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MOULINS: FORMATION AND SIGNIFICANCE

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The causes and conditions of the formation and changes of moulins are considered on the basis of author's own data and literature sources. Moulins can be formed above the water level in crevasses in glacier ice and cannot be formed below the water level. A cylindrical shape of the moulins is associated with splashing of water jets at a certain depth from the glacier surface. The issues related to different mechanisms of the formation of moulins, their depth, age, and water level fluctuations are discussed. A possible connection of moulins with the internal drainage system of glaciers is shown. The relationship between moulins and thrusts in the glacier ice is specially considered, because there are glaciers, in which water does not penetrate to the glacier bed through the moulins.

Keywords*: internal drainage of glaciers, moulins, slip planes inside ice.*

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INTRODUCTION

Many studies somehow related to moulins have appeared recently. Many works are focused on expansion of the ablation zone at the edge of the Greenland Ice Sheet, where meltwater runoff in the upper part of the ablation zone occurs through the moulins [*McGrath et al., 2011; Hoffman et al., 2018; Andrews et al., 2022*]. The entire hydrological structure of the ice sheet depends on discharge of water through the moulins in Greenland. This structure affects the ice movement and contributes to the change in the global ocean level. Therefore, much attention is currently focused on the moulins.

Moulins are vertical cylindrical holes 1–2 m or more in diameter. They are formed in a crevasse of glacier tongue through destruction of ice by flowing meltwater; they are preserved after closure of the crevasse during the glacier movement [*Glaciological Dictionary, 1984*].

The moulins have been known for a long time. At the beginning of the 19th century famous natural scientists J. Forbes [*Forbes, 1845*], L. Agassiz [*Agassiz, 1840*] and E. Désor [*Désor, 1844*] repeatedly visited the glaciers of the Alps and paid special attention to these features [*Mavlyudov, 2006*]. Whether or not the first explorers of the glaciers descended into the moulins is not known for certain.

The concept of the moulins that reach a glacier bed developed in the 19th century. It was related to the fact that evorsion basins (giant potholes), the same as those formed at the bases of waterfalls, were revealed in the area of the glacier tongue retreat [*Glaciological Dictionary, 1984*]. It was obvious that in the presence of a crevasse and thin glacier ice, water from the glacier surface falls into the moulin and reaches the glacier bed, forming an evorsion pothole under it [*Gilbert, 1906*]. It was believed that all moulins reach the glacier bed. In the 19th century, one of the methods to find the evidence that water in the moulins reaches the glacier bed was to lower a hammer with a piece of lard attached to it and tied to a rope to the moulin bottom [*Forbes, 1845*]. According to the researchers' idea, particles of subglacial soil should have stuck to the lard at the moulin bottom proving the penetration of the moulin through the glacier to the bed. However, as soil particles did not stuck to the lard, the question of reaching the glacier bed by the studied moulins remained open. A possible reason for the idea that moulins reach the glacier bottom was the finding of very deep moulins on glaciers. However, no real evidence that all moulins reach the bottom of the glaciers was found at that time. In fact, no such evidence has been found until now.

Currently, moulins on glaciers are generally studied by indirect methods: via assessing moulin discharge and water balance [*McGrath et al., 2011*], conducting georadar [*Stuart et al., 2003; Catania et al., 2008*] and seismic [*Podolskiy, Walter, 2016; Röösli et al., 2016*] surveys, and measuring the water levels in the moulins [*Iken, 1972; Badino, Piccini, 2002*]. Direct speleological methods are used in rare cases [*Schroeder, 1998; Moreau, 2002; Gulley et al., 2009a,b; Covington et al., 2020*]. Many researchers are sure that the moulins penetrate to the glacier bed regardless of the ice thickness. However, for some reason, there is still no definite opinion on the mechanism of the moulin formation. Some authors argue that moulins are formed upon drainage of supraglacial lakes through hydraulically induced crevasses [*Das et al., 2008*]. This idea appeared because a moulin was found at the bottom of a drained lake in Greenland. The drainage of supraglacial lakes and intersection of surface streams by crevasses are considered the widespread mechanism of moulin formation [*Hoffman et al., 2018*]. A group of authors argue that moulins can also be formed as a result of downcutting of surface channels into ice [*Andrews et al., 2022*]. Cuffey and Paterson [*2010, p. 179*] report that the moulins are formed in the places, where meltwater streams cross crevasses or along fractures at the lake bottoms. Many cave channels and moulins are associated with hydraulically induced crevasses [*Gulley et al., 2009b*]. In fact, these are quite different mechanisms of possible formation of the moulins, which are not explained in detail usually. Perhaps, not all researchers have seen moulins with their own eyes, but have observed them on aerial images, photos, or videos.

The purpose of this work is to reveal the patterns of the formation and development of moulins. Let us also consider the questions of how moulins differ from crevasses, how they are related to the internal drainage system of glacier, and what a role they play in the glacier life.

METHODS

Since 1982, the author has been studying glacier caves using speleological methods of penetration into them in the Himalayas, Southern Tibet, Tien Shan, the Caucasus, Spitsbergen, the Andes, and Antarctica. Moulins have been studied in the Caucasus, Tien Shan, Spitsbergen, and Antarctica. Penetration into the moulins has been carried out on temperate, polythermal, and cold glaciers. Having an extensive experience in field study of crevasses and moulins, the author suggested an original theory of the formation of internal drainage of glaciers [*Mavlyudov, 2006, 2007a, 2014*]. This work develops this theory relying on the available literature on the subject.

RESULTS AND DISCUSSION

The Formation of Moulins

It is well known that moulins are formed along crevasses [*Forbes, 1845; Stenborg, 1973*]. The moulin formation requires meeting two conditions: the presence of a crevasse in the ice and the concentrated water streams flowing into it. Generally, crevasses are vertical shear fractures or fractures induced by tension that are located across a glacier and/or at an angle to the glacier edge. It is often seen that the water flow running over the glacier surface is unexpectedly crossed by a newly formed crevasse. Firstly, the crevasse begins to capture the flow partially and then completely absorbs it. Further, two options are possible:

(1) If there is no water outflow from the lower part of the crevasse, the water fills the crevasse completely and flows further in the former channel over the glacier surface. This phenomenon has been repeatedly observed on many glaciers. The crevasse filled with water should exist until it is compressed by the movement of the glacier or until the water freezing. No moulin is formed in this case, although both conditions are met (Fig. 1*a*).

(2) If water has an outflow channel from the lower part of the crevasse into the ice, and the water outflow exceeds inflow, the crevasse is not filled with water, but remains filled with air (Fig. 1*b*). Only in this case, the moulin begins to form along the crevasse [*Stenborg, 1973*].

If the water outflow from the crevasse is less than the water inflow into it, then there are two possible options:

(1) The small outflow of water from the lower part of the crevasse leads to filling of the crevasse with water and to partial overflow of water from the crevasse. However, because of the incomplete outflow of water in the lower part of the crevasse, less water flows out of the crevasse than into it. As the channel that drains the crevasse from below develops and expands, the difference in the amount of water flowing in and out of the crevasse at the top changes until the water flowing into the crevasse no longer overflows through it. After that, the water level in the crevasse begins to descend until the crevasse becomes completely free of stagnant water, and all the water falling down into the crevasse goes into the lower drainage channel. It is then that the formation of the moulin starts (Fig. 1*c*).

