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Thaw-depth monitoring

F.M. Nixon[1]

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Abstract: Fifty-eight sites have been established along a 1200 km transect in the Mackenzie valley to monitor processes linking climate, climate change, permafrost, and the active layer. Annual maximum thaw penetration and surface movement are measured relative to thaw tubes anchored in permafrost. Active layer thickness, calculated from thaw penetration and surface movement, varies as a result of local soil properties, vegetation, and microclimate as well as regional atmospheric climate. Whereas thaw penetration has increased at most sites over the last 6–8 years, this increase is not always reflected by an equivalent increase in active layer thickness because of thaw settlement. Frequent air and shallow ground temperatures provide a complementary record at many sites. Active layer thickness influences biotic soil conditions, foundation performance, slope stability, and hydrology. Monitoring the active layer can contribute to modelling near surface permafrost and the impact of environmental change and can assist adaptation.

Résumé : Pour surveiller les processus faisant intervenir le climat, le changement climatique, le pergélisol et le mollisol, on a établi 58 sites le long d'un transect de 1 200 km traversant la vallée du Mackenzie. On mesure la pénétration maximale du front de dégel annuel et le déplacement du sol superficiel au moyen de tubes de dégel ancrés dans le pergélisol. L'épaisseur du mollisol, calculée à partir de la pénétration du front de dégel et du déplacement de la surface du sol, varie en fonction des propriétés locales du sol, de la végétation, du microclimat et du climat atmosphérique régional. Même si la pénétration du front de dégel a augmenté à la plupart des sites au cours des six à huit dernières années, cela ne se traduit pas toujours par un accroissement équivalent de l'épaisseur du mollisol en raison d'un tassement dû au dégel. Pour compléter ces données, on a mesuré les températures de l'air et du sol à faible profondeur à de nombreux sites. L'épaisseur du mollisol influe sur les conditions biotiques du sol, la solidité des fondations, la stabilité des versants et l'hydrologie. On peut se servir des observations faites sur le mollisol pour modéliser le pergélisol proche de la surface et les répercussions d'un changement environnemental et ainsi faciliter la prise de mesures d'adaptation.

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INTRODUCTION

One feature of permafrost that has responded significantly to past climate change is thickness of the active layer (Mackay, 1975, 1976). The active layer, overlying permafrost, is earth material that thaws from the surface and refreezes each year (Fig. 1). It forms the interface between permafrost and the atmosphere and biosphere, which host many human activities. Active-layer thickness influences vegetation and soil conditions, thereby influencing hunting, gathering, forestry, and agriculture. Thickness, texture, and moisture content of the active layer affects foundation conditions for transportation and construction. Changes in the active layer can contribute to slope instability, with impacts on transportation facilities and other structures. It is important to understand how the active layer varies locally and regionally, and how it will respond to environmental change.

LOCATION AND SITE SELECTION

Figures 2a and 2b show the location of 58 active-layer monitoring sites that have been established in the Mackenzie valley from Fort Simpson to the Arctic coast (Nixon and Taylor, 1994; Nixon et al., 1995). As the development of the active

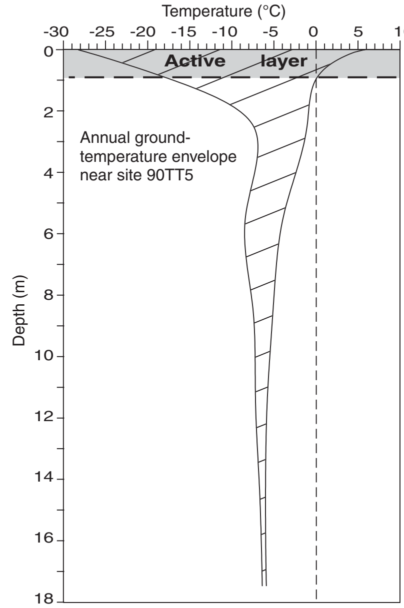

Figure 1. Annual ground-temperature variation and resulting active layer near site 90TT5 on Richards Island, Mackenzie Delta.

