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CRYOGENIC PROCESSES AND FORMATIONS

ISOTOPE COMPOSITION OF PINGO ICE CORE IN THE YEVO-YAKHA RIVER VALLEY, NORTH-WEST SIBERIA

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The paper presents the study of Pestsovoye Pingo with ice core thickness greater than 15 m, developed in the Yevo-Yakha River valley, north-west Siberia. The stable isotope analysis of pingo ice showed that $\delta^{18}O$ values vary from –11.6 to –15.8 ‰, and δD from –93.2 to –123.0 ‰. The isotopic data distribution was compared to Weather Pingo ice core (Alaska) and revealed that $\delta^{18}O$ values in Weather Pingo ice range from –15.5 to –22.0 ‰, and δD values change from –132 to –170 ‰. The vertical distribution diagram of the isotope data for Pestsovoye and Weather Pingos ice being arcuate-shaped, it can be inferred that isotope fractionation during the freezing of the sub-pingo waters was taking place in a closed system, which is evidenced by the isotopic variations in pingo ice: by 4–6 ‰ in $\delta^{18}O$ and by 20–25 ‰ in δD values. Radiocarbon dating of the peat layer covering Pestsovoye Pingo is indicative of the frost heave occurring in two stages: the first stage (about 5 kyr BP) commenced in the distal part of the frost mound; in the second stage (about 2.5 kyr BP), the heaving rebounded actively in the middle part of pingo. Given the heaving rates were very high, more than 2–3 cm per year, the frost mound has grown up to be a 17 m high pingo.

Pingo, oxygen isotope, deuterium, radiocarbon age, north-west Siberia, intrusive ice

INTRODUCTION

Pingo (in Russia termed 'bulgunniakh') is a meso form of relief of convex shape typically 10–12 m, more rarely up to 15–20 m high (the extreme height is 50–70 m), with a basal diameter of tens, sometimes hundreds of meters, surrounded from some or all side slopes by depressions and is generally composed of sandy-loamy sediments with intercalations of sand.

Pingos start to grow when closed taliks freeze through in the course of upward aggradation of permafrost in the closed or semi-closed system (either with inconspicuous addition of water, or in the lack of it) with the formation of ground ice (predominantly, intrusive and segregated) or ice-rich pingo core through ice injection and segregation processes.

More than 6,000 pingos [*Grosse and Jones, 2011*] have been mapped in the Russian territory. In Canada, approximately 500 pingos were encountered in the Yukon area, and 1,350 pingos in the Tuktoyaktuk Peninsula and in the Mackenzie river delta, which constitutes the largest concentration of pingos in the world. Some 1250 pingos were encountered in the north of Alaska [*Jones et al., 2012*], and a lot of them on the islands in the area of Franklin and Quebec districts, and at least several hundred in Scandinavia, on the Tibetan plateau in China, in Mongolia, Antarctica and Greenland, and in the Spitsbergen archipelago. In total, over 11,000 pingos have been found and described in the world [*Mackay, 1988, 1998; Vasil'chuk and Budantseva, 2010; Grosse and Jones, 2011; Yoshikawa, 2014*].

In the north of Western Siberia there are around 1600 pingos [*Grosse and Jones, 2011*]. The authors have studied in detail one pingo in the southern parts of Tazovsky Peninsula.

STUDY AREA

More than 20 pingos were found by the authors at Pestsovoye gas field (66°10′ N, 76–77° E), 10–15 km north of the Tundra station, which is 98–103 km from Novy Urengoy (Fig. 1). The studied pingos averages from 15 to 20 m in height, and 150–200 m in diameter. In most cases, their lower part (5–7 meters high) is distinguished in their profiles as

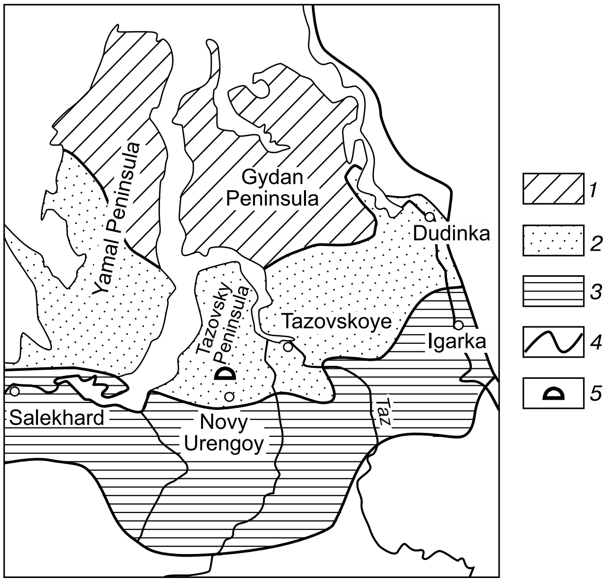


Fig. 1. Map of pingos location in the area of Pestsovoye gas field:

1, *2* – continuous permafrost (northern permafrost zone): *1* – heterogeneous low-temperature permafrost – syngenetic, underlain by epigenetic (tundra subzone), *2* – high temperature permafrost – predominantly epigenetic (forest-tundra subzone); *3* – discontinuous permafrost (northern subzone of the taiga); *4* – boundaries of permafrost zones and subzones; *5* – location of the studied pingos in the Pestsovoye field.

a pedestal, with pingo's main body doming over it (as in the cover picture).

A more detailed examination was done to one of the pingos (Fig. 2) with a height of 17 m, located 10 km north of the Tundra station (St.) located in 29–30 km after turning to Pestsovoye settlement off the main road from Novy Urengoy. The samples were taken from three pits at the pingo summit and its slope for radiocarbon dating, and in winter 2013 it was drilled to a depth of 30 m (Fig. 3), to study the internal structure of the ice core.

Fig. 2. 17 m high pingo in the area of Pestsovoye field, 10 km north of the Tundra station.

Geologists on the top of the pingo for scale.

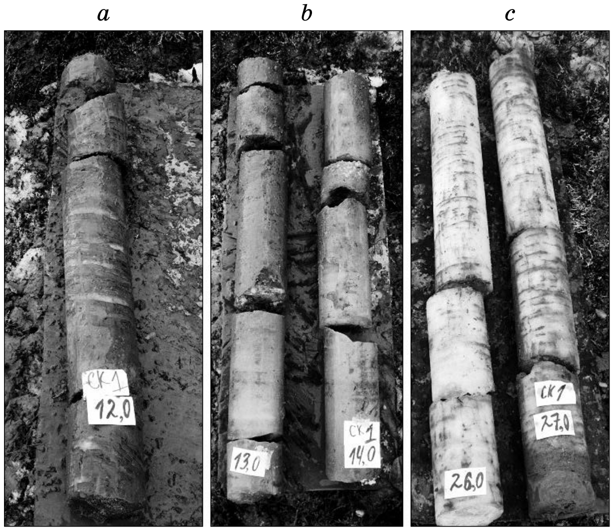


Fig. 3. Ice core samples from the borehole drilled at the top of 17 m high Pestsovoye Pingo.

Depth range: *a* – 11–12 m; *b* – 12–14 m; *c* – 25–27 m.

