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Relationship of ground temperatures to air temperatures in forests

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Taylor, A.E., 2000: Relationship of ground temperatures to air temperatures in forests; in *The Physical Environment of the Mackenzie Valley, Northwest Territories: a Base Line for the Assessment of Environmental Change, (ed.) L.D. Dyke and G.R. Brooks; Geological Survey of Canada, Bulletin 547, p. 111–117.*

Abstract: Ground temperatures differ from air temperatures because of effects of vegetation and humus, other site characteristics, and snow cover. For engineering work, ground surface temperatures may be estimated from the more readily available air temperatures through the use of a single parameter, the n-factor, to represent these effects. In the Mackenzie valley, n-factors have been calculated from measurements of air and ground temperatures at 27 diverse, natural sites. Generally, the n-factor for the thawing (spring-summer) season is higher in more open areas than in shady forests with thick moss. At a particular site, the n-factor for the freezing (fall-winter) season is usually lower than the corresponding n-factor for the thaw season, because of the reduced impact of air temperatures and solar radiation on the ground due to snow cover. One application of n-factors is the calculation of the depth of soil that thaws each year, called the active layer.

Résumé : Les températures du sol diffèrent des températures de l'air en raison de différents éléments, que ce soit la présence de végétation et d'humus, l'existence d'un manteau nival, etc. Dans les travaux d'ingénierie, on peut estimer les températures de la surface du sol à partir des températures de l'air disponibles en utilisant un seul paramètre, le facteur n, pour représenter l'effet de ces éléments. Dans la vallée du Mackenzie, on a calculé les facteurs n à partir des températures de l'air et du sol enregistrées à 27 sites naturels. En général, le facteur n pendant la saison de dégel (printemps et été) est plus élevé dans les zones dégagées que dans les forêts ombragées où le sol est recouvert d'une mousse épaisse. En un endroit donné, le facteur n est habituellement plus bas pendant la saison de gel (automne et hiver) que pendant la saison de dégel du fait que le manteau nival réduit les effets de la température de l'air et du rayonnement solaire sur le sol. Le facteur n sert également à calculer la profondeur du mollisol, le sol de surface qui dégèle à chaque année.

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INTRODUCTION

In permafrost areas, the fundamental condition that controls permafrost is the surface temperature. To predict the distribution of permafrost over an area (*see* Wright et al., 2000), it is necessary to know how much effect the snow, vegetation, humus, and standing water have in reducing the impact of air temperatures and radiation on ground-surface temperatures (Fig. 1). For engineering calculations, the effect of these parameters may be considered through a single parameter, the n-factor, that may be readily obtained from air and corresponding ground temperatures in type areas (e.g. Lunardini, 1981). This simplifying concept offers a practical way of using the more readily available air temperatures to predict ground temperatures where the latter are unknown.

