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Stable isotopes in the closed-system Weather Pingo, Alaska and Pestsovoye Pingo, northwestern Siberia

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ABSTRACT

High-resolution records of the stable isotopic ($\delta^{18}O$ and δD) composition of ice within two closed system (hydrostatic) pingos indicate a complex history of ice formation by segregation and injection and pingo growth. Physical properties and internal structure of continuous ice cores in the center of the Weather Pingo near Prudhoe Bay, Alaska, and the Pestsovoye Pingo, in northwestern Siberia, were described and then sub-sampled for analysis of the isotopic composition. Changes in the isotopic signature and physical properties of ice with depth reveal distinct patterns in both pingos indicative of ice growth as permafrost aggraded into the drained lake basin. In the initial stages following active layer deepening and initial freeze back, in-situ water migrating toward the freezing front froze at a relatively rapid rate as revealed by a complex isotopic record and small ice crystal size in the cores of Weather Pingo. Once the water supply became limited, freezing under equilibrium conditions resulted in an isotopic composition consistent with Rayleigh-type fractionation and $\delta^{18}O$ and δD values that become more negative with depth. The data for the Pestsovoye Pingo reveal similar trends related to the initial stages of water migration and freezing, followed by isotopic fractionation under equilibrium conditions as unfrozen water available in the talik beneath the pingo became limited. Most of the ice in both pingos (~50%) formed during this final stage of permafrost aggradation. Thus temporal variability in water migration and freezing rate at the base of each pingo created a complex isotopic stratigraphy and ice growth history.

1. Introduction

While there are many different types of ice-cored mounds in permafrost terrain, the pingo is a strikingly unique landform. Pingos develop under two ground water flow regimes – a hydraulically connected system with essentially unlimited water supply, or a hydrostatic system where water supply is strictly limited. The resultant pingos are respectively classified as open or closed system types (Washburn, 1980; French, 2007). Open system pingos develop where ground water under artesian pressure flows from intrapermafrost or subpermafrost aquifers to a near surface position where it freezes, creating an uplifted mound of several to tens of meters in height (Müller, 1959). Closed system pingos develop from a water lens and pour water expulsion as a thawed zone surrounded by perennially frozen materials progressively freezes toward the surface and the 0 °C isotherm where ice growth occurs (Mackay, 1998). Most commonly, these hydrostatic conditions appear after lake drainage when lacustrine sediments overlie coarse-grained materials in areas of continuous permafrost (e.g. Mackay, 1973, 1979). Closed system pingos are common across the thaw lake regions in the continuous permafrost zone in northern Alaska and Canada (e.g. Mackay, 1979; French, 2007; Jones et al., 2012). In Russia, closed system pingos occur in Central and Northern Yakutia, and the Yamal, Gydan and Tazovsky Peninsulas. About 1600 pingos have been identified in the northern region of Western Siberia (Andreev, 1936, 1960; Grosse and Jones, 2011).

In closed system pingos, the initial freezing of the exposed lacustrine sediments creates pore ice and as hydrostatic pressures develop, segregated ice forms concomitant with uplift of the ground surface. As ice growth continues with further permafrost aggradation, a sub-pingo water lens under hydrostatic pressure may develop when the addition of water to the bottom of the pingo ice exceeds the downward rate of freezing (Mackay, 1998). Downward freezing of this water forms clear intrusive ice at the base of the pingo's

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core. Closed system pingo heights of several tens of meters or more are attained (e.g. Mackay, 1979, 1986, 1988). The details of closed system pingo formation are, however, not well defined; they likely vary with the continuity of water supply and complications in flow caused by the structure and stratigraphy of subsurface materials, as well as variable rates of permafrost aggradation into the thawed zone and confined aquifer.

One method to provide additional insights into the cryogenic processes and freezing pattern of closed system pingos is analysis of their stable isotope composition. Various techniques and applications are possible as recently reviewed (Michel, 2011; Lacelle, 2011; Yoshikawa et al., 2012; Ishikawa and Yamkhin, 2016) for permafrost regions. There are, however, few studies of the stable isotope composition of pingo ice. Mackay (1990) reported on $\delta^{18}O$ and δD analyses from a closed system pingo in the Tuktoyaktuk Peninsula. The isotopic composition of ice gradually became more negative with depth, exhibiting a linear trend and a co-isotope regression slope of 7.3 which Lacelle (2011) has shown to be consistent with equilibrium freezing under closed system conditions. Yoshikawa (1993) reported on oxygen isotope results from an open system pingo in Svalbard. Here, the oxygen isotope composition remained more or less constant with depth at a $\delta^{18}O$ value near −13‰, reflecting the ground water source, except where dilation cracks introduced new ice within the core after the initial stage of pingo growth and locally changed the isotopic composition reflecting this surface water introduction.

