Polar Geosci., **12**, 258–271, 1999

# MONITORING OF THERMAL CONTRACTION CRACKING AT AN ICE WEDGE SITE, CENTRAL SPITSBERGEN

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***Abstract:*** Thermal contraction cracking was monitored for two years in a continuous permafrost region. A dilatometer read the separation of a pair of benchmarks installed at both sides of an ice-wedge trough. The outputs were recorded in a data logger together with ground temperatures at various depths. Widening of the trough was insignificant during the warmer first winter, while several significant events occurred during the colder second winter. The amount of widening reflected the magnitude of cooling. The maximum widening in the second winter corresponded to the most severe cooling in early February, during which the frozen active layer experienced significant creep, possibly accompanied by cracking. The ground temperature data were analyzed on the basis of a viscoelastic model, which shows that horizontal tensile stress is favored by higher cooling rates and colder ground. The predicted maximum stress at the ground surface and at the permafrost table, which was reached during the maximum widening event, is of the same order of magnitude as the tensile strengths of typical frozen soils and polycrystalline ice, respectively. Consequently, the ground thermal regime during this event was capable of cracking both the frozen active layer and the ice wedge.

**key words:** ice wedge, thermal contraction crack, permafrost, field measurement, Svalbard

## 1. Introduction

Rapid cooling of frozen ground may result in polygonal contraction cracks underlain by a variety of wedge structures. Features and processes of these thermal contraction cracks have been one of the major concerns of permafrost scientists. Dynamic approaches to contraction cracking are nevertheless sparse. Cracking activity was first measured in northern Alaska during the early 1950's by means of interval recording of the distance across polygon troughs (BLACK, 1974). The same methodology was used also in Antarctica (BERG and BLACK, 1966). These pioneering studies were followed by long-term, extensive field monitoring by J.R. MACKAY in Arctic Canada. His monitoring has provided enormous amounts of information on the timing, direction, speed and frequency of cracking, annual growth increments, and intra/interyear displacements in polygonal ground (MACKAY, 1974, 1975, 1984, 1986, 1992, 1993a, b, 1995). In addition to field studies, rheological theories have also highlighted thermal contraction cracking and resulting crack geometries (*e.g.*, LACHENBRUCH, 1962).

However, knowledge is still lacking on the thermal regime in which the ground contracts and eventually cracks. This situation results mainly from the absence of continuous field measurements of displacement across polygon troughs concurrent with the recording of ground temperatures, with the exception of a recent work done by ALLARD and KASPER (1998).

This paper presents the result of two years (1990–1992) of monitoring of the horizontal displacement across a polygon trough and ground temperature at an ice wedge site, central Spitsbergen, Svalbard, where tundra polygons are widespread over perennially frozen ground. The automated monitoring system yielded preliminary data on the relationship between ground thermal regimes and contraction processes. The ground temperature data were also subjected to an analysis of the thermal stress field at which significant contraction occurred, on the basis of the viscoelastic model of ice wedge cracking (LACHENBRUCH, 1962).

## 2. The Study Area and Site

The study area lies in Adventdalen, a wide U-shaped valley upstream of Isfjorden, central Spitsbergen (Fig. 1). Polygonal patterns up to 30 m in diameter are widely developed on the valley-bottom terraces downcut by the Adventelba (river). The valley was entirely covered by the Late Weichselian glacier, deglaciated at *ca.* 10 ka BP, and since then it has remained ice-free until the present (MANGERUD *et al.*, 1992). Isostatic rebound accompanying deglaciation probably caused downcutting of the terraces (ONO *et al.*, 1991). No permafrost would have developed under the warm-based Late Weichselian glacier (BIRKS *et al.*, 1994). These conditions imply that both permafrost and polygons have developed after 10 ka BP under a climate not dissimilar to the present. Permafrost probably underlies a large part of the valley slopes and floor, though it is unlikely to be thick because a number of hydraulic pingos develop on the floodplain (LIESTØL, 1977; YOSHIKAWA, 1993). The terraces are mainly strath terraces covered with loamy till and outwash deposits, which are underlain by shale bedrock and, in places, overlain by peat or loess.

Meteorological data at Svalbard airport, located 25 km downstream of the study site, show that the mean annual air temperature and annual precipitation are –6.5°C and 186

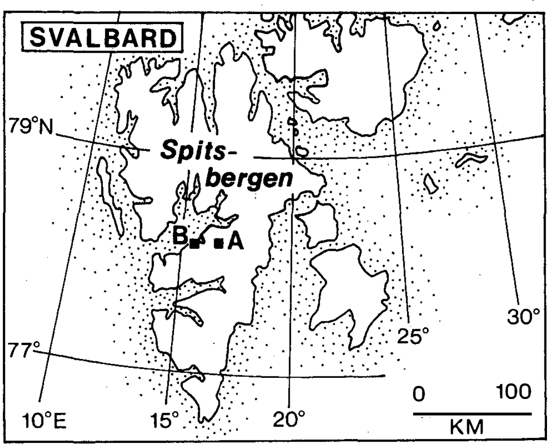


*Fig. 1. The location map. A = Adventdalen measurement site and B = Svalbard airport (meteorological station).*

mm (HANSSEN-BAUER *et al.*, 1990). Although the mean monthly air temperature in winter is moderate (*ca.* –20°C), periodic cold waves occasionally allow air temperature to fall below –40°C. The low precipitation during winter, which rarely raises snow depth greater than 30 cm, favors rapid cooling of the ground during such a cold phase. Seasonal thawing propagates in the frozen ground between June and early September. Excavation of the ground in summer showed that the thickness of the active layer ranges from 60 cm in peaty soils to 200 cm in gravelly sediments.

The vegetation cover is only patchy, composed of herbs and mosses. Whereas part of the terraces is occupied by wetland where peat is being deposited, the rest is dry and subject to wind action. Even on the exposed ground, however, troughs that outline polygons are largely vegetated. Few troughs have standing water in summer.