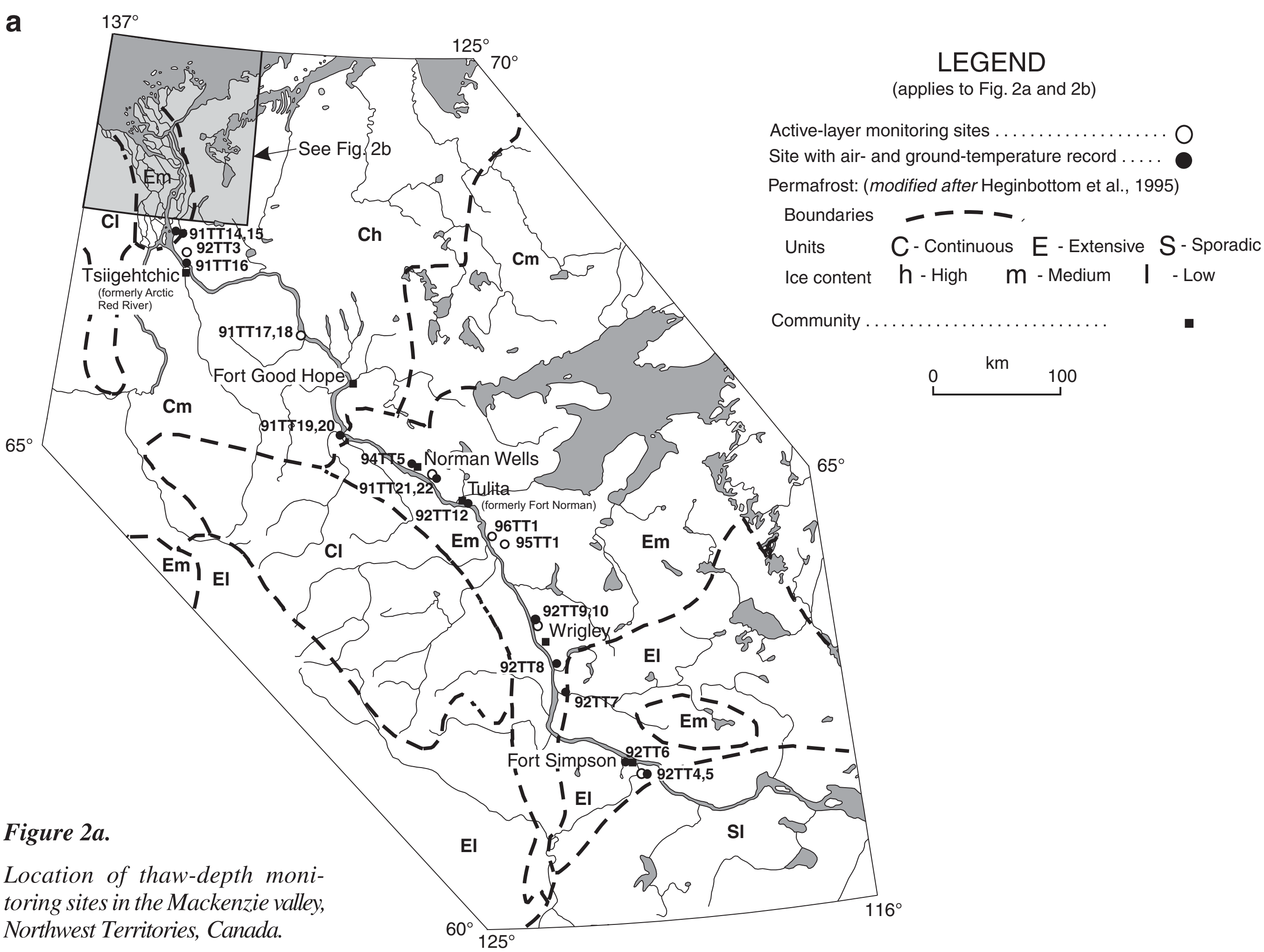

Figure 2a.

Location of thaw-depth monitoring sites in the Mackenzie valley, Northwest Territories, Canada.

layer is affected by climate, vegetation, geomorphology, hydrology, and soil properties, undisturbed sites were chosen to reflect the diversity of these factors. This system will provide a sample of the variability of active-layer thickness in space and time for the Mackenzie valley.

A number of measurements and observations were made initially at each station to characterize the local environment. Landform and surface morphology were described, slope and aspect were estimated, and elevation measured. A description of vegetation was made and soil sampling was carried out to or below the frost table for laboratory determination of moisture content and texture. Some of these observations have been summarized for each station in Table 1.

Site selection and instrumentation were co-ordinated with several other studies in the region (e.g. Gibson et al, 1993; Tarnocai et al., 1995; Mackay, 1997; Quinton and Marsh, 1998; Burgess and Smith, 2000). In particular, air- and ground-temperature data gathered by Tarnocai et al. (1995) and Taylor (1995) provide continuous thermal records at many thaw-tube sites. The transect crosses several ecoclimatic regions (Ecoregions Stratification Working Group, 1989) as well as permafrost boundaries (Heginbottom et al., 1995) and the sites have been selected to provide maximum variety of natural situations while remaining accessible within the Mackenzie valley transportation corridor.

