**THE DATING OF THERMOKARST TERRAIN, PLEISTOCENE MACKENZIE DELTA, CANADA**

Julian B. Murton\(^1\), Hugh M. French\(^2\), Michel Lamothe\(^3\)

\(^1\) School of Chemistry, Physics and Environmental Science, University of Sussex, Brighton BN1 9QJ, UK  
e-mail: J.B.Murton@sussex.ac.uk  
\(^2\) Departments of Geography and Geology, and Ottawa-Carleton Geoscience Centre, University of Ottawa,  
P O Box 450, Station A, Ottawa, ON K1N 6N5, Canada  
e-mail: hfrench@science.uottawa.ca  
\(^3\) Laboratoire de datation par luminescence LUX, Département des Sciences de la Terre, Université du Québec à Montréal,  
CP 8888 Succ. "A", Montréal, QC H3C 3P8, Canada  
e-mail: lamothe.michel@uqam.ca

**Abstract**

Radiocarbon dating in areas of ice-rich permafrost is often problematic because old organic material can be well preserved in permafrost and then redeposited during thermokarst activity. A case study from thermokarst terrain in the Pleistocene Mackenzie Delta, Canada, illustrates the potential application of optical dating of windblown sand in combination with AMS \(^{14}\)C dating of in situ organic material. Optical dating of sand wedges provides a weighted mean age of 14.0 ± 1.0 ka, indicating eolian deposition toward the end of Wisconsinan time. AMS \(^{14}\)C age estimates of 9770 ± 160 BP and 9420 ± 110 BP from in situ rootlets near the base of an involuted palaeo-active layer in which the tops of the sand wedges are commonly deformed suggest that active-layer deepening had probably commenced by ~11,000-10,400 cal BP.

**Introduction**

Most radiometric age estimates from thermokarst terrain have been obtained by radiocarbon dating of organic material (e.g. McCulloch and Hopkins 1966; Carson, 1968; Sher et al., 1979; Nelson, 1982; Astakhov and Isayeva, 1988; Harry and French, 1983; Rampton, 1982; 1988; Burn and Smith, 1990). However, radiocarbon dating in such areas is often problematic because old organic material can be well preserved in permafrost (e.g. Nelson et al., 1988) and redeposited during thermokarst activity, producing anomalously old age estimates for the time of deposition. To circumvent this problem, it is essential to date material that is *in situ*. Dating methods applied to in situ material in thermokarst terrain include radiocarbon dating of tree roots in growth position (e.g. Mackay, 1992, p.10), trapped gases within massive ground ice (Moorman et al., 1996), and thermoluminescence dating of loess (e.g. Carter, 1988).

This paper presents a case study from Richards Island in the Pleistocene Mackenzie Delta, northwest Canada. Optical and radiocarbon dating methods are integrated with a cryostratigraphic approach (Harry and French, 1988; Murton and French, 1994) in order to date a period of active-layer deepening.

**Regional setting**

Richards Island is in the Tuktoyaktuk Coastlands of Western Arctic Canada (Figure 1; Rampton 1988). The northern part of island is underlain by continuous permafrost ~ 600-700 m thick (Judge 1986) and has mean annual ground temperatures of ~ -8 °C to -9 °C (Mackay, 1979).

Richards Island was last glaciated probably during the Late Wisconsinan. This conclusion is based on the extent of Laurentide ice in the northeastern Cordilleran mountain front and the unglaciated basins of northern Yukon (Hughes et al., 1981; Dyke and Prest, 1987), and on cryostratigraphy and optical dating in the Summer Island area (Figure 1; Murton et al., 1997).