Polygonal patterns are either orthogonal or hexagonal in plan but mostly high-centered in profile. Most of the troughs delimiting polygons with diameters of 7 m or more are underlain by an ice wedge, while smaller polygons have a trough associated with an active layer soil wedge (MATSUOKA and HIRAKAWA, 1993). In summer, about 15% of the vegetated troughs are accompanied by open cracks, some of which probably reflect crack activity during the preceding winter. In fact, excavation of such troughs often revealed an ice veinlet, possibly reaching permafrost, on the frost table.

The measurement site is situated near the border between the wet and dry areas, where the ground had undergone sedimentation of peaty loam before having dried up from wetland. The peaty loam is 250 cm thick, sandwiched between the uppermost silty loess-like layer of 10 cm thick and underlying muddy till a few meters thick. Orthogonal patterns with diameters of 7–10 m develop on the vegetated ground (Fig. 2). Troughs are 50–100 cm wide, 10–30 cm deep and bordered by a pair of poorly developed rims. Prior to monitoring, a trough was excavated to the bottom of an ice wedge, 70 cm in top width and 360 cm in vertical dimension, which underlies an active layer 60 cm thick (Wedge AD9 in MATSUOKA and HIRAKAWA, 1993). The ice wedge is thus formed in the peaty loam and till. Since the adjacent troughs with similar dimensions were expected to be also associated with an ice wedge, the monitoring trough was selected at the opposite side of the excavated trough with regard to a polygon (Fig. 2). Excavation after the two-year monitoring revealed that the monitoring trough is underlain by an ice wedge 70 cm in top width and more than 70 cm in vertical dimension (Fig. 3). An open crack

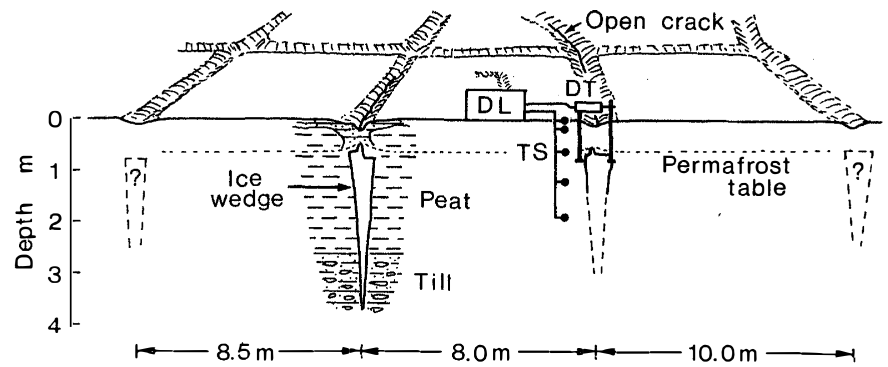


*Fig. 2. The measurement site and instrumentation. DL = data logger, DT = dilatometer and TS = temperature sensors.*

*Fig. 3. The ice wedge underlying the monitoring trough, excavated on 17 July 1992 when the 2-yr monitoring terminated. A secondary wedge (the arrow) protrudes 8 cm above the top of the primary wedge. The horizontal scale at the ground surface is 1 m long.*

occurred at the center of the trough in the observed summers, though whether it accompanied ice wedge cracking or originated from drying or from other processes is uncertain.

Both of the two excavated wedges are accompanied by a secondary wedge 4–5 cm wide that protrudes 8–10 cm above the top of the primary wedge (Fig. 3). The origin of the secondary wedge is equivocal. Since the height is equivalent to the thickness of the loess-like layer, these secondary wedges may have grown contemporaneously with the loess deposition (syngenetic origin). Another possibility is that such a feature may have reflected an episodic thaw penetration several decades ago (*e.g.*, LEWKOWICZ, 1994). The latter interpretation is partly supported by the meteorological records that the summers of 1922 and 1930 were extraordinarily warm and thereafter no summer has experienced such high temperatures (HANSSEN-BAUER *et al.*, 1990).

## 3. Monitoring

### *3.1. Instrumentation*

Figure 2 illustrates the monitoring system. Thermal contraction of the frozen ground was indicated by separation of a pair of benchmarks installed at both sides of the monitoring trough. The benchmarks, made of angle-iron stakes of 5×5 cm wide, were inserted in 6 cm diameter holes to a depth of 15 cm below the permafrost table. Upheaval of the stakes was minimized with timbers attached to the bases. The two stakes, 120 cm apart, were connected at 15 cm above the ground surface using the dilatometer DT-100A (manufactured by Kyowa Electronic Instruments; Fig. 4) in which a strain gauge reads displacement with a resolution of $4\times10^{-2}$ mm. The dilatometer is the

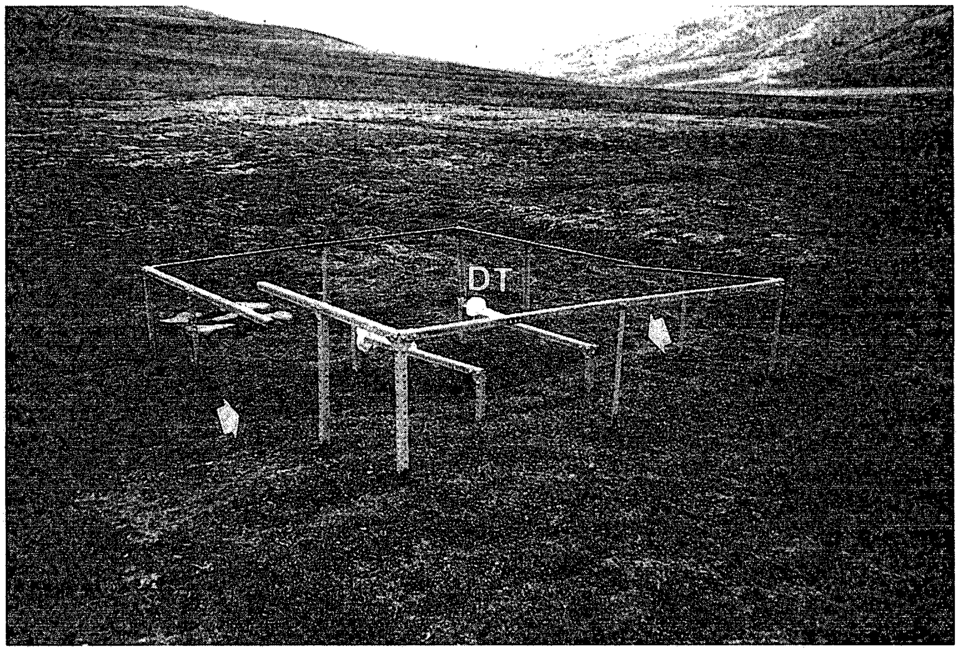


*Fig. 4. The measurement site before monitoring (5 August 1990). The arrow indicates the monitoring trough. A pair of angle-iron stakes anchored in permafrost are connected with the dilatometer (DT) which records lateral movement. The instruments are fenced against animals.*

