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 ($\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ 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.

Key words: pingo, ice core, stable isotopes, Alaska, northwestern Siberia

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 pore 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; Andreev, 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 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, Yamkhin, 2016) for permafrost regions. There are, however, few studies of the stable isotope composition of pingo ice. Mackay (1990) reported on $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ 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 about 5-7 m height around the base of each pingo. The Pestsovoye Pingo is ~17 m high and ~200 m in diameter at its base (Fig. 3). Previous radiocarbon dating of organic matter on and below it suggests that this pingo developed during the mid-Holocene period (Vasil'chuk and Budantseva, 2010). In the winter of 2013, the pingo was cored through its center to the depth of ~30 m using a 12-cm diameter core barrel and the ice core was retained for isotopic analyses.

2.3 Isotopic Analyses

The Weather Pingo samples were analyzed for their oxygen and hydrogen stable isotope composition at the Alaska Stable Isotope Facility in the Water and Environmental Research Center, University of Alaska Fairbanks, using a Pyrolysis Elemental Analysis-Isotope Ratio Mass Spectrometry (Pyrolysis-EA-IRMS) DeltaV system. This method utilizes a ThermoFinnigan MAT high temperature elemental analyzer (TC/EA) and ConFlo III interface with a Delta-V Mass Spectrometer. The pyrolysis reactor consists of a reaction tube packed with glassy carbon (GC)/graphite and silver wool. Other TC/EA conditions during analysis are: a

pyrolysis tube temperature of 1450°C, a Helium flow rate of 120 mL/min, a GC column of 3 m with a 5Å mol sieve and an oven temperature of 75°C to 100°C. Each 0.2 micro L water sample extracted from the ice sub-sample is injected into the TC/EA with a CTC Analytics A200SE liquid auto-sampler. The sample is pyrolyzed into H₂ and CO gases and then separated chromatographically. These gases are then transferred to the mass spectrometer for the isotopic measurements. δD V-SMOW and $\delta^{18}\text{O}$ V-SMOW values are reported in reference to the international isotope standards. We also ran laboratory reference standards every seven sample analyses. Each sequence batch is calibrated to the National Institute of Standards and Technology (NIST) standards, which were analyzed in replicate throughout the sequence.

The Pestsovoye Pingo ice was sub-sampled at 30 cm intervals for isotopic analyses. Samples were analyzed for their oxygen and hydrogen stable isotope composition at the Stable Isotope Laboratory of Geographical Department, Lomonosov Moscow State University using Delta-V mass spectrometer with standard Gas-Bench option. The ^{18}O isotopic composition was determined by equilibration with CO₂ for 18 h, while the D isotopic composition was determined by equilibration with a Pt catalyst for 40 min. International standards V-SMOW, GISP, and SLAP, as well as a laboratory standard (MSU) of fresh snow from the surface of Garabashi Glacier in the Central Caucasus ($\delta^{18}\text{O} = -15.60\text{‰}$, $\delta\text{D} = -110.0\text{‰}$) were also run. The analytical precision is 0.1‰ for $\delta^{18}\text{O}$ and 0.6‰ for δD .

2.4. Data Analyses

Various relationships within the co-isotopic data are useful to interpret conditions and processes of freezing to form the ice core of a pingo. A fundamental empirical relationship was defined by Craig (1961) based on the global correlation of δD and $\delta^{18}\text{O}$ in precipitation. This relationship defines the Global Mean Water Line (GMWL), which plots with a regression slope of 8.0 and δD intercept of 10‰. The slope approximates the ratio of equilibrium fractionation factors

between water and vapor for δD and $\delta^{18}O$, while the intercept reflects effects of kinetic fractionation at the source. With condensation under equilibrium conditions, the changes in its value are an indication of water vapor temperature and relative humidity in the source area. Because of regional factors including proximity to water sources, air temperature and elevation, local values for precipitation deviate from this trend, with Arctic regions based on available data having a LMWL slope of ~ 7.3 and *d-excess* (intercept) of $\sim 6\text{‰}$ (Lacelle, 2011). The value of *d-excess*, the difference between δD and $8\delta^{18}O$ (Dansgaard, 1964), also varies over a wide range in Arctic regions. A potential application of the *d-excess* value is that its relationship to δD can be used to determine if ice is sourced from meteoric waters (slope ~ 0.04), versus the freezing of non-meteoric water sources which produces a negative slope (Lacelle, 2011).