(2) Water does not outflow from the crevasse, but under the pressure of the water column, the crevasse begins to deepen into ice and becomes a hydraulically induced crevasse (Fig. 1*d*). The possibility of the formation of such crevasses in glaciers is still hypothetical and, despite the abundance of publications [*Van der Veen, 2007; Das et al., 2008*] has no reliable evidence. The stress state of ice caused by the glacier movement and low ice temperatures may prevent the formation of such crevasses in glaciers. In other words, stationary temperate glaciers, i.e., dead ice, in which crevasses almost do not form, are favorable for the formation of such crevasses. This means that the possibility of the formation of hydrofractures on glaciers is under great question, as well as the formation of moulins along them.

Let us suppose that a hydraulically-induced crevasse is formed from an ordinary transverse fracture on a glacier, into which water flows. In order to transform the fracture into a hydraulically induced crevasse, an increasing amount of water is required for its deepening at each individual moment compared

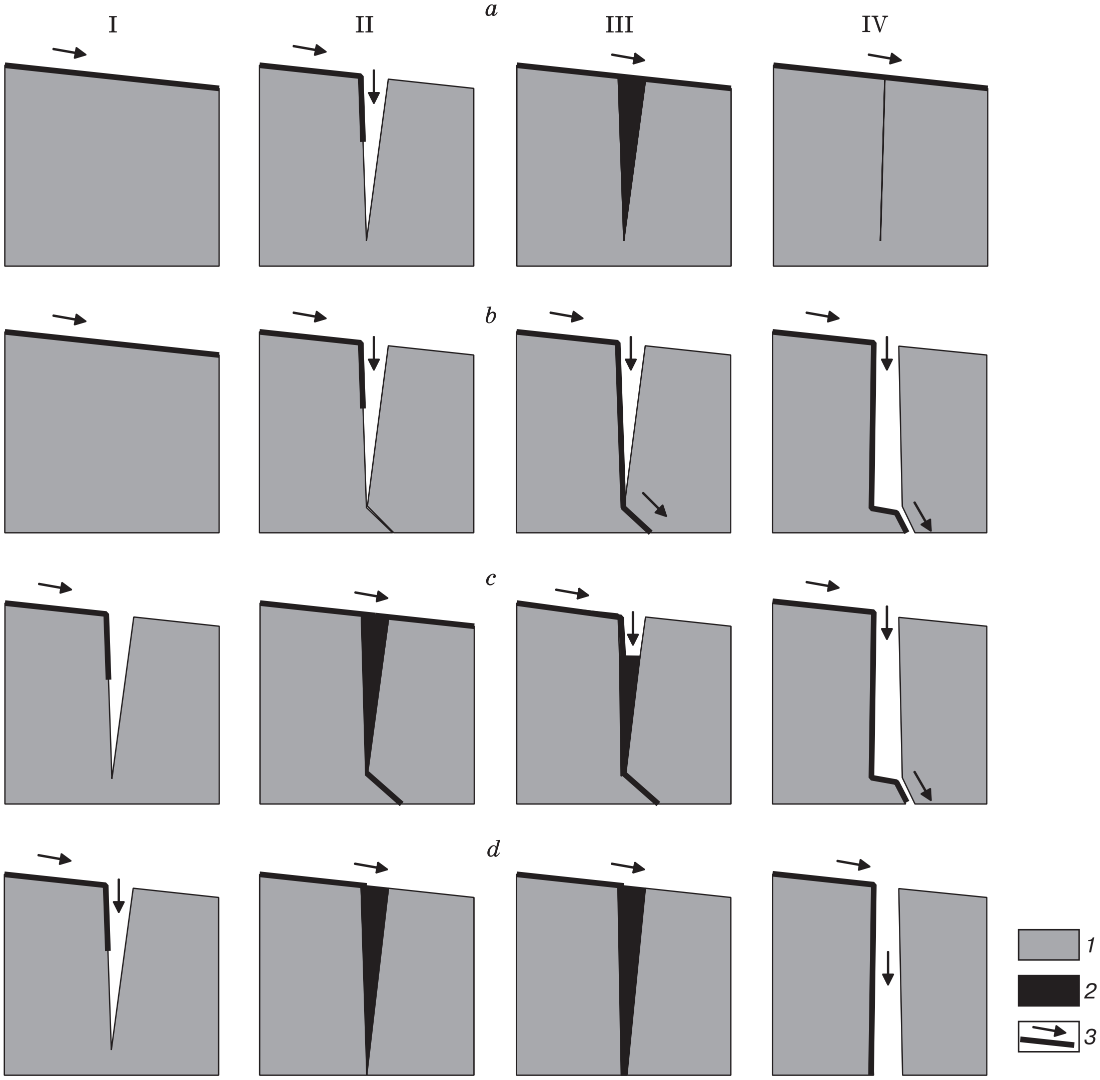

Fig. 1. A scheme of the water inflow into the crevasse appearing on the way of a waterflow, its filling with water, and further flowing (*a*); formation of a moulin (*b, c*); and the presumable formation of the moulin along the hydraulic fissure (*d*).

(*1*) ice; (*2*) water; (*3*) direction of a waterflow. I–IV – sequence of changes.

with the previous moment [*Weertman, 1973*]. This means that there may come a moment, when more water is needed to deepen the crevasse than the available amount of water, which flows into it, because during the deepening of the crevasse its volume would inevitably increase.

If there is no enough water to fill a crevasse, the water level in it begins to drop, and the deepening of the crevasse slows down. Low ice temperatures lead to freezing of not only the lower end of the crevasse but also its entire lower part, so that the process of its deepening stops. It does not start again even after the crevasse is filled with water, which just flows over the water-filled crevasse. This means that, if the formation of hydraulically induced crevasse is possible, it occurs only in the presence of supraglacial lakes with sufficient amount of water, as it regularly happens in Greenland [*Das et al., 2008*]. At the same time, the discharge of water from the lake into the crevasse should occur in the lake basin, not by overflow, otherwise this case is not different from that of inflowing water into the crevasse.

Drainage of a lake through a vertical crevasse is possible only when water from the crevasse has or finds an outlet to an internal drainage system of the glacier. In this case, the type of drainage at the crevasse bottom is not important. A lake is filled with water until the water breakthrough from it onto the glacier surface. The water breakthrough from the lake occurs quickly (in hours [*Das et al., 2008*]), probably at the moment of the crevasse formation (regardless of the reasons for its formation). In this case, the water from the lake rushes down the entire cross section of the crevasse. This means that there is no isolated jet, which only can form a cylindrical moulin. When water discharges through the crevasse, the crevasse width expands by the waterflow in all directions and the expanded gaping crevasse appears. No rounded cross section can form in this case. Therefore, the reports of researchers that the rounded moulins can be formed during the water discharge from lakes on the surface of glaciers [*Das et al., 2008; Benn, Evance, 2010; Cuffey, Paterson, 2010*] are questionable.

Mechanism of Moulin Formation

Unfortunately, the mechanism of the formation of moulins is considered only in a few studies [*Badino, 1992; Mavlyudov, 2006, 2007a*]. It has been found that the moulins can form only along those crevasses that are not filled with water. If the crevasse is filled with water, the moulin cannot form in it.

If an open crevasse is on the way of the waterflow, and the lower part of the crevasse is drained, water falls into it like a waterfall. In this case, the waterfall is located only in the place, where water inflows into the crevasse, and the moulin arises right on this small section of the gaping crevasse. If several streams inflow into the crevasse, then isolated moulins appear in places, where each of them inflows into the crevasse. Generally, newly created crevasses are not wide open (a usual width is 10–15 cm); therefore, the water stream falling into the crevasse hits its opposite (from the stream) side, from which it is reflected to the wall of the crevasse closer to the stream. The reflection from the crevasse walls continues until the flow takes a vertical position. The initial temperature of the stream falling into the crevasse is slightly above zero [*Isenko et al., 2005*]. Therefore, due to thermal erosion, a depression arises in the place, where the stream hits the crevasse wall, which contributes to even greater reflection of the flow onto the opposite wall. Not all of the heat in the place where the flow hits the crevasse wall is fully utilized for ice melting. Thus, some of the heat kept in water affects the opposite wall, so that a depression in ice starts to form there as well. This also contributes to the increase in the reflection of the waterflow to the opposite wall. As far as the jet falls, water is warming up due to transition of potential energy of the flow into kinetic energy. Therefore, the melting of the crevasse walls hit by the reflected jets continues down the crevasse.

