



# Caves of Sky

A journey in the heart of glaciers

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**NAPAPIJRI**  
g e o g r a p h i c







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*Edited by:*  
*G. Badino, A. De Vivo, L. Piccini*

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A journey in the heart of glaciers





*With this marvellously illustrated work, the La Venta exploration team is not only sharing with us the precious memory of more than 20 years of impassioned exploration of “caves of sky” all around the world, but also reminding us all about the fundamental role ice caps and glaciers are playing in the hydrological cycle, while the international community is preparing itself to celebrate 2007-2009 as the International Polar Year. Polar regions and glaciers encapsulate more than seventy percent of the freshwater reserves of the world, and represent also the most sensitive systems to climate change; it is a matter of fact that there could not be any serious scientific investigation of such phenomenon without an acute observation of changes affecting glacial systems.*

*Polar history is made up of spectacular and well popularized expeditions which started during the second half of the nineteenth century; glaciology grew up constantly during the same period, while glacial speleology (or glaciospeleology), considered for too long no more than an extreme sport practice, was recognized as a scientific discipline only during the last decades of the twentieth century. Its development during the last 25 years was considerable, in Europe and Iceland first, then in the rest of the world.*

*Using the extraordinary evocative strength of black and white illustrations, the book “Caves of sky” is also a testimony of the part the La Venta team took in such a development.*

*By sharing this book with them, it is our firm intention to encourage all UNESCO IHP partners to give new impetus to monitoring, research and dissemination efforts in the field of glacial hydrology and the assessment of climate change on the hydrological cycle, hoping that they could be “contaminated” by such a mix of spirit of adventure, openness to discovery, innovation and scientific rigor.*

**Philippe Pypaert**

*Regional Hydrologist*

*UNESCO Regional Bureau for Science and Culture in Europe*



## Nothing but a breath of wind will decide which ocean you will cross

*Many scientific meetings take place in September. Some of them concern glaciology, but I never manage to take part in them because, since twenty years, on the same days I have an irremissible appointment: one with a dozen small glaciers in the western Alps. Only in that month they show off their beauty to who longs to understand them and to enjoy their sight.*

*It is a year long wait. After the winter months, under an icy, dark sky studded with stars, the glacier is the kingdom of anti-cyclonic silence or a white living hell of howling snowstorms. Up there, at three thousand metres, spring appears, by early June. At this time we check the quantity of the snow, sometimes three, sometimes six metres: we dig and weigh it. It is the nourishment of the glacier. But, you don't realize that you're on a sweep of ice, everything is white: rocks, the stony ground, canyons, ledges, avalanches. It is all the same. Yes, in spring it is too early to exchange greetings. We must wait a bit more.*

*In the meantime, on the plain, the temperature begins to warm up. There are some gentle evenings, when it is pleasant to sit under the kiwi pergola with the smell of roasted peppers mingling with the conversations of dear friends, while looking through the leaves at the faraway twinkling stars. And, at the same time, your thoughts are up there, at 3000 metres above sea level, where it doesn't freeze anymore but clear drops of water and streamlets bubble all the night long. Tomorrow, the July sun will make them larger and the snow will diminish, more and more. Yet, it is not the moment to meet each other.*

*Beginning of September, it is time. Just a few profitable days to climb up there, far enough from summer in order for the fierce heat of solstice to have given up its rage over the glacier, but dangerously close to winter, which in a moment can lay a new mantle of snow hiding every trail, burying the signals, preparing traps. Hidden holes. Of course, in a glacier there are crevasses, but usually you know where they are concealed. On the contrary, every now and then a winding streamlet disappears into a sinkhole, into a deep shaft which rumbles and blows its cold breath. It's fascinating: Goodness knows what there is down there! But how to get down? And, after all, it's a bit frightening. Up here it's light, sunny, and warm. Down there it is so dark and so cold. I don't know anything about it, I haven't the equipment, I haven't the courage. At the best I throw down a stone and listen to its thump which says: "Stay away from me". Well, let's go then. Daylight hours pass quickly and there is a lot of work to do: measuring the level rods, updating the maps. One more year is gone and you haven't looked into the shaft.*

*Hot summers are becoming hotter and the water on top of the glaciers runs abundantly into rushing streams, deep like canyons, winding like dragons. The holes increase in number, now there are dozens. They rumble like a storm. It seems impossible that the silence of the glacier may be broken so suddenly, just a few steps beyond the plateau, so quiet shortly before, at the very beginning of such a harmless slope. It makes you feel uneasy, every step is a glance at this roaring mouth. The crevasse is silent, the shaft threatens you with its roars and icy blasts. Hidden falls, empty glacial cylinders which call you inside their chilly bowels which you would like to know better, but you continue to observe only from the outside, skimming over its skin.*

*But, human beings are like those rivulets. Originated from different and distant snowflakes, they meet by chance driven by a rush of wind on top of a mountain ridge. Only a light touch of air will decide which ocean they will cross and a little clear pebble, laying in a certain place, will fix their path: whether they will run side by side or if they will join at a confluence. So, it happened that Giovanni and I, one autumn morning, in freezing air and a clear sky, met inside a shaft of ice. Written in the following pages you will find out what happened, not only inside that glacial pit but even under that gentle pergola, combining together our knowledge, enthusiasm, curiosity, dreams and questions. This experience is helping all of us, eso and endo glaciologists, to understand a fragment, a changeable ephemeral bit of the universe.*

**Luca Mercalli**

Società Meteorologica Italiana  
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# The nature of glaciers

*Les glaces se seront donc augmentées, non tout-à-coup, mais insensiblement; des sommités elles seront descendues dans la vallée, se pressant les unes les autres, se précipitant et s'accumulant dans les gorges où étoient les anciens passages, et ces gorges comblées par le temps, se seront élevées et auront présenté un rampart de glace à ceux qui voulaient tenter les franchir. Telles sont les causes qui auront changé la face de cette vallée, et fermé pour toujours le chemins qui conduiseront à la Val d'Aoste.*

Glaciers would have then increased in size, not suddenly, but imperceptibly; from the mountain tops they would have come down to the valley, crushing against each other, falling and piling up in the ancient canyons; and these canyons, filled up with the passing of time, would have risen up and shown an ice slope to those willing to climb up them. This is the cause that changed the aspect of this valley, and closed forever the routes that lead to Val d'Aosta.

MARC THEODORE BOURRIT, 1785

## Introduction

Glaciers are the part of mountain landscape that has a relatively short time span, which can be compared to the time scale of humankind: they change in centuries, rather than in millions of years. Chronicles and photographs pass down tremendous variations, which deeply altered the landscapes. The experience we get from Alpine valleys is one of endless rivers of ice, spread to fill entire valleys in their apparent

motionlessness. Their surface is a tangle of unsteady boulders, pointy icicles, stagnant water, snow patches, rare water streams and bottomless fissures. At times it becomes impassable, while somewhere else is flat and enticing. The structure of the ice is quite variable, transparent patches through which one can glance at the darkness of glacial depths are flanked by white areas that, upon close observation, appear to be caused by the presence of myriads of tiny air bubbles. It is a world filled with noises; frequent creaks are sometimes replaced by all kinds of snaps, howling, hisses and booms, especially inside the caves. And then there is the screaming of the waters, the blowing of the wind and the faint rustle of water streams that eventually end up in roaring wells.

The initial task facing the naturalists who began to study them, two centuries ago, was to demonstrate that they actually moved; something that at the time was much more difficult to do than we would think nowadays. They eventually got it by patiently repeating difficult summer expeditions, along hunting trails, with no rest posts, measuring the position of the boulders on the surface and of the awe-inspiring glacial wells. We now smile at those quite unreliable landmarks that generally re-form upstream, i.e., move up as the ice slides down. This does not happen all the time though, and through their observations they determined that the glaciers were actual rivers that viscously flowed towards the valleys.

After establishing that, and realising that their size could vary, it was easy to draw what now appears to be an obvious

*Preceding page: Tyndall glacier, Chile. A deep bédrière carves the compact mass of the glacier.*

*Hielo Continental Sur, Patagonia. The steeples of Cerro Torre and Fitz Roy, encircled by small glaciers, stand out against the firm field of Viedma glacier.*

conclusion: many of the inexplicable morphologies found in the mountain ranges and in the Poles were caused by ancient, huge glaciers that are now lost in the undifferentiated sea. It was a real conquest for Intellect; finally, from the landscape one could glimpse at the remnants of ancient climates.

But what are glaciers, anyway?

### **The glaciers**

Glaciers are masses of natural ice that form in those areas where the annual average temperature of the air is close to or below 0 °C, and where the entire stratum of the snow accumulated during one year exceeds that which melts during the summer. Practically, they are rivers of water flowing to the sea, running through such a cold habitat that, year by year, they are permanently frozen.

Water is a bizarre element and many of its physical properties are still inexplicable. Even in ice, its most common solid state, it shows peculiar characteristics: it is less dense than its liquid state, it has an enormous thermal capacity, and is strongly anisotropic. What concerns us here, however, is that its mechanical behaviour is also strange, “non-linear”. To simplify this point, we can say that it behaves like a rock under low pressure (up to a few atmospheres) but then, as the pressure rises, it tends to acquire the characteristics of a viscous liquid (but a particular viscosity, defined with the term “non-Newtonian”). Another important property is its yield strength. In other words, which load we can hang by a hypothetical “rope” made of ice: it is about 2 MPa for ice at 0 °C. For example, considering a rope with a section of one square centimetre we could hang a mass of about 2 kilograms. In other words, we could not make an ice column with a section of one square metre much taller than 20 metres: above this measure it would collapse on itself, its own weight would crush the ice at the base, making it slide away. It is an important fact that we shall refer back to. This





*In the lower zones of the glacial tongues (ablation zones) we proceed on bare ice, among rare crevasses that often form real labyrinths.*



means that the inner parts of the vast masses of ice that we can observe across the Alps are deformed as they slide towards the valleys. Only their surface appears to be motionless and unaltered.

According to glaciologists, the presence of a downhill flowing movement is a decisive factor to distinguish the real glaciers from minor accumulations of ice and snow, more or less persistent and virtually stationary, which are usually called glacio-snowfields.

### **Birth of a glacier**

It is winter: the air comes from distant seas where it was saturated with water in vapour state; perhaps it carries along large clouds. The wind has blown it for hundreds or thousands of kilometres, but all along its journey the air remained stable, at a steady temperature. But, now, perhaps night has fallen. Maybe the wind blew it until it found cold lands, as are those at high latitudes or at the centre of continents. Or maybe it runs into a front of cold air. Maybe the wind has blown it against some mountains and it has to rise in order to pass over them, but in doing so it cools down.

What happens then is that as its temperature falls, the humidity over-saturates, the water in gaseous state is too much and it begins to condense. But, if the temperature is negative, the liquid phase cannot exist either and the gas directly crystallizes into ice (sublimation).

The process begins by forming tiny hexagons, invisible to the naked eye: microscopic crystals with six vertexes and six sides. The vertices are protruding further out compared to the sides and therefore encounter a more external layer of the air, which is just a bit more humid than that encountered laterally. Then, the next depositions take place on the vertices, forming a series of outward ramifications. At this point, the invisible hexagon has originated a dendritic snow crystal, extremely complex, frail and now visible to the naked eye. A crystal that, interlocked with many others, forms a snowflake





*Patagonian glaciers are subject to severe melting. A tangle of lakes, streams and a sort of "bog" of water and ice often cover the surface.*



*Opposite: Upsala glacier. The striking tongue of the Upsala glacier spreads for over 50 kilometres southwards from the southern head of Viedma glacier, down to lake Argentino. In the background, on the right, the imposing mass of Fitz Roy. Since twenty years the glacier has suffered a heavy regression and this has caused the destruction of its drainage network.*

*Bottom. The incredible final tongue of Viedma glacier, spread over a thirty kilometres area, from nunatak Viedma (a rocky island in the middle of the glacier) down to Viedma lake. It is a glacier of an extraordinary interest for the study of karstic phenomena but its access is quite difficult.*







*The mass of Matterhorn is the background for the glacio-speleological research on Gorner glacier. From this point of view, the most interesting among the alpine glaciers.*

that falls lightly in the air. It falls on the ground and it piles up on top of the others. The mantle is soft, the density is extremely low: a new, powdery snow consisting mainly of air entrapped among the crystal branches. Then the mantle's weight compresses the underlying strata and squashes the crystals one on top of the other. Time goes by; days, months. The tips of the branches release aqueous vapour that re-solidifies, in close proximity, in increasingly bigger crystals. The snow is getting more and more compact, the crystals join together, perhaps some water may appear. A denser snow has formed, which in the Alps is called "spring snow".

Even more slowly, it degenerates into a sort of compact ice slush, whose crystals become more and more connected. In one or two years, the "firn" is born, dense and with a granular consistency. From there to the compact ice there is just a short step. The growing pressure of the new layers of snow is enough to force out more air, while that which remains still inside is concentrated in small bubbles, dispersed into a thick mass. This is how, in a few years (the actual time depends on local conditions) the old snowfall has turned into firm ice, with entrapped bubbles of air.

If the ice layer is thin and the ground is not-so steep, then nothing happens but to increase the thickness. However, when the ice thickness reaches dozens of metres it starts to glide under its own weight, sliding downhill leaving a new space on the top of the mountain for the next snowfall.

Little by little a river of ice slides from the basin where the snow accumulates and flows downhill, where it is exposed to the heat of the sun and to the wind.

Its ends are consumed by the outside heat, but before it melts away, it travels a long way, ploughing the landscape and carrying along all the debris fallen from the surrounding slopes.

### **Glacial landscapes**

When talking about glaciers, first of all we must take into consideration a clear distinction between temperate glaciers





*Opposite: the ablation zones of the glaciers are worlds billowing with torrents, shafts and lakes.*

*On Upsala glacier the way is often blocked crosswise by crevasses that have destroyed any surface water circulation.*

*Until the end of the eighties, a wide lake formed in the central part of Gorner glacier; today it has almost completely disappeared.*









*Batura glacier, Karakorum. One of the most interesting in Asia, from a speleological point of view, even if the large detrital cover makes the exploration of the shafts particularly dangerous. The white line on the hydrographic left represents a surface torrent (bédière) that has removed the cover. The wave-shaped structure ("kinematic waves") can clearly be seen. Such waves form due to variations of the feeding conditions of the glacier. They spread downstream much swifter than the ice.*

and cold (or polar) glaciers. In the former, the ice temperature is close to 0 °C, while the latter are well below this threshold and therefore there is no running water.

In temperate glaciers, water lives together with ice in an unstable thermal equilibrium. It flows over, inside and under the surface, and, morphological conditions permitting, it digs gorges, potholes, pits and contact galleries, running as far as the front of the glacier, where it spurts in a turbulent torrent.

All glaciers present two distinct zones: the head, where the snow accumulates, modifies its state and begins to slide (accumulation zone) and the front, at the end of the tongue where the ice turns into water (ablation zone).

Consequently, the accumulation zones are nival environments, because the ice is covered by the snow that is under transformation. If we were to dig a hole, we could find the recent strata of the current-year snowfall (usually a few metres), followed by progressively more compact and granular layers of stratified snow from previous years. Then, without interruption, we would be digging into compact ice.

The ablation zone is quite different: it is situated at a lower altitude, where it snows less and the snow only lasts for a short time. The river of ice isn't fed by local snowfalls but by the upper stream and as it slides down the slope it is "scraped off" and creates a number of puddles, rills and caves.

The ablation zone stretches out towards the valley as far as the place where the glacier is so thin that it has no more thrust downhill. There it stops: it is the front of the glacier. The shape of the glaciers is closely correlated to the morphology of the landscape, which is slowly altered by the glaciers themselves. They are also affected by the changing meteorological conditions, not as promptly as rivers but still in a relatively short time, i.e., years or decades. (G.B.)



# Glacial karstification

*From time to time, adventurous researchers have made descents of moulins. (...) The hazards of this questionable practice are made clear in this quotation from Holmlund and Hooke: "While one of us was down in a moulin measuring its geometry, two loud cracks were heard. Almost immediately, the water level in the moulin (...) began to rise at a rate of about 7 meters per hour".*

DOUGLAS BENN, DAVID EVANS, 1998

## Introduction

The main characteristic of a "karst area" is that the water doesn't flow over the surface but it runs underground inside natural galleries. This is more or less what happens in glaciers too. Summer melt-waters formed on the surface flow into rills absorbed into crevasses, if the surface is fractured, or they form streams, *the bédrière* that invariably fall into actual sinkholes. Once the waters have been absorbed, they flow inside the glacial mass or between it and the bedrock, ending their run into a single river that finally comes out at the front (glacial outlet).

