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High-resolution stable water isotopes as tracers of thaw unconformities in permafrost: A case study from western Arctic Canada

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ABSTRACT

The knowledge of past permafrost conditions is of importance to assess the potential magnitude of changes that periglacial environments may experience as a result of climate warming or disturbance. To assess if past thaw unconformities may be preserved from isotopic and geochemical discontinuities within permafrost, this study investigates the distribution of ground ice, stable water isotopes and major cations in two permafrost cores collected in a hummocky terrain site near Inuvik, Northwest Territories, Canada; a site where the evolution of the active layer during a recent period of permafrost degradation and subsequent aggradation was documented. Based on the high-resolution isotope geochemistry profiles, closed-system Rayleigh-type ionic segregation and isotope fractionation occurred during thermally-induced water migration into shallow permafrost and its freezing along a negative soil temperature gradient. Due to thermally-induced water migration into permafrost, $\delta^{18}O$ may not always be able to identify thaw unconformities; however the calculation of the ^{18}O enrichment factors between ice and water ($\varepsilon^{18}O_{i-w}$) may be used to determine position of thaw unconformities in permafrost, if thaw events are followed by permafrost aggradation. The approach of using $\varepsilon^{18}O_{i-w}$ provides additional information regarding past permafrost conditions that can complement change in cryostructures observed along natural exposures.

1. Introduction

The knowledge of past permafrost conditions is of importance to assess the potential magnitude of changes that periglacial environments may experience as a result of climate warming or disturbance (i.e., Burn, 1997; Froese et al., 2008; Mann et al., 2010). One approach to infer past permafrost conditions is through the identification of thaw unconformities (or discontinuities) that resulted from the thawing of near-surface permafrost due to an increase in active layer thicknesses, followed by refreezing due to subsequent upward aggradation of the permafrost table. Generally, paleo thaw unconformities may be easily recognized by a variation in cryostructures and truncation of ice wedges along natural exposures (Mackay, 1978; Murton and French, 1994; Burn, 1997; French and Shur, 2010). For example (Fig. 1), a paleo thaw unconformity developed in the western Canadian Arctic during the early Holocene warm interval, when summer air temperature was ca. 4–7 °C warmer than the present (Ritchie et al., 1983; Burn, 1997; Clark et al., 2004; Kaufman et al., 2004).

In the absence of cryostratigraphic observations along natural exposures, geochemical and isotopic (i.e., $\delta^{18}O$) discontinuities may be recorded above and below a thaw unconformity and preserved by aggraded permafrost (Mackay, 1983; Murton and French, 1994; Lacelle et al., 2004; Fritz et al., 2012). However, these parameters might not always be diagnostic of a thaw unconformity as thermally-induced water migration may occur into permafrost, which may smooth the initial geochemical and isotopic profiles in permafrost (Michel and Fritz, 1982; Mackay, 1983; Michel et al., 1989). Excluding potential infiltration of active layer water in micro-cracks formed by thermal stress in the frozen soils (Mackay, 1974), water migration from the active layer into permafrost occurs along thermal gradients. The amount of residual water in permafrost is largely controlled by competing hydrogen and Van der Waals bonds between water and soil particles, which prevents ice nucleation at 0 °C. This process is largely dependent on the specific surface area of soils, and by the initial salinity of the water (Anderson and Morgenstern, 1973; Williams and Smith, 1989). The downward flux of water into permafrost in summer is much greater than the upward winter migration due to a larger amount of unfrozen water available at the permafrost table, and to the much higher unfrozen water content and hydraulic conductivity of cryotic soils near 0 °C (Burt and Williams, 1976). The seasonal movement of water into near-surface permafrost often results in the formation of an ice-rich zone in the top of the permafrost, termed the transient layer (Mackay, 1972; Shur et al., 2005).

In addition to changes in cryostructures, it has been suggested that the identification of ice-rich zones (transient layers) below the contemporary active layer may be associated with past permafrost degradation and may also be used as indicators of thaw unconformities (i.e., Kokelj