Ground ice is abundant beneath much of the Tuktoyaktuk Coastlands (Mackay, 1963; Rampton and Mackay, 1971). On Richards Island, ground ice is estimated to comprise 50% by volume of the upper 10 m of permafrost (Pollard and French, 1980). This ice is main-
ly pore and segregated ice (≥ 80%), with ice-wedge ice forming ≤ 20% of the total volumetric ice content. The Coastlands also contain abundant bodies of massive ice and icy sediments (Mackay, 1971; Rampton and Mackay, 1971; French and Harry, 1990). These may comprise both intrasedimental ice (i.e., ice which has formed within pre-existing sediments; Mackay and Dallimore, 1992) and possible buried glacier ice (Dallimore and Wolfe, 1988; French and Harry, 1990). Regional permafrost degradation took place during a warm interval at the end of the Wisconsinan and in the early Holocene, with the resulting thermokarst activity causing widespread retrogressive thaw slumping, the development of thermokarst basins and active-layer deepening (Rampton, 1974, 1988).

**Case study: active-layer deepening, Crumbling Point, Summer Island**

**CRYOSTRATIGRAPHY**

The site at Crumbling Point exposes a layered cryofacies assemblage (at least 15 m thick) which is dominated by sediment-poor ice, sediment-rich ice and ice-rich sediment (i.e., a complex mixture of massive ice and icy sediments). The assemblage is penetrated by large sand wedges and overlain by an involuted layer of sand and diamicton (Murton and French, 1994). The massive ice may be of intrasedimental or buried glacial origin, and pre-dates the sand wedges. The wedges comprise moderately well sorted fine sand to silty sand of aeolian origin (Murton, 1996), and the tops of some wedges are deformed within the involuted layer. Diamicton within the involuted layer is believed to have formed by melt-out of sediment from the underlying layered assemblage during a previous deepening of the active layer (Murton and French, 1994); this is inferred from a thaw unconformity at the base of the diamicton and the textural similarity between the diamicton above the unconformity and that dispersed in the massive ice beneath it. Sand within the involuted layer forms a discontinuous sheet that is contiguous with the tops of some sand wedges. The involutions comprise load casts, pseudo-nodules, ball-and-pillow structures, diapirs and the deformed tops of sand wedges. They are believed to have formed by loading and buoyancy when the sand and diamicton were unfrozen (Murton and French, 1993a). Because the lower parts of sand wedges within the massive ice and icy sediments are undeformed, this episode of soft-sediment deformation must postdate the formation of the sand wedges. Dating of the thermokarst activity has been attempted by both 14C and optical methods.
Optical Dating

The time of deposition of eolian sand can be established by measuring the optically stimulated luminescence (OSL) of sand (Huntley et al., 1985). This method is based on the assumption that previously acquired latent OSL of geologically old minerals is zeroed (bleached) through exposure to sunlight during grain transport. The optical signal is therefore a geochronometer, because the OSL of eolian grains at the time of deposition is, for all practical purposes, near zero (Wintle, 1993), and is gradually regenerated upon exposure to natural ionizing radiation.

Four sand samples from two wedges (Figure 2) at Crumbling Point were dated using the infrared stimulated luminescence (IRSL; Hütt and Jaek, 1989; Julian B. Murton et al. 1993). The diagrammatic stratigraphy at Crumbling Point, showing location of radiocarbon and luminescence samples. AL = modern active layer; IL = involuted layer; TU = thaw unconformity; LCA = layered cryofacies assemblage.

Table 1. IRSL age estimates from sand wedges at Crumbling Point

<table>
<thead>
<tr>
<th>Sample</th>
<th>Grainsize</th>
<th>Dose-rate</th>
<th>Equivalent dose</th>
<th>IRSL Age</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(μm)</td>
<td>(Gy/ka)</td>
<td>(Gy)</td>
<td>(ka)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>160 °C¹</td>
<td>220 °C¹</td>
</tr>
<tr>
<td>CP-1</td>
<td>28</td>
<td>1.96–0.18</td>
<td>265–4.0</td>
<td>135–24</td>
</tr>
<tr>
<td></td>
<td>160-200</td>
<td>2.16–0.15</td>
<td>309–1.9</td>
<td>305–1.5</td>
</tr>
<tr>
<td>CP-2</td>
<td>28</td>
<td>1.92–0.19</td>
<td>278–1.1</td>
<td>148–1.7</td>
</tr>
<tr>
<td></td>
<td>160-200</td>
<td>2.08–0.15</td>
<td>281–1.1</td>
<td>293–1.1</td>
</tr>
<tr>
<td>CP-3</td>
<td>28</td>
<td>2.10–0.21</td>
<td>253–3.4</td>
<td>313–1.2</td>
</tr>
<tr>
<td>CP-4</td>
<td>28</td>
<td>2.09–0.20</td>
<td>296–12</td>
<td>142–1.5</td>
</tr>
<tr>
<td></td>
<td>160-200</td>
<td>2.22–0.16</td>
<td>289–1.9</td>
<td>317–1.6</td>
</tr>
</tbody>
</table>

