ABOUT NEW TYPE OF SUBGLACIAL CHANNELS, SPITSBERGEN

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Abstract

In September 2003 in the tongue of Aldegonda Glacier, Spitsbergen, a new type of englacial channel was found. It represented a flat slot in ice of width of 10-15 m and height up to 0.5-0.6 m. The bottom of the channel was coated with rounded pebbles (alluvial deposits). Similar channels were found on other glaciers of Spitsbergen as well. It is supposed that such channels could be formed at exuberant hydrostatic pressure in a temperate glacier core which could form in ice in the beginning of ablation season because all lower peripheral part of glacier was frozen to glacier bottom and dammed water inside ice. The scheme of evolution of internal drainage system in polythermal glaciers is considered.

О новом типе внутриледных каналов, Шпицберген

В сентябре 2003 г. на языке ледника Альдегонда, архипелага Шпицберген, был найден новый тип внутриледных каналов. Он представлял собой плоскую щель в льду шириной до 10-15 м и высотой до 0,5-0,6 м. Дно канала было покрыто округлой галькой (аллювиальные отложения). Подобные каналы были найдены также на других ледниках архипелага Шпицберген. Предполагается, что такие каналы могли быть сформированы при высоком гидростатическом давлении в теплом льду ядра ледника, которое могло возникнуть во льду в начале сезона абляции из-за того, что вся нижняя периферия ледника была приморожена к основанию ледника и подпруживала воду внутри льда. Рассматривается схема развития внутренней дренажной системы в политермальных ледниках.

Introduction

On Spitsbergen archipelago polythermal and cold glaciers are distributed. The structure of an internal drainage of temperate glaciers on the whole is clear (Fountain, 1993, Fountain, Walder, 1998), at the same time features of an internal drainage of polythermal and cold glaciers remain in many respects unclear, quite often researchers give inconsistent information on this matter. The majority of researchers agree that there are many ambiguities in understanding of drainage from polythermal glaciers (Pattersson, 2004, etc). Difficulty in the explanation of an internal drainage is that tongue of polythermal glacier frozen to glacier bed and is a barrier to water movement, which can accumulate in temperate ice core of glacier. Recent data also proved that winter drainage, which, as always, was considered characteristic for polythermal glaciers, may also be typical for cold glaciers (Irvine-Fynn *at el*., 2005). Aim of the research was to find out the structure specificity of internal drainage of a polythermal glacier on the basis of using new type of glacial channels founded in 2001.

In 2001-2005 we carried out research on glaciers of Spitsbergen in frameworks of glaciological expedition of Institute of geography of the Russian Academy of Sciences. The research problem was to study hydrological structure of glaciers and its changes in conditions of climate change (Mavlyudov, 2003, 2004).

Object of researches

During the expedition glaciers in western and central parts of Island Western Spitsbergen of Spitsbergen archipelago were explored. Objects of researches were glaciers in vicinities of the Russian settlement Barentsburg (Fig. 1) and also glaciers in area of Polish scientific station Koffejra of Torun University.

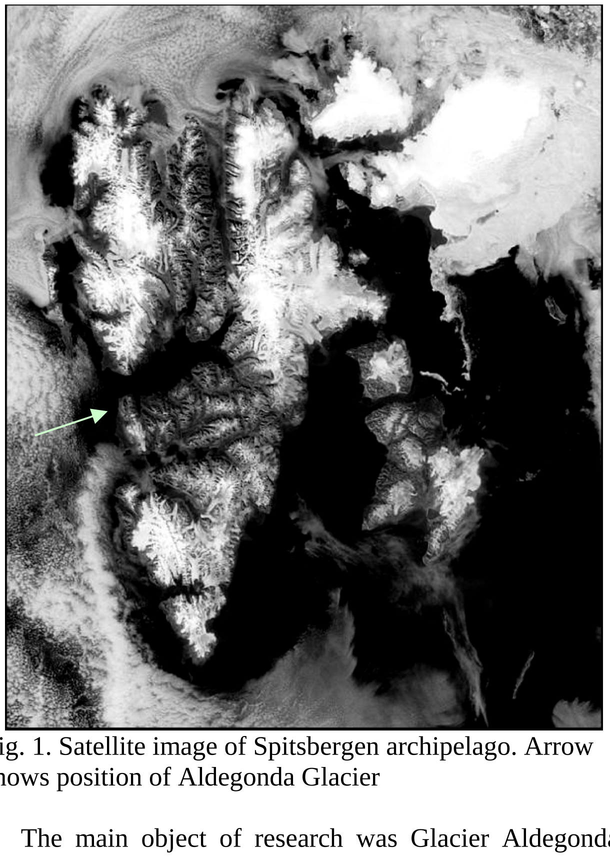

Fig. 1. Satellite image of Spitsbergen archipelago. Arrow shows position of Aldegonda Glacier

