Ice-wedge polygon dynamics in Svalbard: Lessons from a decade of automated multi-sensor monitoring

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Abstract
 Twelve years of continuous monitoring of diverse ground properties reveals the dynamics of three ice wedges and adjacent ground in a low-centered polygon area in Svalbard. The monitoring documented ground displacements, the timing of crack generation, ground thermal and moisture conditions from the surface to the top permafrost, and snow conditions. The focus is on seasonal ground deformation in and around ice-wedge troughs, interannual variability of ice-wedge activity and thermal thresholds for ice-wedge cracking. Seasonal ice-wedge activity is mainly associated with frost heave and thaw settlement, as well as thermal expansion and contraction. In mid- to late winter, temporary expansion and cracking of troughs by thermal contraction occurs during rapid cooling periods. Following intensive ground microcracking events, troughs show rapid expansion and in some cases major cracking in the frozen active layer. A common threshold for cracking is identified by a combination of ground surface cooling below −20°C and a thermal gradient steeper than −10°C m−1 in the upper meter of ground, indicating that cracking requires both a brittle frozen layer and rapid ground cooling. Our results highlight that in marginal thermal conditions for ice-wedge activity, the primary control on ice-wedge cracking is rapid winter cooling enhanced by minimum snow cover.

KEYWORDS
ice wedge, interannual variability, multi-sensor monitoring, permafrost, seasonal deformation, thermal contraction cracking

1 | INTRODUCTION

1.1 | Background: significance of ice-wedge cracking

Thermal contraction cracking in perennially or seasonally frozen ground produces nonsorted polygons underlain by wedge structures filled with ice, soil or their mixture (eg.1,2). These features are among the best indicators of present or past periglacial conditions (eg.3). It is also important to understand their dynamics, as these landforms contain the largest amount of ice in the top permafrost.4 Empirical rules, defined by long-term mean annual air temperature (MAAT) or mean air temperature of the coldest month (MATCM), have typically been applied to inferring paleoclimate conditions from ice-wedge pseudomorphs (eg.5-8). These rules, however, give only rough estimates, because they ignore ground surface conditions (snow and vegetation), and short cold events rather than seasonal conditions may control thermal contraction cracking.9,10 To date, the widely accepted rule is that ice-wedge pseudomorphs indicate the past presence of (probably continuous) permafrost.1 Improving the precision of paleoclimate reconstruction using wedge structures requires more precise
criteria based on the observed dynamics of both seasonal deformation and thermal contraction cracking.4,11 In contrast to the significant number of descriptive stratigraphic and morphological studies, the scarcity of quantitative data defining the environmental conditions causing ground motion and cracking in polygonal terrain has prevented direct validation of climatic indicators controlling ice-wedge dynamics. Only a few theoretical and field-based studies have addressed the dynamics of ice-wedge polygons. Based on a visco-elastic theory of thermal contraction, Lachenbruch12 proposed that the occurrence and geometry of polygonal cracks depended on the coefficient of thermal expansion, thermal conductivity, viscosity and tensile strength of the frozen ground, which are dependent on the ground temperature, cooling rate, soil properties and ice content. Plug and Werner13 numerically modeled the initiation and propagation of fractures in frozen ground, showing the geometric evolution of polygonal networks. Mackay14-18 performed decadal-scale, diversified field observations in both winter and summer in the Canadian Arctic, highlighting the timing and direction of cracking, seasonal and interannual variability of cracking, magnitude and frequency of cracking, and deformation of ice-wedge troughs. Mackay’s observations were mostly based on manual methods requiring seasonal visits to the study sites, except for the timing of cracking automatically controlled by electrical connection of subsurface cables. Later, Fortier and Allard19 performed automated monitoring, detecting the timing of cracking and the temperature profiles at cracking by the breakage of electric cables (thermistors). These observations have provided information on the timing and thresholds for cracking at a few field sites (eg,7). However, to obtain more precise thresholds, comprehensive, long-term observations are needed to document climate and ground conditions concurrently with the three-dimensional deformation of the polygonal patterned ground. Marginal environments for ice-wedge formation (MAAT ca -3°C) suit the evaluation of thresholds, as here the occurrence of cracking is highly sensitive to interannual climatic variations (eg,20) rather than in very cold conditions, where cracking recurs nearly every winter.

1.2 | Key questions

The above review, and that by Christiansen et al.,4 suggest that the following issues need to be solved to understand the dynamic of ice-wedge cracking and thus to use it as a more detailed climatic indicator:

- seasonal movements of polygonal ground (trough-ridge morphology);
- timing, magnitude and frequency of ice-wedge cracking;
- thresholds for ice-wedge cracking;
- controls on interannual variability of cracking.

To address these issues we have conducted a comprehensive field monitoring study of ice-wedge dynamics in a marginal environment for ice-wedge formation (MAAT ca -3°C) using diverse instrumentation and manual techniques.10,21,22 The monitoring campaign started in 2002 and intensified in successive years. This paper focuses on high-resolution ground deformation and thermal contraction cracking of three ice-wedge troughs and associated ridges using 12 years (2005–2017) of data on horizontal and vertical soil movements, cable breaking, acceleration events, air and soil temperatures, soil moisture and snow conditions. The long-term dynamics of polygonal ground, including seasonal deformation, and the spatial variation in cracking activity are under current study, but are beyond the scope of this paper.

2 | THE STUDIED ICE-WEDGE SITE

The ice-wedge research site is located on the outermost part of a large late Holocene alluvial fan23,24 in the Adventdalen valley, central Svalbard (Figure 1a). Adventdalen is a broad U-shaped valley surrounded by flat-top, 800–900 m high mountains composed of sedimentary rocks of Early Permian to Eocene age. The alluvial fan, fed by the tributary Todalen valley, is eroded by the main stream, Adventelva.
forming a 3–6 m high cliff (Figure 1b). The marginal part of the fan is covered with a fine-grained eolian sediment cover 2–3 m thick overlying gravelly loam of fluvial origin. Low-centered polygons dominate the loess-covered area. The ground surface has long-lasting water ponded in deep troughs and polygon centers during snowmelt. The polygons remain wet throughout the summer, although the lowest end of the polygonal field has been subject to recent gully erosion (Figure 1b) (cf). The polygons occur mainly as quadrangles, pentagons and hexagons with an average diameter of about 20 m and three-way junctions (Figure 2). The surface morphology shifts into small polygons (< 3 m in diameter), earth hummocks and mudboils toward the loess-free area higher on the fan.