In freezing ground water to form ice, a Rayleigh-type fractionation occurs between water and ice under equilibrium conditions. Freezing slope values between δD and $\delta^{18}O$ of 6.2 and 7.3 are obtained during ideal Rayleigh-type fractionation. However, fractionation during freezing and thus the resulting isotopic composition is also dependent on the initial isotopic composition of water, freezing rate, thickness of the boundary layer and isotopic diffusion at the ice-water interface (Lacelle, 2011).

3. Results and Interpretation

3.1. Weather Pingo

3.1.1. Physical properties

Based on physical properties and structure, the ice core of the Weather Pingo can be divided into three sections (Fig. 2). The uppermost section (1) consists of fine grained ice with numerous round air bubbles of 1-2 mm diameter distributed evenly through the ice to a depth of

2.2 m in a sand-rich horizon with vertical bubble trains. The middle section (2) between 2.2 and 4.8 m depth contains three sand horizons and slightly elongated air bubbles in a near-vertical orientation. The lowermost section (3) between 4.8 and 13 m consists of clear, debris-free ice with crystal diameters generally larger (>50 mm) than elsewhere in the pingo core. Here, air bubbles are generally several mm in diameter and elongated from ~5 to 30 mm in a near vertical orientation, the longest bubbles occurring in ice below ~9.75 m depth. Associated with these larger air bubbles is a significant increase in the ice crystal size to more than 5 cm across below a depth of 8.8 m. These physical changes indicate a much slower rate of freezing in the latter stages of growth of the pingo's ice core. In contrast, the much smaller crystals in the upper 4.8 m of the ice indicate a more rapid rate of freezing during the early stages of growth.

3.1.2 Isotope composition

The isotope profile of the Weather Pingo ice core reveals three overall trends. The upper section of the ice core (1-2.2 m) is characterized by generally increasing isotopic values. Between 1 and 1.4 m, δD values increase from -157.5‰ to -140.3‰ and $\delta^{18}O$ values increase from -19‰ to -16.5‰ . From 1.4 to 2.2 m, the isotope values increase only slightly with depth (Table 1, Fig. 4). The slope of the regression equation is 6.6 (Fig. 6), indicative of freezing under equilibrium conditions (Lacelle, 2011), and the δD intercept is -31.7 ($r^2=0.93$). This well-defined, positive isotopic trend suggests a change in the composition of the migrating water during the initial stages of ice segregation and permafrost aggradation. Regression analysis of the *d-excess* – δD relation produces a negative slope value ($y = -0.12x - 25.99$; $R^2=0.134$, Fig. 7); without a significant correlation, this is only suggestive of ice formed by freezing of non-meteoric water. We interpret isotopic values at 1 to 1.4 m as indicating a progressive, yet rapid freezing of the waters remaining in the bottom sediments of the lake immediately following its drainage. Freezing of the lake waters in the basin sediments initiated ice formation, affecting only the

uppermost 1.4 m just below the lake bed. Below this depth, the complex isotopic record indicates in-situ waters migrated toward the freezing front and froze at a relatively rapid rate.