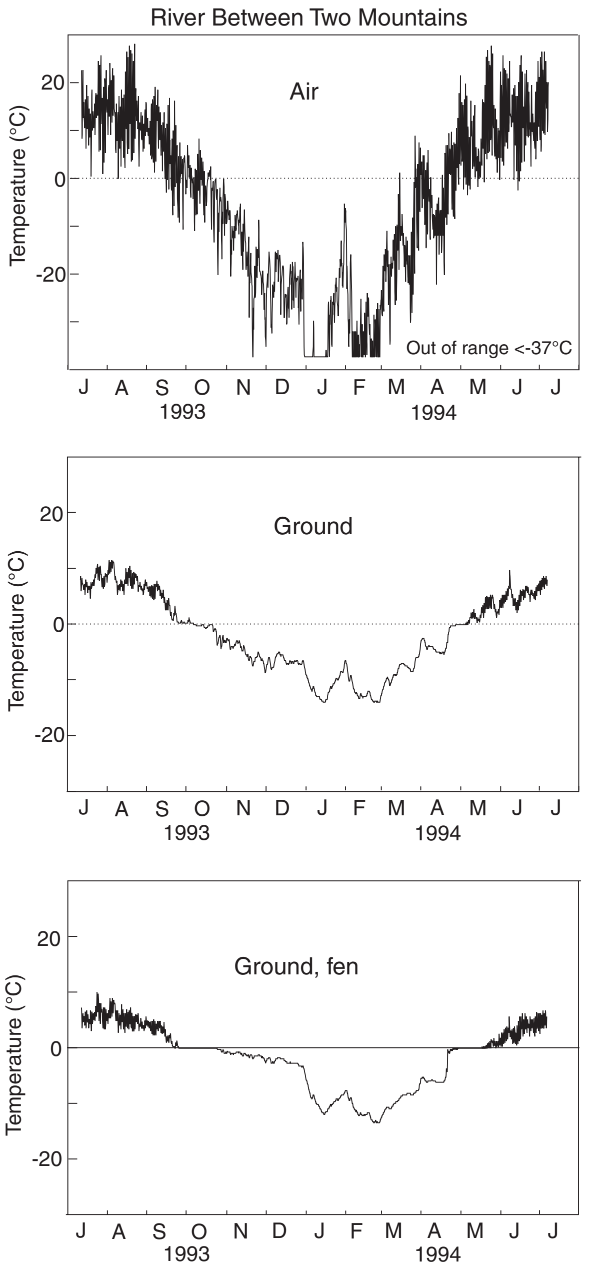

Figure 1. *Typical record of air temperatures (upper graph) and ground temperatures (depth 3–7 cm, middle graph) at an undisturbed forest site (site 'A', Fig. 6). The bottom graph shows ground temperatures in a nearby fen (site 'R', Fig. 6). Delays in freezing in the fall, and in thawing in the spring (zero-curtain effect) observed in the ground temperature arise from the dissipation of latent heat of phase change.*

The thawing season n-factor, n_{th}, is defined as the ratio of the ground surface index of seasonal thawing ($I_{s,th}$) to the air index of seasonal thawing ($I_{a,th}$):

$$n_{th} = \frac{I_{s,th}}{I_{a,th}}$$

and similarly the freezing season n-factor is the ratio of the ground surface index of seasonal freezing ($I_{s,\ fr}$) to the air index of seasonal freezing ($I_{a,\ fr}$):

$$n_{fr} = \frac{I_{s,fr}}{I_{a,fr}}$$

These indices are expressed in degree-days relative to 0°C. Figure 2 shows schematically how n-factors at a site may be calculated from a time-series of air and ground temperatures. An n-factor equal to one results if there is no attenuation (and hence ground-surface temperatures are equal to air temperatures), and the n-factor is less than one for attenuation due to vegetation and snow cover. Note that n_{th} may be greater than one due to direct solar radiation on surfaces devoid of vegetation.

The Geological Survey of Canada has established a latitudinal transect along the Mackenzie valley (Fig. 3) using inexpensive miniature data loggers to record air and ground temperatures that allow the calculation of n-factors (Nixon and Taylor, 1994; Taylor, 1995). Air temperatures are measured every 5 hours in a radiation shield and ground temperatures are measured within 3–7 cm of the surface, generally within a dense peat (e.g. Fig. 1). Figures 4–8 show photographs of a selection of sites chosen to demonstrate the variation in n-factor values that can be readily attributed to site geology and vegetation. Ground-surface temperatures of sites designated "A" are measured in the immediate vicinity of air temperature measurements in radiation shields. Ground-surface temperatures at sites designated "R" are measured at remote sites which are usually within 100 m of the "A" site. It must be emphasized that these n-factor values are for a particular year of data; values will vary somewhat from year to year, largely due to annual variation in snow cover.

The n-factors for the thaw season appear to be highest in more open areas having good sun exposure, and lower in shady forests with thick moss. For example, Figure 4, Mackenzie Highway kilometre post (kp) 504.7: n_{th} = 0.30 in a shady upland hardwood and spruce forest with 10 cm or more moss (site 'A'), whereas some 30 m away, n_{th} = 0.79 in mineral soil on an overgrown, but more exposed cutline through similar forest (site 'R'). Figure 5, Mackenzie Highway kp 507.6: n_{th} = 0.66 in a small, exposed bog between a fen and upland mixed forest; the bog was wet and the data logger was submerged at time of

