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THE GLACIER CAVES OF GORNERGLETSCHER (SWITZERLAND): PRELIMINARY NOTES ON THEIR MORPHOLOGY AND HYDROLOGY

ABSTRACT: PICCINI L., *The glacier caves of Gornergletscher (Switzerland): preliminary notes on their morphology and hydrology.* (IT ISSN 0391-9838, 2001).

In the last 15 years, several investigations in englacial and subglacial caves have been performed in the Alps. The most interesting results have been obtained from Gornergletscher, in the South West of Switzerland, one of the widest glaciers in the Alps. It descends towards WNW from the M. Rosa group, receiving important tributaries from the left. In the ablation zone, between 2600 and 2400 m of altitude, the glacier exhibits a karst-like topography. In this area the surface is relatively planar and a few fractured; this morphological condition allows the surface drainage of meltwater. Some streams feed supraglacial lakes, most of which have no surface outflow.

Meltwater from supraglacial basins often plunges down into vertical holes (moulins) which feed directly into the englacial drainage network. Presently, the surveys have allowed to recognise two different types of moulins: the former is characterised by a vertical pattern, with a first shaft commonly deeper than 40-50 meters; the latter has a gently-dipping development with a small shaft in the entrance. Some of the first type glacier shafts have been explored to the water-table (varying from –30 to –140 m).

On the ground of our observations, the initial geometry of moulins depends on local structural factors, whereas the annual evolution mainly depends on the hydrodynamic behaviour and on the seasonal water-level fluctuations. Geometry and hydrology of englacial caves are very similar to those of karst rock; this morphologic convergence and the hydrodynamic behaviour of moulins suggest the existence of a complex englacial «phreatic» network.

KEY WORDS: Glaciology, Englacial drainage, Glacier morphology, Gornergletscher, Switzerland.

RIASSUNTO: PICCINI L., *Le cavità glaciali del Gornergletscher (Svizzera): considerazioni preliminari sulla morfologia ed idrodinamica.* (IT ISSN 0391-9838, 2001).

Negli ultimi 15 anni sono state compiute molte ricerche nei sistemi di cavità endoglaciali e subglaciali presenti sui ghiacciai delle Alpi. I risultati più interessanti sono stati ottenuti sul ghiacciaio del Gorner, nelle Alpi svizzere Occidentali (gruppo del Monte Rosa), che è caratterizzato da una topografia di superficie per molti versi simile a quella di un paesaggio carsico.

Il Gorner è uno dei ghiacciai maggiori delle Alpi, la lingua principale discende in direzione WNW dal circo montano che fa capo al Monte Rosa; in essa confluiscono da sinistra importanti lingue glaciali provenienti dal Lyskamm e dal Breithorn. Nella zona d'ablazione, il ghiacciaio presenta un'area di circa 5,5 km^2, compresa tra quota 2600 e quota 2400, dove la superficie è relativamente pianeggiante (pendenza media del 5%) e in pratica priva di crepacci aperti, confinati prevalentemente sul lato sinistro. Queste condizioni morfologiche non consentono l'infiltrazione diffusa delle acque di fusione superficiale, che si raccolgono in più sistemi di drenaggio ben sviluppati ed organizzati in bacini chiusi, la cui estensione media è in genere intorno a qualche decina d'ettari.

Alcuni corsi d'acqua epiglaciali alimentano piccoli laghi, alcuni dei quali sono privi d'esutori superficiali. Nella maggior parte dei casi, invece, le acque di fusione sono inghiottite da cavità verticali (mulini) in comunicazione diretta con i sistemi di drenaggio endoglaciale. Attualmente le esplorazioni compiute hanno permesso di individuare due differenti tipi di mulini: un primo tipo caratterizzato da andamento verticale, con pozzi iniziali profondi da 30 ad oltre 80 m, e un secondo tipo caratterizzato invece da uno sviluppo a basso gradiente e un breve pozzo in entrata. Alcuni dei mulini a sviluppo verticale sono stati discesi sino a raggiungere il livello della superficie piezometrica endoglaciale, che è stata intercettata a profondità variabili tra –30 e –140 m (massima profondità raggiunta). Le cavità epidermiche presentano maggiori difficoltà d'esplorazione, per la presenza di lunghi bacini d'acqua, anche profondi, o per le ridotte dimensioni trasversali dei condotti, e pertanto sono state percorse per non più di qualche decina di metri.

