Glacial Karst Phenomenology

Giovanni BADINO
Dip.to Fisica Generale – Università di Torino - Associazione La Venta

Abstract

Twenty years ago some caving groups around the world begun to study the karstic phenomena into the glaciers. A general view of genetic phenomenology of glacial conduits is given.

The roaring shafts (or glacial whirlpools) into which the torrents plunged attracted the attention of the first glaciologists. In 1898 Vallot explored the "*Grand Mulin*" on the *Mer de Glace* on the French side of *Mont Blanc,* descending to a depth of 60.5m.

At that time, no differentiation was made between speleology and glaciology, so those holes were considered to be caves just like the ones formed in limestone. However, as they were almost impossible to tackle using existing techniques the speleologists ended up by losing interest in this particular branch of caving.

So the white surfaces became the domain of the glaciologists unacquainted with karst phenomena. In the Twenties, was noted that on the *Lys* glacier the swallow-holes formed in the same area year after year notwithstanding the movement of the ice (MONTERIN, 1930). He concluded that they must be stable structures like a whirlpool in a river, continuously formed by new water; when the ice reaches that point it takes on the form of a cave, always more or less the same.

But by then glaciologists and karst speleologists had gone their different ways, each coining different terms for the same structures. Cavers forgot about caves in the ice, and glaciologists forgot that they operated in a karst environment (PATERSON, 1969, NYE, 1976).

And so we come to the early Eighties. By now there are techniques and men capable of undertaking the descents and, as often happens with research, when the time is ripe a problem is tackled simultaneously by different groups working independently. Polish speleologists set about the *Svalbard* on *Hansbreen,* the Swiss start on the *Gorner* glacier and in Iceland. The French have another go at the *Grand Mulin* , and the Italians attack the *Gorner* and the *Miage.*

The challenge gathers interest and starts to be tackled systematically. The *Union internationale de spéléologie* sets up a committee and organises periodic meetings on the subject.

The Italian group have the most systematic experience of speleological expeditions and wide-ranging research, with operations in the Alps, Karakorum, Tien Shan, Svalbard and in Patagonia (BADINO, 1995). They soon realise that crevasses and caves have to be considered separately because, if a glacier has a large number of crevasses, the water is absorbed uniformly without the concentration of energy that allows the water to hollow out caves. With the aim of guiding the research in the right direction, we have tried to bridge the gap between glaciologists and karst speleologists going back to the beginning of the century, and linked to the insurmountable technical difficulties posed by the glacier caves.

At the beginning of the Seventies two glaciologists (ROTHLISBERGER, 1972, SHREVE, 1972) tried to build models of what can happen under glaciers: critical areas, conditions for existence, plasticity, etc: However, their research referred to the formation conditions of channels on the rocky bed, a type of water flow of little interest except for the last few tens of metres before the water comes out into the daylight, where the glacier becomes thin. In practice, the ice was not considered capable of supporting karst phenomena in itself, but only as an interface with the rocky base.

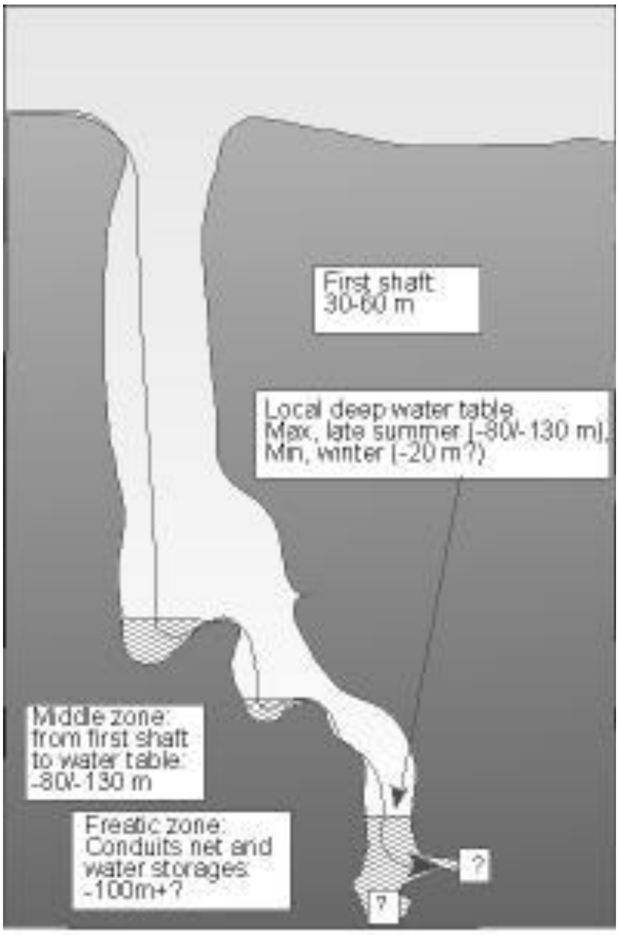
The explanation of this limitation is simple: at that time it was impossible to carry out an experiment in the field, and the structures which could be observed at the mouth of "mountain" glaciers are always situated precisely at the ice-rock interface. Another difficulty encountered in building models was that the calculation of formation conditions of the drainage network, highly cyclical due to the seasons, necessitated the use of digital computers which were rather inaccessible at that time.

