The thermo-mechanical behavior of frost-cracks over ice wedges: new data from extensometer measurements.

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ABSTRACT
Specially adapted extensometers were deployed across eight frost cracks over ice wedges on Bylot Island in order to measure the timing of cracking and width variations of the open cracks over the winter. The cracking-contraction-expansion data were correlated with atmospheric and ground thermal temperature data acquired by automated meteorological stations and thermistor cables. Analysis of the data shows that narrow, sub-millimeter-size cracks first open abruptly early in winter when the active layer is frozen back. The cracks abruptly expand later when permafrost temperature falls below -10 °C. They keep enlarging over the winter, reaching widths between 6.8 and 18.2 mm by the end of March when permafrost temperatures oscillate around -18 to -20 °C. Short and small width variations in winter are associated with warmer spells of a few days duration. The cracks narrow by the end of the winter with warming ground and air temperatures. But they stay open at about half of their maximum width for several weeks in May-June, at the time of snowmelt.

RÉSUMÉ
Des extensomètres spécialement adaptés furent déployés en travers de huit fentes de gel localisées au-dessus de coins de glace à l'Ile Bylot afin de déterminer le moment de la fissuration et de mesurer durant l'hiver les variations en largeur des fissures ouvertes. Les données de fissuration-contraction-expansion ont été corrélées avec des données de température de l'air et du sol acquises à l'aide de stations météorologiques et de câbles à thermistances automatisés. L'analyse des données révèle que d'étroites fissures de l'ordre du millimètre et moins s'ouvrent d'abord au début de l'hiver au moment où la couche active finit de regeler. Les fissures s'élargissent abruptement ensuite lorsque le pergélisol passe à des températures inférieures à -10 °C. Au cours de l'hiver, elles s'élargissent encore davantage, atteignant vers la fin de mars des largeurs entre 6.8 et 18.2 mm pendant que la température du pergélisol oscille autour de -18 à -20 °C. De petites et brèves variations en largeur des fissures en hiver sont associées à des redoux de quelques jours. Les fissures diminuent en largeur vers la fin de l'hiver quand les températures de l'air et du sol se réchauffent. Mais elles restent encore ouvertes d'environ la moitié de leur largeur maximum pendant quelques semaines en mai et juin, au temps de la fonte nivale.

1 INTRODUCTION

Tundra polygon networks which result from repeated thermal contraction cracking and ice-wedge growth are among the most prominent features in terrain underlain by permafrost. It has been thoroughly documented that frozen soils are affected by thermal contraction when the ground surface is submitted to deep winter cold temperatures, giving way to the opening of networks of cracks. Over the years, the repeated filling of the cracks in the permafrost with percolating surface water, mainly from snowmelt in early summer, builds up the ice-wedges that delineate tundra polygons. Thermal contraction cracking is also a widespread process that affects infrastructures such as road and airport runways, often leading to major maintenance and repairs works.

Leffingwell's pioneering field descriptions and interpretations in 1919 provided an understanding of the frost cracking and ice-wedge formation processes that has proven exact up to the present. The physics behind the thermo-mechanical behavior of frost cracks, ice wedges and development of tundra polygons was theoretically formulated by Lachenbruch (1962, 1966) whereas similar thinking based on observations was also presented and discussed by Russian authors such as Grechischev (1973). But we owe to John Ross Mackay the results of innovative field measurements that tested the existing theories and brought a unique understanding of the climate and terrain conditions that regulate frost cracking of the ground (Mackay, 1974, 1975, 1978, 1984, 1992, 1993), soil movements in polygonal terrain (2000) and, even, the growth of new cracks in newly exposed terrain on drained lake bottoms (Mackay and Burn, 2002).