In the middle depths (2.2-8.2 m), isotopic values vary in a range of 1.8‰ for $\delta^{18}\text{O}$ and 10.1‰ for δD . Between 2.2 and 4.8 m depth (Table 1), stable isotope values were relatively constant (δD : ~ -140 ‰, $\delta^{18}\text{O}$: ~ -16.5 ‰), with only slight variations between successive samples. Below 4.8 m to 8.2 m depth, the ice is characterized by a large range in the isotopic composition: from -134.6 to -143 ‰ for δD and from -15.5 ‰ to -17.3 ‰ for $\delta^{18}\text{O}$ (Fig. 4). The regression slope value for δD and $\delta^{18}\text{O}$ is 1.7, with an $R^2=0.2$ (Fig. 6). Regression analysis of the *d-excess* – δD relation produces a positive slope value ($y = 0.04x - 2.99$; $R^2=0.0004$, Fig. 7), but the lack of a significant correlation does not suggest a meteoric or non-meteoric water source.

Between 8.3 m and 11.8 m depth, isotope values become progressively lighter (from -140.9 to -160.1 ‰ for δD and from -17.2 to -20 ‰ for $\delta^{18}\text{O}$). Simultaneously *d-excess* values generally increase with depth from -5.1 to $+1$ ‰ (Table 1, Fig. 4). From 11.8 to 13 m depth at the base of the pingo's ice core, δD and $\delta^{18}\text{O}$ values decrease more rapidly, while *d-excess* sharply increases to positive values. Here the bubble-rich ice, elongated air bubbles and large crystal size suggest slow freezing as the final stages of ice growth took place. A regression slope value between δD and $\delta^{18}\text{O}$ is 5.63 ($R^2=0.93$) and δD intercept is -45.56 (Fig. 6), consistent with freezing under equilibrium conditions. The decreasing δD and $\delta^{18}\text{O}$ values and increase in *d-excess* are consistent with a Rayleigh distillation process during progressive freezing of a limited volume of ground water under hydrostatic conditions (Lacelle, 2011). Similarly a negative slope in the *d-excess* vs. D relationship (-0.3) and a significant correlation (Fig. 7) indicate the pingo ice formed by freezing of non-meteoric water.

3.2. Pestsovoye Pingo

3.2.1 Cryostratigraphy

The borehole drilled through the top of the pingo revealed that the ice core occurred from 11.5 to 30.5 m depth. A 0.9 m peat layer covers the pingo surface. Dark grey loam with ice layers occurs between 0.9 and 11.5 m depth, with thicker (up to 5-7 cm) horizontal ice lenses at ~10.2 m depth. Based on the cryostratigraphy, the ice core was divided into three sections (Fig. 3). In section 1 from 11.5 to 18 m depth, ice layers (5-7 cm thick) alternate with loam layers (10-12 cm thick). The middle section (2) between 18 and 26 m depth contains alternating opaque, transparent and milky ice, with loam layers (2-3 cm thick) at a depth of 20-22.5 m. The lowermost section (3) between 26 and 30.3 m consists of loam with some ice layers up to 5-8 cm thick.

3.2.2. Isotope composition

The isotopic record varies with depth and is generally consistent with the cryostratigraphy of the pingo ice core (Fig. 5, Table 2). The upper section (from 11.5 to ~15 m) is characterized by a positive isotopic trend with depth. The uppermost layer of ice (11.5-12 m depth) at the ice-sediment contact has relatively negative values of δD (-102.2 , -106.5 ‰) and $\delta^{18}O$ (-12.8 , -13.1 ‰). The isotope values then increase to a depth of ~15 m (-97.9 ‰ for δD and -11.6 ‰ for $\delta^{18}O$, Fig. 5). Simultaneously *d-excess* values generally vary between 3.5 and -5.02 ‰ without regard to the depth. The regression slope value between δD and $\delta^{18}O$ is 5.2 ($r^2=0.72$) and the δD intercept of -36.82 ‰ (Fig. 6) are consistent with freezing under equilibrium conditions. The uppermost and oldest ice was formed because of freezing of pore water in the lake (alas) bottom sediments immediately after drainage took place. A negative slope to the *d-excess* vs. D relationship of -0.1 (Fig. 7), albeit with a poor correlation, is however consistent with the pingo ice having formed by freezing of non-meteoric water.

