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GEOLOGICAL CRYOGENIC PROCESSES AND FORMATIONS

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THE SHEAR MECHANISM FOR THE PINGO GROWTH

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Conditions of formation and morphology of injection frost mounds (bulgunniakh, pingo) can find a strict physical explanation from the point of view of mechanics of frozen soils. In the frames of hypothesis of shear mechanism, the mathematical description of conditions of emergence and growth of pingo has been given. A formula for calculating the diameter of their upper surface and slope steepness depending on the composition and soil temperature of the ground has been suggested. The actual data in favor of the hypothesis of the shear mechanism of formation of injectable of pingo have been adduced.

Frost mound, shear mechanism, bulgunniakh, pingo

INTRODUCTION

Perennial intrusive frost mounds (bulgunniakhs, pingos) are widely-distributed in permafrost zone. At present, about 11 thousands of such mounds have been recorded worldwide, including about 5 thousands of those in Russia [*Vasil'chuk et al., 2014*]. For the first time, the detailed and mostly correct ideas concerning the mechanism of their formation was suggested by V.I. Andreev [*1936*]. He supposed that frost mounds were formed in the areas of freezing taliks situated under drying-up lakes. Growth of hydrostatic pressure here could cause the curving up of a freezing layer of upper portion of the talik leading to formation of a frost mound. The water flew into the being formed arch under influence of hydrostatic pressure, and then it froze forming the icy core of the mound. The mound grew owing to annual accretion of its icy core, the growing pressure of which lifted continuously a freezing layer. Later on, V.N. Saks [*1940*] demonstrated that there might not be an icy core inside pingo. Nothing new in principal with regard to the growth mechanism of intrusive frost mounds has been suggested after the expiration of more than 80 years since the time of the V.I. Andreev's study publication. Nevertheless a point of view appeared recently, in accordance with which one of the causes of the intrusive frost mounds formation may be the emissions of natural gas out of earth's depth, causing deformation (up to total destruction) the freezing-from-above portion of lake taliks [*Bogoyavlensky, Garagash, 2015*]. Not denying such a possibility, the author considers that the formation of intrusive frost mounds is of cryogenic nature in overwhelming majority of cases.

PHYSICAL CONDITION FOR THE DEVELOPMENT OF FROST HEAVING IN CLOSED SOIL SYSTEMS

From the point of view of the author, cryogenic heaving that leads to formation of intrusive frost mounds is the result of the interaction of two physical bodies being part of a freezing in closed system 'frozen soil–thawed soil' following the third principle of Newtonian mechanics. According to the principle, the increase in volume of freezing thawed ground causes a force counteraction from the surrounding thawed soil. The anti-freezing counteraction is brought about by the increasing of pressure in thawed strata owing to the impossibility to remove the excess of water (9 %) being formed in the process of the phase transition of water to ice. At that, the freezing layer is squeezed back from an underlying 'support', that is thawed soil. According to the third principle of Newtonian mechanics, the directions of freezing and heaving are opposite.

The conditions for the development of heaving in intrusive frost mounds were contained in V.I. Andreev's work [*1936*]: growth of the mounds occurred as long as the hydrostatic pressure exceeded the resistance of frozen strata. Later, that viewpoint has been reflected in the well-known condition of J.R. Mackay [*1979*], according to which frost heaving is observed only when the resistance of the thawed soil to compression (Q) exceeds the resistance of the frozen strata to uplift (F):

$$Q > F. \quad (1)$$

In the foregoing expression F is made up of the weight of frozen strata (G) and the resistance value of frozen soil to deforming loads (U):