The pingo cross-section (Fig. 4, *a*) exhibited:

0.0–0.5 m: Dark brown peat.

0.5–0.9 m: Dark brown peaty loam.

0.9–12.0 m: Compact dark gray loam. The cryostructure is structureless. In the lower part, thick horizontal ice lens (up to 5–7 cm) were encountered from the depth beneath 10.2 m.

12.0–12.7 m: Alternating layers of loam and ice, with ice layers thickness 5–7 cm, and that of loam 10–12 cm.

12.7–27.0 m: Alternating layers of opaque, transparent and milky white ice. At the intervals 20.0–22.5 and 26–27 m, 2–3 cm thick intercalations of loam were encountered.

27–35 m: Layers of ice (5–8 cm thick) were encountered at depths 27.8, 28.5 and 31.8 m. Loam is compact, grey, with layered cryostructure.

THE RESULTS OF PINGO ISOTOPE AND RADICARBON ANALYSIS

The results of radiocarbon dating. To determine the age of Pestsovoye Pingo the overlying peat was sampled in its middle part and near the base of the pedestal. Radiocarbon dating of peat was carried out at the Geological Institute, Russian Academy of Sciences with the participation of L.D. Sulerzhitsky and revealed a relatively young age of the overlying peat in different parts of the pingo (Table 1).

The age of peat dated to 2560 ± 70 yr BP in the middle part of the pingo, to 5220 ± 50 years at 0.3–0.4 m depth, 5080 ± 50 yr BP at 0.85–0.90 m depth. At the pingo pedestal, at the inteval 0.05–0.15 m the

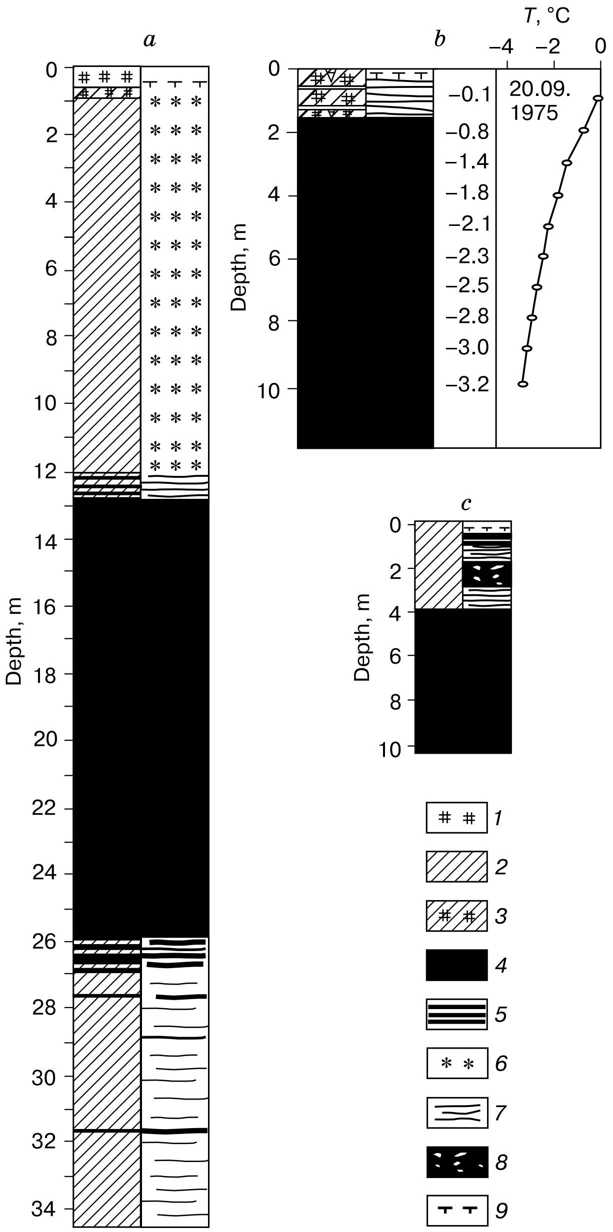


Fig. 4. Cryostratigraphy of boreholes revealed thick ice layers in pingo ice cores in the southern Tazovsky Peninsula.

a – 17 m high Pestsovoye Pingo, 10 km north of Tundra St.; *b* – ca 15 m high pingo on the left bank of the Parovy-Khadutte Rv.; *c* – ca 7 m high pingo in the Tab-Yakha and Yen-Yakha rivers watershed [*Geocryological conditions..., 1983*]; *1* – peat; *2* – clay loam; *3* – plant remains in the sediments; *4* – intrusive ice; *5* – thick ice lens; *6–8* – cryostructure types of ice-rich sediments: *6* – massive, *7* – fine layered and lenticular, *8* – basal; *9* – bottom of the active layer.

peat was dated to 5400 ± 40 years. Interestingly, *E. Olson* and *W. Broecker* [*1959*], using peat sample collected in 1955 by H. Craig from the basal-peat part at a depth of 0.9 m on the pingo summit in the Thelon River valley (64°19′ N, 102°41′ W), the Northwest Territories of Canada, obtained the ^{14}C-date 5500 ± 250 yr BP (L-428), i.e. close to our ^{14}C date for the basal peat of Pestovoye Pingo.

Table 1. **Radiocarbon ages of peat overlying the 17 m high Pestsovoye Pingo**

Field number of specimen	Depth, m	^{14}C-dating, years	Laboratory number of speciemen
Sampling pit 1			
397-YuV/1	0–0.07	2560 ± 70	GIN-13329
397-YuV/4	0.3–0.4	5220 ± 50	GIN-13332
397-YuV/8	0.85–0.90	5080 ± 50	GIN-13335
Sampling pit 2			
397-YuV/9	0.05–0.15	5400 ± 40	GIN-13336

The results of isotopic analysis. Pingo samples were analyzed for stable isotope composition at the isotope laboratory of MSU Department of Geography, using mass-spectrometer Delta-V with the Gas-Bench standard option.

Both international standards including V-SMOW, GISP, SLAP, and fresh snow from the surface of glacier Garabashi, Central Caucasus ($\delta^{18}O$ = −15.60 ‰, δD = −110.0 ‰) – the MSU laboratory standard, were used for the measurements. The analytical precision is 0.1 ‰ for $\delta^{18}O$ and 0.6 ‰ for δD.

The uppermost layer of ice (at 12 m depth) at the upper ice-sediment contact has relatively negative δD (−106.5 ‰) and $\delta^{18}O$ (−13.0 ‰) isotopic values that increase (−97.9 ‰ for δD and −11.6 ‰ for $\delta^{18}O$) at a depth of 15 m (Table 2, Fig. 5, *a*, *d*).

Between 16 and 18 m depth, the stable isotope values were relatively constant (δD ~ −105 ‰, $\delta^{18}O$ ~ −12.5 ‰) with minor variations between the samples (Fig. 5, *a*, *d*). Deuterium excess values (d_{exc}) in the upper 9 meters of ice vary from −7.36 to 1.76, but the vertical distribution of values is random.