The main object of research was Glacier Aldegonda, which is located in the western part of Island Western Spitsbergen within the boundaries of Nordenskiold Earth. This small mountain-valley glacier is situated on western coast of Grønfjord, 10 km southwest from settlement Barentsburg. Now the length of the glacier is 3.5 km, width - up to 2 km, the area is about 7 km^2. Thickness of cold ice layer on glacier according to radio sounding is approximately 100 m and maximal thickness of ice is about 216 m (Vasilenko *at al.*, 2001).

In spite of the fact that the first research of caves on Aldegonda Glacier was carried out in 1980-es (Misztal, Pulina, 1983, Gokhman, 1990) general principles of glaciers internal drainage in those years were not yet developed. Geophysical research specified position of basic internal drainage along the right side of glacier (Vasilenko *et al*., 2001). Now the part of glacier runoff is absorbed by moulins at elevation about 260-280 m and approximately 4/5 of water runoff in moulins gravitates to central and left parts of glacier. All internal water appears at the edge of glacier tongue from a cave in the left side of glacier at elevation of about 130 m, what was proved as a result of dye-tracing of water flowing in moulins in the summer 2005 (Solovyanova I.Yu., 2005, pers. comm.).

Technique of research

During research the speleological method of studying of channels of an internal drainage network was used. For penetration into channels the standard climbing techniques and waterproof clothes were used. Researches of the cavities, which do not receive water inflows, were carried out during summer. Active cavities (moulins) absorbing large water streams were studied after beginning of cold (frost) whether and a cease of ice melting on glacier surface. Usually research of cavities took place during September. For making maps of cavities a standard speleological technique that allows carry out semi-topographical survey was used.

Speleological research on Aldegonda Glacier was carried out in summer 2001, in summer and in autumn 2002, in autumn 2003, in autumn 2004 and in summer 2005 (Mavlyudov, 2002, 2003, 2004, 2005).

In 2002 in cold laboratory of Institute of Low Temperatures Science of Hokkaido University in Japan together with E.V. Isenko and R. Naruse we have carried out a series of experiments with the purpose of studying conditions of origin and evolution of channels in cold glaciers (Isenko *at el*., 2003). At different external temperature in the refrigerating chamber through specially prepared block of transparent ice in the given initial channel water with slight positive temperature was flowing. In order to see changes of the channel form in ice during experiment blue dye was added to water. After each experiment a block of ice was taken from the form and by a vertical saw was sawn across the channel on segments of given length. The cross sections of the channel in each ice segment were transferred all over again onto paper, and subsequently to computer to create a volumetric model of the channel.

Internal drainage system of Aldegonda Glacier

To understand the structure of an internal drainage of Aldegonda Glacier we investigated glacial caves and moulins. It appeared that all investigated moulins had depth of 50-80 m. From bottom of pits a cascade or inclined galleries began which sometimes turned into circular phreatic channels. All investigated inactive cavities (without water feeding) were blocked by channel narrownesses, ice lump blockages, snow-ice plugs. All active glacial shafts ended by siphons on depth of 80-90 m from glacier surface.

In 2001 our attention was drawn to caves at glacier tongue. Characteristic properties of these caves were completely horizontal arches; their width quite often was about 10 m and more (Fig. 2).