Exploratory campaigns and the development of a simulation programme have enabled us to outline the general characteristics of water flow inside the glacial mass.

The incompatibility between the presence of crevasses and the formation of karst phenomena has limited the speleologists' interest to vast, level glaciers. As there also has to be water in the liquid state, the temperature should be around 0°C. In short, it should be a "temperate" glacier.

With regard to the overall structure of cavities, in general they open with a shaft about 40-60m. deep, created by the falling water, but the torrent often disappears into inaccessible cracks at the shaft bottom. Sometimes, however, the first waterfall gives access to an impressive environment where the torrent rushes along a sort of sub-glacial canyon, with shallow waterfalls and brief horizontal stretches, finally to disappear into a pool and drain away (Fig. 1). In general the canyon becomes smaller and smaller and the terminal pool of water is situated about 100 m. under the surface (BADINO&PICCINI, 1995).

The insertion of the mechanical characteristics of the ice of these "karstic" glaciers into a series of mathematical models developed by the *Dipartimento di fisica generale dell'Università di Torino* has enabled us to clarify the overall phenomen of intra-glacial water flow (BADINO, 1990, 1992, 1994) .



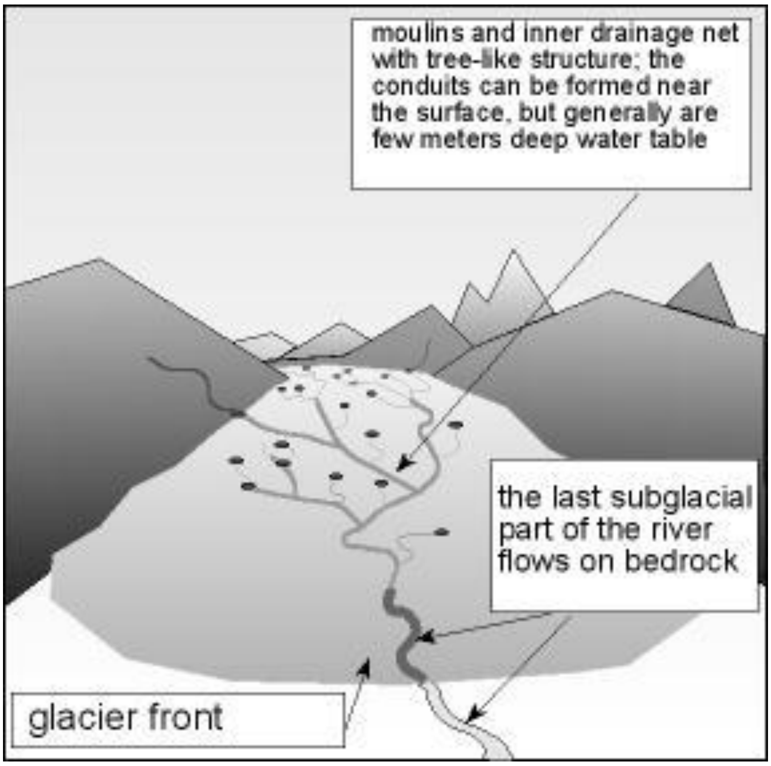
The first essential characteristic regards the plastic behaviour of the ice, which at low pressure is similar to rock, whereas at high pressure it behaves almost like a liquid. More precisely, the deformation it undergoes is proportional to the cubic root of the strain to which it is subjected, and this enables us to calculate an "average" life span (collapse time scale) for every cavity that forms in the glacial mass, on the basis of the pressure to which it is subjected, i.e. its depth below the surface (HOOKE, 1984).