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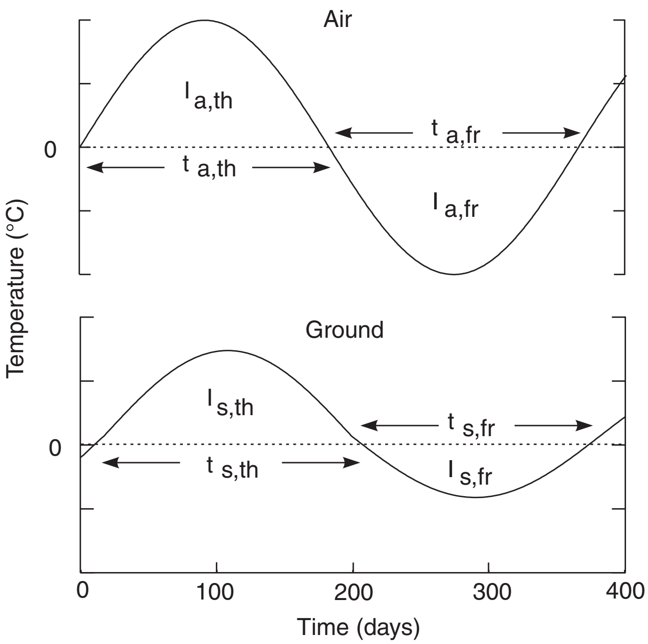

__Figure 2.__ Schematic of air and ground temperatures for just over one year, showing the seasonal thawing and freezing indices needed to calculate n-factors (see *text for definitions). For instance, $I_{a,th}$ is the thawing index (air) and is the area (in degree-days) between the air temperature curve above freezing and the freezing point. The terms $t_{a,th}$ and $t_{a,fr}$ are the length of the thawing season and freezing season, repectively, in air. The terms $t_{s,\ th}$ and $t_{s,\ fr}$ are the length of the thawing season and freezing season, respectively, at the ground surface. Note that the ground-temperature variation lags the air temperatures due to the time required for the signal to penetrate the vegetation and snow.*