$$F = G + U.$$

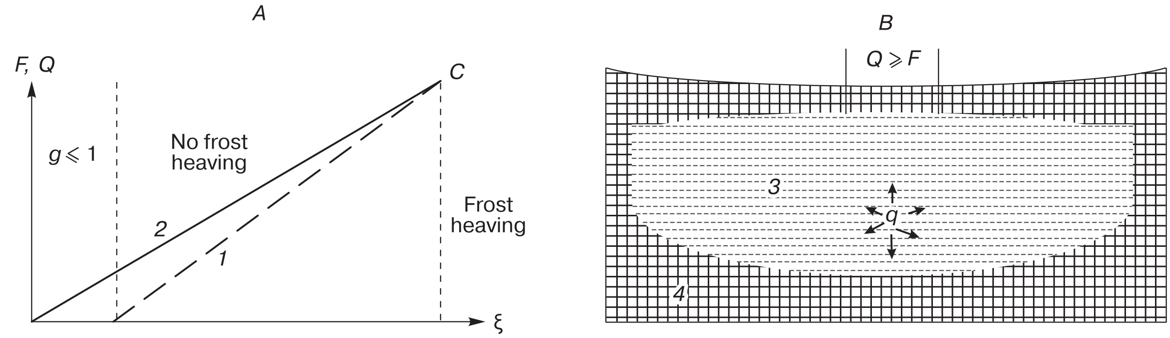

Fig. 1. Spatial-temporal relationship between the forces of resistance of thawed soil to compression *Q* (*1*), and a freezing layer to deformation *F* (*2*).

A – dependence of *Q* and *F* on the freezing depth (ξ) being increased with time for a closed system; *g* is degree of filling of soil pores with water; *B* – scheme of a closed being-frozen talik at a fixed point in time, with specific overpressure (*q*) uniformly distributed inside it; *3* – frozen soil; *4* – thawed soil.

The condition (1) corresponds to the third principle of Newtonian mechanics the force with which the frozen soil is squeezed back from the thawed one (that is the force of frost heaving) is equal to the support reaction force (*Q*), which should be at least no less than the heaving resistance force (*F*) acting in the opposite direction.

It ought to be noted that the condition of frost-heaving development (1) is valid only for the closed-system pingo, and it is not observed in the case of the open-system segregated frost mounds (palsas) where there are no physical conditions for the increasing of pressure. There, the anti-freezing counteraction of the soil is realized through the squeezing of the frozen mass (of increasing volume) under the influence of Archimedean force [*Marakhtanov, 1999, 2015, 2016*].

The correlation between *Q* and *F* in a spatial-temporal sense is displayed in Fig. 1. In the course of the talik freezing, the squeezing out of water at first results in increasing of the degree of filling pores of soil with water in the absence of overpressure (Fig. 1, *A*). After that the pressure starts to increase, but it is not high enough yet to deform the frozen layer inside of which mechanical stress is being augmented. Finally there comes the moment corresponding to condition (1), starting from which the frozen roof deforms, and frost heaving begins (that is corresponding to *C*, the crossing point of graphs in Fig. 1, *A*).

The area in a freezing layer, inside of which condition (1) is valid, is shown in Fig. 1, *B*. The boundaries of the area (vertical lines) corresponds to the point *C* in which $Q = F$ (Fig. 1, *A*). The deformations of frozen ground, resulting in formation of pingo, are observed exactly in that area. Therefore, the question – what is the mechanism of these deformations – is of fundamental importance. Hereinafter we will try to answer it.

SHEAR AS AN ALTERNATIVE TO BENDING IN THE PROCESS OF THE FORMATION OF INTRUSIVE FROST MOUNDS AND ITS MATHEMATICAL DESCRIPTION

It's generally recognized that the deformation of freezing layer in the upper portion of talik, resulting in the formation of intrusive frost mounds (pingo), occurs according to a bending theory [*Andreev, 1936; Saks, 1940*]. However, considering the bending as a main mechanism for the formation of intrusive frost mounds, it is difficult to explain the origin of such their morphological features as predominantly flattened (smoothed one, according to Andreev [*1936*]) rather than dome-shaped, top surface. Moreover, in theory the bending deformation implies the stretching of frozen soil, which in given case is physically impossible. During the freezing of talik the soil is exposed to a force which directed normal to the bottom of freezing layer (opposite to the freezing direction), but not along that layer (what could cause it to stretch and bend). It can be assumed that *the formation of intrusive frost mounds does not occur as a result of bending (as is commonly considered), but due to the shearing up of the upper part of freezing talik.*

Assuming the shearing as a leading mechanism for the formation of intrusive frost mounds, a mathematical description of their occurrence and growth can be developed, the description which would allow to calculate a diameter of the rounded top surface and the angle of slope depending on the composition and temperature of soil.