A cavity (cave or crevasse) at a depth of a few metres has a much longer duration than the local evolution time of the ice (being dragged downhill, seasons) and therefore its plasticity has little importance in its development; it is as if it were carved out of rock. A cavity at a depth of 70-80 metres has an average life span of approximately one season; so that is the maximum depth at which structures linked to seasonal cycles can survive. Below that depth, collapse times are shorter; structures last as long as the agents that form them remain in activity, after which they collapse and disappear inside the mass of fluid ice.

The drainage structures nearer to the surface, where the plasticity is negligible, are therefore rather simple; the streams form and swell in depressions in the glacier, often in areas where glacier tongues converge, moving at different speeds. The internal friction causes melting and consequently the formation of depressions. The torrent rushes there and finds its way underground where the concentrated flow of energy is more than the minimum required to perforate the surface at that point, and so a "glacial whirlpool" forms. (Fig. 2)

Inside the whirlpool the potential energy of the falling water is released into the air at the point where the water strikes. As it is an air pressure system in isothermal conditions (any increase of water enthalpy is utilised in the melting), the system develops proportionally to the energy released by the waterfall. For the first fifty metres the falling water meets no resistance from plastic collapse so the cavity becomes larger and larger throughout the season.

But as the waterfall deepens, the ice walls tend to collapse into the cavity which narrows into the characteristic canyon form. The widest points are those where energy is released, that is the pool of water at the base of the shaft and, in general, where the torrent flows, which doesn't facilitate the work of the researcher …



This simple model seems to explain most of the internal forms of glacial whirlpools, with some notable exceptions, which we shall discuss. Since the first expeditions, it has been clear that the structures through which we advanced with great difficulty must only be a small part of the internal structures of the glacier. The caves tended to be vertical, so they had to be tributaries of the main drainage system which was presumably located beneath the small pools of water where the torrents disappeared at the end of the caves.

On the basis of our observations it seemed that, contrary to what had previously been believed, the torrents did not get as far as the rocky bed, but went to fill one or more of the phreatic strata at the "plastic behaviour" limit of the ice. Our hypothesis was also supported by other clues; some explorers had taken us into tunnels with a roundish section, similar to those which form underwater, by means of resurgence, in calcareous karst phenomena. It was therefore reasonable to try to construct melt-water flow models within the aquifers.

The physical process is slightly more complicated. The collapse times of the cavities within the aquifers is reduced, as what counts is the difference between the pressure of the ice and the pressure in the cavity. If the latter is full of water, the collapse is delayed. As you go deeper, the water pressure rises more quickly than the pressure of the ice because of the increased density (100kg/cub.m. compared with 917); resulting in the formation of deep water deposits, then *jokulhlaup*, and instability, which, in certain conditions, might possibly trigger off a surge of the glacier.

Karstic excavation is also the result of the release of potential energy in the fall between the points upstream and downstream of the melt-water flow network. In this case, however the definition of the model is extremely delicate, because of the key role played by the loss of charge along the channels, a parameter which depends critically on their form, and on water flow conditions, etc.

The main novelty in the phenomenon of intra-glacial melt-water flow, however, regards the overall structure of the network of drainage channels. In fact, the process is no longer isobaric or isothermal as the temperature in equilibrium between water and ice depends on the pressure. From 0°C at atmospheric pressure it decreases by 7.5 millikelvins for every increase of one atmosphere.

In a hypothetical U-shaped sub-glacial channel - a common form in calcareous aquifers (*valchiusane* sources*)* - at the highest point upstream the temperature is about 0°C, but as the water flows down, its pressure increases and, when it becomes "too warm" with respect to the surrounding ice, it uses up excess internal energy to melt the ice on the walls. Therefore the descending stretch of the U-shape becomes wider.

On the contrary, in the ascending stretch, the water which moves towards lower pressures, resulting colder than the ice, solidifies on the walls.

So the process evolves whereby the descending parts widen and the ascending parts become narrower, rendering the passage of the water more difficult. In such a structure, the level of the pool upstream rises to compensate for the increasing impedance in the ascending parts but cannot exceed the level of the outside surface without overflowing. At that point, the glacial whirlpool outside fills with water and forms a lake, but the internal flow stops and the drainage continues elsewhere. So, inside the ice either the U-shaped structure doesn't succeed in forming, or it tends to close up.