Thus, systems of cavities are formed on the opposite walls of the crevasse. The cavities gradually begin to expand down the crevasse as ice melts under the action of the water jets. This leads to widening of the crevasse around the jet impact zone. Now even if the crevasse closes when the glacier moves from the tension zone to the contraction zone, the originated moulin persists and continues to receive water. The widening of the moulin occurs until it reaches the lower end of the crevasse. Further the moulin has nowhere else to go deeper and here the stream flows further along the crevasse system, forming cavities, which are described in [*Fountain, Walder, 1998*].

However, this mechanism of moulin formation cannot deepen unlimitedly. If the growing moulin is up to 20–30 m deep, the water falling into it is preserved in the form of a jet hitting the wall of the moulin opposite to the place of the water inflow. At the point, where the jet comes into contact with ice, the ice melts and the moulin becomes wider. This is why the moulins often expand with depth. After the moulin widening, the jet in the moulin falls freely and the heat released in the water while potential energy is converted into kinetic energy would be used to melt the ice at the base of the moulin. A pit induced by the water jet appears at the moulin bottom at the point, where a jet hits the floor. A depth of the pit depends on the flow rate of the waterstream. The greater the stream discharge, the deeper the pit can be. For example, in 1991 on the South Inylchek Glacier (Kyrgyzstan), the author observed a water pit of about 2 m deep at the moulin bottom with the stream discharge of about 1.5 m^3/s.

Splashing of Water in the Moulins

If the depth of a crevasse and, accordingly, the depth of a resulting moulin exceeds a certain value, then air resistance begins to act. As a result, the waterfall breaks and splits into separate jets and droplets as it falls. This does not apply to the primary stage of the moulin formation with the reflection of the water jet from walls, because in this case, the falling jet has time to pass a short distance from one wall to another. This mechanism begins to work, when the water in the moulin begins to fall freely without touching the walls. Each portion of water has a temperature above the freezing point and is dispersed in all directions, including those towards the moulin walls. As a result, the walls of the moulin begin to melt almost evenly in all directions, so that a moulin takes a shape close to a cylindrical. Thus, the cylindrical shape of the moulin results from the splashing of the waterflow in the air media. Such a cylindrical shape cannot be formed in a vertical crevasse at the bottom of a lake filled with water, because, even if water flow occurs in it, a narrow slot-shaped channel is formed.

The splashing of the water flow occurs in the moulins at a depth of 15–20 m from the surface [*Holmlund, 1988, p. 245*]. The splashing depth of 25 m from the surface was also reported [*Badino, 1992*]. It can be assumed that the intensity of the water splashing in the moulins depends on the waterstream discharge. Probably, the larger the water discharge, the deeper from the surface it splashes. Unfortunately, currently it is impossible to determine the depth, at

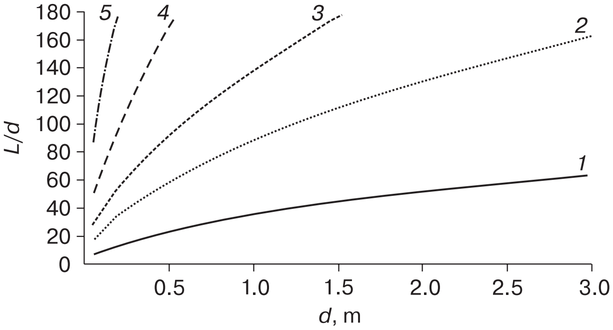

Fig. 2. Dependence of the ratio of the compact section of a jet length to its initial diameter (L/d) on the diameter of the jet (d) and the waterflow rate (U) [*Fetisov, 1995*]:

(*1*) $U = 0.1$ m/s; (*2*) $U = 0.3$ m/s; (*3*) $U = 0.5$ m/s; (*4*) $U = 1$ m/s; (*5*) $U = 2$ m/s.

which the splashing of the waterflow occurs depending on its discharge, because this issue has not yet been solved even at the theoretical level.

In hydraulics, a jet of water falling in the atmosphere is called a non-flooded jet [*Shiryaeva, Grigoryev, 2011; Triandafilov, Efimova, 2012*]. Such a jet flowing into the atmosphere can be structurally divided into three sections along its length: compact, fragmented, and dispersed. In the compact part of the jet, continuity of the flow is provided, and the jet has a shape close to cylindrical. In the fragmented part of the jet, the continuity of the flow is broken, the jet is torn into large parts, its width increases, and it expands in relation to the compact part. The dispersed part of the jet consists of many individual droplets, into which the entire flow transforms. Its width is even larger than that of the fragmented part of the jet.

When the jet moves in the air, it is affected by gravity, air resistance forces, and internal forces caused by turbulent motion of the liquid. At the moment of the jet fragmenting into small drops, surface tension forces of water appeare [*Triandafilov, Efimova, 2012*].

Unfortunately, the mechanics of breakup of free-fall laminar and turbulent jets has been developed only for those with very small diameters, not exceeding several centimeters [*Ervine, Falvey, 1987; Eggers, Villermaux, 2008; Massalha, Digilov, 2013*]. The ratio of the length of the compact section of the jet to its initial diameter was determined to be in the range of 50–100. However, different scales and conditions of the phenomenon do not allow us to apply this ratio directly to larger-diameter water jets rushing into moulins. However, let us apply the results obtained for small water jets to waterfalls in moulins, because there are no other data on this issue. In [*Fetisov, 1995*], an equation for calculating the above ratio for a small turbulent jet falling without acceleration is given as:

$$L/d = 0.94\mathrm{Re}^{0.25}\cdot\mathrm{We}^{0.3},$$

where L is a length of compact jet, m; d is the jet diameter, m; Re is Reynolds number ($\mathrm{Re} = Ud/\nu$); We is Weber number ($\mathrm{We} = \rho U^2 d/\sigma$); U is the initial flow velocity, m/s; ν is a kinematic viscosity of water, m^2/s; ρ is water density, kg/m^3; and σ is water surface tension, Newton/m.

If we use this equation for large streams falling into moulins, then as the initial flow velocity U and flow diameter d increase, the ratio of the length of the compact section of the jet to its initial diameter (L/d) increases rapidly (Fig. 2). This indicates that falling water jets of a larger diameter should be in the compact state over a longer distance.

The highest level of splashing of the jet falling into the moulin occurs at low rates of the waterstream and a smaller diameter (and, hence, flow rate) of the water jet. Small waterstreams are characterized by low flow rates, which is common on the leveled surfaces of glaciers; they break into splashes at depths up to 20 m, which is close to in situ observations [*Holmlund, 1988; Badino, Piccini, 2002*].