same as used for frost heave recording (MATSUOKA, 1994). A spring in the dilatometer exerts a compression of 450 gf between the two stakes. This means that a stake is always pushed away from the trough with a force of 225 gf. However, the force per unit area of the stake is much smaller; such a small force is believed to affect the soil displacement little, unless the soil is too plastic. Since any differential lateral movement between two depths yields tilting of a stake (MACKAY, 1995), the recorded movement may not indicate the exact movement at the surface nor at the permafrost table. Perhaps the dilatometer slightly overestimates real movement in the frozen soil, because the largest movement is expected at the surface where temperature amplitudes are largest.

Ground temperatures were monitored with five platinum sensors. One was placed on the ground surface, so that it indicates temperatures at the bottom of the snow. The rest were installed at 20, 60, 120 and 190 cm depth. The sensor at 60 cm depth represents temperatures at the permafrost table. In plan, the sensors were located 80 cm apart from the trough edge toward the center of the polygon. The sensors can read temperatures with a resolution of 0.1°C, and they were calibrated in the laboratory to provide an error of less than 0.2°C.

The readings from the dilatometer and temperature sensors were simultaneously recorded at 3-h intervals in an 8-channel data logger (Datamark LS3000ptv, manufactured by Hakusan Corporation). Recording began on 6 August 1990 and terminated on 14 July 1992, thus including two winters.

### *3.2. Ground thermal regimes*

The observed two winters were quite different in meteorological conditions (Fig. 5).

Data at Svalbard airport show that the first winter (1990/91) was mild such that the minimum of the mean monthly air temperature was –12.3°C in January, with the mean daily air temperature never falling below –24°C. The second winter (1991/92) was rather severe, with the minimum of the mean daily air temperature as low as –35.2°C recorded on 6 February 1992, though in late winter it became much warmer than in the normal year. In addition, the smaller amount of snowfall during the second winter must have favored cooling of the ground.

The ground thermal condition reflected both air temperature and snow depth. Whereas air temperature fluctuated periodically throughout the two winters, corresponding changes in the ground surface (*i.e.*, the bottom of the snow) temperature were very small after January in the first winter and after March in the second (Fig. 5b), probably in response to increasing snow depth. The surface temperature was followed by subsurface temperatures with a time lag increasing with depth (Fig. 5c). The –10°C isotherm penetrated no deeper than 50 cm during the first winter. In contrast, the near-surface soil layer was maintained below –10°C throughout the second winter, with the –10°C isotherm penetrating below 200 cm depth and the –20°C isotherm to 40 cm depth in mid-