Dalle nostre osservazioni, raccolte a partire dal 1985, risulta che la geometria iniziale dei mulini è condizionata soprattutto da fattori strutturali locali, mentre l'evoluzione risente soprattutto del loro regime idrodinamico e delle oscillazioni a cui è soggetto il livello della superficie piezometrica. Le diverse tipologie di cavità presentano sempre forti analogie, sia morfologiche sia funzionali, con le cavità carsiche e pertanto sono solitamente riconosciute come forme pseudocarsiche (criocarsismo). Le evidenti analogie, unitamente alle numerose osservazioni relative all'idrodinamica dei mulini, suggeriscono l'esistenza di un complesso ma ben strutturato reticolo freatico, analogamente a quanto avviene negli acquiferi carsici in rocce carbonatiche.

TERMINI CHIAVE: Glaciologia, Drenaggio endoglaciale, Morfologia glaciale, Gornergletscher, Svizzera.

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INTRODUCTION

The study of glacier caves commenced in the Alps, more than one century ago. The first investigations were performed by Martel (1898) and Vallot (1898) in the moulins of the Mer de Glace (M. Bianco - France). In recent years, thanks to the new mountain and caving techniques, French, Italian and Swiss speleologists explored some glacier caves of the western alpine glaciers for more than 100 m of depth. After a general investigation on the widest alpine glaciers, the Italian group began periodical research on the Gornergletscher (Swiss Alps). This glacier exhibits a spectacular surface morphology, with streams, canyons, lakes and karst-like forms (sinkholes); furthermore, most of the supraglacial streams plunge into large vertical holes, which feed directly into the englacial drainage network. Our interest focused on this kind of glacier caves (named moulins) on account of the evident analogies with the swallow holes of karst.

In 1985 and 1986 about 15 caves were explored, the largest of which was about 140 m deep, at that time the maximum depth ever reached inside a glacier (Piccini & Vianelli, 1987). In 1989, a moulin 90 m deep and a marginal contact cave were explored. Afterwards, some investigations were performed to verify the annual reactivating of moulins. A new program of research began in 1998, with the priority to follow the seasonal and annual evolution of moulins and, possibly, to do a first attempt at diving exploration of the water-filled system of englacial conduits. In this paper we would like to present a brief and preliminary discussion on old and new investigation.

THE GORNERGLETSCHER

The glacier Gorner is located in the Swiss Alps. Its catchment area encloses the northwestern side of M. Rosa (4554 m) and the northern slopes of Lyskamm-Breithorn (4479-4159 m) ridge. Presently (Landeskarten des Schweiz 1:25.000, Zermatt, ed. 1995), the Gorner and its tributaries cover a total extension of about 63 km^2 (the second largest glacier of the Alps, after the Aletschgletscher). The ablation zone, between the altitude of 2400 and 2600 m, has a mean steepness of 5%. This morphologic setting allows the development of an exceptionally structured drainage system, which exhibits longitudinal streams (*bédières*) and several lakes (fig. 1). Two major medial moraines act as longitudinal watersheds dividing three different zones, hydrologically shared; the central one, the widest, is incised by canyons, up to 40 meters deep, which feed supraglacial lakes. The zone where a well-channelled runoff occurs has a surface area of about 5.5 km^2, whereas the total length of the main supraglacial channels (which have a significant morphological expression) is about 22 km. The main streams flow in the left side of the glaciers; the longest of them has a development of more than 2 km and a feed basin probably wider than 1 km^2. These streams drain most of the supraglacial meltwater and feed englacial drainage through the moulins.