The lower part of the pingo ice core is essentially characterized by a decrease in $\delta^{18}O$ to −15.23 ‰ and δD to −120.0 ‰ (Fig. 5, *a*, *d*). It is notable that d_{exc} values tend to increase there and become in the lower 4 meters almost ubiquitously positive, reaching 6.72 ‰.

Isotope variations in the Pestsovoye Pingo ice core are characterized by a great range of $\delta^{18}O$ values (about 6 ‰) and contrasting distribution in the 15-meter thick ice: they decrease successively downward in the upper portion of ice (with negative $\delta^{18}O$ values changing from −13 to −11.61 ‰), then gradually increase in the semi-lower part of the ice ($\delta^{18}O$ change from −11.61 to −15.23 ‰) and in the bottom part (from −15.12 to −14.09 ‰). Therefore, the isotope profile of Pestsovoye Pingo ice can be characterized by two trends: stable isotopes tend to be slightly

Table 2. **$\delta^{18}O$, δD and d_{exc} variations in ice core of the 17 m high Pestsovoye Pingo**

Sampling depth, m	$\delta^{18}O$, ‰	δD, ‰	d_{exc}	Sampling depth, m	$\delta^{18}O$, ‰	δD, ‰	d_{exc}
11.5	−12.81	−102.2	0.28	20.9	−12.57	−108.1	−7.54
12.0	−13.05	−106.5	−2.10	21.0	−13.21	−106.9	−1.22
12.3	−12.68	−104.0	−2.56	21.4	−13.25	−110.2	−4.20
12.7	−12.56	−103.6	−3.12	21.6	−11.95	−102.9	−7.30
13.0	−12.91	−104.1	−0.82	21.8	−13.41	−104.0	3.28
13.4	−13.00	−100.5	3.50	22.0	−14.24	−107.2	6.72
13.8	−12.59	−103.6	−2.88	22.3	−13.39	−108.5	−1.38
14.0	−12.38	−101.3	2.26	22.8	−13.59	−106.1	2.62
14.3	−11.66	−98.4	−5.12	23.0	−14.08	−111.4	1.24
14.7	−11.60	−94.6	−1.80	23.2	−13.63	−111.3	−2.26
15.0	−11.61	−97.9	−5.02	23.5	−14.11	−108.5	4.38
15.8	−12.05	−95.3	1.10	23.8	−14.01	−110.9	1.18
16.0	−12.18	−104.8	−7.36	24.0	−14.10	−111.5	1.30
16.3	−11.42	−96.0	−4.64	24.3	−13.60	−104.7	4.10
16.7	−11.87	−93.2	1.76	24.7	−14.56	−109.2	7.28
17.0	−12.46	−104.8	−5.12	24.9	−14.05	−108.1	4.30
17.2	−12.05	−104.7	−8.30	25.0	−14.88	−119.6	−0.56
17.5	−12.00	−96.3	−0.30	25.2	−15.19	−116.5	5.02
17.8	−11.97	−98.4	−2.64	25.8	−15.85	−119.9	6.90
18.0	−12.74	−103.8	−1.88	26.0	−15.23	−120.0	1.84
18.3	−11.71	−96.3	−2.62	26.1	−15.12	−117.8	3.16
18.5	−11.58	−100.2	−7.56	26.5	−15.38	−121.1	1.94
19.0	−12.63	−104.0	−2.96	26.9	−15.31	−120.2	2.28
19.6	−12.70	−98.8	2.80	27.2	−15.31	−123.0	−0.52
19.8	−12.33	−102.6	−3.96	27.8	−15.21	−117.5	4.18
20.0	−13.10	−105.8	−1.00	29.5	−14.57	−115.0	1.56
20.3	−13.20	−104.3	1.30	30.3	−14.09	−111.2	1.52

heavier from the top of ice core to a depth of 15 m (about 1.5 ‰ for $\delta^{18}O$ and about 9 ‰ for δD), gradually decreasing in the range of 15–26 m – by 3.8 ‰ for $\delta^{18}O$ and by 23.0 ‰ for δD (Fig. 5, *a*, *d*). Consequently, there may be distinguished two stages of the ice core formation for the pingo.

The isotope analysis results allowed to identify the West Siberian-Yakutian type (also Mackenzie–Alaska type) of pingo, formed usually in a closed system within the bottom of drained or draining lake basin (khasyrey, alas) during its freezing, without additional recharge of water with greatly varying isotope composition. The isotope profile of such pingo is usually contrasting, arcuate-shaped.

DISCUSSION

Determination of the isotopic composition of pingo ice was performed by the Canadian [*Michel and Fritz, 1982; Mackay, 1983, 1990, 1998; Lacelle, 2011*] and Japanese [*Yoshikawa et al., 2012, 2013; Yoshikawa, 2014*] researchers who studied pingos in northern Canada, Spitsbergen and continental regions of Alaska.

J.R. Mackay [*1983*] believes that, with the exception of small-sized pingos, most of pingo ice cores fall into several types, represented by either segregated or intrusive ice, or any combination of these. Ice in cracks (dilation crack ice) often develops in the upper part of pingos, those having summits with craters.

Ice veins can penetrate into the ice core. Therefore, the ice core recovered from drill holes may be a combination of these four types. For example, *K. Fujino* and *K. Kato* [*1978*] have provided a series of $\delta^{18}O$ values from −22.2 to −26.0 ‰ for ice sampled near the summit of pingo, located southwest of the Tuktoyaktuk settlement, which turned out to be ice from ice vein. *F. Michel* and *P. Fritz* [*1982*] obtained $\delta^{18}O$ values from −18 to −28 ‰ for ice from several boreholes drilled at the pingo summits near Ilisarvik, and established that at least part of the ice core was intrusive.

Pingos grow up on drained lakes bottoms on interfluvial plains, floodplains and river terraces. In the area of North-Western Siberia, pingos were studied in detail by *V.N. Andreev* [*1936*]. Numerous pingos were encountered and described by the authors on the Yamal Peninsula, at the Bovanenkovo field area in