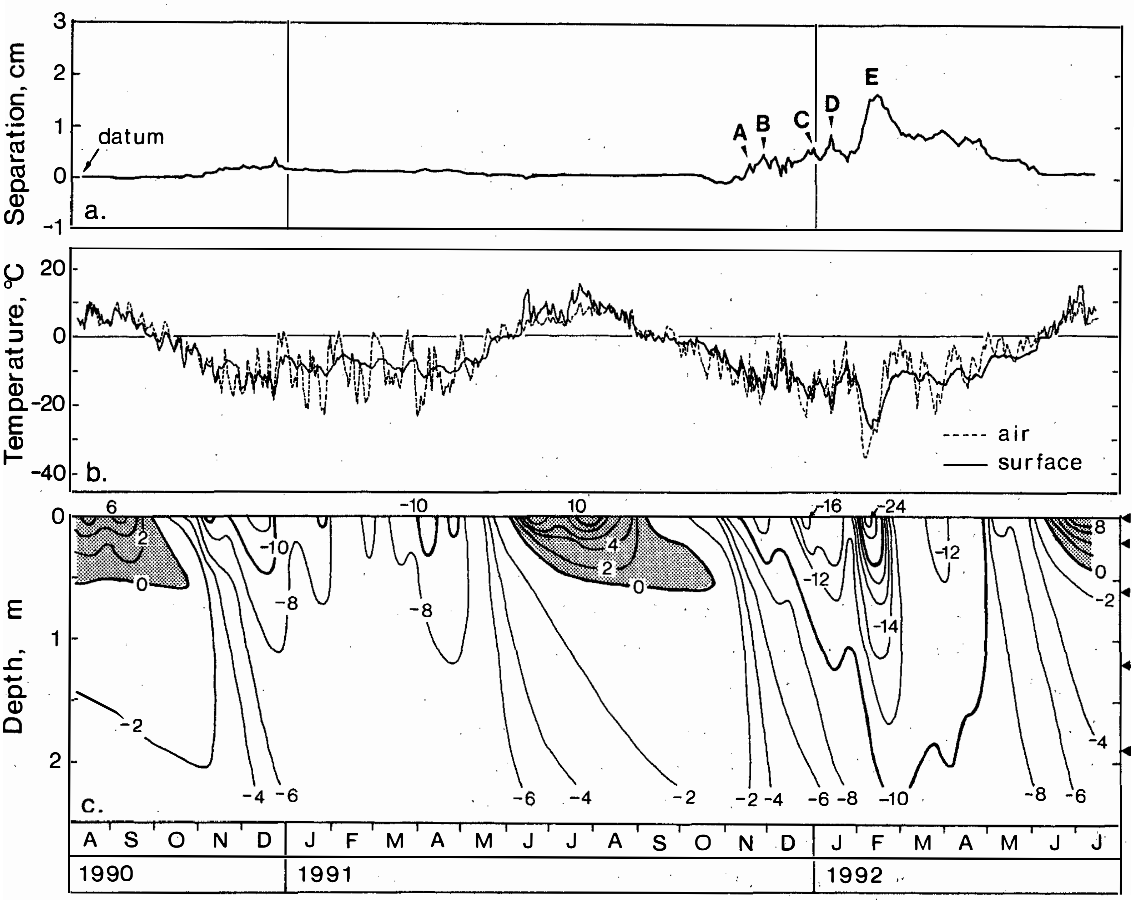


*Fig. 5. Summary of the 2-yr monitoring. a) Horizontal displacement across the monitoring trough. Positive values indicate widening of the trough. b) Daily air and ground surface temperatures. The air temperature was recorded at Svalbard airport. c) Subsurface isotherms, drawn at intervals of 2°C. The active layer is shaded. The marks at the right margin indicate the depths of temperature sensors.*

February. The minimum temperatures that the ground surface and permafrost table (at 60 cm depth) experienced during the second winter were −27.3°C and −17.1°C, respectively.

The maximum thaw depth was about 60 cm in both the 1990 and 1991 summers, corresponding to the depth of the top of the secondary ice wedge. The active layer was entirely refrozen before November.

*3.3. Thermal contraction in ground*

Lateral ground movement occurred only in winter, when a large part of the active layer was frozen (Fig. 5). This indicates that the recorded movement mainly reflected expansion and/or contraction of the frozen ground. The magnitude of movement varied significantly between the two winters, in response to the difference in ground thermal regimes. During the 1990/91 winter, the ground experienced only small contraction, as indicated by the maximum separation of the two benchmarks (*i.e.*, the maximum widening of the trough) no greater than 2 mm. This maximum event occurred in late December, when the ground surface encountered the annual minimum temperature (−18°C). The separation was ephemeral and canceled by the subsequent warming. After this event, significant separation never took place. Finally, prior to melting of the frozen active layer, the distance between the two benchmarks returned to the datum value in the preceding summer.

No relative movement between the two benchmarks occurred during the following 1991 summer. This contrasts with the result of MACKAY (1980, 1981), who observed radial movements from polygon centers toward ice-wedge troughs in summer, which was attributed to thermal expansion in the thawed active layers. The reason for this difference is unclear, but there seem to be two possibilities. First, whereas the polygons studied by MACKAY have a deep trough (*ca.* 1 m) with a pair of distinct rims, the present study site is accompanied only by a shallow trough delimited by indistinct rims. The lack of a deep trough at the latter site would minimize lateral expansion of the active layer toward the trough. Another explanation is that expansion did occur, but failed to be recorded because the rigidity of the angle-iron stake arrested the movement in the active layer. In the latter case, a cavity develops on one side of the stake (MACKAY, 1980). However, since no cavity was observed during the monitoring period, the former effect is likely to be responsible for the absence of summer movement.

During the second winter (1991/92), the ground encountered large contraction which led to a number of significant separation events (Fig. 5a). The onset of contraction corresponded to cooling of the ground below −10°C. The separation events coincided with the minimum ground surface temperature reached during a cold phase. The amount of separation was roughly proportional to the magnitude of the minimum temperature. The maximum separation of 16 mm occurred during the most severe cooling in early February. The subsequent warming, however, canceled half of the separation, and thereafter the fluctuation in the distance between the two benchmarks decreased in response to the small variation in ground surface temperature. Finally, when the ground surface temperature approached 0°C, the separation returned almost to the pre-winter level. The net separation in the 1991/92 period was 0.7 mm.

Figure 6 shows the detailed data in the 1991/92 midwinter. The pre-maximum separation events that took place before February showed similar characteristics: separation corresponded to the minimum temperature at the ground surface with a slight delay of less than 5 h; and it was canceled with rising surface temperature while temperature at the top of permafrost (60 cm depth) was still falling. These evidences indicate that separation occurred only in the uppermost portion of the frozen active layer.

In contrast to the pre-maximum events associated with cooling for only a few days, the maximum one originated from long-term cooling from 28 January to mid-February (Fig. 6). After the first peak in separation was reached on 9 February, a brief cool-back led to the second peak on 14 February. The first peak lagged behind the minimum temperature at the ground surface by a day, but it synchronized with that at 20 cm depth and with the maximum cooling rate at the permafrost table. The second peak corresponded to the minimum temperature at the permafrost table. These conditions suggest that thermal contraction occurred deeper than during the pre-maximum events, possibly throughout the frozen active layer.

The separation events on record indicate at least the creep of frozen ground due to thermal contraction, but they do not necessarily manifest the opening of a contraction