However, for larger waterflows, the splashing depth of the water jet probably increases. How much this corresponds to reality is unknown, because the data for a small jet that does not accelerate during falling have been used [*Fetisov, 1995*]. In reality, any falling jet within its compact section necessarily accelerates as it falls, and the thinning of the jet and the beginning of its breakup are also associated, among other things, with this fact. Besides, all experiments with the falling jet have been carried out under the conditions of unlimited space, while within the moulins, the space has a limitation and a finite volume. At the same time, air entrained by the falling water jet due to the ejector effect constantly comes to the moulins. Some similarity to the falling jet in unlimited space is observed in an open crevasse (before its closure) at the initial moment of the moulin formation. In this case, air sucked by the water flow at the place of its fall into the crevasse can easily leave the crevasse outside the zone of the water flow action, away from it. After the crevasse closes, air can only escape from it the same way the water enters the moulin. This contributes to the rupture and breakup of water jets rushing into the moulin over a shorter distance than the small-jet theory predicts for the open atmosphere, and probably over a shorter distance than at the waterfalls outside glaciers. To correctly estimate the depth of breakup of the water jet in the moulins, additional studies are needed.

Figure 3 demonstrates the scheme of the moulin formation along the crevasse. Let us consider again that the moulins reaching the bottom of the Greenland ice sheet could have been formed during the

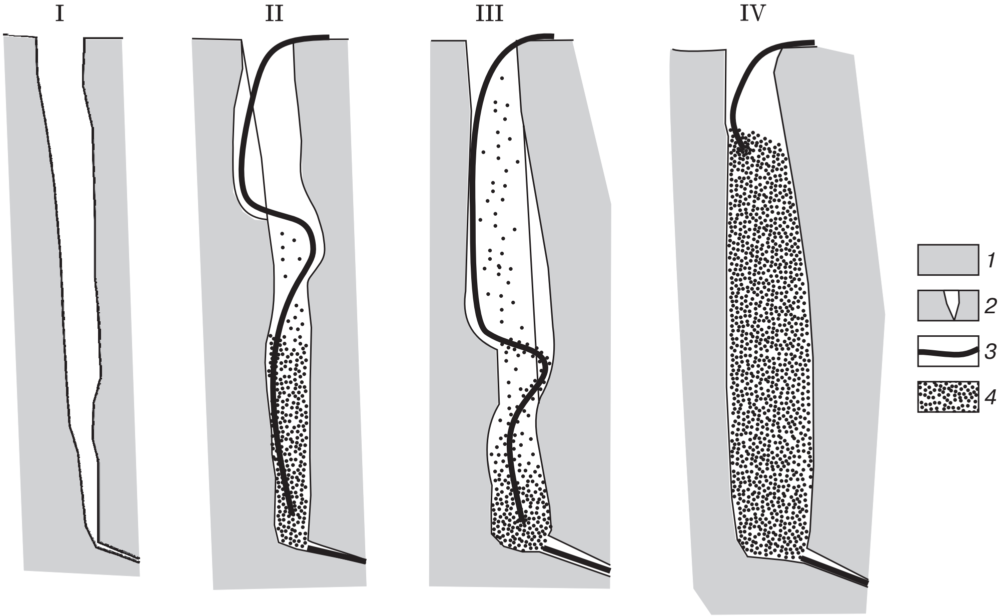

Fig. 3. A scheme of the moulin formation in the open crevasse (I), side view.

II–IV – stages of the moulin development. (*1*) ice; (*2*) crevasse; (*3*) waterflow; (*4*) splash water. Water outflow from the bottom of the crevasse is shown sketchily.

drainage of supraglacial lakes [*Das et al., 2008*]. To form such a moulin, it must have been drained down to the glacier bed during lake drainage. In reality, this did not happen. Therefore, the moulin probably formed before the lake depression was filled with water, then stopped functioning, and was simply renewed at the time of the lake outburst. However, this does not mean that the moulin previously and subsequently has reached the glacier bed. In addition, most glaciers were marked by the water level located in the middle or upper part of the glacial column [*Benn, Evans, 2010; Cuffey, Paterson, 2010*]. This excludes the possibility for the moulins to be formed below the water table. There is no answer to the question of how the hydraulically induced crevasse can rupture the ice, which is in the stressed state and has a large thickness, if its temperature is −20 to −30°C as it is noted in Greenland [*Cuffey, Paterson, 2010*]. The author's model calculations show that an open 10-cm-wide crevasse in ice, through which water flows, can exist without being closed by newly formed ice, if the ice temperature is not lower than −8°C [*Mavlyudov, 1998*]. Earlier, the similar conclusions were made by P.A. Shumsky [*1955*], who reported that there is no free water in glacial ice with temperature below −8°C. This indicates most likely that the newly generated small crevasses rapidly freeze over in their narrow part.

Because falling water in the deep moulins is splashing, droplets falling evenly to the moulin bottom do not induce the formation of the plunge pit. The bottom of the moulin becomes flat or slightly sloped towards the continuation of the channel starting at the bottom of the moulin. The author has repeatedly observed this at the bottom of glacial moulins on Spitsbergen, if their depth exceeded 30–40 m, and the stream discharge in summer time reached 0.5–1.5 m^3/s. The similar situation was observed by the author in the moulins on the glaciers of the Caucasus and Tien Shan.

The Depth of Moulins

The depth of the first moulin in the arising cavity is equal to the depth of the primary crevasse, if the flow enters the crevasse in its center [*Mavlyudov, 2006*]. According to modern concepts, any isolated crevasse, which does not appear at the surface and is located inside any rock (including ice), is a flat round-shaped disk with a small widening in the center [*Tsang, Neretnieks, 1998*]. A vertical crevasse on a glacier appears as a part of this disk deepened in ice. We see only half of such disc-shaped crevasses on the surface of glaciers. Thus, the greatest depth of the crevasse is approximately in the area of its middle and, towards the edges, the depth of the crevasse decreases to zero. Therefore, if the flow enters the crevasse approximately in its middle, the depth of the primary moulin would be at its maximum, and if it occurs closer to the edge of the crevasse, the depth of the moulin would be less (Fig. 4) [*Mavlyudov, 2006*].

If the stream enters the crevasse edge, the water falls into ice along the slope, which leads to the for-

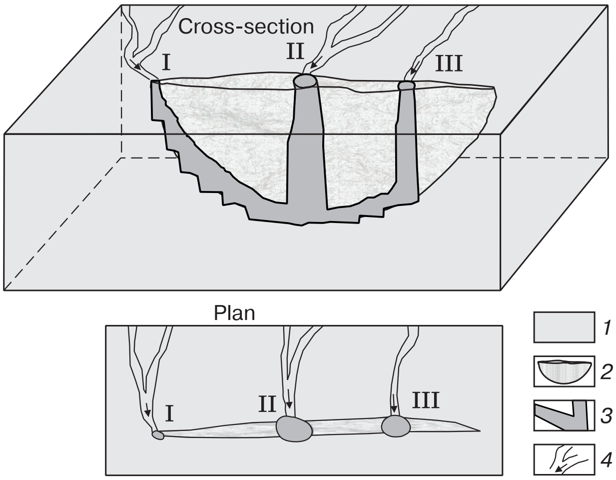

Fig. 4. Block diagram of the moulin formation related to the place, where the watercourse enters the crevasse.

I – a cascade of small pits that appear along the edge of the crevasse; II – a continuous moulin in the central part of the crevasse; III – the moulin with a small cascade. (*1*) a block of glacial ice; (*2*) a cavity of the crevasse; (*3*) a glacial channel that appears along the crevasse; (*4*) surface watercourses and direction of the water flow. The outflow of water from the crevasse bottom is not shown.

mation of a cascade (successive series) of small pits; the depth of these pits in the cascade decreases when approaching the center of the crevasse. The similar structure of the cavity may arise, if the flow is absorbed by an inclined crevasse, the dip of which coincides with the direction of the flow. In this case, the depths of the small pits in the cascade would be approximately equal. The steeper the crevasse, the deeper each pit in the cascade.