GLACIER CAVES AND MOULINS

Two morphological and genetic types of glacier caves have been recognised: marginal caves and swallow-holes (moulins) (fig. 2).

Marginal caves form at the contact between the ice and the lateral moraine, where a creek descends from the valley slopes. Most of them are small, impenetrable, and frequently affected by the collapse of the entrance; these features make the investigation of these caves very difficult and dangerous. Only in one case, in October 1989, we achieved the exploration of a marginal subglacial cave. The cave began with a large canyon, about 10 m high

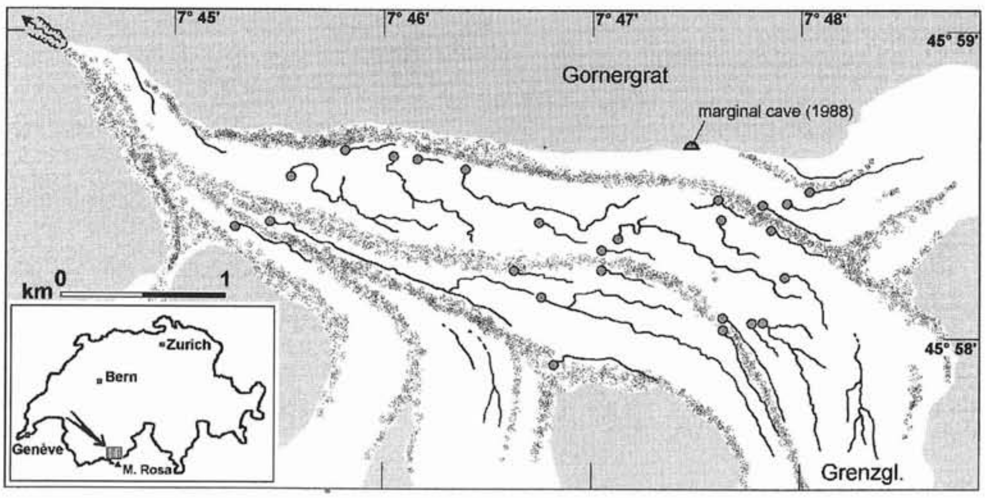

FIG. 1 - Sketch map of the Gornergletscher ablation zone. The small circles indicate the position of the moulins surveyed in 1999.