It's worth noting that the descending part can continue to exist even in the absence of drainage and, dragged downhill by the movement of the glacier, can become a potentially menacing reservoir.

The interdependence between pressure and temperature in equilibrium of water and ice also has a considerable effect on the single channels. In most case, intra-glacial water flow takes place in turbulent conditions, with a complete stirring up of the fluid as it rushes along the channel, whose ceiling is warmer than its floor by almost on thousandth of a degree for each metre of diameter. When the water strikes the floor, it excavates; when it touches the ceiling, it deposits.

The result is that the tunnel moves gradually downwards. The movement is very slow, but it gains speed with the increasing diameter of the tunnel and the speed of the water. In typical intra-glacial water flow conditions, as described in the calculations, tunnels move down one metre per week, which means that the entire network of channels tends to "settle" as low as possible.

Another physical effect which helps to define the structure of the sub-glacial drainage network is the tendency to eliminate possible by-passes. Suppose we have two tunnels that connect two points of the glacier in parallel. The difference in pressure at the tunnel ends will obviously be the same; so if one has a lesser impedance than the other (because it is wider, or shorter) the flow has a strong tendency to favour it, and to concentrate the excavation in that tunnel. The second branch, gradually abandoned, collapses progressively and finally disappears.

As we are dealing with rapid processes, we cannot expect the drainage network to be very complex; it will tend to take the form of a tree which connects the various shafts and then flows into a single catchment channel. This flows under the ice for about 100 metres until, in the vicinity of the end of the glacier tongue, the thinning of the ice above it makes the river spread out over the glacier bed in search of an outlet. From there, by means of one torrent (and a large channel, as in the *Batura* and *Enilchek* glaciers) or numerous torrents, the water emerges into the daylight.

When the sub-glacial channels are full, they behave like structures in equilibrium between excavation caused by loss of charge of the water during transit and filling due to the caving in of the channels. When the flow stops, for instance during the cold nights, the tunnel gradually becomes narrower and impedance increases. Therefore, when the flow resumes, the release of energy will be greater and the excavation will be faster until the previously existing conditions are re-established. In the same way, a temporary increase of the flow enlarges the channel in excess of the section of equilibrium, to which it will return as soon as the flow decreases.

The diameter of these tunnels remains reasonably uniform; any narrowing of the passage, due to collapse, creates an increase of impedance and a concentration of local energy release until uniformity is reinstated.

So, the dimensions depend on the pressure of the ice on the walls, as well as the gradient, shape and depth of the tunnel. Obviously, local tension of the ice, the inclination of the glacier surface and bed, and the depth of the aquifer will all affect the dimensions.

To give a general idea: a tunnel with a flow of 1000kg. of water per second, at a depth of 100m. will have a stable diameter of approx. 0.9 metres and the water will have a speed of almost 1.5 metres per second. If the flow is reduced to 100kg. per second, the diameter of equilibrium becomes 35 centimetres and the water will flow at 1 metre per second.

These figures given by the model are consistent with the few fragmentary sections we have been able to observe.

We have seen how rapid variations in the flow result in slight fluctuations around the structure of equilibrium, in fact calculations and direct observation both show that daily cycles do not cause significant variations.

The situation changes considerably when the variations take place over a longer time span than that of the collapse of a tunnel, for instance with the onslaught of the cold season. The deep flows stop and the channels gradually begin to cave in, in a process contrasted only by the hydrostatic pressure of the aquifers pushing upwards. In the *Gorner* glacier the speed of this rise was approx. two metres per week, rather slow but sufficient to fill the cavity almost up to the surface.

This rising process is rather complex, and a detailed study could provide information on the deep structure of aquifers and on the risk of catastrophic phenomena; for example, the presence of basins included at the end of the network considerably accelerates the rising speed.

In Spring the network still exists, but a bit further downstream and under more pressure than a few months earlier. The external flow of water starts up again in the same way as the previous year, perforating the ice in more or less the same places, as these are linked to the tensive structure of the glacier, which in turn is determined by the binding conditions of the rock. The downstream parts of the network are dragged towards the glacier front and crushed, while upstream, deep within the "new" glacial whirlpools, others are formed.

Therefore, the deep network also proves to be a structure that fluctuates around a pattern of equilibrium according to the seasons, and virtually moves upstream at the same speed as the glacier moves downhill.