Several field studies to measure the atmospheric and ground temperature conditions that induce frost cracking made use of electrical cables laid across runnels or cracks along the sides of tundra polygons. Mackay was truly a pioneer in that matter, starting in 1967 (Mackay 1992). The principle of the breaking electric cables is that a live wire that is laid across a potential crack is severed when the crack opens to release tensile stress generated by intense ground cooling at low temperatures. The electric circuit is then open and the time of breaking is recorded with a proper data logging device. Breaking times (date and hour) of a set of cables can help interpret temperature conditions under which cracking events took place when recorded air and ground temperature data for the study site are available, for example, from thermistors, dataloggers and automated meteorological stations (Allard and Kasper 1998; Fortier and Allard, 2005).

The breaking cable method has yielded significant and fundamentally important results. Generally, the observed temperature values and the measured air and ground cooling rates that induce frost cracking more or less match the theoretical calculations of Lachenbruch (1962,1966). Comparable results from different regions with similar soil conditions (fine grained organic-rich soils of the Mackenzie delta region, from Salluit in Nunavik and from Bylot Island in Nunavut) but with different temperature and climate regime confirm the universality of the thermo-mechanical principles responsible for the frost cracking process, the required ground temperature conditions and the robustness of the physics that describe it (Fortier and Allard, 2005; table 6). However, the measurement method is not perfect and the validity of the results remains subject to caution. Indeed, when a cable is buried in the active layer it becomes an integral part of the frozen soil after freeze back and normally would be expected to break when a crack opens. Some looseness may however be present around the buried cable allowing for a slight adjustment when it is put under tension; also metal wires, mesh and rubber or plastic sheeting of wires can be stretched to some extent and not break right away. For instance, Mackay (1974) noted that despite observed crack openings, 5 to 10 % of his cables did not break. Allard and Kasper (1998) and Fortier and Allard (2005) also noticed that the plastic sheeting of some bigger gauge cables would be stretched at the crack location; the metallic wire of some cables would break, therefore detecting a crack expansion event, but without severing the sheeting. Partial closing of the cracks under soil expansion would close back the circuit. This fortuitous discovery demonstrated that open cracks widen and narrow and that the permafrost alternately contracts and expands in winter with colder and warmer temperature spells.

Other methods to detect the timing of frost cracking can be terrain observations in winter (Christiansen, 2005) and the use of accelerators (shock loggers) buried in the ground (Matsuoka, 1999). Terrain observations are subjected to many misses because of one's lack of capability to be constantly present on site and because of snow cover variations in thickness, density, etc. The timing of vibrations created by sudden movements, such as opening of cracks, is recorded by accelerators and interpreted with temperature data and sometimes concurrently with breaking cables (Matsuoka and Christiansen, 2008). The drawback with this method is that there is no absolute identification of the vibration source such as a given ice wedge or crack. Vibrations in the soil can be created by various minor cracks and sudden deformations at some other locations in the surrounding terrain. Nevertheless Matsuoka and Christiansen's results show that many vibration events may be recorded over one winter near an ice wedge, likely due to dilation and cracking at times different than the breaking cables which, again, suggests that breaking cables probably leaves many cracking events undetected. Extensometers were also used across polygon troughs by Matsuoka (1999) and by Matsuoka and Christiansen (2008) who measured winter dilation phases in relation with cold spells. The results show the potential of using that technology to monitor frost cracks dynamics.

This study presents results obtained with newly adapted extensometers laid across known frost cracks and ice wedges near Centre d'études nordiques's research station on Bylot Island.

2 THE BYLOT ISLAND STUDY SITES

The study sites are located in a glacial outwash valley on the southwestern side of Bylot Island (73°09'38''N, 80°00'43''W) (Figure 1). The valley plain is bordered on both sides by an aggradation terrace 3 to 4 m above the glacio-fluvial outwash (sandur) surface. The sediment cover is made of windblown silt eroded from the outwash plain and deposited over an organic-rich wetland. Since this accumulation of fine-grained organic-rich permafrost has been taking place for over 3500 years, the soil stratigraphy consists of a series of layers of ice-rich silty peat. This aggradation terrace is crisscrossed by a complex network of large syngenetic ice wedges polygons, ponds, tundra lakes, kettle lakes and pingos (Allard, 1996; Fortier and Allard, 2004; Fortier and Allard, 2005).