The second section from 15.8 to 25.8 m is characterized by a generally negative isotopic trend: δD values decrease from -95.3 to -119.9‰ , while $\delta^{18}O$ values decrease from -11.4 to -15.9‰ . The *d-excess* values become mostly positive in the lower 4 m of this section (Table 2, Fig. 5). The decreasing δD and $\delta^{18}O$ values and increase in *d-excess* are consistent with a Rayleigh distillation process during progressive freezing of a limited volume of ground water under hydrostatic conditions (Lacelle, 2011). The regression slope value for δD and $\delta^{18}O$ is 5.11 ($r^2=0.77$) and the δD intercept is -38.42 (Fig. 6). Regression analysis of the *d-excess* – δD relation produces a negative slope value ($y = -0.2x - 22.9$) with low correlation (Fig. 7).

The lowermost section from 26 to 30.3 m exhibits a slight increase in δD (-123 to -111.2‰) and $\delta^{18}O$ (-15.3 to -14.1‰) with depth. The regression slope value between δD and $\delta^{18}O$ is 7.65 ($r^2=0.87$), with a δD intercept of -3.14 , very close to GMWL. The *d-excess* values vary between 4.18 and -0.52‰ . The isotopic variability is generally consistent with freezing under equilibrium conditions (Fig. 5 and 6). Regression analysis of the *d-excess*– δD relation ($y = 0.09x + 12.91$; $R^2=0.06$, Fig. 7) for the ice produces a slightly positive slope value, which suggests a direct meteoric source for water injection, but the lack of a significant correlation indicates this is not definitive.

The δD vs. $\delta^{18}O$ of all samples from the three core sections plot below the GMWL and have a lower slope, indicating homogeneous conditions for the entire ice mass of the pingo and a Rayleigh freezing process. We therefore assume that the water originated from a non-meteoric source: the pore water from the talik beneath the drained lake basin.

4. Discussion

Comparison of the isotope curves of the two pingos shows a greater isotopic range for the Weather Pingo ice core: $\delta^{18}O$ values vary by 6.5‰ (-15.5 to -22‰), while δD values vary by 30‰ (-134.6 to -165.3‰). In the Pestsovoye Pingo, $\delta^{18}O$ values vary by 4.3‰ (-11.4 to $-$

15.9‰), while δD values by 30‰ (−93.2 to −123‰). Moreover, isotopic values of the Weather Pingo ice are generally more negative than those of the Pestsovoye Pingo ice.

We may assume that the isotopic composition of a pingo's ice core depends on the isotopic composition of water in the lake basin before draining and freezing began. Analysis of isotope data of modern northern Alaskan lakes in the continuous permafrost zone shows that they are characterized by a wide range of isotope values. In summer, most have isotopically enriched water due to evaporation, although in limited cases some lakes may have isotopically depleted water even in summer. In this region, isotope values range from −21‰ to −5‰ for $\delta^{18}O$ and from −160‰ to −85‰ for δD (Anderson et al., 2013; Hinzman et al., 2007). We also assume that because of likely differences in the regional paleoclimate, the isotopic composition of lake waters from which the Weather Pingo and Pestsovoye Pingo ice cores were derived, probably differed at that time as well. However, there are no data on isotopic signatures of lake waters during the Holocene at either site, even at the regional scale, and thus there is no way to pinpoint the origin of the isotopic differences in the talik waters from which the pingo ice cores were derived.

The isotopic profile of the Weather Pingo ice demonstrates three overall trends: isotope values generally increase from the top of the ice core to the depth of 2.2 m, while in the middle part of the core (depth 2.2–8.2 m) they are relatively constant, and then decrease nearly linearly to the bottom of the pingo's core at 13 m depth. The isotope profile of the Pestsovoye Pingo ice demonstrates positive trends for the upper and lower sections, while in contrast. the middle section of the ice core has a negative trend (see Fig. 4, 5).