INSTRUMENTATION

Maximum annual thaw penetration and maximum heave and subsidence of the ground surface are measured using a modified version of a frost tube developed by Mackay (1973). The device is a water-filled observation tube located in a heave-resistant access tube (Fig. 3). The ice-water interface in the observation tube corresponds to the frost table in the surrounding ground. A marker (glass bead) rests on the ice surface, descending during the thaw season to be trapped at maximum depth on freeze back in late summer or fall. Through the use of very light equipment and access to sites on foot, disturbance to the vegetation and soils during installation and observation is minimized. Most sites show nearly complete recovery after one or two seasons (Fig. 4).

b

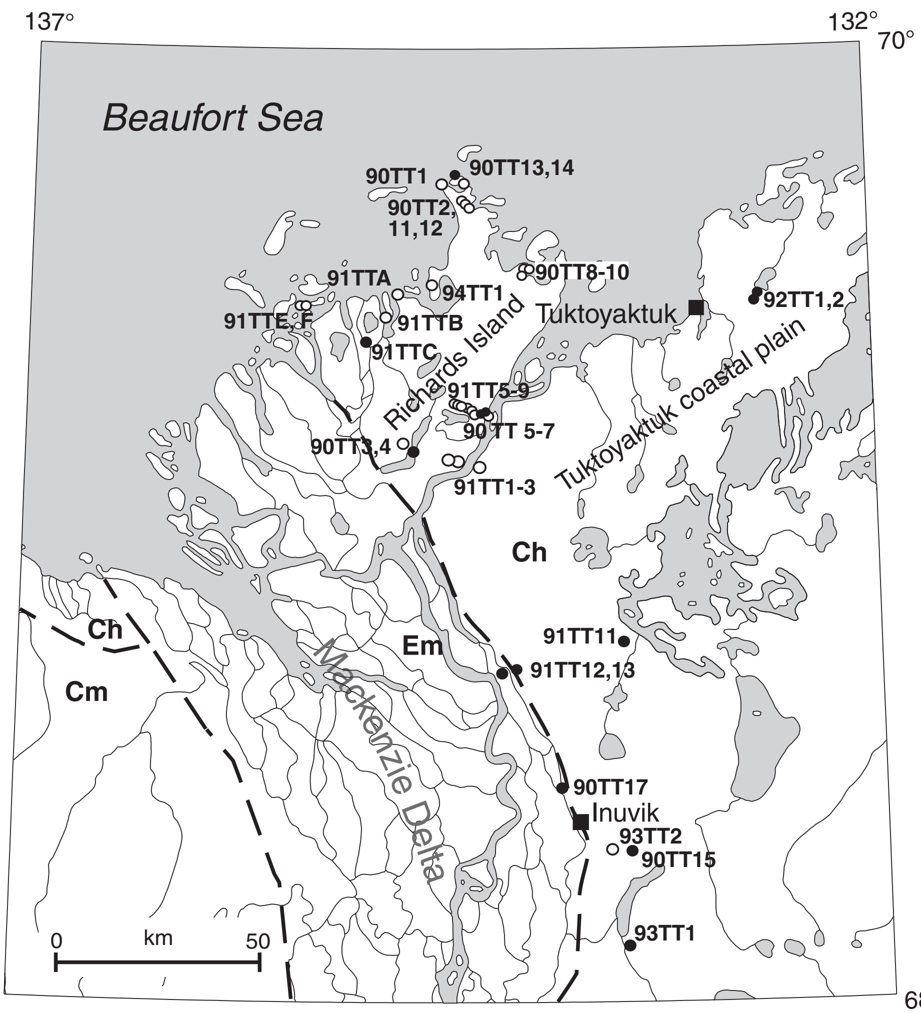

Figure 2b.

Locations of thaw-depth monitoring sites in the Mackenzie Delta area.

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Table 1. Site location and active layer depths, 1993 to 1998 thaw seasons in order of increasing latitude.

