Moulins and marginal contact caves in the Gornergletscher, Switzerland

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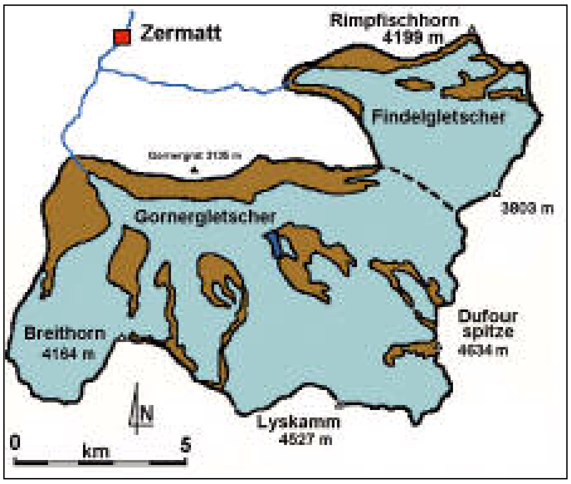
Abstract
The Gornergletscher, in the Mt. Rosa group, is one of the widest glaciers in the Alps. In the ablation zone, between 2600 and 2400 m of altitude, the surface is relatively planar and a few fractured; this morphological condition allows the development of the surface drainage of meltwater. Supraglacial streams feed glacier lakes, most of which have not a surficial outflow, or plunge down into moulins that feed directly the englacial drainage network.

The investigations performed since 1985, have allowed to survey more than 40 englacial caves and some marginal tunnels. Two main different types of moulins have been recognised: the first type is characterised by a vertical pattern, the second type has a gently dipping development with a small shaft in the entrance. Some of the first type shafts have been explored to the water table (depth range: -30 to -140 m). The life of the major moulins ranges from 3 to 5 years and it depends on the local glacier movement rate: the faster the movement, the shorter the life period. Our surveys suggest that an important role in controlling the development rate and the shape of moulins is played by the level of the water table. Our observations seem also to indicate that in the last 15 years the number of moulins and their period of life are increasing. Further studies are now in progress to understand their cyclic life, whose increasing could be referred either to a lower movement rate of the glacier or to different climatic conditions.

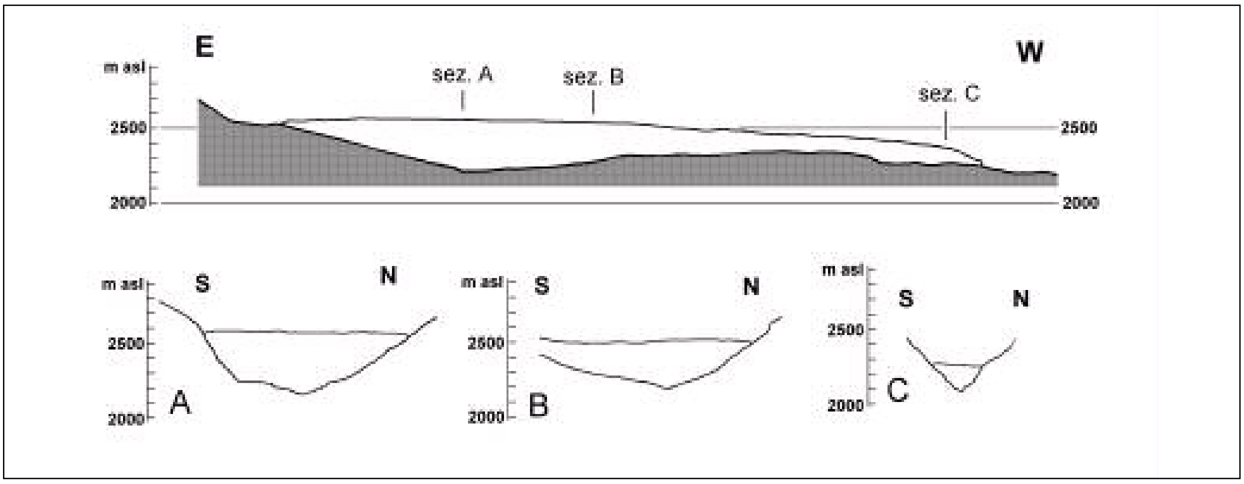
1. A view of the central part of the Gornergletscher. Note the surface streams and lakes. (photo: L. Piccini)