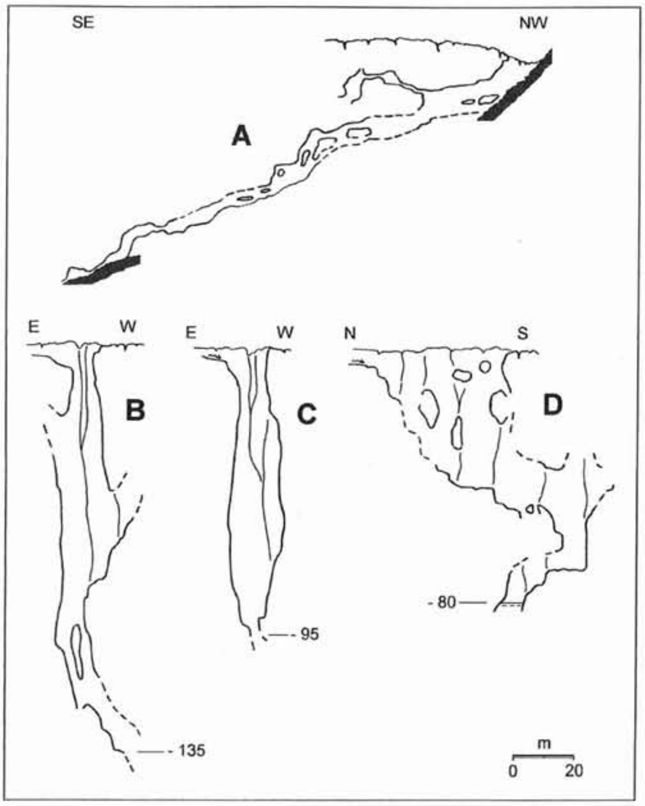

FIG. 2 - Profiles of different type of glacier caves: A) the marginal cave traced in 1988, B and C) two deep shafts surveyed in 1985 and 1986, D) a complex moulin formed by a steep canyon in the lowermost part, survey 1988.

(fig. 3); after 40 meters, a lateral tunnel went up towards the surface of glacier, whereas the canyon continued with a narrow incision. At a depth of 50 m (about 70 m below the glacier surface), the passage became narrow and low, along the contact between the ice and the glacier bed. This cave developed because of the melting action by a little creek (discharge 4-8 l/s) of relatively warm water (3-4 °C) coming from the south-facing slope of the Gornergrat. The upper tunnel, formed by the capture of surface meltwater, was probably enlarged by the action of air circulation (Eraso & Pulina, 1992) assuming a circular section (fig. 4) similar to that of karst phreatic tubes.

«Moulin» is a French word used to indicate the vertical holes where a supraglacial stream sinks into the ice. These caves are usually shaped like a vertical shaft (fig. 5), followed, in some cases, by a high and narrow canyon. It's known that almost all the moulins are, under a certain depth, water filled (Iken, 1972; Rothlisberger, 1972, 1998; Holmlund, 1988; Schroeder, 1995), but only in a few occasions we were able to reach the bottom lakes, which can be interpreted as the level of englacial water table. In this paper we use the term «moulin» to refer to the part above the minimum water level (vadose and epyphreatic zones in the karst systems), where water flows in free-air condition and the pressure is the atmospheric one (Hooke, 1984). The part below the minimum water level represents the water-filled drainage network (phreatic zone in the karst). The structure of this drainage network is not yet known, and only theoretical models can be depicted (Shreve, 1972; Lliboutry, 1983; Hooke, 1984; Seaberg, 1988; Badino, 1995).

On the Gorner, taking only the human accessible ones into account, the total number of moulins is probably more than 30, with a density of about 6 entrances km^{-2}, and a mean recharge area of about 0.15 km^2. Entrances are not homogeneously distributed on the glacier surface. Most of them are located downstream the confluence zone of the Grenzgletscher. In this area, the entrances seem to be located along NE-SW lineaments, which can be observed also from the relief setting of surrounding mountains and from the surface topography of glacier.

FIG. 3 - The canyon of the marginal cave (October 1988, photo M. Vianelli).