The explanation of reasons for the rounded shape of pingos

Let us write down in detail the boundary condition (1) of the moment at which the frost heaving begins ($Q = F$), assuming the shearing as a deformational mechanism of the frozen roof of a intrusive frost mound in the process of its formation:

$$qS = \tau\xi L + \rho\xi S, \quad (2)$$

where q is specific overpressure (that is excessive one compared to atmospheric pressure) in the thawed soil inside a closed soil system (a freezing talik), kPa; S is the base area of the frozen block, m^2; τ is specific shear resistivity at the contact of the being heaved block with the rest of frozen strata, kPa; ξ is thickness of frozen layer at the shear site, m; L is perimeter of a frozen block exposed to frost heaving, m; ρ is frozen soil density, kg/m^3.

Dividing both sides of the expression by S we get:

$$q = \xi\left(\tau\frac{L}{S} + \rho\right). \quad (3)$$

The lesser the right side of the expression (3) for the same values of ξ, τ and ρ, the easier (as far as the value of q is lesser) the frost-heaving condition can be reached. It is easy to understand the least value of q corresponds to the minimum value of the ratio of perimeter to area (L/S) which is known to be characteristic of a circle. Exactly that can explain *the roundness* of intrusive frost mounds. During the shear deformation a rounded shape is energetically most advantageous since in that case the anti-heaving force, applied per the unit of being heaved area (S), is minimal (because of minimal L). In real conditions, of course, the ideal form of such a circle is usually distorted due to the possible spatial heterogeneity of the rest parameters included in the right-hand side of the expression (3).

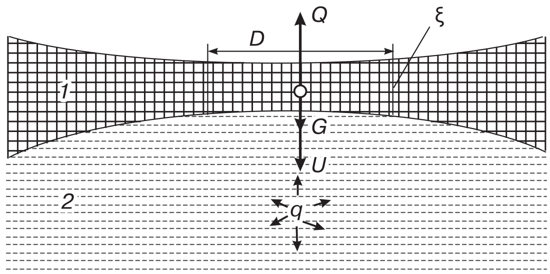

Fig. 2. Part of a closed freezing talik with a block of diameter D in its freezing layer before the start of frost heaving.

1 – frozen soil; *2* – thawed soil; ξ is thickness of frozen soil around the perimeter of the block; D – diameter of the site on a top of the future frost mound; q – specific overpressure in a closed talik; Q – the resistance force of thawed soil to compression, equal in magnitude to the frost heaving force; G – apparent weight of the frozen block subjected to heaving; U – the force of shearing resistance along the perimeter of the block.

Calculation of the diameter of rounded top of a frost mound

Assuming the circular shape of an intrusive frost mound, we can derive a formula for calculating the diameter (D) of the primary block of frozen soil (displacement of which up the shear plane means the beginning of the frost mound formation) in the freezing-from-above portion of the closed talik (Fig. 2). The surface of the frozen block, shown in Fig. 2, is the top surface of the future frost mound.

To calculate the value of D, it is necessary to substitute the values of the parameters corresponding to the circular shape in expression (2), obtaining as a result:

$$q\pi\frac{D^2}{4} = \pi D\xi\tau + \xi\pi\frac{D^2}{4}\rho. \quad (4)$$

Transforming the expression (4) in compliance with the dimensionality of the parameters included in it, we get the final formula for calculating the diameter of the top surface of a frost mound (D, m)

$$D = \frac{4\tau}{q/\xi - 0.01\rho} \text{ with } q > 0.01\xi\rho. \quad (5)$$

The value of specific shear resistivity (τ) in the formula (5) depends on the composition, water content (ice content) and temperature of frozen soil. Let us analyze the influence of these factors on the diameter of the top surface of a frost mound. The necessary input data can be found in the regulatory source [*SNiP 2.02.04-88, Appendix 2, Tables 4, 8*]. On the basis of the τ values presented in it, the diameter values in soils of various compositions at different temperatures have been calculated (Tables 1, 2). The values of the density of frozen soils (ρ) adopted in the calculations are shown in Table 2. The rather arbitrary choice of density values is explained by the fact that a change in that parameter in real ranges has little effect on the value of D. So, for example, in clay at a temperature of –3 °C, a decrease in ρ from 1700 kg/m^3 to 1200 kg/m^3, in accordance with formula (5), leads to a decrease in D from 10.1 m to 9.8 m. A more significant effect on the D value is exerted by soil temperature, which determines the value of τ.