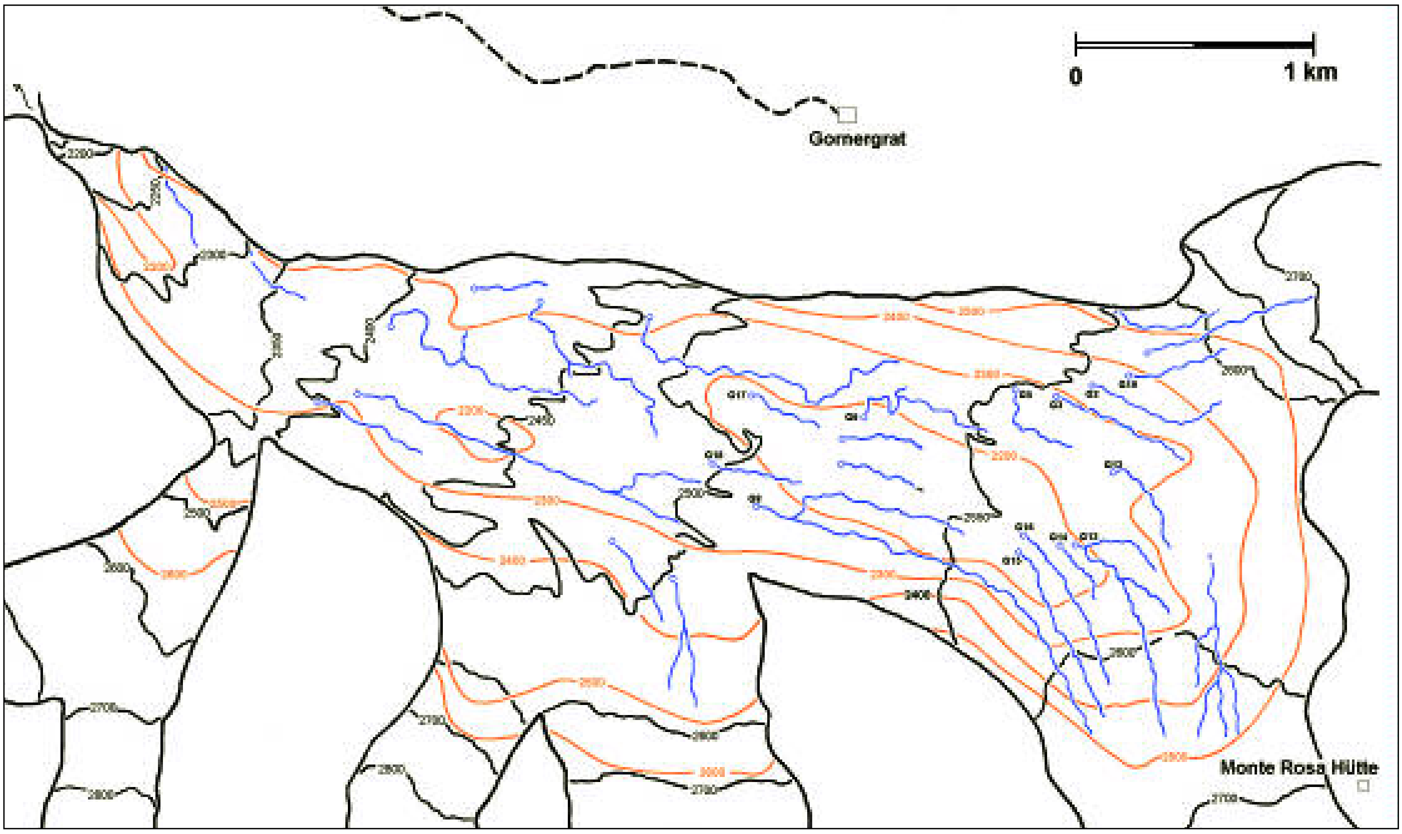
2. Sketch map of the Gornergletscher.

Key Words: glaciology, englacial hydrology, glacier caves, Gornergletscher.