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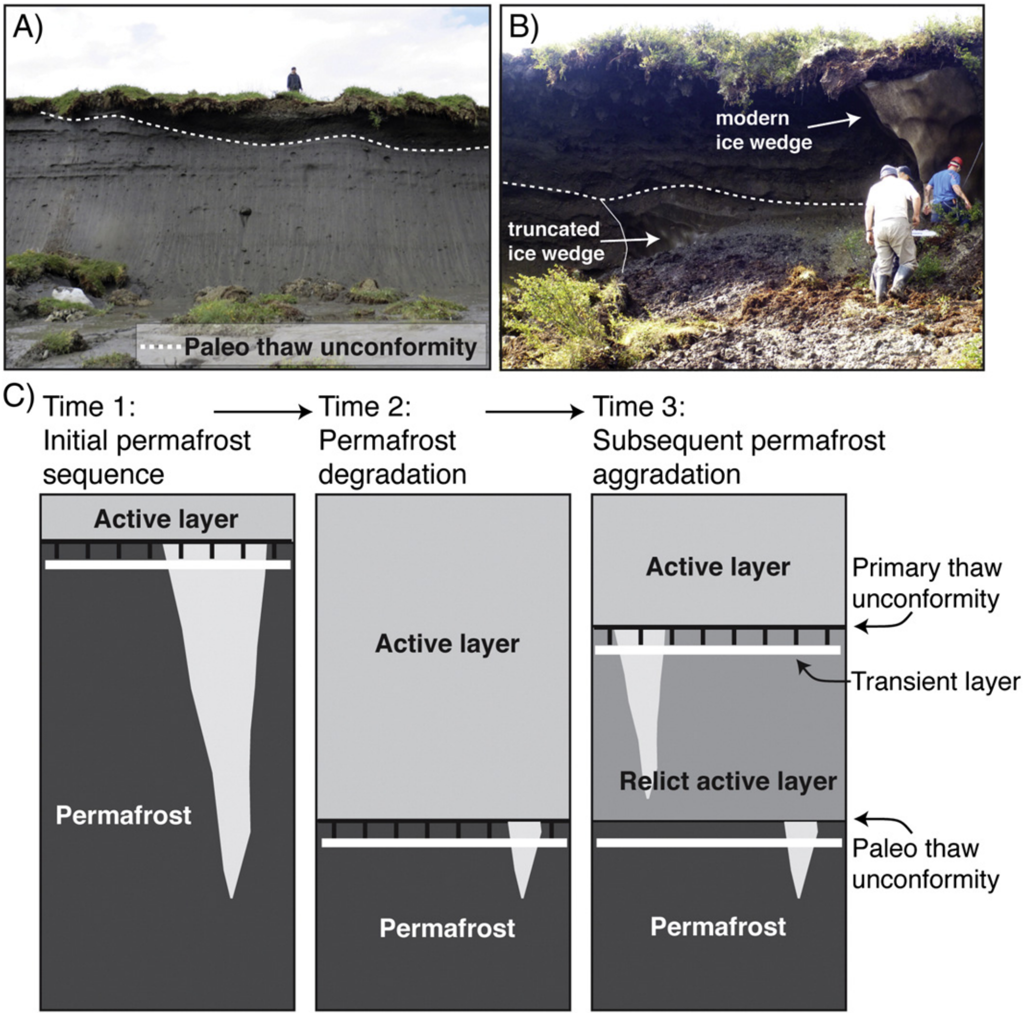

Fig. 1. Field photographs showing: A) thaw unconformity as revealed by a change in cryostructure above and below the unconformity (photograph of the headwall of a thaw slump on the Peel Plateau, Northwest Territories, Canada); B) thaw unconformity as revealed by truncated ice wedge and a change in cryostructure above and below the unconformity (photograph from the headwall of a thaw slump in central Yukon Territory, Canada); C) schematic diagram of development of thaw unconformity and associated change in cryostructure and truncated ice wedges following permafrost degradation and subsequent permafrost aggradation.
Modified from French and Shur (2010).

et al., 2002; Kokelj and Burn, 2003). However, little is known on: i) the behavior of solute and isotope partitioning during thermally-driven water migration into permafrost (i.e., the addition of new water into permafrost containing older ice); and ii) the extent to which geochemical and isotopic approaches may be used to identify past thaw unconformities. Here, we investigate the distribution of ground ice, stable water isotopes and major cations in two permafrost cores collected in a hummocky terrain site near Inuvik, Northwest Territories (NWT), Canada; a site where the evolution of the active layer during a recent period of permafrost degradation and thermal migration of water into permafrost has been documented (i.e., Mackay, 1995; Kokelj and Burn, 2003). To assess if past thaw unconformities may be preserved from high-resolution isotope geochemistry analysis, we compare our results (ground ice content, $\delta^{18}O$ and the calculation of the ^{18}O enrichment factor between ice and water, $\varepsilon^{18}O_{i-w}$) with the 1968–2011 annual variations in active layer thickness at the study site. To further evaluate if calculating $\varepsilon^{18}O_{i-w}$ can provide additional information to conventional permafrost geochemistry investigations, we apply the approach to a study conducted in the western Canadian Arctic that identified a change in cryostructures but not a $\delta^{18}O$ discontinuity between Late Pleistocene and Holocene age permafrost. Finally, this study discusses the usefulness of high-resolution stable water isotope analysis in providing information that can complement change in cryostructures observed in natural exposures regarding past permafrost conditions.

2. Study area

The study area is situated in hummocky terrain along Navy Road near Inuvik, NWT (Fig. 2). The Navy Road site is situated 50 m from a fire-break that protected the town of Inuvik from a 1968 forest fire. This disturbance provided the platform upon which to study the post-fire effects on active layer thickness variations (Mackay, 1995) and various cryogenic processes (i.e., Kokelj and Burn, 2003; Kokelj et al., 2007). As a result, the Navy Road site constitutes one of the longest records of active layer variation in northern Canada and therefore provides a natural setting to investigate isotopic and ionic conditions in permafrost following degradation of near-surface permafrost and subsequent aggradation.

The hummocks at the study site measure up to 50 cm high and 2 m wide (Kokelj et al., 2007). The tops of hummocks are composed of bare soil or thin lichen or moss cover, whereas thick moss tends to accumulate in the depression between the hummock mounds. Since unfrozen organic matter has a much lower thermal conductivity than mineral