Géographie physique et Quaternaire

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Volume 54, Number 1, 2000

URI: https://id.erudit.org/iderudit/004846ar
DOI: https://doi.org/10.7202/004846ar

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Publisher(s)

Les Presses de l'Université de Montréal

ISSN

0705-7199 (print)
1492-143X (digital)

Explore this journal

Cite this article

MacKay, J. R. (2000). Thermally induced movements in ice-wedge polygons, western arctic coast: a long-term study. *Géographie physique et Quaternaire*, *54*(1), 41–68. https://doi.org/10.7202/004846ar

Article abstract

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Géographie physique et Quaternaire, 2000, vol. 54, n° 1, p. 41-68, 43 fig.

THERMALLY INDUCED MOVEMENTS IN ICE-WEDGE POLYGONS, WESTERN ARCTIC COAST: A LONG-TERM STUDY

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ABSTRACT Thermally induced seasonal movements of the active layer and subjacent permafrost have been measured in numerous ice-wedge polygons that have varied in age, type, crack frequency, and topographic location. The field observations show that, in winter, thermal contraction, which is inward, is constrained or vanishes at the polygon centres but, in summer, thermal expansion, which is outward, is unconstrained at the ice-wedge troughs. Therefore, there tends to be a small net summer transport of the active layer, to varying depths, into the ice-wedge troughs. The movement has been observed in all polygons studied. The slow net transport of material into the ice-wedge troughs has implications for: permafrost aggradation and the growth of syngenetic wedges in some troughs; the palaeoclimatic reconstruction of some ice-wedge casts; and the interpretation of polygon stratigraphy based upon the assumption that the polygon material has accumulated *in situ.*

RÉSUMÉ *Mouvements d'origine thermique dans les polygones à fente de gel sur la côte occidentale de l'Arctique : une étude à long terme.* Les mouvements saisonniers d'origine thermique dans le mollisol et le pergélisol sous-jacent ont été mesurés dans plusieurs polygones à fente de gel qui varient selon leur âge, leur nature et la fréquence de fissuration et du site. Les observations de terrain indiquent qu'en hiver la contraction thermique, qui s'effectue vers l'intérieur, est limitée au centre des polygones, alors qu'en été l'expansion thermique, qui se manifeste vers l'extérieur, n'est pas confinée aux fentes de gel. En conséquence, il existe un faible déplacement estival du mollisol, à différentes profondeurs, dans les sillons de fente de gel. Le déplacement a été observé dans tous les polygones étudiés. Le déplacement lent résiduel de matériel dans les sillons de fente de gel a des implications quant à l'expansion du pergélisol et la croissance des fentes de gel de type syngénétique dans certains sillons, quant à la reconstitution paléogéographique de certaines fentes de gel reliques et quant à l'interprétation de la stratigraphie des polygones en se fondant sur la présomption que le matériel des polygones a été accumulé sur place.

ZUSAMMENFASSUNG *Thermisch induzierte Bewegungen in Eiskeilpolygonen, westliche arktische Küste: Eine Langzeitstudie*. Thermisch bedingte, säsonale Bewegungen der Auftauschicht und des umliegenden Permafrostes sind in mehreren Eiskeilpolygonen gemessen worden. Diese sind zu unterscheiden bezüglich ihres Alters, ihrer Art und Rißhäufigkeit und Topographie. Die Geländebeobachtungen zeigen, daß im Winter thermische Kontraktion nach innen stattfinden die sich im Zentrum der Polygone vollzieht. Im Sommer dagegen finded thermische Ausdehnung statt, die in sich den Eiskeilgräben unbehindert vollzieht. Demnach scheint im Sommer ein geringer Transport der aktiven Schicht in unterschiedlichen Tiefen in Eiskeilgräben stattzufinden. Diese Bewegung ist in allen Polygonen beobachtet worden. Der langsame Nettotransport von Material in den Eiskeilgräben hat verschiedene Auswirkungen für die Permafrostentstehung und die Entstehung von syngenetischen Eiskeilen in einigen Eiskeilgräben. Zudem hat er Auswirkungen auf die paleoklimatische Rekonstruktion von einigen Eiskeilformen und die Interpretierung der Polygonstratigraphie, die auf der Annahme beruht, daß das Polygonmaterial am Ort akkumuliert ist.

Manuscrit reçu le 3 juin 1999 ; manuscrit révisé accepté le 13 janvier 2000

INTRODUCTION

Ice-wedge polygons are widely distributed along the Western Arctic Coast of Canada, where wedge-ice may constitute 50 % or more of the upper several metres of permafrost (Pollard and French, 1980). In 1951, field studies were started on ice-wedge polygons along the Western Arctic Coast and, since then, the studies have been continued nearly every summer and in most winters. In 1963, because there were no long-term studies on ice-wedge polygons, anywhere, a decision was made to establish a small field station for long-term summer and winter observations on growth processes. In 1964, a small field station was established at Garry Island, N.W.T. (Fig. 1); in 1978, another small field station was established at Illisarvik (Fig. 1), an experimental drained lake site for the multi-disciplinary study of permafrost processes and periglacial features; and, in 1980, a small field site was established near the inland town of Inuvik (Fig. 1) in the forest-tundra zone. Observations at the three sites have been carried out from the start of the studies to the time of writing, initially by the writer and recently in collaboration with C.R. Burn. The focus of this paper is on field studies from 1965 to 1995 at Garry Island, with brief mention of corroborating data from Illisarvik and Inuvik. The main purposes of this paper are: 1) to demonstrate that, in all ice-wedge polygons studied, irrespective of age, type, crack frequency, and topographic location, there tends to be a small, thermally induced, net summer movement of the active layer outward from the polygon centres towards the bounding ice-wedge troughs; 2) to discuss some of the geomorphic, stratigraphic, and palaeoclimatic implications of the observed movement.

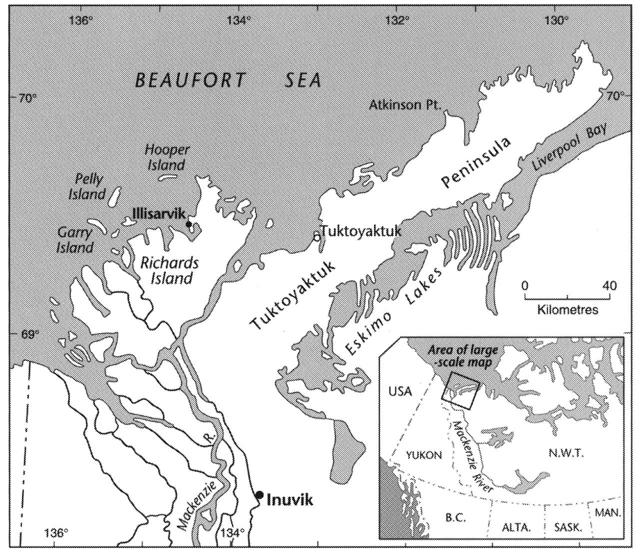


FIGURE 1. Location map: the field sites discussed in the text are Garry Island, a glacier ice-thrust feature, north of the Mackenzie Delta; Illisarvik, the site of a 1978 full-scale field experiment on the growth of permafrost by means of lake drainage; and Inuvik, an inland site in the forest-tundra transition zone.

Localisation des sites dont on parle dans le texte : Garry Island, une forme de chevauchement glaciaire, au nord du delta du Mackenzie ; Illisarvik, le site d'une expérience d'envergure commencée en 1978 sur la croissance du pergélisol à la suite d'un assèchement lacustre ; Inuvik, un site à l'intérieur des terres, à la limite entre la forêt et la toundra.

ICE-WEDGE POLYGONS

Ice-wedge polygons are numerous along the Western Arctic Coast with a few exceptions, such as in some bedrock areas and in some sites with active sedimentation. Ice-wedge polygons are also widely distributed in most other non-bedrock permafrost areas of the world (Brown *et al.*, 1997). In order to provide a uniform background for the terminology used in this paper, a classification of ice wedges based upon growth direction and growth sequence is given in Figure 2 and a companion classification of ice-wedge polygons, based upon polygon morphology and growth sequence is given in Figure 3.

ICE WEDGES

Ice wedges can be classified in a variety of ways (*e.g.* Leffingwell, 1915; Péwé, 1959, 1962, 1966; Lachenbruch, 1962; Romanovskij, 1977, 1985). The classification for the ice wedges that will be discussed in this paper is a system based upon their growth direction (Fig. 2), namely: epigenetic, syngenetic, and anti-syngenetic (Mackay, 1990, 1995a). Epigenetic wedges grow in stable areas with negligible addition or loss of material to or from the ground surface. Syngenetic wedges grow in areas of permafrost aggradation, as from fluvial sedimentation, deposition from mass wasting, and climate change. The growth direction of a syngenetic wedge is upward. In vertical cross-section, most syngenetic wedges tend to have a nested or chevron growth pattern (Dostovalov and Popov, 1966; Lewkowicz, 1994). Anti-syngenetic wedges grow on hillslopes where the tops of the wedges are degraded by removal of material, usually by slow mass wasting. At hillslope sites where the depth of ice-wedge cracking keeps pace with hillslope recession by the downslope removal of active layer material, the bottom of the anti-syngenetic wedge will then penetrate downward at approximately the same rate as the top of the wedge is truncated by thaw. The growth direction of an anti-syngenetic wedge is, as the name implies, the opposite of a syngenetic wedge, *i. e.* downwards in contrast to upwards. Secondary and tertiary wedges may propagate outward from any of the three types of primary wedges to subdivide polygons into smaller divisions (Fig. 2). Secondary wedges propagate, usually orthogonally, outward from primary wedges. Tertiary wedges can propagate outward from either primary or secondary wedges. However, if a tertiary wedge propagates right across a polygon from the primary wedge on one side to the primary wedge on the other side, it may be impossible to distinguish between primary and secondary wedges.

POLYGON MORPHOLOGY

1. Classification

In the absence of a widely accepted classification system for ice-wedge polygons (Washburn, 1956, 1979; Mackay, 1958, 1963; Drew and Tedrow, 1962; Péwé, 1966; Everett, 1980) a simple classification, based essentially on

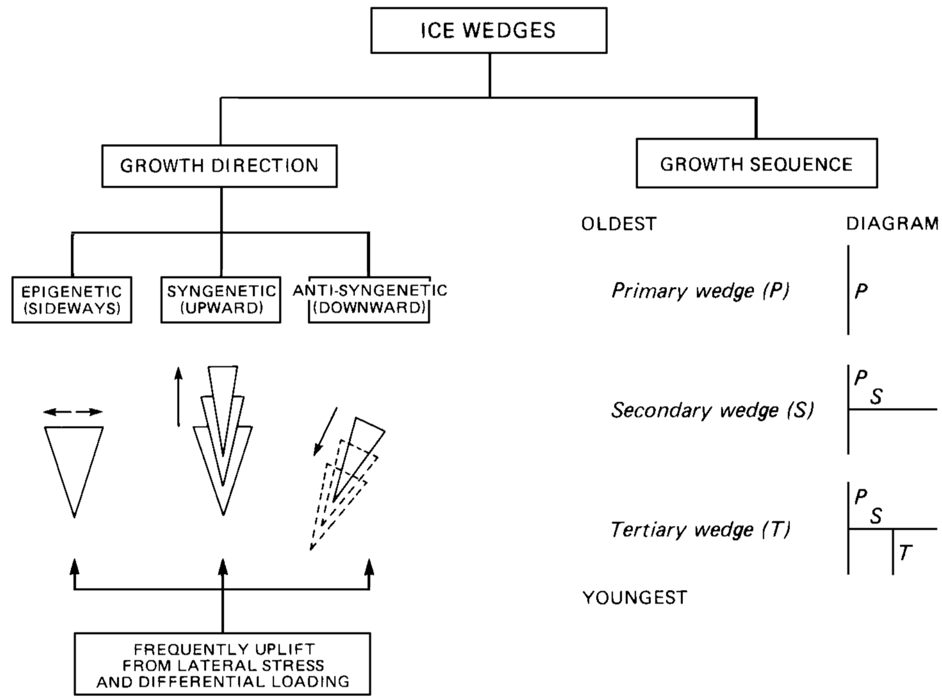


FIGURE 2. Classification system for ice wedges that is based upon the growth direction and growth sequence. The ice wedges are shown in cross sections in vertical profiles. An epigenetic wedge grows in a stable area where the growth is in width but not in height; a syngenetic wedge grows progressively upward at a site of permafrost aggradation; and an anti-syngenetic wedge grows downward at a site where there is removal of material, as by mass wasting. The growth sequence, shown in plan view, is from primary to tertiary wedges.

Système de classification des fentes de gel fondé sur la direction et la séquence de l'accroissement. Les fentes de gel sont montrées en coupe verticale. Une fente de gel épigénétique croît en milieu stable où l'accroissement se fait en largeur, non en hauteur ; une fente de gel syngénétique croît progressivement vers le haut dans un site où le pergélisol est en expansion ; une fente de gel anti-syngénétique croît vers le bas là où il y a évacuation de matériel, comme par solifluxion. La séquence de croissance, vue en plan, va des fentes primaires aux fentes tertiaires.

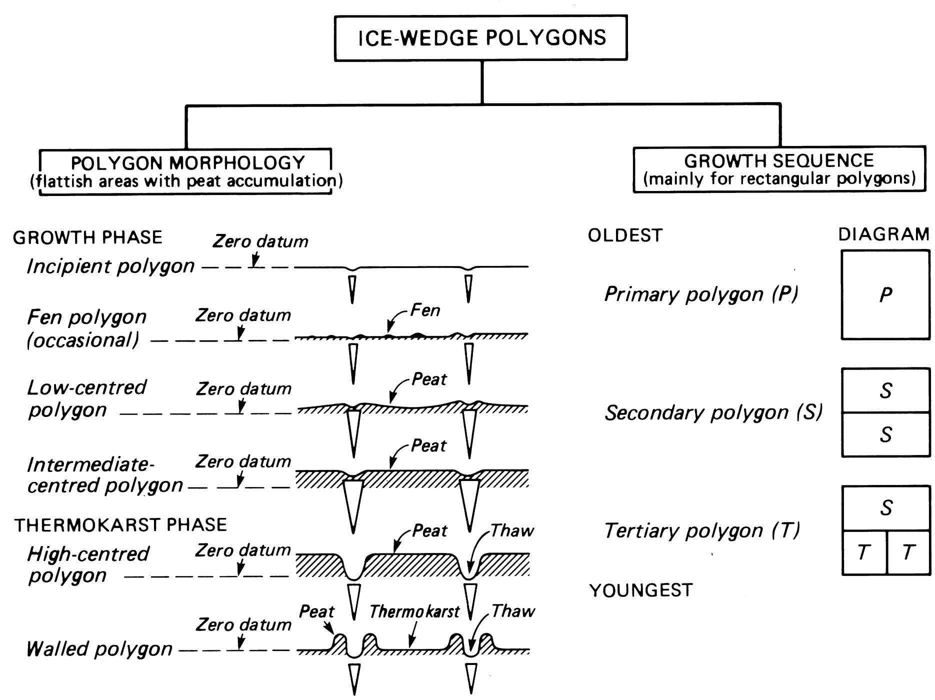


FIGURE 3. Classification system for ice-wedge polygons in flattish areas. The wedges are shown in cross sections in vertical profiles. The growth normally progresses from an incipient polygon to an intermediate centred polygon. The thermokarst phase has been subdivided, for simplicity, into high-centred polygons and walled polygons. The growth sequence, shown in plan view, is from primary polygons, which are often rectangular in homogeneous flattish areas, to tertiary polygons.

Classification des polygones à fente de glace en milieux plutôt plats. Les fentes sont montrées en coupe verticale. L'accroissement progresse normalement à partir d'un polygone naissant à un polygone à centre intermédiaire. La phase thermokarstique a été subdivisée en polygones à centre élevé et en polygones à centre entouré d'une paroi. La séquence de l'accroissement, vue en plan, va des polygones primaires, souvent rectangulaires en milieux uniformément plats, aux polygones tertiaires.

FIGURE 4. The photograph shows two individuals standing 6.5 m apart in the subdued trough of an anti-syngenetic wedge on a hillslope at Illisarvik. The width of the wedge, as determined by trenching down to wedge-ice, exceeded the distance between the two individuals.

La photographie montre deux personnes situées à 6,5 l'une de l'autre dans le sillon adouci d'une fente anti-syngénétique, à Illisarvik. La largeur de la fente, déterminée par excavation jusqu'à la glace, excède la distance entre les deux personnes.

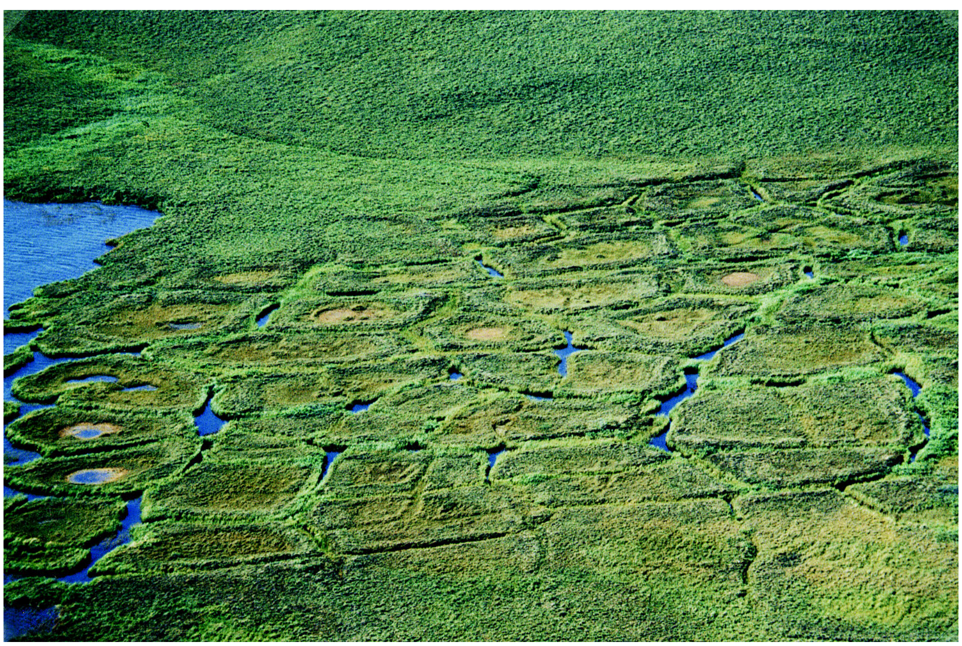


FIGURE 5. Air photograph of low-centred polygons at Garry Island, Site C, with a lake on the left side of the photograph.