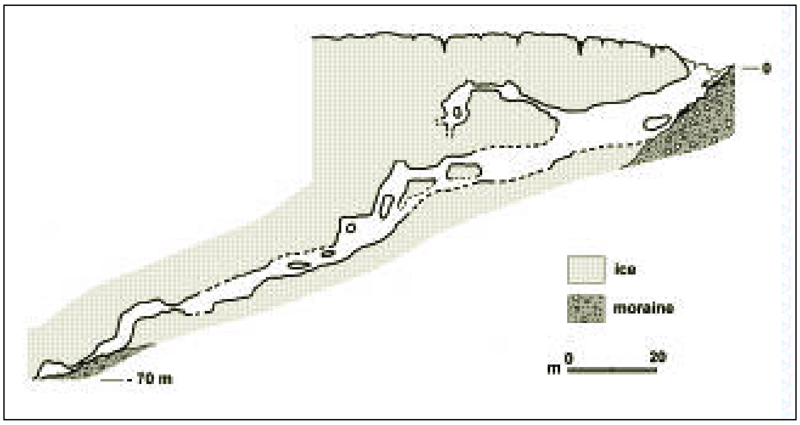
Riassunto
Negli ultimi 15 anni sono state compiute molte ricerche da parte di speleologi italiani nei sistemi di cavità endoglaciali presenti sui ghiacciai delle Alpi. I risultati più interessanti sono stati ottenuti sul ghiacciaio del Gorner, nelle Alpi svizzere Occidentali (gruppo del Monte Rosa), 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 discen-



3.Present longitudinal profile and cross section of the glacier.



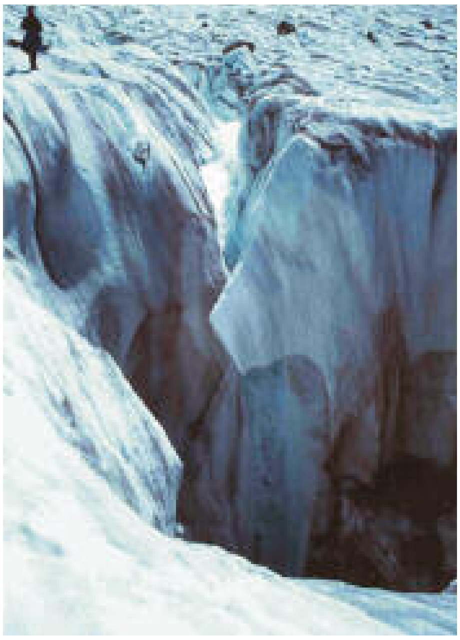
4. *Sketch map of the lower part of the Gornergletscher. The small circles indicate the position of the moulins surveyed in 1999.*



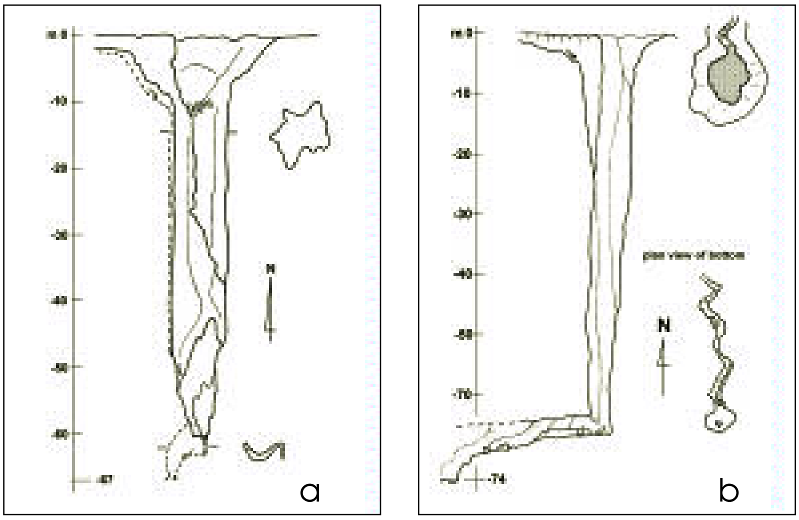
5. *Longitudinal profile of the marginal contact cave traced in 1988.*

6. *A passage in the uppermost tunnel of the marginal cave (October 1988, photo M. Vianelli).*

de 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 parte inferiore (zona d'ablazione), il ghiacciaio presenta un'area, larga circa 1 km e lunga almeno 5,5 km, compresa tra quota 2600 e quota 2400, dove la superficie è relativamente pianeggiante (pendenza media del 5 %) e pressoché priva di crepacci, confinati prevalentemente sul lato sinistro. Queste condizioni morfologiche non consentono l'infiltrazione diffusa delle acque di fusione superficiale, che si raccolgono in un sistema di drenaggio ben sviluppato e organizzato 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 di esutori superficiali. Le acque di fusione sono spesso 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 caratterizzato da andamento verticale, con pozzi iniziali profondi da 30 a 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 stato intercettato a profondità variabili tra -30 e -140 m cir-