The low-centered polygons are delimited by well-defined troughs 0.2–1 m wide and 0.1–0.4 m deep, centered between symmetrical ridges (e.g., 18). The large polygons are subdivided in places by secondary or tertiary cracks, with narrower and shallower troughs often lacking ridges. There is a distinct vegetation zonation, with in particular mosses in the wet centers, tall grasses in the troughs and sporadic low grasses on the ridges, in response to the microtopography of the polygons. Drilling and geophysical investigations show that most of the troughs are underlain by ice wedges below the 0.8–1 m deep active layer, and that the width of trough represents the minimum width of the ice wedges (typically 0.5–3 m). The active layer thickness (ca 1 m) is typical of the sediments in the Adventalen valley.20,31

The frozen active layer and top permafrost are rich in segregation ice, having gravimetric water content of about 50% (excess ice content about 15%).25

MAAT was −5.1°C and annual precipitation was 192 mm from 1990 to 2004 at the Longyearbyen Airport meteorological station 10 km northwest of, and at approximately the same elevation as, the monitoring site (data derived from eKlima). There MAAT rose to −2.6°C during the monitoring period (2005–2017).32 Large air temperature fluctuations between 0 and −20°C to −30°C are common in winter, due to the maritime setting with alternating weather systems, with either low-pressures coming from the south or polar high-pressures extending over the polar areas, including Svalbard. The winter condition contrasts with relatively stable positive temperatures (5–8°C) in summer.30 Shallow snow (< 0.4 m) covers the polygons from October to May, but with varying depth from 0–0.1 m over the ridges to 0.3–0.4 m in the troughs and central polygons.10

The thin snow cover, mainly due to persistent wind erosion in the valley location, favors efficient ground cooling throughout winter. Positive temperatures occasionally occur even during midwinter, causing extensive snowmelt and subsequent ground cooling with formation of a thin ice-cover, such as observed from January to February 2010,31 also enhancing subsequent ground cooling.

Annual mean permafrost temperatures from boreholes in the valley (nearby boreholes AS-B-2 and EN-B-1 in the NORPERM database) varied between −3 and −6°C at about 10 m depth during the International Polar Year (IPY) period (2008–2009).31

3 METHODS

3.1 Instrumentation

Three ice-wedge troughs TR1, TR2 and TR3 were monitored (Figure 2). TR1 (set up in September 2004) is a first-order trough, which constitutes major polygons, about 1.5 m wide and 0.3 m deep, centered within a pair of well-developed ridges about 1 m wide and partly lacking vegetation (Figure 3a). Open cracks (0.05–0.1 m wide, 0.2 m deep) extend downward from top of ridges (Figure 3a). Boreholes across the trough show that the active layer thickness (ALT), defined by the top of the ice wedge (TIW), is 0.9–1.0 m in the ridges and 0.7–0.8 m in the trough, and the ice wedge is about 2.5 m wide at the top. TR2 (set up in June 2006) is a third-order narrow and shallow trough (0.7 m wide, 0.1 m deep), lacking well-defined ridges (Figure 3b). Boreholes indicate that ALT is 0.9 m and the width of ice wedge less than 1 m. TR3 (set up in August 2009) is a first-order trough, 2 m long between intersections, 2 m wide and 0.4 m deep.

Figure 2: Geometry of polygons and monitored troughs (TR1–TR3). Legends for the right figure: dotted area = wet ground, dark areas = pond, thick solid line = first-order trough, thin solid line = second- or third-order trough, long broken line = pbscured trough, short broken line = ridge. Some new cracks in the polygon center are also shown with black solid lines [Colour figure can be viewed at wileyonlinelibrary.com]
centered within well-developed ridges (Figures 2 and 3a). TR3 is one of the most active troughs, revealed by mapping of new cracks at the end of every winter. ALT is about 0.8 m deep at the slope between the ridge and trough.

Since September 2002 air temperatures have been monitored 1 m above the ground using a shielded Tinytag miniature data logger. Ground temperatures have been monitored at 4–6 depths for each trough (Figure 4): the detailed settings are described in Supporting Information Appendix S1.

The distribution and duration of the snow cover at the study site are documented daily at noon from around February 1 to around November 1 using an automatic digital time-lapse camera (Harbotronics) installed...
next to the study site. Three graduated (10-cm height intervals) snow poles are included in the photographs, allowing direct reading of daily snow depth on the ridge, in the trough about 10 m from TR1 and in the polygon center north of TR1, respectively (Figure 3c). The camera operated continuously through most winters, but had longer periods missing data in 2016 and 2017 (Figure 5).

The monitoring system for ice-wedge activity (Figures 3 and 4) consists of several sensors and data loggers that provide data on ground motion (horizontal and vertical movements), cracking and associated environmental conditions (air and soil temperatures, and soil moisture). Cracking activity is monitored using a combination of three independent, complementary subsystems: extensometers (expansion and contraction of the ground), accelerometers (intensity and frequency of cracking; hereafter shock loggers) and breaking cables connected to timing devices (timing of major cracking events). The details of the monitoring set-up at each trough are described in Supporting Information Appendix S1. Data were recorded at 1-hour intervals (otherwise noted in Appendix S1) and offloaded every summer or at shorter intervals. Most of the subsurface sensors and angle-iron frames were installed in boreholes 50 mm in diameter, drilled with a motorized hand-held auger and refilled with the same soil or, when antiheaving was required, with fluvial gravel.

The sensor-logger systems at the three sites have provided long-term records continuously for 6–13 years, although malfunction has occasionally interrupted their operation (Figure 5). Because data on soil temperatures in the upper part of permafrost, frost heave and cable breaking for the first year (2004/5) at TR1 were missing due to malfunction, the first year is regarded as a trial period. We only present data from 2005 onwards (ie, for 12 y). Monitoring of both horizontal and vertical movements of the ridge was terminated in August 2011, as deformation of the angle-iron frame installed on the ridge of TR1 prevented further measurements. At TR3 data on cable breaking for the first year (2009/10) are missing due to a faulty electrical connection.

3.2 Thermal parameters

In this paper, the thermal state is reported in terms of the ground surface temperature ($T_s$) represented by the value at 0.02 m depth, the temperature at the top of the permafrost ($T_{TOP}$), the temperature at 1.0 m depth ($T_{100}$), the thermal gradient in the active layer (G$\text{AL}$) calculated from the $T_s$ and $T_{TOP}$ values, and the cooling rate at the surface ($R_{SC}$). When associating $R_{SC}$ with a cracking event, we used an average 3-day rate preceding the event.

The following parameters are derived from data on air and soil temperatures. The annual mean air temperature (AMAT), annual mean ground surface temperature (AMST) and annual mean temperature at the top of the permafrost (AMTTOP) are calculated for hydrological years, here defined by 365 days from August 1. The winter mean values of air temperature (WMAT), winter mean ground surface temperature (WMST) and winter mean temperature at the top of permafrost (WMTTOP) are defined from data for the period from November 1 to April 30. The coldest-day mean values of air temperature (CDAT), coldest-day ground surface temperature (CDST) and coldest-day temperature at the top of permafrost (CDTTOP) are also determined for each winter. Note that the mean annual values (eg, MAAT) representing long-term means are distinguished from the annual mean values (eg, AMAT) indicating values for each year. The ALT is computed by linear interpolation between temperatures at two sensor depths showing temperature close to 0°C, when the temperatures at the two depths (1.0 and 1.5 m at TR1) reach the annual highest values; the uncertainties of the computed ALTs are 0.05–0.1 m.

4 | SEASONAL AND INTERANNUAL DYNAMICS OF TROUGH-RIDGE MORPHOLOGY

4.1 Snow, thermal and hydrological regimes

The daily automatic photographs of the ice-wedge polygon show that, through the observation winters, the ridges had up to 0.1 m, but typically only 0.05 m snow cover, whereas the troughs and polygon centers had up to 0.4 m, in accordance with the microrelief of the low-centered ice-wedge polygon (Figure 3c). Sequential photographs demonstrate how the troughs collect up to 0.3 m of snow.
within a day during storms, while the ridges have only 0.05 cm deep snow, suggesting the significance of wind redistribution in controlling the snow depth distribution in the entire ice-wedge polygon. The polygon centers have snow cover throughout the winter with the maximum depth reached in late winter. The ridges show temporary ice cover in several periods following snow storms. Continuous snow transport in the Adventdalen valley, which parallels the dominant wind direction in winter, minimizes any interannual variation in snow depth.