Photographie aérienne de polygones à centre abaissé au site C, à Garry Island, avec un lac à gauche.

topography, is given in Figure 3. On hillslopes, where the ice-wedge troughs tend to become obscured by mass wasting (Fig. 4), differences in polygon topography tend to be minimal. Incipient polygons develop in areas with newly exposed mineral soil, such as in the low seaward islands of the Mackenzie Delta and in the bottoms of recently drained lakes. Fen polygons, which are characterized by peaty ridges usually aligned at right angles to a sluggish surface drainage, tend to develop where there is a downslope flow, particularly during the snowmelt period. The ribbed patterns are not restricted to permafrost areas (*e.g.* Zoltai and Tarnocai, 1975; Seppälä and Koutaniemi, 1985). Low-centred polygons commence growth as incipient polygons but, with the gradual accumulation of peat and the displacement of material by the growth of wedge-ice, ridges usually develop parallel to the sides of the ice-wedge troughs (Fig. 5). Intermediate-centred polygons evolve from low-centred polygons by the growth of vegetation, peat accumulation, and continued deformation of the polygons from the growth of wedge-ice. The tops of the ice wedges may be squeezed upward above the original zero datum by the growth of wedge-ice, where the ice tends to be truncated by thaw. High-centred polygons, a phase of thermokarst development, result from the lowering of the water level in the ice-wedge troughs of

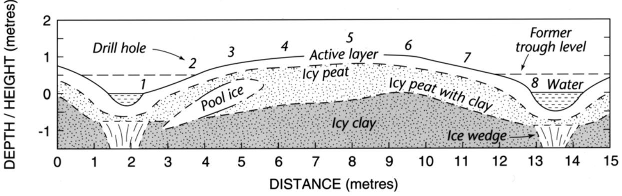


FIGURE 6. The high-centred polygon evolved from a medium-centred polygon by thermokarst subsidence in the ice-wedge troughs, following the rapid lowering of the water level in the ice-wedge troughs because of drainage of a nearby lake. The pool ice probably froze from water injected into the peat by cryostatic pressure in the adjacent ice-wedge trough, prior to lake drainage, during an autumn freeze-back period.

Le polygone à centre élevé évolue à partir d'un polygone à centre intermédiaire par affaissement thermokarstique dans le sillon de la fente de gel, à la suite d'un abaissement rapide du niveau de l'eau dans le sillon, en raison de l'assèchement d'un lac voisin. La masse de glace s'est probablement formée à partir de l'eau injectée dans la tourbe par presssion cryostatique dans le sillon de la fente de gel adjacent, avant l'assèchement du lac, au cours d'une période de regel au cours de l'automne.

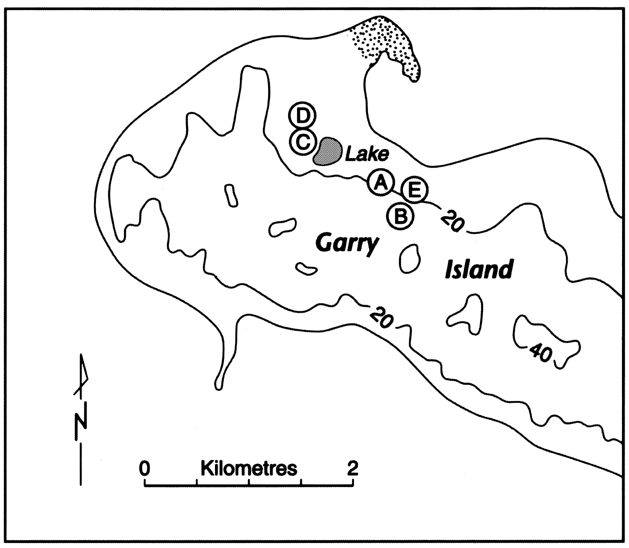


FIGURE 7. Location map for the field sites (A, B, C, D, E) on the northwest end of Garry Island. The contours are in metres.

Carte de localisation des sites (A, B, C, D, E), à l'extrémité nord-ouest de Garry Island. Les courbes sont en mètres.

intermediate-centred polygons to leave domed areas above the troughs (Fig. 6). Walled or fortress polygons (Root, 1975) are a thermokarst phase of low-centred to intermediate-centred polygons that have an exceptionally high ice content in the central part of the polygon. These polygons can develop within a decade after a rapid lowering of the water level in the ice-wedge troughs, the most common cause being lake drainage.

2. Pool ice.

Many of the low-centred to high-centred polygons have discrete masses of clear ice (Fig. 6), often referred to as pool ice (Mackay, 1988a, 1992a) or thermokarst cave ice in the Russian literature (*e.g.* Shumskiy, 1959; Shumskiy and Vtyurin, 1966; Kuznetsova, 1972). The pool ice usually forms from the underground flow of water along ice-wedge cracks in the spring (Mackay, 1974a, 1997) with subsequent freezing of water that has been trapped in underground pools or channels. Some pool ice also results from the freezing of water that has been injected into the active layer of polygon ridges by cryostatic pressure in the ice-wedge troughs during the autumn freeze-back period, similar to the water injected by hydrostatic pressure into some arctic stream banks (Kane, 1981). Pool ice may be present as discrete masses of ice beneath polygon ridges so that such ridges are particularly vulnerable to thermokarst disturbances.

3. Polygon subdivision

The growth sequences of many ice-wedge polygons are evolutionary, with some primary polygons being subdivided by transverse ice-wedge cracks to produce secondary polygons and these, in turn, further subdivided to produce tertiary polygons (Dostovalov and Popov, 1966; Kudryavtsev *et al.*, 1978, p. 151-155; Plug and Werner, 1998). Because the thermally induced stresses of a primary polygon are altered by subdivision, conclusions derived from the study of primary polygons cannot necessarily be transferred, without field study, to their component polygons.

GARRY ISLAND SITE A: 1965 - 1982

Garry Island, a glacier ice-thrust feature covered with tundra, is 11 km long, 1 to 3 km wide, and the highest point rises about 50 m above sea level (Mackay, 1971). The mean annual subsurface ground temperature is about –8 °C. Site A (Figs. 7 and 8), a small site, has only about ten polygons which defy simple classification, because they vary from incomplete low-centre polygons to incomplete high-centre polygons (Fig. 8). The polygons are at the drainage outlet of a large amphitheatre shaped depression (Mackay and MacKay, 1974). Ice-wedge cracking was monitored for 12 years, from 1967 to 1979, across nine ice-wedge cross sections (Mackay, 1992b). During the 12 winters, two out of the nine wedges never cracked; three wedges cracked once; two wedges cracked three times; and two wedges cracked four times. Therefore, the wedges were only moderately active.

MOVEMENTS OF SEMI-FLEXIBLE PLASTIC TUBES: 1965 - 1977

In 1965, in order to monitor, in vertical profile, the seasonal movements from the ground surface down into permafrost, eleven sets of semi-flexible plastic (polyethylene) tubes were inserted into augered holes to a depth of 0.5 m into permafrost (Mackay, 1981a). Each set consisted of an outer tube, 2.5 cm in outside diameter, with a smaller inner tube that fitted snugly inside the outer tube. Because all tubes had slight natural curvatures, the inner tubes were inserted into the outer tubes with their curvatures in opposite directions in order to have as straight a set as possible. In addition, at the time of installation, a steel rod was inserted into the inner tube to maintain straightness, water was

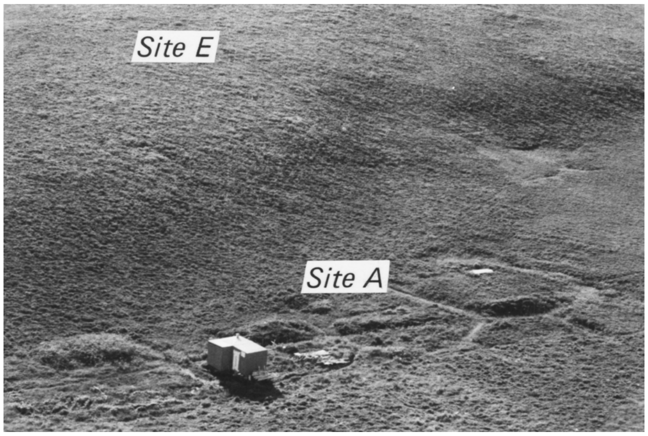


FIGURE 8. Photograph showing the polygons of Site A, a nearby small winterized field cabin, and one of the hills of Site E.

Photographie montrant le polygone du site A, un petit abri de terrain chauffé et une des collines du site E.

poured down the hole to fill the gap created by drilling into frozen ground, and the steel rod was withdrawn after the water had frozen. The tubes were located in polygon ridges, on the sloping sides of ice-wedge troughs, and in ice-wedge troughs. The tube curvatures were measured with a short strain gauge probe (Williams, 1957, 1966). Readings were made throughout the year. During the autumn and winter, there were periods when the strain gauge probe could not be pushed down some tubes into permafrost, because of inflections at the bottom of either the active layer or below the top of permafrost. The inflections appear to have resulted from differential frost heave in the freeze-back period and, after freeze-back, either from differential movements associated with thermal contraction in winter or thermal expansion in the spring. The separations between the tops of the tubes were measured to the nearest mm with a surveyor's tape, temperature corrected, and under fixed tension. When the 11 tubes were excavated in 1977, after having been in the ground for 12 years, the tops of 10 tubes had moved outward from the polygon centres towards the nearest ice-wedge troughs, the exception being tube #4 which was on an exceptionally high polygon ridge about 4 m from the nearest ice-wedge trough. The movements occurred irrespective of whether the nearest ice wedge had cracked or had not cracked in the preceding twelve winters. Typical results are shown in Figure 9. The tops of tubes #14 and #24 had each moved towards the ice wedge between them, while the tops of tubes #15 and #16 also moved towards each other, despite the fact that both tubes were anchored in the same ice wedge and the wedge had cracked only three times in 12 years. The 12-year differential movements for the tops of the tubes with respect to the bottoms ranged from 0 for #4 on a high polygon ridge to 0.4 cm a^{-1} for a tube closer to an ice wedge, similar to the data previously reported for four other tubes in the same area (Mackay, 1981a). Most of the tubes had active layer cavities on the sides facing the nearest ice wedges thus showing that the total movement at ground level exceeded the displacements of the tops of the tubes with respect to the bottoms which were anchored in permafrost. Therefore, the maximum rates exceeded 0.4 cm a^{-1} and, for the tubes with the largest cavities, probably more than 0.5 or 0.6 cm a^{-1}.

MOVEMENTS OF STEEL BENCH MARKS: 1968 - 1982

In July 1968, 30 bench marks, which were 1.5 m long steel pipes of 3.5 cm outer diameter, were inserted into augered holes at site A (Fig. 10a) to a 0.5 m depth into permafrost. Within 5 years, active layer cavities had begun to develop on the ice-wedge sides of most of the bench marks, similar to those on the ice-wedge sides of the semi-flexible plastic tubes. Furthermore, the bench marks began to tilt towards the nearest ice wedge. The tilts were measured first with a manual tiltmeter and later with an electronic tiltmeter. The 1968 to 1982 changes in separation between the tops of the bench marks are shown in Figure 10b. The separations from the polygon centres (BM 26, BM 27 and BM 30) to the bench marks near the ice wedges tended to increase, and those between bench marks on opposite sides of an ice wedge tended to decrease. The movement rates at ground level towards the nearest ice wedge were from about 0.4 to 0.5 cm a^{-1}. When allowance is made for the additional movement shown by the cavities, the rates at ground level towards the nearest ice wedge probably exceeded 0.5 or 0.6 cm a^{-1}, similar to the estimated rates for the semi-flexible tubes.

GARRY ISLAND SITE B: 1967 - 1979

The polygons in Site B (Fig. 7) have grown in a depression surrounded on three sides by higher land. Most of the polygons are intermediate-centred polygons (Fig. 3). The crack frequency was monitored for 59 ice-wedge cross sections from 1967 to 1979. Most ice wedges were inactive, because 17 wedges or about one-third never cracked, the median crack frequency was one crack in 12 years, and the maximum crack frequency was 11 cracks in 12 years.

GARRY ISLAND SITE C: 1965 - 1995

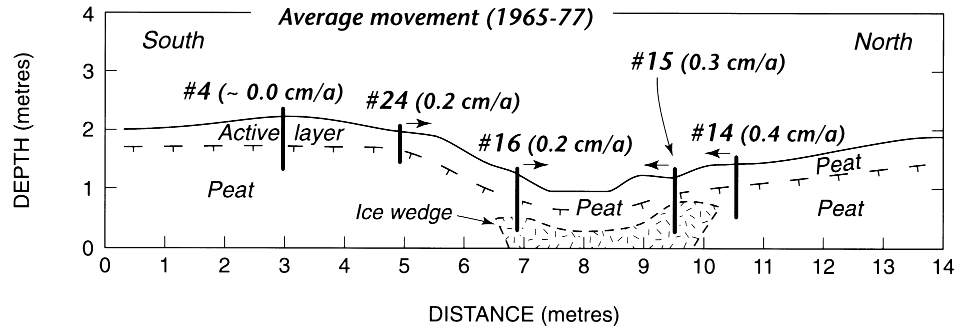
The ice-wedge polygons at Site C (Fig. 5) are in a broad flat-bottomed valley through which water from a thermokarst lake flows through ice-wedge troughs to the sea. Some fen polygons border the sides of the valley. Most of the polygons are primary low-centred polygons, a few are secondary low-centred polygons, and a minority are tertiary low-centred polygons. In 1965 a group of four polygons and the nearby area was selected for a long-term study (Fig. 11).

STRATIGRAPHY

The stratigraphy at Site C, from the ground surface downward, comprises an active layer peat about 0.3 to 0.5 m or more in thickness; below, in permafrost, a hard icy peat from about 0.75 to 1.25 m; and below that an icy clay to at least 2 m, the maximum depth of drilling. Although the surface of the clay was probably horizontal prior to the accumulation of the peat, the present peat-clay contact is involuted with pods of clay having been squeezed upward into the peat. When the peat above the clay accumulated to a depth greater than

FIGURE 9. Partial cross section of two polygons at Site A showing the average 12 year (1965 to 1977) rate of movement of the tops of five semi-plastic tubes installed into permafrost.

Coupe partielle de deux polygones du site A illustrant le taux de déplacement moyen réparti sur 12 ans (1965-1977) de la partie supérieure de cinq tubes semi-plastifiés enfoncés dans le pergélisol.



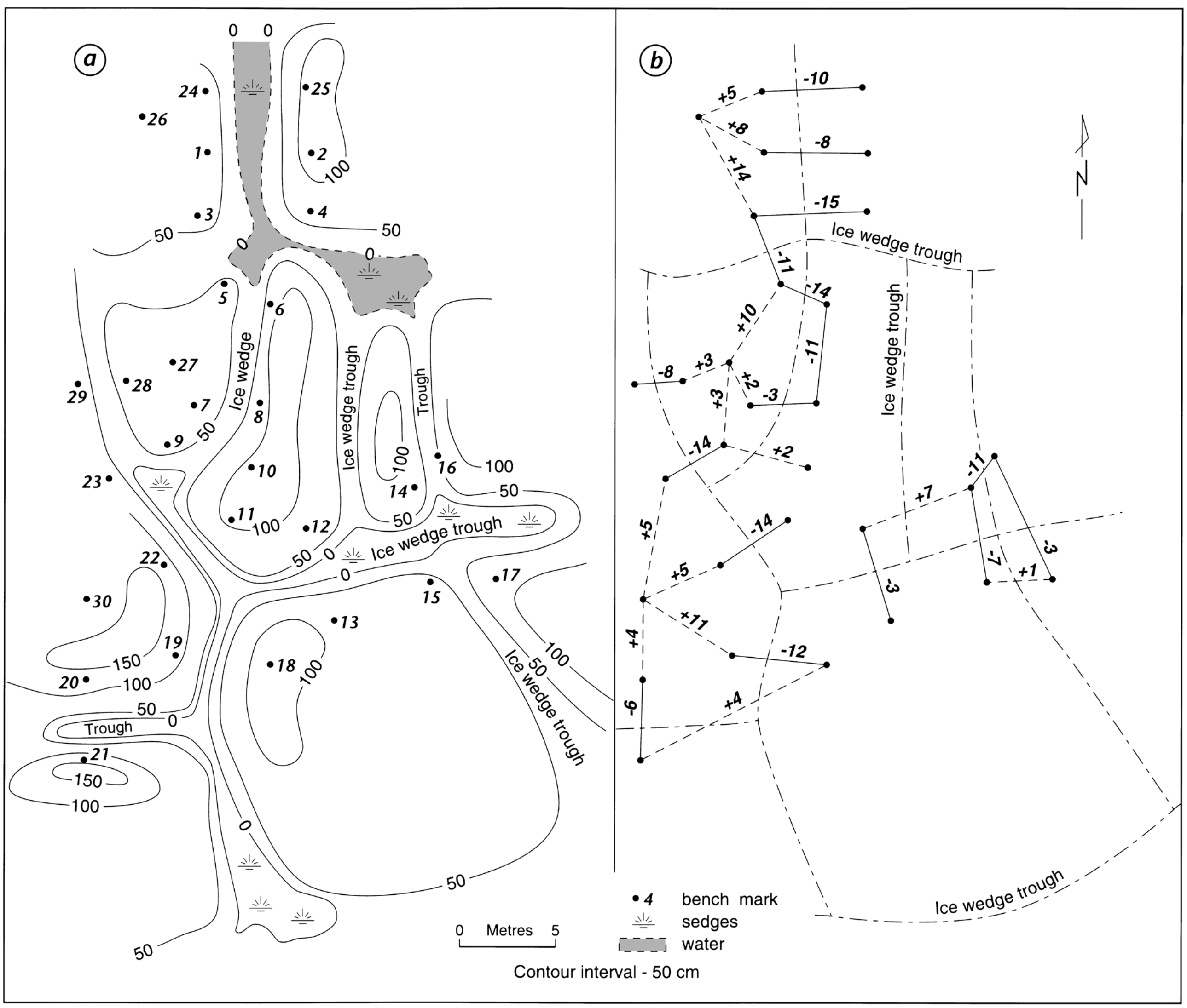


FIGURE 10. (a) Contour map of the polygons at Site A showing the locations of the 30 bench marks installed in 1968 into permafrost. (b) Changes in separation, in cm, between the tops of the bench marks from 12 July 1968 to 7 August 1982.

a) Courbes de niveau des polygones du site A, montrant l'emplacement des 30 repères installés en 1968 dans le pergélisol ; b) changements dans l'écart (en cm) entre les parties supérieures des repères, du 12 juillet 1968 et le 7 août 1982.