Most often, moulins on mountain glaciers and on glacial sheets are formed on small waterstreams, the water discharge of which in any case does not allow the formation of hydrofractutes (regardless of whether they exist or not). As far as the depth of crevasses in glaciers is limited, the depth of moulins also has limitations. For example, for temperate glaciers, the depth of ordinary transverse glacial crevasses does not exceed 25–30 m [*Cuffey, Paterson, 2010*]. One can assume that exceptions may appear, such as on the Mer de Glace Glacier (France), where the depth of the moulins can reach 80 m [*Reynaud, 1987*], or even 105 m [*Forbes, 1845*]. For cold and polythermal glaciers, typical crevasses are deeper, because they appear in stiffer cold ice. Probably, the depth of crevasses in this case rarely exceeds 100 m [*Golubev, 1976*], although in some cases, it may reach 150 m [*Schroeder, 1998*]. Perhaps, the crevasses can be deeper on the floating edges of the outlet and shelf glaciers in Antarctica. If that is so, then the possibility of the existence of the moulins of 400–600 m in depth on the Greenland ice sheet outside the limits of the outlet glaciers is questionable [*Andrews et al., 2014*]; moulins deeper than 173 m [*Reynaud, Moreau, 1995*] or 203 m [*Gulley et al., 2009b*] have not been found there using the speleological methods. Probably, this depth of the known moulins approximately corresponds to the depth of the crevasses, along which they were formed. In addition, the moulin depth of 400 or 600 m should mean that the crevasses, in which these moulins are formed, should be drained to this depth, which is not confirmed by observations of the water level in the moulins.

The author's studies on Spitsbergen showed that the depth of the moulins on polythermal glaciers is approximately equal to the thickness of the cold ice layer and usually does not exceed 75–80 m (for example, on the Aldegonda Glacier, Nordenskiöld Land, West Spitsbergen) [*Mavlyudov, Solovyanova, 2003*]. The moulin bottoms here usually have a slightly inclined englacial gallery, which, in some cases, is alternated with small pits from 0.5 to 8 m deep. In some cases, there is water at the bottom of the subhorizontal part of the cavity on the ice. In cold glaciers, the moulins may reach a glacier bed, as it was observed on the Tavle Glacier (Nordenskiöld Land, West Spitsbergen), where one of the studied moulins reached a depth of 100 m. The other moulin was about 80 m deep, but further, in a long englacial gallery, the flow cascaded down to the glacier bed at a depth of about 100 m. The fact that the bottom moraine was frozen was evidenced by the presence of solifluction flow in the area, where the channel crossed the ice/moraine interface. The subglacial ground thawed due to its warming by water flowing earlier in a glacial channel. The moulins deepened to the bed of the glacier were also observed in the northern part of this glacier's tongue having ice thickness of about 15 m [*Mavlyudov, 2007b*]. On the South Inylchek Glacier (Kyrgyzstan), all the moulins studied in different years ended by water-filled channels at a depth of 80–100 m [*Mavlyudov, 2022b*].

Other Mechanisms of Moulin Formation

The author discovered another mechanism for the formation of moulins. It was observed in the glaciers without crevasses [*Mavlyudov, 2015*]. Deep ice canyons were originally formed on such glaciers during the prolonged downcutting of the surface water streams into the ice. Usually, the depth of such canyons does not exceed 15 m (rarely up to 30 m). When this depth is reached, the canyons partially or completely die off, because the water finds other paths of movement over the glacier surface. The abandoned or simply deepened canyons are closed by plastic deformation of ice, filled from above with snow, aufeis ice, and superimposed ice, and are transformed into englacial channels [*Vatne, 2001; Mavlyudov, 2006; Gulley et al., 2009a*]. If any surface water stream flowing over the glacier surface crosses the sealed canyon in some part, its water may enter the canyon. At first, water forms a small channel in the snow-ice plug overlapping the canyon. This channel eventually turns into a real moulin. In this case, the empty space of the ice canyon plays the role of a crevasse in the formation of the moulin. However, the maximum depth of such a moulin is always limited by the depth of the ice canyon. The author observed such moulins in many cold glaciers of Spitsbergen.

It was suggested that the moulin in the englacial channel of the Brøgger Glacier on Spitsbergen appeared during the headward erosion of a waterflow over the inclined cascade of shallow pits (Fig. 5) [*Myreng, 2015; Vatne, Irvine-Fynn, 2015*]. This hypothesis is open to argument. In fact, in the cascade of shallow pits, the headward erosion affects all vertical walls of all shallow pits in the cascade to the same extent. This is proved by the fact that, when water falls, the heat is evenly distributed along the entire length of the falling stream due to the transition of potential energy into kinetic energy. This means that all the shallow pits will be displaced almost equally in space and in time under the impact of the headward erosion. However, in order for the single moulin to originate from the inclined cascade of shallow pits, the headward erosion in the lower part of the cascade should be much higher than that in the upper part, i.e., the headward erosion should intensify from the top to the bottom. There is no natural reason for this, and this mechanism seems to be impossible.

It is probable that the moulin formation in place of the cascade of small pits can be explained by the appearance of a vertical crevasse in place of the first pit in the cascade. To form the new moulin in such a crevasse at the beginning of the cascade, one melting season is sufficient. In the given study [*Vatne, Irvine-Fynn, 2015*], the intervals between visits to the moulin were several years. That is why, most likely, the authors did not manage to trace directly the real transformation of the cascade into the moulin.

In the Aldegonda Glacier on Spitsbergen, in one of the moulins in the middle part of the glacier, with a one-year time span, the author observed the following. During the first visit, the depth of the inlet moulin was 45 m, from where a vertically oriented subhorizontal slot-type gallery began. The next year, the depth of the inlet moulin was about 60 m, and the new subhorizontal vertical slot-type gallery appeared at its bottom. The new gallery was located exactly beneath the old gallery, because they were both formed in the same vertical crevasse. The deepening of the moulin in this case was due to the deepening of the crevasse. A similar situation could have occurred on the Brögger Glacier, too.

The Lifetime of the Moulins

Moulins originate, exist for some time, and die. Evolution of the moulins is associated with a change in the regime of water supply, which occurs either due to the glacier movement and the new crevasse formation upwards from the existing moulin on the glacier, or due to a change in the surface drainage network of the glacier. A moulin, which has lost its flow water supply, continues to get water only from the melting crust, which freezes on the walls of the moulin due to reserve of cold inside the ice column, and gradually get filled in with snow and ice. After the moulin's lower outlet is sealed by ice, it gets filled with water, which also begins to freeze on the moulin walls.

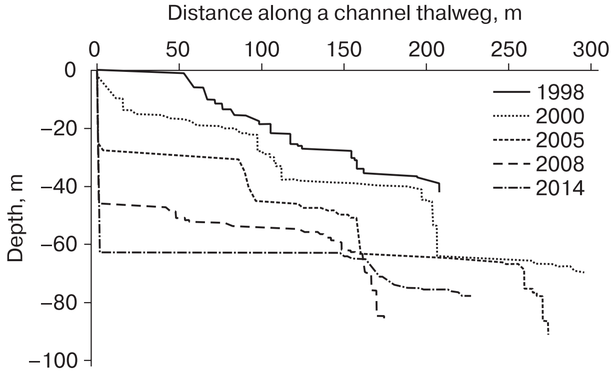

Fig. 5. Lengthwise profiles of englacial channel of the Brögger Glacier from multitemporal topographic surveys.

The *x*-axis shows the distance along the channel thalweg, not the horizontal distance [*Vatne, Irvine-Fynn, 2015*].