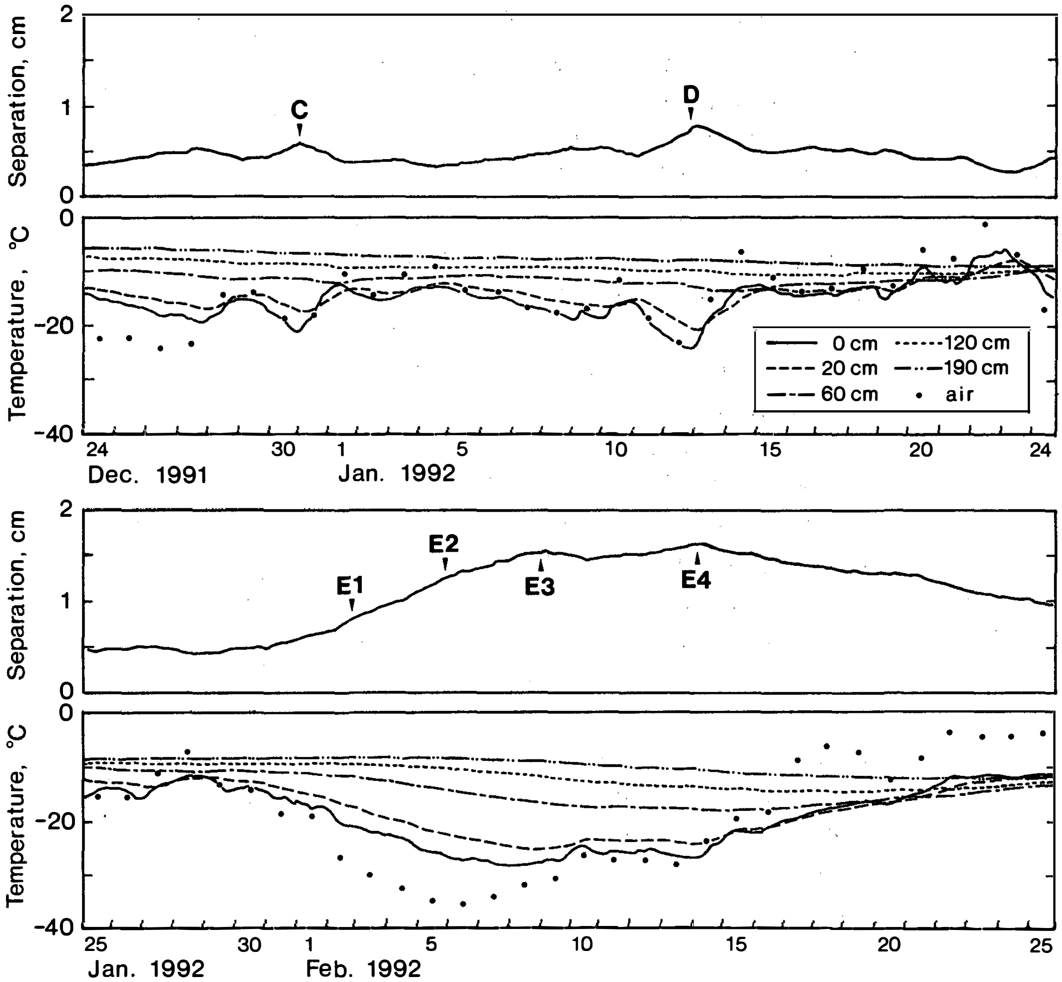


*Fig. 6. Horizontal displacement across the monitoring trough in the midwinter of 1991/92, displayed with air and ground temperatures. The dots represent the mean daily air temperatures.*

crack. MACKAY (1993b) indeed observed that separation occurred in every winter irrespective of crack generation. At the present study site, the crack at the center of the trough is likely to have acted as a weakness against the tensile stress and re-opened during the recorded separation events. Excavation of the trough in July 1992 displayed ice veinlets on the frost table. The veinlets extended into the secondary ice wedge. Although opening of the surface crack was uncertain, these veinlets may have resulted from cracking during the second winter. If a crack reaching the ice wedge occurred, it was most likely during the maximum event when the greatest cooling rate at the permafrost table was recorded. However, the separation data indicate that a large part of the crack had closed before snow or meltwater entered permafrost; as a result, the ice wedge growth was very small.

## 4. Analysis

### 4.1. Methodology

Irrespective of the occurrence of cracking, the observed separation events demonstrate that the frozen ground underwent tensile stress originating from thermal contraction. The positive relationship between the separation and minimum temperature suggests that the amount of separation reflects the magnitude of the tensile stress.

Ice-wedge cracking has been described in terms of two sets of rheological models: elastic (*e.g.*, DOSTOVALOV, 1957; ROMANOVSKIJ, 1973) and viscoelastic (*e.g.*, LACHENBRUCH, 1962; GRECHISHCHEV, 1976). The elastic model yields a maximum tensile stress an order of magnitude greater than the tensile strength of frozen soils, and it predicts that cracking takes place as soon as temperature dropped a few degrees below its mean annual value (LACHENBRUCH, 1962; MACKAY, 1975). The former condition implies that the creep of frozen soil results in some stress relaxation (*e.g.*, WILLIAMS and SMITH, 1989) and the latter disagrees with the field observations showing high cracking activity during midwinter (*e.g.*, MACKAY, 1974). More realistic is the viscoelastic model proposed by LACHENBRUCH (1962), of which application to ground temperature data at Barrow, Alaska, allowed reasonable prediction of cracking. Consequently, the present analysis follows the viscoelastic model.

The principal assumption of the viscoelastic model is that the creep behavior of frozen soil follows GLEN's (1955) flow law for polycrystalline ice:

$$\dot{\varepsilon}=B\sigma^n, \tag{1}$$

where $\varepsilon$ is the rate of permanent strain under a constant stress, and $\sigma$, and $B$ and $n$ are the creep parameters. For polycrystalline ice, $n$ averages about 3, and $B$ is a function of temperature (*e.g.*, GLEN, 1955; PATERSON, 1994). Data on these parameters are only fragmentary for frozen soils. Available data suggest that, for practical use, the creep behavior of ice approximates that of ice-rich soils (*e.g.*, MCROBERTS *et al.*, 1978; MORGENSTERN *et al.*, 1980; SAVIGNY and MORGENSTERN, 1986).

For a constant rate of temperature change, the tensile stress asymptotically approaches a value $\tau$:

$$\tau=3(\alpha\Theta/B)^{1/3}, \tag{2}$$

where $\alpha$ is the coefficient of linear thermal expansion and $\Theta$ is the cooling rate (LACHENBRUCH, 1962). A constant rate of cooling produces a stress of 90% of the asymptotic value after a period, $\delta$, from zero initial stress such that

$$\delta=3.6[(1-\nu)/E]\ [B(\alpha\Theta)^2]^{-1/3}, \tag{3}$$

where $E$ is Young's modulus and $\nu$ is Poisson's ratio of the frozen soil (LACHENBRUCH, 1962). In other words, when the constant cooling rate $\Theta$ is sustained for a period exceeding $\delta$, the tensile stress at the depth virtually equals $\tau$.