The data shown in Table 2 are obtained for fixed values of q = 100 kPa and ξ = 1 m. For other combinations of the values of these parameters, taken into account through the ratio q/ξ, there is a formula for calculating the correction coefficient K in the bottom row of Table 2. To get a specific value of D, it is necessary to multiply the diameter value D of each cell by the coefficient K. For example, at a temperature of –3 °C for clay with ξ = 3 m and q = 120 kPa (Table 1) and accordingly q/ξ = 40, the coefficient K is 83/23 = 3.6, and the diameter D is 10.1·3.6 = 36.4 m.

The analysis of the formula (5) and the data of Tables 1, 2 allows us to draw the following conclusions about *the conditions for the origin* of intrusive frost mounds.

1. The formation of intrusive frost mounds is characteristic of the bottoms of lake basins where peat or peaty deposits having the lowest specific shear resistance (τ), lay directly on the surface (Table 1).

Table 1. **Specific shear resistivity (τ, kPa) of various soils depending on the lithological composition and temperature by [*SNiP 2.02.04-88, 2005*]**

Temperature, °C	Sand	Clay	Peaty soils				Peat
			Sandy	Clayey	Sandy	Clayey	
			$0.03 < I \leqslant 0.1$		$0.3 < I \leqslant 0.5$		
–0.3	80	50	30	20	8	3	2
–0.5	120	80	60	50	20	20	10
–1.0	170	120	100	70	40	30	20
–1.5	210	150	140	90	60	40	30
–2.0	240	170	160	110	80	60	40
–2.5	270	190	190	120	90	70	60
–3.0	300	210	230	140	100	90	80
–3.5	320	230	260	170	120	100	90
–4.0	340	250	270	200	140	110	100
–6.0	420	300	310	250	150	140	120
–8.0	480	340	330	270	180	150	140
–10.0	540	380	350	300	210	170	160

N o t e. Specific organic content (I) is equal to the ratio of the weight of plant residues to the weight of dry soil.

Table 2. **Diameter (D, m) of the top of frost mound depending on the lithological composition and temperature of the soil of the frozen talik roof**

Temperature, °C	Sand	Clay	Peaty soils				Peat
			Sandy	Clayey	Sandy	Clayey	
			$0.03 < I \leqslant 0.1$		$0.3 < I \leqslant 0.5$		
–0.3	3.9	2.4	1.4	0.9	0.4	0.2	0.1
–0.5	5.8	3.9	2.9	2.4	0.9	0.9	0.4
–1.0	8.2	5.8	4.8	3.3	1.9	1.4	0.9
–1.5	10.1	7.2	6.7	4.3	2.8	1.9	1.3
–2.0	11.6	8.2	7.6	5.2	3.7	2.8	1.8
–2.5	13.0	9.2	9.0	5.7	4.2	3.3	2.7
–3.0	14.5	10.1	11.0	6.7	4.7	4.2	3.6
–3.5	15.4	11.1	12.4	8.1	5.6	4.7	4.0
–4.0	16.4	12.0	12.9	9.5	6.5	5.1	4.4
–6.0	20.2	14.5	14.8	11.9	7.0	6.5	5.3
–8.0	23.1	16.4	15.7	12.9	8.4	7.0	6.2
–10.0	26.0	18.3	16.7	14.3	9.8	7.9	7.1
ρ, kg/m^3	1700		1500		1300		1000
K	$\frac{83}{q/\xi-17}$		$\frac{85}{q/\xi-15}$		$\frac{87}{q/\xi-13}$		$\frac{90}{q/\xi-10}$

N o t e. Tabular values of D for specific values of q (kPa) and ξ (m) are multiplied by the correction factor K.

2. The foci of the emergence of frost mounds are the areas characterized by the highest soil temperature and the lowest thickness of a freezing layer in the upper portion of closed talik where the value of τ is relatively reduced. Commonly that occur at the place of the residual body of water, where the bottom sediments do not thaw in summer, or in places of increased snow accumulation, for example, in shrubs.

3. In temporal terms, most favorable period for the emergence of mounds is the season which characterized by increased temperature (by decreased τ) and reduced thickness of the frozen layer of the upper part of the talik in the summer-autumn season (for example, [*Vasil'chuk, Budantseva, 2010*]).