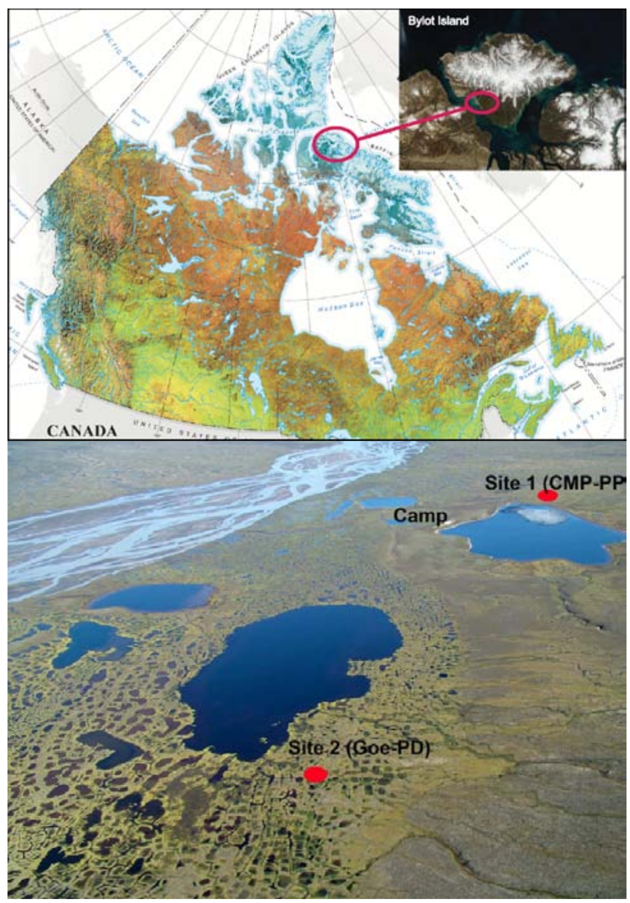

Figure 1. Top: location of Bylot Island. Bottom: location of the study sites. Sites CMP and PP are at the north end of the upper lake. Sites PD are near the large lake in forefront.

As calculated from the 1999 to 2010 period, the mean annual air temperature (MAAT) at the study site is -14.4°C. The active layer is about 40 cm deep. The freezing index varies from 4700 to 6000 degree-days. The mean volumetric water content is 72% after thaw. At every field season, abundant open frost cracks are visible along polygon sides and in troughs throughout the landscape. Many “virtual” cracks can also be found cutting through the moss cover along polygons sides until late in the summer. Coring through many ice veins in the active layer typically shows annual veins penetrating into ice wedges below the permafrost table (figure 2a). Indeed the permafrost and the climate conditions are conductive to widespread and repeated frost-cracking as air temperatures fall below -10 °C in October and stay in the -20 and -30 °C range until the end of April. Temperature variations and cold spells occur frequently. Published breaking cable data indicate average temperatures of -34.3°C in the air and of -18.6 °C at the permafrost table at cable breaks (interpreted as openings of cracks). The average air cooling rate before crack opening was calculated at -0.5 °C/h over a mean period of about 17 hours (see Fortier and Allard, 2006 for more details).