7. *The entrance of a large reactivated moulin (G13 - August 1999, photo A. Romeo)*



8 a, b. Profiles and plan view of two vertical moulins (G13 and G16).

ca (massima profondità raggiunta). Le cavità epidermiche presentano maggiori difficoltà di esplorazione, per la presenza di lunghi bacini di acqua, anche profondi, o per le ridotte dimensioni trasversali dei condotti, e pertanto sono state percorse per non più di qualche decina di metri. 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 o termocarsismo). Le evidenti analogie morfologiche, 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. Per queste ragioni lo sviluppo e l'evoluzione dei mulini sono sempre fortemente influenzati dalle oscillazioni della superficie piezometrica endoglaciale. Il periodo di attività dei mulini di maggiori dimensioni varia in genere da 3 a 5 anni e dipende dalla velocità locale di movimento del ghiacciaio: maggiore è la velocità, minore è il periodo di vita. I nostri rilievi suggeriscono che un importante ruolo nell'influenzare lo sviluppo dei mulini è giocato dalle variazioni nel livello dell'acqua. Le nostre osservazioni sembrano inoltre indicare che negli ultimi 15 anni il numero di mulini e il loro periodo di vita sono andati crescendo. Nel 1985, 86 e 88 trovammo situazioni sempre differenti, con solo pochi relitti della situazione dell'anno precedente; nel 1998 e 1999, al contrario, la situazione era praticamente identica. Ulteriori studi sono in corso con lo scopo di capire meglio il ciclo di sviluppo dei mulini, il cui aumento potrebbe essere legato ad un rallentamento nella velocità di scivolamento del ghiacciaio o a differenti condizioni climatiche.

Termini Chiave: glaciologia, drenaggio endoglaciale, grotte glaciali, Gornergletscher.

Introduction

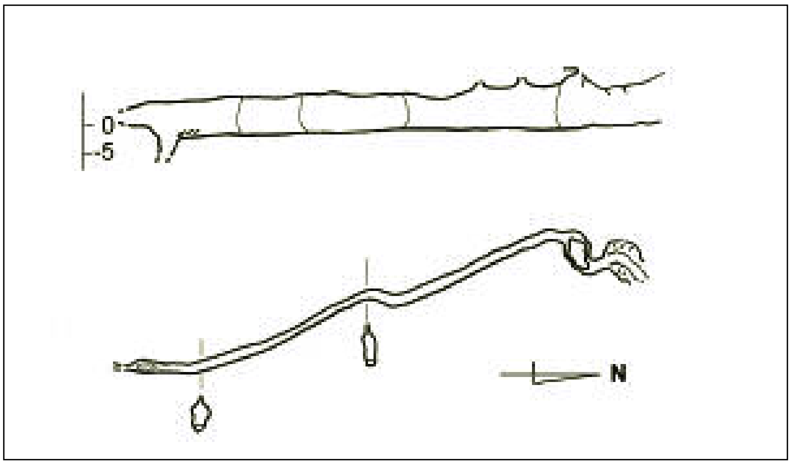
The Gornergletscher is located in the Valais region (Switzerland) and it is one of the most studied glaciers in the world, particularly by speleologists.

After first investigations by Swiss cavers at the beginning of '80 (G. Favre, pers. com.), in 1985 and 1986 a group of Italian speleologists performed the descents of deep moulins up to the depth of 140 m (Piccini, Vianelli, 1987). In 1988 and 1989 Italian and Swiss speleologists conducted further explorations of moulins and marginal contact caves. In 1993 and 1994, French cavers descended some moulins up to 55 m of depth (Wenger, 1994).