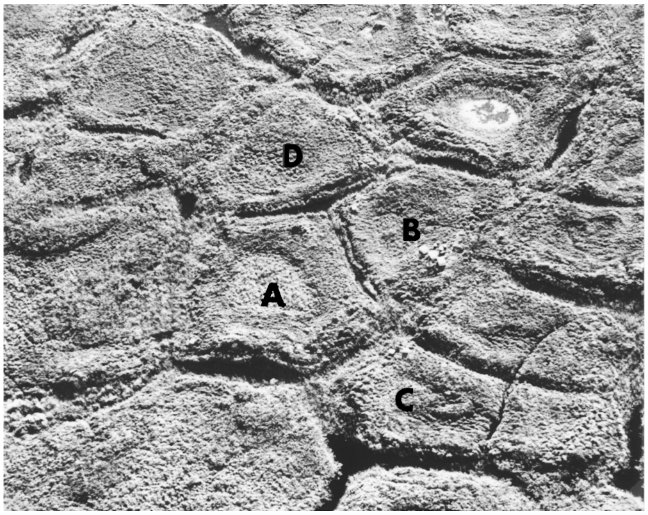


FIGURE 11. Vertical air photograph showing the principal research area of Site C. Polygons A, B, and D are primary polygons and Polygon C is a tertiary polygon.

Photographie aérienne montrant la principale partie à l'étude du site C. Les polygones B et D sont de de type primaire, tandis que le polygone C est de type tertiaire.

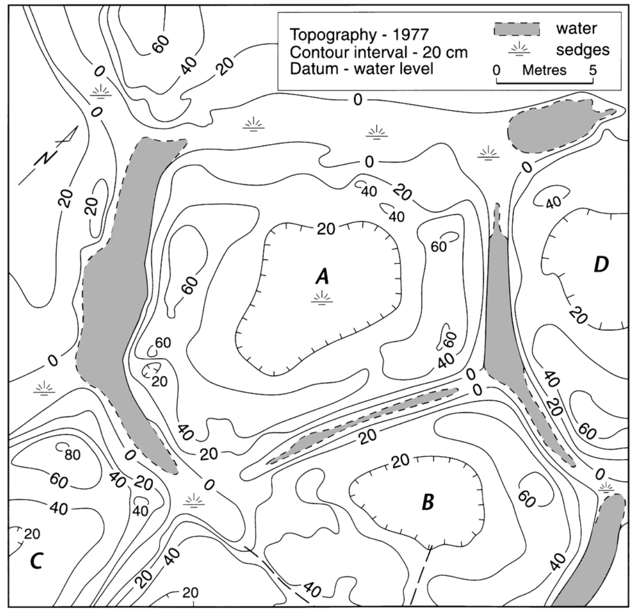


FIGURE 12. Topographic map of part of Site C showing Polygon A, Polygon B, parts of Polygons C and D, and adjacent areas. The datum was the water level in the interconnected ice-wedge troughs.

Topographie d'une partie du site C montrant les polygones A et B, certaines parties des polygones C et D et des environs. Le niveau de référence est le niveau de l'eau dans les sillons de fente de gel intercommuniquants.

the maximum depth of summer thaw, the ground surface was gradually elevated by the growth of aggradational ice in both the peat and clay which were in permafrost as shown by the very high gravimetric ice content (Mackay, 1972, 1983a; Parmuzina, 1978; Cheng, 1983; Chen, 1984; Burn and Michel, 1988; Shur and Jorgenson, 1998). In addition to the peat and clay, masses of clear pool ice, as in Figure 6, have formed from the injection and freezing of water beneath some of the polygon ridges as at Site A.

1. The active layer

The 1977 topographic map of the ground surface and the corresponding map of the depth of thaw, as defined by the 0 °C isotherm, for 8 August 1989 are shown in Figures 12 and 13. The bottom of the "active layer", as used in this paper, is the 0 °C isotherm (Muller, 1945, Fig. 20) and not the bottom of the active layer, as defined by the ice-nucleation temperature (Harris, *et al.*, 1988) which cannot be mapped in the field (Mackay, 1995b; Burn, 1998). Because the zero contour for the bottom of the depth of thaw (Fig. 13) was the water level in the interconnected ice-wedge troughs, all areas with negative contours were saturated when the maps were drawn (*e.g.* Mackay, 1963, Fig. 25). Furthermore, as the depth of thaw continued to increase for several weeks until the end of August, the saturated areas in the autumn freeze-back period would have exceeded the areas shown in Figure13. Consequently, frost heave resulted not only from the 9 % volume increase in the freezing of pore water but also from the growth of segregation ice. In addition, during the freeze-back period, additional water was probably derived from the ice-wedge troughs by capillarity and possibly also by water injected into the unfrozen part of the active layer by cryostatic pressure from the adjacent ice-wedge troughs (Black, 1974; Mackay, 1974b). The amount of winter frost heave has been measured, many times, by comparing the heights that the bench marks protruded above ground level before and after freeze-back.

The gravimetric water content for more than thirty widely distributed peat samples from parts of the frozen active layers of Polygons A, B, C, and D, collected in the early summer of 1985, at depths of 0.3 to 0.5 m, ranged from about 1000 to 2000 %, an indication that there had been substantial growth of ice during the previous autumn and winter. The water for much of the ice probably came from the ice-wedge troughs during freeze-back. As the depth of thaw increased during the summer of 1985, ground subsidence was extensive where the gravimetric water content had been unusually high. The preceding observations on the extent to which the bottom of the active layer was or was not saturated at freeze-back has important implications for other polygons where the water content at the bottom of much of the active layer is controlled by the water level in the adjacent ice-wedge troughs. For example, if the water level in the polygon troughs were to increase or decrease, as from climatic or geomorphic change, the immediate response would be an increase or a decrease in the amount of frost heave in winter and subsidence in summer in those areas affected by the change. There would also be an effect, although unknown, on ice-wedge cracking in winter.

2. Ice content near the top of permafrost

In 1983, the mean gravimetric water (ice) content and dry bulk densities from the top of permafrost were obtained, from numerous drill cores from Polygons A, B, C, and D. Two typical profiles of the gravimetric water content are shown in Figure 14. The mean gravimetric water content of 19 samples of icy peat from a depth of 0.50 to 0.75 m in permafrost was 1050 %, and that for 7 samples of icy peat from 0.75 to 1.30 m, although less, still averaged 750 %. The mean gravimetric water content for 8 samples of the icy peaty-clay from the upper part of permafrost from a depth of 0.5 to 0.75 m was 420 %, and the mean of 13 samples from 0.75 to 1.30 m had decreased to 250 %, but the water content was still substantial. The dry bulk density of most samples was less than 1.0, an indication of a high organic content. The potential thaw subsidence of the upper part of permafrost was estimated by measuring the subsidence when two frozen drill cores, from permafrost, with lengths of 0.65 m and 0.75 m, were thawed in tubes of the same inner diameter as the core diameter. The supernatant water, above each of the two thawed cores, occupied about 50 % of the total core length. Consequently, if the upper part of permafrost were to degrade, as from climate change or a surface disturbance, the settlement would probably amount to about two thirds of the thickness of permafrost that had been degraded.

POLYGON DEFORMATION: 1965 - 1986

1. Movements of semi-flexible plastic tubes: 1965 - 1977

In 1965 three sets of semi-flexible plastic tubes (#5, #6, and #7), similar to those at Site A, were installed on the ridges of Polygons A, B, and D (Figs. 12 and 15) with the natural curvature of each tube being away from the nearest ice wedge. Tube #5 was near BM 14 in Polygon D; #6 was near BM 4 in Polygon B; and #7 was near BM 7 in Polygon A. The three tubes were excavated in 1977. The 12 year movement of the top of each tube, relative to the bottom which was in permafrost as at Site A, was towards the nearest ice wedge. The average 12 year rates were: 0.2 cm a^{-1} for tubes #5 and #6; and 0.3 cm a^{-1} for tube #7. Because each tube had an active layer cavity on the ice-wedge side of the tube, the 12 year rates probably exceeded the tube deformation rates by at least 50 %.

2. Bench mark separations: 1966 - 1986

In 1966, twenty-five steel bench marks, similar to those at Site A, were inserted into augered holes to a depth of 0.8 m into permafrost in Polygons A, B, C, D and three adjacent polygons (Fig. 15). The separations between the tops of more than 60 pairs of bench marks were measured summer and winter from 1966 to 1986. The results of the 20 year measurements are summarized as follows. 1) The three bench marks in the centres of primary Polygon A (BM 13), primary Polygon B (BM 1), and tertiary Polygon C (BM 24) remained stable, because the distances between the three centres remained constant, within measurement error; the seasonal changes in tilt were minimal; and cavities did not develop adjacent to the centre bench marks as they did with most of the other bench marks. 2) The distances from the centres of Polygon A (BM 13) and Polygon B (BM 1) to the bench marks on their polygon ridges all increased (Fig. 16).

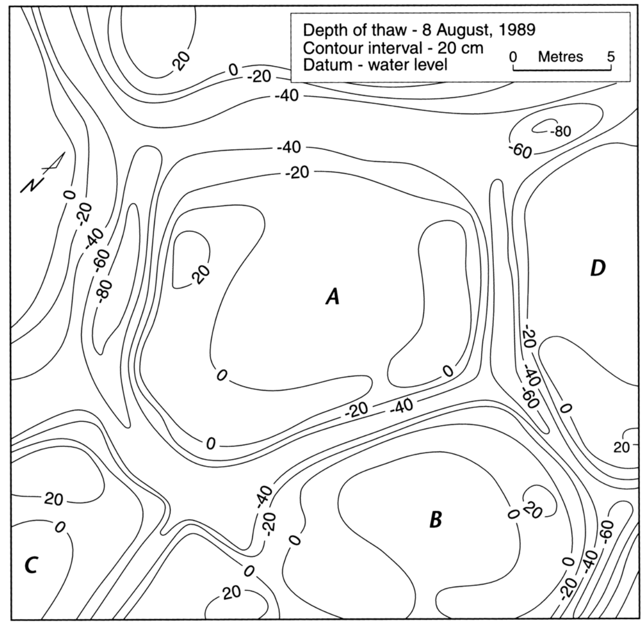


FIGURE 13. Topographic map of part of Site C of the bottom of the thawed layer for the area of Figure 12 on 8 August 1989. The depth of the thawed layer was measured at numerous points both with a soil probe and also with a calibrated temperature probe. The datum was the water level in the interconnected ice-wedge troughs. Note that all areas with negative contours were below the water level of the troughs.

Topographie d'une partie du site C au plancher du mollisol dont la superficie coïncide avec celle de la figure 12, le 8 août 1989. La profondeur du mollisol a été mesurée en différents endroits avec une tarière de sondage et une sonde à température calibrée. Le niveau de référence est le niveau de l'eau dans les sillons de fentes de gel intercommunicants. À noter que tous les parties dont les courbes sont négatives sont sous le niveau de l'eau des sillons.

3) The distances between pairs of bench marks on opposite polygon ridges of an ice-wedge trough all decreased (Fig. 17), irrespective of crack frequency. 4) The distances between adjacent bench marks on the same polygon ridge varied, some increasing, others decreasing, and a few showing no measurable change (Figs. 16, 17). 5) The distance from the stable centre of tertiary Polygon C (BM 24) to BM 22 on the nearest ridge decreased rather than increasing (Fig. 17). Although the cause of the decrease is uncertain, the stress system in what is now tertiary Polygon C was changed when the primary polygon was subdivided into secondary polygons and later into tertiary polygons (Fig. 11). 6) The increases in distance between bench marks in the primary polygon centres to bench marks on the polygon ridges (Fig. 16), when taken in conjunction with the corresponding decreases between bench marks on opposite ridges of an ice-wedge trough (Fig. 17), demonstrate that there had been a 20 year (1966-1986) outward movement of active layer material, and probably also the top of permafrost to an unknown depth, from polygon centres towards the bounding ice-wedge troughs. The outward movement occurred irrespective of cracking frequency. The total 20 year change in distance from the centre of Polygon A to the centre of Polygon B was about + 1 to + 2 cm, or within measurement error, considering the slight change in bench mark tilts.

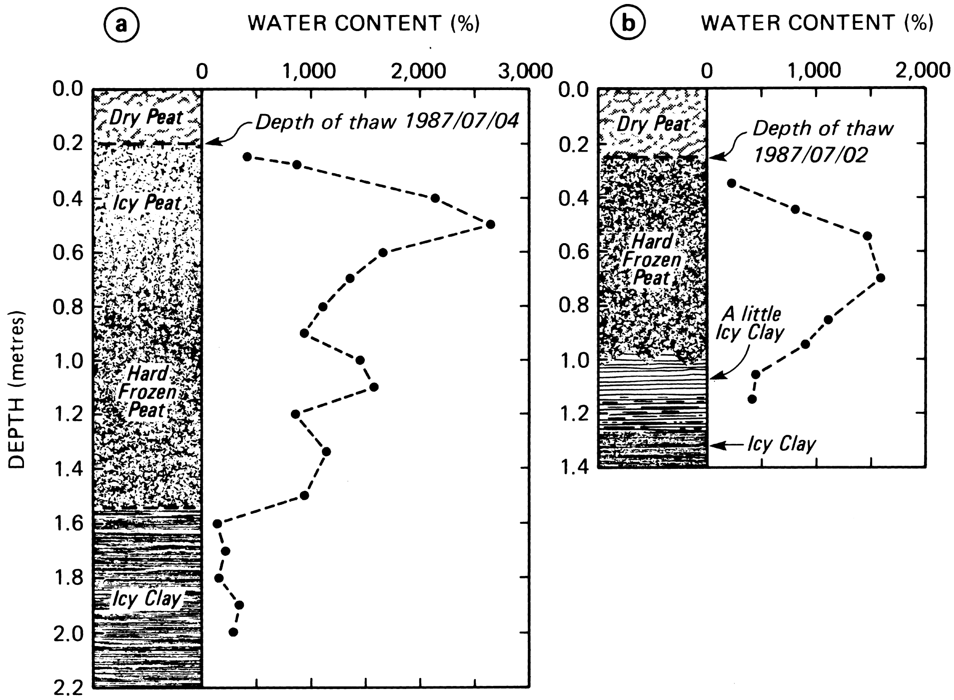


FIGURE 14. (a) Gravimetric water (ice) content of one of the 60 cm high ridges of Polygon A as drilled on 4 July, 1987. (b) Gravimetric water (ice) content for a typical site near the centre of Polygon A for 2 July 1987.

a) Teneur en eau (glace) gravimétrique de l'une des crêtes de 20 cm du polygone A, le 4 juillet 1987 ; b) teneur en eau (glace) gravimétrique dans un site caractéristique près du centre du polygone A, le 2 juillet 1987.

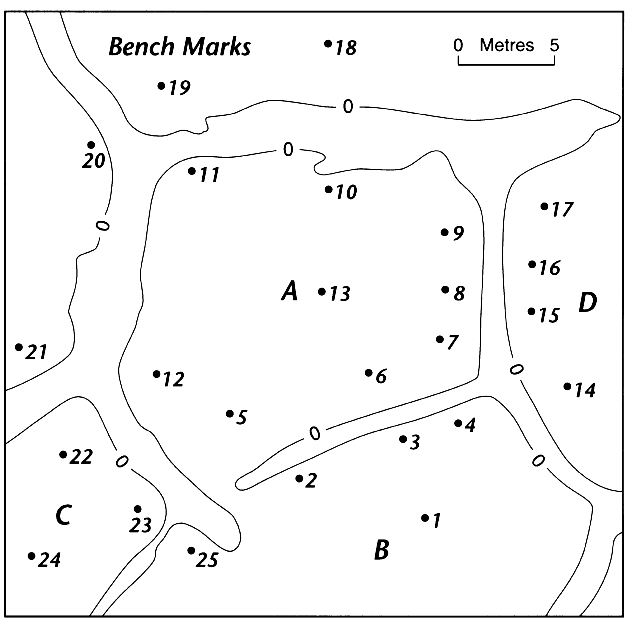


FIGURE 15. The numbers refer to the locations of steel bench marks installed in 1966 in Polygons A, B, C, D, and two adjacent polygons (See Fig. 12).

Les nombres localisent les repères en acier installés en 1966 dans les polygones, A, B, C, D et deux polygones voisins (voir la fig. 12).