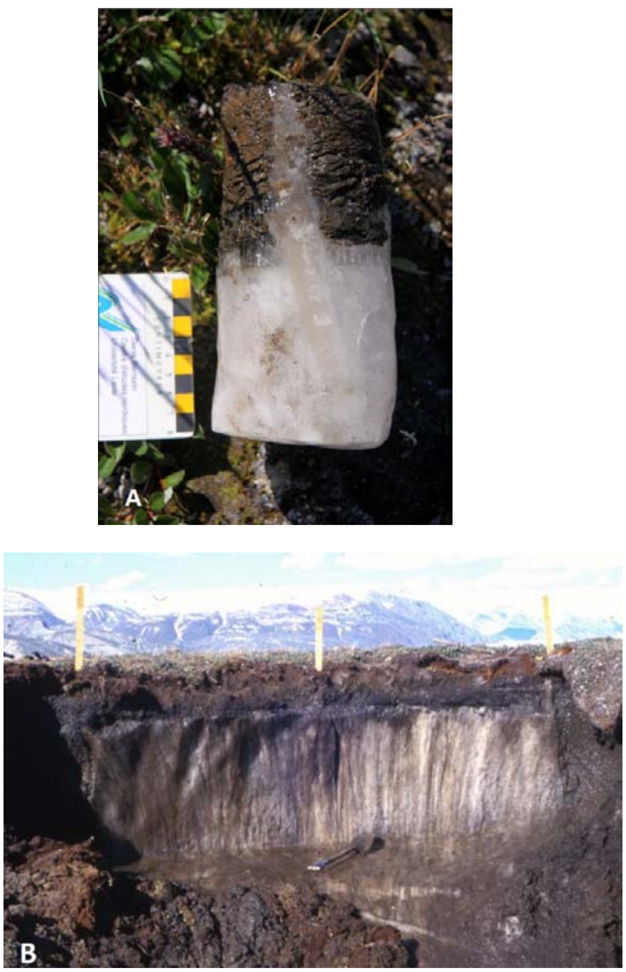

Figure 2. A. Ice veins penetrating into wedge ice at the permafrost table. B. A 2 m wide ice-wedge under flat terrain.

3 METHODS

The extensometers used consist of rotating potentiometers originally designed in a joint venture between the Finnish Forest Research Institute and the University of Oulu to measure tree stem diameter variations for dendrology work (Pesonen et al., 2004). Instead of having the instrument tied as a girth around a tree, the free end of the instrument’s stainless-steel band was screwed to a steel corner iron driven to the top of the permafrost (maximum thaw depth in late summer). The instrument itself was firmly attached with tie-wraps to another corner iron anchored into the ground on the other side of a crack (Figure 3). The electrical potentiometer in the instrument converts the length of extended stainless-steel band into electrical resistance values that can be recorded with a Campbell Scientific datalogger. Tests for forestry applications show that the instrument is thermally insensitive with an accuracy of 0.03 mm. The steel anchors were set about 25 cm apart, i.e. about 12 cm on each side of a crack. The height of the steel band and the top of the steel corner anchors was only about 3-5 cm above the soil surface.

The extensometers were deployed across eight cracks in two distinct networks separated by a distance of 1700 m. The selected cracks were on flat terrain; that is to say over permafrost wedges not having ramparts and runnels (example in figure 2b). This set up makes it sure that only the crack opening, widening, narrowing and closing are measured and that no dilation-contraction movements either between ridges or between troughs and ridges interfere with the measurements of a single crack width. Being set deep enough and protruding only 3-5 cm above ground also ensure that tilting of the anchors with surface freezing and thawing is not affecting the measurements either. A plastic box was placed upside down over the extensometer to prevent malfunction from snow cover, freezing rain and damage by animals. All sites are equipped with thermistors cables, some of which are designed to monitor the ground thermal regime at the surface and at depths of 40 cm (about the permafrost table) and 80 cm (in the permafrost). A CEN’s SILA automated meteorological station measures atmospheric temperatures. The two field sites were also equipped with snow depth recorders (Campbell Scientific SR-50 snow depth recorders).

The cracking-contraction-expansion data were graphed over time together with atmospheric and ground thermal temperature data for interpretation.

Figure 3 An extensometer installed across a crack.

4 RESULTS

4.1 Thermo-mechanical behavior of frost-cracks

Two of the installed systems failed. Over the six years with data, the behavior of all the working extensometers was similar and repetitive (Figures 4, 5 and 6). We therefore present detailed results obtained from six extensometers tried at the two sites (PD and CMP; Figure 1) over the winters 2009-2010 and 2010-2011 (Table 1). The first two ones (PD_95577 and Cmp_93698) were first installed in summer 2005. The four others (PD_93521, Cmp_93585, Cmp_93708, PP_93522) were installed in summer 2007-2008. Battery failures, water infiltrations and datalogger malfunctions are responsible for the absence of data in some years in the table. It has been noted that some extensometers on one or two occasions did not measure any cracking activity during a given winter even if the instrumentation was in working order. Fresh rootlets crossing the cracking planes indicated that no cracking had occurred the previous winter in those cases.