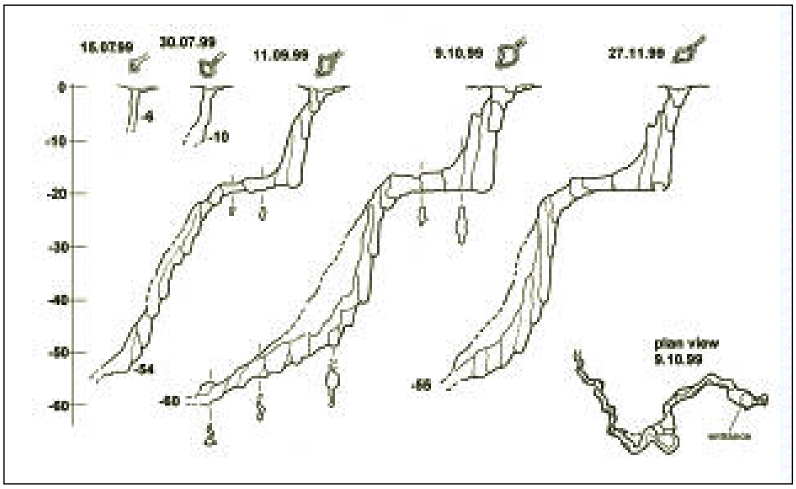
Since 1992, a group of Swiss cavers, led by A. Pahud, are carrying on many explorations of moulins and subcutaneous conduits. The great number of explored caves emphasises the exceptional development of englacial drainage: in spite of this no exhaustive publications about the result of such a speleological investigation are still available. Before the interest of speleologists, glacio-physical studies were conducted inside the project of the Grande Dixence hydroelec-

9. The entrance of a new active moulin (G10 - July 1999 - photo, L. Piccini).

10. An horizontal tunnel in the subcutaneous cave (G12).



11. On right: profile of a subcutaneous cave (G12).



12. Evolution of vertical profile of G10 since 15/7/99 to 27/11/99.

tric system, which captures the waters of Gornera creek, just downstream the portal of the glacier. In particular, the measurements of the subglacial water pressure and the reconstruction of the bedrock geometry allowed a good knowledge of the hydrodynamic setting of the glacier and led Rothlisberger (1972) to formulate his model of the englacial drainage. In the last years, Collins (1981, 1989) and Iken *et al* (1996) carried out further studies on the hydrology of Gorner. Few other glaciers in the world have been object of such detailed investigations. For all these reasons, the Gorner is an exceptional site for studying the evolution of moulins and their hydrological behaviour.

Since 1998, researchers coming from the Dip.to di Fisica Generale of Univ. Torino, Dip.to di Scienze della Terra of Univ. Firenze and from the Associazione La Venta have started a new campaign of investigation. The aim is the physical and morphological characterisation of moulins, the monitoring of their seasonal evolution, and the diving exploration of englacial pools. This paper deals with the first results of this study.

Geographic and morphological features of Gorner

The Gornergletscher originates from the confluence of different ice streams descending from the mountain group of M. Rosa (Fig. 2).

The whole glacial system covers about 64 km^2 (from IGS map, 1996) with a maximum length of 14 km. The major elevations in the feed basin are more than 4000 m high (Dufour Spitze 4634 m, M. Lyskamm 4527 m, M. Breithorn 4164); the minimum elevation is 2130 m, at the portal of the subglacial river. The present equilibrium line altitude (ELA) is about at 3250 m.

Below the altitude of 2600 m, two medial moraines separate the glacier in three major ice streams; the central and largest one is the continuation of the Grenzgletscher, whose accumulation zone is located between M. Rosa and M. Lyskamm. The maximum thickness of ice is probably more than 400 m (unprinted surveys by Grande Dixence SA, 1963), just downstream the confluence of Grenzgletscher and Gornergletscher, where the glacier reaches also the maximum width of 2 km. Below this altitude the width rapidly decrease: at 2350 m, just 1 km upstream the front of the glacier, it is only 700 m wide, whereas the thickness is about 250 m (Fig. 3).

In the ablation zone, between the altitude of 2400 and 2600 m, the glacier exhibits a wide flat area with a mean steepness of 5 %. In this area, which has a surface of about 6 km^2, the morphologic setting and the few crevasses allow the development of a well structured drainage system, with longitudinal streams and several lakes (see photos). The supraglacial lakes, some of which are wider than 10,000 m^2, are one of the most relevant morphologic features of Gorner: no other glacier in the Alps presents a so great number of lakes.

The total length of major supraglacial channels (bédières) is about 22 km; some of them are more than 2 km long and have a catchment basin wider than 1 km^2. In the upper part of ablation zone, the pattern of channels is rectilinear, along the direction of glacier movement, while in the lower part, where the topography is more rugged, the pattern is more complex.

