INTERNAL DRAINAGE OF GLACIERS AND ITS ORIGIN

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Abstract
Ways of occurrence of elements of an internal drainage of glaciers and also origin of internal drainage systems as a whole are considered. It is shown that elements of an internal drainage can be formed either on the base of fissures and crevasses or by incision of water streams into ice from glacier surface. The basic way of glacier drainage is formed on the base of sliding plane which is formed closely to glacier bed and smooth all roughnesses of the bed. Spreading of water on the surface of this plane during spring time forms not effective drainage system however during ablation season drainage channels are formed along this sliding plane and it is an effective drainage system. The offered point of view explains selective erosion on the glacier bed, spring accelerations of ice movement velocity, formation of eskers and outbreaks of glacier-dammed lakes.

Keywords
glacier hydrology, glaciospeleology, internal drainage systems, fractures, crevasses, hydrofractures

Introduction
The internal drainage is inherent for very many glaciers without dependences on glaciers types and their thermal conditions. In spite of the fact that internal drainage was known long ago, its researches were carried out until recently only by indirect methods: modelling, geophysical, hydrological, etc. (Benn & Evans, 2010; Fountain & Walder, 1998). Scientists think about an internal drainage as about «black box» which has signals on input and on exit (Murray et al., 1995).

Speleologists and cavers were the first who started to study elements of an internal drainage of glaciers (Freyfeld, 1963; Gallo, 1968; Halliday & Anderson, 1969; Poluektov et al., 1966). And they do it throughout more than 50 years. For these years the set of articles devoted to studying of glacial caves have been published (Eraso, 1991, 2003; Pulina, 1992; Slupetsky, 1998; Badino, 2002; Mavlyudov, 2005a; Tyc & Stefaniak, 2007; Griselin, 1995), the monographs dedicated to an internal drainage are published (Eraso & Pulina, 2010; Mavlyudov, 2006). However glaciologists persistently did not want to recognize the data received earlier by speleological methods.

We already wrote about internal drainage systems of glaciers (Mavlyudov, 2006, 2007a). These works were based both on our own investigations and on studying of glacial caves by other groups of researchers (Badino, 2002; Reynaud & Moreau, 1995; Grizelin, Marlin, 1993, Pulina, Rehác, 1991, Rehác J., Rehác, 1995, Schroeder, 1998, et al.). Recently there were enough many articles devoted to studying of glacial caves by glaciologists (Gulley, Benn, 2007, 2009a, 2009b et al.). Thus for last years enough extensive material on elements of an internal drainage of the glaciers has collected, it was received in different regions of the world that allows to make some generalisations connected with internal drainage at the new scientific level. This article exactly is dedicated to problems of an origin of glaciers internal drainage.

Methods
The author carried out researches of glacial caves since 1982. Our researches of glacial caves cover regions: Spitsbergen, Caucasus, the Alps, Tien-Shan, Pamir, Suntar-Hayata, the Himalayas and Antarctic. Some researches were at single visit and other was repeated throughout many years to reveal dynamics of elements of an internal drainage. In glacial caves were studied: a structure of cavities (on the base of observations and topographic survey), ice structures, ice temperatures, velocity of incision of water streams into ice, intensity ice creep, etc.

Our data have been complemented by data of other researchers of glacial caves which cover now practically all glacial areas.
Results