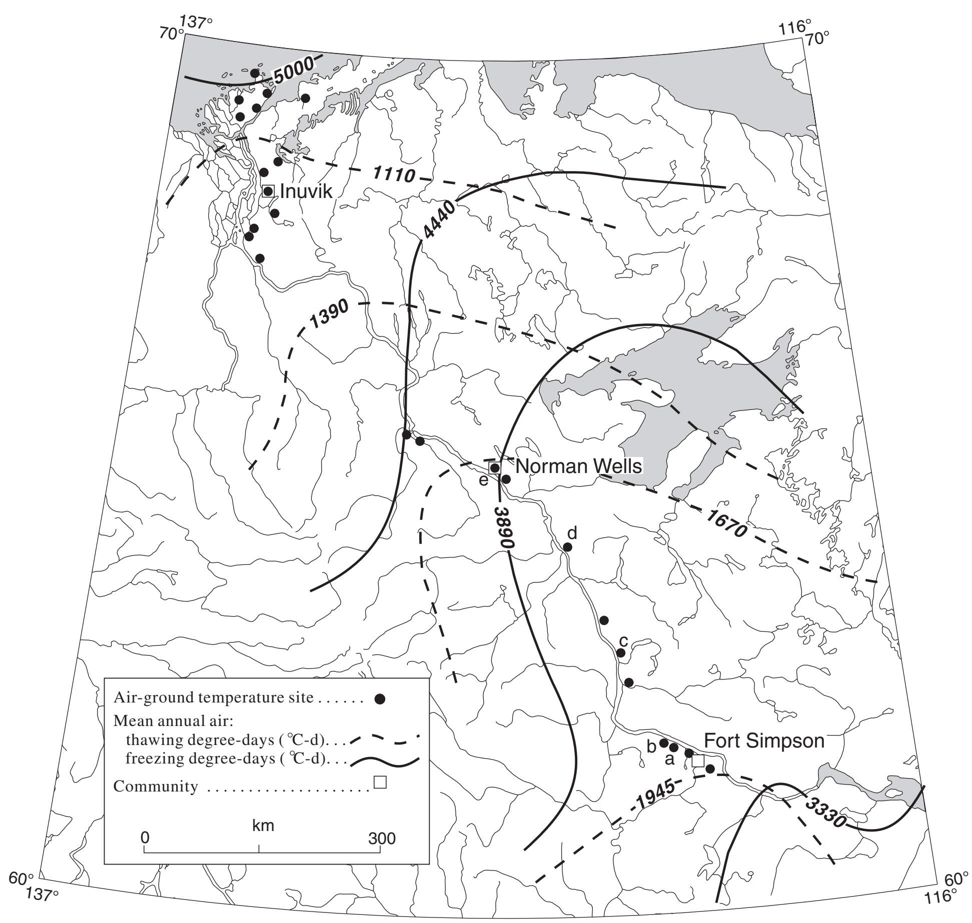

__Figure 3.__ Location of sites where air and ground temperatures are being recorded for the calculation of n-factors. Labels a to e reference sites shown in Figures 4–8, respectively. Contours are shown for mean annual thawing ($I_{a,th}$) and freezing indices ($I_{a,fr}$) in air (degree Celsius-days above and below 0°C, respectively).

Figure 4.

Mackenzie Hwy. kp 504.7
Site A: $n_{th} = 0.30$ $n_{fr} = 0.20$
Site R: $n_{th} = 0.79$ $n_{fr} = 0.17$
***Location**: 61°58′N; 121°49′W. Approximately 70 m south of Mackenzie Highway kilometre post 504.7. Site A (Fig. 4a), 30 m west of old cutline in spruce forest; site R (Fig. 4b) on cutline. **Geology**: Silt of lacustrine plain. **Vegetation**: Site A in upland hardwood spruce forest, some larch and aspen, thick sphagnum ground cover. Site R, overgrown cutline, aspen 10 cm diameter, peat/mineral soil.*

Figure 5.

Mackenzie Hwy. kp 507.6
Site A: $n_{th} = 0.66$ $n_{fr} =0.12$
Site R: $n_{th} = 0.54$ $n_{fr} =0.45$
***Location**: 61°58′N; 121°52′W. Approximately 100 m west of Mackenzie Highway kilometre post 507.6. The air screen is in small bog, whereas site R is on upland ridge beyond bog (at arrow). **Geology**: Bog developed on lacustrine plain. **Vegetation**: Area of mast, small hummocky bog, with standing pools of water in July 1993 but drier in July 1994. Site R, in mineral soil with upland spruce, juniper. Both sites open onto fen to west (to left of photo).*

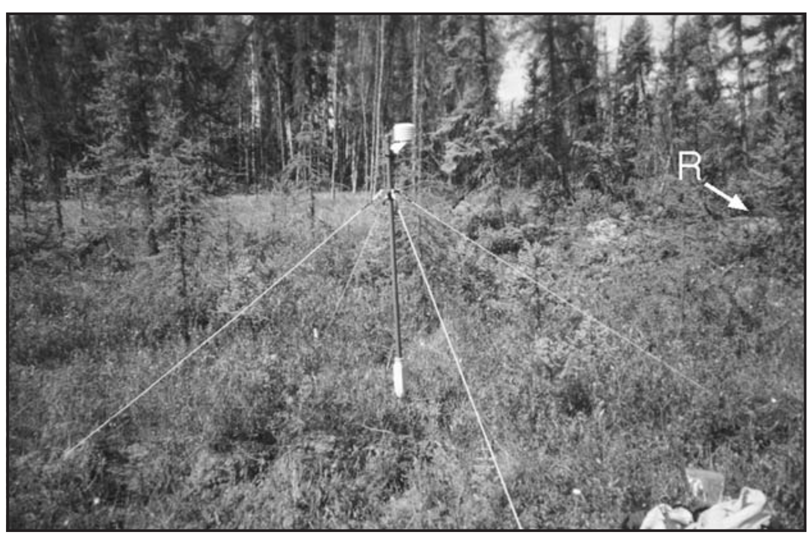

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Figure 6. *River Between Two Mountains*
Site A: n_{th} = 0.44 n_{fr} = 0.36
Site R: n_{th} = 0.26 n_{fr} = 0.29
***Location**: 62°57′40″N; 123°12′32″W*
***Elevation**: 100 m.*
*Site A (fig. 6a), top of bank of small tributary stream of Mackenzie River downstream of River Between Two Mountains. Site R (Fig. 6b), 50 m east of site A in bog bordered by fen. **Geology**: Silt on alluvial terrace. 15–20 cm fibrous rooty organic material grading to very organic, oxidized silt. Site A, well drained. **Vegetation**: Site A, tall open hardwood and spruce upland forest. White spruce, birch mature forest with aspens and willows. Site R, bog. **Active Layer**: Site A, maximum 0.75 m (1993).*