Fig. 2. Flat arch of horizontal cavity at tongue of Aldegonda Glacier, 2003

The cavity was cut in porous alluvial sediments and runoff from cavity was very small (some liters per second). At that time we were surprised with a structure of these cavities but could not find any explanation to this phenomenon. Horizontal cavities at glacier tongue were visited also in 2002 and 2003. Attempts to penetrate into a cave with all outflow water from under the glacier in 2001 and 2002 were unsuccessful because after first tenth meters from entrance cave became too narrow for man to go further. In the autumn of 2003 we have successfully attempted to penetrating this cave. It was possible because glacier tongue in 2003 has strongly reduced (approximately by 70 m). Water stream flowing from the cave have changed the channel and water began to flow not on rock surface but began to cut into moraine sediments. It has allowed water to cut into these sediments closely to glacier tongue therefore water began to cut into ice and cave channel height increased and became accessible at the beginning of winter. Unfortunately in 2003 we have no time for channel studying and it was explored approximately to the length of 250 m without survey. The end of reached cave part channel represented a horizontal crevasse in ice with width up to 15 m and height about 0.5 m. The bottom of the channel was covered by a layer of rounded pebbles with thickness up to 0.1 m (alluvial sediments). Further cave inspection was stopped because of time shortage. But after this visit it became clear that we deal with completely new before unknown type of the glacier channel. Presence of such type of channels at glacier tongues can explain how water drainage from temperate zone of polythermal glaciers may occur.

In the end of August, 2004 we try to study entrance part of the same cave of glacier tongue. It appeared that in comparison to 2003 the form of cavity has strongly changed. Water stream cutting in ice has continued, therefore at entrance part the height of the channel reached 2.5 m but it gradually decreased with distance from cave entrance. Besides, approximately 50 m from entrance the channel has changed direction. If in 2003 it went to the west, in 2004 - to southwest. Thus in place of the last years channel under the arch only a layer of a pebble in ice was possible to see. The channel that last year had height of about 1 m, now was completely closed. This can testify that the assumption of an opportunity of existence of paleo channels inside glacial ice in tongues of polythermal glaciers (Irvine-Fynn *at el*., 2005) is most likely improbable. Big quantity of water in cavity has not allowed to carry out further research. However in middle of September, 2004, when the runoff from cave has completely ceased, we continued to explore it to the end.

It appeared that the cave channel was incorporated on almost horizontal crevasse in ice and had width up to 10 m at height from 0.5 up to 1.5 m. The bottom of gallery was in fully or partially covered by alluvial sediments (pebbles). In 2004 the length of the investigated cave gallery exceeded 500 m. The channel was almost rectilinearly stretched from entrance to southeast and all was supervised by one crevasse plane. Inclination of arch and a bottom of channel did not exceed 2-3°. In places where channel passed near ice surface illusive bluish light has penetrated into cavity. Approximately 350 m from cave entrance the channel has left ice and further was of subglacial nature. Channel arch still represented an ice plane; channel bottom was covered by poorly rounded rocks boulders 0.2-0.3 m in diameter. In 2 lateral tributary channels in place of englacial channel ending (further channel became subglacial) were found out some funnels covered by pebbles. Funnel diameter reached 2-3 m and had depth about 1 m. Apparently, here we found traces of upwellings. Most likely here there were water outflows from limestone, which were pumped from under the glacier. Probably water input has occurred at the upper edge of rock crossbar.

Approximately after 200 m from the cave channel began its subglacial way its height decreased to 0.2-0.3 m and it has divided into several branches. The argument of subglacial channel position was finding of limestone outcrop in one of channel walls. It appeared, that wide channels with the flat arch were met on this glacier and earlier. We have found out the description of channel with similar form and width up to 20 m in tongue of Aldegonda Glacier in 1980es (Misztal, Pulina, 1983). It means that formation of channels of such type is characteristic phenomenon for this glacier.

Other glaciers

Researches of channels on Aldegonda Glacier have forced us to reconsider the data we received on other glaciers. In 2001 in the tongue of the isolate right tributary of Åavatsmark Glacier (Fig. 3) small horizontal cavities at several levels were found. At that time we also have not given considerable value to this phenomenon. But now it is clear that in 2001 we found first evidence of horizontal crevasses existence at glacier tongues.

In 2004 we have visited Western Grønfjord Glacier several times, which is located 5 km to the south from Aldegonda Glacier. The basic outflow of water from under this glacier was carried out through upwelling in glacier tongue (Fig. 4a). Thus it was visible that water flows through subglacial channel. Alluvial sediments, which were carry out by water stream from upwelling, strongly contrasted with surrounded moraine sediments: if pebbles submitted the first, the second was covered by angular rock fragments. Research of this part of glacier has shown that at least in 2 places pebble accumulations among angular sediments were found out. There was no water outflow but all these points situated on one line with active upwelling. This line is located parallel to glacier edge.

Visiting of glacier in the beginning of September 2004 has shown that on the place of upwelling glacial cave has appeared which was located on horizontal crevasse (Fig. 4b). To visit this cave it was possible to explore this cave to the length of 20 m, further part of channel cross section was filled by flowing water.