Process of the pingos growth

The mound growth takes place in the form of successive cycles (Fig. 3). During each cycle, a disk-shaped frozen soil block is sheared and displaced upward, being accompanied by the intrusion to its lower surface of pressurized thawed soil or water, which subsequently freeze, forming a frozen (icy) mound

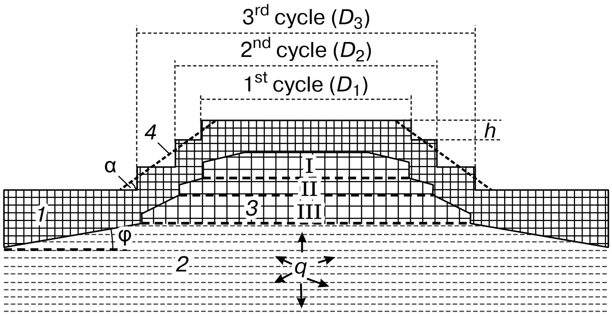

Fig. 3. Cyclical growth of intrusive frost mound.

1 – frozen soil; *2* – thawed soil (water) under overpressure (q); *3* – frozen (icy) core of frost mound; *4* – contour of slope; I, II, III – consecutive positions of the lower boundary (dashed line) of soil (or water) that invaded the mound during each cycle and subsequently froze; D_1, D_2, D_3 – diameters of the mound top at the end of the 1st, 2nd and 3rd cycles of frost heaving; h – value of frost heaving per a cycle; α – slope angle; φ – tilt angle of lower surface of permafrost base; q – specific overpressure.

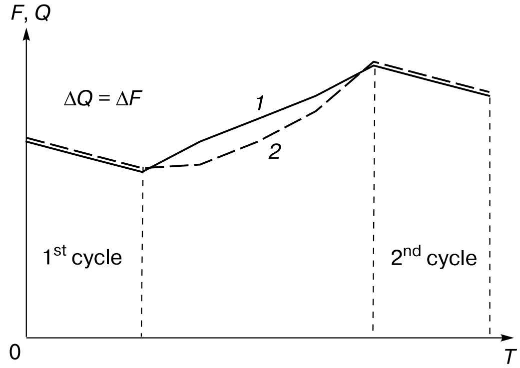

Fig. 4. Change in time T of the resistance forces of frozen soil to deformation F (*1*) and the resistance forces of thawed soil to compression Q (*2*) for two heaving cycles.

core. In the process of the frozen block lifting, the overpressure q decreases, approaching atmospheric one, the frost heaving stops, and the height of rise corresponds to the frost heaving value h of the mound in that cycle.

Upon completion of the first cycle, the second (like all subsequent ones) should proceed with an extension of the frost heaving area S (as well as extension of the diameter D) as compared with the previous cycle (Fig. 3). That is due to the fact that condition (1) is satisfied for increasingly large parameters of its right-hand side, the sum of which is equal to F: the weight increase (ΔG) due to the weight of the frozen soil which was heaved up during the previous cycle, and the increase in shear resistance (ΔU) of the frozen disk along its contact with the rest of the frozen strata. That increase is due to an increase in thickness of freezing layer in the direction from the center to the periphery of a mound (Fig. 3). Since now the value of Q in condition (1) increases by ΔQ, then we can write:

$$\Delta Q = \Delta F = \Delta G + \Delta U. \qquad (6)$$

The dynamics of changes in the values of Q and F in the time interval from the beginning of the first heaving cycle to the end of the second is shown in Fig. 4. During each cycle, the values of Q and F are equal, and in the intervals between cycles F is greater than Q. Naturally, a similar picture is characteristic of any two other cycles of frost heaving.

Calculation of the slope angle of a frost mound

Based on the equality (6), we can derive a formula for calculating the slope angle of a mound.

1. The formula (6) is equivalent to the following:

$$q(S' - S) = h\rho S + \tau L'\Delta\xi, \qquad (7)$$

where S and S' are the areas of the base of the frozen disk in the previous and subsequent cycles; h is the value of frost heaving in the previous cycle (Fig. 3); ρ is the density of soil (or ice) formed inside the mound in the previous cycle; L' is the perimeter of a frozen disk in the subsequent cycle; $\Delta\xi$ is an increase in the frozen soil thickness in the next subsequent cycle due to the inclination of the frozen-layer bottom (φ) from the center of a mound to its periphery (Fig. 3).