Such a moulin is sealed with ice from the surface and turns into a vertical closed cavity filled with water. Intra-water ice crystals begin to grow from the walls of the moulin inside a cavity, and the cavity gradually fills with ice. Such a dead and completely frozen moulin differs substantially by its giant-crystal radial-ray structure from the surrounding glacial ice when exposed on its surface [*Stenborg, 1973; Mavlyudov, 2006*]. Attempts have been made to reconstruct the structure of a moulin by fixing the position of moulin's cross sections with radial-ray structure at several time spans [*Holmlund, 1988*]. Generally, such recrystallized moulins cannot revive, even if they receive water supply. The same is true for the partially recrystallized moulins, where the cavity with water is still preserved in their core.

Analyses of the quantity of rings in the fully recrystallized cavity often allows us to judge the duration of the complete freezing of the moulin. For example, in Spitsbergen, the most common time of the complete freezing of moulins is from 1 to 6 years. However, on the Tavle Glacier (Nordenskiöld Land, Spitsbergen), the author managed to count 13 annual layers in one of the dead moulins.

Generally, moulins remain active for several years, after which they die, giving rise to new moulins. In [*Holmlund, 1988*], the age of the moulins in the axial part of the Stor Glacier (Sweden) is up to 10 years. It was determined through indirect signs that the moulins in the Hans Glacier (Spitsbergen) could be active of up to 20 years and more [*Schroeder, 1998*]. But even if this is true, it is an exception rather than the rule. Dead moulins also exist for several years until they are completely filled with snow and ice. Snow quickly fills the dead moulins because they are traps for snow drifts in winter.

Water Levels in the Moulins

Dynamics of the water levels in the moulins is studied to determine their influence on the glacier movement [*Iken, 1972; Badino, Piccini, 2002*]. The study of moulins (even in the complete absence of lakes on the glacier surface) has shown that the water level rise in these features corresponds to acceleration of the glacier movement in spring [*Iken, 1972*]. This means that water levels in the moulins are somehow related to the movement of the glaciers. A typical explanation is an assumption that water enters a glacier bed through the moulins and moistens it leading to the acceleration of the glacier movement. This is attributed to the fact that the water flowing to the bed through the moulins creates pressure at the ice base, which is sufficient for the glacier to float up and start moving faster. Indeed, according to the author's observations in Spitsbergen at the beginning of the ablation season, many moulins are filled with water almost completely, as evidenced by shore ice and firn particles adhered and adfrozen to the moulin walls marking previous water levels. During the summer season, the water level in the active moulins gradually decreases reaching its minimum at the end of the summer season, when melting on the glacier surface stops.

In addition, daily fluctuations of the water level in the moulins of the Tindal Glacier (Argentina) were observed [*Badino, Piccini, 2002*], which is probably associated both with limitations of the water discharge capacity of the channels at the base of the moulins, and with possible systematic restructuring of the internal drainage channels themselves. In the same article, the authors prove that the internal glacier drainage system is englacial; it is linked to the local water level in the glacier. The amplitude of daily water level fluctuations in the Vicecapo moulin was about 90 m.

Daily fluctuations of the water levels were measured in the moulins in the western Greenland [*Andrews et al., 2014; Covington et al., 2020*], where the amplitude of water level fluctuations was up to 45 m in the moulin at 765 m asl and up to 20–30 m at 950 m asl [*Covington et al., 2020*], while at 700 m asl, the fluctuations were up to 150 m [*Andrews et al., 2014*]. It is interesting that fluctuations of the water level in moulins separated by a considerable distance occur synchronously but with different amplitudes [*Covington et al., 2020*]. This is not a sign of the direct connection of these moulins, but rather of the similarity of the external climatic conditions responsible for ice melting and for meltwater inflow into these moulins.

Moulin modeling was performed to explain daily fluctuations of the water levels in the Greenland Sheet moulins [*Trunz et al., 2022*]. While the earlier model calculations assumed the cross-section of the moulins to be cylindrical from the surface to the bed, the authors used not only the cylindrical shape of the moulins but also expanding upward, expanding downward, goblet-shaped, bottle-shaped, first expanding then narrowing, and first narrowing and then expanding. They assumed that moulins reach the bed of the ice sheet. The authors believed that water accumulation in the glacier column plays the key role in relation to meltwater input and glacier movement. They suggested that moulins change through the combination of the melting due to turbulent water flow, as well as viscous and elastic deformations of ice. This means that the authors do not really consider the moulins, confusing them with internal glacier drainage systems, the structure of which is unknown but for surely differs from that of the moulins. We can assert this, because channels inside the ice are formed under the phreatic conditions, when they are permanently filled with water, while moulins are formed by splashing water flow, when the water level is below the base of the moulin. Within the framework of the hypothesis of the authors [*Trunz et al., 2022*], the shape of the moulins, which narrow downward, cannot be adequately explained. In addition, as it has been mentioned above, the moulins cannot have the same or expanding shape of a hole below the level of the water table, because they are formed only in the splash zone of the waterfalls, i.e., above the water level, which means that these models of the moulin functioning [*Covington et al., 2020; Trunz et al., 2022*] have no physical basis. The same applies to the moulin models in [*Andrews et al., 2022*].

Despite the fact that the water level in the moulins changes throughout the year, the presence of water in the moulin warms the surrounding ice [*Schroeder, 2007*].

Moulins and Drainage Systems of Glaciers

Let us consider, where does water escape from the crevasse bottom, in which the moulin forms, if the water does not reach the glacier bed, as it has been observed in some cases? One possible answer is the overflow of water into another crevasse, which is located near or crosses the primary crevasse, but the depth of which is equal to or larger than the first one. The author envisioned this as follows (Fig. 6) [*Mavlyudov, 2007a*].

If the second crevasse is close to the first crevasse without crossing it, the water overflows from a crevasse to a crevasse through a system of smaller feathering fissures, which can connect the larger crevasses with one another. In this case, small channels appear along the smaller fissures first; later, they change into the large channels [*Schroeder, 1998*]. In the case of the connection with a deeper crevasse or with a crevasse that does not appear at the surface, when water falls into the next crevasse filled with air, a moulin is also shaped it. The depth of the moulin then depends on the depth of the deeper crevasse. Thus, through systems of parallel crevasses, water may or may not reach the glacier bed. Most researchers believe that water in any case reaches the glacier bed [*Benn, Evans, 2010*]. In this case, it seems that the watering of the bed accelerates the movement of the glacier.

It is not quite clear how this process can occur, if the bed, for example, is not rocky, but is composed of loose sediments. If water does not reach the bed, which is observed in some glaciers of Spitsbergen and other territories, then the spring acceleration of the glacier movement cannot be explained. A similar scenario would arise, if it turns out that water cannot reach the bed of the ice sheet and outlet glaciers through the moulins in Greenland. All this suggests that the mechanism of the spring acceleration of glaciers may be different.

The available direct observations do not always confirm water delivery to the bed of some glaciers. In particular, boreholes that did not reach the bed in the South Glacier in the St. Elias Mountains (Yukon, Canada), had exactly the same water level fluctuations as those that reached the bed [*Rada, Schoof, 2018*]. Attempts to obtain water from the glacier bed through tunnels mined under the Argentiére Glacier (France) were unsuccessful; no water was found there. In addition, the subglacial laboratory equipped in the same glacier, partly in a cavity in the shadow of a rock ledge, has never been completely filled with water since 1968, and there has never been any water in it, except for a tiny stream [*Moreau, 1992, 1995; Benoit et al., 2015*].