The use of eq. (2) requires the two frozen soil properties, $B$ and $\alpha$, as well as $\Theta$ determined from ground temperature data. Since no data are available on $B$ and $\alpha$ of the frozen peaty soil at the measurement site, the two properties were represented by experimental data for polycrystalline ice, as done by LACHENBRUCH (1962). The coefficient of linear thermal expansion for ice is given by $\alpha\approx5\times10^{-5}\ ^\circ C^{-1}$ (*e.g.*, HOBBS, 1974), though $\alpha$ for frozen peaty soils is dependent on temperature and can be up to six times greater than that for ice (CAMELEIA and BRUSHKOV, 1987). Thus calculations based on $\alpha$ for ice tend to slightly underestimate $\tau$ for peaty soils. The parameter $B$ was determined for the mean temperature during each cooling phase, using the laboratory-derived relationships between $B$ and temperature (GLEN, 1955; STEINEMANN, 1958; BARNES *et al.*, 1971; HAWKES and MELLOR, 1972; MORGENSTERN *et al.*, 1980). The cooling rate $\Theta$ during a separation event was evaluated for a period exceeding $\delta$ in eq. (3): trials showed that typical ranges for $\delta$ are 10–20 h at the ground surface and 20–30 h at the permafrost table. Under these conditions, eq. (2) yielded the mean tensile stress during the event. The analysis was done for the maximum (E) and four pre-maximum (A–D) separation events in the 1991/92 winter (see Fig. 5).

### *4.2. Stress conditions for the pre-maximum separation events in the 1991/92 winter*

Calculations for the pre-maximum events predicted tensile stresses of 0.8–1.6 MPa at the ground surface and of 0.3–0.5 MPa at the permafrost table (Fig. 7a). The magni-

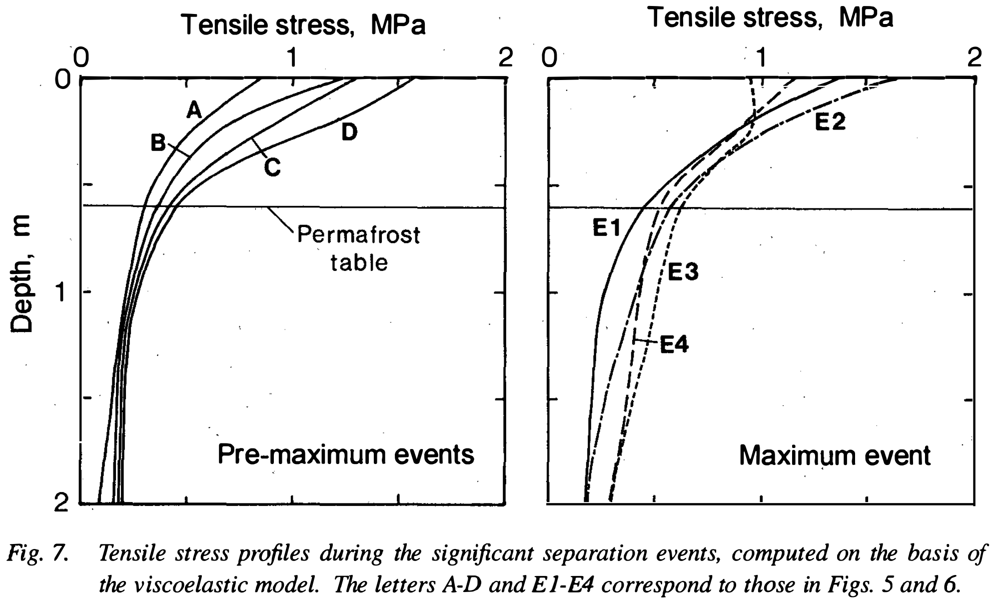


*Fig. 7. Tensile stress profiles during the significant separation events, computed on the basis of the viscoelastic model. The letters A-D and E1-E4 correspond to those in Figs. 5 and 6.*

tude of stress was mirrored by the amount of separation indicative of the horizontal tensile strain in frozen ground. A tensile stress exceeding the tensile strength of the frozen ground can result in a new crack. Available experimental data show that frozen silts and clays have tensile strengths of 1–3 MPa between –4°C and –10°C (TSYTOVICH, 1975) and of 5–7 MPa between –10°C and –30°C (HAYNES, 1978a). The calculated tensile stresses at the surface thus seem to be considerably smaller than the strength, probably being incapable of initiating a new crack. It is worth noting, however, that a frozen soil mass of the order of polygon diameters may have a tensile strength less than half of the laboratory value (LACHENBRUCH, 1962). Moreover, a frozen soil accompanied by pre-existing cracks can fail at a stress much lower than the tensile strength of the intact soil.

The tensile strength of massive polycrystalline ice is about 2 MPa at temperatures between –5°C and –20°C (HAWKES and MELLOR, 1972; HAYNES, 1978b), the value being about five times greater than the calculated tensile stress at the permafrost table. The tensile stress seems to be too small to crack the wedge ice, even though vertical foliation and high bubble content decrease the strength of wedge ice (*e.g.*, MACKAY, 1975). These estimates suggest that tensile stresses during the pre-maximum events could open the pre-existing crack at the surface, but they were insufficient for the wedge ice to crack.

### *4.3. Stress conditions during the maximum separation event in the 1991/92 winter*

The stress condition during the maximum event was analyzed for four stages (E1–E4 in Fig. 6). Calculations indicated a marked variation in stress distribution during the event (Fig. 7b). The maximum stress of 1.7 MPa was predicted at the surface on 5 February, when the separation was still in progress. On 8 February when separation reached the first peak, the tensile stress at the surface already turned to decrease while that at the permafrost table reached the maximum value (0.62 MPa) during the event. The second peak on 14 February was accompanied by smaller stresses than the first peak. The predicted maximum stresses at the surface and permafrost table were considerably smaller than the tensile strengths of frozen soils and polycrystalline ice, respectively. Nevertheless, the greater stresses throughout the frozen active layer than during the pre-maximum events suggest that during the maximum event thermal contraction was more capable of cracking to the deeper part of the frozen active layer and possibly to the uppermost permafrost.