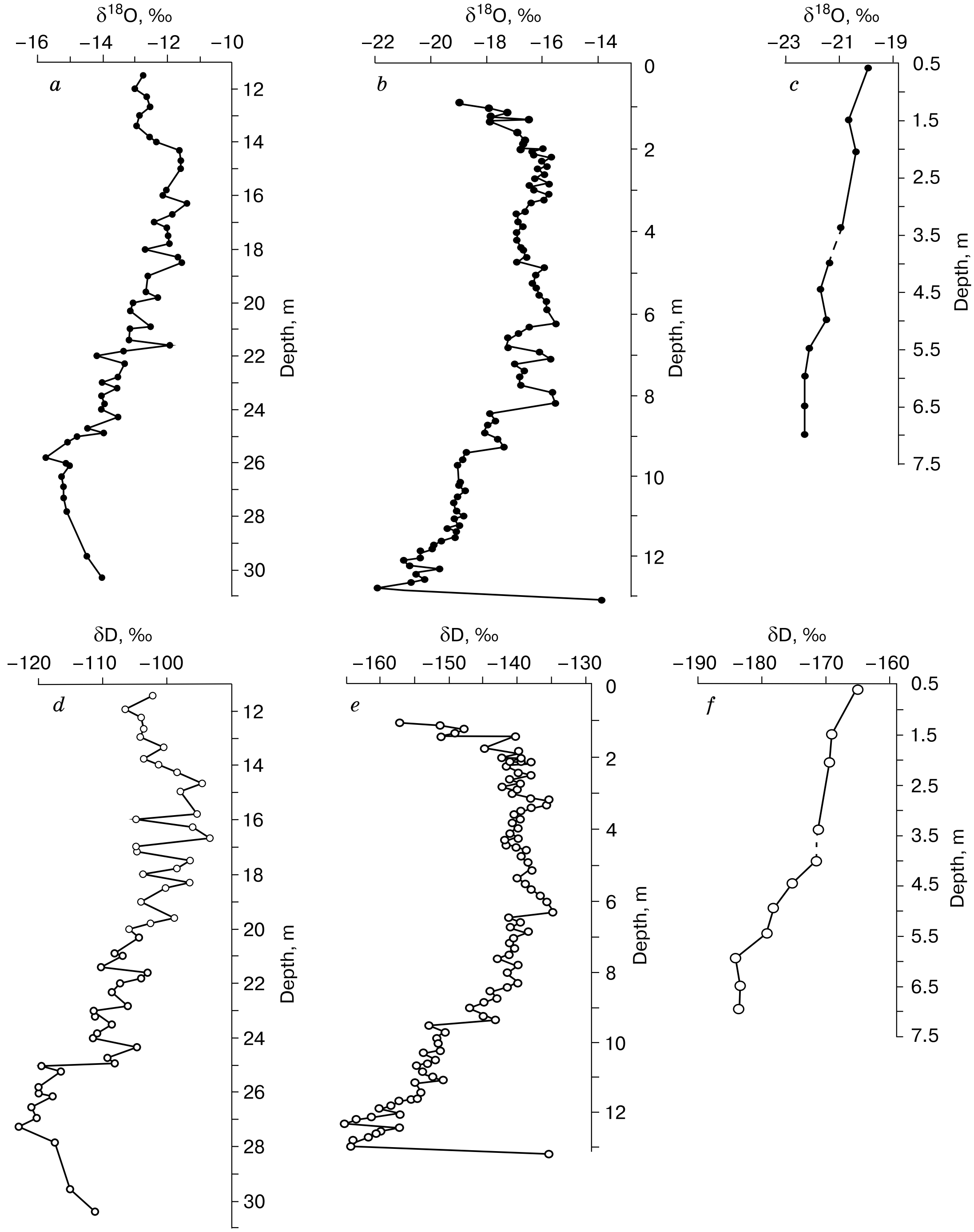


Fig. 5. $\delta^{18}O$ and δD profiles of pingo ice.

a, d – Pestsovoye Pingo; *b, e* – Weather Pingo (according to [*Yoshikawa et al., 2012*]); *c, f* – Pingo 20 (according to [*Mackay, 1990*]).

the Laborovskaya depression. A large well-shaped pingo on the floodplain of the Yer-Yakha River in the eastern Yamal Peninsula was drilled to a depth of 11 m, and even at this depth the ice-rich core failed to be encountered (Fig. 6, *a*). Relying on the new data available now along with those obtained from the drilling and field examination of Pestsovoye Pingo, we can confidently say that the pingo ice lens occurs at a depth beneath 12 m in the floodplain of the Yer-Yakha River.

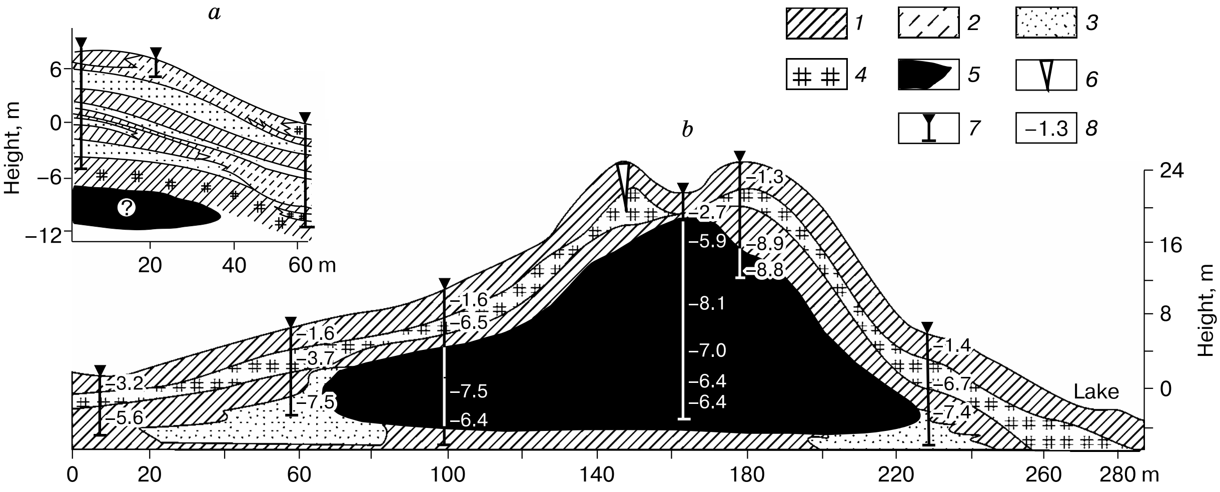


Fig. 6. Geocryological cross-section of pingos in the northern West Siberia.

a – on the Yer-Yakha River floodplain, Eastern Yamal Peninsula, drilled by the authors on July, 28 1978; *b* – 6 km south-east of Messoyakha settlement in the watershed of the Yupa-Yakha and Upper Pendoma rivers, on the bottom khasyrey with a length of 1.8 km and width of 1 km (according to the data from [*Anisimova and Karpov, 1978*]); *1* – clay loam, *2* – sandy loam, *3* – sand, *4* – peat, *5* – pingo ice core, *6* – ice wedge, *7* – boreholes, *8* – temperature measurements in the boreholes.

Large concentrations of pingos on the Tazovsky Peninsula have been mapped and studied by the researchers from Moscow State University, VSEGINGEO and PNIIIS in the basins of the Nadym, Yamsovey, Yevo-Yakha, Tab-Yakha and Khadutte Rivers [*Andreev, 1960; Minaev, 1963; Geocryological conditions..., 1983*]. The height of pingos varies from 4–5 to 15–20 m, and the diameter – from tens to a few hundreds of meters. Many large pingos have a "pedestal" along their circumferential periphery in the form of terrace-like "steps" up to 1–2 meters high. At present, not only newly sprung frost mounds of intrusive and segregated-intrusive origin are developing, but pingos formed in earlier stages of the Holocene proceed to grow up [*Vasil'chuk, 2013*].