During the monitoring period from August 1 2005 to July 31 2017 the AMAT fluctuated between −0.9°C in 2015–16 and −4.3°C in 2010–11 (mean = −2.7°C, 1σ = 0.83) (Figure 6a). The winter air temperatures fluctuated more, with WMAT ranging from −5.6 to −12.0°C (mean = −8.1°C, 1σ = 1.81) and CDAT from −17.1 to −26.9°C (mean = −21.3°C, 1σ = 2.77) (Figure 6a). These air temperature indices, on the whole, did not show a clear warming or cooling trend over the 12 years (Figure 6a). When the study period was divided in two, however, the first half showed a slight cooling trend (AMAT ca −0.3°C y⁻¹; WMAT ca −0.9°C y⁻¹), and the second half a slightly warming trend (AMAT ca 0.3°C y⁻¹; WMAT ca 0.5°C y⁻¹).

The annual mean ground temperatures at TR1 were almost stable during the first half period but rose slightly at an average rate of about 0.3°C y⁻¹ during the second half (Figure 6b). AMST ranged from −1.1 to −4.6°C (mean = −3.0°C, 1σ = 1.11), which nearly equaled AMTTOP ranging from −1.7 to −4.5°C (mean = −3.3°C, 1σ = 0.93). In contrast, winter temperatures showed a large interannual variability with a rising trend during the second half period (Figure 6b). WMST and WMTTOP ranged from −5.7 to −11.1°C (mean = −8.8°C, 1σ = 1.96) and −2.8 to −7.6°C (mean = −5.5°C, 1σ = 1.68), respectively. CDST and CDTTOP reached around −20 and −11°C, respectively. The winter ground temperatures (eg, WMTTOP) also remained almost stable during the first half period, but there was a warming trend (0.5°C y⁻¹) during the second half period (Figure 6b).

The interannual variation in winter air temperature generally parallels that in winter ground temperature, but a discrepancy between the two is prominent in two winters (Figure 6). In winter 2008/09 the ground was relatively warm (WMTTOP = −7.6°C, CDTTOP = −10.5°C), although the lowest air temperature in the monitoring period was recorded (WMAT = −10.6°C, CDAT = −26.9°C). In winter 2009/10 the ground temporarily experienced the lowest daily temperature (CDTTOP = −13.2°C, CDST = −23.6°C) despite relatively high air temperature (WMAT = −7.6°C, CDAT = −21.0°C) (Figure 6). The main difference between the two winters was, as shown by the daily photographs, the occurrence of an extensive ice cover on the ridges and polygon centers during much of the winter 2009/10, whereas snow was still trapped in the trough. The ice cover probably promoted efficient ground cooling despite a warm winter, contrasting with winter 2008/9 during which snow extensively covered the polygon.

![FIGURE 6](wileyonlinelibrary.com)  
Summary of thermal regimes and ice-wedge activity in 2005–17. Acronyms: AM = annual mean (for 365 d from August 1), WM = winter mean (from November 1 to April 30), CD = coldest day, AT = air temperature, ST = surface temperature, TTOP = temperature at the top of permafrost [Colour figure can be viewed at wileyonlinelibrary.com]
The ALT in the ridge at TR1 fluctuated between 1.0 and 1.4 m (mean 1.2 m) over the 12-year period. ALT showed a slight increasing trend, but the rate during the second half of the period (ca 0.04 m y⁻¹) was twice that during the first half (ca 0.02 m y⁻¹) (Figure 6c).

The volumetric water content (VWC) of the active layer had a large consistent seasonal variation (Figure 7g). VWC remained low and stable (10%–20%) in all winters when the soil was frozen, whereas the value at 0.2 m depth rose to 50%–60% just after thawing and then gradually decreased to about 30% with significant fluctuation until refreezing: note that values below 30% and above 50% are outside the calibration range (Supporting information Appendix S1). The high moisture content in the initial part of the thawing period is consistent with the presence of wet ground and ponded water in many troughs and polygon centers. The daily photographs show that the thawing period is always initiated with 1–1.5 months of lakes filling the low-centered polygons, occurring in the period from mid-May to mid-July. During some wet summer periods VWC at 0.2 m depth fluctuated in response to rainfall. When compared with meteorological data at Svalbard Airport, rapid VWC increases coincided with rainfall (usually >10 mm d⁻¹), while decreasing VWC occurred during rain-free periods of several weeks, although rain events did not always induce significant wetting. At 0.4 m depth the thaw season VWC values were consistently 40 ± 2% in all summers.

4.2 Ground dynamics at TR1 (first-order ice-wedge crack)

All the automated monitoring results at TR1 had nearly continuous data sets for 12 years (2005–17) (Figure 7). This first-order ice-wedge trough has the longest monitoring record. The vertical extensometer on the ridge recorded annual cycles of seasonal frost heave of 34 ± 8 mm and thaw settlement of 58 ± 2 mm during 5 years (2006–11), with no significant short-term frost heave activity (Figure 7a). The disparity between the amounts of heave and settlement (average 24 mm a⁻¹) probably originates from several factors. Two-thirds is explained by the upheaving of the iron frame despite the antiheaving procedure, as the manually measured exposure of the frame above the ground during the same period was 15 mm a⁻¹ on average. The origin of the remainder (9 mm a⁻¹) is unclear, but it could be attributed to solifluction toward the trough, surface soil loss by wind erosion, or net subsidence of the ridge. Consequently, the actual annual amount of seasonal frost heave is considered around

![FIGURE 7](image-url) Twelve years (2005–17) of ice-wedge dynamics across TR1, including 2D movements of the trough-ridge morphology, cracking activities and ground thermal/hydrological conditions. Thick arrows indicate short-term expansion in mid-winter. Winter months (November–April) are shaded [Colour figure can be viewed at wileyonlinelibrary.com]
50 mm (i.e., 34 + 15 mm). Ground heaving was concentrated in early winter from late September to early November, coinciding with frost penetration to a depth of 0.6 m. Thaw settlement started in late May or early June following snowmelt as ground thawing began, and it almost stopped when the thaw depth reached 0.6 m by the end of July. This indicates that frost heaving is primarily associated with the upper part of the active layer, whereas heaving due to upward freezing from the permafrost table seems less important.

The horizontal extensometers showed contrasting movements between the trough and ridge (Figure 7b, d). The trough shrank in early winter and expanded slightly in early summer, whereas the ridge did the opposite at the same time but with larger movements. The accumulated seasonal movements resulted in year-by-year expansion of the ridge and contraction of the trough, with the former about 50% larger than the latter (Figure 7b, d). In contrast, the trough extended slightly during the second half period (Figure 7d). The reason is unclear, but the rigid angle irons may have resisted further inward tilting.

Combining the horizontal and vertical movements (Figure 7a, b) suggests that the ridge cracks opened during frost heaving in winter (type a in Figure 8) and partially closed during thaw consolidation in summer (type b in Figure 8), showing a feature of a dilation crack. The trough did not respond to thaw settlement of the ridge, probably because its delayed thawing prevented the deformation of the rigid frozen substrate. In mid-August, when much of the active layer had thawed, the trough shrank over a short time, contemporarily with the ridge crack opening by about 20 mm without vertical movement (type c in Figure 8). This opening could be attributed to shrinkage due to desiccation of the topsoil around the ridge crack, although the soil moisture level at 0.2–0.4 m depth was stable during this period (Figure 8).