Earlier we assumed that systems of an internal drainage at the end of ablation season represent the developed system of the pipelike channels most part of which is located under a glacier (except of vertical parts which are englacial) (Mavlyudov, 2006, 2007a). This structure of channels is considered as effective system of drainage (Benn, Evans, 2010). A typical glacier was generated. Earlier we offered two ideas which basically could explain formation of internal drainage systems (Mavlyudov, 1995). The first of them consisted that similar to (Fountain, Walder, 1998) we believed that drainage channels can be generated on shear cracks and consequently is situated along glacier edge (marginal caves). For example we observed similar caves on the Southern Inylchek Glacier in Tien-Shan. It was supposed that at merge of two branches of a glacier two marginal drainage systems connect into one central drainage system. It looks logical but one circumstance afflicted - it was not possible to find such connection of drainage systems in reality. And even if the similar mechanism of formation of internal drainage channels exists it is not universal as far as it cannot explain formation of drainage channels in glaciers without tributaries. The second idea supposes that similar as at (Fountain, Walder, 1998) channels of an internal drainage were initially formed at crevasse zones i.e. in tension zone (Mavlyudov, 1995). In this case we started with the assumption which however was proved by direct observations that crevasses on glaciers can be filled by water but water cannot move deeper. It means that water inflow into at the beginning of crevasse zone and water outflow on the termination of a crevasse zone on a glacier surface. Such phenomenon was observed repeatedly on many glaciers. As ice moves downstream of glacier in crevasse zone lower crevasses were closed but in upper part of crevasse zone new crevasses begin to grow. It was supposed that in lower closed crevasses there was a channel in which water situated under ice surface which below from closed crevasses outflow to ice surface. At glacier movement the buried channel increases its length until the buried channel did not reach glacier tongue. So the central drainage system could be generated. However and this idea has not appeared universal as she cannot explain all cases of occurrence of an internal drainage of glaciers. For example on many glaciers we can see water absorbed by crevasse instead of outflow from other end of a crevasse. Thus it is necessary to state that now there is no satisfactory theory of formation of internal drainage systems of glaciers.

But there are enough possibilities for explanation of formation of separate elements of an internal drainage systems. It is known that moulins are formed on crevasses (Paterson, 1998, Fountain, Walder, 1998, Fountain et al., 2005, Benn, Evans, 2010). However there are glaciers on which moulins are present but crevasses are absent. They are formed on the base of walls of the buried ice
canyons. In this case depth of moulin cannot exceed depth of a parent canyon. Also moulins can origin on ice/rock contact. In case of usual moulins their depth is comparable with depth of a parent crevasse. And as crevasses for example in temperate glaciers cannot exceed depth of 25-30 m (Paterson, 1998) the depth of moulins on temperate glaciers should have comparable size. In many cases this condition is carried out but is far not always. For example on the temperate glacier Merde-Glace (Alps) moulins which actually also give name for all moulins had depth more than 80 m (Reynaud, Moreau, 1995). On the same glacier the moulin with depth more than 100 m was known (Forbes, 1845). Musketov (1881) in his book informed that moulins on glaciers can reach depth up to 300 m. Probably it is an error as in a source whence Musketov took these data were feet instead of meters. Moulin investigated on temperate Bashkara Glacier (Caucasus) had depth more than 40 m (Mavlyudov, Solovyanova, 2005). Apparently in ice movement and ice creep there are some moments which existing theories do not explain.

In more rigid cold ice increases of crevasses depth is possible. As it was found out on polythermal glaciers depth of moulins is comparable with thickness of cold ice layer (Mavlyudov, Solovyanova, 2003). On Aldegonda Glacier (Spitsbergen) we studied Moulin up to depth about 80 m and on Tavle Glacier (Spitsbergen) the moulin depth was about 100 m from a surface to glacier bed that say about absence of a layer of temperate ice under this glacier. In cold glaciers moulins depth can be even more. So in Greenland moulins were investigated up to depth about 173 m (Reynaud, Moreau, 1995) and even to 205 m (Gulley et al., 2009b). But the moulins that reach glacial bed as was supposed in (Das et al., 2008) here were not found.

In some cases we see not one large Moulin but series of small pits (the cascade of pits). It is possible to explain cascade form if moulin was generated on the edge of a crevasse (if to look at a glacial crevasse from sideways it in form will correspond to a semicircle) and water flowing down to the crevasse centre forms the cascade. By other way when dead moulin has been deleted by ablation the cascade can be opened subsequently.