Note: CP-1, CP-2 and CP-3 are at a depth of 3.0 m and horizontal spacing of 0.5 m across the first wedge, orthogonal to its axial plane, with CP-1 located in the centre. CP-4 is from a similar depth in the centre of a second wedge ~50 m from the first (see Fig. 5). Gravimetric water (ice) content is estimated at 22 ± 3 %. Gamma dose includes cosmic contributions of 0.14 ± 0.02 Gy/ka. Alpha-efficiency factor, α = 0.08 ± 0.01. Dose-rate was calculated from INAA abundance of U (1.2–1.7 ppm), Th (3.2–3.8 ppm), and K2O (1.35–1.50 %). Equilibrium of the U and Th chains was confirmed using alpha spectrometric measurements. For the coarse grains, the internal beta dose-rate is the sum of three contributions: 0.49 ± 0.05 Gy/ka from K, 0.03 ± 0.01 Gy/ka from U and Th, and 0.13 ± 0.02 Gy/ka from Rb. ¹Preheat temperature. IRSL age is the average of both equivalent doses at 160 °C and 220 °C when two were available.

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Ollerhead et al., 1994) of two grain-size fractions: (i) 160-200 mm diameter K-feldspars grains (Mejdahl, 1983) and (ii) 2-8 mm polymineralic grains (Berger, 1988). Bulk grains of < 2.58 s.g. were prepared and mostly consist of K-feldspars. Two grain-size fractions were prepared in order to test the consistency of the luminescence results. Optical luminescence was detected through a blue transmitting filter combination, which is believed to selectively enhance the most stable part of the luminescence signal (Balescu and Lamothe, 1992). The equivalent doses were measured using the additive dose method (Aitken, 1992), with a calibrated gamma source ($^{60}$Co) artificially inducing the luminescence dose-response curves. Samples were dated using both 160 °C (8 to 10 hours) and 220 °C (10 minutes) preheats (Li, 1991) in order to detect sensitivity changes due to the preheat treatments. All the data were dose normalized.

The age estimates obtained range from 13.5 ± 2.4 ka to 14.8 ± 1.7 ka (Table 1). Assuming the samples are broadly coeval, the weighted (by inverse variance) mean age and the standard error (at 1 σ), encompassing both random and systematic contributions, should be a reasonable estimate for the age of deposition (see Aitken, 1985, p. 250-251). This mean is obtained by weighting the individual ages of both coarse- and fine-grain fractions according to their associated standard error. The weighted mean age is 14.0 ± 1.0 ka.

The IRSL age estimates indicate that eolian deposition occurred toward the end of Wisconsinan time. The concordance of ages suggests that the wedges formed rapidly. A maximum period of formation of ~2.0-3.0 ka is based on the difference between the average IRSL age and onset of rapid climatic amelioration at ~12 ka, and abrupt increases in pollen influxes at ~11 ka (Ritchie, 1984). As climate ameliorated between 14 and 11 ka, sand-wedge development likely ceased, probably because of vegetative stabilization of sand, increased winter snow cover or temperature, or some combination of these factors.