The trough-ridge morphology was generally stable throughout the winter, but the trough experienced horizontal expansion of about 5 mm in four winters (March 2006, April 2012, February 2015 and April 2017: thick arrows in Figure 7d). This movement, concurrent with efficient ground cooling and accompanied by disconnection of the subsurface wires within the frozen active layer (Figure 7e), is attributed to thermal contraction cracking of the frozen topsoil. Excavation in the following summer confirmed that the wire disconnection occurred near the center of the trough (Figure 9a). The shallower wire at 0.2 m broke in four out of the ten winters, but the deeper one at 0.4 m broke only in two out of the 12 winters. Note that data on the shallower wire were interrupted during winter 2006/07 due to missing connection between the sensor and logger, but the stability of the horizontal extensometers implies the absence of disconnection. In addition, the broken shallow wire was not replaced in summer 2016 because the water-filled trough prevented excavation and reinstallation, which led to missing data in winter 2016/17. The disconnection

![FIGURE 8 Ice-wedge dynamics recorded from mid-May to mid-November 2007 at TR1, including 2D movements of the trough-ridge morphology, cracking activities and ground thermal conditions. Symbols a–c represent types of movements described in the text. Small acceleration events during summer result from human/animal activities, which means the absence of natural acceleration events in this period.](image-url)
of 0.4 m deep wire in early April 2017, however, suggests the generation of a deep fracture.

The shock logger placed in the trough fracture (Figure 4) detected seasonal acceleration events, mainly in late winter associated with thermal contraction (Figure 7). The shock logger at the bottom of the ridge fracture also recorded significant events in late winter, but it rarely responded to seasonal frost heave and thaw settlement as this type of movement does not occur as accelerations (Figures 7c and 8). Both loggers registered sporadic events in midsummer (Figure 8), which mainly represented human or animal activities around the monitoring site. Furthermore, the shock logger in the ridge registered exceptionally continuous events lasting for a month from October 24 2006, which followed the completion of seasonal frost heave and were uncorrelated with any horizontal movements (Figure 7c); the origin is unclear but the logger probably malfunctioned, because such continuous events are not normal for cracking. The detailed processes of thermal contraction cracking in winter is described in Section 5.

4.3 | Ground dynamics at TR2 (third-order ice-wedge crack)

The near-surface temperature at TR2 showed similar seasonal conditions as at TR1, fluctuating between about 10°C in summer and −15 to −20°C in winter (Figure 10d). The sensors at 0.9 m or below never rose above 0°C, indicating that the permafrost table was close to 0.9 m.

The horizontal extensometers showed more complex movements than at TR1 (Figure 10a); they involve three types of

![Visual evidence for cracking in winter 2014/15 confirmed in the following summer.](wileyonlinelibrary.com)

![Nine years (2006–15) of ice-wedge dynamics recorded across TR2, including horizontal movements, cracking activities and ground thermal conditions. Thick arrows indicate short-term expansion in mid-winter. Symbols a–c represent types of movements described in the text. Thick arrows indicate short-term expansion in mid-winter. Winter months (November–April) are shaded.](wileyonlinelibrary.com)
expansion-contraction cycles, despite sometimes lacking either expansion or contraction. First, the trough slightly opened by 2–10 mm at the onset of seasonal freezing (type a in Figure 10a) and closed with seasonal thawing (type b), possibly associated with seasonal frost heave and thaw settlement of the active layer, respectively. The second cycle (type c) comprised opening by up to 10 mm occurring in midsummer and subsequent contraction that started with cooling of the active layer and continued until refreezing. This cycle is likely to reflect thermal expansion and contraction of unfrozen soil.

The third cycle was associated with rapid cooling and subsequent warming in winter 2009/10 and 2011/12 (thick arrows in Figure 10a), probably representing thermal contraction of the frozen active layer and its recovery. In both winters rapid cooling induced 2-mm scale expansion several times. However, it is unclear whether the expansion was accompanied by cracking. In fact, the copper wires did not break in winter 2011/12. Data show that the two wires broke in winter 2009/10 (Figure 10b), when TR1 and TR3 also recorded cracking. However, excavation in June 2010 confirmed the continuity of the two wires across the trough, but the wires broke just outside the logger box (above the ground surface). Accordingly, the wire disconnection is considered to have originated from tension above the ground surface. To date, it is unclear whether the 2-mm scale expansion includes the opening of the crack or originated only from creep of frozen soil.

The shock logger registered many and large acceleration events in winter 2011/12 and 2014/15 (Figure 10c). The former was associated with temporary horizontal expansion, and both synchronized with high cracking activity at the other troughs (Figure 7). These results imply that this ice wedge is active. Due to the uncertainties, however, the activity of TR2 is excluded from further analysis.

4.4 Ground dynamics at TR3 (first-order ice-wedge crack, most frequently cracking)

TR3 experienced soil thermal regimes similar to TR1 and TR2, but the deeper trough favored snow accumulation, leading to slightly slower cooling and smaller ground temperature variation in winter (Figure 11d), as well as delayed snow melting in spring compared to both TR1 and TR2. Active layer temperatures showed a long zero-curtain period lasting for 2–3 months in early winter followed by rapid cooling, indicating release of a large amount of latent heat from the freezing wet ground.

The horizontal movement of the trough also resembled that of TR1 and TR2, on the whole (Figure 11a). It consisted of contraction in early winter (type a), possibly associated with frost heave on the ridges, expansion in early summer (type b), possibly associated with thaw settlement on the ridges, an expansion-contraction cycle in summer (type c) and short-term expansion of a magnitude of 5–10 mm in the late winters of 2009/10, 2012/13, 2014/15 and 2015/16 (thick arrows). The occurrences, however, are subjected to significant interannual variations.

The wire at 0.2 m depth broke in five out of the six winters, but the deeper one at 0.4 m never broke (Figure 11b). Excavation in the following summer confirmed that the upper wire broke near the
center of the trough for all events. These disconnection events generally accompanied significant horizontal expansion in late winters, whereas in two winters (2010/11, 2013/14) they corresponded to much smaller expansion (Figure 11).

The shock logger data support the above observations (Figure 11c). A high magnitude and frequency of acceleration events was concentrated in late winters of 2009/10, 2010/11, 2011/12, 2014/15 and 2015/16. Small and sporadic events were recorded also in the other winters and occasionally in summers. Note that the shock logger was placed in TR3 on August 26 2010, and earlier data derived from a logger placed between TR1 and TR3.

5 | THERMAL CONTRACTION CRACKING EVENTS IN LATE WINTER

The monitoring systems indicated significant cracking activity in at least eight out of the 12 winters. Figure 12 illustrates detailed processes of the late-winter cracking recorded at TR1 and TR3. Significant cracking events were identified by rapid expansion of the trough, the occurrence of wire disconnection across the trough and/or the magnitude and frequency of acceleration events. These cracking events are symbolized as “C” plus year (e.g., C05 represents the cracking event in 2005) and, when an event has multiple phases, subdivided.