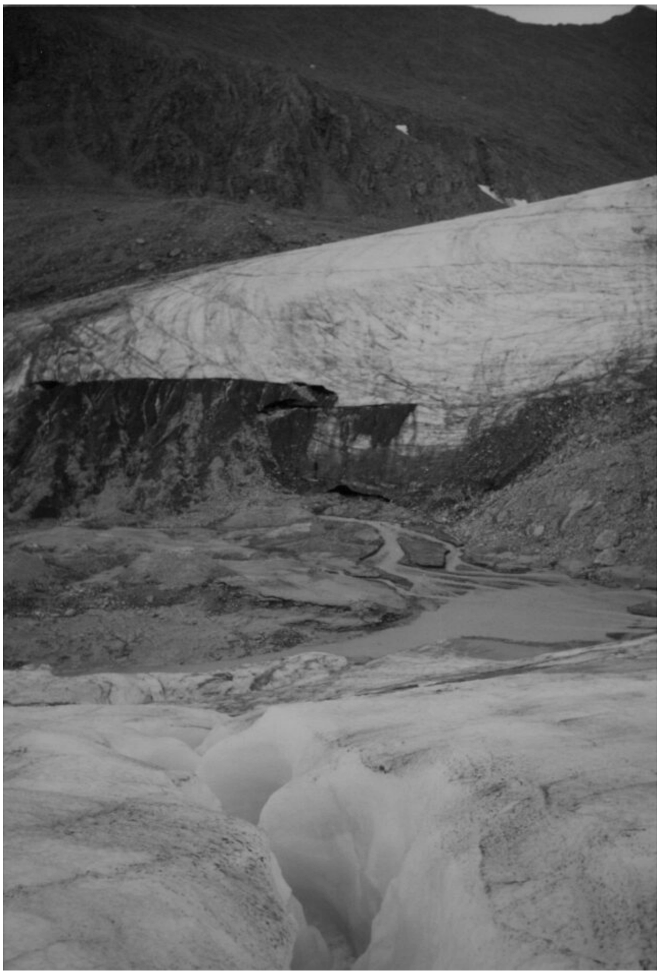

Fig. 3. Subhorizontal crevasses at the tongue of right tributary of Åavatsmark Glacier. It is possible to see alluvial sediments streams from crevasses.

The analysis of photos executed on glaciers in 2001-2005 allowed to find out traces of horizontal crevasses and in other parts of tongue of a Western Grønfjord Glacier, and also on glacier Fridtjof. These crevasses are shown as «anthills» extended along one line (Fridtjof and Aldegonda Glaciers) or as sediment-streams beginning from horizontal line on glacier surface (Åavatsmark and Grønfjord Glaciers). The trace of controlling horizontal crevasse is seen as well in a photo of upwelling on tongue of Midre Lovén Glacier in vicinity of Ny-Ålesund, Sitsbergen (photo in article of T.D.L. Irvine-Fynn *at el*., in this manuscript).

Fig. 4. Upwelling at tongue of a Western Grønfjord Glacier; a – in July 2004, b – in September 2004

Discussion

After exploration of cave in the tongue of Aldegonda Glacier, that originates from a horizontal crevasse, other caves with horizontal vaults at this glacier tongue and also findings of horizontal crevasses with channels located on them on other glaciers, it became clear that formation englacial drainage channels on the base of horizontal crevasses in tongues of polythermal glaciers may help to solve a problem of water drainage from such kind of glaciers.

How such channels in glaciers are formed is not quite clear yet. Most likely it can occurs in a following way. After beginning of spring melt water on glacier surface pours into ice thickness through moulins. Internal drainage system of many glaciers in winter is broken into a lot of completely isolated reservoirs filled by water (Mavlyudov, 2002). After filling by melting water of uppermost reservoir connected with moulin, large water pressure occurs in ice around reservoir. This water overpressure promotes formation of horizontal crevasses (it can be for example overthrust) and connection of isolated water reservoirs through these crevasses. Connection of water reservoirs occurs one by one consistently from the top downward. Eventually there is an opening of all channels of an internal drainage, and the runoff of melting water through internal drainage system renews. Thus restoration of glacier internal drainage network inhibited for winter is carried out. However most likely not only horizontal crevasses are born due to growth of water pressure in the reservoir but also crevasses of different directions. Water will flow in all of them trying to find the most simple and sometimes the shortest way. If the way from the reservoir to glacier surface through crevasse appears as the more shortest, than up to the next reservoir water will flow to glacier surface under pressure. In this case we will see fountains on glaciers surface (Gokhman, 1990). But after restoration of the channel connecting separate reservoirs fountains run low (Fig.5).