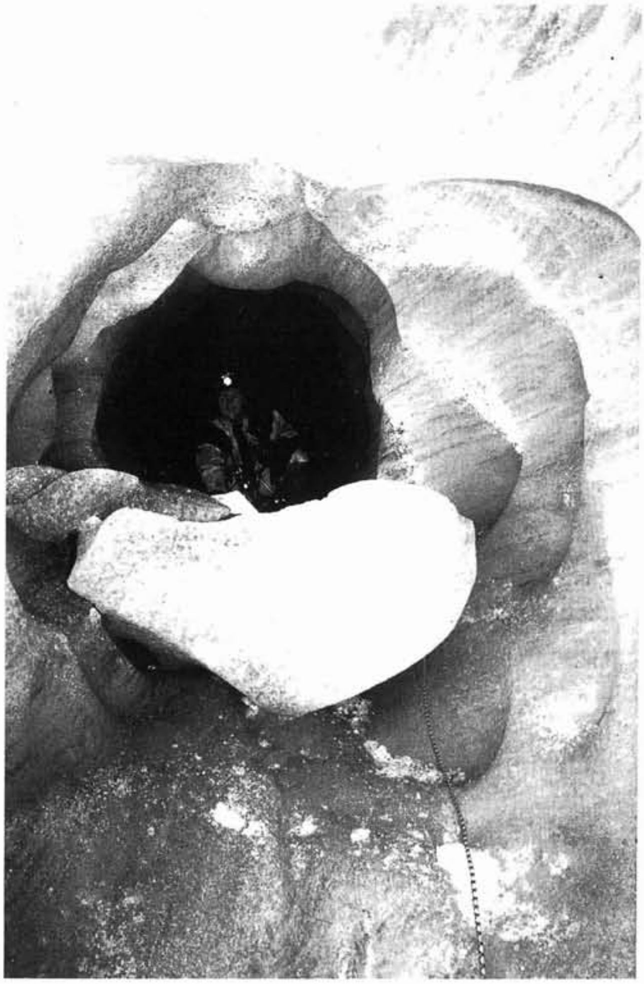

FIG. 4 - The uppermost tunnel of the marginal cave (October 1988, photo M. Vianelli).

This circumstance suggests that the position of the major swallow-holes is along the extension zones controlled by the morphology of the glacier bed. Another event that seems to confirm this hypothesis is the fact that almost all the moulins open on transversal fracture.

Another group of active moulins is located in the lowermost part of the glacier. Some of these have wide feed basins (up to 1 km^2), and experience large in-flowing discharges. Our investigations concerned prevalently the former zone, where we have surveyed about 25 active caves since 1985 to 1999.

The entrances of moulins have dimensions ranging from some tens of cm up to 10-15 m. An important morphologic difference concerns the form of the new moulins in respect of the reactivated ones. The former, in the beginning of summer, have small elliptical entrances, with the major axis on the direction of an extension fracture, laterally filled by refreezing ice. At the end of the seasonal period of evolution (usually the end of October) the entrances exhibit an elongated form because of the regressive erosion of the waterfall rim. If the moulin captures more than one stream, in the final stage, the entrance displays a star-shaped plan view.

The uppermost part of moulins is usually vertical and straight. The deepest shafts reach the maximum width after 20-30 m; going down the section elongates in the direction of the fracture on which the moulin develops. At a greater depth the form of passages tends to change from almost vertical shafts to gently-dipping canyons. The depth of the first shaft depends by several factors, which will be discussed in the following pages. The profile pattern varies from almost perfectly vertical (ice shaft) to almost horizontal. In some cases, the latter are subcutaneous caves which develop from meandering supraglacial channels filled by *firn* or refreezing ice. Moulins with a different pattern, horizontal in the first part and vertical in the second, also exist.