There is information about moulin on Brøgger Glacier (Spitsbergen) that during some years has changed from the cascade to one continuous pit (Irvine-Fynn, 2011). Authors have assumed that the new moulin was generated without crevasse participation. However it is impossible because for formation of moulins the primary flat surface is necessary along which water move. It can be a crevasse, a wall of an ice canyon or vertical contact between ice and rocks.

So water gets into a crevasse and forms moulin. Where it moves further? In glacial cavities in the basis of moulins we observe more often cascades of smaller pits. By analogy to an example of explanation of formation of the cascade described above we can say that cascades in caves are formed on the base of inclined fissure or crevasse. Thus the more abruptly incline the parent fissure the more depth of pits on the cascade and the less step between pits and on the contrary the more flat the parent fissure the less depth of pits and more step between pits. Accordingly horizontal fissure will give rise to horizontal galleries without pits. As moulins meet widely on many glaciers we need believe that in thickness of ice there can exist fissures and cracks of different orientation.

As to horizontal galleries at the bottom of vertical pits (moulins) their genesis is not quite clear. More often they are the canyons of incision generated on the base of vertical crevasses which walls were closed above. I.e. on the channel arch there is a trace in the form of a white strip which represents the channel compressed by ice plastic deformation (ice creep). Often at the compressed channel is present snow like masses brought by streams from glacier surface. We observed the similar phenomena in a moulin № 1 on Aldegonda Glacier (Spitsbergen, Fig. 1). Actually galleries of caves in glaciers tongues are formed on contact of ice and bed or on the base of horizontal fissure of not clear genesis.

In article (Gulley, Benn, 2007) is affirmed that cave channels can be formed on the base of vertical superficial crevasses after their filling by moraine fragments and compression by plastic deformation. It is an error. Even in the photos in this article is clearly visible that these investigated channels were formed by cutting into ice from glacier surface.

Thus we see that all elements of internal drainage system are formed on the base of crevasses or along elements of old channels and also by cutting into ice. In the latter...
Carrying out researches of evolution of the drainage channel in the iceblock in cold laboratory of university of Hokkaido (Japan) in 2002 (Isenko et al., 2003), we have found out that at water flow in a horizontal fissure channel is formed englacial channel which very much reminds by its cross-section section the entrance channel in the cave on Aldegonda Glacier investigated in 2003. Analyzing these data and the data received also from research in caves on Western Grønfeld Glaciers, Fridtjoff and Åavatsmark (Spitsbergen) we understand that fissure channels are not similar to englacial and the subglacial channels that were before investigated and described (R-channels, N-channels, H-channels) (Röthlisberger, 1972, Nye, 1976, Hooke, 1984). It means here we deal with new type of glacial channels - fissure channels which are generated on the base of subhorizontal fissures. An important point was that these fissure channels under different conditions could change into other kinds of channels (R-channels, N-channels, H-channels). It means that all these fissure channels were primary and all other channels have occurred from them.

Having carried out researches in variety of glacial caves on other glaciers (Bertil, Spitsbergen; Bashkara, Caucasus; small caves on the edge of the glacial dome Bellinghausen on King George Island, the Southern Shetland Islands, Antarctic) we have found out in them primary horizontal fissures. Thus it was found that glacial caves at tongues of glaciers without dependence from their thermal conditions can origin basically on subhorizontal fissures. Analysis of references has shown that subhorizontal fissures have been found in other glacial caves on Loven Glacier (Spitsbergen) (Irvine-Fynn et al., 2005) and in glacial caves on Tien-Shan (Mikhajlev, 1989). All it said that it may be not universal but a widespread situation.

The researches realized in a glacial cave at tongue of Aldegonda Glacier in 2004-2008 have shown that the subhorizontal fissure is not unique. We have found at least 3 such subparallel fissure. It means that the cave channel arose, later it was closed by plastic deformation, next arose again and was closed again. Besides it was found that initially englacial cave channel further inside cave is changed into the subglacial channel. After that it became clear that the cave channel is formed on the basis of subhorizontal fissure which passes through tops of juts on glacial bed. From this follows that cave channel case cutting depth does not usually exceed 10-15 m and in rare case reaches 30 m as it was observed in upper part of Tavle Glacier (Spitsbergen) (Mavlyudov, 2007b). But it does not give an explanation of formation of an internal drainage as a whole.