![FIGURE 12 Major cracking events in late winter, showing interaction of data from the different sensors. From top to bottom: horizontal expansion of trough, air and soil temperatures (thick lines show $T_s$ and $T_{TOP}$), hourly maximum acceleration (events <0.2 G are removed) and thermal gradient in the active layer [Colour figure can be viewed at wileyonlinelibrary.com]](image-url)
using lower case letters (eg. C12a and C12b). The conditions during these events are summarized in Table 1. For comparison between the monitored troughs, the temperature near the permafrost table is represented by the value at 1.0 m \((T_{100})\) instead of \(T_{TOP}\). At TR1 \(T_{100}\) equals \(T_{TOP}\). At TR3 \(T_{100}\) is given by \((T_{TOP} + T_{120})/2\), where \(T_{TOP}\) is recorded at 0.8 m and \(T_{120}\) is the temperature at 1.2 m.

The amount of thermally induced crack opening in winter was estimated from the difference between the extensometer reading just before the rapid expansion and the maximum width in late winter (Table 1). To derive the opening at the ground surface, the data were corrected with reference to tilting of the frame and upheaval of the frame due to frost heave and settlement (Supporting information Appendix S2). Such estimations and corrections were conducted for the winters accompanied by rapid expansion events.

5.1 | Event C06

Event C06 was observed at TR1 in February–March 2006 (Figure 12a). All three sensors detected signals indicative of thermal contraction cracking within this period. First, the shock logger in the trough recorded acceleration events on February 14–16 and 22–23, during two rapid cooling phases lasting for 5–10 days. These events probably indicate progressive superficial cracking starting when the ground surface had cooled below \(-10^\circ\)C. Next, the upper extensometer 0.4 m above the ground recorded the first, rapid 2 mm expansion of the trough on February 28, when \(T_S\) reached \(-20.9^\circ\)C. \(T_{TOP}\) reached \(-9.8^\circ\)C, \(R_{SC}\) \(1.8^\circ\)C d\(^{-1}\) and a maximum 5 G acceleration event occurred. This initial pulse was followed by gradual expansion and warming. The second, less drastic expansion started on March 17 with recovery of cooling, which continued until the end of March. The upper extensometer recorded total expansion \((W_L)\) of 5.5 mm. The lower extensometer also gradually extended from February 28 and recorded total expansion \((W_L)\) of 3.6 mm. The differential expansion \((W_L - W_U)\) reduced the total expansion (crack opening) at the surface \((W_U)\) to 1.7 mm (cf Supporting information Appendix S2). The shallower copper wire at 0.2 m depth in the trough broke with rapid cooling \((R_{SC} = 2.8^\circ\)C d\(^{-1}\)) to \(-20.1^\circ\)C at the surface and \(-11.0^\circ\)C at 1 m depth on March 18, whereas the deeper one at 0.5 m depth stayed intact throughout the winter. No acceleration was recorded on March 18.

The sudden termination of the cold period on April 1 probably prevented further propagation of the crack into the permafrost. Both extensometers recorded contraction in early April synchronized with warming of the ground, indicating closure of the thermal contraction crack.

This event suggests that a major crack opening took place at the ground surface, probably on February 28. The crack seems to have propagated gradually into the ground with increasing horizontal expansion, as indicated by the disconnection of the upper wire 18 days later. The delayed breakage of the shallower wire and survival of the deeper wire may have reflected the looseness of the wire before expansion and/or the stretching or resistance of the wire against tension (cf14,15). Visual inspection on April 9 2006 supported the occurrence of a new crack on the bottom of the snow-filled monitored trough.

5.2 | Event C10

The 2009/10 winter was unusual among the observed winters, encountering extensive melting of snow cover due to rainfall and formation of a water pool in late January, and subsequent intensive cooling that produced extensive ice cover in February.\(^{20}\) WMST \((-10.0^\circ\)C) in the winter was about the average. However, following an extraordinary warming in mid-January 2010 (air temperature > 0°C for 4 d, \(T_S\) reached \(-1^\circ\)C), the ground surface was cooled below \(-20^\circ\)C \((-23.6^\circ\)C) in February and March, when \(T_{TOP}\) fell below \(-13.2^\circ\)C (lowest during the 10 y). Event C10 was only recorded at TR3 from late February to late March 2010 in a similar manner to event C06 at TR1. Rapid ground cooling started on February 14 \((R_{SC} = 2.1^\circ\)C d\(^{-1}\)) for the first few days but later reduced and produced significant acceleration events probably representing microcracking and subsequently triggered sudden expansion on February 22 when \(T_S\) and \(T_{100}\) reached \(-20.9^\circ\)C and \(-9.5^\circ\)C, respectively, and \(R_{SC}\) was 1.0°C d\(^{-1}\) (Figure 12d, Table 1). Expansion continued until the end of March with two significant pulses during cooling and finally amounted to 7.8 mm without tilting of the iron frame \((I_e = W_L = W_S)\). Disconnection of the copper wire at 0.2 m depth was confirmed by excavation in June 2010, whereas the deeper wire survived. The disconnection may have been associated with the expansion event, but its timing was not resolved by the data. The field visit on February 28 confirmed the extensive occurrence of new cracks on the ice cover.\(^{20}\) Probing of some of the new cracks with a metal stick in this winter also showed that the new cracks reached down to a depth of 1.9 m, well into the permafrost.

5.3 | Event C11

Only the shallower copper wire at TR3 broke on February 16 2011, which was confirmed by excavation in August 2011. The disconnection took place during a cold phase, but cooling was not effective, expansion was small (\(<\) 1 mm) and no ground acceleration was registered. Minor, short-lived contraction could have produced the cracking. When the wire was broken \(T_{100}\) was already low \((-11^\circ\)C) comparable to the cracking condition in the other winters, but \(T_S\) dropped to \(-14.6^\circ\)C and \(R_{SC}\) reached only 0.4°C d\(^{-1}\) (Table 1).

5.4 | Event C12

Event C12 was contemporarily recorded at both TR1 and TR3, involving two steps of distinct, rapid expansion (a, b) at TR3 (Figure 12e), although the earlier step was much less developed at TR1 (Figure 12b). The first step (C12a) recorded at TR3 on February 13 2012 comprised rapid expansion (2.7 mm) of the upper extensometer and smaller expansion (1.2 mm) of the lower one, accompanied by intensive acceleration events but unaccompanied by wire disconnection. The expansion coincided with rapidly falling air temperature to \(-18^\circ\)C but with still high ground temperature (ca. \(-2^\circ\)C), whereas it preceded rapid ground cooling \((R_{SC} = 2.4^\circ\)C d\(^{-1}\)) by a few days (Figure 12e). Local snow trapped in the relatively deep trough may have caused the delayed response of the subsurface thermal probes to cooling in the air and surrounding ground. Between the two steps, all ground cooling phases had acceleration events indicative of microcracking but lacked significant
### TABLE 1  Summary of thermal conditions for winter cracking detected with extensometers and breaking cables at TR1 and TR3