From the hydro-geological point of view, glaciers behave like karst areas and their morphology is also similar. Often, besides swallet holes and shafts, we can find enclosed depressions similar to dolines, caused both by seepage and the collapse of englacial cavities. On a smaller scale, it is possible to notice some other shapes, created by water streaming, like the "ploughed fields", or by the

water gathering into small puddles, whose appearance resembles actual small karstic basins.

The most important point that induces us to talk about glacial karstification is the presence of cavities: real caves excavated inside the glacier or at the ice-rock interface.

Leaving out the caves due to collapses or to mechanical phenomena of stretching (the crevasses), the glacial melted cavities can be divided into two main categories: contact caves, that form between the glacier and the substratum of rock (subglacial caves), and englacial (or interglacial) caves, that form inside the glacier.

The former will be described in detail in Chapter 6; here we concentrate on the caves that are formed inside the ice, originating from the sinkholes into which the rumbling waters fall. They are usually named "glacial moulins", a synonym for "glacial shafts".

## The moulins

Glacial moulins open mostly on vast glacial tongues characterised by a slight slope and few crevasses, belonging to glacial formations prevalently found in temperate valleys or sub-polar habitats. Their openings originate from the concentrated absorption of superficial melt-waters (ablation) channelled into epiglacial torrents. That is why moulins do not form in areas bearing many crevasses, where the waters are diffusely absorbed.

The descents carried out inside these cavities showed that, generally, they open with a 40 to 60 metres deep shaft; at



*Glacial torrents originate from zones like this one, in which the melting water of the surrounding area gathers.*

*A gallery in the Gorner glacier, part of a rather wide network of conduits, a few metres below the surface, quite certainly formed underwater.*



*Page 26. Descent in a glacial shaft using the same techniques and equipment as for rock caving. The shapes of the glacial shafts are those typical due to the passage of the water, that is, very different from those caused by the mechanical fracture of the crevasses.*

the bottom, it is almost impossible to proceed any further because the stream disappears into impassable clefts. Sometimes, however, the first drop leads to impressive environments, a sort of subglacial gorge along which the stream runs by small leaps and short horizontal tracts, until it flows into a pool and then drains from underneath. The widths of these environments gradually decrease and most of the final puddles are located more or less a hundred metres from the surface, rarely more than that. In practice, as opposed to what glaciology had previously hypothesised, the water streams do not reach the rock footwall but end up in “aquifers” situated at the limit of the “plastic behaviour” of the ice.

### **Formation of glacial shafts**

The mechanical behaviour of the ice is the most important factor affecting the morphology of the glacial galleries. In fact, at low pressure, ice is rigid whereas at high pressure its reaction is more like that of a fluid.

As a consequence, at a depth of a few metres a cave lasts much longer than the local ice evolution time in the same area; in other terms, it is as if it was dug inside the rock. At a depth of 50 metres, however, a cave has an average life span of about one season; indeed, this is the maximum depth where the structures dependent on the cycle of the seasons can survive. As depth increases, the collapse time is even shorter and therefore these structures form and last for as long as the agents causing the process are still active. After that, they collapse and “quickly” disappear into the mass of fluid ice.

The superficial drainage, where plasticity is negligible, consists of rather simple structures: the streams form and swell up on sunken areas and then seep through the ice at its weakest points.

Inside the shaft, the kinetic energy of the waterfall is transferred to the air and to the ice. Where the water

*The mouth of a glacial shaft formed by the fall of a torrent. These shafts, which from the hydrological point of view are "sinkholes", in glaciology are called "glacial moulins". A term that the nineteenth-century naturalists took from Chamonix guides, inspired by the turbulence of the water that hurls into them, like in the "ritrecine moulins".*

crashes, the energy release leads to the melting of the ice. As a consequence, the width of the shaft is directly proportional to the energy released by the waterfall. Along the first tract, down to a depth of 50 metres, the hole will not be damaged from the plastic collapse, so, throughout the summer, the cavities widen. Only when the flows begin to reduce, the walls start to collapse into the hole, particularly at a further depth, where, during the winter, the sections of the pits get narrow. Beyond this threshold, the ice plasticity prevails and the walls tend to take up the space of the cavity that becomes more and more narrow until it forms very high canyons, wider at the bottom, where the water flows. These simple processes explain most of the structures so far observed inside the glaciers, but it is clear that these caves are just the early stage of the whole draining system of the glacier.

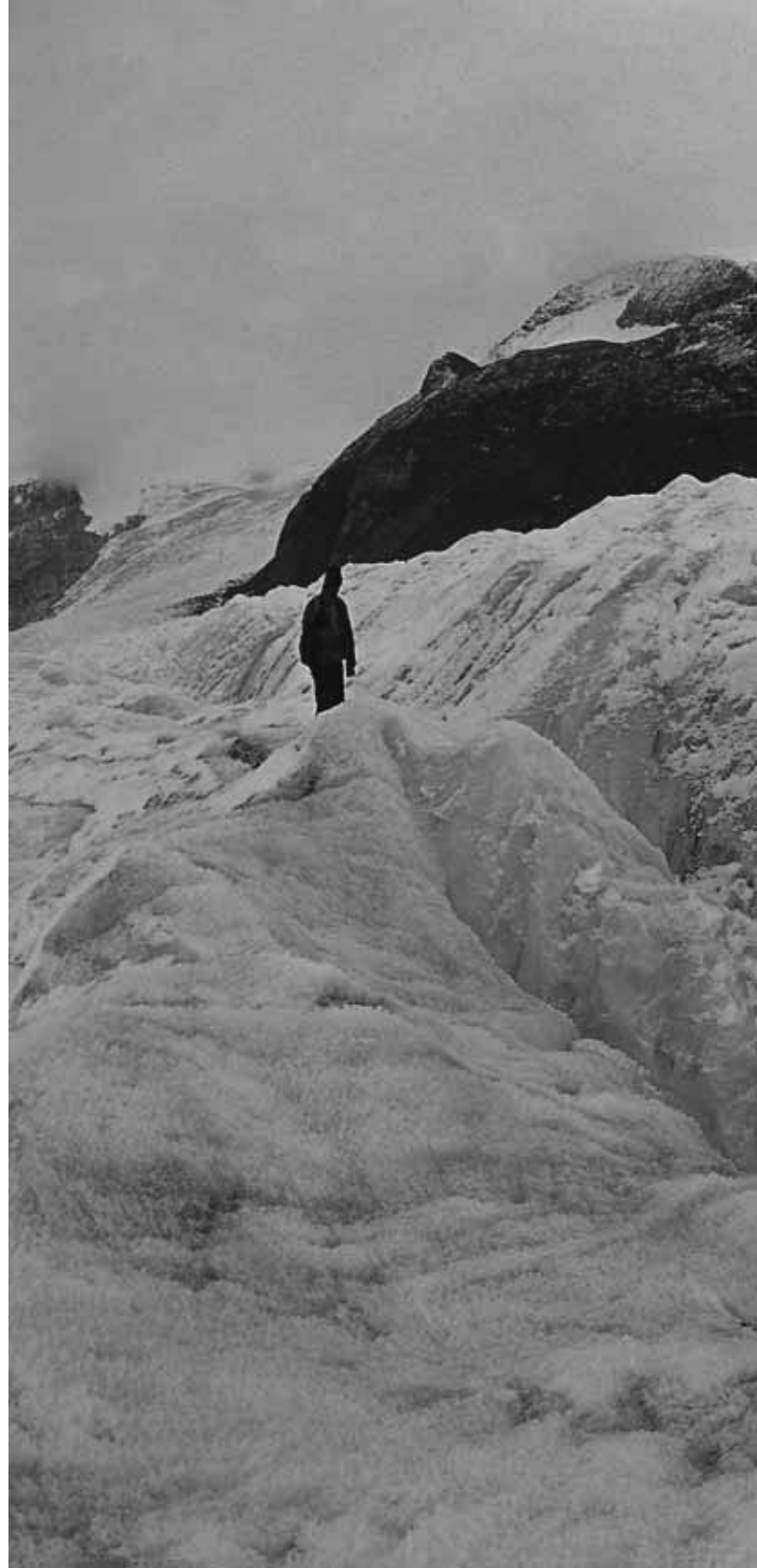
### **The submerged network**

Up to now, the numerical analysis was the only tool available to clarify the processes going on inside the englacial aquifer.

Underwater excavation is generated by the potential energy released by the fall of the water from the top to the bottom of the drainage network. This forms liquid-filled channels that are the result of a balance between the tendency of the running water to widen them and the tendency of the walls to obstruct them.

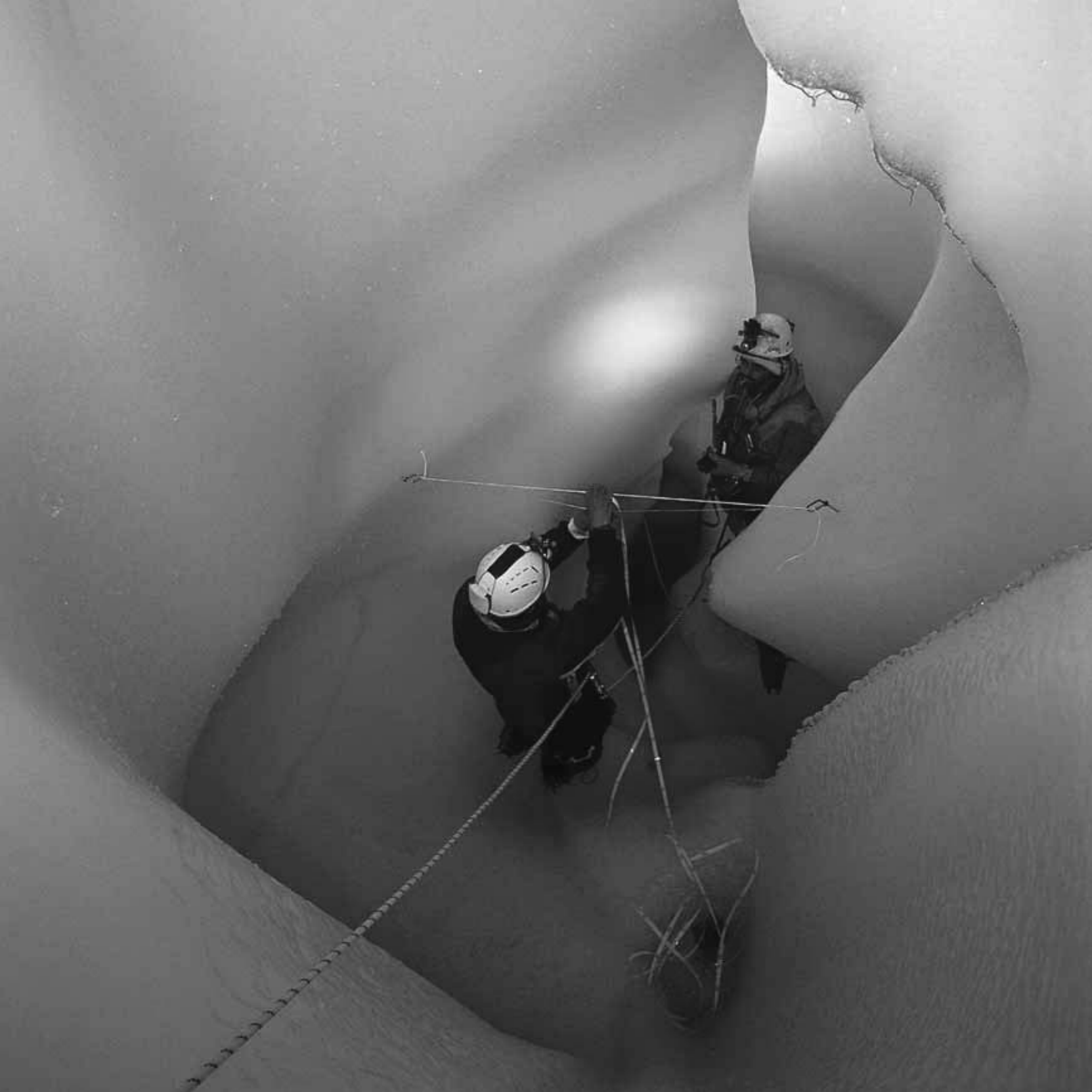
The galleries have an even diameter, because any narrowing increases the friction and, consequently, the eroding power of the water, which in the end removes the bottleneck.

When the water flow stops, for example during cold nights, the gallery slowly narrows, increasing the resistance to the flow of the stream. As soon as the flow restarts, the energy released is much more intense and









*Opposite. Gorner glacier cave. Measurements of the walls' deformation speed at 60 metres depth in G6. The ice plasticity – i.e. its tendency to slide under stress – is one of the most important features in the formation of glacial caves.*

*A wide gallery under the surface of the Tyndall glacier. These structures are real open windows onto the internal structure of the glacier.*



*Perito Moreno glacier. An imposing gallery at -60 metres depth, recently abandoned by the water.*



the excavation speeds up, to restore the previous conditions. Similarly, a transitory increase of the flow pushes the channel width beyond its equilibrium threshold, to which, however, the conduit returns as soon as the flow decreases.

It is a self-stabilizing process (negative feedback), so the draining galleries are stable.

The dimensions depend on the pressure of the ice against the walls, on the slope and the shape of the gallery. For example, calculation shows that a gallery, where the water runs at 1000 kg/s, at a depth of 100 metres, becomes stable with a diameter of 90 cm, with a water flow close to 1.5 m/s. With a flow of 100 kg/s, the balancing diameter drops to 35 cm and the water runs at 1 m/s.

When compared to the drainage network existing in the calcareous mountains, the most important finding concerns the global structure of the channels' network and it is due to the fact that the temperature equilibrium point between water and ice depends on the pressure. At the atmospheric pressure, the equilibrium temperature is 0 °C, but it decreases by 7.5 thousandths of a degree for an increase of one atmosphere (that is, an increase of 10 metres in depth).

This effect plays a fundamental role, as in the situations in which the water runs upward it progressively meets a lower pressure, it becomes too cold compared to the surrounding ice and eventually solidifies on the walls. The process goes on, widening the descending tracts and narrowing the ascending ones.

Even on a single channel, this phenomenon produces a relevant effect: when the water flows downward it erodes and when it touches the roof it leaves a deposit. As a consequence, the gallery slowly migrates downwards and the network tends "to flatten" over the local surface of the aquifer.

The long-term stability of the network is interesting as

*Perito Moreno glacier. Descent in a moulin.*













*Opposite. In some glacial caves it is possible to descend down to 100-150 metres below the surface, finding the spaces gradually narrowing due to the plastic collapse of the ice.*

*Bottom. The morphologies of surface flows are very much similar to those of calcareous rocks, with more or less deep meanders.*

*Preceding pages. Aletsch glacier, Switzerland. The glacier surface in a zone of glacial shafts. It is by far the greatest glacier of the Alps, but here the karstic phenomenon (cryo-karstification) is less developed than in the nearby Gorner glacier.*



well. We have observed that rapid variations in the flows only lead to slight fluctuations around the equilibrium structure; indeed, both calculation and direct observations show that the diurnal cycles do not produce significant modifications in the structure of the channels.

The situation changes considerably when the variation lasts longer than that which causes the collapse of the tunnel, i.e., during the winter. The deep flows come to a stop and the channels slowly begin to withdraw. Only the hydrostatic pressure of the ground water pushed upward contrasts this process. Gradually, the glacier falls into its aquifer, whose level increases and fills the upper tracts, almost to the surface.

In springtime, even if it is lower and with a higher pressure than a few months before, the network is still present. The springs thaw and flow again, the inner aquifers ebb, the water stream starts again, with a pattern similar to that of the previous year, and it re-excavates the shafts, practically in the same places.

### **Formation points**

In the middle of the nineteenth century, glaciologists hotly debated about the point where a glacial shaft forms. More recent research has given us the possibility to clarify the subject, correlating it to the strain state and the permeability of the ice.