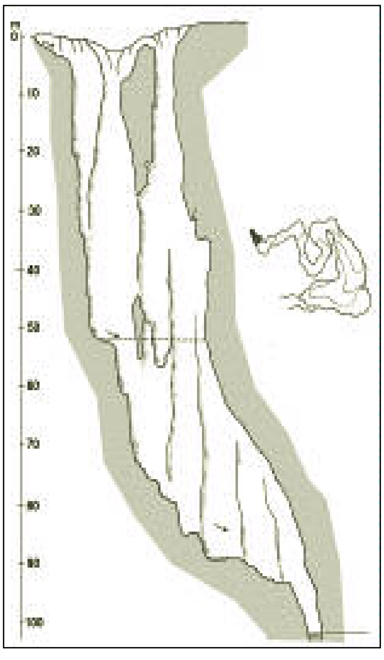
Almost all the streams feed englacial drainage through swallow holes (moulins). Moulins are not homogeneously distributed, but they are located along transversal extension zones controlled by the morphology of the glacier bed. Most of the moulins are in the confluence zone of the Grenzgletscher (Piccini, 1999), another group of active moulins is located in the lowermost part of the glacier (Fig. 4); some of these have wide feed basins (up to 1 km^2), and experience the major inflowing discharges.

The total number of human accessible caves is more than 35 (1998-1999); with a spatial density of about 6 entrances for km^2, and a mean recharge area of 15 ha.

Marginal caves and moulins

A glacier cave is formed by the melting action of water flowing along a «crevasse» or at the contact between ice and bedrock (Eraso, Pulina, 1992; Badino, Piccini, 1995). In the former case the water derives from the surface melting of ice and runs into supraglacial stream, in the latter the water comes from lateral-slope runoff.

14. A deep lake in the Gorner lower part, object of a scuba survey during autumn 1999.



13. On right: vertical profile of G8.

15. The lake on the Gorner glacier during summer 1985.

16. The first shaft of G8.

These two different situations give origin to two morphological and genetic types of glacier caves: marginal caves and supraglacial swallow-holes, usually named "moulins". Marginal caves develop near the lateral contact between ice and moraine or bedrock; most of them are small, impenetrable, and frequently affected by the collapse of the entrance. The largest known marginal caves of Gorner, explored in September 1999 for more than 200 m, are located just upstream the confluence of Gornergletscher with Grenzgletscher (MG2 and MG3 in Fig. 4). These caves act as subglacial outflows of an ice dammed lake, named Gornersee, which usually forms in May and is completely empty at the beginning of July (Rothlisberger, 1972). In October 1989, we explored a large marginal cave (MG1, Fig. 4) generated by a small lateral creek descending from the south slope of the Gornergrat (Fig. 5).

The entrance tunnel (3x6 m^2) was probably enlarged by air circulation through an upper entrance on the glacier surface. Sculptures due to airflow were quite evident in the wall of the upper passages, where the conduit had a circular section similar to that of karst phreatic tubes (Fig. 6). Some 50 m below the entrance the cross-section became progressively larger and lower. After a pathway of about 200 m, 80 m below the ice surface, the distance between the ice ceiling and bed-moraine reduced to less than 20 cm.

When englacial conduits drain water plunging down into a crevasse away, the flow of water releases frictional heat and the conduit enlarges; if the water flow persists a moulin is formed. An active moulin is usually structured like a vertical shaft, followed by a high and narrow canyon. An important morphologic difference concerns the evolution stage; the new moulins, at the beginning of summer, have small elliptical entrances, with the major axis in the direction of an extension fracture (Fig. 9). 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 (Fig. 7). The entrances of moulins older than one year have a more complex morphology; in many cases they present parallel shafts with deep lateral incisions. In the confluence zone of Grenzgletscher and Gornergletscher (2550-2600 m), the moulins usually have a vertical pattern, with a first shaft 40-80 m deep, followed by narrow and steep canyons (e.g. G13 and G16, Fig. 8 a,b).

On the contrary, in the down-glacier part the morphologic pattern of moulins tends toward a less steep configuration. An excellent example of horizontal moulin is the G12, a subcutaneous cave developed along a N-S fracture (Fig. 10 and 11) that, in October 1999, was 60 m long; at the end of the tunnel a narrow vertical fissure captured all the water. The origin of horizontal caves is not clear: if transversally oriented in respect of the ice-flow direction, they can be referred to a very surficial fracture. Some down-glacier oriented caves reveal, to a more careful exam, to be the result of meandering supraglacial channels filled by firn or refreezing ice. On the contrary, some moulins, with a small first shaft followed by a gently steep canyon, seem to be controlled by englacial hydraulic factors.