Extens. no.	Observations	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010	2010-2011
PD_93521	DGCI			26 Nov.	17 Nov.	10 Nov.	19 Dec.
	DMW			24 Mar.	3 Mar.	10 Mar.	18 Apr.
	MW			15.3	13.9	13.7	9.3
PD_93577	DGCI	19 Dec.	4 Dec.	24 Nov.	17 Nov.	13 Nov.	19 Dec.
	DMW	22 Mar.	28 Dec.	23 Mar.	28 Mar.	10 Mar.	13 Apr.
	MW	10.2	6.8	18.2	16.4	13.2	12.6
Cmp_93585	DGCI			29 Nov.	16 Nov.		21 Dec.
	DMW			26 Mar.	28 Mar.		20 Apr.
	MW			13.5	13.6		10.2
Cmp_93698	DGCI	8 Jan.	25 Dec.	19 Dec.	16 Nov.		23 Dec.
	DMW	21 Mar.	19 Mar.	27 Mar.	26 Mar.		10 Apr.
	MW	7.4	8.6	8.6	13.7		8.0
Cmp_93708	DGCI			14 Dec.			
	DMW			27 Mar.			
	MW			7.2			
PP_93522	DGCI			28 Nov.	23 Nov.	29 Nov.	
	DMW			12 Mar.	1 Mar.	17 Jan.	
	MW			13.5	13.2	10.8	

Table 1. Data summary of the six extensometers. DGCI, Date of ground contraction initiation. DMW, Date of maximum crack width. MW, Maximum recorded crack width (rounded to nearest tenth of mm).

Winter 2009-2010

Figure 4 depicts the behavior of three extensometers from September 2009, i.e. before the start of the freezing season, to late June 2010, i.e. late after air temperatures got back above freezing values, thus providing a complete winter cycle. Two of the extensometers started to expand by a little less than a millimeter on 10 and 13 November when air temperatures fell in the -20 to -25 °C range. When extensometer PD_93521 started to open, the temperature was -11 °C near the soil surface, -4.5 °C 40 cm deep, about at the permafrost table, and -2 °C at the depth of 80 cm, in the permafrost. Then it expanded more rapidly to 3 mm at the same time as PD_93577 suddenly opened and expanded to more than 2 mm as temperatures fell to -18 °C near the surface, -10 °C at the permafrost table and -8 °C at the depth of 80 cm. PD_93522 had a somewhat different behavior: it opened gradually to 1 mm from late October when near surface soil temperatures fell below 0 °C until 29 November, on which day it suddenly expanded to about 4 mm. That day of abrupt opening, air temperatures were -24 °C and surface soil temperature was about -24 °C; it was -15 °C at the depth of 40 cm and -13 °C at the depth of 80 cm.

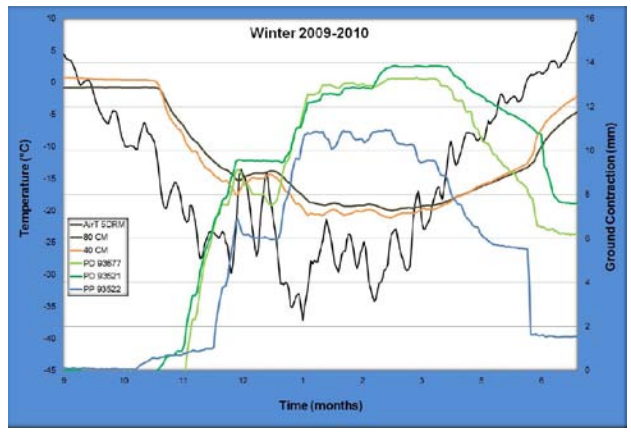

Figure 4. Extensometer expansion across three active frost cracks in the winter 2009-2010. Also shown: time-temperature curves for air, 40 cm and 80 cm depths.