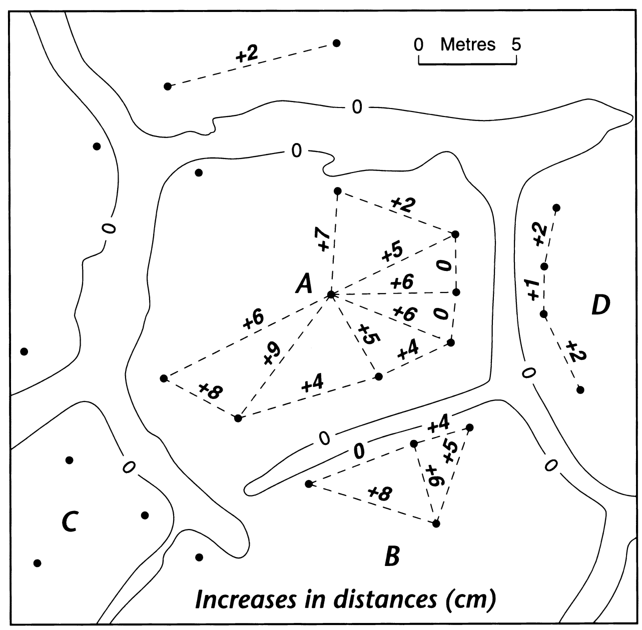


FIGURE 16. Increases in separation between the tops of pairs of bench marks (see Fig. 15) from 23 August 1966 to 15 June 1986.

Augmentation de l'écart entre les parties supérieures des paires de repères (voir la fig. 15) du 23 août 1966 au 15 juin 1986.

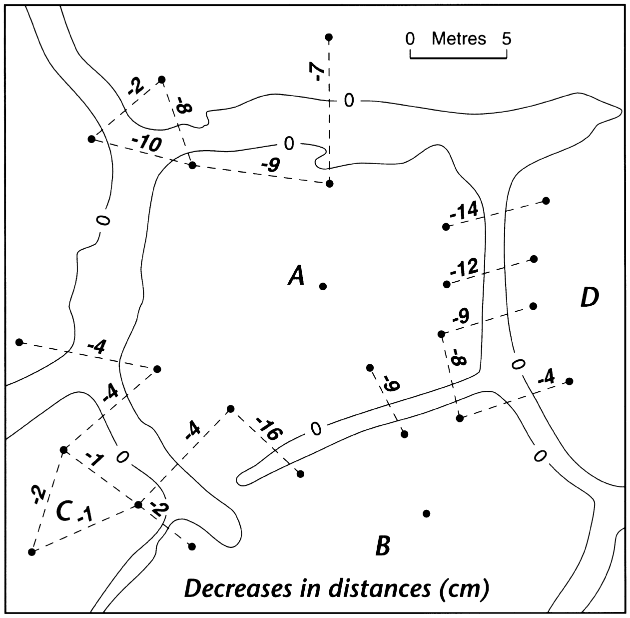


FIGURE 17. Decreases in separation between the tops of pairs of bench marks (see Fig. 15) from 23 August 1966 to 15 June 1986.

Diminution de l'écart entre les parties supérieures des paires de repères (voir la fig. 15) du 23 août 1966 au15 juin 1986.

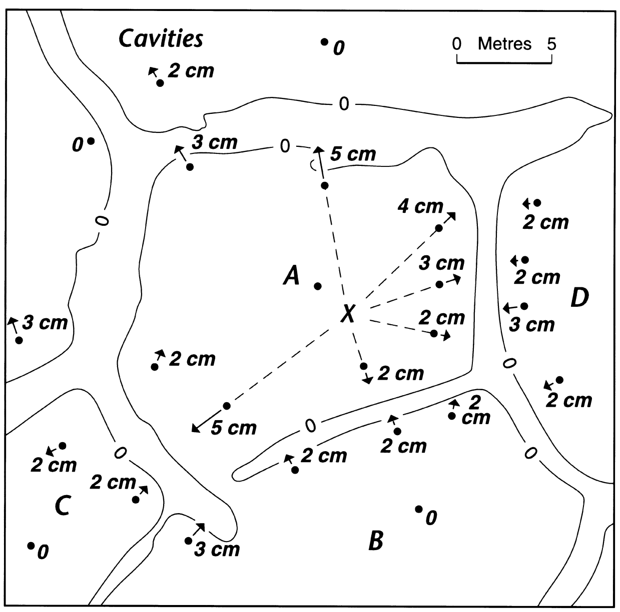


FIGURE 18. The ground surface diameters and orientations of the active layer cavities associated with the bench marks of Figure15 for 9 January 1978. There were no cavities for the bench marks in the polygon centres. The locus of outward movement for most of the cavities in Polygon A was at location X.

Le diamètre et l'orientation à la surface du sol des cavités du mollisol, en association avec les repères de la figure 15, le 9 janvier 1978. Il n'y a pas de cavité en rapport avec les repères au centre des polygones. Le lieu géométrique du déplacement vers l'extérieur pour la plupart des cavités du polygone A est situé en X.

3. Active layer cavity development

When the bench marks were installed into augered holes in 1966, the small gaps around the bench marks were infilled with soil and their existence forgotten. However, by the early 1970's, new small cavities were noticed to have developed on the ice-wedge side of many bench marks (Mackay, 1980) as at Site A. When continued observations confirmed that the cavities were enlarging, their sizes and depths were measured frequently throughout the year. In the spring (March, April, May) the sizes and depths of the cavities tended to remain constant; in summer (June, July, August) the sizes and depths of the cavities tended to increase; and in autumn and winter (September to February) both the sizes and depths of the cavities tended to decrease. Because it was evident that the cavities developed from the movement of the active layer past the bench marks, on 9 January 1978, in order to try to determine if there was a locus of outward movement, straight lines were drawn in the snow (by a field companion, in order to avoid a personal bias) in the direction opposite to that of the cavities. As shown in Figure 18, the lines converged within a small area at point X, which was about 2.8 m from the centre at BM 13. The same procedure of drawing lines in the snow was repeated in subsequent winters with similar results. The cavities reached a quasi-equilibrium size in the late 1970's (Fig. 18), probably because the distal end towards the ice wedge gradually closed from lateral pressure. Although cavities formed on the ice-wedge sides of the 1966 bench marks, which were 3.5 cm in outer diameter, fewer cavities formed on the ice-wedge sides of the smaller 2.5 cm in outer diameter bench marks installed in 1985, 1987, and 1990. The conclusion is that the larger 3.5 cm diameter bench marks impeded the movement of the unfrozen active layer past them more than the smaller 2.5 cm diameter bench marks.

4. Bench mark tilts

The bench mark tilts were measured from 1973 to 1980 with a manual tiltmeter which had the advantage over an electronic tiltmeter in that it could be used both at low winter temperatures and in blowing snow. However, in order to obtain greater precision, the manual tiltmeter was replaced in 1980 with an electronic tiltmeter (Slope Indicator Company, sensor model 50322, indicator model 50306, and plate 50323 modified for field use). Orientation keys on each bench mark, aligned in the direction of the nearest ice-wedge, ensured that the tilts were always measured in the same direction. Because tilts measured with the electronic tiltmeter were more precise than those with the manual tiltmeter, only the 5 year changes in tilts, as measured with the electronic tiltmeter from 1 June 1980 to 14 June 1985, are plotted in Figure 19. With minor exceptions, the changes in tilt, which were towards the nearest ice wedge, corresponded with the orientations of the cavities (Fig. 18), thus indicating similar responses to polygon deformation.

POLYGON DEFORMATION: 1985 - 1995

The 15 new bench marks installed in 1985 and the 12 more installed in 1987 were 2.5 cm in outer diameter, 1.55 m

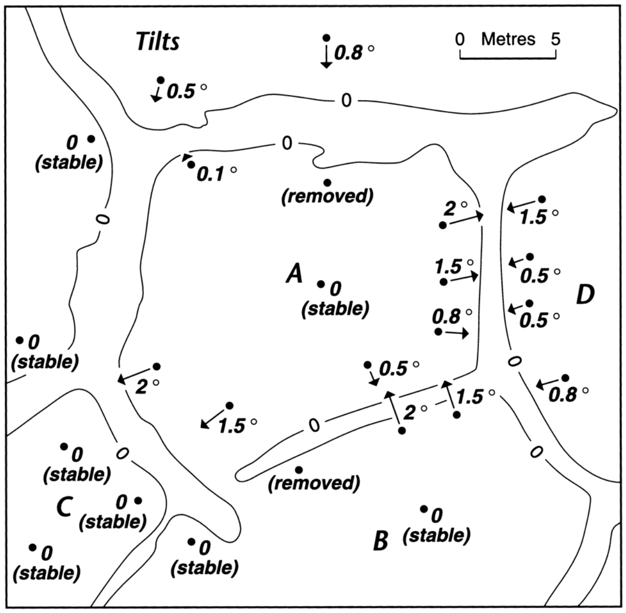


FIGURE 19. Changes in tilt, in degrees, from 1 June 1980 to 14 June 1985 for the bench marks in Figure 15.

Changements dans l'inclinaison (en degrés) des repères de la figure 15, du 1er juin 1980 au 14 juin 1985.

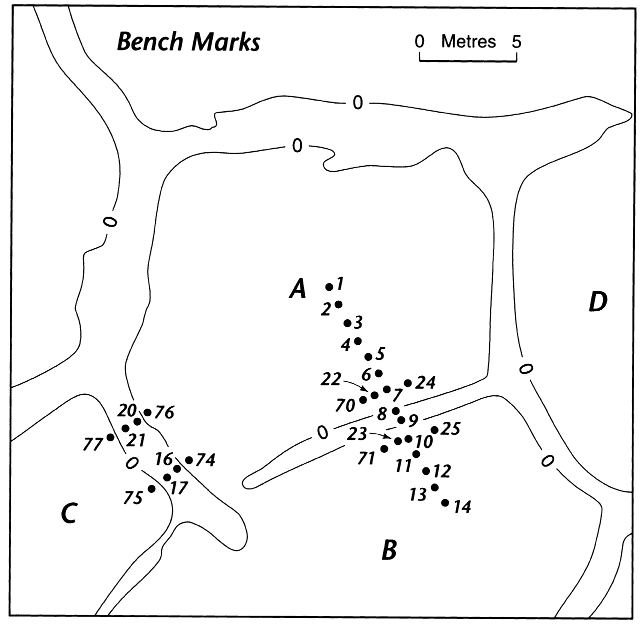


FIGURE 20. The numbers refer to the locations of steel bench marks installed in 1985 and 1987 in Polygons A, B, and C.

Les nombres localisent les repères en acier installés en 1985 et en 1987, dans les polygones A, B et C.

long, and each bench mark had a 6 cm diameter antiheave steel disk welded at the bottom in order to help minimize frost heave. The bench marks were inserted into augered holes with the bottom disks at depths which ranged from 0.7 to 1.2 m, depending upon the specific research objectives. In 1990, six additional pairs of bench marks were installed in ice-wedge troughs in order to measure deformations in both wedge-ice and the adjoining material. The 1990 bench marks were 1.85 m long, but the bottom antiheave disks were small, being only 3.8 cm in diameter, in order to minimize disturbances during installation. The locations of the 1985, 1987, and 1990 bench marks are shown in Figures 20 and 21.

1. The "pivot zone"

The bench marks on the polygon ridges tilted slightly back and forth in the direction of the nearest ice wedge in response to seasonal temperature changes. In addition, most of the bench marks developed a residual tilt towards the nearest ice wedge (Fig. 19), with the result that the separation between the tops of a pair of bench marks located on opposite polygon ridges tended to decrease year by year (*e.g.* Fig. 17). To illustrate, in Figure 22, BM A and BM B are assumed to be a pair of bench marks located on opposite polygon ridges with an ice wedge between them. Because the bench mark separations, lengths, and tilt angles (α and β) are known for every set of measurements, the corresponding bottom separations are easily calculated. Furthermore, because the amount that each bench mark protrudes above ground level, the thickness of the active layer, and the installation depth in permafrost are all known, estimates can be made as to where the fulcrum or "pivot zone" for the seasonal movements is located. For example, if the bottom separation increases and the top separation decreases, the "pivot zone" is below the ground surface but above the bottom of the bench marks; if both the top and bottom separations decrease, the "pivot zone" is in permafrost below the bottom of the bench marks; and if the separations of the bottoms of bench marks on opposite sides of an ice wedge increase, the ice wedge between the bench marks may be growing.

2. Differential movements between Polygon A and Polygon B: 1985 - 1995

A vertical profile from BM 1, in the centre of Polygon A, to BM 14, in the centre of Polygon B, is shown in Figure 23 for the bench marks in Figure 20. Typical data for 6 weeks in a summer (6 July 1987 to 17 August 1987) showing the changes in distances and bench mark tilts from BM 1 to BM 14, are plotted in Figure 24. Because BM 1 and BM 14 were stable, and the changes in distances resulted primarily from changes in tilt, the trends for the changes in distances and tilts were similar. When changes in distances and tilts are plotted for yearly periods, rather than just for the summer months, the movements of the tops and bottoms of the bench marks are roughly sinusoidal with a period of one year but out of phase so the seasonal movements for the tops and bottoms are mirror images of each other. For example, the 1987 to 1989 changes in separation between BM 1 in the centre of Polygon A to BM 7 on the polygon ridge were similar to the changes in separation between BM 14 in the centre of Polygon B and BM 10 on the polygon ridge (Fig. 25). Because both BM 1 and BM 14 in the centres of Polygon A and Polygon B remained stable throughout the year, the

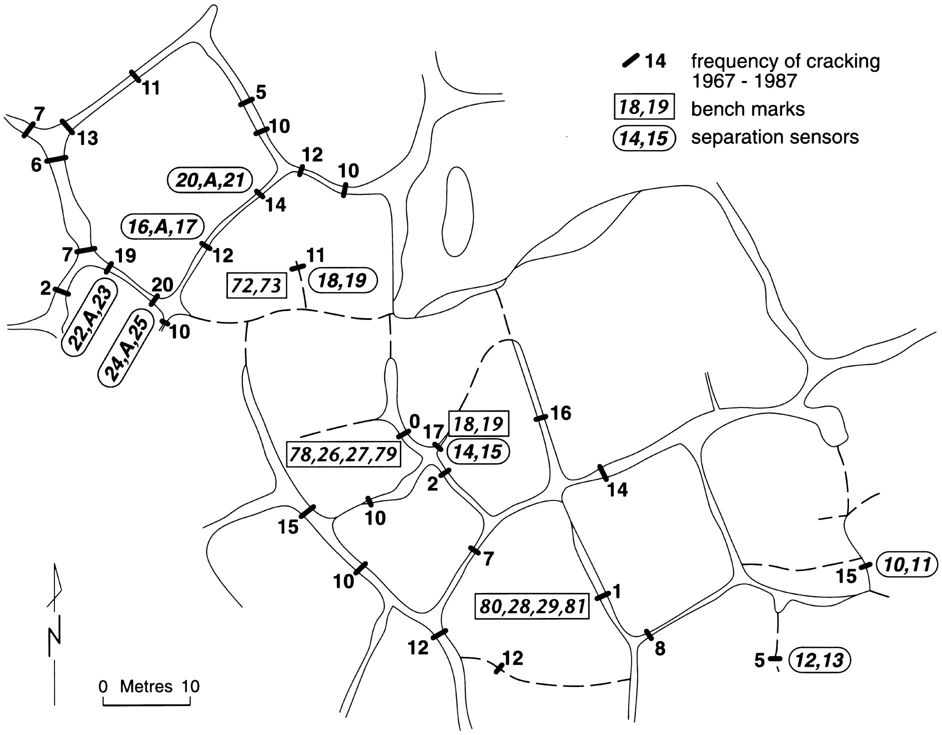


FIGURE 21. Map showing Polygon A (top left corner) and other polygons in the area of investigation at Site C. The legend gives: the 1967 to 1987 frequency of ice-wedge cracking; the locations of bench marks not shown in Figures 15 and 20; and the locations of free-floating separation sensors installed into wedge-ice.

Carte montrant le polygone A (coin supérieur gauche), ainsi que d'autres polygones dans la partie à l'étude du site C. La légende donne : la fréquence de la fissuration des fentes de gel, de 1967 à 1987 ; l'emplacement des repères qui ne sont pas montrés aux figures 15 et 20 ; l'emplacement des senseurs flottants de mesures de l'écart installés dans la glace des fentes.

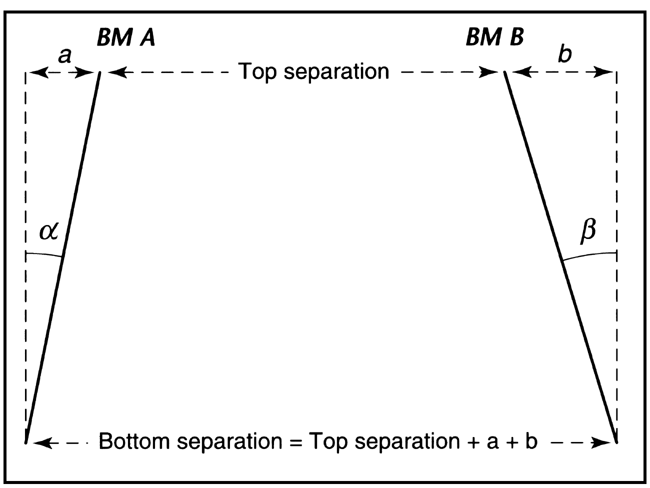


FIGURE 22. Vertical cross section showing the geometry of bench marks BM A and BM B on polygon ridges on opposite sides of an ice-wedge trough. Because the top separation between the bench marks, their tilts (α and β), and the bench marks lengths are known from measurement, the bottom separation can be calculated.

Coupe verticale montrant la géométrie des repères BM A et BM B installés sur les bourrelets latéraux d'un polygone sur les côtés opposés d'un sillon de fente de gel. L'écart entre les parties supérieures des repères, leur inclinaison (α et β) et leur longueur étant connus par des mesures, on peut calculer l'écart entre les parties inférieures.

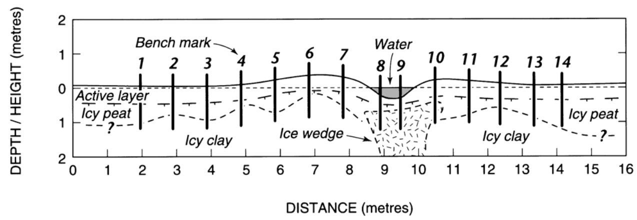


FIGURE 23. Vertical cross section from near BM 1 in the centre of Polygon A to BM 14 in the centre of Polygon B (see Fig. 20).