The shafts tend to form near the areas rich with crevasses, i.e., those areas where the ice is subjected to tensile stress. Even at their margins the ice undergoes traction, but it isn't enough to fracture it. However, there is strong evidence that the traction increases the permeability of the ice, allowing the inner water to flow downwards, widening and digging a pit. Roughly, this will re-form in the same place, because a glacial pit reduces the stresses inside the surrounding ice which, consequently, tends to "fall" into it. So, upstream of the shaft the ice onto which



*Very deep water basins are pretty common in Patagonian glaciers; they probably result from the obstruction of the run-off at the base of the glacial moulins, causing them to fill up to the brim.*

*Water basin in Tyndall glacier. These water deposits tend to increase in size and turn into a menace for the people living downstream the glacier, particularly during regression phases like the present one.*



*Perito Moreno glacier. Here, the rivers tend to flow into gorges and, often, to disappear completely, running a few metres under the surface.*



*All the rills in the end always find a way leading into the glacier's heart.*



*Bottom. Terminal parts of the bédière, before the corresponding shaft, are deeply carved.*



the feeding torrent flows is more permeable and the water begins to form small seepages along the streambed. Little by little, the circulating water widens the course until the seepage becomes a new shaft that captures the whole torrent, while the downstream shaft “fossilises”, destined to be filled with collapsing ice, snow or, often, stagnant water.

The deep network also turns out to be a structure that fluctuates seasonally around a state of equilibrium; in practice it migrates upwards, albeit in fits and starts, at the same speed of the ice that slides downhill.

Under normal conditions the process recurs every year, but it might not take place on still glaciers that are standing; on the other hand, in case of an intense melting on rapid glaciers, like those of Patagonia, it might recur more than once during a season.



### Water basins

The study of inner water deposits is the most relevant aspect for a practical use of glacial speleology.

It is well known that, periodically, large quantities of accumulated water suddenly spurt out from the glaciers. Where were they? How did they form?

The processes that form the sub-glacial drainage network are the same that, under particular conditions, “degenerate” and form these internal deposits of water. The latter are not balanced structures with constant dimensions: on the contrary, the larger they are, the deeper inside the glacial mass they tend to penetrate, increasing in width.

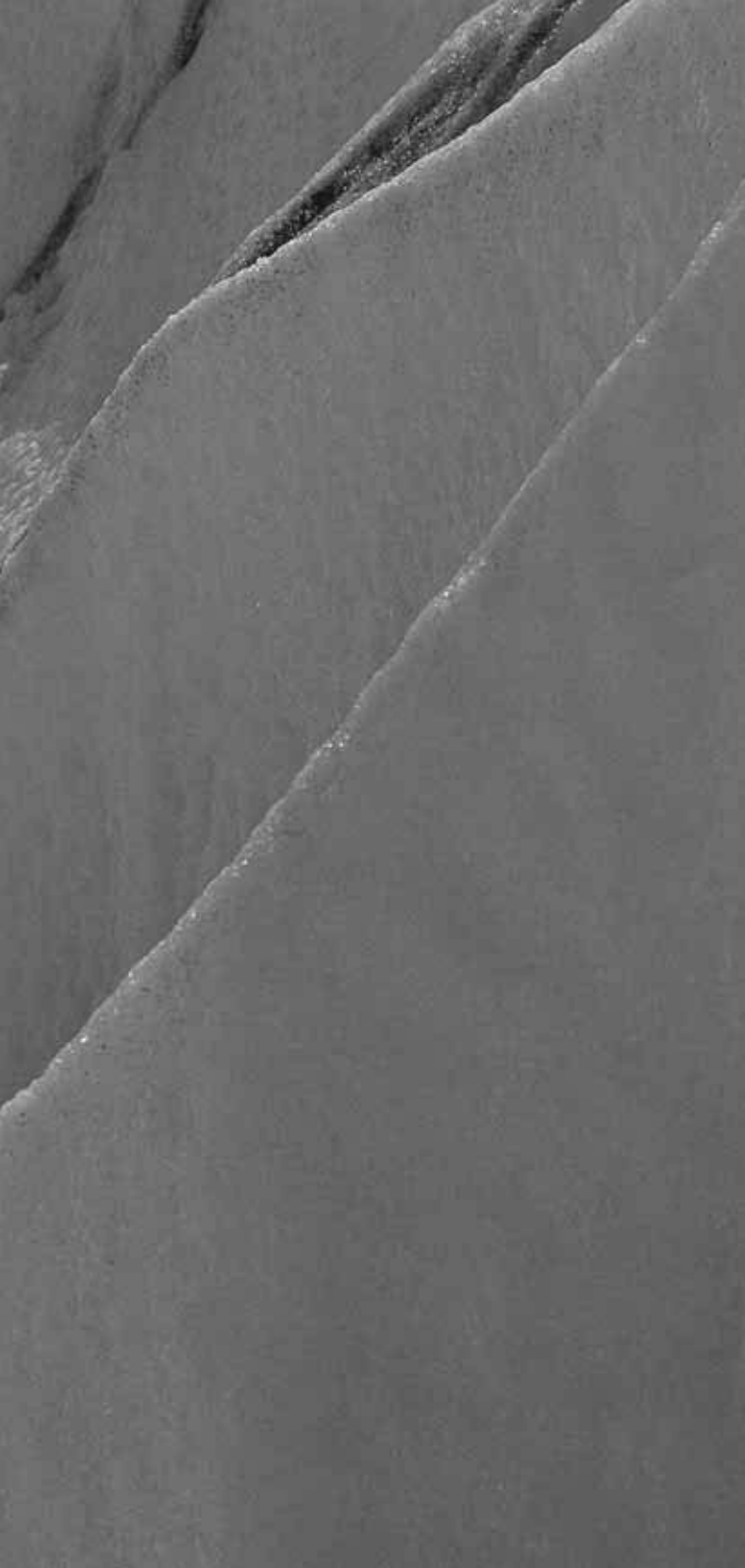
This is due to three factors, which will be described briefly. The first one is connected to the density of pure water that peaks at 4 °C; when heated up by the sun or by the external air, it goes down, penetrating and melting the ice. Due to this process, a basin exposed to the sun conveys the absorbed energy to its depths: Its outer surface might appear unchanged, but its volume is secretly increasing.

The second factor is connected with water turbulence, which excavates the bottom and deposits the ice at the top of the basin because of the above cited relationship existing between pressure and the equilibrium temperature of water and ice.

The third and last reason for the widening is the fact that the density of the water is greater than that of the ice, so at the base of the reservoir the pressure tends to push the ice away. A deposit of water tends to “sink” into the glacier, although this process is only relevant for very deep basins or over a long period of time.

In practice, thanks to these processes large water reservoirs are unstable and tend to widen; this in turn triggers a positive feedback, until they break through towards the valley. These are “catastrophic” processes, both from a mathematical point of view and in practice.





*Tyndall glacier. Crossing a large  
bédière. Sticks and crampons are  
the essential tools to move in  
search of caves.*

### **Climatic changes and glacial risk**

The above-described processes are made even more rapid and impressive in the present situation, in which the glacial masses and the environment are clearly not in a steady state.

The reduction of the water supply has slowed down many glaciers almost to a standstill. In these conditions, the drainage network is no longer a balancing structure that regenerates constantly, moving upward at the same speed at which the glacier slides downhill. On the Alps, we now find the same caves from one year to the next, and we are not talking about external shapes, like vortices; we mean exactly the same caves, in the same ice we had hammered at a year before. Inside these caves the walls accumulate tremendous tensions, which cause the explosion of large sections after every stroke of our crampons and ice axes.

The most threatening aspect, however, is due to the fact that it becomes possible to cross the thin line that separates the behaviour of the drainage network, self-stabilising by negative feedback, from that of the water deposits, which instead tend to “diverge” by positive feedback. In practice, the risk is that the obsolete network of conduits could turn into a mere water deposit, destined to make the whole glacial mass unstable. It is as if the deep channels of these now still glaciers were suffering an “aneurysm”. (G.B.)





*Granite Block on the Mer de Glace.*



# The discovery of the phenomenon

*It is, in this respect, absolutely comparable to the water of a river, which has here its deep pools, here its constant eddy, continually changing in substance, yet ever the same in form.*

JAMES FORBES, 1859

*Ne derivava che esse sono strutture stabili come il gorgo in un fiume, fatto di acque sempre nuove: quando il ghiaccio arriva in quel punto assume la forma di una grotta, sempre più o meno quella.*

They were therefore steady structures, like a vortex in a river, made of constantly renewed water; when the ice reaches that point it always takes the shape of a cave, always more or less the same.

GIOVANNI BADINO, 1999

## Introduction

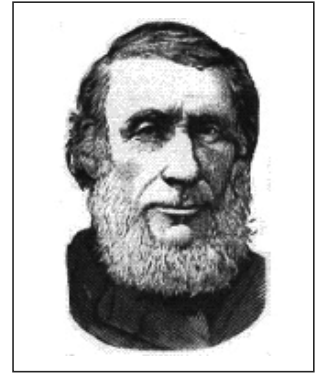
Glacial speleology has developed amidst the most absolute unconcern, both of glaciology that regards it as an extreme sport and of speleology that considers it as a technical exercise lacking the depth given by the exploration of new territories. On the contrary, researches undertaken during the last twenty years now show that these are interesting and, as we recently found, important topics. After all, they deal with quite relevant structures situated in particular areas. How come nobody had ever noticed them?

When we went looking for the quotations made by naturalists

who first described the glaciers, we were greatly surprised to discover that they had made accurate descriptions of the phenomena concerning the glacial shafts. Sadly, those notes have been neglected, practically for a century, due to the fact that technical difficulties had relegated the caves in the ice among things devoid of interest. And, as the quotations at the beginning of this chapter show, we ended up repeating the same conclusions, almost with the same words.

## The early researches

At the end of the eighteenth century, Genevan Horace-Bénédict De Saussure and Marc Theodore Bourrit were the first ones to report accurate observations about Alpine glaciers, although they concentrated particularly on landscapes or, at most, on crevasses. It is not until 1840 that we meet the Swiss-German Jean de Charpentier and his text that can be classified as scientific glaciology. In this work he is concerned about where the water goes when it is engulfed in the depth of the ice and he is the first one to hypothesise that it crossed the whole thickness to flow on the rocky bed. Generally untrue, this was however a reasonable supposition, which still is in fashion amongst glaciologists. Louis Agassiz and Edmond Désor, from Switzerland, and the Scottish James Forbes were the first people who really studied in detail the problems linked to glacial shafts, around 1840. Their writings indicate that their researches aroused a lively interest in a large audience, so much so to justify the publication of some, still valuable, books.



Agassiz was the first one to describe the moulins of the Gorner Glacier. He realized that the formation of the glacial karstification needed a scarcity of crevasses and a slight slant. He then pioneered glacial speleology, having himself lowered into a shaft of the Unteraar Glacier. The techniques he used were going to be the standard in speleology for about a half century: many people holding a rope at the end of which there was a board on which the explorer was sitting. Interestingly, during his descent he noticed something that, even now, has not been understood by many glaciologists: the fact that glacial caves are an open window on the real physical properties of the ice which, on the outside, are concealed by the thermal exchange with the atmosphere and the sun.

Désor is often neglected in the history of glaciology, mainly because his writings were scarce and less exciting than those of his two opponents (who were constantly battling over the paternity of the discoveries). Yet, even though he was less of a writer, Désor was more accurate than Agassiz. He concentrated on how glacial shafts could prove the movement of the glacier, reflecting, with unexpected accuracy, upon their position. He distinctly sensed that the ice was subjected to tensions that differed from point to point, even when the absence of the crevasses did not highlight it. He understood the importance of tensions in the formation of the shafts, anticipating by 160 years the studies that now deal with this matter.

### Glacial karst enters the scene

Agassiz was extremely brilliant, but Forbes, who during the same years was working on Mer de Glace on the French side

Opposite. From left to right: James Forbes (1809-1868); Edouard Desor (1811-1882); Louis Agassiz (1807-1873); John Tyndall (1820-1893).

Opposite bottom. Mer de Glace. Contact between ice and rock (Forbes, 1843).

Bottom. Aar glacier. Hôtel Neuchâtelois (Desor, 1844).

Preceding page. Mer de Glace. A granite block. (Forbes, 1843).







On the way to Gorner glacier. Ever since 1840 Agassiz cited its exceptional surface drainage network, by far the most intense among the alpine glaciers.

of Mount Blanc, was more careful, accurate and clear. Yet, it was the latter who imposed the futile term *moulin* to indicate the glacial shafts, picking the word from his Chamonix guides. For them, in fact, the tumultuous waters inside glacial pits resembled those of the domestic mills; small vertical structures built under their houses, known as “ritrecine” and quoted as “terraceous moulins” in the Divine Comedy (Inferno XXIII).

It was Forbes who explicitly compared them to the calcareous caves and, in particular, it was he who clearly described in his 1859 book their seasonal forming, the pivotal datum of glacial speleology.

*All these facts, attested by long and invariable experience, prove that the ice of the glaciers is insensibly and continually moulding itself under the influence of external circumstances, of which the principal, be it remarked, is its own weight affecting its figure, in connection with the surfaces over which it passes, and between which it struggles onwards. It is, in this respect, absolutely comparable to the water of a river, which has here its deep pools, here its constant eddy, continually changing in substance, yet ever the same in form.*

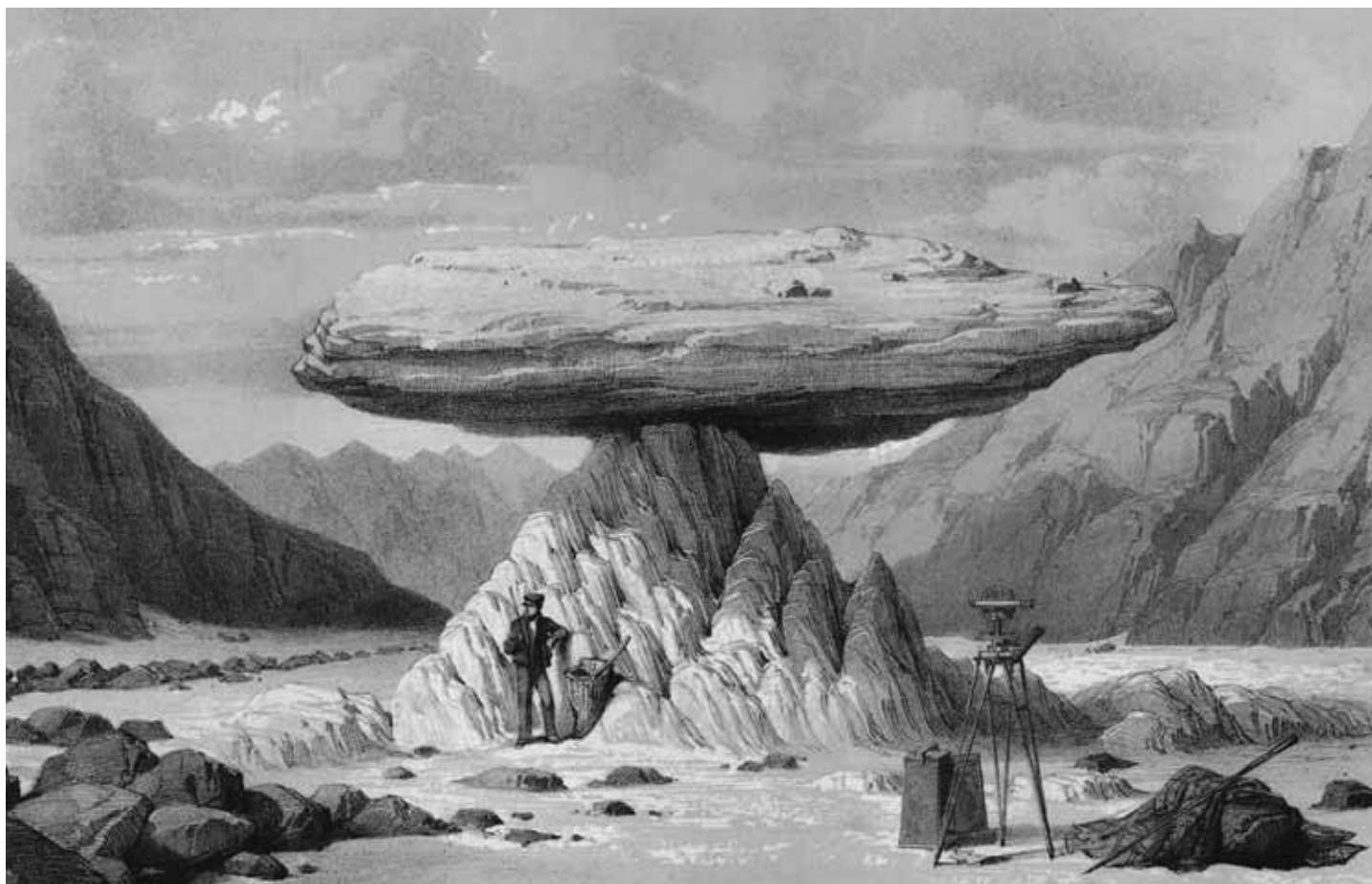
So, Forbes, Agassiz and Désor have described the glaciers not only in their overall phenomenology but also in their ablative forms, in particular in their karst phenomena. They were naturalists and travellers who studied the glaciers sensing that they were complicated structures to be understood, rather than a mere accumulation of ice. This has been their great merit.