The isotope curve of the Pestsovoye Pingo ice has less pronounced peaks, compared to those of the Weather Pingo. This may be explained by more intensive replenishment from a sub-pingo water lens, or possibly the borehole in the Weather Pingo was slightly askew of center and did not core directly into the location where the former sub-pingo water lens was located.

Our regression analysis of the *d-excess* – δD relation in the Weather Pingo ice, as well as in the Pestsovoye Pingo ice, produces a generally negative slope value, but the usual lack of a

strong correlation suggests a non-direct meteoric source for the water (Lacelle, 2011), consistent with freezing under closed system conditions.

It is possible that the freezing rate may have had an effect on the variability in isotope values. According to Lacelle [2011], if the freezing rate is slower than the diffusion rate, this allows for HD¹⁶O and H₂¹⁸O diffusion towards the freezing front to occur, and as a result, during progressive freezing, the extent of isotopic fractionation is controlled by the equilibrium fractionation factor. As the freezing rate increases to values much higher than the diffusion coefficient and boundary-layer thickness, the extent of fractionation between ice and water is reduced because freezing occurs through the well-mixed water reservoir. Variations in the freezing rate can produce small fluctuations in the isotope profile that will be smaller than the equilibrium fractionation value. However, the sampling interval needs to be very detailed (cm scale) in order to see these variations fully [Michel, 2011].

5. Conclusion

The high-resolution $\delta^{18}\text{O}$ and δD records of ice within two typical closed-system pingos in northern Alaska and northwestern Siberia have revealed a complex history of ice formation and pingo growth. Comparison of co-isotopic trends for the Weather Pingo and Pestsovoye Pingo demonstrates isotopic similarity, particularly in section 3 of the Weather Pingo and section 2 of the Pestsovoye Pingo. Large crystal size and elongated bubbles in the lower part of the Weather Pingo ice core indicate a much slower freezing rate than in the upper part of its ice core.

Isotope values suggest that most of the ice grew under equilibrium freezing conditions in both the Weather and Pestsovoye pingos, although both intrusive and segregation mechanisms of ice formation may have been more prevalent for the Pestsovoye Pingo. Limited periods of isotopic fractionation are evident in the isotopic curves. The sharp isotope shift at the basal ice-sediment interface for the Weather Pingo suggests that its growth terminated before the talik beneath the former lake had completely frozen. Ice cores of both pingos were mostly formed after permafrost had aggraded into the drained lake basin sediments, and pore-fluid expulsion created hydrostatic pressures and rather continuous supply of water to the freezing front at their bases.

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Figures captions

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

Fig. 2. Weather Pingo, North Slope, Alaska. The sketch shows the location of the three sections of the drill core within a cross section of the pingo.

Fig. 3. Pestsovoye Pingo, Tazovsky Peninsula, northwestern Siberia. The sketch shows the location of the three sections of the drill core within a cross section of the pingo.

Fig. 4. Profiles of the oxygen and hydrogen isotopic values and calculated *d-excess* with depth in the Weather Pingo ice core. The three sections are located in Figure 2.

Fig. 5. Profiles of the oxygen and hydrogen isotopic values and calculated *d-excess* with depth in the Pestsovoye Pingo ice core. The three sections are located in Figure 3.

Fig. 6. $\delta^{18}\text{O}$ – δD diagram with results of the regression analysis for each of the three sections within the Weather Pingo and Pestsovoye Pingo ice cores. Table 1 lists the isotopic values for Weather Pingo and Table 2 for Pestsovoye Pingo

449 **Fig. 7.** δD - d_{excess} diagram with the regression analysis results indicated for each of the three
450 sections of the Weather Pingo and Pestsovoye Pingo ice cores.