Coupe verticale à partir du repère BM 1, au centre du polygone A, au repère BM 14, au centre du polygone B (voir la fig. 20).

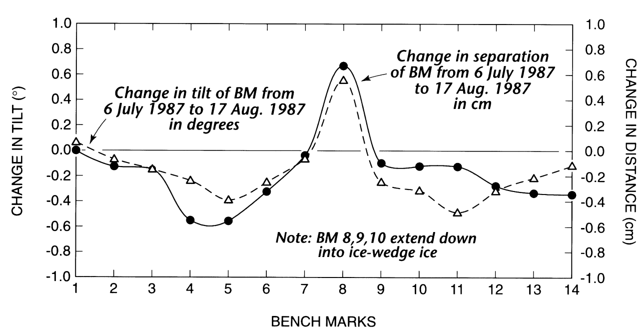


FIGURE 24. Graph showing the summer changes in distances and tilts from BM 1 in the centre of Polygon A to BM 4 in the centre of Polygon B (see Fig. 23). A positive tilt is towards the ice-wedge trough.

Graphique montrant les changements estivaux dans les écarts et les inclinaisons à partir du repère BM 1, au centre du polygone A, au repère BM 14, au centre du polygone 14 (voir la fig. 23). Une inclinaison positive se fait vers le sillon de fente de gel.

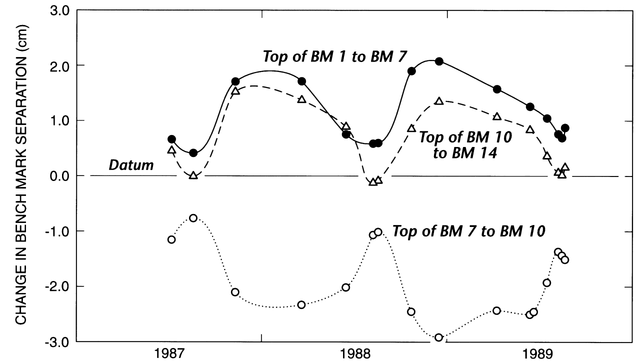


FIGURE 25. Graphs showing that the 1987 to 1989 changes in the top bench mark separations from the centre of Polygon A (BM 1) to its polygon ridge (BM 7) were similar to those from the centre of Polygon B (BM 14) to its polygon ridge (BM 10), whereas the top separations between BM 7 and BM 10 on opposite ridges (Fig. 23) were their mirror images. The maximum seasonal changes were in mid-winter and the minimums in late summer.

Graphiques montrant que les changements survenus de 1987 à 1989 dans l'écart entre les parties supérieures des repères, à partir du centre du polygone A (BM 1) jusqu'à son bourrelet latéral (BM 7), étaient similaires à ceux survenus à partir du centre du polygone B (BM 14) jusqu'à ses bourrelets latéraux (BM 10), tandis que les écarts supérieurs entre BM 7 et BM 10 sur les bourrelets opposés (fig. 23) étaient leur parfait reflet. Les changements maximaux surviennent à la mi-hiver et les changements minimaux, en été.

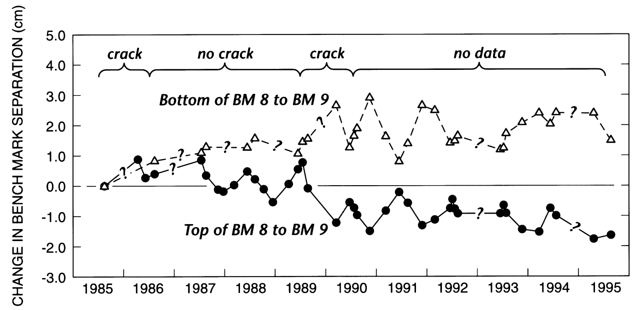


FIGURE 26. Graph showing seasonal changes in separation between the tops and bottoms of BM 8 and BM 9, which were installed down into wedge ice, between Polygon A and Polygon B (see Fig. 23). The changes in separation of the tops and bottoms resulted from ice-wedge cracking, growth of wedge-ice, the creep of wedge-ice, and probably from other factors, known and unknown.

Graphique montrant les changements saisonniers survenus entre les écarts des parties supérieures et inférieures des repères BM 8 et BM 9, installés dans la glace de la fente de gel entre les polygones A et B (fig. 23). Les changements d'écart supérieurs et inférieurs résultent de la fissutation, de l'accroissement et du fluage de la fente de gel, ainsi que d'autres facteurs, connus et inconnus.

changes in separation resulted primarily from a slight horizontal movement together with a slight tilting of BM 7 and BM 10 towards their respective centres in late summer (*i.e.* August) and away from the centres in mid-winter (*i.e.* January and February). Therefore, the changes in separation between BM 7 and BM 10, on opposite polygon ridges, moved in seasonal curves, the mirror images of those from the polygon centres (Fig. 25).

3. Movement in an ice wedge: 1985 - 1995

In 1985 BM 8 and BM 9 were installed in the ice-wedge trough between Polygon A and Polygon B (Fig. 23). The bench marks, which were 1.55 m long, protruded about 0.35 m above the water level in the ice-wedge trough, the active layer was about 0.45 m thick, and the bench marks extended down about 0.75 m into permafrost. The lowest 0.50 to 0.60 m of the bench marks were in wedge-ice. The separation changes between the tops and bottoms of BM 8 and BM 9, for the 1985 to 1995 period, shown Figure 26, moved seasonally with those for the tops and bottoms being mirror images. The pivot zone appears to have been at, or close to, the bottom of the active layer. In the 1985 to 1995 period the separation decreases and increases between the tops and bottoms of BM 8 and BM 9 were variable, although the general trend suggests a net decrease of about 1.5 cm for the top separation and a net increase of about 2 cm for the bottom separation (Fig. 26). Here it should be stressed that the seasonal movements and the progressive distance changes occurred irrespective of whether the ice wedge between the bench marks cracked, as it did in the winters of 1985/86 and 1989/90, or when it did not crack, as in the winters of 1986/87, 1987/88 and 1988/89 (Mackay, 1993a).

4. Movements in the active layer and subjacent permafrost

Four pairs of rigid bench marks of increasing lengths were installed to increasing depths on opposite ridges of Polygon A and Polygon B (Figs. 20 and 27) with the tops protruding the same height above ground level. BM 24 and BM 25, the shortest bench marks, were installed to a depth at 0.7 m below the ground surface; BM 22 and BM 23, the next in length, were installed to a depth of 0.95 m; BM 7 and BM 10, the next in length, were installed to a depth of 1.20 m; and BM 70 and BM 71, the longest pair, were installed to a depth of 1.5 m. The changes in separation for the tops and bottoms of the four pairs of bench marks, for the 1990 to 1992 period, are plotted in Figure 28. The seasonal oscillations were similar to those shown in Figure 25. However, when the data are plotted according to the installation depth, the data show an inverse relation between the top separations and the installation depths (Fig. 29). The decreases and increases between the tops were greatest for BM 24 and BM 25, the shortest pair of bench marks, and least for BM 70 and BM 71, the longest pair of bench marks. Upward and downward projections of the curves drawn through the bottoms of the bench marks for the decreases and increases in separation, as plotted in Figure 29, show that the greatest zone of movement was probably in the active layer and the zone of least movement was in permafrost at a depth below 1 m. An estimate can be made of the rate of movement in the active layer from the decrease in separation between the tops of BM 24 and BM 25. The 5 year decrease in separation between the tops was about -4.2 cm or about -4 cm at ground level, because of the slight tilting of the bench marks towards each other. Therefore, the 5 year ground level movement of the active layer past each

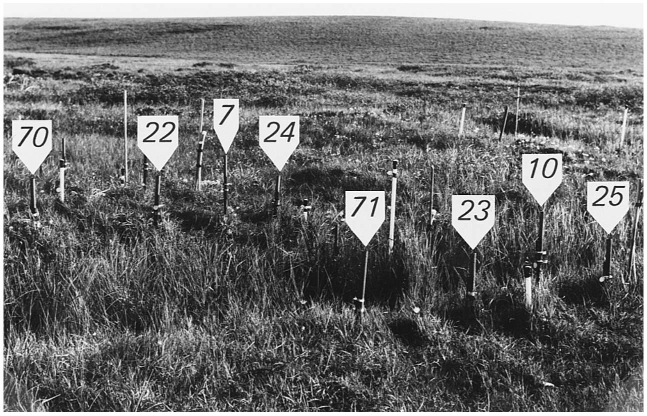


FIGURE 27. Photograph of four pairs of bench marks of different lengths installed to different depths on the polygon ridges between Polygon A and Polygon B (See Fig. 20 for locations).

Photographie de quatre paires de repères de différentes longueurs installés à différentes profondeurs sur les bourrelets latéraux entre les polygones A et B (localisation à la fig. 20).

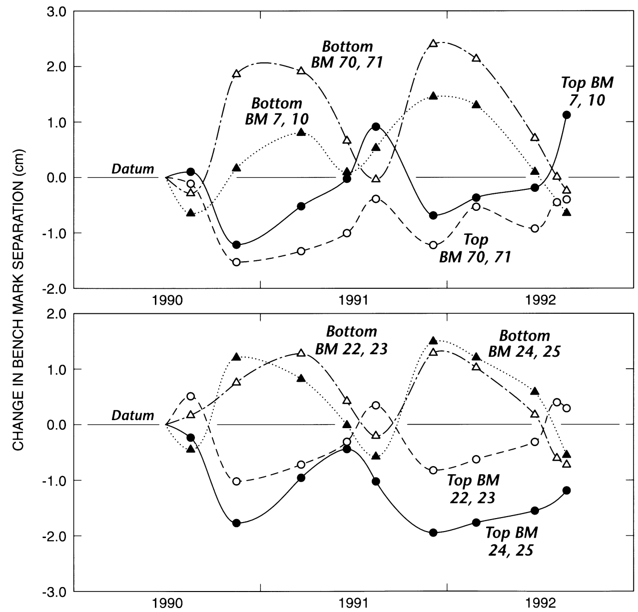


FIGURE 28. Seasonal changes in bench mark separation for the tops and bottoms of the four pairs of bench marks shown in Figure 27. Note that the bottom separations increased in winter whereas the top separations decreased.

Changements saisonniers dans l'écart des parties supérieures et inférieures des quatre paires de repères de la figure 27. À noter que les écarts inférieurs augmentaient en hiver, alors que les écarts supérieurs diminuaient.

of the two bench marks towards the ice-wedge trough was about 2 cm, for a rate of about 0.4 cm a^{-1} past each bench mark. The movement pattern suggests that if a very short pair of bench marks had been installed with the bottoms slightly above the top of permafrost, the active layer movement would have been much greater than 0.4 cm a^{-1}. The slight 0.5 cm increase in separation between the bottoms of the longest bench marks may have reflected, in part, the growth of wedge-ice as previously discussed for BM 8 and BM 9 (Fig. 26).

5. Vertical movements of bench marks: 1988 - 1995

The differences in heights among the tops of the bench marks were measured by precise levelling from 1988 to 1995 in order to assess, if possible, the extent of any vertical movements. Because the lower portions of BM 8 and BM 9 were in wedge-ice, which would have tended to limit frost heave, BM 8 was used as the initial datum for the profile from BM 1 to BM 14 (Fig. 23). When BM 8 was used as datum, the changes in height of BM 4, BM 9, and BM 14 were within the limits of measurement, about 0.1 cm; BM 2 and BM 3 had increased 1 to 2 cm in height; BM 1, BM 10, BM 12, and BM 13 had increased 3 to 4 cm in height; and BM 5, BM 6, BM 7, and BM 11 had increased 4 to 7 cm in height. Therefore, all bench marks with the exception of BM 4, BM 9, and BM 14 had increased from 1 to 7 cm in height with reference to BM 8. Although the depths of the mid-August thawed layer at each bench mark remained relatively constant during the 7 year survey period, the heights of the tops of the bench marks relative to ground level tended to increase. Because the 1988 to 1995 increase in the amounts by which the tops of the bench marks protruded above ground level tended to exceed the increases in height by several centimetres, the increases in the amounts protruding were not caused solely by frost heave. In view of the high gravimetric ice content at the top of permafrost (Fig. 14), the increase in the amounts that some bench marks protruded above ground level was probably the result of both winter frost heave and a lesser amount of summer subsidence from the thaw of a few centimetres of the top of ice-rich permafrost.

6. Separation sensors

Eight sets of “free-floating” sensors (Bison Instruments Inc., Soil Strain Gage Model 4101A) were installed at a depth of about 0.5 m below the bottom of the active layer into wedge-ice for the purpose of measuring, *in situ*, horizontal movements that resulted from ice-wedge cracking and the subsequent growth of ice veinlets (Mackay, 1993b). The sensors, which were disk-shaped coils about 10 cm in diameter and 1 cm in thickness, were installed at sites where the 1967 to 1987 cracking frequencies were known (Fig. 21). Each set consisted of either two or three parallel sensors spaced from 0.2 to 0.3 m apart with the sensor planes vertical and parallel to the sides of the trough. The readout cable from each sensor was inserted inside a rigid plastic tube whose top protruded above the surface of the ice-wedge trough (Fig. 30). An inductance bridge was used to measure the electromagnetic coupling between sensors that was used to derive the separation between each sensor pair. A surface calibration box was used to calibrate the bridge in adverse weather conditions. Regrettably, many of the readout cables or sensors became damaged, some probably by ice-wedge cracking, so only one long-term data set was obtained (Fig. 31). Although the ice wedge cracked at least four times during the 1984 to 1993 period,

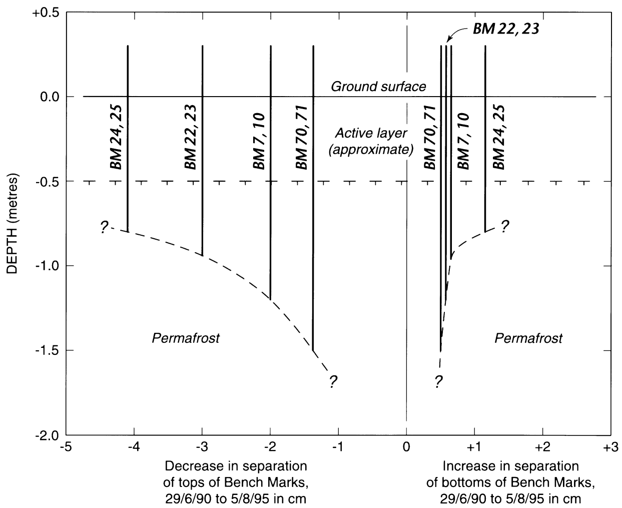


FIGURE 29. Changes in separation for the tops and bottoms of the bench marks shown in Figures 27 and 28 arranged according to the depth of installation into permafrost. See text.

Changements dans l'écart des parties supérieures et inférieures des repères des figures 27 et 28 présentés selon leur profondeur dans le pergélisol. Voir le texte.

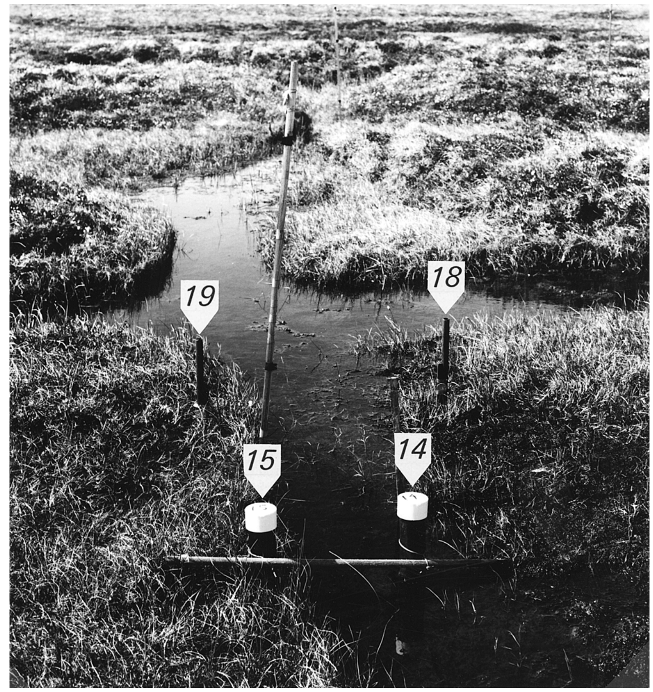


FIGURE 30. The two free floating sensors (#14 and #15) were installed about 0.5 m below the bottom of the active layer into wedge-ice. The two nearby steel bench marks (#18 and #19) were installed to a depth of 1.2 m below trough level and so into permafrost (see Fig. 21 for locations).

Les deux senseurs flottants (n^os 14 et 15) ont été installés à environ 0,5 m sous le plancher du mollisol dans la glace de la fente de gel. Les deux repères en acier (n^os 18 et 19) ont été installés à une profondeur de 1,2 m sous le niveau du sillon, dans le pergélisol (localisation à la fig. 21).

the separation between the sensors oscillated back and forth instead of gradually increasing in response to incremental ice veinlet growth. However, variations in sensor separation were expected, because previous measurements of the *in situ* widths of ice-wedge cracks at different depths had shown that thermal expansion from the downward propagation of the spring warming temperature wave gradually narrowed or even closed some ice-wedge cracks before snowmelt could enter them in the spring thaw period of May to early June (Mackay, 1975a, 1988b). Nevertheless, during the 1984 to 1993 period, there was a gradual net increase in the sensor separation of about 2 cm. The corresponding changes in the separations of the tops of BM 18 and BM 19, which were less than one metre away and on either side of the same ice wedge as the sensors, are shown in Figure 32. If the data for the overlapping period of 1985 to 1993 are used for both the sensors and the bench marks, the separations of both the sensors and the tops of BM 18 and BM 19 increased about 2 cm, whereas the separations of the bottoms of BM 18 and BM 19 increased only about 1 cm. Nevertheless, at the time of cracking the increase in separation between the bottoms of the bench marks, at times, exceeded 2 cm. The difference is explained by the fact that a narrow syngenetic wedge, confirmed by excavation, had been growing, since at least 1970, from the epigenetic wedge below. Previous studies had shown that when a crack recurs along the same line on the frozen surface of an ice-wedge trough, the surface crack results from the upward propagation of an ice-wedge crack from a narrow syngenetic wedge below (*cf.* Figs. 33 and 34). In Figure 32, data are shown for the separations between the tops of BM 18 and BM 19 and also those for the tops of BM 16 and BM 17, which were 40 m distant in Polygon A. The objective of using the two graphs is to show a common pattern of movement for ice wedges that crack frequently, because, between 1967 and 1987, the ice wedge between BM 18 and BM 19 cracked seventeen times and the wedge between BM 16 and BM 17 (Fig. 20) cracked twenty times (Fig. 21). Another example of the increase in separation was for sensors #18 and #19 (Fig. 21) where the increase from 1984 to 1991 was about 1.5 cm at a site where the ice wedge cracked eleven times between 1967 and 1987. The mean width of an ice-wedge crack at the surface of the ice-wedge trough is usually about 1 cm or less and the width tapers downward to the top of wedge-ice (Mackay, 1973, 1974a, 1974b, 1984, 1992b). Thus, when the data for the sensors and crack frequencies are combined, the long-term increases in the widths of the ice wedges were substantially less than the sum of the widths of the ice-wedge cracks at the tops of the ice wedges, as determined by probing in winter.