Compared with our specific theme, i.e., the accurate descriptions of karst phenomena of the temperate glaciers, Forbes seems to be the one who understood, with unnerving clarity, topics that since then have been neglected by glaciology and only now are being reconsidered.

*Mer de Glace. Large glacier table  
(Forbes, 1843).*

*Opposite. From left to right:  
Antonio Stoppani (1824-1891);  
Joseph Vallot (1854-1925);  
Umberto Monterin (1887-1940);  
Ubaldo Valbusa (1872-1939).*

*Opposite bottom. Mount  
Matterhorn. View from Riffelberg,  
near Mount Rosa (Forbes, 1843).*







Yes, we believe that it is Forbes who could boast of being the father of the studies about glacial karstification, and not one of the very expert speleologists from the end of the nineteenth century.

### **The century ends, and so ends the interest**

A few decades later, near the end of the century, we meet another great naturalist, the Irishman John Tyndall; with him, the observations about glacial karstification become decisively accurate. In his book about the glaciers of the Alps he dedicated a whole chapter to "The moulins of the glacier".

He tried to investigate them, correctly presuming that they might not reach the glacial bed. He tried to reconstruct their origin; he identified the fossil shafts, understanding that they form seasonally; he mapped their positions; he lowered sounding lines into them. In conclusion, his work was as good as it gets: what he wrote is still very much up-to-date. He was missing just one thing: actually descending down there himself. At that time, though, that was really hard to do.

The next name we meet, crossing the two centuries, is that of the Italian Antonio Stoppani, from Lecco, an excellent scientific populariser. In his work about Italy (1876) he deals with glacial shafts with great detail, but with a lot of imagination, too. His observations are basically mistaken, but they will be quite popular for many decades to come, especially amongst Italian naturalists.

He concentrated his attention on "glacial moulins" because he believed that they crossed the whole thickness of the tongue and therefore the waterfalls that were engulfed





Gorner glacier (Agassiz, 1847).

inside them were able to excavate the rocky bed. Stoppani thought that this mechanism could explain the formation of the so-called “giants’ potholes”, the impressive circular excavation that form under the glaciers.

He suggested various untenable hypotheses about their genesis, but he was the first to clearly sense the existence of a structural stability in some glacial cavities. He correctly credited it to the fact that, in certain conditions, the running water and the ensuing melting of the ice equilibrated the plastic collapse of the cavities.

At the end of the nineteenth century, Frenchman Joseph Vallot made the first “modern” descent, from the point of view of speleology, inside the glacial caves of Mer de Glace. He descended more than 20 metres into a fossil shaft, using the techniques of speleology available at the time (already quite efficient). He found that the bottom was full of snow and debris and therefore was not a practicable way to reach the rocky layer.

He was obviously disappointed and surrendered the privi-

Miage glacier and its moraine (Forbes, 1843).







*Macugnaga glacier.*  
(Forbes, 1843).



*Arolla glacier.* (Forbes, 1843).





*Tyndall glacier. Big epiglacial torrent. The flows of these torrents can become impressive, up to many cubic metres per second.*

lege to continue the descent to one of his acquaintances, a shy Alpinist by the name of Mr. Fontaine. On September the 9<sup>th</sup> 1897, Fontaine descended for more than 60 metres inside a glacial pit, describing and sketching it with great accuracy. For about eighty years, it was going to be the last documented descent inside a glacier.

*Bravo Fontaine!*

In the report Vallot wrote from dictation of the Alpinist, the shafts were delineated as geographical places with certain peculiar characteristics (suspended terraces, gravels, dissolution ways and so on). But those notes also conveyed the fact that glacial shafts were not very interesting and even if they ended up published in a speleological journal, glaciologists never quoted them.

The history of explorations was over. Reaching the bottom of active glacial shafts was going to firstly require the mastery of the right techniques, then the re-discovery of glacial shafts (re-writing, incidentally, what had been written 150 years before), and eventually the actual descent inside them. It took almost a century, even if all this time still does not seem to be sufficient to make this activity acceptable by many speleologists and glaciologists. (G.B.)



# The birth of glaciospeleology

*Ma al pozzo glaciale vero e proprio, indiscutibile, qui descritto nella sua formazione ed illustrato, come si è potuto nella sua apertura, sopra imbutiforme e sotto cilindrica (...) quale nome egli intende di dare? Se ne trovi uno più proprio ed efficace di "pozzo glaciale"! Mulino no eh, non è adatto, perché questo pozzo non mulina proprio niente. Né tutti gli altri mulinano alcuna cosa!*

But what name is he planning to give to the actual, indisputable glacial shaft that we describe here, to the best of our ability, with its funnel-shaped opening that turns into a cylinder down below (...)? A more appropriate and telling term should be found, rather than "glacial shaft". Surely not moulin, it wouldn't be suitable, as this shaft does not whirl at all. Nor do the others, in any way!

UBALDO VALBUSA, 1937

## A faint interest

The second half of the nineteenth century was a pioneering era, during which some of the most famous names of the young field of glaciology had an interest in glacial cavities and, in particular, glacial shafts. Later, the study and exploration of these fascinating structures underwent a long period of stasis and almost sank into oblivion.

As far as we know, during the first half of the twentieth century only a few Italian glaciologists, in particular Mònterin and Valbusa, continued to keep the attention

alive on these phenomena, probably due to the importance they had in Stoppani's work. Valbusa studied them with a particular perspicuity, but from the outside: the period of the descents was really over.

After the Second World War, during several glaciological campaigns concerning an ever-increasing number of glaciers world-wide, some of the contact caves situated in the areas of the glacial fronts received sporadic and quick explorations. Meanwhile the glacial shafts, still called "moulin" –following the French custom– were at most the subject of brief reports.

The caves that form under the ice along the slopes of large volcanoes, which were found mostly in the US, had a different story. In the 1960s, a group of speleologists, members of the Glaciospeleological Survey, carried out methodical researches in the contact caves of the Rocky Mountains, following a modern explorative approach. The best results were obtained on Mount Rainer, a 4400-metre-high volcano in the state of Washington, where unexpected continuations of Paradise Ice Cave were found (the entrances of the cave were already known since the end of the nineteenth century). In May 1978 it was reported that the cave was about 13 km long. The passages, all formed at the contact point between the ice and the rock, were in part originated by the emissions of hot vapours from the volcano's slopes and in part by the subglacial torrents that flow through them.

In Europe, interest in caves within glaciers was revived







*Gorner glacier. Life at the camp on bare ice.*

*Preceding page. Gorner glacier. A wonderful gallery, probably formed underwater, in the marginal zone of the tongue.*

only since 1957 in the Svalbard Islands, more precisely in Spitsbergen, by some Polish researchers and, a few years later, also by French scholars. Aside from a few sporadic descents inside some caves found in Alaskan and Alpine glaciers (e.g., the Gorner glacier in Switzerland), the studies of glacial cavities formed by melting were concentrated just in the Svalbard Islands, mainly under the guidance of M. Pulina and J. Rehak. That was the period in which the activity we today call glaciospeleology reasserted itself.

### **The birth of glacial speleology**

Great strides were made in the following decades, especially due to the arrival of new speleological techniques for rope ascent and to the evolution of ice mountaineering clothing that allowed a simpler and safer descent inside the deep glacial shafts.

Important news, concerning the contact caves came from Iceland, 'par excellence' land of fire and ice, where in the early eighties a group of Swiss speleologists, led by Gérald Favre, explored a vast system of galleries excavated by volcanic hot water that had a drop of 525 metres and was more than 3 km in length.

In the same years, in Spitsbergen the research and explorative activities intensified and new researchers from Canada, Czechoslovakia, Russia and Spain joined the Polish and the French. During those campaigns of study two remarkable depths were reached: 90 metres in 1983 and 134 metres in 1988.

In the early eighties, Italian speleologists also began to take an interest in glacial caves, prompted by the Bolognese Mario Vianelli. The first descents took place in 1983, in some moulins on Miage Glacier, in the Mont Blanc group. Two years later focus was turned to the Gorner Glacier, where the phenomenon reaches an extension like nowhere else in the Alps. In 1985 and 1986, about a dozen deep glacial shafts were explored; in two of them a depth

*Biafo glacier, Karakorum. A night descent in a large moulin, taking the opportunity of low water flow conditions.*



*Svalbard. Glacial moulin near Ny Alesund. These caves are excavated in the ice at about -5 °C. We are just at the northern limit of the glacial karsification area.*



*Bottom. Biafo glacier, Karakorum. The vast expanse of the glacier, seen from the camp of the first extra-European glacio-speleological survey.*





of 90 and 140 metres was reached, establishing the depth record of the time. During the same years, Swiss researchers recommenced their researches on the Gorner Glacier.

At the end of the eighties, systematic researches on glacial moulins were carried out only on the Alps, particularly on the Gorner, by Swiss and Italians, and in Spitsbergen, mostly by Poles.

Other than those, the only moulins explored that we know of are located in some glaciers of North America and Sweden, where in 1988 Per Holmund carried out one of the first proper studies.

### **The early expeditions**

At the time, the world's largest glacial systems outside the polar caps, i.e., the farthest end of South America and the glaciers of the Himalayan ranges, were still left out.

The first expedition outside Europe and North America was organized in 1987 by some Italian researchers; their destination was the Biafo Glacier, on the mountains of Karakorum in Pakistan. At the end of the long tongue of Biafo, the small group comprising M. Vianelli, G. Badino and L. Piccini, accompanied by a guide and a few porters, discovered a good number of moulins, some quite large, fed by glacial torrents with a flow of more than 2-3 cubic metres per second.

Two years later, another group of Italian speleologists from the Marche Region, led by G. Antonini from Ancona, went back to the same glacier. They descended in several glacial shafts, in an area slightly higher than the one explored in 1987, reaching a depth of 120-140 metres: the deepest ever reached outside of Europe at the time.

These early expeditions confirmed that, in the presence of the necessary morphological and climatic conditions, glacial shafts and pseudo-karst melting phenomena were indeed spread worldwide.



*Gorner glacier. Descent in a moulin. Note the multiple anchorage, so as to share out the load on different points. The external anchors are particularly risky because the screws become privileged points of melting and can come out rather rapidly.*

As the dimensions of the glacial pits were obviously directly correlated with the flow of the torrents that fed them, it was reasonable to expect that the most sensational results should come when researching the glaciers characterised by large superficial collectors. Greenland and Patagonia seemed particularly promising areas.

The former is the subject of French researchers, who had already carried out initial surveys in 1986. However, it is from the beginning of 1989 that, under the guidance of J. Lamberton, some large cavities were discovered in the *inlandsis* of Greenland; more precisely, at the top of the huge glacier Jacobshavn, famous for its exceptional sliding speed of about 7 km a year. A large cavity, fed by an almost-50 km-long river, which during the season of maximum melting reaches a flow of 35-40 cubic metres per second, was explored for over 150 metres down, where a deep lake stopped the descent.

### **Glaciospeleology grows to adulthood**

At the end of the eighties, news about the results obtained through explorations of the moulins, began to influence the whole world of speleology and glaciology. In those years, prompted by the Spaniard A. Eraso, a Committee for the study of these structures, and in general of the pseudo-karst phenomena in glaciers, was established within the Union Internationale de Spéléologie (UIS). The Committee proposed the creation of a new term—"cryokarst". The first conference of the international board "Glacier Caves and Karst in Polar Regions" was held in 1990 in Madrid and it represented the various groups of researchers who, for various reasons, were interested in these topics, their first real chance for encounter and discussion. The most important result of the Conference was to better define the general phenomenon and to stress the need for accurate scientific studies to contribute to the researches about the physics of glaciers. So, during the







nineties we witnessed the shift from a first, essentially exploratory phase to a period of study and research, which directly involves researchers from universities and scientific foundations. At the same time, the research range widened considerably, thanks to the participation of an ever larger number of scholars from all over the world.

### **Most recent campaigns**

Italians, who in time had accumulated many experiences and formed a particularly fine-tuned group, began to show an interest in Patagonia and, in 1991, a first survey was carried out on the Marconi Glacier.

In 1995, following other preliminary surveys, the members of the Association La Venta undertook an expedition on Perito Moreno, one of the most renowned and accessible glaciers of Argentinean Patagonia, obtaining important results. In particular, they discovered an epidermal cavity that stretches for more than 1 km just a few metres below the surface of the glacier. They also carried out dye-tracing tests, which revealed the presence of a complex system of peripheral channels that drain the superficial melting water. They also tried the exploration of some submerged englacial cavities using scuba-diving techniques, but many technical problems did not permit a dive of more than a few dozen metres.

Again in 1995, Italian speleologists from the Marche region organized an expedition on Marconi Glacier, exploring several deep shafts. In 1997 the Viedma Glacier was the subject of a preliminary survey; the glacier turned out to have great potential, as well as significant logistic problems. In 2000, a large expedition on the Tyndall Glacier (Chilean Patagonia), organized once again by the Association La Venta, discovered some large moulins characterised by daily increase-decrease cycles of the water level, caused by flow changes of the feeding torrents.

In the Italian territory, the most significant researches were

carried out on the Forni Glacier (Ortles-Cevedale) by researchers from the universities of Milan and Padua. They found several moulins, whose development was monitored for several years.

Meanwhile, in Greenland (1998) the French reached a depth of 203 metres inside the huge shaft Isortoq. This is still the maximum depth ever reached in a glacier.

In 1999, for the first time an Italian expedition surveyed a glacier in Greenland, exploring some cavities (one of which was 160 metres deep). Another group of Italians, mainly from Verona, went to a glacier in Alaska. Here too, a few moulins were discovered and explored, even though their size was not impressive.

In 2000, the Association La Venta organized the first speleological-only expedition in Antarctica; thanks to the support of the Geographic Institute of the Russian Academy of Sciences, researches were carried out on Collins Glacier (King George Island). The explored moulins had modest dimensions compared with those of other areas, but they were very interesting for their geographical position: the extreme southern limit for the formation of these structures.

Over the past few years, researches have been concentrated in precise areas, where the phenomena appear to be particularly developed. On Gornier Glacier work is proceeding, mostly thanks to the activity of G. Favre, A. Pahud and of several Italian groups. Their exploration, with interesting results, has been extended to the largest glacier in the Alps, the Aletsch.

The northern islands of the Svalbard are still the subject of the work of Poles and Norwegians; their studies are now focused on glaciological analyses, in an attempt to correlate the evolution of cryokarst forms with climatic change. In Patagonia, the La Venta Association is working on the preparation of a major project, whose ambitious goal is to survey all the main glaciers that descend from the Hielo







*Biafo glacier. Big epiglacial torrent. There is no direct correlation between cave size and glacier extent. There can be few huge caves in fairly small glaciers, as well as a large number of small caves in very vast glaciers.*

Continental Sur. In 2004, La Venta carried out two more expeditions, on the Upsala and on the Grey Glaciers, finding more area characterised by intense cryokarst phenomena.

In conclusion, from the early seventies glacio-speleological research, while remaining a 'niche' field, has spread to many geographical areas and has received the interest of an ever-increasing number of researchers. Many glaciers still have to be investigated, but we can say that the global picture of cryokarst phenomena is now clear enough. Indeed, the many direct observations have demonstrated a good concordance with mathematical and theoretical models (see Chapter 2).

Even though official glaciology is still reluctant to admit it, the melting forms caused by the drainage inside glaciers are definitely an important indicator of the glaciers' "health"; they can play a decisive role in the alterations of their balance that can cause sudden mass losses. (L.P., A.R.)





# Glacial karst in the world

*Nous avons vu de ces entonnoirs qui avaient plus de trente pieds de diamètre et dans lesquels venaient s'engrouffer de véritables torrents. Il est impossible d'imaginer un plus beau spectacle que celui de pareilles rivières coulant ainsi dans des parois de glace et allant se perdre à grand bruit dans l'intérieur du glacier!*

We saw some funnels more than thirty feet in diameter, swallowing true water streams. It is impossible to imagine a more striking sight than such rivers flowing between ice walls and finally disappearing, in the uproar, into the depth of the glacier.

LOUIS AGASSIZ, 1840

## A summary

This chapter presents a short summary of the main results obtained by our group since 1983, the year that marks the beginning of Italian glacioc speleology.