| Trough | Event | Conditions for major expansion | Conditions for wire disconnection | Total crack opening at surface (mm) |
|--------|-------|---------------------------------|-----------------------------------|-----------------------------------|
|        | Date  | $T_S$ (°C)                      | $T_{TOP}$ (°C)                    | $T_{100}$ (°C)                     | $G_{AL}$ (°C m$^{-1}$) | $R_{SC}$ (°C d$^{-1}$) | Date  | $T_S$ (°C) | $T_{TOP}$ (°C) | $T_{100}$ (°C) | $G_{AL}$ (°C m$^{-1}$) | $R_{SC}$ (°C d$^{-1}$) |                     |
| TR1    |       |                                 |                                   |                                  |                             |                         |       |             |               |               |                             |                         |                     |
|        | C06   | Feb 28 2006 -20.9               | -9.8                              | -9.8                             | -11.3                        | 1.8                      | Mar 18 2006 | -20.1        | -11.0          | -11.0          | -9.3                        | 2.8                      | 1.7                  |
|        | C12b  | Apr 4 2012 -15.3               | -8.5                              | -8.5                             | -6.9                         | 2.1                      | Mar 31 2012 | -12.2        | -6.7           | -6.7           | -5.6                        | 1.8                      | 5.8                  |
|        | C15a  | Jan 30 2015 -18.0              | -6.8                              | -6.8                             | -11.5                        | 1.7                      | Feb 9 2015  | -18.1        | -9.3           | -9.3           | -9.1                        | 2.1                      | 6.5$^a$              |
|        | C15b  | Feb 23 2015 -21.8              | -11.4                             | -11.4                            | -10.6                        | 2.6                      | Feb 24 2015 | -21.1        | -11.8          | -11.8          | -9.4                        | 2.6                      |                     |
|        | C17   | Mar 29 2017 -15.5              | -7.9                              | -7.9                             | -7.8                         | 2.1                      | Apr 2 2017  | -16.4        | -10.0          | -10.0          | -6.5                        | 0.8                      | 6.8                  |
| TR3    |       |                                 |                                   |                                  |                             |                         |       |             |               |               |                             |                         |                     |
|        | C10   | Feb 22 2010 -20.9              | -10.6                             | -9.5                             | -11.6                        | 1.0                      | Broken, but date unknown |               |               |                             |                         | 7.8                  |
|        | C11   | Only minor extension           |                                   |                                  |                             |                         | Feb 16 2011 | -14.6        | -10.9          | -10.5          | -4.2                        | 0.4                      |                     |
|        | C12a  | Feb 13 2012 -1.7               | -2.7                              | -2.8                             | 1.1                         | 0.5                      | No event     |               |               |                             |                         |                     |
|        | C12b  | Apr 4 2012 -13.7              | -7.8                              | -7.3                             | -6.5                        | 0.6                      | Apr 7 2012  | -14.8        | -8.7           | -8.1           | -6.8                        | 0.4                      |                     |
|        | C14   | Only minor extension           |                                   |                                  |                             |                         | Mar 19 2014 | nd           | -5.5           | -5.3           | -5.3                        | nd                      | -                     |
|        | C15a  | Jan 31 2015 -13.4              | -5.9                              | -5.3                             | -8.3                        | 1.5                      | Feb 10 2015 | -14.2        | nd             | nd             | nd                          | nd                      | 9.6$^{ab}$            |
|        | C15b  | Feb 22 2015 -15.1              | nd                                | nd                               | nd                           | 1.5                      | No event     |               |               |                             |                         |                     |
|        | C16   | Mar 18 2016 nd                 | -4.8                              | -4.7                             | nd                          | nd                      | Mar 20 2016 | nd           | -5.3           | -5.1           | nd                          | nd                      | 4.2$^b$               |

$^a$Sum of two events.

$^b$Sum of two events, and representing only the lower extensometer.

*Abbreviations: $T_S$ = ground surface temperature (at 0.02 m depth), $T_{TOP}$ = temperature at top of permafrost, $T_{100}$ = temperature at 100 cm depth; $G_{AL}$ = thermal gradient in frozen active layer (negative values indicate upward cooling), $R_{SC}$ = cooling rate at the ground surface (determined by linear regression of $T_S$ values for 3 days before the event); nd = no data.*
expansion. The second step (C12b) occurred at both troughs from late March to early April 2012. At TR1, ground cooling from March 28 first caused acceleration events that intensified progressively, and on April 4 triggered a rapid expansion of about 3 mm, followed by an additional gradual expansion of 2 mm, as recorded by both extensometers. The rapid expansion occurred when $T_S$ reached $-15.3^\circ C$, $T_{100} = 8.5^\circ C$, and $R_{SC} = 2.1^\circ C$ $d^{-1}$, concurrently with maximum acceleration events of 5 G recorded both on April 1 and 5 (Figure 12b, Table 1). The copper wire at 0.2 m depth broke already on March 31, before the rapid expansion. Event C12b progressed similarly at TR3, apart from a delayed start of 1 d, more energetic acceleration events and later wire breakage on April 7: rapid expansion started when $T_S$, $T_{100}$ and $R_{SC}$ reached $-13.7^\circ C$, $-7.3^\circ C$ and $0.6^\circ C$ $d^{-1}$, respectively, and cracking occurred when these values were $-14.8^\circ C$, $-8.1^\circ C$ and $0.4^\circ C$ $d^{-1}$, respectively (Table 1). The total expansion at the surface ($W_S$) including the two steps reached 5.8 mm at TR1 and 6.0 mm at TR3.

5.5 | Event C14

The 2013/14 winter was relatively mild (WMST = $-6.4^\circ C$) and lacked very cold periods. $T_S$ fell below $-10^\circ C$ only briefly for short periods in early January (minimum $-11.5^\circ C$) and in April. $T_{TOP}$ reached only $-7.1^\circ C$. During the winter, TR3 experienced wire disconnection on March 19 2014 at 0.2 m depth (Event C14), despite minor cooling ($R_{SC} = 0.3^\circ C$ $d^{-1}$) and insignificant expansion (Table 1). The disconnection was confirmed by excavation in August 2014. The shock logger recorded a single acceleration event on March 17, which could be the precursor of the disconnection, but otherwise no event in March. Whether thermal contraction or another mechanism induced this event is unclear.

5.6 | Event C15

Both TR1 and TR3 were active during winter 2014/15. TR1 registered two rapid expansion events (ca 2 and 1 mm, respectively) on January 30–31 (C15a) and February 23–24 2015 (C15b) and one gentle event in between (Figure 12c). The total expansion at the surface ($W_S$) was 6.5 mm. The two rapid events coincided with rapid cooling ($R_{SC} = 1.7$ and $2.6^\circ C$ $d^{-1}$, respectively) lasting for 7–10 days. Event C15a occurred when $T_S$ and $T_{100}$ reached $-18$ and $-6.8^\circ C$, respectively, and C15b corresponded to $T_S = -21.8^\circ C$ and $T_{100} = -11.4^\circ C$ (Table 1). The breakage at 0.2 m depth was also associated with rapid cooling ($R_{SC} = 2.1^\circ C$ $d^{-1}$) but unaccompanied by expansion, whereas breakage at 0.4 m depth lagged 1 d behind the second expansion. Excavation in August 2015 confirmed the disconnections of both wires. The shallower loop (at 0.2 m depth) broke at two locations where the new crack crossed the wire. In contrast, the deeper loop (at 0.4 m depth) broke at only one of such locations (Figure 9a), indicating that the copper wire escaped crack opening at an intersection. Medium-scale (ca 2 G) ground acceleration accompanied most of the rapid cooling, expansion and breaking events in this period (Figure 12c).