2. Assuming the shape of the base area of a mound as circular, the expression (7) for the second frost heaving cycle can be written as:

$$q\pi\left(r_2^2 - r_1^2\right) = h\rho\pi r_1^2 + \tau 2\pi r_1\,\Delta\xi, \qquad (8)$$

where r_1 and r_2 are the base radii of the disk in the first and second cycles.

3. Since $\left(r_2^2 - r_1^2\right) = \left(r_2 - r_1\right)\left(r_2 + r_1\right),$ and the values of the radii in the previous and subsequent cycles differ a little $\left(r_2 \approx r_1\right)$, the formula (8) can be replaced by the approximate equality:

$$q2r\Delta r \approx h\rho r^2 + 2\tau r\Delta\xi. \qquad (9)$$

4. Dividing both parts of the approximate equality (9) by $2r\Delta r$, and also taking into account that $r_1 = D/2$, $h/\Delta r$ is the tangent of the mound slope angle (α), $\Delta\xi/\Delta r$ is the tangent of the inclination angle of the frozen talik roof φ (Fig. 3), we obtain:

$$q \approx \frac{D}{4} 0.01\rho\,\mathrm{tg}\,\alpha + \tau\,\mathrm{tg}\,\varphi. \qquad (10)$$

5. Replacing D in the formula (10) with its analytical expression (5), we obtain the formula for calculating of the mound slope angle (α):

$$\alpha \approx \mathrm{arctg}\left[\left(\frac{q}{\tau} - \mathrm{tg}\,\varphi\right)\left(\frac{100q}{\xi\rho} - 1\right)\right],$$

$$q \geqslant \max\,(\tau\ \mathrm{tg}\ \varphi;\ 0.01\xi\rho). \qquad (11)$$

Fig. 5. Pingo with a "pedestal" [https://булгуннях фото].

Slope angle of the central mound is 27°, slope angle of the "pedestal" is 13°.

Analyzing the formula (11), we can draw the following conclusions about *the growth conditions* of intrusive frost mounds.

1. The value of slope angle α in the formula (11) is directly dependent on the specific overpressure (q) causing the frost heaving in a closed talik, and is inversely dependent on the values of other parameters (τ, ξ, φ, ρ) which impede that process. Therefore, an increase in the values of α indicates an improvement in frost-heaving conditions, and a decrease in those means the opposite, i.e. a deterioration of conditions.

2. Other things being equal, the greatest influence on the value of α is exerted by the specific shear resistivity, which is directly dependent on the temperature of freezing layer. Its lowering can cause a decrease in the slope angle up to the formation of a specifically shaped 'pedestal' (Fig. 5).

3. Spatial change in the parameters, included in formula (11), along the periphery of a frost mound, can lead to a change in the profile of its slopes in different directions from the top surface, causing asymmetry of its shape.

4. The growth of a frost mound stops either if one of the two conditions of double non-strict inequality (which determine the minimal value of q) is not met or when talik is completely frozen. In the second case, the resumption of frost heaving is impossible.

Possible combinations of the parameters determining the diameters of rounded top surface of the frost mounds and their slope angles

Naturally, a question arises: to what extent are the results of calculations by formulas (5) and (11) consistent with the observed-in-nature diameters of the rounded surface and slope angles of intrusive frost mounds? The answer can only be obtained by performing the appropriate calculations in relation to specific objects of research. Unfortunately, the author could not find in the literature sources such intrusive frost mounds for which all the parameters needed for calculations by the foregoing formulas would be given. However, it is possible, using the formulas (5), (11) and a method of selection, to obtain possible combinations of the parameters which determine the diameter (D) of the upper surface and the slope angle (α) of specific frost mounds. Such calculations have been performed for two pingos described by J.R. Mackay (Fig. 6) [*Solomatin, 2013, p. 137*] and for one pingo described by P.A. Solovyov (Fig. 7) [*Fundamentals of Geocryology, 1959, p. 292*]. The results are presented in Table 3.