During more than 20 years of activity we have visited about twenty glaciers; some were the target of full-fledged explorations, others were mere surveys, at times just from the air. The knowledge we acquired about these phenomena is a worldwide, unique asset, which allows us to trace an interesting global picture.

## Europe

We carried out several investigations on almost every major glacier in the Alps. The most interesting results were those

about the Gorner and the Aletsch, in the Swiss Valais.

Modest-sized cavities were also found in the Miage and the Mer de Glace glaciers, both part of the Mount Blanc group, in the Arolla and Unteraar, in the Swiss Alps, and in the Mandrone Glacier, in the Adamello group.

**Aletschgletscher** (Switzerland) - It is the main glacier in the Alps, with a surface of more than 130 square kilometres. The main tongue descends along a SW direction for about 26 kilometres. The tongue is fed by a very large glacial cirque named Konkordiaplatz, which collects the snow coming from a vast, amphitheatre-shaped mountain range more than 4000 metres high (amongst them is the Jungfrau, with its 4166 metres). The front usually goes all the way down to 1370 metres, that is, more than 1200 metres below the limit of perennial snow. In the ablation zone one can find areas with crevasses, as well as areas that are relatively compact and flat; there is a superficial flow of melting waters, well channelled but scarcely organised. Glacial shafts are distributed along transversal lines, just upstream of the fractured zones. At times, there are three known zones where most of the deepest shafts are clustered. The central one, located at an altitude of about 2500 metres, is the one hosting the most significant phenomena and is also the place where most of the *bédrière* can be found. A short survey, carried out in October 2004, led to the exploration of about ten moulins, up to 60-70 metres deep, and some large sub-glacial cavities.

Preceding page. Tyndall glacier. Big surface conduit.

Sketch of the areas which have been the object of glacio-speleological explorations by the Association La Venta. Generally speaking, we may say that glaciers form where the mean yearly temperature is below  $0^{\circ}\text{C}$ , whereas glacial caves form where, for a significant part of the year, there is water run-off and therefore the temperature is positive. This means that the interesting areas are exactly near the yearly isotherm  $0^{\circ}\text{C}$ , ranging from  $+5^{\circ}\text{C}$  of Perito Moreno glacier, in Patagonia, to  $-7^{\circ}\text{C}$  of the Hansbreen glacier, in the Svalbard Islands. Of course, the cryo-karstic phenomenon is proportional to the mean temperature. Nevertheless, other climate indicators, more precise than the mean yearly temperature, allow us to foresee with accuracy the intensity of the cryo-karstic phenomenon in a certain area.





*Tyndall glacier. Descent in an immense shaft.*



*Perito Moreno glacier. Proceeding with watertight suits inside Perito Meccanico cave, surveyed for over one kilometre. It is still the longest known glacial cave. It is formed by a big torrent that flows at 5-20 metres under the surface of the glacier.*



*Bottom. Diving in a submerged stretch, down the same cave of the preceding page. The dive in such icy water presents considerable technical problems, only partially solved.*



*Gorner glacier. At eighty metres depth inside G8 moulin, one of the greatest of the glacier.*

*Gornergletscher* (Switzerland) - The second largest glacier in the Alps, Gorner originates from the confluence of several tongues derived from the ridge that connects Mount Rosa to the Breithorn. Its one-of-a-kind surface morphology is its most noteworthy feature, which makes it one of the most interesting in the world. In particular, the surface of the ablation zone is carved by torrents that flow inside winding gorges as deep as 20 metres, which link a series of epi-glacial lakes. It is a very rough morphology, despite its overall low slope.

The water streams merge into large torrents that end up in a series of wide and deep moulins, located mainly in the central part of the main tongue, at an altitude of 2400-2600 metres. Many of these moulins, which have been the subject of several descents since 1985, show a relatively stable position and a structure that tends to replicate itself with little variation year after year.

It is definitely the most-studied glacier in the world, as far as glacial karstification is concerned; it has been the subject of repeated investigations carried out by Swiss speleologists and also by other Italian groups. We have carried out several surveys there since 1985, almost on a yearly basis, and three major explorations (2000, 2001 and 2003).

*Miage glacier* (Italy) - The tongue of this glacier, covered by a large amount of debris, descends from Mount Blanc towards SE. There are many points that act as sinkholes for the numerous torrents that flow beside the medial moraines. The main moulins take up a small area in the central part of the tongue and have small, hard-to-enter accesses; amongst the few that have been explored in 1983, some have shown a depth of just a few dozen metres. It is now in a phase of major regression and its debris cover has thickened even more.

*Skeidararjökull* and *Kviarjökul* (Iceland) - During the 1997 expedition we surveyed on these two tongues, which origi-









*Aletsch glacier. Base camp on the vastest glacier of the Alps and the only one with definitely Patagonian forms.*

nate from the large ice cap of the Vatna Glacier.

The investigations, carried out with the collaboration of researchers from the University of Madrid, aimed chiefly at the study of the mechanical factors that regulate the formation of the draining conduits within the glacial mass. Widespread karst forms, albeit rather small, were found in both tongues. Such modest size was due to the small area of the tongues and, above all, to the presence of a water-saturated layer just a few dozen metres below the surface, corresponding to the level of the lake that sits just at the front of the glacier.

The Breidamer and Skeidarar glaciers are more interesting. The former has been the target of just one very brief survey and, given that it ends into a wide lake, appears to be a promising ground for the search of springs at its front. The latter has been the subject of a series of more accurate researches, aimed at finding traces of the great 1996 flood (see Chapter 7) and appears to be quite interesting from a karstification point of view.

## **Asia**

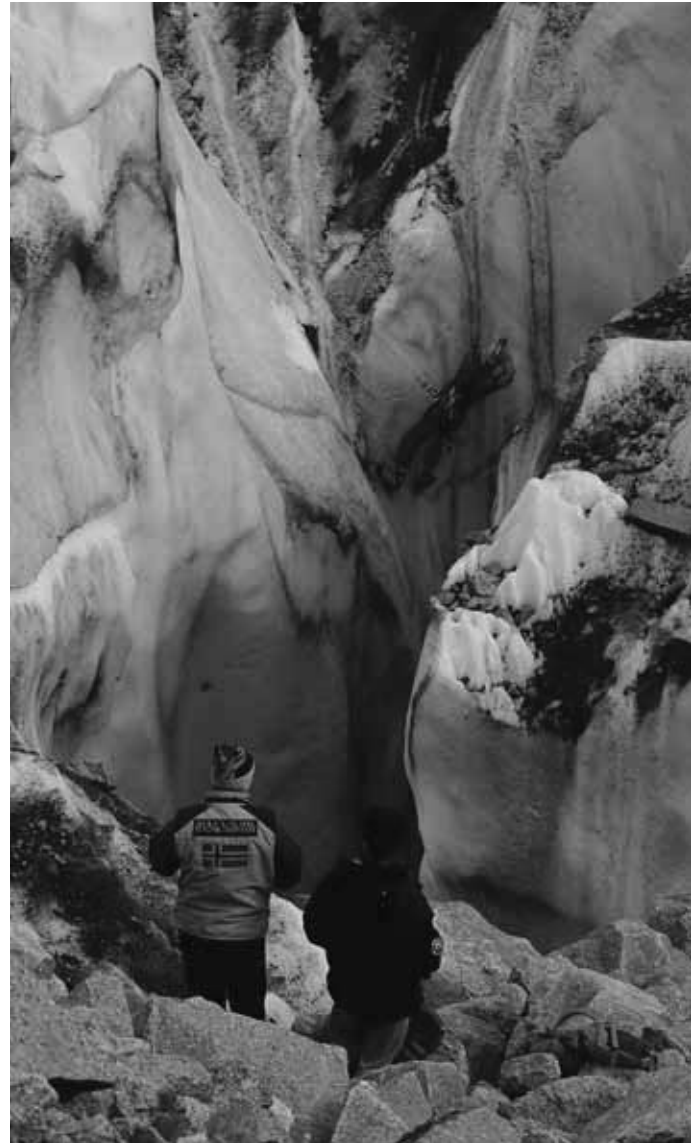
*Enilchek lednik* (Kirghizistan) - This is a very wide and long glacier, descending westbound from the highest area of the Tien Shan Range. The presence of abundant debris on its surface prevents the formation of significant melting structures. The glacier is renowned for the yearly flooding of its glacial-stream that takes place when the Merzbacher Lake, which is formed at the beginning of the summer 14 kilometres upstream of the front, is drained through the conduits that are formed either inside or at the base of the glacier.

During the expedition, carried out in collaboration with Russian speleologists, we only managed to explore the area close to the lake, the only one presenting a well-structured drainage. The explored cavity was mainly a large shaft more than 40 metres deep, likely an old sinkhole that ends with a series of small gorges. Their vaults are made of ice blocks

*Kviar glacier, a secondary tongue of Vatnajökull, Iceland. At the base of a large shaft. It is possible to follow the torrent along tiny sub-horizontal ducts down to the base aquifer.*



*Batura glacier, Karakorum. A vast moulin. The detrital sheet causes serious safety problems for the exploration of these shafts.*



*Opposite. The depth at which the aquifer may be reached ranges depending on the type of glacier and can vary from zone to zone, even in the same tongue. Usually, it is found near 80-120 metres under the surface.*



A moulin in the small Marconi glacier, the first one explored in Patagonia, one of the tongues that encircle Mount Fitz Roy.



melted together, which are close to the lake's aquifer (See Chapter 7).

**Biafo glacier** (Pakistan) - This was the very first non-European glacier we explored with a speleological approach, in September 1987. More than 60 kilometres long, it descends along a South-East direction from the large basin that also feeds the Hyspar Glacier as well as from the tongues coming from the massif Latok Range (7151 metres). Karst phenomena are widespread and quite large, especially in the middle of the very long and extended ablation area positioned between 4300 and 4600 metres. Here the *bédière* and the moulins are formed, regularly spaced, along the sides of the central moraine, probably in correspondence to low-lying zones originated by the differential sliding of the tongues. In this area we explored some small moulins, both active and inactive, down to a maximum depth of 40 metres.

In the lower part, a dozen kilometres upstream from the front, two torrents become quite massive and sink beyond unexplored sub-horizontal portals. That was actually the very first time we could suspect that part of the sub-glacial draining happens just below the surface, without sudden drainage in sinkholes. From a speleological point of view, these rare caves are, no doubt, the most interesting.

**Batura glacier** (Pakistan): This glacier was the subject of an expedition organized by the Gruppo Speleologico Piemontese in 1993, in collaboration with our Association. It is located in the Hunza Valley, on the Pakistani side of the Karakorum, underneath the Batura Peak.

The tongue, not as large as the one described above, presents a well-developed karstification. There are numerous small moulins, a few impressive ones, large sub-glacial blow-out caves and traces of superficial conduits. During the expeditions we also explored several shafts, but in

*Matterhorn really proved to be the Sacred Mountain, the mountain that saw the birth and development of modern glacio-speleology.*





*Opposite top. The base camp on the ridge of Collins glacier, during the first expedition ever carried out in Antarctica, in search of caves.*

*Opposite bottom. Collins glacier. This ice cap glacier covers almost entirely King George Island in the Austral Shetlands. The karstic phenomenon does exist, but it is very limited, due to both the low average temperature and the steepness of the glacier surface.*

*Gorner glacier. Climbing up a vast moulin.*

almost all of them the water stream was so intense that we could not proceed for more than a few dozen metres. The deepest shafts could be explored for 40-50 metres at the most.

### **South America**

*Glaciar Perito Moreno* (Argentina) - This was the subject of a survey in 1994 and of an expedition in 1995. It is a very well known glacier, located on the western part of the Argentinean Lake (in the Santa Cruz province). It is one of the six tongues that drain the Hielo Continental Sur. Patagonian glaciers are characterised by the huge size of their feeding basin (more than 20,000 square kilometres) and this is particularly true for the Perito Moreno. This in turn explains why the draining lines, few and relatively small (!), can descend to relatively low altitudes.

Glacial shafts are numerous and often impressive. The main drain is gathered at the centre of the tongue in a torrent that jumps into a large shaft, which cannot be explored because of its water flow (several cubic metres per second). However, this sinkhole forms many times during a single season, leaving downstream many fossil shafts. One of these, which we entered for approximately 60 metres, continues for approximately 200 metres with large tunnels.

The river is absorbed just upstream from the extension zone, characterised by many crevasses, that precedes the front. The other moulins tend to appear all along the sides of the tongue, where the ice flows are less homogeneous and hence there is a higher permeability.

By far, though, the most interesting aspect is the presence of horizontal, superficial conduits. Amongst these, we were able to explore and map one that was 1150 metres long: it is still the longest glacial cave in the world, as well as one of the most beautiful. Dye-tracing showed that, before reaching the surface, the river still continued under the ice for at least twice that distance.





Enilckek glacier (Tien Shan, Central Asia). Exploration of the very large shaft that forms near the temporary Merzbacher lake. Every year the lake disappears through endoglacial ways and the whole area undergoes stretching stresses, forming imposing caves.



**Glaciar Viedma** (Argentina) - This is one of the largest and grandest glaciers in the whole region. It was the subject of a demanding survey in 1997, which could however only cover a small sector (20 square kilometres) around the base camp. We also surveyed it from the air in 1995 and 2004.

The glacier is located west of the Cordillera that ends with the spectacular peaks of Fitz Roy and Cerro Torre. Surveys spotted numerous moulins, but the state of the surface varies a lot between different zones. Its irregular, almost triangular, shape is characterised by the presence of a huge drainage basin. A *nunatak*, a rocky island amidst the ice, breaks the glacier into several sectors, often divided by hard-to-cross regions with many *seracs*. The same *nunatak* also fragments the glacier's hydrography. In general, waters are usually quickly absorbed into small shafts. In the central part there is a large river that likely sinks into the sliding area located before the front.

Around the *nunatak* there are other very interesting areas; there are also signs that suggest the existence of superficial conduits.

**Glaciar Upsala** (Argentina) - After an aerial survey in 1995, this was the subject of an expedition in 2004. The main Argentinean glacier, it originates from the same region as the Viedma but it drains towards the South.

For the past few years it has undergone a phase of almost catastrophic regression that has drastically affected it. Since 1991 the ice altitude has dropped about one hundred metres, which translates into the loss of tens of cubic kilometres of water. Scientific literature indicates that the balance crisis has been worsened by the fact that, during its slow regression, in the mid 1990s the glacier lost the support of two islets at its front, which prevented it from "crumbling" into the lake. Once such support was gone the whole tongue slid downstream; such massive movement opened crevasses, perpendicularly to the flow direction, up to 12 km

*Upsala glacier. Floating ice blocks (tempano) opposite to the glacier front.*







*Diving in a lake of Gorner glacier.  
Note the morphology of the walls  
excavated underwater when the lake  
level was higher.*

from the front! This in turn completely destroyed the drainage network, both internally and externally.

We found many traces of karstification, which however is completely fragmented by the crevassed areas. The only areas that host some cavities are those upstream from the crevasses and some small zones at the front of the left tongue.

The former is located at the level of the Laguna Azul, which is the only part of the glacier that cannot be crossed. There are many mid-sized rivers that fall into not-so-impressive shafts. In this area we could not carry out any significant exploration, as there were no inactive shafts (the ice flow was too slow for them to form).

The caves that were formed in the left tongue were much more interesting, although at the present melting rate they are bound to disappear soon. They are rather superficial conduits, rather short and occasionally grand, that appear to have formed mostly at the bottom of ancient lakes. They turned out to be very interesting, as they allowed us to see the draining micro-structures inside the glacial mass.

**Glacier Grey** (Chile) - This was the subject of an expedition in 2004. Located in the Paine area, this glacier is a minor, eastbound tongue of the large basin that also feeds the Tyndall Glacier. It shares many similarities with the Upsala Glacier; the research concentrated on the tongue at the orographic left. This latter presents a draining network that fans out with small-sized rivers flowing along very wide and flattened dells. The rivers then run into rather wide, albeit shallow, shafts that tend to fill up with water (indeed, it is not uncommon to find abandoned shafts on the surface, completely flooded).

We explored and mapped 17 caves, up to 70 metres deep but with a plan length of just a few metres.

**Glacier Tyndall** (Chile) - It was the subject on an expedition in 2000. It is the main glacier of the Paine region, with a wide

Gorner glacier. An epidermal gallery.



Opposite. Perito Moreno glacier. Climbing up the immense Coltrane shaft, the largest moulin of this glacier. Its depth reaches 60 metres and gives access to 200 metres of huge galleries.

feeding basin. The tongue descends southbound into the Tyndall Lake, where the glacier's front ends.