The possible errors that arise from the analogy between polycrystalline ice and frozen soils should be taken into account. On the assumption that $\alpha$ for frozen peaty soils ranges from $5\times10^{-5}$ to $15\times10^{-5}\,^{\circ}C^{-1}$ at –20°C and from $10\times10^{-5}$ to $30\times10^{-5}\,^{\circ}C^{-1}$ at –5°C (CAMELEIA and BRUSHKOV, 1987), eq. (2) yields tensile stresses up to 2.5 MPa at the surface and 0.8 MPa at the permafrost table during the maximum event. Since B for ice represents the upper bound of that for frozen soils (NIXON, 1978; SAVIGNY and MORGENSTERN, 1986), eq. (2) predicts also a slightly greater stress for the latter material. Both effects indicate that the use of ice properties tends to underestimate tensile stresses for frozen soils. Consequently, for the maximum separation event, the tensile stresses must be slightly greater than those illustrated in Fig. 7b, approaching the tensile strength of frozen soils.

The above analysis demonstrates that Lachenbruch's equation predicts tensile stresses proportional to the amount of separation and provides a yearly maximum stress of the same order of the strength of frozen soils. This indicates that, for the first approximation, the viscoelastic model based on Glen's flow law is applicable to the thermal contraction cracking in frozen ground.

## 5. Conclusions

The two-year continuous recording of the horizontal ground movement across an ice-wedge trough showed that, while separation of a pair of benchmarks at both sides of the trough was insignificant during the warmer first winter, several significant events occurred during the much colder second winter. The maximum separation (16 mm) was reached during the most severe cooling in early February. The maximum event corresponded also to the minimum annual temperatures in the frozen active layer, –27.3°C at the ground surface and –17.1°C at the permafrost table. Although the observed separation cannot indicate the occurrence of ice-wedge cracking, it does indicate that the frozen active layer experienced significant creep resulting from thermal contraction.

The ground temperature data during the significant separation events were analyzed on the basis of the viscoelastic model, which shows that thermal contraction is favored by higher cooling rates and colder ground. The predicted tensile stresses were nearly proportional to the magnitude of separation. The maximum stress at the surface and at the permafrost table, which was reached during the maximum separation event, was of the same order of magnitude as the tensile strengths of frozen soils and polycrystalline ice, respectively. Thus the ground thermal regime during the maximum separation event was such that both the frozen active layer and the ice wedge can crack.

The field monitoring system described here allows us to evaluate, with the help of another method that can detect cracking directly (*e.g.*, breaking cables by MACKAY, 1974), the detailed processes involved in the creep of frozen ground and subsequent opening and closing of the contraction crack. However, in order to determine the actual amount of crack widening, the instrumentation should be improved to be capable of measuring the tilt of stakes. Furthermore, more accurate prediction based on the viscoelastic model requires additional data on the thermal and rheological properties of frozen soils. The combination of these techniques will make it possible to determine the thermal regime in which the frozen ground contracts and eventually cracks.

## Acknowledgments

I would like to thank Profs. Y. ONO and T. KOAZE for allowing my participation in the studies on Svalbard. I am also grateful to Profs. K. HIRAKAWA, K. MORIWAKI, Drs. S. SAWAGUCHI, H. HASEGAWA, T. SHIRAIWA, K. YOSHIKAWA, T. SAWAGAKI, H. MIURA, T. UMEMOTO and Mr. A. HARADA, for their collaboration, advice and comments during the fieldwork. My special thanks are given to Prof. J.R. MACKAY for providing several relevant publications and many valuable comments on an early version of this paper. The fieldwork was supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science and Culture, Japan (02041081, Principal investigator: T. KOAZE, Meiji University) .

## References


ALLARD, M. and KASPER, J.K. (1998): Temperature conditions for ice-wedge cracking: Field measurements from Salluit, Northern Québec. Proc. 7th Internatl Conf. Permafrost, ed. by A.G. LEWKOWICZ and M. ALLARD. Québec, Centre d'études nordiques, Université Laval, 5–12.

BARNES, P., TABOR, D., WALKER, F.R.S. and WALKER, J.C.F. (1971): The friction and creep of polycrystalline ice. Proc. Royal Soc. London, Ser. A, **324**, 127–155.

BERG, T.M. and BLACK, R.T. (1966): Preliminary measurements of growth of nonsorted polygons, Victoria Land, Antarctica. Antarctic Soils and Soil-Forming Processes, ed. by J.C.F. TEDROW. Washington, D.C., Am. Geophys. Union, 61–108 (Antarct. Res. Ser., **8**).

BIRKS, H.H., PAUS, A., SVENDSEN, J.I., ALM, T., MANGERUD, J. and LANDVIK, J.Y. (1994): Late Weichselian environmental change in Norway, including Svalbard. J. Quat. Sci., **9**, 133–145.

BLACK, R.F. (1974): Ice-wedge polygons of Northern Alaska. Glacial Geomorphology, ed. by D.R. COATES. London, George Allen & Unwin, 247–275.

CAMELEIA, A.V. and BRUSHKOV, A.V. (1987): Frost cracking on Peninsula Jamal in region of Lake Turin-To. Geocryological Investigations, Issues of Moscow State University, 212–219 (in Russian).

DOSTOVALOV, B.N. (1957): Change in volume of unconsolidated ground during the freezing and formation of frost cracks. Materially po laboratornym issledovaniyam merzlykh gruntov, Sbornik 3, Akademii Nauk USSR, 41–51 (in Russian).

GLEN, J.W. (1955): The creep of polycrystalline ice. Proc. Royal Soc. London, Ser. A, **228**, 519–538.

GRECHISHCHEV, S.E. (1976): Basis of method for predicting thermal stresses and deformations in frozen soils. National Research Council of Canada, Technical Translation, **1886**, 52 p.

HANSSEN-BAUER, M., SOLÅS, M.K. and STEFFENSEN, E.L. (1990): The Climate of Spitsbergen. Klima, Den Norske Meteorologiske Institutt Rapport, **39/90**, 40 p.