In our opinion stress in ice thickness connected with water overpressure caused in glacier internal drainage system promotes formation of horizontal channels in which the outflow of water passes which has been accumulated in temperate ice core of polythermal glacier.

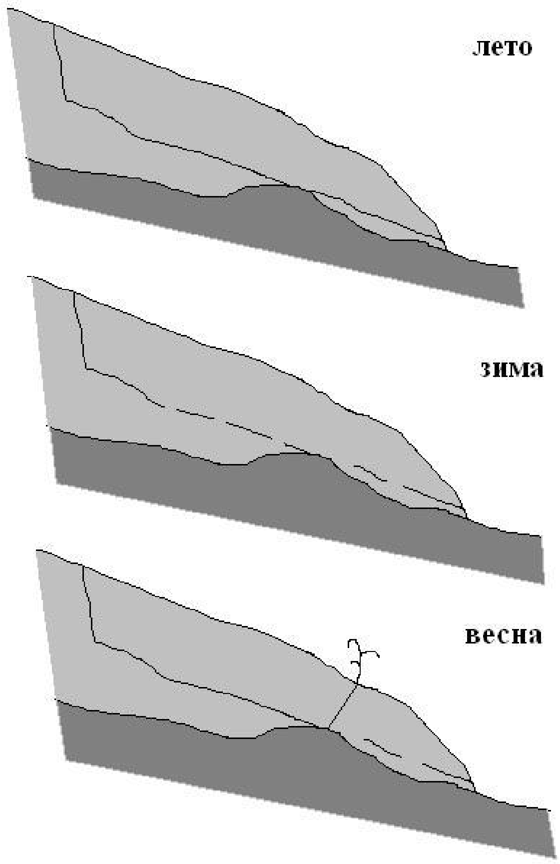

Fig. 5. Evolution of englacial channel in polythermal glacier: upper – summer, middle – winter, lower - spring; light gray – glacier, dark gray – rocks, lines – channels and water fountain

In case of impossibility of formation of a similar individual crevasse, for example when glacier base constructed by impenetrable or poorly permeable sediments, water pressure in ice thickness may grow until there will be a sharp destruction of solid mass of ice, expressing in water outbursts or fast motions of glacier (surges). Thus, probably, well-developed systems of channels of internal drainage are capable to prevent fast motions of glaciers and water outbursts promoting removal of water overpressure in ice thickness.

Once again probably it is necessary to accent attention that englacial channels are capable to occur and disappear very quickly. It shows a large variability of both separate channels and separate parts and even all system of an internal drainage, and also new arising channels apparently are remarkable means of removal of water overpressure in ice thickness.

How does such channel in ice thickness function? After the horizontal crevasse is formed, water from pours the reservoir directly into it. Findings of alluvial sediments on all width of crevasse (Fig. 6) prove that water goes in crevasse by wide front and consequently it is capable to expand and deepen the channel only insignificantly.

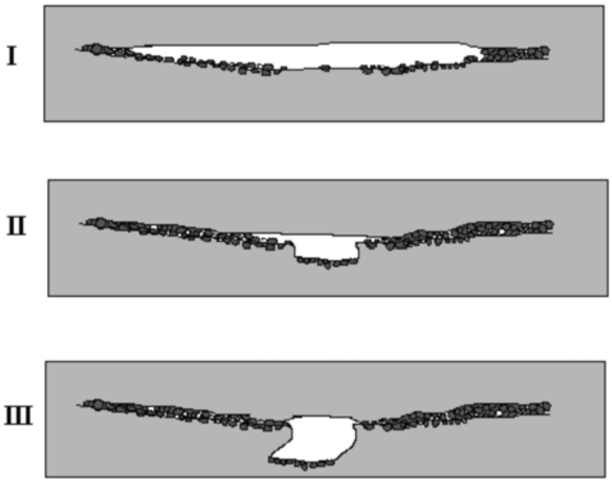

Fig. 6. Evolution of crevasse channel

Quick emission of water through crevasse right after its formations is most likely to be a single phenomenon intended to lower water pressure in ice thickness. After water pressure reduces and reduction of water stream will occur the crevasse begins to close. Thus long time current of poorly pressured water in crevasse cannot cover large area and water stream is inevitably broken into separate jets. It was shown that character of water flow does not depend on dimensions of fissures (crevasses) and type of rock in which these fissures originate (Chernyshov, 1983, Tsang, Neretnieks, 1998). Thus, there are some drainage channels cutting into ice, and the parent crevasse on each side is completely closed. Some time later one channel wins the struggle and carries out the main quantity of water. Gradual stream cutting into ice results in formation of channels of the habitual form (R-channels or H-channels) (Fig. 7).