The surface of the glacier is rather regular. The whole ablation area is crossed by a series of large, parallel rivers; similar to the Perito Moreno, but on a much larger scale. The rivers flow into large shafts, whose water levels depend on the feeding flow. In one of them we were able to record the water level during a 24 hour cycle, measuring a variation ranging from -10 to -105 metres. For the first time, the loading/unloading curve allowed us to determine, indirectly, that the drainage was located 140 metres below the surface; that was exactly the level predicted by the numeric models of glacial karsification.

During the expedition we descended into a dozen moulins; some of them were vertical, up to 50 metres deep, while others were horizontal and developed like gorges. The englacial water level appears to undergo quick fluctuations, driven by the weather conditions; as a consequence, the shafts (some of which are very deep) can get completely flooded.

Overall, the glacial karst phenomena are quite significant. We did not find any superficial conduits of noticeable length.

### **Antarctica**

Our Association had the privilege of carrying out the first speleological expedition in the Sixth Continent. These are boundless expanses of ice (actually, almost all that exists on the planet...), its temperature is, however, well below zero Celsius. Liquid water can only be found in very limited amounts and for brief periods; glacial karstification can therefore exist only with very small phenomena, or with forms that are totally different from those found in temperate glaciers.

*Collins Glacier* (King George - South Shetland) - In Antarctica we were able to visit only a very small area in a





*Collins glacier. Descent in a crevasse to verify the possible presence of an aquifer.*



*Perito Moreno. Inside a small moulin. The ice is very transparent and its walls diffuse a blue light down to a 50 metres depth.*



*Tyndall glacier. A large shaft.*



*Bottom. Tyndall glacier. Inside a sub-glacial cave.*







*Gorner glacier. A night image of the base camp. The night is the most favourable time to explore glacial caves during autumn, since it is the moment in which the water flows stop almost completely.*

single glacier of the Antarctica Peninsula, just south of the Polar Circle. The other cavities we found elsewhere in the continent are described in a different chapter, as their genesis is completely different.

In this glacier the ablation areas are small and weak (they do not go beyond 100 metres above sea level) as most of the ice loss takes place directly at sea level *via* the formation of large icebergs. We did find some cavities near the coast, but they were quite small and with a maximum depth of a few dozen metres. They were located in the lateral zones of the glacial lobes that descend from the cap and enter the sea.

***Campbell Glacier*** (Terra Nova Bay, Ross Sea) - This glacier was visited during the XVI Expedition of the Italian Antarctica Project. The complete lack of liquid water prevents any form of sliding glacial karstification, but we did find some massive, and unexpected, karst phenomena derived from sublimation processes (see Chapter 6).

### **General remarks**

Through our researches we were able to draw a fairly clear picture of the processes of melting karstification and the associated endo-and sub-glacial forms.

Glaciers cannot exist in areas where the average yearly temperature is much higher than 0 °C; on the other hand, cave-digging rills cannot exist in areas that are too cold, so we expect that the average temperature of the karst glacial areas does not differ much from 0 °C.

We have actually designed a more refined quantitative model that, starting from the seasonal temperature variation, allows us to define an index of potential karstification (**glacier karst factor**), which provides a measurement of the energy available for the thawing processes.

The contact cavities we were able to explore along the edges of the glaciers appear to be linked to localised conditions, in which lateral feedings of rill waters penetrate underneath

*A large entrance in the heart of Tyndall glacier. Situated at the southern limit of Hielo Continental Sur, it is one of the most interesting Patagonian glaciers, with two enormous epiglacial rivers and recurrent oscillations of the aquifers.*



*Perito Moreno glacier. Diving at 24 metres depth.*



*Bottom. Tyndall glacier. Inside a subglacial cave.*



relatively stable parts of the glacier (often corresponding to areas of “dead”, i.e. not-moving, ice). These often-spectacular cavities only rarely extend beyond a length of 100 metres, as they become impassable when the ice thickness is above 30-40 metres.

The low slope that is normally found in the middle part of the largest tongues usually points towards an even sliding and a high ice thickness; in these conditions the effect of the substrate morphology is only marginal. In turns, this translates into an even surface and allows the formation of a superficial draining network, which collects the fusion waters into torrents that can reach noticeable sizes. The statistical elaboration of our findings indicates that the “karst” slope is around 5%.

As far as the formation of glacial shafts is concerned, in general their presence depends on factors linked to morphology, structure and climate. In particular, they tend to form in the areas in which the ice undergoes extensive stresses, as long as such forces stay below the yielding threshold (which would otherwise lead to the formation of crevasses). In these conditions the ice becomes more permeable to the water and allows the formation of water circulation between the torrents’ beds and the pre-existing cavities found downstream. (G.B., L.P.)



*Tyndall glacier. Subglacial cave.  
Contact caves between rock and ice  
are, in general, less interesting and  
can be very risky.*



*Unlike the external anchoring, the internal ones don't present particular problems and it is possible to use the standard ice climbing screws.*



*Perito Moreno glacier. At a depth of - 40 metres.*









*Tyndall glacier. Everyday evening life at the base camp.*

*Perito Meccanico. Its 1200 metre development makes it, up to now, the major glacial cave discovered.*





## Contact caves

*Stalactites of ice (...) hanging from the walls and sides exactly like those in the finest calcareous grotto, but infinitely superior in so far as the light which shews them is not the smoky glare of a few tallow candles, but a mellow radiance streaming from the sides of the cavern itself.*

JAMES FORBES, 1851

### Glacial caves of different origin

Besides the types of caves we have seen so far, created by the ablation waters inside the glaciers (en-glacial cavities), there are two more different kinds: those carved at the contact point between rock and ice (sub-glacial cavities) and those created by sublimation, formed by the contact between extremely cold ice and temperate ice.

The former can originate from outside torrents penetrating into the glacier, or from the inside torrent that comes out of it, as well as by fumaroles or volcanic resurgences of hot water.

Sublimation caves, on the other hand, have only been reported in Antarctica, where the glaciers meet the sea. They can therefore be classified as “sea caves”, as it is hard to imagine the conditions needed for their formation could be found anywhere else.

### Marginal sub-glacial caves

These cavities can be often found along the sides of large glaciers (we detected their presence almost in every explo-

ration). They are formed by the relatively warm waters of torrents that enter the glacier after flowing for a long tract outside. Running onto the rock base, they slowly melt the ice ceiling and gradually widen the cavity.

Of course, what we have seen for the englacial cavities also applies here, i.e., when the ice layer sitting above is thicker than 50-80 metres the tunnel narrows rather quickly. When inside, one has to proceed through a progressively darker and flatter environment, down to the point when the torrent disappears between the rock and the ice.

They are generally very dangerous caves, as their section tends to grow larger and larger until it causes massive collapses, which tend to happen with regular timing. Such events can block the flow, creating a lake along the side of the glacier. At the bottom, tunnels can continue to widen, as we observed both in the Tyndall and Perito Moreno glaciers.

### Sub-glacial caves in the fronts

The caves that can be found at the front of the glacier, at the exit point of glacial torrents, are formed through the mechanism we have just described.

The streams of glacial waters tend to join together towards the end of their internal path and, as the glacier gets thinner near its front, they end up flowing onto the moraine bed and become enriched in glacial silt.

In the very last part the ice is quite rigid and the empty





*Mount Melbourne, Antarctica. The entrance of volcanic contact cavities. The steam that comes out from the galleries below, only partially explored, frosts over at the contact with the icy external temperature and forms a real "well-curb" at the entrance.*

*Preceding page. Tyndall glacier. Small sub-glacial cave.*

spaces carved inside it by the torrent cannot be filled by its plasticity. The result is a wide exit mouth, sometimes quite large and with a complex structure, that can be entered only for a few dozen metres, until the weight of the ice above pushes the ceiling on the torrent. At times, though, from the opening one can access a network of tunnels that can be explored for hundreds of metres, as is the case in the Batura Glacier. As already mentioned, the factor controlling the accessibility is the thickness of the ice above the caves, which should not exceed a few dozen metres. As opposed to what happens with the cavities carved by external water streams, the equilibrium between these caves and the glacial mass is rather stable and they exhibit a limited tendency to become larger to the point of abrupt collapse. This is actually good, as many of these caves are visited by hikers...

### **Volcanic sub-glacial caves**

The sub-glacial cavities that form along the sides of volcanoes due to the emission of hot gas or waters are much larger and easy to explore.

The most significant examples are the caves found on Mount Rainer, a 4400-metre-high volcano in Washington State whose Paradise Cave reaches a length of about 13 kilometres, and the countless volcanic caves found in Iceland. In particular, below the ice covering the sides of a small volcano in the north of Vatnajökull there is a remarkable network of tunnels spanning over five hundred metres between its lower and higher altitude (Kverkfjöll).

Two similar cavities also exist in two Antarctic volcanoes: the Erebus, located near the McMurdo base and sketchily explored by French volcanologists towards the end of the 1960s, and the Melbourne, by the Terra Nova base, which we surveyed in the year 2000.

The cavities formed by the Antarctic volcanoes have a fea-



*Mount Melbourne, Antarctica. Inside the fumarolic cave at the top of the mountain. These are real ecological islands at 0 °C, in an environment where the external average temperature is -40 °C degrees.*



*Tyndall glacier. Under the ice, in a cave subject to recurrent floods.*



*The 15 metre deep shaft to enter the fumarolic cave of Mount Melbourne.*



*Aletsch glacier. Collapse phenomena in a sub-glacial cave. Unlike endoglacial caves, those at the contact between ice and rock can be very fragile and unstable.*



*Bottom. Campbell glacier, Antarctica. Sublimation cave originated by the different temperatures between glacier ice and marine ice.*



ture that set them apart from all the others. In the Sixth Continent, the outside temperature is so low (about  $-30^{\circ}\text{C}$ ) that the water formed by the fumaroles cannot flow away in a liquid form and the steam that escapes from the openings re-freezes immediately, forming a ridge around the entrance of the cavity.

The morphological effects of such features have not yet been studied, but the main consequence is actually biological. These caves are ecological islands in an otherwise biologically impassable sea and have therefore developed a very interesting endemic microbial life (for this reason they have been declared integrally protected areas).

It is possible that the same phenomenon takes place in glaciers found on top of very high active volcanoes, e.g., those found in the Andes, but so far no specific research has been carried out.

### **Sublimation caves**

“Sublimation” caves are a recent and unexpected discovery made during the XVI expedition of the National Project for Antarctic Researches (Progetto Nazionale Ricerche Antartiche) of the Italian Government in the year 2000.

The huge glacial tongues that descend from the Transantarctica range stretch into the sea for up to dozens of kilometres. Their temperature is around  $-20^{\circ}\text{C}$ , a little below the local average, while the sea is approximately at  $-2^{\circ}\text{C}$ . The marine ice that covers it, albeit colder, does not go below  $-6^{\circ}\text{C}$ .

Therefore, the contact areas are characterised by a drastic thermal variation that leads to the formation of cavities, at times quite large, at the front of the glacier. Inside them, the floor is relatively warm and is subjected to constant sublimation; the “warm” water vapour then reaches the ceiling, where at the same time carves by melting and also forms crystal deposits. The rate of carving at the ceiling is

*Gorner glacier. Sub-glacial cave on the right side of the glacier. It is characterised by a strong air draught at  $0^{\circ}\text{C}$  that comes out during the winter, producing sublimation phenomena at the entrance. This proves even the existence of a draining net for the air, inside the glacier.*







*Campbell glacier, Antarctica. A wide entrance in the front of the glacier. This type of glacial cave forms without the liquid phase. The ice that slides from the Antarctic plateau has a temperature of about -20 °C and stretches out for kilometres, floating into the sea, whose temperature is -2 °C. The thermal contact brings on sublimation which, little by little, creates even imposing structures.*

*Following pages. The arrival on the ice-pack, at the karstified front of Campbell glacier, not far from the Italian base of Terra Nova, Antarctica. So far, the coldest explored cavities in the world, many of them menacingly ready to collapse.*

impressive - centimetres per day, in striking contrast with the apparent frozen motionlessness of these environments.

The largest cavities also present a strong air stream arriving from the heart of the glacier, through unknown paths. Such current probably plays an important role in removing the excess of vapour from these extraordinary caves, which are the coldest known in the world.

Unfortunately, until now we haven't been able to perform more accurate studies, but we hope to do so in the future. (G.B.)









# Jökulhlaup

*L'acqua, tenuta così sospesa entro il ghiacciajo suddetto, formando una colonna dell'altezza di un centinaio di metri, doveva necessariamente premere con forza idraulica immensa contro la morena frontale, cioè contro la collina del Belvedere, che gli si addossa sbarrando quasi per intero la valle. Infatti quella colossale barriera fu d'improvviso forzata e sfondata, aprendovisi, con un rumore simile al tuono, da cima a fondo una breccia della larghezza di settanta metri e più. Fu quello un vero diluvio glaciale. Il torrente, rotto ogni freno, portando nella sua furia la crollante morena, ne disperse i ruderi giù per la valle, lasciando una area di un chilometro quadrato e più sepolta sotto una valanga di massi, molti dei quali possono misurare da quattro a otto metri cubici di volume.*

The water, held floating inside the above-mentioned glacier, must have formed a column at least a hundred metres high. It surely had to exert an immense hydraulic pressure against the front moraine, i.e., the Belvedere hill, which leans against it blocking the valley almost completely. That massive barrier was, in fact, suddenly bored and crashed. A top-to-bottom crack, with a width of 70 metres or more, opened up with a thundering noise. That was a real glacial deluge. The now unrestrained torrent carried in its fury the crumbling moraine, spreading its remains down in the valley. An area larger than one square kilometre was then buried under an avalanche of boulders, many of them had a volume of four to eight cubic metres.

ANTONIO STOPPANI, 1876

## The second river in the world

In November 1996, in the Southwest of Iceland, the flow of an insignificant river, just 25 km long, swelled until it reached 50,000 cubic metres per second, stealing, for a few hours, the river Congo's privilege of being the richest water in the world after the Amazon. A piece of geographical news, spread all over the world by TV newscasts, called by the unpronounceable Icelandic word used to define these not unusual phenomena in that island: *jökulhlaup*. Literally, "glacier's flood".

Under the huge ice cap of the glacier Vatnajökull a volcanic eruption had released 330 billion kWh, ten times the power of the Hiroshima bomb, melting more than 3 cubic kilometres of ice. The water had moved away filling a subglacial caldera, the Grimsvötn. The Icelandic volcanologists knew that, in a short time, the water would have found a way out to debouch 50 kilometres south of Skeidararjökull, the major glacial tongue that descends from the Vatnajökull. The area from which the harmless river forms was evacuated.

From 8 a.m. of November 5<sup>th</sup> to 4 p.m. of the following day, three billion tons of water spurted from the glacier and overflowed towards the sea, sweeping away any man-made object in its way.

The movement of the water from the area where it had formed to the one from which it debouched happened through inner ways, inside what surely was the world's largest cave (albeit with an ephemeral existence).

Less than two years later, we went there to find the trails of



*In the exit area of the flood, the glacier was carved for over one kilometre of depth and width, while icebergs weighing thousands of tons, ripped by the river, floated away.*



*Restoration works opposite the Vatna glacier front. For a few hours, the river spurting from it became the second major river in the world, almost 60,000 cubic metres per second.*

*Preceding page. Vatna glacier, Iceland. The immense flood rushed out from the heart of the glacier swept away all traces of human work in front of it, digging out a new kilometres-wide riverbed.*

*Pont Saint Martin, Lower Valle d'Aosta. The stupefying roman bridge. The dimensions of the work, excessive if compared to the modesty of the river, might be connected to the fear of eventual floods due to the melting of the glaciers above.*







*The chaotic surface of Enilchek glacier. In the background, Metzbaier lake, that every year empties succeeding in finding a 14 km long way through the ice.*

the river mouth and the traces of the cave through which the river had crossed the Vatna.

The survey allowed us to analyse the final area where the river had flowed, where a “fjord” 300 metres wide and with a depth of 1 kilometre had been excavated at the front of the glacier. It was really incredible. From there, icebergs weighing up to 5000 tons have been ripped away. Those weighing up to 2000 tons were floated by the river, which used them as battering rams to remodel the area in front of the glacier. Where once there was a very long, frail bridge, now there was the quiet, flat sand desert that glaciologists call *sandur*. Then, we succeeded in climbing over the glacier and proceeded for about 10 kilometres towards the top, searching inside the numerous caves for a tell-tale air draught that demonstrated how, in the depths, the Monster would still be detectable. Instead, we demonstrated the opposite: the conveying gallery has disappeared and the ice plasticity had completely restored a coherent drainage network.