MOVEMENTS OF SEMI-RIGID PLASTIC TUBES: 1971 - 1994

In 1971, four semi-rigid PVC (polyvinylchloride) plastic tubes, 5.1 cm in outer diameter and 4.1 cm in inner diameter, were installed to a depth of 1.5 m, or about 1 m into permafrost, with one tube in Polygon A and three tubes in Polygon B. In order to try to minimize frost heave, four anti-heave plastic rings were cemented onto each tube at

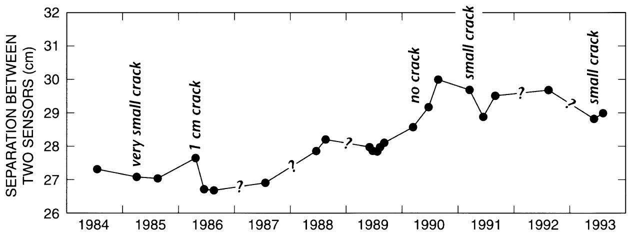


FIGURE 31. The 1984 to 1993 changes in separation for the two free-floating sensors (#14 and #5) shown in Figure 30. See text.

Les changements survenus de 1984 à 1993 dans l'écart entre les deux senseurs flottants (n^{os} 14 et 15) illustrés à la figure 30. Voir le texte.

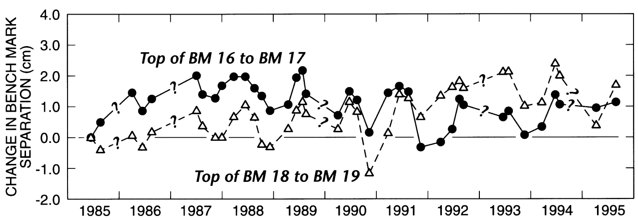


FIGURE 32. Changes in separation for the tops of BM 18 and BM 19 (Fig. 30) and also for BM 16 and BM 17 (Fig. 20).

Changements dans l'écart entre les parties supérieures des repères BM 18 et BM 19 (fig. 30), ainsi que de BM 16 et BM 17 (fig. 20).

10 cm intervals, the lowest ring being at the bottom end of the tube. The tube curvatures were measured with an inclinometer and confirmed by excavation. All four tubes were installed on polygon ridges. The first tube, installed in Polygon B near BM 3 (Fig. 15), was excavated in 1985 to provide a 14 year movement record. The top of the tube had moved about 2.5 cm towards the ice wedge and there was a cavity on the ice-wedge side. The second tube was installed on the ridge of Polygon A between BM 8 and BM 9 (Fig. 15). The tube was excavated in 1987 to provide a 16 year movement record. The top of the tube had moved about 3.5 cm towards the ice wedge and there was a slight cavity on the ice-wedge side. The third tube was installed near the top of a ridge of Polygon B in a line between BM 1 and BM 14 (Fig. 15). The tube was excavated in 1988 to give a 17 year movement record. The top of the tube had moved about 5 cm and a 4 cm cavity was on the upslope side of the ridge towards the ice wedge (Fig. 35). The fourth tube was installed in Polygon B on the same ridge as the third tube but about 3 m away in a clockwise direction. The 1971 to 1991 change in curvature of the tube, as measured with an inclinometer, is shown in Figure 36. The tube was excavated in 1994 to provide a 23 year movement record. The tube curvature, measured after excavation, confirmed the curvature as derived from the inclinometer readings (Fig. 36.) The results can be summarized as follows: 1) The tubes started to bend at depths between about 0.2 and 0.4 m in the active layer and the bends continued down into permafrost to depths of about 0.1 to 0.3 m. Because the tubes were semi-rigid, the locations of the

FIGURE 33. Photo of a drilling unit that was being used to collect a frozen core in an ice-wedge trough where, in the 1967 to 1987 period, winter observations showed that the wedge cracked 15 times along the same line at the frozen surface of the ice-wedge trough (Mackay, 1992b, Fig. 6, site 60).

Photographie de la foreuse qui a servi à recueillir une carotte gelée dans un sillon de fente de gel où, de 1967 à 1987, les observations menées en hiver ont montré que la fente s'est fissurée 15 fois le long d'une même ligne à la surface gelée du sillon (Mackay, 1992b, fig. 6, site 60).

bends in the active layer and permafrost should be considered as approximations. 2) The cavity on the ice-wedge side of each tube indicated that the movement of the active layer towards the nearest ice wedge exceeded the bending capability of the tube. 3.) The ground level movements of the four tubes towards the nearest ice wedges were at rates from about 0.2 to 0.3 cm a^{-1}. If the cavity data are added to the measured ground level movements past the tubes, the minimum movement rates were probably from about 0.3 to 0.5 cm a^{-1}. In view of the fact that the polygons have probably been growing for some thousands of years, such a movement across a polygon ridge, if maintained for the past 1000 years, would have been several metres and so would have resulted in substantial infilling of ice-wedge troughs.

DISTANCE CHANGE FROM POLYGON A TO POLYGON B: 1966 - 1995

In the 20 year period from 1966 to 1986, as discussed above, the distance change for the 1966 bench marks from the centre of Polygon A to the centre of Polygon B (Fig. 15) was + 1 to +2 cm, which was within measurement error, because of slight tilting of some bench marks. In the 10 year period from 21 August 1985 to 6 August 1995 the distance changes for the 1985 bench marks (Fig. 20) were: + 3.3 cm from the centre of Polygon A to BM 7 on the polygon ridge;- 3.4 cm from BM 7 to BM 10 on opposite polygon ridges; and + 1.1 cm from BM 10 to BM 14 in the centre of Polygon B.

FIGURE 34. Drill core collected at the drilling site of Figure 33 showing the top of a narrow syngenetic wedge that propagated upward from the epigenetic wedge at the bottom. The 20 cm long trowel provides scale.

Carotte recueillie au site de forage de la figure 33 montrant la partie supérieure d'une fente syngénétique étroite qui s'est étendue vers le haut à partir de la fente épigénétique du fond. La truelle mesure 20 cm.

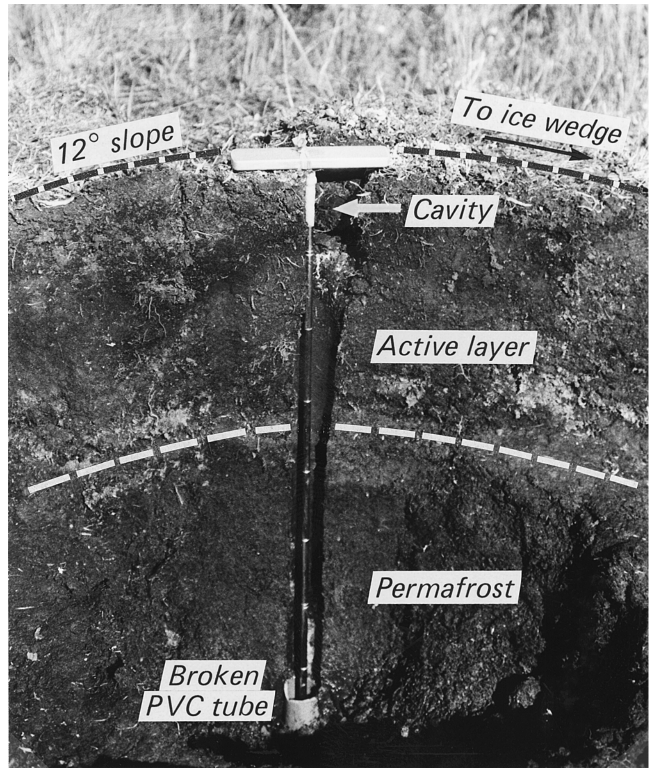


FIGURE 35. Movement of a semi-rigid PVC (polyvinylchloride) tube, 5.1 cm in outer diameter and 4.1 cm in inner diameter installed in 1971 on a ridge of Polygon B not far from BM 4 (Fig. 15) and excavated in 1988.

Déplacement d'un tube semi-rigide de PVC, de 5,1 cm de diamètre externe et de 4,1 de diamètre interne, installé en 1971 sur un bourrelet du polygone B près du repère BM 4 (fig. 5) et recouvré en 1988.

Thus, the 1985 to 1995 change from the centre of Polygon A to the centre of Polygon B was about + 1 cm, which was within measurement error. Here it should be noted that when the 1985 bench marks (Fig. 20) were installed in the centres of Polygons A and B, they were located a short distance away from those installed in the centres in 1966 (Fig. 15) so the distance changes from polygon centres should not be exactly the same. Therefore, within measurement error, the distance between the centre of Polygon A and the centre of Polygon B from 1966 to 1995 remained unchanged.

DISPLACEMENT OF MATERIAL BY ICE-WEDGE GROWTH

The ice-wedge widths at Site C have been estimated from numerous holes drilled into ice wedges for the installation of bench marks, separation sensors, and temperature cables. The minimum ice-wedge depths have been estimated from hundreds of probings of ice-wedge cracks for more than 20 winters. The data suggest that the average ice-wedge width at the top is about 2 m and the average depth probably exceeds 4 m. Because most ice wedges flare out at the top, probably from thermal expansion effects, the average ice wedge will be assumed to be 1.5 m wide at the top, 4 m in depth, triangular in cross-section and 3 m^2 in area. The growth of an average ice wedge would then have displaced about 3 m^3 of polygon material (mineral, organic, and ice) per metre of ice-wedge length or about 1.5 m^3 of polygon material on each side of the wedge. To use Polygon A as an example, the total length of ice wedges surrounding Polygon A (Fig. 12) is about 60 m; the volume of Polygon A material displaced by the growth of the 60 m of ice wedges would have been about 90 m^3; the area of Polygon A is about 250 m^2; so the average increase in height caused by the displacement of Polygon A material, if distributed evenly over the polygon, would have been approximately 0.35 m. However, because some of the displaced material would eventually become part of the active layer, thaw subsidence and many other factors would then help to explain the differences between the expected and observed amount of material displaced by the growth of wedge-ice. Because the volume increase caused by the growth of wedge-ice would tend to be concentrated on the sides of the wedge, the ridges of low-centred polygons can be attributed, in part, to the lateral displacement of material by the growth of wedge-ice, and the growth of vegetation with the accumulation of peat. However, polygon ridges are also numerous in many bare areas, such as on raised beaches in the Arctic Islands (Mackay, 1953) and in the bare sand-wedge polygon areas in Antarctica (Péwé, 1959).

GARRY ISLAND SITE D

Site D, at its nearest point, is only 30 m from Site C (Fig. 7). In the summer of 1974, two 30 m long slatted wooden snow fences, 1.2 m high, were installed 20 m apart

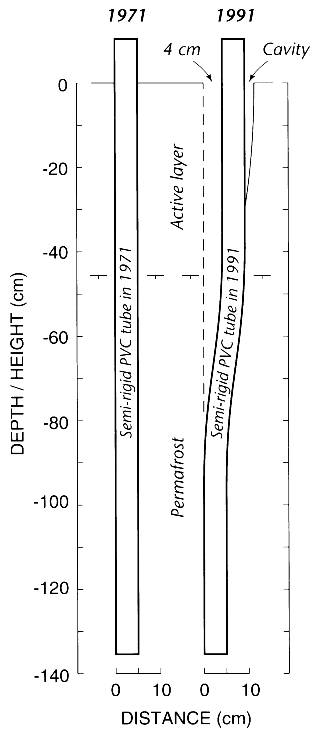


FIGURE 36. Movement of a semi-rigid PVC (polyvinylchloride) tube similar to that in Figure 35 on the same ridge but 3 m farther away. In the 1971 to 1991 period the top of the tube moved 4 cm towards the nearest ice wedge, there was a cavity on the ice-wedge side of the tube, and the bending of the tube extended down into permafrost. The tube was excavated in 1994 to provide a 23 year record of movement.

Déplacement d'un tube semi-rigide de PVC semblable à celui de la figure 35 situé sur le même bourrelet mais à 3 m de ce dernier. De 1971 à 1991, la partie supérieure du tube s'est déplacée de 4 cm vers la fente de gel la plus proche et une cavité s'est formée sur le côté de la fente de gel. Il y a eu flexion jusqu'au pergélisol. Le tube, recouvré en 1994, a fourni des données réparties sur 23 ans.

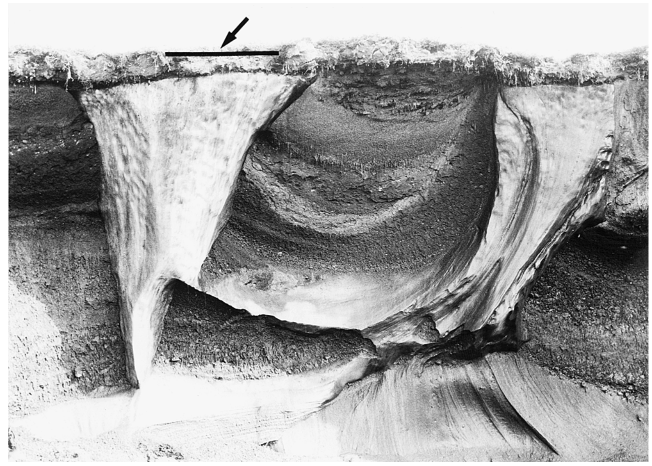


FIGURE 37. Exposure of two large anti-syngenetic wedges on the northwest coast of Garry Island in terrain similar to that of Site E. The hillslope was about 6°. The arrow points to a 2 m long black line for scale. The ice wedge was about 4 m wide at the top and the vertical extent was about 6 m. Note the absence of a trough above the ice wedge and that the top of the wedge-ice was at, or else very close to, the bottom of the active layer.

Mise au jour de deux volumineuses fentes de gel anti-syngénétiques sur la côte nord-ouest de Garry Island dans un millieu similaire à celui du site E. La pente est d'environ 6°. La flèche pointe sur une ligne noire représentant 2 m de longueur. La largeur de la fente de gel est d'environ 4 m et sa longueur, d'environ 6 m. À noter l'absence d'une dépression au-dessus de la fente de gel et la coïncidence, sinon la grande proximité, du sommet de la glace avec le plancher du mollisol.

in parallel lines to increase the winter snow depth and thereby decrease the frequency of ice-wedge cracking. The snow fences were removed in 1977. The results showed that a snow cover of about 0.6 to 1.0 m effectively prevented ice-wedge cracking for the 1974-1977 observation period (Mackay, 1978b). Studies of the distribution of snow at other sites show that the coldest winter ground temperatures are in the windblown flats, hilltops, and exposed slopes, so that the ice-wedge cracking frequency is closely associated with snow depths (Mackay and MacKay, 1974; Mackay, 1993a, 1999).

GARRY ISLAND SITE E

Site E is an area of low rolling hills (Fig. 8). Although ice-wedge polygons are numerous, the hillslope troughs are so subdued that many of the polygon patterns would be difficult to delineate without the benefit of large scale air photographs. The ice wedges at Site E have had a much more complicated history than those at Sites A, B, C, and D. Numerous exposures along the Western Arctic Coast, including Garry Island, Pelly Island, and other offshore islands (Fig. 1), and also the adjacent north coast of Alaska show that large ice wedges had been growing for thousands of years before the tops were truncated by a deepening active layer during the Hypsithermal or postglacial thermal maximum that ended about 9000 to 8000 years BP (Péwé, 1975; Mackay, 1975b, 1978a, 1983b, 1990, 1995a; Black, 1983; Burn, *et al.,* 1986; Burn, 1997). As the climate gradually cooled, following the warm period, the active layer thinned and some of the ice wedges, previously truncated during the Hypsithermal, were re-activated by upward cracking. The renewed ice-wedge growth may have started during the cooling period, possibly about 4500 BP (Ritchie, 1984). Although some of the ice wedges at Site E are probably pre-Hypsithermal wedges rejuvenated by upward cracking, there is no present method of identifying them, except, perhaps, by detailed drilling. Field studies of the downslope rate of active layer movement, carried out from 1964 to 1980 on several slopes at Site E, showed that the entire late summer active layer moved, almost as a unit, downslope at rates that ranged from 0.2 cm a $^{-1}$ to about 1 cm a^{-1} (Mackay, 1981a). Although the hilltop wedges have probably been little modified by mass wasting following the postglacial warm period, downslope mass movement on the hillslopes has probably been appreciable. To illustrate, Figure 37 shows a large hillslope wedge about 4 m wide at the top, as seen in true, not oblique, cross section (Mackay, 1977), exposed in a ground ice slump along the coast of Garry Island about due south of Site C. The wedge was on a 6° slope. Because the top of the wedge was at or very near to the bottom of the active layer, the wedge was then an anti-syngenetic wedge that was being slowly degraded by downslope mass movement. Although the ice-wedge crack frequency has not been monitored at Site E, many wedges are active, because cracks can be seen in the hard windpacked winter snow, the result of upward crack propagation from wedge-ice at depth.