Site	Latitude/ longitude	Elevation (m)	Active layer (cm)	Environmental conditions
92TT4	61°46¢13² 121°11¢33²	126	101, 109, 118, 118, 118, 121	Open hardwood forest, 60% ground cover, 30 cm organic layer, well drained, riverbank (river »120 m a.s.l.), SW aspect, 85 cm snowpack
92TT5	61°45¢58² 121°11¢6²	142	160, 174, 177, 182, 183, 189	Aspen thicket, 10 cm organic layer, well drained, inland, 55 cm snowpack
92TT6	61°53¢13² 121°35¢59²	»165	95, 106, 123, >128, n.a., n.a.	Open spruce forest, complete ground cover, 25 cm organic layer, imperfect drainage, inland
92TT7	62°41¢48² 123°3¢46²	103	79, 83, 84, 90, 87, 89	Open spruce with hardwood forest, 100% ground cover, 25 cm organic layer, imperfect drainage, river bar inland from Mackenzie River (Willowlake River »95 m)
92TT8	62°57¢40² 123°12¢32²	99	75, 76, <80, 81, >89	Open hardwood with spruce forest, complete ground cover, 20 cm organic layer, well drained, bank 6 m above river, southern aspect
92TT9	63°27¢40² 123°41¢42²	97	<52, 52, 52, 51, 49, 49	Open spruce with hardwoods, complete ground cover, 40 cm organic layer, poorly drained, bank 7 m above river, 35 cm snowpack
92TT10	63°27¢59² 123°41¢35²	97	<58, 60, 58, <64, <65, 66	Open spruce forest, complete ground cover, 30 cm organic layer, imperfect drainage, inland, 40 cm snowpack
92TT11	64°17¢20² 124°31¢28²	99	96, destroyed 1994	Open spruce with hardwoods, 20 cm organic layer, well drained, steep bank 12 m above river, western aspect, 35 cm snowpack
92TT12	64°54¢40² 125°34¢32²	93	<55, n.a., n.a., n.a., 61, 66	Open black spruce, complete ground cover, >45 cm organic layer, imperfect drainage, inland, gentle westerly slope, 50 cm snowpack
91TT21	65°11¢29² 126°27¢35²	54	149, 149, 149, 165, >175, n.a.	Open spruce with hardwoods, complete ground cover, 15 cm organic layer, river bank, 60 cm snowpack
91TT22	65°11¢52² 126°27¢56²	51	63, 61, 61, 59, 59, 66	Open spruce forest, complete ground cover, 30 cm organic layer, 65 cm snowpack
94TT5	65°17¢54² 126°50¢43²	65	n.a., n.a., 96, 95, 103, 103	Open spruce with hardwoods, complete ground cover, 30 cm organic layer, fair drainage, inland
91TT19	65°39¢41² 128°46¢10²	3	71, 73, 73, 71, 72, 74	Very open spruce, 98% ground cover, >35 cm organic layer, riverbank, 55 cm snowpack
91TT20	65°40¢29² 128°49¢37²	39	59, 62, 62, 58, 59, 62	Hardwood thicket, complete ground cover, 15 cm organic layer, inland, base of north-facing scarp, 60 cm snowpack
91TT17	66°47¢16² 130°07¢15²	22	85, n.a., 86, (n.a. after 1995)	Open spruce, no organic layer, well drained, riverbank, 50 cm snowpack
91TT18	66°47¢10² 130°07¢6²	24	75, 78, 80, n.a., n.a., 91	Scattered black spruce, complete ground cover, 15 cm organic layer, imperfect drainage, inland, 50 cm snowpack
91TT16	67°29¢03² 133°45¢47²	14	93, 97, 98, 85, 88, 96	Open high shrub, 75% ground cover, no organic layer, well drained, river bar, 65 cm snowpack
92TT3	67°29¢44² 133°45¢47²	»30	n.a., 73, 75, 76, 76, 83	Open black spruce, complete ground cover, 10 cm organic layer, imperfect drainage, 65 cm snowpack
91TT14	67°47¢42² 134°07¢34²	13	106,111, 111, 108, 110, 116	Open spruce with hardwoods, complete ground cover, no organic layer, well drained, riverbank
91TT15	67°45¢58² 134°04¢43²	8	75, 80, 76, 74, 74, 80	Open spruce with hardwoods, 95% ground cover, no organic layer, imperfect drainage, inland lakeshore
93TT1	68°06¢39² 133°28¢29²	»30	68, 54, 58, 57, 64, 69	Scattered black spruce, complete ground cover, inland, 40 cm snowpack
90TT15	68°18¢57² 133°25¢51²	83	74, 90, 88, 87, 86, 101	Open bog, organics 2.5 m thick, inland, 75 cm snowpack
93TT2	68°19¢13² 133°30¢48²	»80	n.a., 55, 59, 60, 58, 65	Scattered black spruce, complete ground cover, 12 cm organics, imperfect drainage, inland, 70 cm snowpack
90TT17	68°24¢59² 133°47¢13²	5	n.a., 128, >138, (n.a. after 1995)	Open high shrub, incomplete ground cover, no organic layer, well drained, delta-surface channel bank, 60 cm snowpack
91TT11	68°44¢13² 133°29¢15²	53	69, 68, 68, 67, <68, 69	Shrub tundra, complete ground cover, 10 cm organic layer, inland, 40 cm snowpack
91TT12	68°41¢24² 134°06¢18²	152	70, 76, 71, 71, 71, 73	Low-shrub tundra, partial ground cover with bare hummock surfaces, no organic layer, inland, 13 cm snowpack
91TT13	68°41¢03² 134°08¢20²	5	129, 132, 136, 134, 135, 140	High shrub, incomplete ground cover, no organic layer, well drained, delta-surface bar, 60 cm snowpack