Hydrology of moulins

Thanks to high insolation, on the Gorner the surface melting is very high, probably equivalent to more than 3 m per year of water in the ablation zone. Supraglacial runoff begins in May and at the end of June the glacier surface is usually free of snow beneath 3000 m. According to our measurements, we can assume a surface ice melting of 20-30 mm per day in the months July and August, this means that the mean meltwater discharge ranges from about 0.23 to 0.35 m^{3}s^{-1}km^{-2} (Piccini, 1999). In October surface melting reduces to few millimetres.

In the period July-August the discharge of Gornera, the river fed by the basin of Gorner, is usually 18-20 m^{3}s^{-1} (Collins, 1989), while the mean total discharge of infiltration through moulins in the ablation zone can be estimate about 2 m^{3}s^{-1}. Comparing this measures we can infer that the infiltration in caves provides about the 10% of the total discharge. During the high-melting season, the major moulins experience the minimum discharge early in the morning, and the maximum late in the afternoon. The largest streams, whose feed basin is wider than 1 km^2, have a maximum discharge of 1-2 m^{3}s^{-1} and a minimum discharge often lower than 10-20 l s^{-1}. In the period of maximum surface melting, the total discharge of infiltration through moulins probably reaches 10 m^{3}s^{-1}. The depth of water level inside moulins ranges from few meters to more than 100 m from surface. Indeed the water table has a complex geometry and we have found different levels in caves only few tens of meters far. The diurnal fluctuation of water level is not known: we can presume a rise of few meters during high discharges, but the lack of morphological markers suggests that there is not a recurrent upper level of water.

Seasonal fluctuations of water level show different behaviours. In most of the cases we observe a rapid rise of water level during the period of decreasing discharge (October), but in some case there was only a slow and partial rise.

This different behaviour does not depend on the in-flow discharge, because the flow regime is the same for all the moulins. The most

17. A general view of Gorner glacier karst during 1988 (photo: G. Badino).

accepted explanation is that such different hydrologic behaviour could depend on the different collapsing rate of the water-filled englacial conduits (Rothlisberger 1998; Badino, 1995).

Conclusions

According to our observations, in the Gornergletscher the life of the largest moulins ranges from 3 to 5 years and it depends on the local glacier movement rate: the faster the movement, the shorter the active period. The depth of the original crevasse, the hydrodynamic of the in-flowing stream and the temperature of ice, influence the internal pattern of moulins.

Most of the supraglacial channels survive during winter, thus the drainage network is reactivated with only small differences from the previous year. It has been observed that melting runoff reactivates the previous year swallow holes only if a new swallow-hole does not develop upstream capturing the water. It is widely demonstrated (Forbes, 1842; Monterin, Somigliana, 1930; Holmlund, 1988; Schroeder, 1995) that spatial distribution of shafts remains almost the same year after year, because their position depends on the distribution of stress inside the glacier and the effect of this on the surface topography; also the main morphological features of moulins show small differences in following years.

In the beginning of the melting season we can observe different generation of moulins: the new moulins, formed by the upstream capture of a stream, the reactivated moulins, inherited from the previous year, and the relict ones, no more fed by running water (Forbes, 1859). In the new moulins, the connection with the englacial network is, in the initial stage, characterised by a minor hydraulic conductivity and thus the water table is very near to the surface and descends slowly with the progressive widening of the waterfilled conduits. In 1999, we could fortunately follow the evolution of a new moulin (G10), from the moment of the first stage of evolution, to the final pattern (Fig. 12). In June the level of water was only 6 m beneath the surface, and it did not show relevant change with the diurnal fluctuation of discharge. The moulins older than one year do not show relevant modification during the evolution season (e.g. G8, Fig. 13 and 16), probably because they can use again the previous englacial drainage conduit, which is preserved during winter, although reduced in dimension. Thus, when the shaft is reactivated the water table rapidly falls to the ordinary summer level.

Anyway, diurnal and seasonal fluctuations of water level have a relevant role in the evolution of moulins, (Rothlisberger, 1972; Lliboutry, 1983; Badino, 1992) and further studies should necessarily try to record such fluctuations with a phreatimetric data-logger.

Our observations seem also 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 situation was almost the same. The increasing of the cyclic life of these structures could be referred either to a lower movement rate of the glacier or to different climatic conditions. If confirmed, the increasing of the life period of moulins could be due to the deglaciation phase, which is now in progress.

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