A general possibility for the growth of frost mounds previously formed due to the subsequent water injections was convincingly demonstrated by *N.P. Anisimova* [*1981*] on the basis of the chemical composition analysis of a very large pingo near Messoyakha settlement (Fig. 6, *b*), which prompted the following inferences: the injection (and segregation) of water appears to have been recurrent during the formation of pingo ice core; the chemical composition of ice in the freezing sub-lake talik changed from bicarbonate-magnesium-calcium (in early stages of heaving) to bicarbonate-sodium (in later stages); the upper layers of ice (at 2–5 m depth) formed at a relatively rapid and complete crystallization of water, while those lying deeper developed at slower rates of crystallization. The latter is evidenced by inconspicuous concentrations of calcium and magnesium ions at the base of ice lens that precipitate from solution during the slow proceeding crystallization [*Anisimova and Karpov, 1978; Anisimova, 1981*].

Pingo formation rates can be very high. *P.A. Solov'yov* [*1952, 1975*] provided the observation evidences that about 50 years ago in the vast Nyamchir alas basin, located in the Suola river valley, 8 km south-east of the Abalakh settlement an extensive area was subjected to heaving, gradually taking shape of a pingo, due to the lake draining and further freezing of its bottom, with their height aggradation rates about 0.5 m per year. Later, numerous small frost mounds grew up in the vicinity. The borehole drilled into area of heaving penetrated the 4.3 m thick loamy sediments with ice lenses, and revealed a residual sub-lake talik in the underlying medium-grained sands at ca 10 m depth.

With the ongoing long-term observations, the pingos growth and degradation have been given a thorough study to. Growth of pingos on the Perry Peninsula thus has been observed for a period of over 100 years, which is supplemented by photos taken by V. Stefansson in 1908, and those taken later by other researchers in 1971, 1996 and 2008 [*Mackay and Burn, 2011*].

The fluctuation dynamics of Pingo 15 located in the Mackenzie Rv. delta, near the Tuktoyaktuk settlement was studied by *J.R. Mackay* [*1998*]). The pingo grew up in the lake basin after its catastrophic draining through the outflow streams from the lake, caused by ice wedges thermally eroding. The drained lake was nearly circular in shape with a diameter approximately 650 m; two pingos have developed in the residual water bodies located in the middle part of the lake bed. Judging from the age of willows grown up in the drained lake bed, the draining of the lake could have occurred earlier than 1915. By 1935, Pingo15 was large enough to be identified on the aerial photograph. In the winter of 1974 yet another heaving generated mound A, close to Pingo 15, which proved continuable, as mound B sprang up next to mound A in 1983. When drilling into the mound on June 15–25 1976, once the ice-rich perennially frozen sediments were penetrated at a depth of 23 m, water containing a lot of sand sprayed upward from the drill hole. The ejection of water lasted for three days, with the water temperature remaining almost constant (about −0.2 °C).

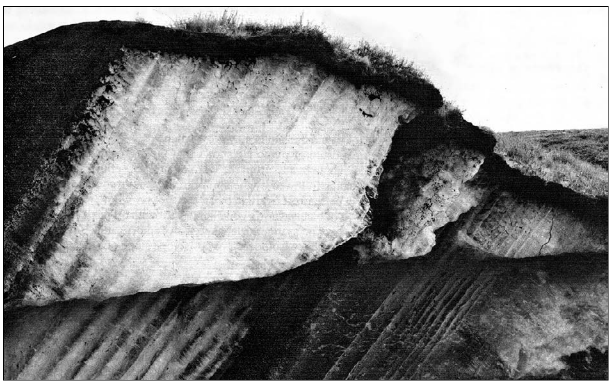
Mound A (in the vicinity of Pingo 15), first discovered in 1974, by that time (June 1976) had reached a height of approximately 2.3 m and ceased growing. Mound B (near Pingo 15) proceeded to grow from July 1980 until the end of July 1983. The large mound had grown up to 33 m in height and 20 to 25 m in diameter by 1983, with its highest point rising more than 2 m above the lake bed. The observations showed that mound B remained unchanged from 1983 to 1992 during a brief on-site visit in 1996, J.R. Mackay reported no observable changes to mound B, unlike in mound A, which had become a satellite frost mound to Pingo 15. Three boreholes drilled into the mound on June 30, 1988, encountered water lenses in the sediments underlying the intrusive ice [*Mackay, 1998*].

Distribution of stable isotopes in pingos. Three ice samples and three samples of water from mound B (near Pingo 15) located in the Mackenzie Rv. delta, were analyzed for stable isotopes by *J.R. Mackay* [*1998*]. The isotope composition of water samples was more negative than that of ice samples: $\delta^{18}O$ values for ice varied from −18 to −19 ‰, δD values were about −160 ‰, whereas the $\delta^{18}O$ values for the water were about −25, −26 ‰, δD values were lower than −190 ‰. The regression slope value for δD and $\delta^{18}O$ is about 5.2. J.R. Mackay inferred, that both water and ice in mound B underwent several stages of fractionation: a) fractionation associated with the downward freezing of sediments and pore water expulsion; b) fractionation during the formation of intrusive ice in Pingo 15, as the underlying water lens froze; c) freezing of water in mound B, supplied from a water lens beneath Pingo 15 [*Mackay, 1998*].

J.R. Mackay also performed isotope analyses for Pingo 20 located 80 km north-east of Tuktoyaktuk, Northwest Territories of Canada [*Mackay, 1990*]. The layering of ice is clearly visible in the outcropping ice core, represented by clearly alternating pairs of pure transparent and opaque ice with air bubbles (Fig. 7). Pingo 20, like most of the pingos at the Tuktoyaktuk Peninsula is a hydrostatic (closed) system pingo that grows up on the bottom of drained thermokarst lakes. Prior to the draining, the lake had been oval-shaped with a length of about 700 m and 350 m in width. Given the draining of the lake occurred very rapidly, the long-term freezing of the bottom lake sediments commenced from the first winter on.

It has been emphasized that most of the ice of Pingo 20 is nearly pure intrusive ice formed from the freezing of a constantly replenished sub-pingo water lens. *J.R. Mackay* [*1990*] proposed that each band pair accounts for one annual cycle of freezing of a water lens and probably represents one year of pingo growth. The clear bands are believed to have been caused by rapid freezing that accompanies the downward propagation of the cold winter temperature wave. The bubble bands may have resulted form slow freezing from the downward propagation of the warm summer temperature wave. According to Mackay, the widths of the clear and bubble bands when cumulated from year 2 to year 31 show the growth of the ice core of Pingo 20. Thirty pairs of clear and bubble bands with total thickness of about 6 m were counted in the ice core, suggesting that the age of Pingo 20 in 1988 was at least 30 years. Freezing rates decreased from

a



b

Fig. 7. Subvertical stratification of ice in Pingo 20 core ice 20 (*a*) and pingo main view (*b*), the Tuktoyaktuk Peninsula, 80 km northeast of Tuktoyaktuk settlement.

The arrow points to the location of outcrop on the pingo summit. Photograph by J.R. Mackay.