The active layer is defined as the thaw recorded in the thaw tube, minus the height of the tube above the ground surface at maximum surface subsidence, assumed to occur about the time of maximum thaw. Minimum values indicate that the value of maximum subsidence was not available, and the ground-surface height measured during mid-summer in the year following the record is used as a minimum subsidence at time of maximum thaw. Sites are arranged from south to north. Snowpack observations were taken during March or April, and snowpack is reported as a typical value from all the observations at the site. n.a. — not available.

Table 1 (cont.)

Site	Latitude/ longitude	Elevation (m)	Active layer (cm)	Environmental conditions
90TT3	69°08¢44² 134°42¢45²	40	96, 102, 101, 100, <102, 104	Low-shrub tundra, 80% ground cover, no organic layer, well drained, inland hilltop, 10 cm snowpack
90TT4	69°08¢44² 134°41¢53²	10	87, 93, 91, 92, <95, 97	Shrub tundra, complete ground cover, no organic layer, near lakeshore, 25 cm snowpack
91TT1	69°06¢30² 134°23¢56²	8	61, 64, 64, 59, <66, 67	Shrub tundra, complete ground cover, 10 cm organic layer, imperfect drainage, inland, gentle east-facing slope, 38 cm snowpack
91TT2	69°06¢35² 134°22¢50²	3	75, 76, 77, 76, <80, 83	High shrub, incomplete ground cover, no organic layer, imperfect drainage, floodplain, 95 cm snowpack
91TT3	69°06¢31² 134°20¢53²	11	46, 50, 48, 46, <49, 49	Shrub tundra, complete ground cover, 30 cm organic layer, well drained, west-facing slope, 29 cm snowpack
91TT5	69°14¢27² 134°25¢52²	53	78, 87, 89, 83, <94, 98	Low-shrub tundra, disturbed ground cover, cryoturbated organics to 25 cm, inland hilltop, 10 cm snowpack
91TT6	69°14¢28² 134°25¢09²	23	46, 48, 46, 46, <52, 52	Low-shrub polygonized wetland, 75% ground cover, >20 cm organic layer, inland basin, 5 cm snowpack
91TT7	69°14¢26² 134°24¢13²	37	55, 62, 64, 64, <70, 78	Low-shrub tundra, 80% ground cover, >20 cm cryoturbated organics, imperfect drainage, inland hilltop, 10 cm snowpack
91TT4	69°13¢45² 134°20¢58²	25	110 , ('91 only)	Grass sedge wetland, complete ground cover, no organic layer, recently drained lake basin, inland, 25 cm snowpack
91TT8	69°13¢35² 134°20¢12²	»50	61, 56, 61, 57, <63	Low-shrub tundra, inland hilltop, 20 cm snowpack
91TT9	69°12¢58² 134°17¢40²	16	41, 40, 38, 38, <39, 84	Shrub-sedge polygonized wetlands, complete ground cover, inland basin, 20 cm snowpack
90TT5	69°13¢06² 134°17¢05²	39	80, 86, 85, 75, <89, 91	Low-shrub tundra, complete ground cover, 5 cm organic layer, inland hilltop, 20 cm snowpack
90TT6	69°13¢01² 134°16¢40²	9	58, 61, 60, 46, <61, 64	Shrub tundra, complete ground cover, >25 cm organics, riverbank, 30 cm snowpack
90TT7	69°13¢04² 134°16¢25²	1	77, 78, 75, 61, n.a., 75	Sedge wetland, complete ground cover, no organic layer, saturated, water covered, floodplain, 20 cm snowpack
92TT1	69°28¢22² 132°37¢37²	25	48, 47, 48, 47, 48, 48	Shrub tundra, complete ground cover, 20 cm organic layer, well drained, inland hilltop, 20 cm snowpack
92TT2	69°28¢27² 132°38¢04²	4	<44, 49, 50, <53, 53, 60	Shrub wetland, complete ground cover, 10 cm organic layer, inland thermokarst basin, 53 cm snowpack