During December, the three extensometers recorded expansion up to widths of 6 to 9 mm, with some short pauses on warmer days (or spells of 2-3 days). Increased expansion took place from the end of December and in January as air temperatures rapidly dropped to reach a minimum near -40 °C and as the permafrost temperature dropped to -16 °C. Small oscillations in width by 0.5 to 1 mm followed air temperature variations during the cold winter months. Maximum opening occurred in March even as air temperatures (still cold) started to generally warm up but as the temperature in permafrost continued to cool down to about -20 °C (80 cm deep). The maximum expansion reached values between 11 and 14 mm.

With warming air and soil temperatures, starting either in mid-March (PP_93522) or in April, depending on sites, the gaps narrowed progressively, with small pauses during colder spells of one to three days. Then they abruptly narrowed again just as air temperatures rose over 0 °C. However the gaps never close back totally, which indicates that the frost cracks stayed partially open after the winter was over. The residual gap values measured by the three extensometers vary in width from 1.8 to 7.8 mm. Given that maximum expansion varied from 11 to 14 mm, gap closing at the beginning of summer was from 46 to 93 %.

Winter 2010-2011

The whole pattern was identical the following winter (Figure 5). Extensometer PD_93577 opened by about 1 mm in mid-October as the active layer started to freeze-back when the air temperature fell to -14°C, the soil surface temperature (2 cm) fell to -3.4 °C and the ground temperature 40 cm deep just fell below 0 °C. Then a spell of 7-8 warmer days with surface soil temperature rising back to 0 °C corresponded with a closing of the incipient gap. Starting in mid-November, extensometer PD_93521 expanded to a width of 1 mm in a two-step phase corresponding to air temperature fluctuations; the soil surface temperature had just fallen to -10 °C and the ground temperature 40 cm deep had just fallen to -6 °C. It still enlarged to 1.7 mm as PD_93577 expanded to 1 mm over two weeks in mid-December over a long cold spell during which air temperatures oscillated between -19 °C and -37°C. Then both of them enlarged rapidly and other extensometers (Cmp_93585 and Cmp_83698) rapidly opened as temperature in the permafrost (80 cm deep) fell below -10 °C. By the end of December, the four extensometers had opened with gaps varying between 2.2 and 5.5 mm in width. There was no widening during the first two weeks of January as air temperatures were warmer (up to -12 °C) and the permafrost temperature remained stable slightly below -10 °C. Expansion of all the extensometers resumed in late January and occurred until late April as permafrost temperatures were about -18 °C. The maximum expansion of the four extensometers varied from 8 to 12.6 mm. The expansion rate was at its fastest from mid-January to mid- March with short pauses when the air temperatures peaked and more expansion when it dropped. As warming begun, all gaps were reduced. The narrowing stopped as the permafrost temperature rose above -10 °C and the gaps stayed open by 4 to 7 mm. Gap closing from maximum aperture from late April to the advent of above 0 °C air temperatures at the beginning of June was from 45 to 51%.

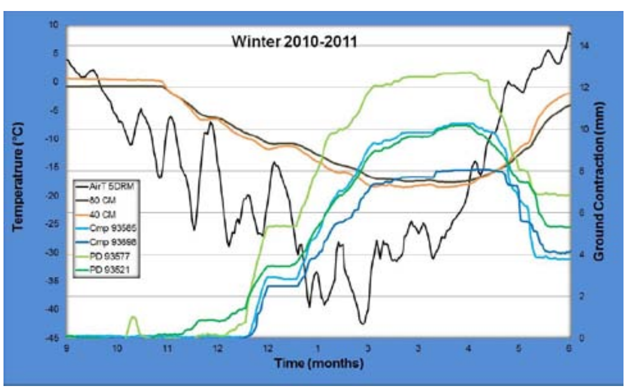

Figure 5. Extensometer expansion-contraction across four active frost cracks in the winter 2010-2011. Also shown: time-temperature curves for air, 40 cm and 80 cm depths.

