ridge morphology is muted on hill slopes, except where ice wedges are degrading and troughs are evident.

The hypothesis implies that while secondary ice wedge initiation may be associated with a very cold winter, it is also likely associated with development of specific conditions restricting cracking of nearby primary ice wedges, so that the additional stress cannot be relieved by crack expansion.

In several papers, Mackay indicated that ice-wedge networks, although conceptually simple and accounted for elegantly by Lachenbruch (1962), are in reality complex systems because of changes in surface conditions brought about by wedge growth (e.g., Mackay 1989, 1992).

6 CONCLUSION

The purpose of this paper was to discuss a theory for development of primary, secondary, and tertiary phases of ice wedge networks that accounted for these phases with reference to climate variation. The position advanced is that evolution of topography associated with ice wedges alters the thermal stress field within a polygon field, mainly by altering snow accumulation patterns. Therefore, secondary or tertiary ice wedges may develop without climate variation.

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