90TT8	69°31¢48² 134°00¢57²	14	74, 76, 77, <70, <83, 87	Low-shrub tundra, 75–80% ground cover, no organic layer, north-facing slope, 5 cm snowpack
90TT9	69°31¢51² 134°00¢21²	4	72, 70, 70, 64, <79, 91	Low-shrub tundra, complete ground cover, 90 cm organic layer, coastal, 5 cm snowpack
90TT10	69°31¢42² 134°02¢15²		76, 86, 84, <77, <90, 90	Low-shrub tundra, 75–80% ground cover, no organic layer, south-facing slope, inland, 10 cm snowpack
90TT2	69°39¢46² 134°23¢07²	29	54, 53, 51, 50, <53, 56	Low-shrub tundra, 95% ground cover, organic layer to 45 cm, inland hilltop
90TT11	69°39¢35² 134°22¢34²	16	63, 65, 64, 58, n.a., 70	Low-shrub tundra, complete ground cover, organics from 30 to 45 cm, moderate east slope, inland
90TT12	69°39¢25² 134°21¢44²	3	59, 57, 59, 53, <57, 56	Low-shrub tundra wetland, 80% ground cover, mixed organics and silt to 80 cm, coastal
94TT1	69°29¢07² 134°33¢43²	5	n.a., n.a., 63, 61	Low-shrub tundra, complete ground cover, mixed silt and organics to 110 cm, inland, 20 cm snowpack
90TT1	69°42¢53² 134°29¢02²	17	<56, 53, n.a., <49 (n.a. after 1996)	Low-shrub tundra, complete ground cover, 35 cm organic layer, high coastal bluff
90TT13	69°43¢18² 134°27¢14²	»3	63, 64, 62, 60, <66, 70	Low-shrub tundra, complete ground cover, mixed silt and organics to 40 cm, low coastal, 13 cm snowpack
90TT14	69°43¢07² 134°26¢29²	15	<81, 82, 79, (n.a. after 1995)	Low-shrub tundra, 75% ground cover, mixed silt and organics to 35 cm, well drained, inland scarp edge, 5 cm snowpack
91TTA	69°28¢53² 134°49¢43²	< 2	75, 78, 77, 70, n.a., 77	Sedge, grass wetland with low shrub, 100% ground cover, very organic silt 30 cm, outer delta, coastal, 34 cm snowpack
91TTB	69°24¢36² 134°50¢35²	< 2	117, 113, <123, 104, (n.a. after 1996)	Open high shrub, 60% ground cover, no organic layer, outer delta, inland
91TTC	69°22¢09² 134°56¢55²	< 2	<119, 118, >124, <112, 118, n.a.	High shrub, 50% ground cover, no organic layer, well drained, outer delta, inland, 70 cm snowpack
91TTE	69°26¢34² 135°21¢53²	< 2	n.a., < 99, 91, (n.a. after 1995)	Grass and sedge wetland, no organic layer, outer delta island, coastal
91TTF	69°26¢55² 135°20¢22²	< 2	112, 117, 114, 95, 107, 150	Grass and sedge wetland, 75% ground cover, no organic layer, saturated, under shallow water, outer delta island, coastal

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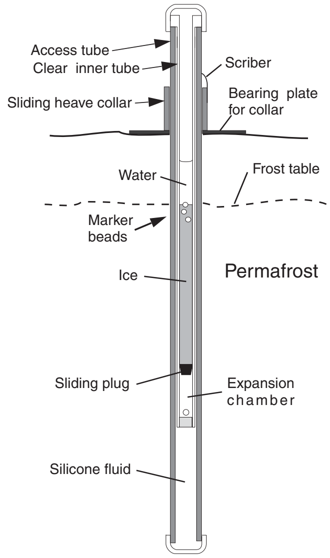

Figure 3. *Apparatus used to record maximum thaw penetration and maximum ground-surface movement at active-layer monitoring sites. Drawing is not to scale: length is about 4 m, diameter of outer tube is about 3 cm.*

Figure 4. *Thaw-depth monitoring site (92TT8) one year after installation, showing minimal disturbance of ground surface. Photograph by F.M. Nixon. GSC 2000-032*

RESULTS AND DISCUSSION

The active-layer thickness, reported in Table 1, is calculated by subtracting the distance between the tube top and the ground surface at maximum subsidence, recorded by the heave/subsidence scriber, from the distance between the tube top and last season's marker bead. This assumes maximum penetration of thaw corresponds to maximum ground-surface subsidence.