Table 3. **$\delta^{18}O$, δD and d_{exc} variations in ice core of Pingo 20 at the Mackenzie Rv. Delta, 80 km northeast of Tuktoyuktuk settlement**

Age of layer, yr	$\delta^{18}O$, ‰	δD, ‰	d_{exc}
2	−19.9	−165.8	−6.8
4	−20.7	−168.9	−3.3
7	−20.5	−169.3	−5.3
10	−20.9	−172.1	−4.9
13	−21.2	−173.7	−4.1
16	−21.8	−175.6	−1.1
19	−21.7	−178.2	−4.6
22	−22.1	−179.7	−2.9
25	−22.4	−184.3	−5.1
28	−22.4	−183.2	−4.0
31	−22.4	−184.0	−4.8

Note. The research was carried out July, 6 1988 by *J.R. Mackay* [*1990*].

20 nm/s in year 2 to 4 nm/s in year 31. The widths of the clear and bubble bands decrease downward from the pingo soil-ice contact from 25–30 cm to 5–15 cm [*Mackay, 1990*].

The values of $\delta^{18}O$ and δD of Pingo 20 ice decreased linearly from year 2 to year 25 (from the depth of 0.5 to 6 m): $\delta^{18}O$ values change from −19.9 to −22.4 ‰, δD values – from −165.8 to −184.3 ‰ (Table 3; Fig. 5, *b*, *f*). After year 25 the isotope values remained constant till year 31 (6.75 m depth). The co-isotope trend is linear with a slope of 7.2 (Fig. 8, *c*) [*Mackay, 1990*].

As an example of pingo formed in a closed system, we considered Weather Pingo in the area of the Prudhoe Bay, Alaska, on the basis of the detailed isotope data received by K. Yoshikawa. Both physical properties and isotope composition of ice (Fig. 5, *b*, *e*) indicate that the formation and evolution of Weather Pingo occurred in the variable hydrological conditions.

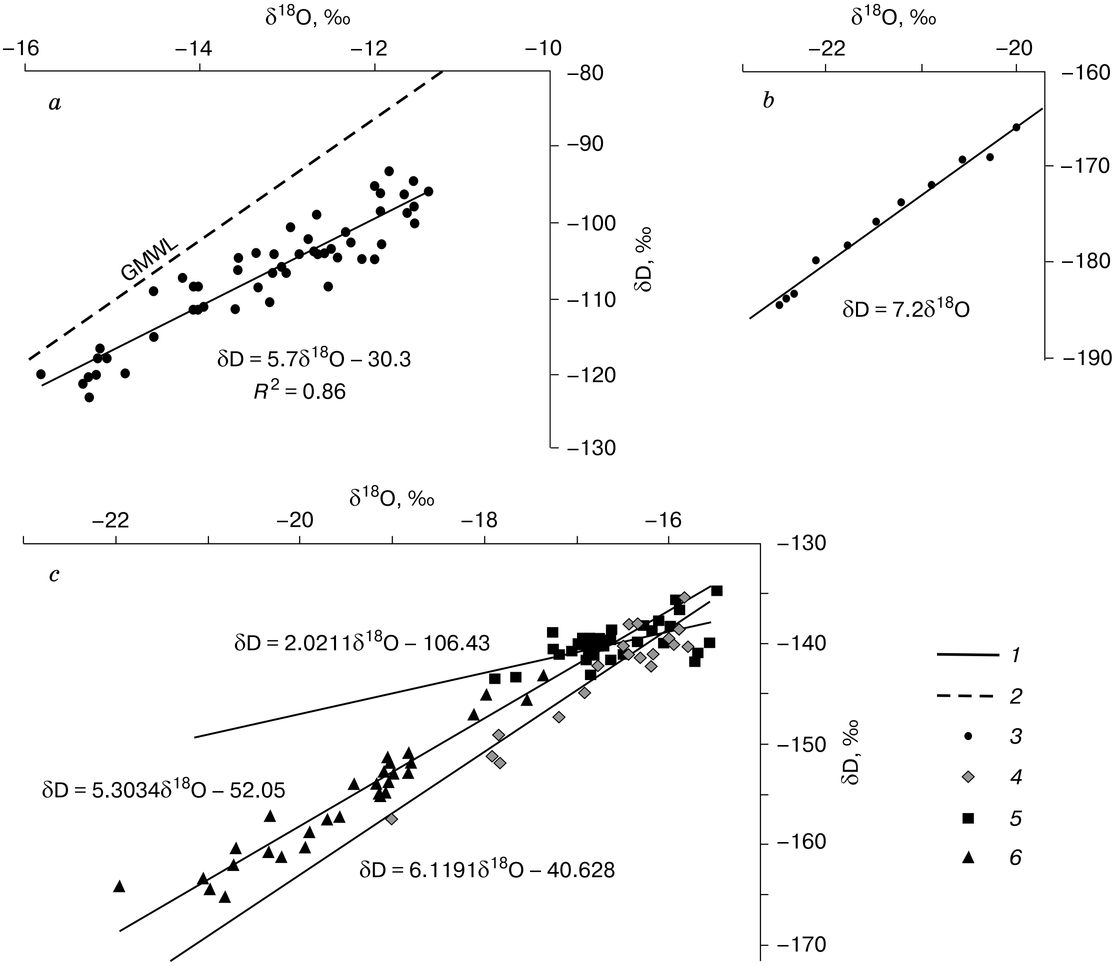


Fig. 8. $\delta^{18}O$ and δD ratios in pingo ice.

a – Pestsovoye Pingo; *b* – Pingo 20 [*Mackay, 1990*]; *c* – Weather Pingo; *1* – local regression lines for the studied pingos; *2* – Global Meteoric Water Line (GMWL); *3* – isotope values for Pestsovoye Pingo and Pingo 20; *4–6* – isotope values for Weather Pingo, depth intervals: *4* – 0–2.2 m, *5* – 2.2–4.8 m, *6* – 4.8–13.0 m.

The uppermost section consists of fine grained ice with numerous round air bubbles of 1–2 mm diameter distributed evenly through the ice to a depth of 2.8 m at a sand-rich horizon with vertical bubble trains. The middle section between 2.8 and 6.3 m depth contains three sand horizons and slightly elongated air bubbles developed in a near-vertical orientation. The lower section of ice core between 6.3 and 13 m consists of clear, debris-free ice with crystal diameters generally larger than elsewhere in the pingo core.

The uppermost layer of ice (at 1 m depth) is in contact with the sediments overlying the pingo and has relatively negative δD (–150...–155 ‰) and $\delta^{18}O$ (–19 ‰) isotopic values that increase (–140 ‰ for δD, –16 ‰ for $\delta^{18}O$) to a depth of 1.4 m (Fig. 5, *b*, *e*). K. Yoshikawa interprets these values to be a result of rapid freezing of water in the lake bottom sediments, which immediately followed its draining.

In the 1.4–2.2 m interval the values of $\delta^{18}O$ and δD increase slightly with depth, but with an apparent recurrency of increasing and decreasing values (Fig. 5, *b*, *e*), which can be indicative of short-term changes either in the water flow or freezing rates. The regression slope value between δD and $\delta^{18}O$ is 6.1. Between 2.8 and 4.4 m depth, the stable isotope values were relatively constant (δD ~ –140 ‰, $\delta^{18}O$ ~ –16.5 ‰) with only slight variations between successive samples. The d_{exc} values, however, vary over a wide range (from –5 to –14 ‰), which may attest to continuous migration of water from the ambient surroundings to sub-pingo water lens.