In order to study the movement of the active layer at Site E, a simple device, termed a crackmeter, was used (Mackay, 1995a). The crackmeter consisted of two vertical rods that were inserted only into the active layer in the central part of an ice-wedge trough. The two vertical rods were connected by a horizontal rod which had one end attached to the top of one of the vertical rods and the other end free to slide back and forth past a marker along the top of the other rod so that changes in separation between the tops of the two vertical rods could be measured. A total of 24 crackmeters were installed on hill tops, mid slopes, lower slopes, and flats in three widely separated areas of Site E. The crackmeter separations were measured throughout the year. Subsequent excavations across four troughs showed that the widths of three wedges were 3.3 m, 3.7 m, and 4.4 m and the width of the fourth wedge exceeded 2.1 m. In each of the preceding cases, the widths of the ice wedges exceeded the separation of the two vertical crackmeter rods. Significantly, because the two vertical crackmeter rods were installed only in the active layer above wedge-ice, the separation measurements showed, for these four sites and also for the other sites, that the active layer moved seasonally inward, towards the centres of the troughs, thus confirming the observations for the numerous bench marks at Site C. Although the inward movement could only take place if there were a slow compensating downslope movement, the downslope component has not yet been measured.

DISCUSSION

The long-term data for Garry Island that have been derived from the separations between the tops and bottoms of numerous pairs of bench marks; the progressive tilts of bench marks towards the nearest ice-wedges; the bending of semi-flexible and semi-rigid plastic tubes on polygon ridges towards the nearest ice wedges; the active layer cavity development on the ice-wedge side of bench marks; the gradual infilling of some ice-wedge troughs with active layer material; the growth of syngenetic wedges in some ice-wedge troughs; and the inward movement of crackmeters installed only into the active layer above wedge-ice on hilltops, hillslopes, and lower slopes all combine to demonstrate that there is a small net summer movement of the active layer outward from the stable polygon centres towards the ice-wedge troughs, independent of crack frequency. The outward movement can be attributed primarily to the differential effects of thermal expansion and contraction, ground temperatures, the stratigraphy and the polygon relief.

LINEAR COEFFICIENTS OF THERMAL EXPANSION AND CONTRACTION

The purpose of the following extended discussion and literature review is to show that, although the thermal contraction theory for the growth of ice-wedge polygons was proposed by A.A. Bunge in 1884, more than a century ago (Shumskiy, 1959, p. 6), field data on the thermal coefficients of frozen ground are virtually non-existent, to the writer's knowledge. The coefficients of thermal expansion and contraction used in ice-wedge studies have been based upon laboratory data, primarily in the former USSR (*e.g.* Grechishchev, 1970; Shusherina *et al.,*1970; Shusherina and Zaitsev, 1976; Horiguchi, 1978; Votyakov, 1978; Ponomarjov, 1982; Lebedenko *et al.*, 1984; Bourbonnais and Ladanyi, 1985; Gamaleia and Brushkov, 1987; AL-Moussawi, 1988; Mordovskii *et al.,* 1993). The linear coefficient of thermal expansion or contraction of ice in the temperature range of ice-wedge cracking is about 5×10^{-5} °C^{-1} (Hobbs, 1974). The laboratory studies have shown that the coefficients for a great variety of frozen soils can be either much lower or much higher than that of ice, depending upon variables such as the mineralogy of the frozen material; the granulometric composition; the organic content; the variation in the unfrozen water content in cooling and warming cycles; the gravimetric water content; the degree of saturation; the gaseous component; the past thermal history; and the time required for the coefficient to stabilize after the temperature has become constant, *i.e.* the "thermal aftereffect" (Grechishchev, 1970, 1978, 1984). Yershov (1990) cites the following ranges in value in the temperature interval from – 1 to – 10 °C: the coefficient for frozen clay is from 1×10^{-2} to 1×10^{-4} °C^{-1}: in frozen sandy silts and silty clays from 1×10^{-3} to 1×10^{-4} °C^{-1}; and in sands from 1×10^{-4} to 1×10^{-5} °C^{-1}. Some laboratory tests have shown that peats, with a gravimetric water content of 400 %, may have a linear coefficient of thermal expansion as high as 3×10^{-4} °C^{-1} which is much higher than that of ice (Gamaleia and Brushkov, 1987). This observation, if applicable to field conditions, is critical, because peat with a gravimetric water (ice) content of 400 % or more is abundant in the active layer of many ice-wedge polygons under observation at Garry Island (Fig. 14) and doubtless at many other arctic sites. For some frozen soils, the coefficients may change signs in the temperature range from just below 0 °C to about -6 °C because of changes in the unfrozen water content. Furthermore, the coefficients may not be the same in the directions parallel and perpendicular to the isotherms (Grechishchev, 1984). To further complicate the field problem, the ice content in a vertical profile through the active layer down into the upper part of permafrost may vary seasonally, because of the tendency of water to move in the direction of decreasing temperature, *i.e.* downward from the active layer into permafrost in summer and upwards from permafrost into the active layer in winter (*e.g*. Parmuzina, 1978; Cheng, 1983; Chen, 1984; Lebedenko *et al.,* 1984; Mackay, 1983a; Burn *et al.*, 1986; Burn and Michel, 1988). Furthermore, according to laboratory studies, the thermal coefficients may not be the same in the directions parallel and perpendicular to the stratification (Bourbonnais and Ladanyi, 1985). The inevitable conclusion to be drawn from the preceding literature review is that the coefficients will be site specific and time dependent.

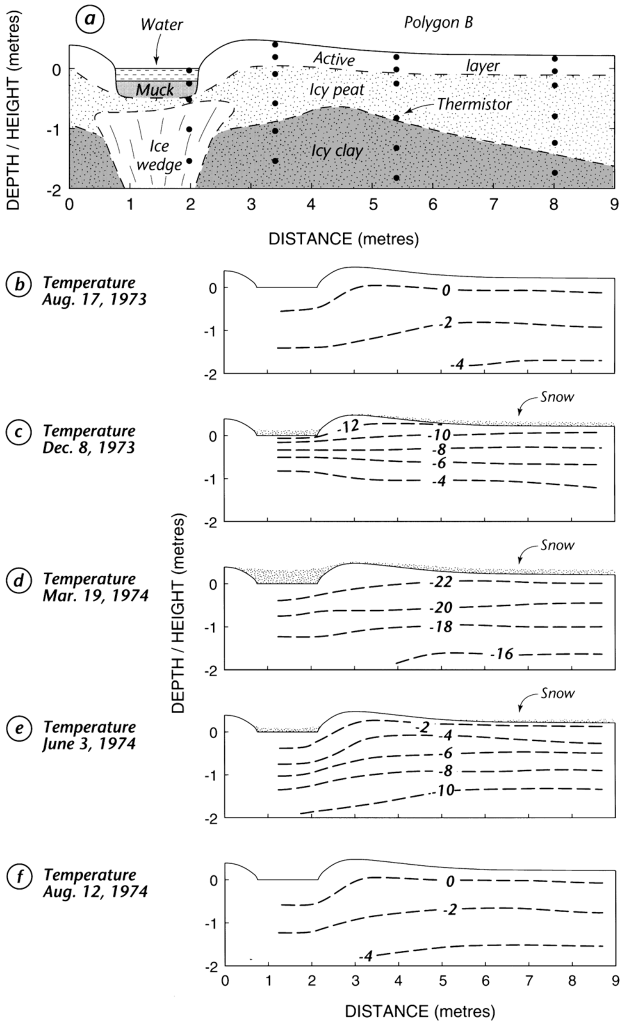


FIGURE 38. (a) A cross section of Polygon B (Fig. 23) showing the locations of the thermistor cables which were connected to recorders for continuous temperature measurements. The ground temperatures for one year, for selected dates, are given in diagrams (b) to (f). See text.

(a) Le polygone B vu en coupe (fig. 23) montrant l'emplacement des câbles de mesures thermiques branchés à un appareil qui assure des mesures sur une base continue. Les températures du sol d'une année donnée à des dates choisies sont illustrées dans les diagrammes (b) à (f). Voir le texte.

SEASONAL CHANGES IN GROUND TEMPERATURES

The seasonal changes in the thermal regime of Polygon B, Site C, are shown in Figure 38 to a depth of 2 m for one year, August 1973 to August 1974. On August 17, 1973 (Fig. 38a), the bottom of the thawed layer was near its maximum depth while the temperature at a depth of 1 m was about – 2 °C and increasing (Fig. 38b). In the next four months, from August to December, the temperature at the bottom of the active layer decreased about 10 °C whereas the temperature at a depth of 1 m decreased only about 2 °C (Fig. 38c). The temperature delay at the 1 m depth was caused by the release of the latent heat of fusion from the freezing of pore water and the growth of segregation ice during the autumn freeze-back of the active layer. From December 8, 1973 to March 19, 1974, the temperature near the bottom of the active layer decreased about 10 °C while that at a depth of 1 m decreased about 14 °C (Fig. 38d). This is the period of most frequent ice-wedge cracking (Mackay, 1993a, 1993b; cf. Allard and Kasper, 1998). From March 19, 1974 to June 3, 1974 with the approach of summer, the temperature of the active layer increased about 20 °C and that at a depth of 1 m increased about 10 °C (Fig. 38e). From June 3, 1974 to August 12, 1974, the temperature at the bottom of the active layer increased only about 3 °C whereas that at a depth of 1 m increased about 6 °C (Fig. 38f). Thus, although the linear coefficients of thermal expansion and contraction are unknown, the seasonal temperature changes with depth are of interest in attempting to interpret the movements of bench marks and plastic tubes that were installed through the active layer into permafrost.

THE TRANSPORT EFFECT

The explanation for the small net outward transport of the material in the active layer each summer and, to an unknown extent, the subjacent permafrost for Polygon A and Polygon B, which will be used as examples, appears to be as follows: 1) In the winter cooling period, thermal contraction, which is inward from the ice-wedge troughs, is constrained at the polygon centres, because of movements from opposite directions (Fig. 39a) and, for this reason, the bench marks at the polygon centres remain stable. 2) In the spring warming period, as ground temperatures rise, the thermal expansion, which is outward from the polygon centres, is unconstrained at the “free face” of the ice-wedge troughs. 3) In summer, although thermal expansion in the active layer will cease as it thaws, expansion will still continue in both the frozen part of the active layer beneath and also in the subjacent permafrost. Therefore, the thawing part of the active layer will be carried, in “piggyback” fashion, towards the ice-wedge troughs (Fig. 39b). The outward movement of the thawed and frozen active layer, to varying depths, towards the ice-wedge troughs is referred to here as the “transport” effect. The net annual long-term outward movement of the near-surface part of the active layer for the polygons at Garry Island Sites A and C, as previously discussed, ranged from about 0.4 to 0.6 cm a^{-1}; the distances from the polygon centres to the ice-wedge troughs varied from about 4 to 10 m; and the temperature rise from March to August for the active layer was usually in the range of about 20 °C (Fig. 38). If conservative values are used (*i.e.* a net movement of 0.4 cm a^{-1} in a distance of 7 m with a temperature rise of 20 °C the apparent linear transport coefficient for the near surface active layer on the polygon ridges would be about 2.5×10^{-5} °C^{-1} or about half the linear thermal expansion coefficient of ice.

INFILLING OF ICE-WEDGE TROUGHS

The outward transport of active layer material into the ice-wedge troughs, as discussed above for the polygon ridges, has been at the rate of about 0.4 cm a^{-1} or more from each side of an ice-wedge trough. The average thickness of the active layer material transported is estimated, very approximately, at about 0.1 m. The volumetric transport per metre of

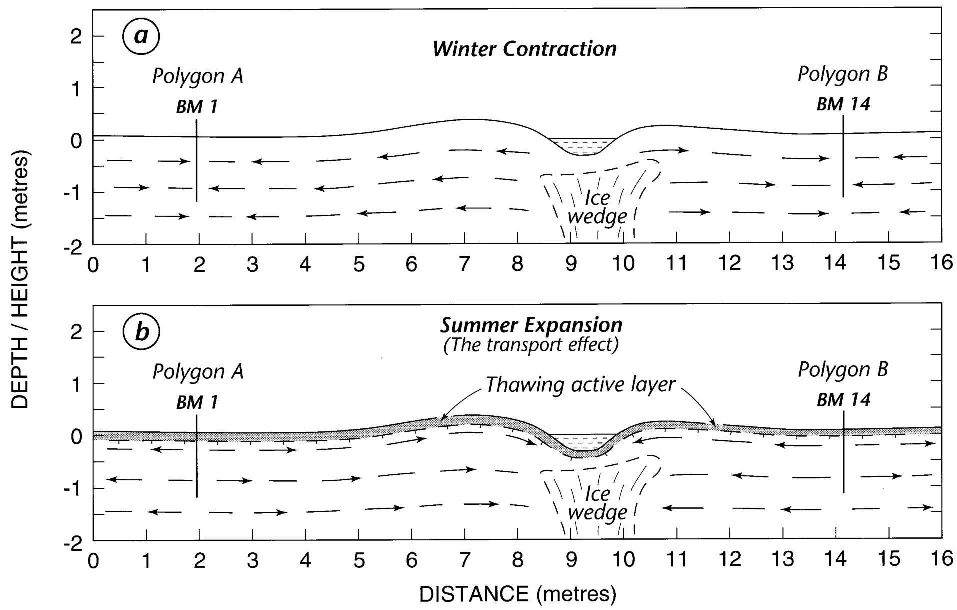


FIGURE 39. Cross sections of Polygon A and Polygon B (Fig. 23). (a) In winter, thermal contraction, which is inward (shown by arrows), is towards the polygon centres which remain stable because of movements from all directions. (b) In summer, thermal expansion is outward from the polygon centres towards the ice-wedge troughs, where movement is unconstrained, and, as a result, there tends to be a small net annual movement of the active layer, to varying depths, to the ice-wedge troughs.

Les polygones A et B vus en coupe (fig. 23). (a) En hiver, la contraction thermique, vers l'intérieur (illustrée par les flèches), se fait vers le centre des polygones qui demeure stable en raison des mouvements venant de toutes les directions. (b) En été, l'expansion thermique, vers l'extérieur à partir du centre des polygones, se fait vers le sillon de fente de gel, où le mouvement est libre ; il en résulte un faible déplacement annuel du mollisol, à des profondeurs variables, vers le sillon de fente de gel.

trough length from both ridges into the ice-wedge trough between them would then be about 0.8 m^3 or more in 1000 years. At Site C, where eight holes were drilled in ice-wedge troughs for the installation of bench marks, the thickness of peat ranged from about 0.45 to 1.2 m, with a mean of about 0.8 m. Although some of the peat accumulated from vegetation growth in the troughs, the abundance of peat in many ice-wedge troughs suggests substantial infilling for hundreds of years. Here an uncertainty exists, because the effect of infilling will depend not only upon the addition of peat to the trough but also upon the rate at which the trough widens because of the growth of wedge-ice. The gradual infilling of ice-wedge troughs by peat has resulted in permafrost aggradation and syngenetic ice-wedge growth in many troughs at Garry Island and elsewhere, because syngenetic wedges in the peat of ice-wedge troughs can be seen in numerous wave-cut exposures along the Western Arctic Coast.

ILLISARVIK

The field site at Illisarvik (Fig. 1), about 50 km due east of Garry Island, was established in 1978. On 13 August, 1978, Lake Illisarvik, which was about 600 m long and 350 m wide, was artificially drained in less than a day, with Land Use Permission, for the purpose of carrying out a long-term multidisciplinary study on the growth of permafrost and periglacial features on the newly exposed drained lake bottom (Mackay, 1981b).

OBSERVATIONS

1. The first winter's crack (1978/79)

An 80 m long thermal contraction crack opened in the winter of 1978/79, the first winter after lake drainage (Mackay, 1984, 1986, 1997). The main crack propagated normal to the contour and temperature gradient. Lateral cracks then propagated outward along the contour from the main crack. The linear coefficient of thermal contraction, as estimated from the crack widths at the ground surface, the distances between cracks, and the ground temperatures, was several times that of ice. In 1980 two pairs of bench marks (BM 43 and BM 44; BM 45 and BM 46) were installed along the first winter's crack. For the first few years the separations (ΔL) for the two pairs of bench marks moved sinusoidally (Fig. 40) like those at Garry Island (Mackay, 1993c). However, with the gradual growth of vegetation, particularly at BM 43 and BM 44, snow entrapment, and a resulting rise in winter ground temperatures (Mackay, 1999) the crack frequency declined, the seasonal changes in separation decreased, and the troughs became obliterated with summer transport of material into them.

2. A second winter's crack (1979/80)

In the second winter (1979/80) a large 100 m long thermal contraction crack opened in a flattish area, this being the largest crack system that developed in the second winter after drainage (Mackay, 1986, Site 4). In some places, the crack was more than 2 m deep. In order to measure the seasonal movements in the active layer, small "arch" type crackmeters (Fig. 41) , similar in concept to the rod type crackmeters at Garry Island, were installed along the second winter's crack and also at several other sites. The arch type crackmeters consisted of two steel rods bent into right angles with the solid end of one rod fitting into the hollow end of the other to form an inverted U. The two vertical rods were inserted about 0.3 m into the active layer to form an arch assembly. The changes in separation between the two vertical rods were measured with

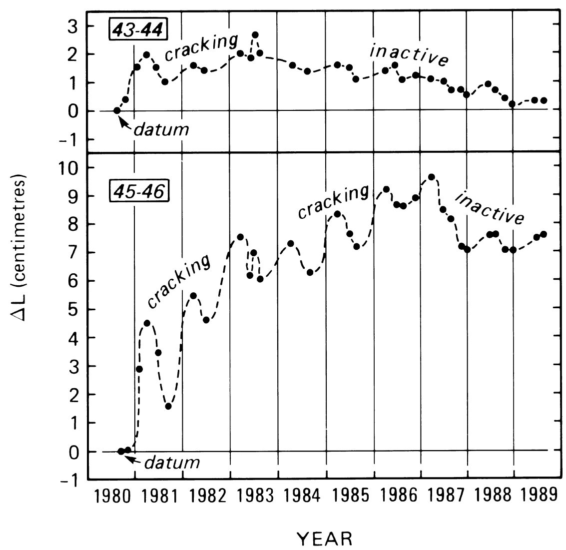


FIGURE 40. In the first winter (1978/79) after drainage of Lake Illisarvik, an 80 m long thermal contraction crack opened on the exposed lake bottom. Two pairs of steel bench marks (BM 43 and BM 44; BM 45 and BM 46), similar to those at Garry Island, were installed along the crack in the summer of 1980. The graph shows the changes in separation (ΔL) for the tops of the bench marks from 1980 to 1989.