The only remaining traces were the *scallop*s, proving that there were water outlets from the lower moulins, and the surface appeared slightly depressed in comparison with the surrounding areas. The depressed zone was a few hundred metres wide, with a drop of about a dozen metres.

The gallery was so wide that in a short time it had collapsed under the weight of the vault.

### **Central Asia**

Enilchek Glacier lies in Kirghizistan, central Asia, just at the easternmost end of the country and of the Tien Shan range. It flows in two branches, under the two highest mountains of those areas, Kask Chaal (or Pic Pobeda, 7450 m) and the marvellous Chang Tengri, of about 7000 metres.

It is stretched over a vast valley (it is said to be the world's third largest glacial valley, outside the polar zones), dominated by stony mountains; the action of past glaciers has rounded every landform, leaving only the tongue we call



Enilchek. In a lateral valley, fourteen kilometres upstream of its mouth, we find Lake Merzbacher. Five kilometres long, one kilometre wide and 130 metres deep, it is named after the German geographer who described it in the early twentieth century. Downhill from there, the glacier stands as a dam but every year in August the water pressure rises enough to cause the opening of unknown galleries in its depth. The lake level begins to lower, while the torrent mouth becomes larger and larger.

In a matter of two or three days the small river in the front turns into a giant, with a flow of about 800 cubic metres per second (just a bit less than what is found at the mouth of the Po River). The lake level quickly decreases, exposing its bed, while the surrounding ice, not restrained anymore by the water, discharges icebergs into the lake. In a few days it is all over. The valley is empty and the torrent returns to a normal flow of a few hundred litres per second.

### **The Gornersee**

The largest glacial flood in the Alpine range happens yearly in the Gorner Glacier, in the Vallese zone of Switzerland.

Gorner is formed by the confluence of several tongues, the main ones merging at the foot of the massive Monte Rosa. Where the two main ice streams meet, there is a wide depression, roughly of triangular form, just at the foot of the western steep flank of Monte Rosa.

In springtime, with the snow melting, the depression is filled by water, forming the Gornersee Lake, which extends for about 20-30 hectares and reaches a maximum depth of 50 metres. At the moment of its maximum expansion it usually receives something like 4-6 million cubic metres of water, but there are years in which its estimated volume has exceeded 11 million.

At the end of spring, usually during the first two weeks of June, the lake is on the point of overflowing and the hydro-



*Opposite. The exit mouth of Enilchek glacier, from which every year the water of Merzbacher lake comes out, reaching a flow of 800 cubic metres per second.*

*A big block of ice left from the subsiding of the damming lake which forms every year at the margin of Gorner glacier.*





*Grey glacier, Patagonia. Glacial shaft completely filled by water.*



*The wide moulin named Vicecapo (second-in-command), a shaft in which the water level daily varies from -15 to -105 metres. The study of the fluctuation curve determined that the drainage occurs 140 metres under the surface.*

*Gorner glacier. Draining gallery of Gornersee, the glacier's lake that every year empties through internal ducts.*

static pressure is enough to make the surrounding ice mass rise. This way, the water mass seeps under the glacier, exerting a pressure on what is left of the subglacial channel network that has formed during the previous summer. Shortly after, the torrent that pours from the glacier front, about 5 kilometres towards the valley and almost 400 metres lower, undergoes a sudden flow rise. In a few hours it goes from a few cubic metres per second to several dozen. From the information in our possession, in 1944 the maximum flow recorded reached a peak of 200 cubic metres per second, but usually the flow peak does not exceed 30 cubic metres per second. Quite a negligible amount, if compared with other documented events all over the world, but very impressive for the channel that crosses the peaceful village of Zermatt. In a few days, the lake dries up and the glacier repositions itself on its rock bed. Perhaps this phenomenon could have an important role in the reactivation of the moulins, which in that phase change from the winter, flooded situation to



*Gorner glacier. The sub-glacial torrent that comes out from the front of the glacier during the summer season.*



Gorner glacier. Entrance to a gallery  
in one of its epiglacial lakes.



the summer one, with a rapid flow.

Big blocks of ice, which only a few days before were floating on the lake, now lie with sandy and slimy sediments on the dry bottom of the basin.

For several months, the first 100-200 metres of the drainage channels are still passable. In October 2000 we had the chance to cover a tract of 150 metres, roughly the point where the thickness of the ice, exceeding 50-60 metres, is enough to crush the vault of the conduits, lowering them to a height of a few centimetres.

### **Glacier floods**

An event similar to that of the Vatnajökull, helped by the middle-Atlantic *rift*, over which it leans, is definitively an exceptional phenomenon. Yet, all glaciers are more or less able to produce similar disasters, though on a smaller scale. The reasons have been partially discussed in Chapter 2: a large water basin that formed inside a glacier tends to increase. Practically, it continues to accumulate water and energy, unable to discharge them until something yields and then the whole mass is released.

In huge glaciers, this break out evolves slowly (hours or days), because the deposit is held back by gigantic masses of ice, and the only thing the water can do is force a way through them. At that moment the discharge begins, tending to rise quickly, because the running water widens the passage until it reaches an enormous dimension, as in the Icelandic event. However, it is not a sudden release.

In the smaller glaciers, the ice dam may be so thin that it could be capsized by the water pressure, releasing in a few minutes the energy accumulated throughout the years.

These glacier floods tend to happen in periods during which the climate becomes warm, owing to the concurrence of three phenomena. The first one concerns the melting process, which becomes very intense and deposits a large quantity of water where before only ice was accumulated.

*Enilcheck glacier. Ascending the big  
moulin that opens near Merzbacher  
lake.*







*Tyndall glacier. Glacial shafts turned into water deposits. They can open a few metres away from active and deep pits and this proves that the glacial groundwater can be independent, even at a short distance from each other. We have observed, on many occasions, the quick and dangerous rise of the water level in the caves, explainable only as internal pouring from one aquifer to another.*

The second involves the glaciers that are in a withdrawal phase that, while receding, “thin” the dams that held back the inner basins. The third and last is connected to the reduction of their thickness; a fact that slows down their progression and makes the excavation of caves more and more frenetic over the same zones, widening them over the equilibrium level.

Just at the entrance of Valle d’Aosta, on the hydrographical left, there is an impressive clue suggesting that, in the valleys that have a glacier at one end, warm climate phases lead to massive floods. The spectacular arc of the roman bridge of Saint Martin appears absolutely excessive to avoid the “normal” floods of the torrent that it crosses; in fact, the extreme floods of 1994 and 2000 didn’t even reach the basis of its pillars. Yet, that arc of 36 metres, whose height is passed only by the Trajan Bridge over the Danube, didn’t look excessive to Roman engineers. They probably had gathered testimonies of anomalous floods, *jökulhlaup*, from the Lys Glacier, which took place in those last centuries of a now-forgotten global warming cycle.

The bridge had to protect the hugely important “Way to Gaul” from the impenetrable peculiarities of a glacier. It succeeded. Quite different matters overwhelmed that road and the Empire. In these last decades, the Lys Glacier has shrunk almost out of existence, but the farsightedness of those designers is still amazing. (G.B., L.P.)





## Environmental techniques

*Les guides fixèrent au bout de la corde une planche qui me devait servir de siège, puis ils m'attachèrent à cette même cordeau moyen d'un courroie qu'ils me passèrent sous les bras de manière à me laisser les mains libres. Pour me garantir contre l'eau qui n'avait pu être détournée complètement, ils me couvrirent les épaules d'une peau de chèvre et me mirent sur la tête un bonnet de peau de marmotte. (...)*

*J'ordonnai aussitôt qu'on me remontât; mais l'ordre fut mal compris, et au lieu de me remonter, on me laissait toujours descendre. Je poussai alors un cri de détresse qui fut entendu, et l'on me retira avant que je fusse dans le cas de nager. Il me semblait que dans ma vie je n'avais rencontré d'eau aussi froide; à sa surface flottaient des fragments de glace, sans doute des débris des glaçons. Les parois des puits étaient âpres au toucher, ce qui provenait sans doute des fissures capillaires.*

*J'aurais bien voulu pouvoir m'arrêter plus longtemps à examiner les détails de la structure de la glace et à jouir du spectacle unique qu'offrait le bleu du ciel vu du fond de ce gouffre; mais le froid m'obligea à remonter plus vite.*

The guides tied a wooden board to the tip of the rope, to be used as a seat, then they anchored me to the same rope by means of a strap, passing it under my arms, in order to let my hands free. To protect me from the falling water, which could not be totally deviated, they covered my shoulders with a goat skin and made me wear a marmot skin hat. (...) I immediately ordered to be pulled up; but the order was not well understood, and in place of rescuing me they kept lowering me further down. I then uttered a cry of discour-

agement, and finally they rescued me before I drowned. I thought I had never experienced such cold water in all my life; some ice fragments, pieces of icicles, floated on its surface. The walls of the shaft were rough, surely due to the capillary cracks. I wish I could have stopped for a longer time to examine the details of the ice structure, and to rejoice at the unique sight of the blue sky seen from the bottom of the shaft; but the cold forced me to reach the top as fast as possible.

L. AGASSIZ, QUOTED IN EDMOND DÉSOL, 1844

### Environmental conditions

A lot of water has run into the Aar glacier moulin, into which, back in 1848, the fearless Swiss glaciologist had had himself lowered. It was the very first time that someone actually answered to the fascination of glacial shafts. It was a great, maybe foolish, proof of courage, if we consider the overwhelming gap existing between the environmental conditions and the materials available at the time to face them. Today's (few) glacio-speleologists have to move through the very same environment, but the technical materials, the outfits and the practical and theoretical knowledge about the glaciers and their cavities are quite different from those available a century and a half ago.

Yet, exploring glacial moulins is a tricky business, constantly in need of materials and techniques that would allow the surpassing of many obstacles that still exist, or at any rate to decrease the risks linked to such activities.

Single rope techniques in glacial caves are identical to those used in caving in limestone caves, with a waist ascender fixed on the harness and another jammer on top of it connected to the foot sling.



Preceding page. Night snowfall over the attempt to dive into the deep waters of Gorner glacier. The dives must take place in late autumn, when the entering water flow has almost stopped but the winter rise of the glacier aquifers has not yet started.

### Searching for moulins

In order to descend into glacial moulins one has to find them first, following, and often crossing, the course of rushing *bédrière*, walking long stretches of glaciers for hours at a time. The outfits used for these researches differs from that used for the descents and this in turn means that one has to carry along twice the amount of materials compared to a normal hike. On the surface one uses a standard mountain outfit, appropriate for the local weather conditions that can be quite different depending on latitude, altitude and season.

Shoes play a fundamental role, too. Although it might not seem so, it is better to wear light climbing boots, as they would be less tiring for the feet during long traverses.

As already mentioned above, areas one should search in are the ablation zones, where it is often possible to move around without the aid of crampons, especially during the warmest hours of the day, when the sun has demolished the hard and smooth surface of the “nocturnal” ice. At times, however, one has to pass areas with crevasses or *seracs*, where crampons are absolutely indispensable.

Rope progression calls for the use of the individual techniques and equipment that are normally used in speleology.

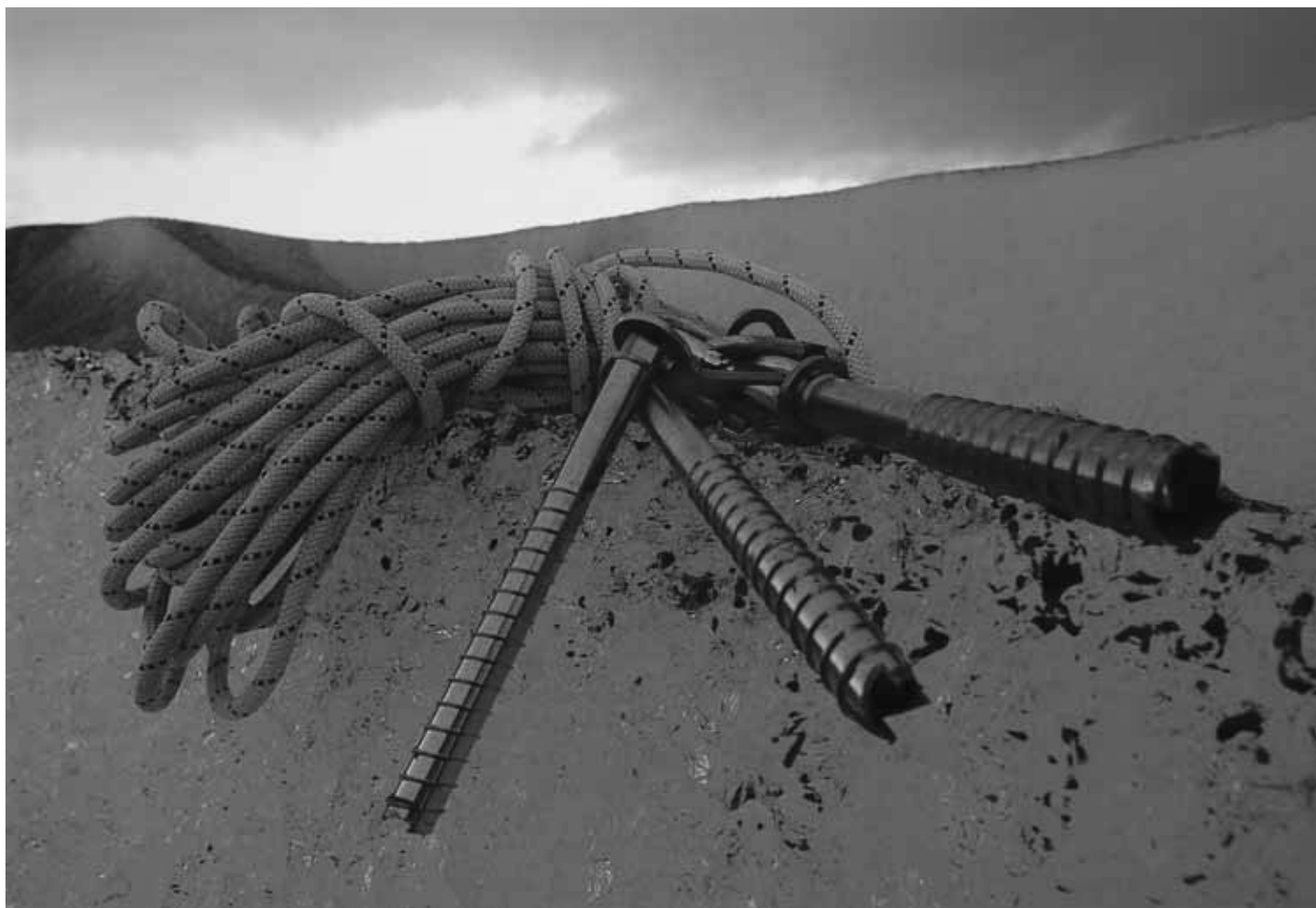
Last but not least, personal equipment must include an ice-axe, to be used in the most demanding tracts, and a pair of telescopic poles, inseparable partners for coordination, balance and small-scale probing of treacherous zones.

### Anchoring in glacial shafts

Upon reaching the moulins, one has to set them up for the descent by placing static ropes of the kind used in speleology (usually the 9 mm type, not too heavy and bulky to carry around). Anchors are set with mountaineering ice screws. These are hollow pitons made of aluminium or titanium alloy, twenty to thirty centimetres long, which carry an external thread in their terminal tip and a closed fastening ring to the other end.

The anchoring points placed at the entry of the shaft are the

*Glacial shafts are equipped with common caving static ropes and tubular ice screws for ice climbing.*







*External rigging is particularly delicate, because the screws rapidly melt the ice in which they are inserted.. Risk may be reduced making use of peculiar rigging techniques with double anchoring and a lot of experience.*

most complex to set, as the ice is not very compact and the pitons, exposed to the external heat, tend to melt the ice around them. Nowadays it is almost standard procedure to use a double, "in parallel" anchoring. This involves the insertion of four screws, linked in couples with rope rings. The two fastening points so obtained are then linked with a third ring, which connects them in parallel; finally, the third ring is used to hook a karabiner, which becomes the main anchoring point.

For enhanced security, the end of the descent rope is also tied to one of the pitons before being fastened to the main karabiner. Pitons must be covered with crushed ice or, better still, with aluminium foil.

Besides distributing the load amongst four pitons, the great advantage of this arrangement is its capability to withstand traction from any direction. This greatly simplifies the rigging procedures, as often in complex shafts one does not know right away what the descent direction will be like. This anchoring can be set high up, in a safe area, and then used both for the initial inspection and for the actual descent.