The lower sections in the pingo's ice core to 8.3 m depth are characterized by generally decreasing δD and $\delta^{18}O$, except for several short sections with increasing values (Fig. 5, *b*, *e*). For example from about 5.3 to 6.1 m depth, a well-defined substage of progressively heavier isotopic composition suggests a change in the composition of the migrating water, whereas from 8.0 to 8.3 m depth, progressively lighter δD and $\delta^{18}O$ values suggest the reduced flow to the freezing front and thus fractionation during the freezing of a limited volume of sub-pingo water.

From 11.8 to 13 m at the base of the pingo's ice core, the δD and $\delta^{18}O$ values decrease more rapidly while d_{exc} sharply increases to positive values (Fig. 5, *b*, *e*). The lower portion of ice is characterized by a regression slope value between δD and $\delta^{18}O$ equal to 5.3 (Fig. 8, *c*), which is lower than that of local meteoric water line (7–8).

According to K. Yoshikawa the isotope fractionation hardly occurred at the initial stage of freezing and during the formation of the upper portion of pingo ice core, as it is more likely to have taken place at later stages of the ice core formation, after the head water ceased to feed from meltwater deposits beneath the drained lake bottom. The process of primary heaving of pingo above the surrounding surface was launched by ice aggradation during the later period of water migration, due to the increased volumes. As the lake basin proceeded to freeze, this caused a consistent reduction in the talik volume, and the expulsion of excessive moisture created hydrostatic pressure.

The comparison of the isotope profiles of Weather Pingo, Pestsovoye Pingo and Pingo 20 shows slightly greater range of isotope values in the ice of Weather Pingo (its isotope curve is more arcuate) versus the range of values for the ice of Pestsovoye Pingo and Pingo 20 (Fig. 5, 8; Table 3).

$\delta^{18}O$ values in the Weather Pingo ice core vary from –15.5 to –22.0 ‰, δD values vary from –132 to –170 ‰, in the Pestsovoye Pingo ice core $\delta^{18}O$ values vary from –11.6 to –15.8 ‰, and δD – from –93.2 to –123.0 ‰, whereas in the ice core of Pingo 20 $\delta^{18}O$ values vary from –19.9 to –22.4 ‰, δD – from –165.8 to –184.3 ‰. It should also be noted that the isotope values for Weather Pingo and Pingo 20 are altogether lower, than for Pestsovoye Pingo (Fig. 5).

Isotope variations in the ice core of Weather Pingo are characterized by a great range of $\delta^{18}O$ values – about 6 ‰ and monotone distribution in the 13-meter thick massive ice – decreasing consistently from the surface downward ($\delta^{18}O$ change from –19 to –16 ‰), and then consistently increasing at the lower part ($\delta^{18}O$ values change from –16 to –22 ‰). Ice core of Weather Pingo has been divided into three depth intervals: 0–2.2 m, 2.2–4.8 m and 4.8–13.0 m, according to physical properties and isotope composition of ice.

The two trends that characterize the Pestsovoye Pingo isotope profile are: insignificant increase in $\delta^{18}O$ (about 1.5 ‰) and δD (about 9 ‰) values in the 12–15 m depth interval; and gradual decrease in the isotope values at the depth interval 15–26 m (by 3.8 ‰ for $\delta^{18}O$ and by 23 ‰ for δD values).

The comparison of the isotope profiles revealed a greater arcuating isotope curve for Weather Pingo in comparison with that for Pestsovoye Pingo, and similar pattern of the isotope values distribution in the lower parts of the Weather Pingo and Pestsovoye Pingo ice cores, versus their distribution in the ice of Pingo 20. This may be accounted for by the bottom intrusive ice of Pingo 20 having formed in the conditions of constantly replenished sub-pingo water lenses, as field observation by *J.R. Mackay* [*1990*] have shown.

The upper portion of ice core of both Weather and Pestsovoye Pingos developed, in contrast, in the course of progressive freezing of trapped water, which was reflected in the isotope depletion of ice from top downwards. Consequently, at least two stages of ice core formation may be identified in these pingos. This is also evidenced by the presence of a pedestal at Pestsovoye Pingo.

Isotope profile of Pingo 20 ice is characterized by a gradual decrease of values from the top to bottom of the ice core. No sharp increasing of isotope values for ice Pestsovoye Pingo and Pingo 20 have been documented, which may be accounted for by more intensive (as compared, for example, with Weather Pingo) water supply from beneath.

Given that ice is known to become always isotopically heavier than initial water during freezing, at least, by 1–3 ‰ for oxygen and by 10–25 ‰ for deuterium, the remaining water tends to become heavier during the progressive freezing, and, respectively, ice in the closed volume is supposed to become isotopically heavier [*Vasil'chuk, 2011*]. This freezing pattern accounts for the upper 5–6 meters of ice cores of Weather Pingo and Pestsovoye Pingo, where stable isotope values have increased: $\delta^{18}O$ – by 3–5 ‰ and δD – by 10–20 ‰ (Fig. 5). The isotope curves for the lower 6–10 m of ice cores are almost similar to the isotope curve for Pingo 20 and is characterized by a decrease in isotope values: $\delta^{18}O$ by 4–6 ‰ and δD by 20–25 ‰, which probably depicts a higher involvement of segregated and congelation ice formation in the course of ice lenses development.

Three co-isotope lines were plotted for ice of Weather Pingo from three depth intervals: 0–2.2 m, 2.2–4.8 m and 4.8–13.0 m. For the upper part of ice the regression slope is 6.1, which is close to Global Meteoric Water Line (GMWL). For the middle part of pingo ice the regression slope is 2. For the lower part of pingo ice the regression slope is 5.3, which is lower than those for local meteoric water line (7–8).

The analysis of co-isotope lines for Weather Pingo, Pestsovoye Pingo and Pingo 20 demonstrates isotope similarity of Pestsovoye Pingo ice and ice of the lower section of Weather Pingo (Fig. 8, *a*, *c*). The regression slope of co-isotope line of Pingo 20 ice is 7.2, which is close to GWML (Fig. 8, *b*).

When comparing the isotopic curves in general terms it may be inferred that the system was closed to the greatest degree when the Weather Pingo ice formation occured. Pingo 20 formed, most likely, in the ultimately open system with intensive additional water inflow and, obviously, with intrusive and segregation (and congelation) ice being actively formed, which defined the isotopic curve to be that weakly arcuated. The isotope diagram for Pestsovoye Pingo reflected the active formation of intrusive and segregation (congelation) ice taking place concurrently, therefore the isotope profile convexity represents an average between the curves for Weather Pingo and Pingo 20.