TR3 also registered Event C15a (ca 3 mm of expansion) on January 31 2015, followed by a few gentler expansions in February (Figure 12f). Total expansion, represented by $W_L$ because of the malfunction of the upper extensometer, amounted to 9.6 mm. These expansion pulses corresponded to rapid ground cooling. Event C15a occurred when $T_S$ reached $-13.4^\circ C$ and $R_{SC} = 1.5^\circ C$ $d^{-1}$ (Table 1; $T_{100}$ not available). The copper wire at 0.2 m depth broke on February 10, when the ground surface was cooling to $-14.2^\circ C$ at a rate of $1.0^\circ C$ $d^{-1}$ and the trough experienced gentle expansion. Also here medium-scale (ca 2 G) ground acceleration accompanied most of the rapid cooling, expansion and breaking events in this period, with one maximum (5 G) acceleration signal already reached on January 29 (Figure 12f). The pattern of ground acceleration was very similar between TR1 and TR3 during this event. The crack was still visible at the surface in midsummer (Figure 9b).

5.7 | Event C16

Despite winter 2015/16 being the warmest winter during the 12 year study period (WMAT = $-5.6^\circ C$, WMST = $-5.7^\circ C$) TR3 experienced wire disconnection at 0.2 m depth on March 20 2016, following up to 3 G acceleration events during March 16–18 and rapid cooling (shown at 0.2 m or deeper soil) accompanied by gentle expansion from March 18. $T_S$ values were missing, but available data showed that both expansion and disconnection occurred when $T_{100}$ decreased to about $-5^\circ C$ (Table 1).

5.8 | Event C17

The 2016/17 winter was the second warmest during the study period (WMAT = $-7.6^\circ C$, WMST = $-5.9^\circ C$). TR3 lost data due to submergence of the logger during snowmelt. TR1 showed significant cracking. A small expansion began on February 14 with up to 2 G acceleration events. This was followed by a rapid and large expansion ($W_S = 6.8$ mm) with large acceleration events (max 4 G) from March 28 when $T_S$, $T_{100}$ and $R_{SC}$ reached $-15.9^\circ C$, $-7.9^\circ C$ and $2.1^\circ C$ $d^{-1}$, respectively. The wire at 0.4 m depth broke on April 2 when $T_S$, $T_{100}$ and $R_{SC}$ reached $-16.4^\circ C$, $-10.0^\circ C$ and $0.8^\circ C$ $d^{-1}$, respectively (Table 1). The large expansion and disconnection of the deeper wire imply also a major cracking event in this last winter of the 12 year study period.

6 | DISCUSSION

6.1 | Seasonal deformation of ice-wedge polygon margins

The combination of instrumental data acquired at TR1 suggests an annual cycle of ice-wedge polygon dynamics mainly driven by three mechanisms (Figure 13): (1) frost heave and thaw settlement, (2) thermal expansion of the thawed layer in summer and (3) thermal contraction of the frozen layer in winter.

The seasonal frost heave and thaw settlement of the ice-wedge ridges has not been documented in earlier ice-wedge polygon studies. The two-dimensional movements of the order of several centimeters tracked by the vertical and horizontal extensometers (Figure 7a, b, d) reflect frost heave activity in the ridges along ice-wedge troughs. The crack on the ridge opens during frost heaving in October (Figure 13: first phase), and closes in early summer (Figure 13: third phase). The
resulting expansion of the ridges causes the trough to shrink slightly in early winter. In contrast, closing of the ridge crack in early summer is rarely associated with trough expansion (Figure 8), probably because the still-frozen substrate resists the tensile force. Ground acceleration events are lacking during seasonal frost heave and thaw settlement (Figure 8), indicating that opening and closing of the ridge crack are not accompanied by distinct cracking activity.

The termination of thaw settlement is followed by thermal expansion of the thawed layer in August, which leads to temporary opening of the ridge crack counteracted by contraction of the trough (Figure 13: fourth phase). Corresponding to the highest near-surface temperatures in the ridges, this movement appears to locally originate from thermal expansion of the ridges and may occur as a part of the entire polygon expansion from the center toward the trough18 (Figure 13: fourth phase). Solifluction from the adjacent ridges may enhance contraction of the trough where thaw settlement occurs in late summer. The contrasting movements between the ridge and trough indicate that the seasonal soil deformation within the active layer below a pair of ridges basically constrains the deformation of the intervening trough.

The thermal contraction of the frozen layer, which promotes ice-wedge growth, occurs when well-cooled (ie, rigid) frozen ground is subject to further rapid cooling in mid- to late winter. A series of cracking activities in troughs begin with superficial microcracking detected by small-scale ground acceleration, which is unaccompanied by soil deformation detectable with extensometers nor major cracking indicated by cable disconnection. Progressive cooling increases horizontal tensile stress, which eventually produces rapid expansion of the trough that probably indicates opening of a crack a few millimeters in width.

Thermal contraction cracking can propagate in two ways: downwards from the ground surface and upwards from the top of the ice wedge.12,15 Cracking starts at the ground surface where a maximum tensile stress is exerted and propagates downwards if the preceding crack in the active layer has not been reset during summer, whereas it may begin at the top of the ice wedge with a minimum tensile strength and propagates upwards if the preceding crack has been reset.12,15 At our study site, cracks are still visible in summer. In addition, the shallower wire is more frequently broken than the deeper one and, when both wires are broken, the shallower one breaks earlier. These situations suggest the predominance of downward crack propagation.

The depth of the thermal contraction crack is uncertain, because copper wires can only detect the first significant crack. This first crack may be deep enough to propagate into the permafrost in some cases, or the subsequent cooling phases may allow the crack to propagate down into the frozen active layer and possibly into the permafrost, as suggested by the occurrences of multiple expansion events.

**FIGURE 13** Seasonal dynamics of trough-ridge margins of ice-wedge polygons, based on the 12-year monitoring study in Adventdalen. Phases 1, 3 and 4 correspond to the types of movements a, b and c in Figures 8, 10 and 11, respectively. Note: arrows do not represent the magnitude of movement or cracking, but just indicate the direction of major movement; ridge height and crack width (in particular, trough in the second phase) are exaggerated; the overall displacements within polygons in the second and fourth phases are consistent with Mackay's observation in the Canadian Arctic18 [Colour figure can be viewed at wileyonlinelibrary.com]
where cooling rate: at a given depth that asymptotically approaches a value for a constant law, Lachenbruch12 (1962) derived the horizontal thermal stress

Assuming that the creep behavior of frozen soil follows Glen’s flow and contraction, elastic deformation and viscous relaxation.12,34

elastic model in which the total strain comprises thermal expansion

The thermal behavior of frozen ground has been described by a viscoelastic model in which the total strain comprises thermal expansion

6.2 | Thresholds for cracking

The thermal behavior of frozen ground has been described by a viscoelastic model in which the total strain comprises thermal expansion and contraction, elastic deformation and viscous relaxation.12,34 Assuming that the creep behavior of frozen soil follows Glen’s flow law, Lachenbruch12 (1962) derived the horizontal thermal stress \( \sigma_H \) at a given depth that asymptotically approaches a value for a constant cooling rate:

\[
\sigma_H = 3 \left( \alpha R_C / B \right)^{1/3}
\]

where \( \alpha \) is the coefficient of linear thermal expansion, \( R_C \) is the cooling rate and \( B \) is a creep parameter (inversely related to viscosity) indicative of deformability of frozen soil. The parameter \( B \) is primarily temperature-dependent, increasing with rising temperature toward 0°C.35 This equation indicates that, for a given soil type and ice content, the tensile stress at a given depth increases with decreasing temperature and increasing cooling rate. The model is in general agreement with observations from northern Alaska12, Svalbard36 and Martian high latitudes,34 and is supported by our field observations showing that colder (more brittle) frozen ground subject to more rapid cooling favors thermal contraction cracking.