A few metres into the shaft the effects of the sun and of the external temperature are gone. The problem of the screw sliding out is then replaced by the need to arrange the descent line so that it is as sheltered as possible from the fall of water and ice blocks. Regular ice screws can be used from here on.

Rigging the external anchoring point is always a complex problem, but nowhere more so than in Patagonian glaciers. Here the challenge cannot be solved with standard tools, as the external temperatures can be so high that they can melt up to twenty centimetres of superficial ice in one day. The ice is then filled with water, especially in the parts closer to the surface. Once a screw is inserted it quickly becomes a point of preferential melting (as it absorbs the solar radiation and conduces the heat of the air down inside) and in a matter of few minutes it widens its seat into a conical shape from which it easily slides out. Multiple screw rigging is also completely unsuitable: once everyone has resurfaced a little shake to the rope is all it takes to extract all the

*Diving in such icy water needs particular precautions to avoid the blockage of the valves, in which air expands and therefore the temperature falls under 0 °C degrees.*

*Inside glacial caves rigging on ice screws is very reliable, unlike external anchoring.*







*Collins glacier, Antarctica. Survival hole. The catabatic wind had destroyed the camp and forced the speleologists into this ditch, frenetically dug.*



*Following pages. The big epigacial torrents often represent an almost insurmountable obstacle, requiring long walks to bypass them. The simplest way to dodge them is using "tyroleans", provided that it might be possible to rig reliably.*

*"Triple V" rigging is the most used. It allows the distribution of the load on four screws.*

pitons from their seats. It is not a nice feeling, although the time needed to dismantle the rigging is quite reduced... In practice, there should be an external support team that continuously replaces the anchoring points. All this led to the need to develop a new kind of piton.

Our initial experiments date back to 1994, when, during the preparation of the Perito Moreno expedition, we made new, stainless steel pitons that were three times as long as the commercially available ones.

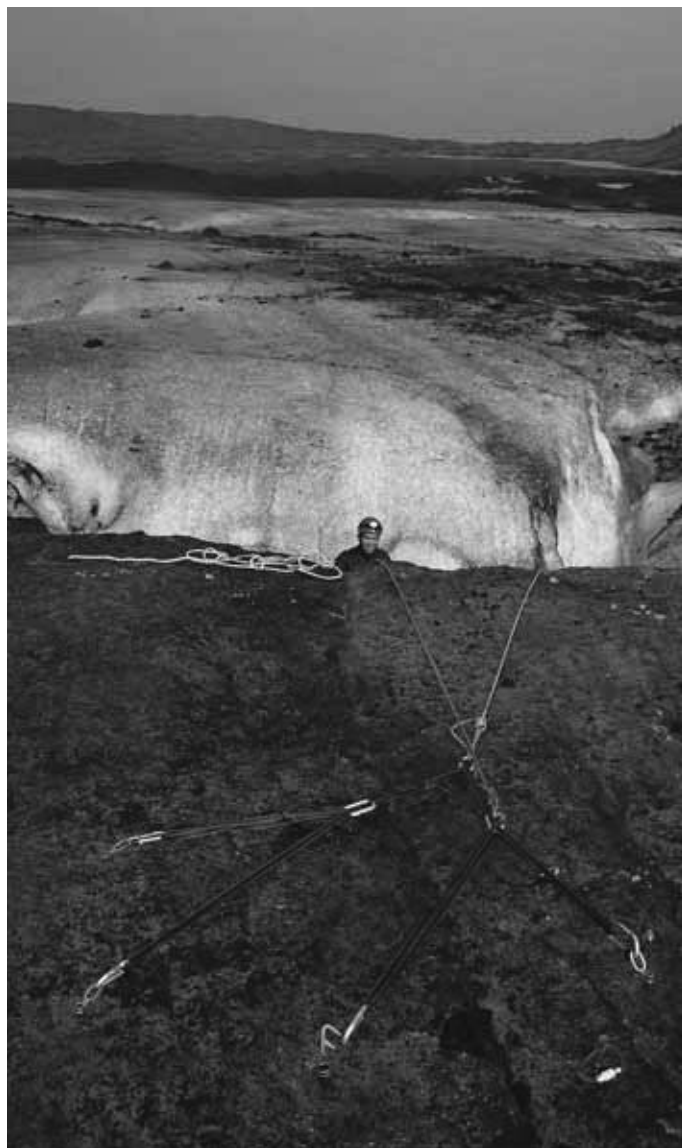
These screws were adequately safe, but in very warm days the ice around the seat still melted too much for a thread of that depth. At any rate, the thread was too shallow compared to the total diameter and the safety margins were drastically reduced. The real solution had to be found in a different thread.

In 2003 the second generation of ice screws was born, made, as the previous one, at the manufacturing facility of the Bernardi High School for Technical Professions in Padova. Again, pitons were made both in stainless steel and aluminium alloy.

They are 60 centimetres long, with an external diameter of 40 millimetres and a thickness of 3.3 millimetres. However, the epochal change, which also created the most problems in their making, was the 5 mm deep screw thread, characterised by a 12 mm pitch and, above all, a 4-5% slant (i.e., the pitch of the thread is less than 90°). This way, while the screwing-in phase is normal, the extraction is much more difficult. Besides, the thread covers half the length of the piton.

Altogether, this means that the ice-metal contact surface is huge compared to standard pitons and even in the case of melting the shape of the thread prolongs the grip. The contact surface is also increased because the thread covers the whole distal half of the screw, rather than being just at its end.

As far as the binding heads are concerned, the aluminium ones were derived from a solid block, bored and polished with loving care, whereas the steel ones were derived from a 1 cm plate, bent in a press and then bored. They should stand a load between 4000 and 5000 kilograms. We could easily use them to







*Safety calls for a minimum admissible rigging distributing the load over at least two common ice screws.*



drag Patagonian icebergs to the warm African climates... The use of these pitons makes the quadruple anchoring unnecessary; one piton is always enough, although sometimes we use a pair to make the rigging more practical.

### **Clothing**

Inside glacial caves, the main technical problems derive from the very peculiar environmental conditions: walls of polished ice, a water flow rate with conspicuous daily variations, shafts that can be quite deep.

Temperature is always around 0 °C, with the co-existence of water and ice. To us, it would be better to have temperatures well below zero and no water; for this reason we often decide to go for night explorations, when the waterfalls are much less intense or have stopped altogether.

It is easy to see, then, how down there clothing is the critical aspect; not for the cold, which is not too extreme and indeed one can still sweat while working, but rather for the water, which wets the walls and falls down into the shafts. Clothing must therefore be waterproof, breathable, warm and yet not clumsy. At present, no outfit fulfils all these requirements and therefore we have to choose between different solutions, depending on the features of the cave we are going to descend in.

As far as thermal insulation goes, mountain woollens or caving polyester fibre suits are enough. In any case it is not a good idea to overdress, as normally one does not spend too much time in the caves.

In vertical, not too-wet caves, on top of the jumpsuit one can wear water-resistant garments, possibly made with breathable fabric. In the presence of waterfalls causing a lot of mist it is better to opt for highly waterproof fabrics, such as canoeing or sailing suits (two-piece sets are also acceptable). When one has to pass flooded areas, however, there is no alternative to wearing a scuba or sailing watertight wetsuit.

Feet must be protected from cold and water. A good solution is to replace the inner shoes of a pair of plastic ice-boots with a

*The internal environment of glacial caves is not much colder than what we find in common alpine limestone caves and, generally, warmer than the outside. The real difficulty comes from the water, often with large flows in very narrow spaces.*





*Diving into glacial basins is still at the early stages.*



*The ropes must be anchored with screws where they touch the wall to keep them from penetrating the ice or making the ascent difficult.*

pair of tall neoprene boots, worn on top of thick socks. If one is careful enough, in many occasions a pair of regular ice-boots will suffice. Gaiters can be useful, too, both to prevent the entry of water or ice from the top of the boots and to protect the lower part of the pants (or of the wetsuit) from being ripped by the crampons.

Hands must be well protected at all times, not much from the cold (which is never too intense) but from the roughness of the ice. When in dry caves, normal waterproof mountain gloves do just fine, whereas in wet environments one can use lined, rubber work-gloves or neoprene scuba or canoeing ones.

Wearing a helmet is a must, as the fall of small fragments of ice detached by the ropes or by the other team members is quite common.

On the boots one must wear crampons. They don't have to be particularly sophisticated; a pair of light, 10-spikes will fit the bill. In vertical caves, one has almost invariably to climb with ropes, which means one has to be equipped with regular speleological climbing gear: harness, descender, chest ascender, handle with pedal, safety sling and the regular provision of karabiners. Carrying at least one hammer/ice-axe is useful, if not indispensable.

Proceeding through meanders or semi-flooded horizontal conduits might require either rigging the walls with static ropes or stem progression, which are easier to describe than to carry out. Lighting can be provided by headlamps with ultra-bright LED; they fulfil the need for a lightweight, reliable and sturdy light source with suitable battery duration.

Four or five LED's usually provide enough light, given that the white and glossy walls of ice caves are highly reflective. Acetylene speleological lamps are not in use anymore, as they are heavy, bulky and with a water reservoir that can freeze.

### **Underwater explorations**

For the past few years people have been trying to explore the glacial aquifer by scuba diving, given that, as we have seen above, most of glaciers' enigmas are hidden in their submerged parts.







*Common rope caving techniques provide the descent using particular devices which amplify the friction on the rope (descenders) and the ascent with a couple of auto blocking systems (ascenders). Ascending speed is generally around 7-10 metres per minute.*

It is, however, an extremely difficult activity that is reserved only for well-trained professionals. The equipment is the same as that used for cave diving, with double tanks and independent regulators. So far, there have been dives in epiglacial lakes (Gorner, Switzerland), in flooded crevasses and in flooded superficial conduits (Perito Moreno, Argentina). These were not attempts to pass siphons to continue the exploration beyond the flooded tracts; here the aim was to study the morphology in sections that could not have been reached otherwise.

As one can easily see, the main problem is represented by the low water temperature, which forces the divers to don water-proof suits with thermal outfits underneath. The hands are the most critical point; since one needs to be able to use them, they cannot be protected by exceedingly thick gloves.

Also to be remembered is the extremely cold temperature of the air that the diver breathes. Altogether, these factors reduce the diving time to a few dozen minutes.

From a technical point of view the main problem is represented by the possibility that the first stage of the regulator jams because of the low temperature, thereby providing a continuous airflow. The same problem can happen with the valves of the waterproof suit.

Underwater explorations of the glaciers gave us the gift of extraordinary images, even though we are still far from being able to follow the course of submerged tunnels for long stretches. Who knows if we will ever be able to do so. We wonder, though, what would Agassiz say if he could see, perhaps with a touch of envy, the images of us “glacionauts” at the bottom of the holes in the water? (A.D.V.)



# Conclusions

## Glacial karst: is it real karst?

The term karst, derived from the geographic area located inland between Trieste and Lubiana, has long been used to describe the phenomena of alteration and modelling of calcareous rocks.

It is a process that originates from the water-driven chemical dissolution of these rocks that, in time, create a landscape whose features are a poorly-developed superficial draining, the presence of closed hollows (the dolines) and underground karst systems (the caves).

Recently the term acquired a wider meaning, as morphological and hydrological situations like these are not limited to limestone alone; for example, they are also found in dolomites, gypsum and sometimes in quartzite. Besides leaching, there are often other kinds of carving phenomena; karst systems, especially the largest ones, often have a “polygenetic” origin.

The term “pseudo-karst”, on the other hand, indicates those cases in which there are shapes similar to those found in real karst but dissolution was completely absent or played a negligible role.

Amongst the many cases of morphological convergence with actual karst, glaciers are striking from several points of view. Quite often, their superficial morphology is very similar to that of karst areas and, due to the presence of cavities that “swallow” the superficial glacial torrents, the two hydrogeological layouts are also very much alike.

Altogether, the phenomena that go under the name of

“glacial karst” are based on a process, the melting of the ice, which differs from dissolution in that it is regulated by thermal, rather than chemical, equilibriums. At the end of the day though, the final result is the same and the landscapes are shaped similarly.

So, although it is wrong to say that the ice “is dissolved” by the water (it actually melts, or liquefies) the result is comparable to what happens when a salt goes into solution. Of course, in the former case solvent and solute are two different phases (liquid and solid) of the same substance.

What should we call, then, the phenomena that within the glaciers lead to conditions virtually identical to those found in actual karst areas?

The best term would probably be “glacio-karst”. Unfortunately, this word is already used by geomorphologists to indicate the rock karstification processes that take place in glacial areas, in which liquid water derives from the melting of ice or snow.

A second alternative could be “thermal-karst”, which some authors use to refer to the melting shapes found in the glaciers. Once again, though, the term is already used to indicate the pseudo-karst phenomena created by the melting of soil that is usually frozen (the *permafrost*). These forms are typical of cold regions, especially those at high latitudes.

For all these reasons a specifically created committee of the Union International de Spéléologie (UIS) suggested using the term “cryo-karst”, i.e., ice karst phenomena.

Truth to be told, this word reminds one more of the processes

Glacial shaft in the Tyndall glacier.



Preceding page. Inside Brunello di Montalcino, the first cave explored by a speleological expedition in Antarctica. As a matter of fact, it is a quite small cave compared to those found on glaciers in warmer zones.

linked to freezing (like the “cryo-clastism”, the breaking of rocks caused by the freezing of the water present in their fractures) rather than to the opposite process of melting. Unfortunately, there are no alternatives and the official, correct name to describe melting-driven pseudo-karstification phenomena within the glaciers is *cryo-karst*.

If we do not want to put too much emphasis on strictly terminology matters, we can generally talk about *glacial karst*, thereby highlighting the extraordinary analogies that exist between glaciers and karst areas. (L.P.)

### Glaciers and climate

The huge structure of a glacier is hence the final result of the balance between the accumulation of snow at high altitude and its melting in the lower zones. Such process is mediated by countless factors such as the morphology of the ice bed, sun exposure, the presence of superficial debris, the ice temperature, latitude, average cloud cover and so forth. A warming of Earth’s climate raises the altitude where the yearly average temperature is 0 °C but, on the other hand, it increases the evaporation from the seas. More evaporation then means more precipitations, which, above a certain altitude, are always in the form of snow. For a glacier, then, climate warming means more melting but can also mean increased feeding; besides, as temperatures rise the ice becomes more fluid and the glacier can slide faster.

The relative weight of each of these contrasting factors depends on the particular situation of each tongue; this is why one can find a glacier that is progressing just beside another one that is in regression.

Altogether, though, we can say that, especially in the Alps (steep and with small-sized accumulation zones), the present warming phase is causing a marked regression in the tongues.

This is not happening for the first time, as shown by the quote by Bourrit that opens Chapter 1. That piece was writ-



ten by one of the founders of glaciology, who was describing the slow progression of the glaciers. The Author had gathered the collective memory, passed down by the inhabitants of the valley, of a time when one could reach Courmayeur from "Chamouni" crossing the Giant's Mount. Yet, that passage was by then blocked by a large ice mass, as it now still is. Bourrit was writing when glaciers had reached their maximum extension, at the peak of a cooling cycle that had started some centuries before.

Now the climate is getting warmer, almost all glaciers are withdrawing and some will disappear altogether. However, we can rest assured that they will be back, even though it will take a long time.

As years go by, snow will accumulate again on Mont Blanc. The tongues that descend from it will merge and will proceed, larger and larger, towards the sea, year after year. They will once again plough the Valle d'Aosta, as they already did countless times up to a moment ago, carrying along the remains of what we once called Courmayeur and Aosta in an entangled moraine mass down to where Ivrea now stands.

And this will also happen in the Susa Valley, as well as in the North American and Patagonian Plains.

All this will happen for sure, slowly for the eyes of our descendants but quickly in geological terms. The ice deposits we now see are the buds from which huge glaciers will form, reclaiming vast expanses of planet Earth and reducing its seas.

Studying their internal structures has useful applications, but it is first of all a beautiful privilege. It is like watching the planet's geology in a cranked-up movie, appreciating, from one year to the next, the shifting in the waterways, in the shapes and in the network of micro-conduits that secretly drain them. It means discovering the functioning of what Agassiz called "God's ploughs".

Glacial speleology is very young, born as a spin-off of sport

speleology for strictly aesthetic appeal; yet, many clues have us believe that, in the future, our skills in penetrating the "floating world" lying underneath the glaciers' white surfaces will gather a lot of interest.

There is still an infinite territory to explore out there. (G.B.)







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