If formation of horizontal crevasse occurs closely to glacier base or directly on contact with ice-rock or ice-moraine subglacial channel (N-channel) is formed very quickly. The form of such channel cross section will be different depending on structure of glacier base. If glacier base is constructed by easily dithering sediments the channel has form of a canyon. If glacier base is composed by hard rocks water stream begins to wander under the glacier and forms flat channel with arch being a plane of an initial crevasse.

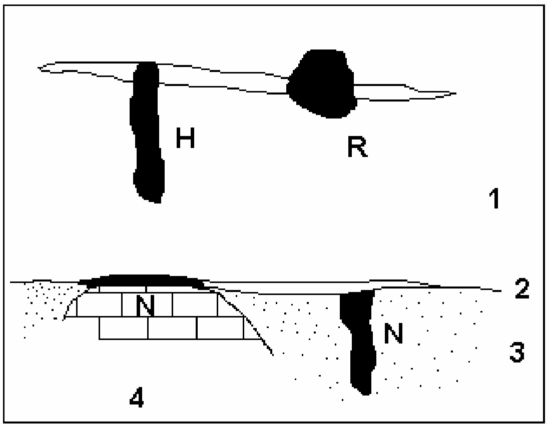

Fig. 7. Different kinds of channels that can origin from subhorizontal crevasses in ice and at contact ice-rock; R – Rothlisberger channel, H – Hooke channel, N – Nye channel, 1 – ice, 2 – contact ice-rock, 3 – moraine, 4 – rock, black – channels cross sections.

In one of our experiments (Isenko *at el.*, 2003) carried out in cold laboratory we studied evolution of englacial channels developing from horizontal fissure primarily existing in ice. In experiment fissure was modeled by channel with width about 6 sm and height about 0.3 sm. It appeared that after some time water stream began to cut into ice forming the channel.

This channel appeared similar to the channel, which formed in cold ice in tongue of polythermal glacier and has origin in subhorizontal crevasse (Fig. 8). During channel growth the traces of an initial fissure completely disappeared.

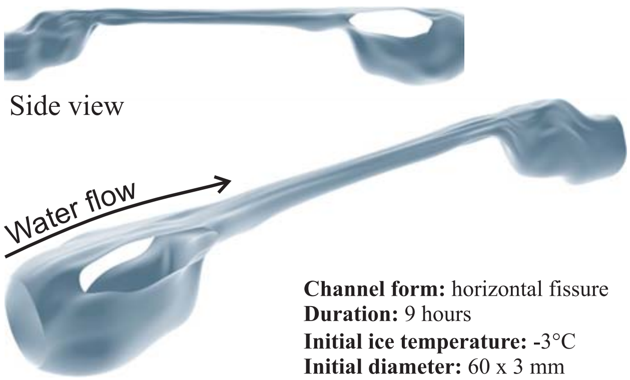

Fig. 8. View on model of channel formed during water flow through horizontal fissure (middle part of channel). It is seen that received channel similar to channels at glaciers tongues.

Basing on this we should consider the problem of formation of internal drainage systems in polythermal glaciers. It is possible to mark three basic types of internal drainage system formation for polythermal glaciers.

a) Water gets in ice thickness through crevasses and penetrates to the basis of a cold ice layer or to glacier base (Fig. 9a). We know that channels with flowing water (conduits) in cold ice with temperatures closely to zero are more stable than channels in temperate ice (Isenko, 2005). Probably primarily origin of channels of internal drainage system occurred near each side of glacier where ice thickness is approximately equal to thickness of cold ice layer. Water from glacier surface through crevasses gets directly under the glacier. Here channels can exist longer than in the central parts of glacier where it is easier to close them by ice plastic deformation. It is possible to assume that exactly marginal channels in the basis of cold ice layer are the main drains of an internal drainage and channels from other parts of glacier are their tributaries. Probably the similar picture is observed and on outlet glaciers. The less will be glacier ice thickness and the closer it will be to thickness of cold ice layer, the such idealized picture of existence of two basic drainage channels inside polythermal glaciers will be broken.