**Discussion**

To understand how all system of an internal drainage of glaciers as a whole is formed we will address at first to caves at glaciers tongues. Carrying out researches of glacial caves on Aldegonda Glacier tongue in 2003 we have found out that at movement inside glacial cave usual englacial channel (R-channel) changed into fissure oriented subhorizontally (Mavlyudov, 2005b). At the lower surface of this fissure were small canals cutting into ice which used for drainage of the largest water streams. The bottom of the fissure channel has been covered rounded and non rounded rock fragments. The width of the fissure channel reached 15 m and maximum height did not exceed 0,7 m. It was possible to see that sideward the channel gradually reduces height and turns into a layer of fragments of rocks clamped in ice.

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**Figure 1.** White strip on roof of englacial channel as trace of previous compressed channel, moulin № 1 Aldegonda Glacier, Spitsbergen.
is not purely subglacial or englacial and represents alternation of subglacial and englacial sites. Information about water movement under a glacier by such way we can find and in work (Fountain, Walder, 1998) but they assume that such channel cut from glacier surface. Researches of Stor Glacier in Sweden have led to the conclusion that its left internal drainage channel is not subglacial and passes in ice above deepening on a glacier bed (Hooke, 1988).

The further way of reasoning was next. If there is the certain fissure which passing above bed juts smooths an actual bed relief and creates some not so rough surface on which water in the glacier basis can move we can ask why actually on the same surface cannot move and a glacier? Really, the glacier can move on the basis of this smoothed surface and its movement will occur with a smaller friction than on glacier bed because in this case ice in the glacier basis should not flow round numerous obstacles. And if still to add that water can be found on this surface that will support for glacier the best sliding is becomes clear that movement on this surface will be more preferable to a glacier than along the bed (Fig. 2).

If we accept this statement it means that we will receive some consequences. First in that case ice in the glacier basis slide on crests of juts where exaration take place, contrariwise ice between juts does not move also and is quite possible to consider it as dead ice. One of proofs of possibility of such phenomenon is the finding of the remained vegetation and soil under Longyear Glacier in Spitsbergen (Humlund et al., 2005). Secondly, it is possible to explain spring glacier movement acceleration by not water inflow to glacier bed but water inflow to this sliding surface under a glacier. For example on Unteraar Glacier in the Alps surface uplifting in the spring was noticed that is the indirect certificate of water accumulation in the glacier basis (Iken et al., 1983). Thirdly, as water inflow on a sliding surface is distributed enough widely and non-we will have inefficient drainage system uniformly in this case. During ablation season when the quantity of melt water under a glacier increases water starts to form the dedicated ways of movement along sliding surface of glacier; these canals increase during time. As a result water movement on sliding surface of a glacier as film or pseudo-film begin more and more channelized. In result at the end of summer along this sliding surface will form well worked flat channels which already represent effective system of drainage. However even a short cold snap when melting on a glacier surface is ended and water ceases to arrive on sliding surface is quite enough that the channels generated earlier along it were closed by ice plastic deformation and the drainage system under a glacier became again ineffective. Such situation can proceed up to spring or up the nearest weather warming. Then all will repeat. The annual cycle of functioning of system of an internal drainage works by such way.

Fourthly, it is possible to assume that the mechanism of movement of ice and water on sliding surface is similar both for mountain glaciers and for glacial sheets. In that

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**Figure 2.** Longitudinal cross section through glacier with internal drainage system; sliding surface located at the bottom of glacier. 1 – firn, 2 – ice, 3 – dead ice, 4 – channels of internal drainage system, 5 – crevasses, 6 – moraine deposits, 7 – lakes, 8 – glacier bed.
case and drainage channels on glacial sheets adhered to these sliding surfaces. On the base of these channels possibly were formed eskers which after ice melting were projected on underlying relief. Probably for this reason some eskers are indifferent to underlying relief.