Au cours du premier hiver (1978-1979) après l'assèchement du lac Illisarvik, une fissure de contraction thermique de 80 m de longueur s'est ouverte sur le fond du lac mis au jour. À l'été 1980, deux paires de repères en acier (BM 43 et BM 44 ; BM 45 et BM 46), semblables à ceux de Garry Island, ont été installés le long de la fissure. Le graphique illustre les changements survenus dans l'écart (ΔL) de la partie supérieure des repères de 1980 à 1989.

FIGURE 41. The photograph shows the ice-wedge trough of a crack that opened in the second winter (1979/80) following lake drainage at Illisarvik. The change in separation across the ice-wedge trough, from the previous measurement, was being measured with an "arch" type of crackmeter where the two vertical supports were inserted only into the active layer. The separation being measured was for crackmeter #85 (see Fig. 42).

La photographie montre le sillon de fente de gel d'une fissure qui s'est formée au cours du deuxième hiver (1979-1980) après l'assèchement du lac Illisarvik. Le changement dans l'écart entre les deux côtés du sillon a été mesuré avec un " fissuromètre " en forme d'arceau dont les deux tiges verticales ont été enfoncées dans le mollisol. Il s'agissait du " fissuromètre " n^{o} 80 (voir la fig. 42).

a micrometer. The ice wedge cracked every winter in the 1985 to 1989 period, and the separation change (ΔL) for each of the three crackmeters plotted in Figure 42 increased rapidly, because the ice veinlets were many times wider than those in old ice-wedge polygons. As both the crack frequency and crack widths declined from the growth of vegetation and snow entrapment, the sizes of the annual separation increments also decreased, and soil began to infill the troughs, similar to the troughs at the first winter's crack.

3. Ice wedges in hilly terrain

The ice-wedge polygons on the low hills that partially surround the Illisarvik drained lake bottom are similar to those at Garry Island, Site E. A few wedges may be rejuvenated pre-Hypsithermal wedges. In flattish hilltop areas most of the wedges are probably epigenetic wedges that commenced growth in the cooling period that followed the climatic optimum. Anti-syngenetic wedges probably predominate on receding hillslopes and syngenetic wedges where there is deposition on the lower slopes. In 1990, six of the Garry Island rod type crackmeters and six pairs of bench marks were installed across or in ice-wedge troughs. The separations between the vertical rods oscillated seasonally similar to those at Garry Island, Site E (Mackay, 1995a.). The widths of all of the ice wedges were greater than the separations of the bench marks. The width at the top of the ice-wedge, shown in Figure 4, exceeded the distance between the two individuals. The width of another ice wedge, as determined by trenching, exceeded 8.4 m. The seasonal movements of the tops and bottoms of a pair of bench marks on a 7° slope are shown in Figure 43. The bench marks were 2.65 m apart and installed in the middle of an ice-wedge trough where the width of the ice wedge, as determined by excavation, exceeded 4.1 m. The oscillations for the separations of the tops and bottoms of the bench marks, shown in Figure 43, were similar to those of BM 8 and BM 9, which were also in wedge-ice at Garry Island, Site C (Fig. 26).

SUMMARY

The movements of all bench marks and crackmeters installed on the drained lake bottom and also on the surrounding hills were similar to the movement patterns at Garry Island. Here it should be stressed that the large crack that developed in the first winter and the large crack that developed in the second winter, as discussed above, have remained as single isolated cracks and neither has since become one side of an ice-wedge polygon. The movements include those of bench marks installed into frozen ground, prior to the development of permafrost, along the first winter's crack; the movements of the arch type crackmeters installed only into the active layer along a crack that opened in the second winter; the movements of the rod type crack-

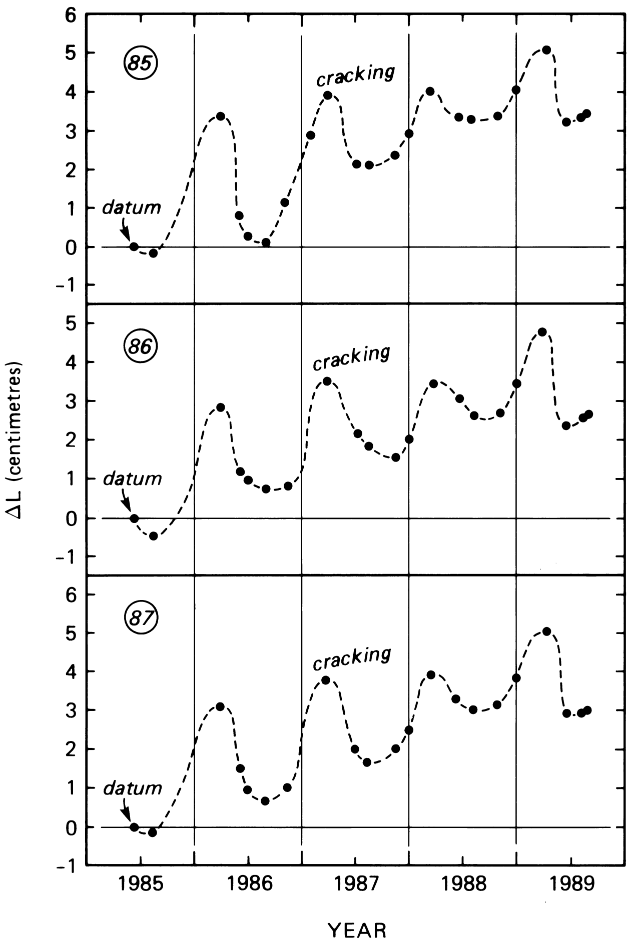


FIGURE 42. Seasonal movements of three arch type crackmeters (#85 is the crackmeter shown in Fig. 41) from 1985 to 1989. The increase in separation (ΔL) for the four crackmeters resulted from ice-wedge cracking and the growth of large ice veinlets every winter from 1985 to 1989.

Déplacements saisonniers de trois “ fissuromètres ” en forme d'arceau de 1985 à 1989 (le n^o 85 est illustré à la fig. 41). L'augmentation de l'écart (ΔL) dans tous les cas est le résultat de la fissuration de la fente de gel et de l'accroissement de grosses veinules de glace au cours des hivers de 1985 à 1989.

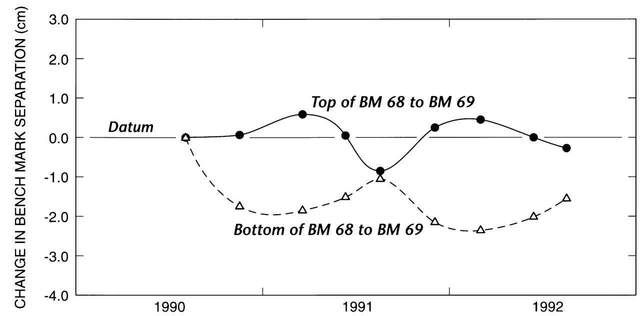


FIGURE 43. Changes in separation for the tops and bottoms of steel bench marks (BM 68 and BM 69) installed into permafrost on a hillslope at Illisarvik (Mackay, 1995a). The barely detectable ice-wedge trough trended at a slight angle to the contour on a 7° slope. The bench marks, which were 2.65 m apart, extended down into wedge-ice. The minimum width of the ice wedge, as determined by trenching, exceeded 4.1 m. The wedge was a large active anti-syngenetic wedge.

Changements dans l'écart entre les parties supérieures et inférieures des repères en acier (BM 68 et BM 69) installés dans le pergélisol de la pente d'une colline à Illusarvik (Mackay, 1995). Sur une pente de 7°, le sillon de fente de gel, à peine repérable, se trouve légèrement incliné. Les repères, dont l'écart était de 2,65 m, se sont enfoncés dans la glace de la fente de gel. La largeur minimale de la fente de gel, déterrminée par excavation, dépasse 4,1 m. Il s'agit d'une grosse fente de gel anti-syngénétique active.

meters installed only into the active layer on the surrounding hills; and the movements of bench marks installed into permafrost on the surrounding hills where most wedges are probably active anti-syngenetic wedges.

INUVIK

In 1980 observations were started at a small field site with ice-wedge polygons in the forest-tundra transition zone near the inland town of Inuvik (Fig. 1) where spruce grow on the edges of some ice-wedge troughs. No ice-wedge cracking was observed in ten ice-wedge cross sections that involved five polygons during the monitoring period from 1980 to 1988 (Mackay, 1992b). In 1990, three pairs of bench marks and three pairs of rod type crackmeters were installed on either side of ice-wedge troughs. The study, which is continuing in collaboration with C.R. Burn and L. Kutny, has confirmed, so far, the observations at Garry Island and Illisarvik.

DISCUSSION

RELEVANCE TO OTHER SITES

1. Bench mark tilts at other sites

The only example, known to the writer, of episodic long-term measurements of the separation between bench marks astride ice-wedge troughs are those in Antarctica (Black and Berg, 1963, 1966; Berg and Black, 1966; Black 1973, 1982: Malin and Ravine, 1994). Starting in 1961, steel stakes (*i.e.* bench marks) were driven to a depth of about 2 to 12 cm into permafrost on either side of more than 500 sand-wedge and ice-wedge troughs at many different sites. The stake separations were re-measured in 1969, 1982 and 1994. According to the re-measurements, many stake separations decreased between successive measurement dates (*e.g.* Black, 1973, Table I). The decreases were attributed to the time of measurement, climatic, and other factors. Stake tilts were never measured. However, it seems improbable that the stakes could have maintained their installed near-vertical angles for 30 years, without any tilting, while the active layer and subjacent permafrost underwent seasonal cycles of thermal contraction and thermal expansion and many ice and sand wedges continued to grow. Consequently, stake tilting provides a possible explanation for many of the unexplained decreases in stake separation.

2. Ice-wedges in bedrock

Although ice wedges can grow in bedrock, measurements are very few. Dyke (1984, p. 402) in describing ice-wedges in bedrock on Bathurst Island, Queen Elizabeth Islands, Arctic Canada, writes: “Resurveying of markers established on either side of troughs in the Griper Sandstone (...) shows an inward movement of blocks on the edges of the troughs. It is suggested that this represents slumping into the trough accompanying trough widening.” The movement of blocks towards the ice-wedge troughs could be the bedrock counterpart of the transport of active layer material into the ice-wedge troughs in non bedrock areas.

3. Seasonal movements in other areas

Observations on near-surface and deep-seated permafrost creep elsewhere suggest that thermally induced seasonal movements in permafrost might be relatively common. On eastern Melville Island, Queen Elizabeth Islands, Arctic Canada, an upslope creep near the top of permafrost, at some sites, may have resulted from thermal contraction (Bennett and French, 1988). At the “Involuted Hill Site” about 15 km east of Tuktoyaktuk (Fig. 1), about 3 to 10 m of diamicton overlies 10 to 30 m of massive ice which is underlain by sands (Mackay, 1963, 1983b; Mackay and Dallimore, 1992). The creep pattern, measured to a depth of 25 m, has displayed a quasi-sinusoidal downslope movement with significant upslope movement during the late winter and early summer. The fluctuation is thought to be due to the effects of thermal contraction (Dallimore*, et al.,* 1996; Foriero, *et al.,*1998).

4. Ice-wedge casts

Ice-wedge casts have been described from many parts of the world. An old feature interpreted as an ice-wedge cast, reportedly more than 2300 m.y. old, has been found near Espanola, Ontario (Young and Long, 1976) and only a few hundred kilometres away, ice-wedge casts in southern Québec provide evidence of ice-wedge polygons during the retreat of the last ice sheet between 13 000 and 11 000 years BP (Dionne, 1975). The infills of ice-wedge casts (*e.g.* Gray and Seppälä, 1991) can often be used for palaeoclimatic interpretations. Thus, the concept of the transport process may assist in the interpretation of the stratigraphy of some ice-wedge casts.

CONCLUSIONS

The conclusions discussed below have been based upon long-term summer and winter studies of numerous ice-wedge polygons which have varied greatly in type, age, size, topographic location, and vegetation cover. The general conclusions, discussed below, also apply to the single ice wedges at Illisarvik that have never become part of a polygon system. 1) In all polygons studied there tends to be a small net summer movement of part of the near surface active layer away from the polygon centres and towards the bounding ice-wedge troughs. The depths and profiles for the movements are site specific. 2) The outward transport of near surface material at the polygon ridges for the most intensively studied Garry Island sites is estimated at about 0.4 to 0.6 cm a^{-1}. 3) The linear transport coefficient at Garry Island Site C, for the polygons studied, is estimated at about 2.5×10^{-5} °C or about half the linear coefficient of thermal expansion or contraction of ice in the same temperature range. 4) Where the long-term transport of thawed active layer material into ice-wedge troughs results in trough infilling accompanied by permafrost aggradation, syngenetic wedges may grow. 5) A narrow active syngenetic wedge can usually be recognized, in winter, by repetitive cracking along the same line on the frozen trough surface, a conclusion that can be checked by drilling. 6) The data from the changes in separation of bench marks of different lengths, when combined with data from the bending of semi-flexible and semi-rigid plastic tubes, indicate that, for most of the Garry Island sites, the outward movement of material towards the ice-wedge troughs is primarily from the upper two-thirds of the active layer. 7) The graphs of the separations between the tops and bottoms of bench marks on either side of an ice-wedge trough move seasonally each year. The seasonal movements between the tops and bottoms are mirror images of each other. 8) The location of the “pivot zone” for the seasonal and long-term changes in separation of a pair of bench marks can probably be estimated from the geometry of the changes in separation between the tops and bottoms of the bench marks. 9) On hillslopes where slow downslope mass movement smooths over the depressions of an ice-wedge trough, measurements with bench marks and crackmeters show that there tends to be, nevertheless, a movement towards the centres of the underlying wedges, although the widths of some ice wedges may exceed, by many metres, the separations of both the bench marks and the crackmeters. 10) The inward movement of hillslope bench marks, anchored in wedge-ice, towards the centre of a wedge implies wedge deformation and a slow downslope movement of the active layer that is above the wedge-ice. 11) The growth rate of an ice wedge is less than the sum of the widths of the thermal contraction cracks at the top of wedge-ice. 12) It seems highly unlikely that the ages of ice wedges, such as those under study, can be estimated from crack widths at the top of wedge-ice. 13) Field observations indicate that the stress pattern in a primary polygon may not be replicated when a primary polygon is subdivided into secondary or tertiary polygons. 14) The extent to which much of the late summer active layer of an ice-wedge polygon is below or above the water levels in the ice-wedge troughs has important implications for frost heave during the freeze-back period and therefore for the response of the polygon to climate and geomorphic change. 15) Reconstructions and dating based upon the assumption of the *in situ* accumulation of material in an ice-wedge polygon may be misleading unless the probability of the outward movement of near surface material towards the ice-wedge troughs is taken into consideration. 16) In the palaeoclimatic interpretation of ice-wedge casts, the possibility that an ice-wedge cast may include material that has been transported into the ice-wedge trough from the adjacent polygons, prior to ice-wedge degradation, may be of assistance in such studies. 17) In view of the substantial evidence for the outward transport of material, it seems possible that plants near the ice-wedge troughs may, in some way, respond to the outward movement. Preliminary studies in the summer of 1998 at Garry Island and Inuvik showed that the roots of those plants that were excavated on polygon ridges and also in a flattish area close to an ice-wedge trough trailed towards the polygon centres. This preliminary observation will be explored more in the future.

ACKNOWLEDGEMENTS

I would like to express my thanks to the numerous individuals and organizations that have assisted me in my field work for more than four decades. Support has been received from: the Geographical Branch, Department of Mines and Technical Surveys, Ottawa; the National Research Council of Canada; The Geological Survey of Canada; the Natural Sciences and Engineering Research Council, Canada; the Polar Continent Shelf Project, Department of Natural Resources, Canada; and the Inuvik Research Laboratory, Inuvik, NWT. Many colleagues, field assistants, friends, and others have been of invaluable help in summer and winter field studies. I would like to thank P. A. Batson, P. Benham, J. Bellamy, D. Blythe, R. Boyd, M. J. Bovis, N. Buckley, C. R. Burn, K. E. Champion, G. H. C. Clarke, A. Collett, Cui Zhijiu, P. Davidson, C. Diana, D. F. Dickins, J. Duncan, J. Dwyer, B. Enderton, W. A. Gell, J. M. Gill, D. J. Gregory, G. Gruson, R. C. Harris, D. G. Harry, J. E. Hay, A. J. Heginbottom, S. E. B. Irwin, W. Kay, N. King, S. Kokelj, V. N. Konishchev, A. Kriss, L. Kutny, F. Lane, E. Lennie, G. O. Lougheed, D. K. MacKay, V. A. Mackay, W. H. Mathews, D. G. McPhee, M. McRae, J. V. Minghi, R. A. Myers, R. N. North, N. Oke, T. R. Oke, A. Oliver, A. Olney, J. Ostrick, S. I. Outcalt, A. J. Podrouzek, J. D. Radke, T. Randall, G. Rempel, M. S. Samuels, A. H. Siemens, H. O. Slaymaker, V. Solomatin, J. K. Stager, D. G. Steyn, G. Thompson, R. W. Toews, M. Wark, T. Watmore, B. Woods, P. Wright, and G. Wynn. Professor J. J. Solecki has translated numerous Russian publications that have made access to some of the abundant Russian literature possible. The writer would like to thank the two referees for their helpful comments. The cartography is by Paul Jance.

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