The data on the values of overpressure (q_f) in Table 3 are taken from the publication of V.I. Solomatin [*Solomatin, 2013, p. 137*] (Fig. 6), those on the height of the hydrostatic head of an aquifer (10 m) are received from another literature source [*Fundamentals of Geocryology, 1959, p. 292*] (Fig. 7). The calculated shear resistivity (τ_p) for both mounds was determined according to Table 1 for clay at the temperature of −1 °C. The thickness of frozen layer (ξ) at the beginning of frost heaving was assumed to be approximately equal to the thickness of the frozen soil above the ice (Fig. 6) and ice-soil (Fig. 7) core at the top of the mound. The tilt angle of a frozen-layer at the bottom of talik (φ) for P.A. Solovyov's pingo (Fig. 7) was accepted the same as for J.R. Mackay's pingo (average slope angle is shown in Fig. 6). With such input data, the calculated and measured values of D and α are close. It is natural that specific combinations of the values of these parameters during the emergence and growth of those mounds could be different, but perhaps the differences were not significant.

Table 3. **Calculated and measured values of the mound parameters**

Mound	Soil of frozen roof of talik	q_f, kPa	ρ_p, kg/m^3	ξ_p, m	τ_p, kPa	φ, degree		D, m		α, degree	
						calculated	measured	calculated	measured	calculated	measured
Pingo (Fig. 6)	Clay	105	1700	2.0	120	–	35	14	12	20	16
Pingo (Fig. 7)	Loam	100	1700	2.8	120	35	–	24	24	8	9

Note. Designations of parameters see in the text.

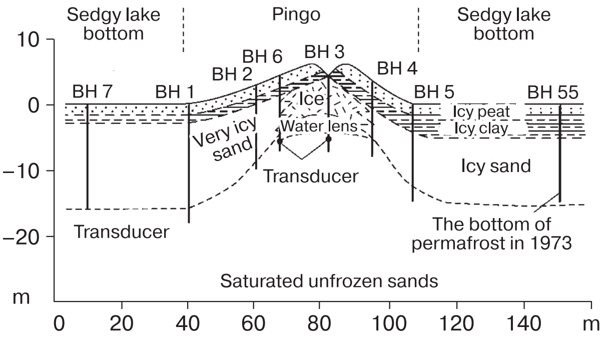

Fig. 6. The pingo of J.R. Mackay.

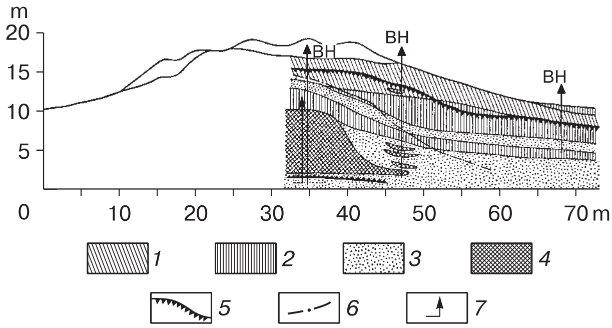

Fig. 7. The Pingo described by P.A. Solovyov.

1 – sandy loam; *2* – loam; *3* – sand; *4* – ice; *5* – permafrost table; *6* – core border with lenses of pure ice; *7* – hydrostatic cryogenic head of the aquifer.

EVIDENCE SUPPORTING THE VALIDITY OF THE SHEAR-MECHANISM HYPOTHESIS

The morphological sign of cyclical manifestation in the process of frost heaving during the formation of intrusive mounds may be the terraced appearance of their slopes, where the height of terrace ledge approximately corresponds to the frost heaving value during one cycle (Fig. 3). As a rule, such stepping is smoothed out due to the overlapping of frozen blocks with an active layer, as well as more intensive thawing of the protruded parts of the frozen blocks. However, sometimes on the mound-side one can notice traces of the terracing, which is supposedly due to the cyclical character of the frost heaving process (Fig. 8).

Fig. 8. Pingo with signs of the slope terracing [https://булгунняхи фото].