HAWKES, I. and MELLOR, M. (1972): Deformation and fracture of ice under uniaxial stress. J. Glaciol., **11**, 103–131.

HAYNES, F.D. (1978a): Strength and deformation of frozen silt. Proc. 3rd Internatl Conf. Permafrost, 1. Ottawa, National Research Council of Canada, 655–661.

HAYNES, F.D. (1978b): Effect of temperature on the strength of snow-ice. CRREL Report, **78-27**, 18 p.

HOBBS, P.V. (1974): Ice Physics. Oxford, Clarendon Press, 837 p.

LACHENBRUCH, A.H. (1962): Mechanics of thermal contraction cracks and ice-wedge polygons in permafrost. Geol. Soc. Am., Spec. Pap., **70**, 69 p.

LEWKOWICZ, A.G. (1994): Ice-wedge rejuvenation, Fosheim Peninsula, Ellesmere Island, Canada. Permafrost Periglac. Process., **5**, 251–268.

LIESTØL, O. (1977): Pingos, springs, and permafrost in Spitsbergen. Norsk Polarinstitutt Årbok 1975, 7–29.

MACKAY, J.R. (1974): Ice-wedge cracks, Garry Island, Northwest Territories. Canad. J. Earth Sci., **11**, 1366–1383.

MACKAY, J.R. (1975): The closing of ice-wedge cracks in permafrost, Garry Island, Northwest Territories. Canad. J. Earth Sci., **12**, 1668–1674.

MACKAY, J.R. (1980): Deformation of ice-wedge polygons, Garry Island, Northwest Territories. Current Research, Part A, Geol. Surv. Canad. Pap., **80-1A**, 287–291.

MACKAY, J.R. (1981): Active layer slope movement in a continuous permafrost environment, Garry Island, Northwest Territories. Canad. J. Earth Sci., **18**, 1666–1680.

MACKAY, J.R. (1984): The direction of ice-wedge cracking in permafrost: downward or upward? Canad. J. Earth Sci., **21**, 516–524.

MACKAY, J.R. (1986): The first 7 years (1978–1985) of ice wedge growth, Illisarvik experimental drained lake site, western Arctic coast. Canad. J. Earth Sci., **23**, 1782–1795.

MACKAY, J.R. (1992): The frequency of ice-wedge cracking (1967–1987) at Garry Island, western Arctic Coast, Canada. Canad. J. Earth Sci., **29**, 236–248.

MACKAY, J.R. (1993a): The sound and speed of ice-wedge cracking, Arctic Canada. Canad. J. Earth Sci., **30**, 509–519.

MACKAY, J.R. (1993b): Air temperature, snow cover, creep of frozen ground, and the time of ice-wedge cracking, western Arctic Coast. Canad. J. Earth Sci., **30**, 1720–1729.

MACKAY, J.R. (1995): Ice wedges on hillslopes and landform evolution in the late Quaternary, western Arctic coast, Canada. Canad. J. Earth Sci., **32**, 1093–1105.

MANGERUD, J., BOLSTAD, M., ELGERSMA, A., HELLIKSEN, D., LANDVIK, J.Y., LØNNE, I, LYCKE, A.K., SALVIGSEN, O., SANDAHL, T. and SVENDSEN, J.I. (1992): The last glacial maximum on Spitsbergen, Svalbard. Quat. Res., **38**, 1–31.

MATSUOKA, N. (1994): Continuous recording of frost heave and creep on a Japanese alpine slope. Arct. Alp. Res., **26**, 245–254.

MATSUOKA, N. and HIRAKAWA, K. (1993): Critical polygon size for ice-wedge formation in Svalbard and Antarctica. Proc. 6th Internatl Conf. Permafrost, 1. Wushan, South China University of Technology Press, 449–454.

McROBERTS, E.C., LAW, T.C. and MURRAY, T. (1978): Creep test on undisturbed ice-rich silt. Proc. 3rd Internatl Conf. Permafrost, 1. Ottawa, National Research Council of Canada, 539–545.

MORGENSTERN, N.R., ROGGENSACK, W.D. and WEAVER, J.S. (1980): The behaviour of friction piles in ice and ice-rich soils. Canad. Geotech. J., **17**, 405–415.

NIXON, J.F. (1978): First Canadian Geotechnical Colloquium: Foundation design approaches in permafrost areas. Canad. Geotech. J., **15**, 96–112.

ONO, Y., MATSUOKA, N., SAWAGUCHI, S., SHIMOKAWA, K., FUKUDA, M., TAKAHASHI, N., SHIRAIWA, T., HASEGAWA, Y., YOSHIKAWA, K. and MUTO, H. (1991): Geomorphological results of the Japanese expedition to Svalbard, 1988-1989. Mount. Res. Develop., **11**, 259–269.

PATERSON, W.S.B. (1994): The Physics of Glaciers, 3rd Edition. Oxford, Pargamon, 480 p.

ROMANOVSKIJ, N.N. (1973): Regularities in formation of frost fissures and development of frost fissure polygons. Biul. Perygl., **23**, 237–277.

SAVIGNY, K.W. and MORGENSTERN, N.R. (1986): Creep behavior of undisturbed clay permafrost. Canad. Geotech. J., **23**, 515–527.

STEINEMANN, S. (1958): Experimentelle Untersuchungen zur Plastizität von Eis. Beiträge zur Geologie der Schweiz Hydrologie, **10**, 72 p.

TSYTOVICH, N.A. (1975): The Mechanics of Frozen Ground. Washington, D.C., Scripta Book Company, 426 p.

WILLIAMS, P.J. and SMITH, M.W. (1989): The Frozen Earth: Fundamentals of Geocryology. Cambridge, Cambridge University Press, 306 p.

YOSHIKAWA, K. (1993): Notes on open-system pingo ice, Adventdalen, Spitsbergen. Permafrost Periglac. Process., **4**, 327–334.

*(Received January 21, 1999; Accepted April 5, 1999)*