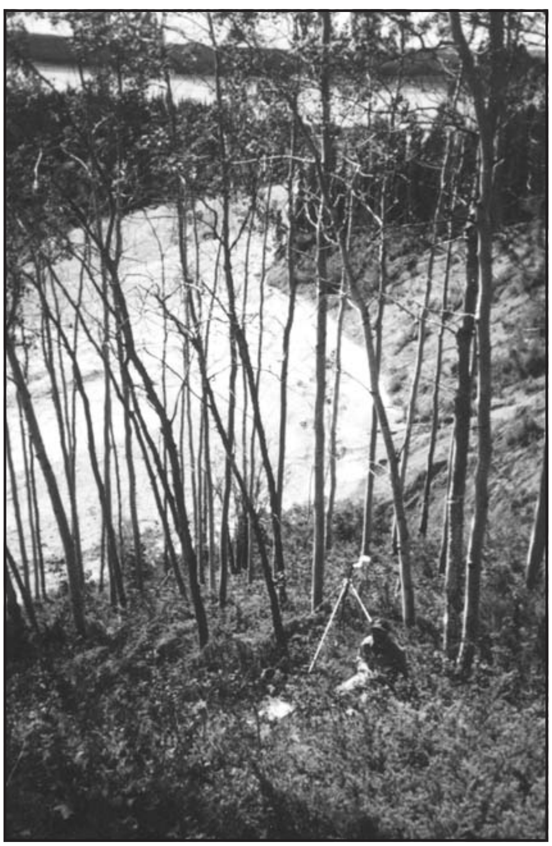

***Figure 7**. Saline River*
Site A: n_{th} = 0.72 n_{fr} = 0.28
***Location**: 64°17′39″N; 124°31′07″W. North side of Saline River, 0.7 km from Mackenzie River. On approximately 30° south-facing slope above 30 m cutback. **Geology**: Spur cut in high stony alluvial terrace. Well drained. **Vegetation**: Open aspen grove. Moss, buffalo berry, northern bedstraw, bush cranberry, some juniper, alder, rose. Cover 100%.*

installation in July, 1993 but dry in July, 1994. Figure 6, River Between Two Mountains: this site illustrates how both freezing and thawing n-factors are higher in the hardwood/spruce forest (site ‘A’) than in the open fen some 30 m distant (site ‘R’). This may result from higher evapotranspiration and a longer ‘zero curtain’ (Fig. 1) at the wetter fen site. Figure 7, Saline River: n_{th} = 0.7 on a steep (~30°) south-facing slope in open aspens; a low cranberry cover may keep the n-factor from being higher under this exposure. Figure 8, Norman Wells AES: n_{th} = 0.72 in the short grass of the cleared area of the AES compound (site ‘R’), while about 100 m further north in bush and moss, n_{th} = 0.34 (site ‘A’).

The above relationships tend to hold in the full data set, as apparent by the clustering in a cross plot of n_{th} and n_{fr} (Fig. 9). Also, n-factors for the freezing season are lower in most cases than the corresponding thaw-season values, reflecting the reduced impact of air temperatures and solar radiation on the ground surface due to the addition of an insulating snow cover. Of 27 determinations in the full data set,

$$n_{th}\ (\text{average}) = 0.5 \pm 0.2$$
$$n_{fr}\ (\text{average}) = 0.3 \pm 0.1$$

Figure 8. *Norman Wells AES*
Site A: $n_{th} = 0.34$ $n_{fr} = 0.13$
Site R: $n_{th} = 0.72$ $n_{fr} = 0.13$
Location*: 65°17′35″W; 126°45′40″W*
Site A (Fig. 8a) in bush area 0.2 km north of AES Upper Atmosphere Station. Site R (fig. 8b) in AES Upper Air Station compound. ***Geology****: Till plain.* ***Vegetation****: Site A, low, open black spruce and hardwoods, low white spruce, some alder and willow. Feather moss. Ground cover of labrador tea, blueberry, bush cranberry, Saskatoon berry, rose bushes, horsetail. Site R, cleared area, short grass, about 20 cm organic mat remains.* ***Active layer****: Deeper than 1.2 m in mid-July (note frost probe handle to right of stake).*