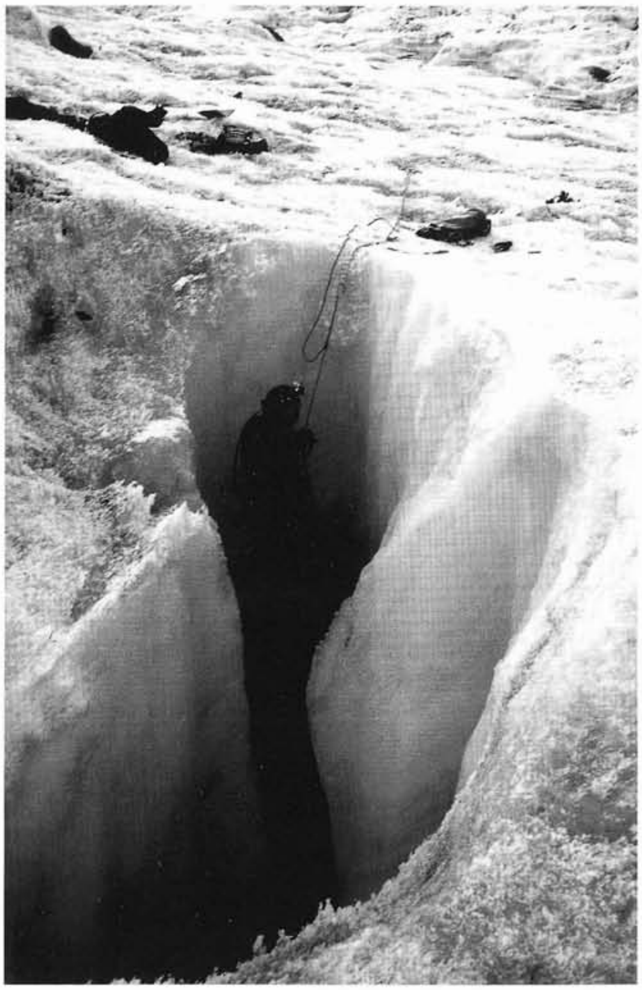

FIG. 5 - The entrance-shaft of an active moulin (photo, L. Piccini).

Moulins present significant morphological and evolution analogies with the swallow holes of karst (Clayton, 1964), for this reason they can be considered as pseudokarst or cryokarst forms (Eraso & Pulina, 1992).

HYDROLOGY OF MOULINS

The Gorner lays in a wide E-W oriented valley; although the elevation of the watershed, which borders the glacier on the S, is more than 4000 m, the form of the valley results in a high insulation, all year. For this reason the surface melting is very high, probably more than 3 m a^{-1}. According to our measurements, performed in different years (1985-1999), we can assume a maximum daily surface melting of 30 mm in the months July and August. In this period, the mean meltwater discharge usually ranges from 230 to 350 l s^{-1} on a surface of 1 km^2.

During the high-melting season, the moulins experience a diurnal fluctuation of discharge that displays a minimum early in the morning (about 1 hour after the sunrise), and a maximum in the afternoon. The ratio between maximum and minimum discharge is always very high. In July-August, most of the moulins have a peak discharge upper than 100-300 l s^{-1}, which falls to a few l s^{-1} during the night. The largest ones, whose feed basin is wider than 1 km^2, have a maximum discharge of 1-2 10^3 l s^{-1} and a minimum discharge often lower than 10-20 l s^{-1}. Discharge excursion heavily depends on weather conditions; major excursions occur on clear days of late summer, when the insulation is still high, while during the nigh the surface of glacier freezes.

Seasonal discharge curve is less dependent on weather conditions. The activation of moulins probably starts in the beginning of May, by the meltwater flowing at the contact between ice and snow. Absolute maximum discharges occur in the end of July and in the firs half of August. In September, discharge progressively decreases, and by the end of October it is completely exhausted.

The discharge changes result in diurnal and seasonal fluctuation of englacial water table.

In the investigated zones of the Gorner, at a depth that usually ranges from 30 to 120 m, the moulins are water-filled. The depth of the water level from the glacier surface depends on several factors, the most important of which are: seasonal evolution stage, discharge and ice deformation.

Seasonal evolution stage - In winter time, when the englacial drainage network collapses, the water level rises up until the pressure of water balances the weight of ice; the equilibrium is usually reached when the water level stands 10-15 m below the surface of glacier (Badino, 1992). In the end of spring, when the moulins are reactivated or new moulins are forming, the water level is only few meters below the surface of ice. During the summer time, the englacial network conduits enlarge, assuming a progressively higher hydraulic conductivity, and the water table falls. The minimum level of water is usually reached in the end of September; when the hydraulic conductivity is still high and the discharge begin to decrease. These observations seem to be in contrast with measurements of subglacial water pressure performed by some authors at the glacier bed (Rothlisberger, 1972; Hooke & *alii*, 1990; Iken & *alii*, 1996). A possible explanation is that in the winter the connection between englacial drainage conduits and subglacial channels is interrupted by the collapse of conduits.