CONCLUSIONS

- A vertical profile of stable isotope values in pingo ice core for the first time was obtained for the Russian permafrost.
- Due to Pestsovoye Pingo was formed at the bottom of draining lake depression (hasyrey) during its freezing in closed system conditions with little additional water inflow, it has a contrasting arcuate-shaped isotope profile.
- The formation of pingo ice core occurring in the conditions of the closed or semi-closed system with cryogenic fractionation that revealed through changes in the isotopic composition of ice: by 4–6 ‰ for $\delta^{18}O$ values and by 20–25 ‰ for δD values.
- The vertical distribution of isotope data has shown greater arcuate shape in the isotope profile for Weather Pingo versus Pestsovoye Pingo, and revealed similar pattern of $\delta^{18}O$ and δD values distributions in the lower parts of ice cores of these pingos.
- The regression slope line for ice of Pestsovoye Pingo is close to that of ice from the lower part of Weather Pingo, while regression slope line of Pingo 20 ice is close to GWML.
- The lower parts of ice cores of Weather Pingo and Pestsovoye Pingo, including entire ice of Pingo 20, are likely to have formed with systematic additional water flows from the sub-pingo water lens.
- The upper parts of ice cores of Weather Pingo and Pestsovoye Pingo were formed during of progressive downward freezing of the closed volume of water, which has led to the downward isotopic depletion of ice.
- The formation of Pestsovoye Pingo ice core may have occurred in two stages, which is evidenced by the presence of the pedestal at Pestsovoye Pingo.
- Radiocarbon dating of the overlaying peat of Pestsovoye Pingo allowed to establish that the heaving occurred in two stages: at the first stage, it commenced at the pingo periphery about 5000 years BP, and at the second stage the heaving became more active about 2500 years BP in the middle part of pingo.
- The heaving rates of Pestsovoye Pingo were very high – more than 2–3 cm/year, which resulted in the formation of 17 m high pingo over a relatively short period.

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References

Andreev, V.N., 1936. Hydrolaccoliths (bulgunnyakhs) in West Siberian tundra. Proceedings of the Russian State Geographic Society, No. 68(2), p. 40–47. (in Russian)

Andreev, Y.F., 1960. On the relationship is linear-ridge relief with tectonic structures in the north of Western Siberia (in the permafrost area). Geology and Geochemistry, No. 3 (IX), pp. 76–94.

Anisimova, N.P., 1981. Cryo-hydrogeochemical specific features of the permafrost zone. Nauka, Novosibirsk, 153 pp. (in Russian)

Anisimova, N.P., Karpov, E.G., 1978. Chemical composition of intrusive ice. In: Geocryological and hydrogeological studies in Yakutia. Yakutsk, pp. 125–137. (in Russian)

Fujino, K., Kato, K., 1978. Determination of oxygen isotopic concentration in the ground ice of a tundra area. In Joint studies on physical and biological environments in the permafrost. Alaska and North Canada / Editor S. Kinishita. Institute of Low Temperature Science. Hokkaido University, Sapporo, pp. 77–83.

Geocryological conditions of the West-Siberian oil province, 1983 / Editor Ye.S. Melnikov. Nauka, Novosibirsk, 199 pp. (in Russian)

Grosse, G., Jones, B.M., 2011. Spatial distribution of pingos in northern Asia. The Cryosphere 5, p. 13–33.

Jones, B.M., Grosse, G., Hinkel, K.M., Arp, C.D., Walker, S., Beck, R.A., Galloway, J.P., 2012. Assessment of pingo distribution and morphometry using an IfSAR derived digital surface model, western Arctic Coastal Plain, Northern Alaska. Geomorphology 138 (1), p. 1–14.

Lacelle, D., 2011. On the $\delta^{18}O$, δD and D-excess relations in meteoric precipitation and during equilibrium freezing: Theoretical approach and field examples. Permafrost and Periglacial Processes, No. 22, p. 13–25.

Mackay, J.R., 1983. Oxygen isotope variations in permafrost, Tuktoyaktuk Peninsula area, Northwest Territories. Geol. Surv. Canada. Current Res. Pt B, pap. 83–1B, p. 67–74.

Mackay, J.R., 1988. Pingo collapse and paleoclimatic reconstruction. Can. J. Earth Sci. No. 25 (4), p. 495–511.

Mackay, J.R., 1990. Seasonal growth bands in pingo ice. Can. J. Earth Sci., vol. 27, No. 8, p. 1115–1125.

Mackay, J.R., 1998. Pingo growth and collapse, Tuktoyaktuk-Peninsula area, Western Arctic coast, Canada: a long-term field study. Géographie Physique et Quaternaire, vol. 52, No. 3, p. 271–323.

Mackay, J.R., Burn, C.R., 2011. A century (1910–2008) of change in a collapsing pingo, Parry Peninsula, Arctic coast, Canada. Permafrost and Periglacial Processes, vol. 22, p. 262–272.

Michel, F.A., Fritz, P., 1982. Significance of isotope variations in permafrost waters at Illisarvik, N.W.T. In: Permafrost. Proc. of the 4th Canadian Permafrost Conf. / Ed. by H.M. French. Calgary, National Res. Council of Canada, pp. 173–181.

Minaev, A.N., 1963. Large hydrolaccoliths of West Siberian lowland. In: Permafrost of various regions of USSR. USSR Academy of Science Publishing, Moscow, pp. 120–125. (in Russian)

Olson, E.A., Broecker, W.S., 1959. Lamont natural radiocarbon measurements V. Amer. J. Science, vol. 257, No. 1, p. 1–11.

Solov'yev, P.A., 1952. Bulgunnyakhs of Central Yakutia. In: Permafrost studies of Yakutia Republic, iss. 3. USSR Academy of Science Publishing, pp. 226–258. (in Russian)

Solov'yev, P.A., 1975. Thermokarst phenomena and forms of perennial frost (cryogenic) heave in central Yakutia. In: Palaeogeography and Periglacial Phenomena of Pleistocene. Nauka, Moscow, pp. 23–36. (in Russian)

Vasil'chuk, Yu.K., 2011. Experimental study of isotopic fractionation in water during congelation ice formation. Kriosfera Zemli XV (3), 51–55.

Vasil'chuk, Yu.K., 2013. Cryogenic processes. In Engineering Geology of Russia. Vol. 2, Engineering Geodynamics of Russia / Editors V.T. Trofimov, E.V. Kalinin. KDU, Moscow, pp. 361–464. (in Russian)

Vasil'chuk, Yu.K., Budantseva, N.A., 2010. Radiocarbon dating of the pingo of the Pestsovoye gas field in the north of West Siberia. Engineering Geology, No. 2, p. 16–23.

Yoshikawa, K., 2014. Pingos. In: Treatise on Geomorphology. Vol. 8. Glacial and Periglacial Geomorphology / Ed. by J. F. Shroder, R. Giardino, J. Harbor. Acad. Press, SanDiego, pp. 274–297.

Yoshikawa, K., Lawson, D., Sharkhuu N., 2012. Stable isotope composition of ice core in open- and closed-system pingos. In: Permafrost. Proc. of the 10th Intern. Conf. / Ed. by K.M. Hinkel (Salekhard, 25–29 June, 2012). Salekhard, Russia, The Northern Publ., vol. 1, pp. 473–478.

Yoshikawa, K., Sharkhuu, N., Sharkhuu A., 2013. Ground water hydrology and stable isotope analysis of an open-system pingo in Northwestern Mongolia. Permafrost and Periglacial Processes, vol. 24, No. 3, p. 175–183.

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