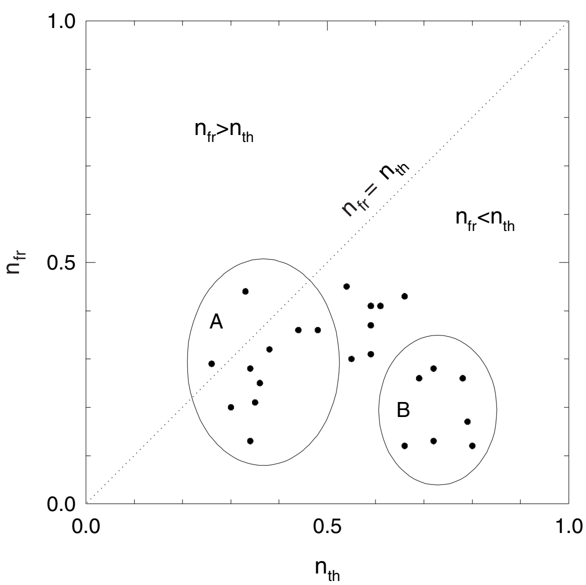

Figure 9. *Cross plot of* n_{th} *and* n_{fr}. *There is no functional relation between these two parameters, but this diagram shows the clustering that might be attributed to vegetation. Cluster A, shady bush sites, and usually with thick moss cover; cluster B, more open sites (old cutlines or open forest).*

While these values are preliminary and pertain, strictly speaking, to the 1993–1994 year and to the sites of measurement, the intent is that they might be generally representative of similar sites within the region. ‘Equivalent sites’ might be those having a similar site description or the same forest classification.

EXAMPLE APPLICATION

In permafrost regions, the depth of the soil that seasonally thaws (the active layer, *see* Nixon (2000)) may be estimated from air temperatures and the thermal properties of the ground if an appropriate n-factor is used to account for the effect of vegetation and snow cover in the Stefan equation (Lunardini, 1981):

$$\text{Thaw depth} = \lambda\sqrt{2\frac{k_{th}}{L}I_{s,th}}$$

where k_{th} is the unfrozen soil thermal conductivity and L the latent heat of fusion of the water or ice in the soil. The term λ accounts for the need to warm the soil before thawing can commence and is a function of the soil properties and climate;

for the upper Mackenzie valley, $\lambda = 0.7–0.8$. As $I_{s,th}$ is generally not known, it can be calculated from the air-thawing index available at nearby weather stations: $I_{s,th} = n_{th} * I_{a,th}$.

As an example, we estimate the contrast in maximum active-layer thicknesses between the natural forest (site 'A') and the cleared area (site 'R') at the Norman Wells upper atmosphere station, using values of n-factors measured at these sites (Fig. 8). Estimates of other parameters needed in the equation are: $k_{th} = 2$ W/mK and $L = 6.7 \times 10^7$ J/m^3 for till with 20% volumetric water content, $\lambda = 0.7$ and $I_{a,th} = 1670$ degree-days for Norman Wells weather station (Fig. 3). For the forest site, $n_{th} = 0.34$ so $I_{s,th} = 0.34 \times 1670 = 568$ degree-days or 4.9×10^7 degree-seconds. Note that the ground surface beneath the vegetation and snow receives only one third of the degree-days of thawing potential 'available' in the air at this site. Hence,

$$Thaw\ depth,\ forest = 0.7\sqrt{\frac{2\,x\,2.0\,x\,4.9\,x\,10^7}{6.7\,x\,10^7}} = 1.2 \text{ m}$$

$$Thaw\ depth,\ cleared\ site = 0.7\sqrt{\frac{2\,x\,2.010.4\,x\,10^7}{6.7\,x\,10^7}} = 1.7 \text{ m}$$

If there was no attenuation due to the grass at this latter site (i.e. $n_{th} = 1.0$), the maximum thaw would be deeper (2.1 m).

ACKNOWLEDGMENTS

Invaluable advice and logistic assistance in the field were provided by Pat Wood and staff, Water Resources Branch, Environment Canada, and B. Gauthier, Indian and Northern Affairs Canada, both in Fort Simpson, Northwest Territories. V. Allen designed the air temperature masts. Funding was provided by the Geological Survey of Canada under the Green Plan, and by the Panel for Energy Research and Development, Natural Resources Canada. V. Lunardini is thanked for his thorough review of the manuscript.

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