4.2 Snow cover and ground contraction and expansion

Figure 6 shows the behavior of four extensometers under snow cover at sites equipped with snow depth recorders, from 2005 to 2009. The maximum snow bank thickness varied from 23 cm to a 37 cm peak of short duration in 2006. Although snow cover thickness did not vary by much from one year to the next, the gaps opened to larger values in winters 2007-2008 (up to 20 mm for PD_93577) and 2008-2009 as snow accumulation was less abundant in early winter. The residual gaps at snowmelt time were wider in those years also. Most of the gaps begin to close under the snow cover several weeks before it begins to melt. The time series of air and ground temperatures vs snow depth variations and crack dilation-contraction rates however still need to be analyzed in more details.

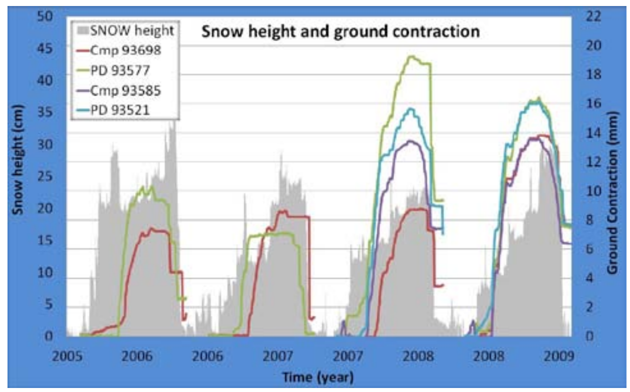

Figure 6. Snow height vs extensometer expansion (crack opening/enlarging and ground contraction) for a series of four successive winters.

4.3 Comparison with breaking cables

A comparative test was run to check extensometers against breaking cables (Figure 7). Seven cables (same gauge as in Fortier and Allard, 2005) with a thermistor at their end were buried near the soil surface, running across two cracks. The results show that the cables broke at various dates during the coldest winter months when the cracks in the permafrost were already open. The cracking events occurred after steps in the expansion curves of the extensometer, i.e. when cold spells increased the rate of spreading. The latest event in March even took place during a slight phase of extra widening by a fraction of a millimeter. Breaking occurred at temperatures between -14 and -22 °C.

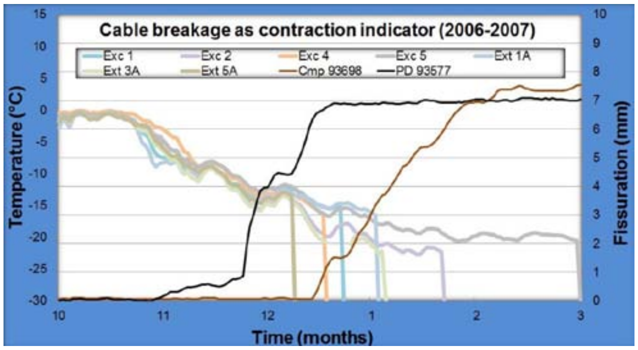

Figure 7. Comparison between two extensometers and five breaking thermistor cables installed near the surface across cracks in winter 2006-2007. Vertical lines are when cables broke.

5 DISCUSSION

The excellent agreement between air, surface, active layer and permafrost temperatures fluctuations on the one side and extensometer variations on the other side brings confidence that thermal contraction and expansion of the soil and frost crack behavior are truly recorded by the instruments. The high sensitivity of the instruments when installed across known frost cracks over active ice wedges brings insights on processes that were not possible previously with breaking cables and shock loggers. There is very little doubt that the extensometers measure the opening and variations in width of the frost cracks on the ground surface over the ice wedges.