During the summer of 1994, the first complete survey of the active-layer monitoring system in the Mackenzie valley was achieved. A preliminary analysis of the data indicates that active layers, ranging from 38 cm to 182 cm, vary from site to site as a result of a complex interplay of site-specific and regional factors. The intuitive correspondence between active-layer thickness and latitude (Fig. 5) is statistically significant, though weak (correlation coefficient = 0.44). This test was applied after the removal of Mackenzie Delta and recently drained tundra lake sites showing anomalously thick active layers due to locally warmer ground-temperature profiles (Smith, 1976; Mackay, 1985). The scatter may be, in part, due to the fact that thawing air temperatures do not vary continuously with latitude at undisturbed temperature monitoring sites in the Mackenzie valley (Tarnocai et al., 1995). The influence of local factors, such as organic cover and snow depth, will also mask the effect of latitudinal change in climate (Burn, 1998). When tested, neither snow nor organic cover showed a significant correlation with thickness of active layer. Despite this, at some adjacent sites, for instance 90TT5/90TT6 and 91TT1/91TT3, it is apparent that organic cover is the most effective local factor controlling active-layer development (Table 1). Other local factors such as snow depth and density are certainly just as dominant elsewhere.

Data are available from as early as 1990 to 1996 for selected sites, and these can be used to display interannual variation of thaw at each (Fig. 6). The parameter plotted on this graph is not active-layer thickness, but maximum thaw penetration measured from a standard reference point that is assumed stable and independent of the moving ground surface. Records that may contain a component of heave have been discarded. The choice of this parameter for comparison of thaw from year to year simplifies the interpretation by eliminating such complexities as ground-ice melting and soil compaction. Most sites show a steady increase in maximum thaw until 1996, a trend also reported for soil climate sites throughout the valley (Tarnocai et al., 1995). This may reflect warmer air temperatures in the area. Summer average air temperatures between 1991 and 1992, recorded at three automatic weather stations on Richards Island, increased consistently by 2°C. (A.S. Judge, unpub. data, 1994). A longer 1993 thaw season, higher annual average temperature (+0.6°C), and higher summer average (+1.8°C) is reported for the Arctic Tundra Canadian climate region in which these sites are located. The adjacent Mackenzie climate region also experienced a longer thaw season and higher annual average temperature in 1993 (Fig. 5, 7, 8 *in* Skinner and Maxwell, 1994). Summer averages for tundra soil climate sites where higher in 1994 than any year since 1990, and shallow summer soil temperatures at

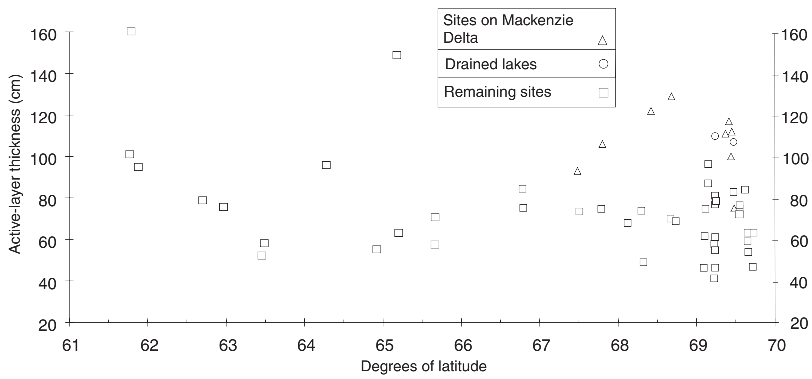

Figure 5.

Plot of thaw depth versus latitude for each monitoring site in 1993.