Table 1

$\delta^{18}\text{O}$ (SMOW), δD (SMOW) and *d-excess* values of Weather Pingo, Alaska

Depth (m)	$\delta^{18}\text{O}$ (‰) VSMOW	$\delta^2\text{H}$ (‰) VSMOW	<i>d-excess</i>	Section no
1	-19.02	-157.49	-5.33	Section 1
1.1	-17.84	-151.76	-9.04	
1.2	-17.21	-147.22	-9.52	
1.3	-17.84	-149.06	-6.33	
1.4	-17.92	-151.13	-7.75	
1.4	-16.48	-140.34	-8.53	
1.7	-16.91	-144.71	-9.43	
1.9	-16.60	-139.73	-6.90	
2	-16.75	-142.23	-8.24	
2.1	-16.73	-141.22	-7.42	
2.15	-16.43	-138.19	-6.79	
2.1	-15.97	-140.17	-12.39	
2.2	-16.31	-141.52	-11.06	
2.3	-15.77	-140.32	-14.16	Section 2
2.4	-16.04	-139.62	-11.29	
2.5	-15.90	-138.41	-11.18	
2.6	-16.16	-141.03	-11.78	
2.7	-16.02	-139.48	-11.29	
2.8	-16.20	-141.95	-12.32	
2.9	-15.81	-140.43	-13.98	
3	-16.46	-140.75	-9.08	
3.1	-16.35	-138.07	-7.25	
3.2	-15.83	-135.48	-8.84	
3.3	-15.92	-135.82	-8.45	
3.4	-16.41	-138.26	-6.98	
3.5	-16.60	-139.63	-6.86	
3.6	-16.66	-140.18	-6.86	
3.7	-16.86	-140.33	-5.44	
3.8	-16.81	-140.43	-5.94	
3.9	-16.91	-140.18	-4.89	
4	-16.75	-140.51	-6.51	
4.1	-16.86	-141.15	-6.25	
4.2	-16.95	-139.98	-4.38	
4.3	-16.90	-141.57	-6.38	
4.4	-16.81	-141.53	-7.04	
4.5	-16.74	-139.41	-5.47	
4.6	-16.62	-138.92	-5.98	
4.7	-16.61	-139.67	-6.77	
4.8	-16.87	-139.45	-4.46	
4.95	-15.98	-138.33	-10.52	
5.1	-16.27	-138.21	-8.01	
5.35	-16.35	-139.94	-9.17	

5.5	-16.17	-138.83	-9.44	Section 3
5.65	-16.11	-137.77	-8.87	
5.8	-15.87	-136.73	-9.78	
5.95	-15.89	-135.90	-8.74	
6.3	-15.50	-134.63	-10.64	
6.4	-16.51	-141.19	-9.12	
6.55	-16.92	-139.46	-4.09	
6.7	-17.16	-141.09	-3.79	
6.85	-17.27	-138.88	-0.75	
7	-16.06	-140.02	-11.54	
7.15	-15.69	-140.87	-15.38	
7.3	-17.05	-140.72	-4.34	
7.45	-16.68	-141.47	-8.07	
7.6	-16.84	-143.04	-8.31	
7.8	-16.74	-140.01	-6.07	
8	-15.72	-141.67	-15.92	
8.2	-15.55	-139.85	-15.44	
8.35	-17.24	-140.94	-3.05	
8.5	-17.89	-143.49	-0.40	
8.65	-17.65	-143.19	-2.01	
8.8	-18.02	-144.87	-0.74	
8.95	-18.12	-146.82	-1.90	
9.1	-17.56	-145.56	-5.09	
9.3	-17.38	-143.31	-4.28	
9.45	-18.84	-152.65	-1.95	
9.6	-18.80	-150.82	-0.45	
9.75	-19.02	-151.70	0.50	
9.9	-19.05	-151.41	0.96	
10.1	-19.03	-151.43	0.83	
10.2	-19.03	-153.67	-1.46	
10.35	-18.81	-151.99	-1.54	
10.45	-19.00	-152.80	-0.80	
10.55	-19.13	-154.66	-1.58	
10.65	-19.15	-153.74	-0.56	
10.75	-19.18	-153.96	-0.53	
10.85	-19.09	-152.73	-0.02	
10.95	-18.79	-150.99	-0.64	
11.05	-19.14	-154.97	-1.86	
11.15	-19.06	-154.67	-2.19	
11.25	-19.38	-154.05	1.01	
11.35	-19.06	-154.76	-2.24	
11.45	-19.13	-155.12	-2.09	
11.55	-19.58	-157.03	-0.41	
11.65	-19.92	-158.66	0.72	
11.75	-19.95	-160.07	-0.47	
11.85	-20.35	-157.16	5.63	
11.95	-20.35	-160.66	2.12	
12.05	-21.03	-163.22	5.01	
12.15	-20.82	-165.26	1.32	
12.25	-19.69	-157.46	0.04	