**Table 2. 14C age estimates from Crumbling Point, Summer Island**

<table>
<thead>
<tr>
<th>Laboratory number</th>
<th>description</th>
<th>14C age (years BP)</th>
<th>significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beta-66047</td>
<td>peat above involuted layer</td>
<td>3 650 ± 60</td>
<td>postdates involutions and active-layer deepening</td>
</tr>
<tr>
<td>TO-4238*</td>
<td>rootlets in upper 60 cm of layered assemblage</td>
<td>9 420 ± 110</td>
<td>coincides with active-layer deepening</td>
</tr>
<tr>
<td>TO-4237*</td>
<td>rootlets in basal 30 cm of palaeo-thaw layer</td>
<td>9 770 ± 160</td>
<td>coincides with active-layer deepening</td>
</tr>
<tr>
<td>Beta-46224</td>
<td>wood in peat above sand overlying □ thaw unconformity</td>
<td>9 480 ± 100</td>
<td>postdates sand and coincides with former □ warm period</td>
</tr>
<tr>
<td>Beta-46223</td>
<td>wood in slump sediments</td>
<td>8 860 ± 180</td>
<td>slumping during former warm period</td>
</tr>
</tbody>
</table>

* AMS age estimate

**Radiocarbon Dating**

Several radiocarbon age estimates have been obtained from Crumbling Point (Table 2 and Figure. 2) which relate to the early Holocene deepening of the active layer. Two 14C age estimates of 9 480 ± 100 years B.P. (Beta-46224) and 8 860 ± 180 years B.P. (Beta-46223) were obtained from wood fragments above the layered assemblage (Murton and French, 1993b). The first was from the bottom of a 40-cm thick layer of fibric peat overlying a 1.0-1.5-m thick sand lens separated from the underlying secondary thaw contact by 2-3 cm of melt-out diamicton. The second was from a root suspended in slump-floor deposits above a slump-floor secondary thaw contact. Although the simplest interpretation of these age estimates is that the wood grew during the warm interval which triggered the thaw slumping and which formed both the melt-out diamicton and the underlying thaw contact, the possibility of reworking of wood older than the thaw interval cannot be excluded.

To avoid the possibility of reworking of old organic material during the inferred warm interval two AMS 14C age estimates were obtained from in situ rootlets near the base of the involuted layer. These yielded age estimates of 9770 ± 160 BP (TO-4237) and 9420 ± 110 BP (TO-4238) for rootlets respectively in the basal 30 cm of the involuted layer and the upper 60 cm of the underlying layered assemblage (Murton et al., 1997). Because the deepest rootlets probably grew during a time of thaw, the AMS age estimates are believed to indicate the time of active-layer deepening. Accordingly, active-layer deepening had probably commenced by ~11,000-10,400 cal BP (calibrated according to Stuiver and Reimer, 1993).

An age estimate of 3 650 ± 60 14C years BP (Beta-66047) was obtained from peat above the involuted layer, providing a minimum age for active-layer deepening and the formation of the involutions.
Conclusions

This paper demonstrates the potential for optical dating of thermokarst terrain in the Pleistocene Mackenzie Delta. At Crumbling Point concordant IRSL age estimates of ~14.0 ka have been obtained from two grain-size fractions of sand wedges. As expected, the IRSL estimates are older than AMS 14C estimates obtained from nearby in situ rootlets. Thus, sand-wedge formation at Crumbling Point is thought to have ceased by ~11 ka, at which time active-layer deepening had begun.

Optical dating might usefully be applied to other areas of thermokarst containing aeolian sediments. Examples include the loessic Yedoma of northeastern Siberia and northern Alaska, and the aeolian and flu-vio-aeolian sands of southwest Banks Island, Canada.

Acknowledgments

Fieldwork was supported by Natural Sciences and Engineering Research Council operating grants A-8367 (H. M. French) and OCP0037375 (M. Lamothe); The Geological Survey of Canada; The Science Institute of the Northwest Territories; and The Polar Continental Shelf Project, Natural Resources Canada. The authors thank Bruce Lowe and Dr Andy Green for field assistance; M. Auclair for supervising the IRSL measurements; and Dr David Huntley for discussing the luminescence data.

References


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