The same sliding surfaces can be used for water outbursts from glacier-dammed lakes.

If we accept the aforesaid above point of view it is necessary for us to find how the sliding surface could be generated. In present time we do not have completely satisfying explanation of this phenomenon. As the assumption it is probable to offer some possible mechanisms: 1) such mechanism probably works here: for a glacier it is more energy-favourable to not crawl through bed deepening but namely move above deepening along contact of dead ice. 2) probably it was impossible without hydrofractures (Benn et al., 2009b) which by high pressure have generated a sliding surface. 3) both offered mechanisms can work.

Now it is necessary to find as water through glacial crevasses and moulins gets to a sliding surface. There is such assumption. Water fills a glacial crevasse and begins propping of fracture At the end of crevasse as a result fractures begin to move to depth (Weertman, 1973). Having met any small transversal fissure water will be switched to this fissure because to open an existing fissure incomparably easier than to create the new one. Along this fissure water will directed aside and on the way will find the gaping crevasse which does not have exit to glacier surface and will start to fill it. If there is a lot of water and the parallel crevasse have more deep low end in comparison with first crevasse, in this case second crevasse will start to move into depth faster because bigger pressure influences on its edge than upon the edge of the first crevasse. Having met on a way the next transversal fissure, water will direct along it. So it will proceed until water will not reach a sliding surface. Probably it is slow or may be fast process. Anyway speed of hydrofracture penetration through kilometer thickness of the Greenland ice sheet by calculations is estimated in 8 m/s (Tsai, Rice, 2010). But most likely that speed strongly depends on concrete conditions.

Thus we have shown possible ways of formation of sliding surface and also possible mechanisms of penetration of water to it. As a result we have received the formation mechanism of all system of an internal drainage. And as a consequence we have received an explanation of the mechanism of spring acceleration of glaciers movement. Here it is necessary to make a reservation. Actually this mechanism does not explain acceleration of ice movement on the Greenland sheet. Otherwise we should agree that water gets to a glacier bed through a hydrofracture (Das et al., 2008). It is difficult to believe in it because such crevasses will blocked by ice if water penetrates in crevasse at ice wall temperature about -29°C. Crevasse cannot blocked by ice if crevasse from the very beginning was gaping and its width should be not less than several tens of centimeters (calculations show that at ice temperature about -8°C the width of a crevasse should be more than 10 cm) and stream velocity should be really monstrous which simply does not exist in the nature (calculations show that even at temperature -5°C that ice on a crevasse wall was in thermal balance with water, stream velocity 60 seconds after the current beginning should exceed 21 m/s) (Mavlyudov, 1998). And as it is supposed that the propping of crevasse by water should begin from zero width, water in crevasse will freeze at once, i.e. penetration of a crevasse into depth of such cold ice simply physically is impossible. From here follows the conclusion that water in this case to a bed does not move and reaches any depth from a surface on which it will transported towards the nearest crevasse zone. Probably on any depth from an ice surface there is a sliding surface and getting water on it lead to acceleration of glacier movement. However for such assumption there should be proofs which for the present are absent. It is possible to assume that if depth of moulins on this place of the Greenland sheet does not exceed 205 m it is possible to expect that somewhere on this depth exist a sliding plane.

**Conclusion**

We have considered that was known how elements of an internal drainage of glaciers are formed and have offered the new concept of formation of the basic system of glaciers drainage. According to this concept the basic drainage channels of glaciers are formed along sliding surface of glacier which represents the certain surface that smooth all roughnesses of a glacial bed and have touch with rocky juts. Water penetration on this sliding surface provides both an internal drainage of water in a glacier and the accelerated movement of a glacier in the spring. During spring time water spreads along a sliding
surface creating inefficient system of drainage. After
channels formation along this sliding surface the system
of water drainage becomes effective. This concept is
proved because the studied glacial caves were generated
on the basis of subhorizontal fissures and represent
alternation of englacial and subglacial sections.

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