12.35	−20.68	−160.29	5.17	
12.45	−20.22	−161.24	0.55	
12.55	−20.71	−161.91	3.73	
12.69	−21.96	−164.11	11.58	
12.75	−20.96	−164.23	3.49	
13.00	−13.93	−135.26	−23.82	water

Table 2

$\delta^{18}\text{O}$ (SMOW), δD (SMOW) and *d-excess* values of Pestsovoye Pingo ice core, Tazovsky Peninsula, north-west Siberia

Depth (m)	$\delta^{18}\text{O}$ (‰) VSMOW	$\delta^2\text{H}$ (‰) VSMOW	<i>d-excess</i>	Section no
11.5	−12.81	−102.2	0.28	Section 1
12	−13.05	−106.5	−2.1	
12.3	−12.68	−104	−2.56	
12.7	−12.56	−103.6	−3.12	
13	−12.91	−104.1	−0.82	
13.4	−13	−100.5	3.5	
13.8	−12.59	−103.6	−2.88	
14	−12.38	−101.3	−2.26	
14.3	−11.66	−98.4	−5.12	
14.7	−11.6	−94.6	−1.8	
15	−11.61	−97.9	−5.02	
15.8	−12.05	−95.3	1.1	Section 2
16	−12.18	−104.8	−7.36	
16.3	−11.42	−96	−4.64	
16.7	−11.87	−93.2	1.76	
17	−12.46	−104.8	−5.12	
17.2	−12.05	−104.7	−8.3	
17.5	−12	−96.3	−0.3	
17.8	−11.97	−98.4	−2.64	
18	−12.74	−103.8	−1.88	
18.3	−11.71	−96.3	−2.62	
18.5	−11.58	−100.2	−7.56	
19	−12.63	−104	−2.96	
19.6	−12.7	−98.8	2.8	
19.8	−12.33	−102.6	−3.96	
20	−13.1	−105.8	−1	
20.3	−13.2	−104.3	1.3	
20.9	−12.57	−108.1	−7.54	
21	−13.21	−106.9	−1.22	
21.4	−13.25	−110.2	−4.2	
21.6	−11.95	−102.9	−7.3	
21.8	−13.41	−104	3.28	
22	−14.24	−107.2	6.72	
22.3	−13.39	−108.5	−1.38	
22.8	−13.59	−106.1	2.62	

23	-14.08	-111.4	1.24	
23.2	-13.63	-111.3	-2.26	
23.5	-14.11	-108.5	4.38	
23.8	-14.01	-110.9	1.18	
24	-14.1	-111.5	1.3	
24.3	-13.6	-104.7	4.1	
24.7	-14.56	-109.2	7.28	
24.9	-14.05	-108.1	4.3	
25	-14.88	-119.6	-0.56	
25.2	-15.19	-116.5	5.02	
25.8	-15.85	-119.9	6.9	
26	-15.23	-120	1.84	Section 3
26.1	-15.12	-117.8	3.16	
26.5	-15.38	-121.1	1.94	
26.9	-15.31	-120.1	2.38	
27.2	-15.31	-123	-0.52	
27.8	-15.21	-117.5	4.18	
29.5	-14.57	-115	1.56	
30.3	-14.09	-111.2	1.52	

Figure(s)

fig. 1

fig. 2

fig. 3

fig. 4

fig. 5

fig. 6

fig. 7