What concerns the connection of separate channels inside glacier, it will occur below a layer of cold ice. New tributary channels will be formed on vertical crevasses, which may penetrate directly through layer of cold ice. Thus connection of new channels with existing channels of internal drainage system will occur through system of crevasses by a principle of connected cavities. Water outflow from internal drainage system in polythermal glaciers can occur through marginal drainage system (outlet glaciers) or through subhorizontal crevasses. After formation such crevasses are filled by alluvial sediments that made further water outflow through them easier after crevasses close.

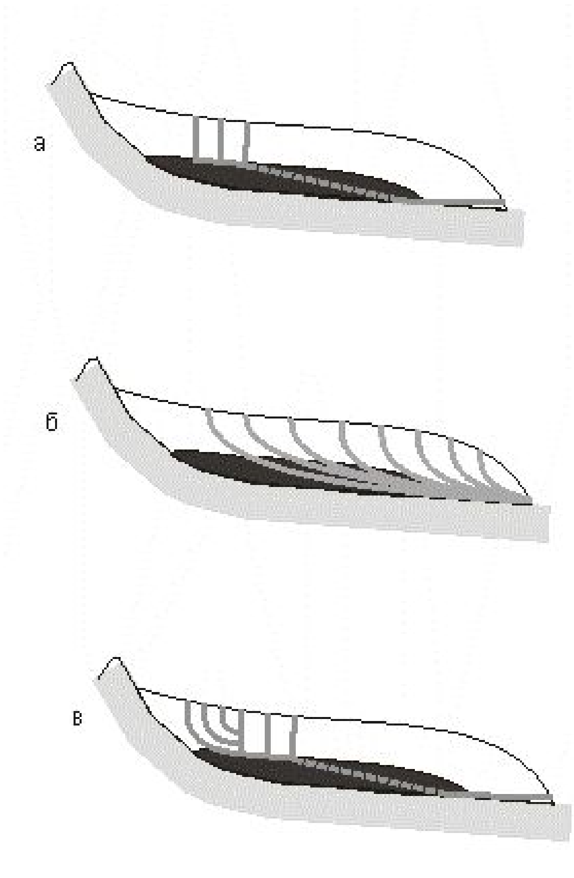

Fig. 9. Schematic image of ways of channels formation of an internal drainage in the polythermal glacier. Continuous and dashed lines are shown englacial channels; white – cold ice, black – temperate ice. Channels forming: a –on the base of crevasses, b – by streams cutting in ice, c – by both ways

b) Channels in ice thickness appeared after cutting of superficial water-streams in ice with their subsequent burial by snow and ice (Fig. 10b). Thus intensity of stream cutting into ice should exceed on size superficial ablation. This way of an internal drainage network formation in glaciers is possible only at theoretical level as at the big ice thickness above the channel it is enough one small defect in system (for example, some channel narrowing) and one cold summer (or year) for all drainage system to be corked and to die off. Therefore the formation of superficial canyons in ice is probable, which usually have depth up to 15 m, but canyons with depth up to 20 m are also quite possible. Most likely formation of channels in such way may explain the existence of under surface channels at small depth that were found out on many glaciers. Probably sometimes in such way can be developed as a rule small marginal internal drainage systems. This kind of glacier channels are more typical not for polythermal but for cold glaciers.**c**) The system of channels is formed as well as in type «a» but connection of separate new channels with already existing channels of internal drainage system occurs by a principle «b» i.e. by channel cutting from glacier surface (Fig. 10c). Most likely it is possible in some cases and only on glaciers with rather big surfaces slope (5-10° and more) as it was observed on Tavle and Longier Glaciers. In both cases channel cutting from glacier surface up to depth about 15-30 m was marked. It is possible only because intensity of channel cutting in this case essentially should exceed superficial ablation that will be coordinated to calculations (Hooke, 1984).

Conclusion

Thus, the new type of found channels is capable to explain not only the reasons of drainage through cold ice in tongues of polythermal glaciers that were frozen to glacier bases, but also can help us to develop the general conception of formation and evolution of internal drainage systems in polythermal glaciers.

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