Consequently, based on frozen ground rheology, the threshold for thermal contraction cracking can be expressed in terms of two basic parameters, \( T_{TOP} \) (or \( T_{100} \)) and the thermal gradient of the frozen active layer (\( G_{AL} \)). We mainly use average values of \( G_{AL} \) in the whole active layer instead of the cooling rate, because the latter is variable on both temporal and spatial (depth) scales and thus difficult to define the representative values. The significance of the two parameters is supported by our results as the timing of effective cracking (indicated by rapid expansion and/or wire disconnection) generally corresponds to lowering of both \( T_{TOP} \) and \( G_{AL} \) (Figure 12, Table 1). The minimum condition for cracking at TR1 is approximately given by a combination of \( T_{100} < -8^\circ C \) and \( G_{AL} < -8^\circ C \) m\(^{-1}\). The threshold at TR3, albeit derived from fewer data, appears to be slightly milder \( (T_{100} < -5^\circ C \) and \( G_{AL} < -7^\circ C \) m\(^{-1}\)) with exceptionally modest values for the C12a event \( (T_{100} = -2.8^\circ C \) and \( G_{AL} = 1.1^\circ C \) m\(^{-1}\)), but this probably reflects the deeper trough (and deeper snow) at the locations of the thermal probes. The marginal values around the threshold, however, may represent shallow cracking confined within the frozen active layer. For intensive (and deep) cracking reaching the ice wedge (eg, C17), we identify a slightly lower threshold given by a combination of \( T_{100} < -10^\circ C \) and \( G_{AL} < -10^\circ C \) m\(^{-1}\). In terms of surface temperature, this threshold for effective ice-wedge cracking is rewritten as \( T_S < -20^\circ C \) and \( G_{AL} < -10^\circ C \) m\(^{-1}\), which is applicable to regions with different ALT and regardless of \( T_{TOP} \) (Figure 14). In terms of the cooling rate at the ground surface, effective cracking mostly occurs when \( R_{SC} > 1.5^\circ C \) d\(^{-1}\), although the copper wires often break at lower values (Table 1).

The threshold applies to fine-grained soils where the buffer layers (snow/vegetation) at the surface have little impact on the ground thermal regime, because a snow cover thicker than 0.4–0.6 m significantly prevents ground cooling.37,38 Observations in colder permafrost areas in the Canadian Arctic suggest similar thresholds to ours obtained for Svalbard, showing that the mean annual thermal conditions do not play a decisive role. Mackay36 proposed \( G_{AL} < -10^\circ C \) m\(^{-1}\) for initiating cracking. Fortier and Allard22 found that subsurface electric cables across ice-wedge troughs break when \( G_{AL} = -4 \) to \(-19^\circ C \) m\(^{-1}\) (mean \(-11^\circ C \) m\(^{-1}\)) and \( T_{TOP} < -13 \) to \(-24^\circ C \) (mean \(-19^\circ C \)) at 0.4 m depth: the latter threshold (mean value) is equivalent to \( T_{100} < -11.5^\circ C \). Because of much colder winters, these Canadian Arctic sites experience earlier cracking15 and longer and wider expansion39 than the Adventdalen sites. Kokelj et al.20 used thresholds for organic soils of \( T_S < -15^\circ C \) and average 5-day cooling rates at the surface before cracking \( >0.5^\circ C \) d\(^{-1}\). Slight differences between the proposed values may reflect varying soil compositions (eg, between organic and mineral, and between gravelly and fine-grained). The threshold proposed here is also applicable to the reconstruction of past climate using ice-wedge pseudomorphs in fine-grained soils, where the ground is considered to have had minimum snow or vegetation covers. To define more precise and universal criteria for ice-wedge cracking, however, requires long-term monitoring in various permafrost and substrate conditions.

6.3 | Interannual variability of ice-wedge dynamics

The 12-year monitoring allows us to assess interannual variability of ice-wedge dynamics and its deviation from the long-term trend. This distinction is crucial for marginal ice-wedge environments like the Svalbard study site, where ice wedges may cease to crack as the climate warms, thereby impairing the microrelief and hydrology.
Intensive ice-wedge activity does not necessarily reflect low average air or ground temperatures on both the annual and the winter time scales, but rather indicates the significance of cold winter spells causing rapid ground cooling, such as in the winters of 2005/6, 2009/10, 2014/15 and 2016/17 (Figure 6b). Intensive activity occurs even in winters with relatively high average air temperatures, such as in 2009/10, 2011/12 and 2016/17. This is because a short cold phase with a minimum snow cover can induce rapid cooling in an already well-cooled frozen active layer even within a warm winter, triggering opening of wide and deep cracks. This situation is further intensified when rainfall turns a shallow snow cover into an ice cover (e.g., C10 event), allowing more effective ground cooling. In addition, the warming trend in the second half of the monitoring period has not yet effectively degraded cracking activity, supported by short, but rapid cooling events recurring almost every winter.

In summary, climatic conditions at the monitoring site with generally shallow snow, thin vegetation cover and large thermal fluctuations in winter favor intensive ice-wedge cracking despite marginal thermal condition. Cracking occurs even in a period with relatively high seasonal air and ground temperatures, although the frequency of cracking may be decreasing. Our study suggests that ice-wedge pseudomorphs indicate former permafrost with little or no snow and vegetation that experienced severe winter cold spells. Contrary to common belief, they provide little information about former mean annual air/ground temperature.

7 | CONCLUSIONS

The long-term, multi-method monitoring of ice-wedge activity in Svalbard leads to the following conclusions.

1. The dominant processes driving near-surface seasonal ground motion at the perimeter of ice-wedge polygons are frost heave, thaw settlement, and thermal expansion and contraction.

2. Rapid cooling events during mid- to late winter often triggered temporary expansion and cracking of the troughs by thermal contraction of the surrounding permafrost, indicated by ground acceleration events, followed by rapid trough expansion and in some cases cracking in the frozen active layer. Thermal contraction cracking occurred in at least eight out of the 12 winters, although the occurrences were spatially variable.

3. A common threshold for cracking extending into the permafrost is a combination of ground surface cooling below -20°C and a thermal gradient steeper than -10°C m⁻¹ within the top 1 m of the frozen ground, as well as a cooling rate at the surface larger than 1.5°C d⁻¹, indicating that cracking is intensified by both a brittle frozen layer and rapid cooling. The results apply to fine-grained soils with minimum surface offsets produced by buffer layers (snow/vegetation). More precise and universal criteria for ice-wedge cracking would require long-term monitoring in various permafrost areas differing in snow and substrate conditions.

4. Short cold spells lasting for 5–10 days in midwinter can induce effective ice-wedge cracking even in overall warm winters, supporting ice-wedge activity in a marginal thermal area and under a warming climate.

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SUPPORTING INFORMATION
Additional supporting information may be found online in the Supporting Information section at the end of the article.

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