The freatic tunnels inside the glaciers are extremely unstable; once abandoned by the water they cave in, and the deeper they are, the more quickly they collapse. So, a consistent network of fossil tunnels like those that can be found in calcareous mountains, probably doesn't exist in glaciers.

Direct observation of these water flow networks is therefore extremely difficult. In practice it is only possible to visit the superficial part where collapse times are much longer, but often these channels are fragmented by the forward movement of the glacier, and above all by ablation. The "stable" submerged part with an active flow of water, is almost inaccessible.

However we are perfecting techniques to explore it in late autumn, when the water has finally stopped but the overall rise of the aquifer is still slight.

We have already delineated "normal" intra-glacial water flow conditions. The exposed parts of the network which can be directly explored are rather few, whereas the submerged parts require an enormous technical effort. It is a fact, however, that structural variations in sub-glacial caves are manifold, and above all are linked to meteorological conditions in the area, and the local situation of the ice.

Most of our efforts are therefore concentrated in search of particular conditions which would enable us to explore more thoroughly. We found the most favourable conditions in the glaciers supplied by *lo Hielo Continental Sur* in Patagonia, some 22,000 square kilometres of ice. The glacier tongues that drain it can descend as low as 300 - 400 m. above sea level, where ablation is very intense. In addition the orography permits the formation of very wide glacier tongues with a regular gradient. The glacier nuclei are practically impenetrable to water, and extremely transparent.

In these conditions, on the one hand, fantastic environments are created by the light which acts as a "wave guide". In fact, high frequency light is propagated more easily, with the result that every crack seems to emit blue light and the cave walls appear luminescent to a depth of 80-90 m. below the surface.

The other, and structurally more important, effect is that the flow of energy necessary to perforate the deeper parts is much greater than normal.

Rivers that flow under the glacier surface do so superficially, overcoming the first "permeable" stratum of ice to a depth which can vary from a few decimetres to about twenty metres. Then, when they come up against the glacier's "impermeable" nucleus, they flow over it.

So, just below the surface, and parallel to it, drainage networks form which can be explored when the flow is reduced. One of these, situated in a minor glacier and only partially explored, extends 1200 m. and is the longest endo-glacial cavern known to date.

Glacio-speleology was born very recently as a branch of amateur speleology, but it is already succeeding in clarifying many of the processes that occur in glaciers, and in delineating the world contained inside them. In the short term this will improve accuracy in evaluating the "mass balance" of vast, temperate glaciers, precisely those which are used to estimate global climate changes.

In the longer term it will lead to a better understanding of transitory and catastrophic phenomena, characteristic of just those glaciers where karst phenomena are present.

Bibliography

Badino, "Fisica dei buchi nell'acqua", Proc. of 1st Int. Symposium of Glacier Caves and Karst in Polar Regions, Madrid, 1990, 119-133

Badino, “Ice Shaft Genesis: a Simple Numerical Approach”, Proc. of 2nd Int. Symposium of Glacier Caves and Karst in Polar Regions, Miedzygorze, 1992, 21-27

Badino, “Estrema Thule...”, Speleologia, 32, 1995, 27-38

Badino, “Phenomenology and First Numerical Simulations of the Freatic Drainage Network Inside Glaciers”, Proc. of 3th Int. Symposium of Glacier Caves and Karst in Polar Regions, Chamonix, 1994,47-54

Badino, Piccini, Aspetti Morfologici ed Evolutivi delle Cavità Endoglaciali di Origine Criocarsica, Geogr. Fis. Din. Quat.,18 (1995), 225-228

Hooke, "On the role of mechanical energy in maintening subglacial water conduits at atmospheric pressure", Journal of Glaciology, 30, 105, 1984,180-187

Monterin, "Sulla costanza di posizione dei pozzi glaciali", Boll. Com. Glac. It., 10, 211, 1930, 211-227

Nye, "Water Flow in Glaciers...", Journal of Glaciology, 17,76,181, 1976 181-207

Paterson, "The physics of glaciers", Pergamon Press, 1969

Rothlisberger (1972), "Water Pressure in Intra and Subglacial Channels", Journal of Glaciology, 11, 62, 177, 1972,177-203

Shreve (1972), "Movement of water in glacier", Journal of Glaciology, 11, 62, 1972, 205-214.