The boreholes drilled on the Argentiére Glacier (France) in the area of the bed overdeepening showed the absence of water at the bed; at the same time, a zone of ice permeability exists at a depth of 100 m from the surface with the ice thickness of about 230 m [*Hantz, Lliboutry, 1983*]. On the Greenland Ice Sheet, there is some evidence of strong englacial reflectors of radar waves that have been detected in the Swedish Camp area [*Catania et al., 2008; Catania, Neumann, 2010*]. These strong englacial reflectors were probably produced by water accumulated inside the glacier ice [*Lüthi et al., 2015*]. The authors believe that very deep water-filled crevasses, rather than moulins, are the main sources of heat in the ice column in the ablation area.

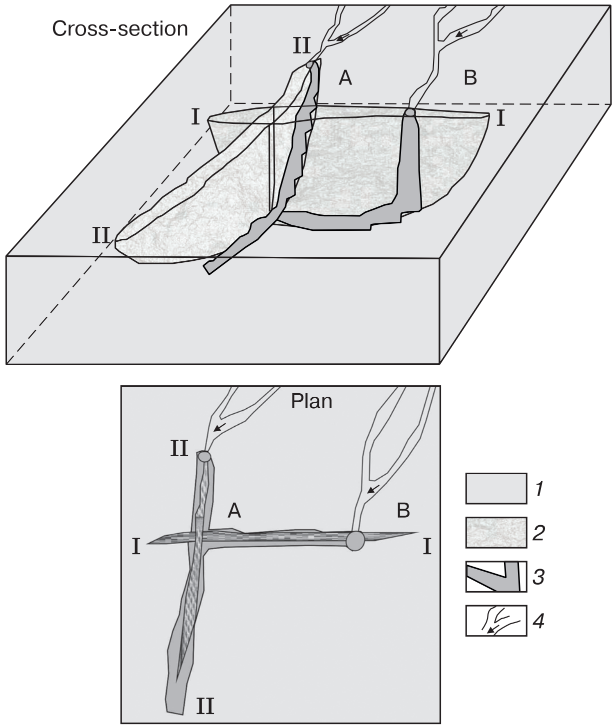

Fig. 6. Block diagram of the moulin formation and channels at the base of two intersecting crevasses.

I–I and II–II – planes of crevasses; A, B – numbers of waterstreams, from which channels start. Further direction of the channel after crevasse II–II is not shown. (*1*) a schematic block of glacial ice; (*2*) crevasses; (*3*) channels; (*4*) water streams.

None of the 13 moulins studied on the Aldegonda Glacier in Spitsbergen (some of them were repeatedly studied) reached the glacier bed [*Mavlyudov, 2022a*]. Some of the moulins in the lower part exposed a layer of transparent ice, which was typical for the base of many Spitsbergen glaciers, but all the channels did not reach the bed itself. In addition, the glacial cave at the edge of the overdeepened glacier bed near its northern side was englacial, becoming subglacial only on the rock ledges, which allowed the author to assume the englacial position of the channels branching from the moulin bases. An additional confirmation of the author's hypothesis is the unchanged chemical composition of water flowing into the moulins on the Aldegonda Glacier surface and flowing out of the cave on the glacier tongue, which indicates the absence of the contact of the flow inside the glacier with the bed [*Borisik et al., 2021*]. The moulin on the Brögger Glacier in Spitsbergen also ended up in a subhorizontal englacial gallery [*Vatne, 2001*]. A similar pattern was observed on the Middle Loven Glacier, where an englacial water outlet was found on the glacier tongue [*Irvine-Fynn et al., 2005*]. The englacial channel located near the glacier bed may deepen into the ice upon lowering of the base of erosion for the flow in the glacier tongue; thus, it may subsequently become a subglacial channel. Thus, not all glaciers with the subglacial water outlet on the glacier tongue formed their internal drainage directly under the ice. The internal drainage may have been primarily formed through an englacial way. If at least the part of the glaciers has no water underneath, it becomes unclear how the spring acceleration of ice movement occurs and how the internal drainage system is formed in the glaciers.

The author suggested some possible options of the formation of internal drainage systems in glaciers, where water discharge from the surface does not reach the bed [*Mavlyudov, 2006*]. First, it was suggested that the internal drainage of a glacier does not arise at a single moment, but is formed gradually over a long time. For example, the internal drainage could have arisen in the stretching zone of a glacier, where there are many glacial crevasses. As the glacier moved, the crevasses on the surface closed, while the internal drainage channels were preserved [*Mavlyudov, 1995*]. The newly forming glacier crevasses provided internal drainage that combined with the existing zone. Thus, the internal drainage could reach the glacier tongue over many decades and centuries.

This is theoretically possible, but is unlikely in practice, because in this case it is assumed that the cave system inside the glacier exists for decades, if not hundreds of years, which is difficult to imagine under the conditions of highly variable glacial caves that change in years and even in months.

Second, the central internal drainage system of the glacier may form from the merging of two marginal drainage systems at the confluence of two branches of the glacier [*Mavlyudov, 1995*]. The marginal drainage systems are formed along a system of parallel oblique crevasses, which arise during the glacier movement. Theoretically, such merging of the marginal channels is possible, although this has not been proven in practice. However, if such a mechanism is present somewhere, it cannot explain the formation of channels in the glacial sheets and the presence of a large number of moulins in them. Therefore, no real mechanism of the internal drainage formation has been proposed so far for the glaciers, where water does not reach the bed.

In some glaciers, the moulins with their outgoing channels do not reach the glacier bed. What could be the reason for this phenomenon? In 2003, a new type of englacial channel was discovered in the Aldegonda Glacier on Spitsbergen. It represents a subhorizontal slot in ice with a visible width of more than 20–30 m and the height of 0.5 m or less in its middle part washed out by water. Along this part, the flow carried subglacial deposits represented by a washed-out bottom moraine [*Mavlyudov, 2005*]. When the base level of erosion is lowering, the stream begins to cut an ice canyon in this slot. Once the horizontal slot is closed by plastic deformation of the ice, this canyon turns into the real cave canal the next year. Traces of a preexisting slot could be seen for several years under a flat ceiling of the channel on its two sides in the form of layers of pebbles and gravel sandwiched in ice. This means that before the formation of the channel, there was some plane along which the crevasse channel appeared. In the author's opinion, this is the plane of a thrust, along which ice moved at the base of the polythermal glacier. In other words, in this case, the ice did not move along the bed, but along the plane of the thrust at the base of the ice column. This thrust plane was used by waterflows that came to its surface through the glacier moulins for transportation to the glacier tongue. This also means that it is the watering of the thrust plane by meltwater that leads to the spring acceleration of the ice movement, which has been observed at many glaciers. Formation of the thrust could have occurred due to considerable pressure of water at the interface of temperate and cold ice, which entered there through the glacier moulins [*Mavlyudov, 2014*].

Let us assume that all this is true for a particular glacier, although the cause of this glacier origin is not fully known. Does this mean that the similar phenomenon is widespread and can be found at other glaciers? A similar pattern was observed on the tongues of the Brögger Glacier [*Vatne, 2001*] and Middle Loven Glacier [*Irvine-Fynn et al., 2005*] and on one of the right branches of the Aavatsmark Glacier [*Mavlyudov, 2005*]. The author's studies on the temperate Bashkara Glacier in the Caucasus showed that the subglacial cave in the glacier tongue in its distant part transformed into an englacial cave in the form of a subhorizontal slot channel [*Mavlyudov, Solovyanova, 2005*]. The author's observations showed that water on the tongue of the temperate Hailugou Glacier (Gongushan, China) also comes out of a subhorizontal englacial slot. As it was noted above, on the temperate Tindal Glacier (Argentina), water from the surface also does not reach the glacier bed [*Badino, Piccini, 2002*]. This means that the development of subhorizontal crevasses or thrusts is possible not only in polythermal but also in temperate glaciers.