Field observations show that existing cracks do not totally seal in the active layer in summer. In fact, it is often possible to split open coherent soils along the virtual cracks with bare hands or with the spade of a shovel. Observers further report that vegetation roots do not run across active cracks. In fact, root spreading across cracks is an indication of cessation of activity (Kokelj et al., 2007). The extensometer data answer some questions raised by Mackay in several papers and discussed by Lachenbruch (1962, 1969). For instance, do cracks extend downward from the surface or upward from the top of the ice wedges at the permafrost table (Mackay, 1984)? Our data indicate that, over already active ice wedges, many cracks open with a small gap of about 1 mm or less as soon as the active layer is frozen back but as the permafrost is still not cold enough to crack. This small gap opening is probably related to the low contraction coefficient of the active layer which contains relatively little ice.

At the cracking-prone sites of Bylot Island, the surface cracks widen abruptly after the permafrost (80 cm deep) has reached a temperature below about -10 °C, thus suggesting that the cracks then open in the permafrost and in the ice wedges. Therefore some cracks also open first at the top of the ice wedges, as shown by some gaps larger than 2 mm that first open at permafrost temperatures below -10 °C. The larger gap generated when permafrost cracks is likely due to the high contraction coefficient of the ice-rich ground and/or wedge ice.

The cracks enlarge and double in width over the winter as the cold wave penetrates deeper and permafrost reaches temperatures of -18 to -20 °C. Over the winter they enlarge during drops of temperature and either stop widening or slightly reduce in width during warmer spells. Slight variations of a few tenths of a degree 80 cm deep in the permafrost are reflected by sub-millimeter variations in crack width at the surface, therefore indicating that the permafrost expands and contracts with temperature oscillations. Thinning of the cracks at the surface begins as the permafrost temperature starts to rise above -18 °C in May, but it becomes much faster when the air and surface temperature rise above 0 °C. This indicates that soil expansion begins near the surface and is delayed or slowly propagates at depth. The surface gaps stop closing as permafrost temperature reaches values between -14 and -10 °C, in fact -10 °C in most cases.

It is likely that a crack deep in the permafrost would narrow and eventually close later in the summer as the annual heat wave penetrates at deeper levels and the permafrost re-expands. However the cracks are still open up to the surface at snowmelt and water can freely flow into them, freeze as a new vein and contribute to ice-wedge growth (Figures 2A, 6 and 8). The new vein is an addition to wedge size and to the volume of ice in the permafrost.

Comparison of two extensometers with a few breaking cables show that most cables are severed when the cracks are already open by 1.5 to 3 mm at the surface and as ground temperatures are below about -15 °C. Others break when temperatures fall in the -20 °C values (Figure 7). The -13 to -24 °C temperatures at the top of permafrost obtained from breaking wires and thought to be mean temperature for permafrost cracking in previous studies (Mackay, 1984,1993; Kasper and Allard, 1998; Fortier and Allard, 2005) seem therefore to correspond to the temperature range at which the cracks are enlarging to their maximum width rather than when they first open. This would be the time when the cables are subject to the strongest tensile stress.

Figure 8. An open frost-crack recently filled with ice in Mid-June.

6 CONCLUSION

The monitoring of cracks width at Bylot Island with new sensitive extensometers allowed a better understanding of the thermo-mechanical behavior of permafrost and ice wedge-polygons. Over some active ice wedges, cracking begins in the active layer when it has just frozen back at the beginning of winter. The permafrost itself cracks a few days or weeks later when its temperature falls below -10 °C. Some cracks start in the active layer, other start at the top of ice-wedges. The small gaps initiated in the active at the beginning of winter get suddenly larger when the permafrost underneath cracks a few weeks later. The cracks enlarge under colder temperatures in the cold winter months and begin to narrow with warming temperatures in April. Expansion and contraction of permafrost is a very sensitive temperature driven process. Thermal contraction cracks are still open at about 50% of their maximum width when the snow cover melts. Water can percolate in them to form new veins in the ice wedges.

The adapted extensometers originally designed for dendrology work yielded results of a precision not attained so far in frost-cracking studies.

7 ACKNOWLEDGEMENTS

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