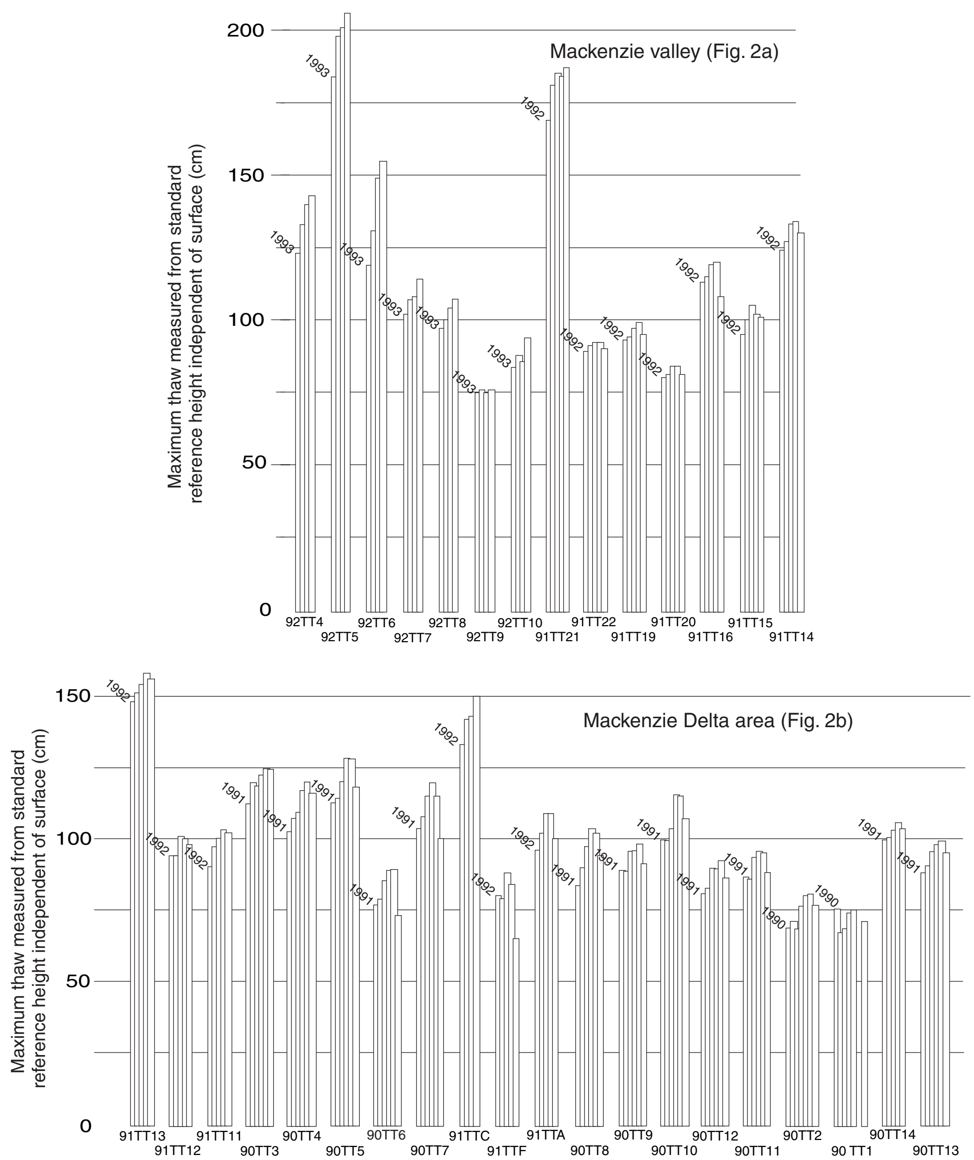

Figure 6.

Year-to-year variability of the maximum thaw for selected sites up to 1996, grouped according to Figure 2a and 2b. The year record began is indicated.

the same sites were as warm as any year on record (Tarnocai et al., 1995). A decrease in thaw penetration in 1996 at sites north of Norman Wells corresponds to the coldest summer mean temperature for this area in more than four years, with August and September being about 2°C cooler than normal (Canadian Meteorological Centre, 1996). The record from thaw-depth monitoring tubes is presently too short to make any inference about temporal trends at a climate scale.

Changes to active-layer thickness will influence surface stability through thaw settlement, frost heave potential, and bearing capacity. Slope stability will also be affected (Aylsworth and Egginton, 1994). Besides these geotechnical characteristics, changes in active-layer thickness will affect hydrology (Hinzman and Kane, 1992) and, through a combination of enhanced mass-movement disturbance, changes in soil moisture (Edlund et al., 1989), and nutrient availability (Waelbroeck et al., 1997), can affect the ecology of an area through modified vegetation. Monitoring of annual active-layer development in a variety of settings and analysis of how this development relates to widely available or easily measured parameters will provide field data to test models which include active-layer response in their portrayal of climate-change effects.

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