The presence of such a slip plane (thrust) in some cases may explain the absence of water on the glacier bed, as it was observed on the bed of the Argentiére Glacier (France) within overdeepened zones [*Hantz, Lliboutry, 1983*]. In this case, the channels may pass through the overdeepened zones of the glacier bed along the slip planes inside ice rather than cutting in from the ice surface [*Fountain, Walder, 1998*]. In [*Benn, Evans, 2010, p. 68*], the authors consider possible existence of crevasses above the polythermal glacier bed along the interface of cold and temperate ice, which helps the englacial waters to run off the glacier. Without these crevasses, the runoff will be blocked by adfreezing of a glacier tongue to its bed.

Could similar thrusts (or slip planes) in the ice column occur in the ice sheets as well? At the Antarctic ice sheet, the analysis of glacial cores and inclinometry of four boreholes revealed that in the 1400-km-long section of the route there are several manifested layers of about 100 m in thickness in the upper part of the snow-firn formation, along which the most intensive ice movement with different rates takes place [*Markov, 2007*]. It also turned out that the upper layer of the formation moves in a different direction (up to the opposite one) than the underlying layer. If such layers with slip planes exist in Antarctica, they may also exist in Greenland.

One of the possible reasons for the formation of such layers in the Greenland ice sheet could be the preservation of the buried firn layer in the column of infiltration glacier ice. This preserved firn layer may act as the weakened zone, along which the movement of the upper layer of ice began. If such a slip layer within the ice sheet exists, it could also explain the formation of the internal drainage systems of any length in glaciers and ice sheets. Such a slip plane does not depend on unevenness of the glacier or the ice sheet bed, but is parallel to their surface. This means that the slip plane has a constant inclination towards the glacier tongue. Owing to the fact that such a slip plane is close to the ice surface, crevasses can easily reach this plane, and therefore, its depth determines the depth of the moulins (Fig. 7).

Water penetrating through crevasses and moulins down to the slip plane spreads over it causing the acceleration of ice movement in the spring. This is how an inefficient drainage system appears [*Mavlyudov, 2014*]. During the ablation season, englacial channels are formed along the slip plane creating an efficient drainage system. In this case, the daily fluctuations of the water level in the moulins correspond to the discharge capacity of the channels along the slip plane. With cold weather, the channels on the slip plane are closed by plastic deformation of ice, and the flow along the slip plane resumes in the spring due to gradual recovery of the drainage system at increasing water level in the moulins. The slip plane itself does not disappear, because ice movement along it continues in winter. Perhaps, in some cases, several such slip planes may occur in the ice column at different depths from the surface. However, even in this case the ice movement along the bed may also occur.

The movement of ice along the slip plane can help to explain the formation of surges, breakthroughs of supraglacial and dammed glacial lakes, as well as the formation of eskers. In particular, the eskers can form when the thrust plane touches the bed ledges at one or several points. In this case, in the channels that appear along the thrust plane, water carries material from the ledges and then deposits it in the ice bed. As a result of ice melting during the glacier degradation, the material filling the channel is projected onto the underlying landforms in the form of eskers. When the dammed glacial lakes are filled with water, part of the ice adjacent to the lake floats up, opening the way for water into the inner slip plane, along which the lake discharge channel is formed. After water leaves the lake, the lowered ice dam cuts off water access to the slip plane, and water in the lake basin begins to accumulate again. Supraglacial lakes are drained through newly created crevasses on their bottoms reaching the slip plane. When the water coming from the glacier surface to the slip plane does not have time to create drainage channels,

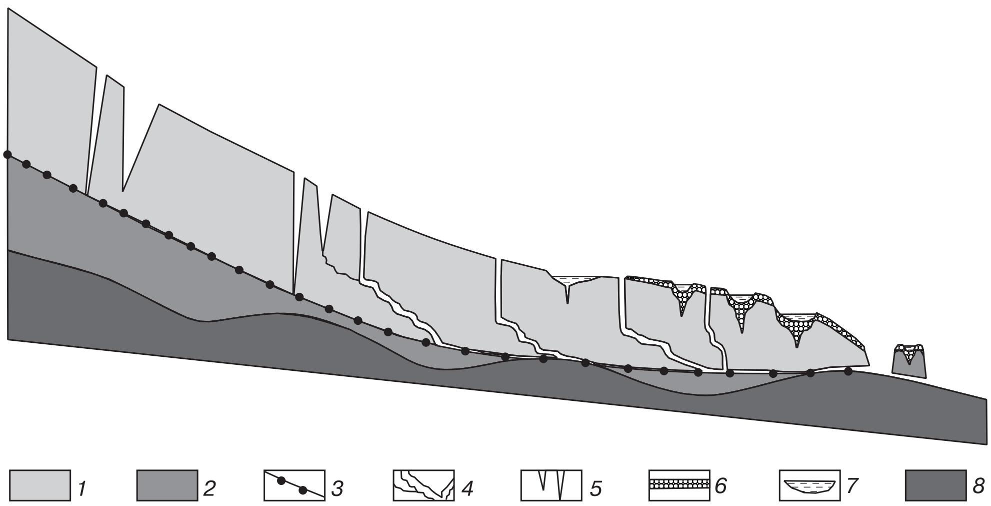

Fig. 7. A schematic lengthwise cross-section through the glacier tongue or edge of an ice sheet with an internal drainage system.

(*1*) ice, more actively moving layer; (*2*) more stable or dead ice; (*3*) slip plane; (*4*) channels; (*5*) crevasses; (*6*) moraine deposits; (*7*) lakes; (*8*) bedrocks.

the whole glacier or its part along the moistened slip plane starts moving faster. This is how glacier pulsation or surges are formed. The author does not yet know whether there is other evidence of the presence of the slip planes in glaciers and ice sheets. Further research should clarify this question.

CONCLUSIONS

It is argued that moulins can form along the air-filled crevasses with water drainage into the ice column, or along buried ice canyons. The penetration depths of these features determines the depth of the moulins. Draining surface lakes cannot form the moulins, but simply widen crevasses. However, if the lake drainage occurs through the moulins, it means that they were formed before the lake basin got filled with water. The water jet of the surface waterflow on the glacier falling into the crevasse filled with air leads to a local expansion of a crevasse portion. After the crevasse closes, its expanded portion turns into a vertical channel – a moulin. The splashing of the water jet falling into the moulin is responsible for its cylindrical shape. It has been established by speleological methods that, in at least some glaciers, meltwater that is absorbed by moulins does not reach the glacier bed. Such glaciers may be either polythermal or temperate.

This does not support the generally accepted hypothesis of the moulins reaching the glacier and ice sheet beds regardless of the ice thickness and temperature. On the contrary, the hypothesis, which is based on the formation of thrust within the ice column along which the slip plane develops, explains the formation of the internal drainage of such glaciers. The formation of the internal subhorizontal thrusts within the ice column has been confirmed by studying moulins and caves by speleological methods. Most likely, not all glaciers have a system of thrusts inside the ice column, but it is probably a relatively widespread phenomenon. It is the plane of such thrust that may serve as the basis for the formation of the internal drainage system, where water enters the slip plane through the moulins. Using the hypothesis of the presence of an englacial slip plane allows us to explain the formation of the internal drainage network of any size in mountain glaciers and glacial sheets. The presence of such slip planes within glaciers makes the role of the moulins clearer: they serve as a connector for transportation of the surface meltwater to the slip planes of glaciers and ice sheets, which provides for the accelerated spring movement of glaciers.

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