Discharge - The water level is surely affected by diurnal fluctuations, Iken (1972), for instance, describes a diurnal rise of water level up to 15 m in a moulin on the White Glacier (Canada). On the Gorner we have no direct measurements of these fluctuations, because during high-discharge period it is not possible to descend inside moulins. We can suppose a rise of some meters, but the lack of morphological evidence suggests that there is not a recurrent upper level of the water. For future research we are planning to use a phreatimeter coupled with a datalogger, in order to collect a complete record of diurnal water-level fluctuation.

Ice deformation - In a few occasions, we have witnessed relatively fast changes of the water level without a significant variation of discharge. The rate of these fluctuations ranges from 1 to 10 m/h and they could be ascribed either to the effect of a local compression on the englacial network or to a water transfer between zones of the glacier with a different water-table elevation (Badino & Piccini, 1995). In 1989, in a moulin about 90 m deep, we measured a rise of the water of about 15 m, during few hours, without a significant change of the in-flowing discharge.

EVOLUTION OF MOULINS

The way in which moulins develop is not yet completely clear. Investigations in several middle-latitude and subpolar glaciers have shown recurrent morphological and genetic features (Reynaud, 1987; Pulina & Rehak, 1992, Rehak & Rehak, 1995, Schroeder, 1995, Holmlund, 1988).

A moulins develops where an extension fracture crosses a supraglacial channel. In the initial stage it is only a little conduit, completely water-filled, connected with the englacial drainage network through a fracture (protomoulins, after Schroeder, 1991). In a few days the entrance hole is enlarged by the melting action of the inflowing water. When the section of the first shaft is large enough, the water that falls into it also exerts a mechanical abrasion by suspended load. According to the energetic balance of the formation of moulins (Badino, 1992) we can argue that the ice melting is the dominant process in most of cases, none the less, in those fed by waters flowing from marginal or medial moraines, abrasion can play a significant role.

Our surveys suggest that an important role in controlling the development rate and the shape of moulins is played by the hydrologic factors and, particularly, by the level of the water. The depth of the first shaft corresponds to the minimum level of the water in most of the observed situation. The water level divides two energetically different zone: in the uppermost («vadose zone»), energy is high because of the turbulence of the waterfalls, and the pattern of cave is controlled by gravity, in the lowermost, the water flows in water-filled passageways and the pattern of conduit follows the pressure-hydraulic gradient.

CONCLUSIONS

On the ground of our measurements, the initial geometry of moulins depends on local structural factors, whereas the annual evolution mainly depends on the hydrodynamic behaviour and on the seasonal water-level fluctuations.

Moulins and subglacial marginal caves act an important role on the dynamic of glaciers. In particular, their cyclic life is strictly correlated with the ice-flow velocity and with the trend (positive or negative) of the mass-balance. In the Gornergletscher, the life of the largest moulins range from 3 to 5 years and it largely depends on the local glacier movement rate: the faster the movement, the shorter the life period.

Presently, most of the supraglacial channels survive during the winter time, thus every spring the drainage network is reactivated with only small differences from the previous year. In other words, every year, the meltwater drainage replicates its structure and moulins can be reactivated by runoff meltwater. This happens only if a new swallow-hole does not develop upstream capturing the water in the feed channel. This eventuality is not rare because the moulins tend to form always in the same place (Monterin & Somigliana, 1930, Badino & Piccini, 1995), thus a moulin, moving downglacier, is progressively farther from it's origin point.

Our observations seem to indicate that in the last 15 years the number of moulins and their period of life are increasing. In 1985, 1986 and 1988, we find different situations with only little remnants of the previous year's setting. In 1998 and 1999, conversely, the distribution and morphology of moulins was almost the same. Further studies are necessary to understand well the cyclic life of moulins, whose increasing, in number and dimensions, could be referred either to a slower movement rate of the glacier or to different climatic conditions. If confirmed, the increasing of the life period of moulins could be related to the deglaciation phase, which is now in progress.

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