In 1969, M.A. Velikotsky carried out field research in the Yana-Indigirka Lowland. In the valley of Tenkechehen Brook, he had discovered a pingo, exposed as a result of erosive activity of the stream (Fig. 9). In Fig. 9, *B* on an enlarged scale, part of the section is shown in the zone of the shearing of frozen soil that occurred during the last frost heaving cycle, the apparent value of which was 40 cm (Fig. 9, *A*). The vertical extent of a shear plane (with a width of

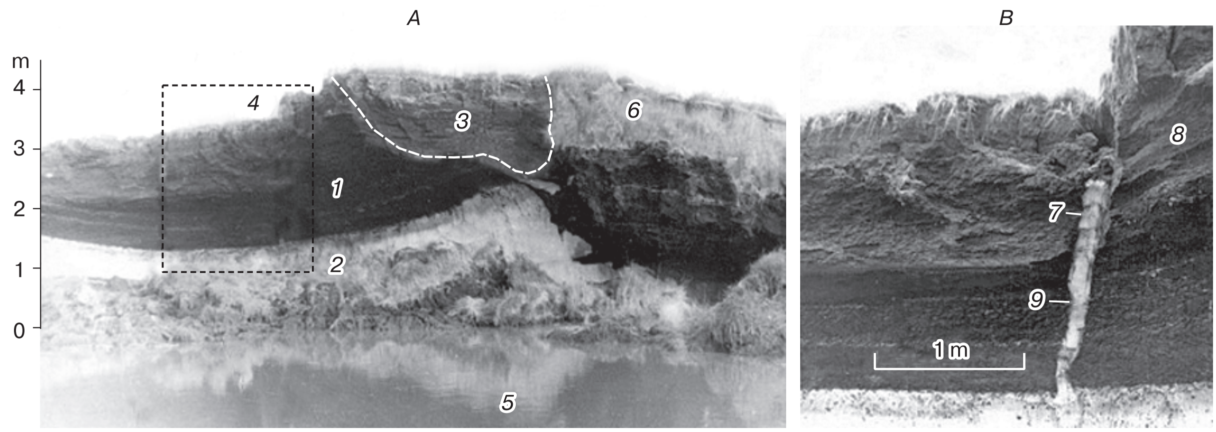

Fig. 9. Pingo exposed in the valley of Tenkechehen Brook.

A – general view; *B* – enlarged fragment of a photograph; *1* – frozen silt; *2* – ice; *3* – thermocirque formed due to thawing and erosion removal of the central part of the mound; *4* – frozen ledge of the block of the last frost heaving cycle; *5* – water surface of a small lake at the foot of the exposure; *6* – a cover of cereal-sedge sod hanging from the exposure edge; *7* – a shear plane of the last cycle, filled with fragments of frozen silt and ice; *8* – the deformation of soil layers; *9* – ice in a frost crack. Photo by M.A. Velikotsky with additions of V.P. Marakhtanov.

about 15 cm) is 1.2 m, lower portion of which (approximately 0.7 m long) is filled with frozen-into-ice fragments of crushed (during the shearing) frozen silt, and upper portion of which is thawed (Fig. 9, *B*). To the right of the shearing plane, deformations of adjacent soil are emphasized by a bending of stratification. A frost crack has been developed below the shear plane, having penetrated into silt and ice. The crack apparently has inherited the shear plane after the complete freezing of talik, because the ice, into which it intruded, was probably formed during the freezing of a water lens underlying the frost mound.

CONCLUSION

Within the framework of the concept of a shear mechanism, the conditions for the emergence and growth of perennial intrusive frost mounds (pingos), find an objective physical justification along with the corresponding mathematical description. Here there is an interaction of two directly opposite processes, which are cooling with freezing and heating with thawing. The first increases the driving force of heaving through an increase in pressure in a closed talik as it freezes in winter. The second contributes to the further realization of that force, since as the frozen layer warms up in the upper part of the closed talik and its thickness decreases during its gradual thawing in summer, the shear resistivity of the frozen soil decreases, thereby facilitating the frost heaving process. The validity of the shear mechanism action is confirmed by actual data on the morphology of the frost mounds and the permafrost-facial conditions of their distribution.

Further research within the framework of the concept of a shear mechanism can be carried out in the following main directions:

– obtaining of factual material on specific frost mounds sufficient to perform objective calculations according to the proposed formulas;

– establishment of the main factors determining the morphological features of the upper surface of frost mounds;

– explanation of the role of the shear mechanism in the formation of an ice core and the water lens feeding it;

– using of data on the morphology of frost mounds in a palaeogeographic aspect.

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