In this paper, we present the results of $\delta^{18}O$ and δD analyses of ice within the Weather Pingo near Prudhoe Bay, Alaska (Everett, 1980) and the Pestsovoye Pingo, in Northwestern Siberia (Fig. 1). We analyzed the physical properties and isotopic stratigraphy of continuous cores of ice drilled through the center of both pingos. Using the isotope stratigraphy, we reconstructed the ice growth history of the pingos. Our data indicate a complex history of ice formation reflected in the physical properties of the ice and its isotopic composition, and suggest that freezing rates and water availability varied during ice formation and growth of both pingos.

2. Study area and methods

2.1. Weather Pingo

During the spring of 1982, the Weather Pingo in the continuous permafrost zone near Prudhoe Bay (70°16′ N, 148°34′ W), Alaska was cored using a modified SIPRE core barrel of 8 cm in diameter (Brockett, 1982). The Weather Pingo is a closed system pingo located in a drained lake basin near the Putuligayuk River (Fig. 1a). It is also referred to as the IBP Pingo because of focused studies of it during the International Biological Program in the 1980's (Walker et al., 1985). Its age (period of growth) is unknown but most likely formed during the Holocene.

The borehole, which was located in the center of the pingo where its height is about 6 m, reached a depth of ~13 m, penetrating through the central ice core to the underlying frozen gravelly sands (Fig. 2). At that time, the temperature at the bottom of the borehole was −8.7 °C. Segmented cores of ice ranged from ~0.3 to 0.6 m in length. The core sections were tightly wrapped and sealed in plastic tubing and stored in a cold room at −30 °C in the CRREL-Hanover facility. In May 2010, we sub-sampled the ice at a 10–20 cm interval from near the center of each section of core using a 2 cm dia. coring device; no sublimated surfaces nor other changes to the core were evident after nearly three decades in storage. Ice crystals showed no effects of physical modification by melt or sublimation and were measured before sub-sampling, along with the length, diameter and orientation of air bubbles.

2.2. Pestsovoye Pingo

The Pestsovoye Pingo is located within the continuous permafrost zone in the Pestsovoye gas field (66°10′ N., 76°30′ E.) on the Tazovsky Peninsula, Northwestern Siberia. About 20 pingos occur within an area of 10–15 km north of Tundra station, 98–103 km north of Novy Urengoy town (Fig. 1b). These pingos range in height from 15 to 20 m and have a basal diameter of about 150–200 m. Commonly, there is a pedestal of

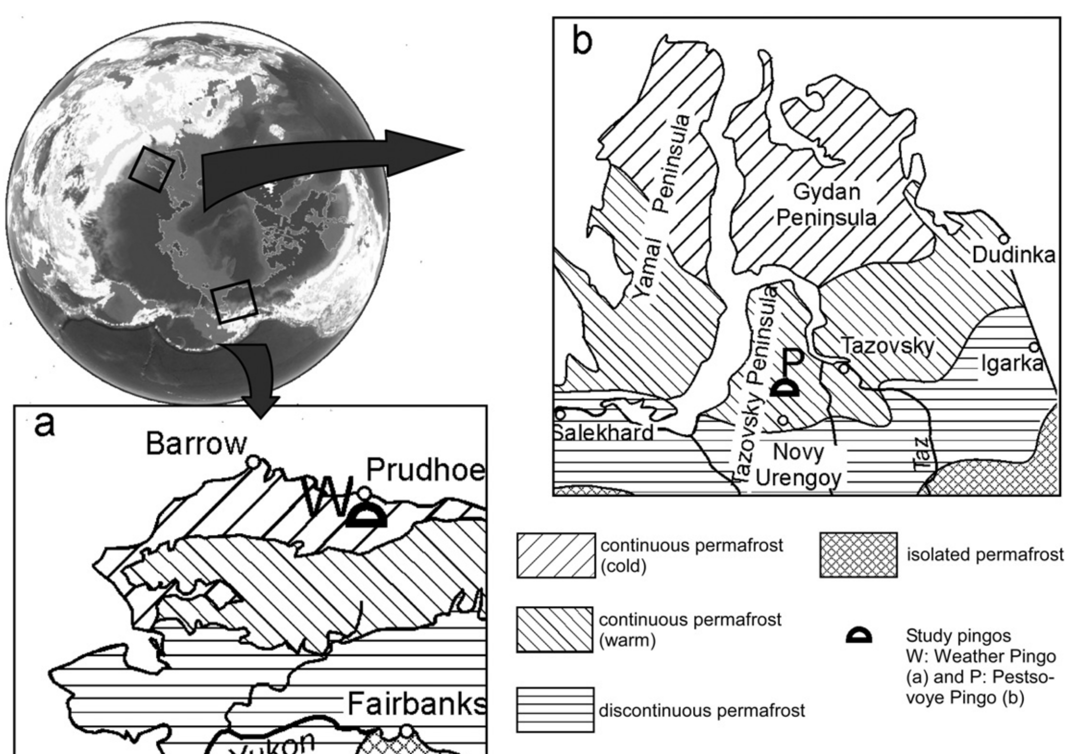

Fig. 1. Map showing the locations of the two pingos and permafrost distribution in Alaska (a) and in northwestern Siberia (b).