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Ten years of research in the region of

Emosson-Salanfe-Susanfe, Valais (Switzerland), and Fer-à-Cheval (France) to reveal the regional hydrogeology

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Abstract

The hydrogeology of the High Calcareous Alps lying across the border between Haute-Savoie (France) and Valais (Switzerland) has been investigated. A satisfactory model of the underground karstic transfer can be proposed. The Malm limestone strata are mostly involved in these circulations. Balances, either for glaciers and their resurgences, or for a major spring, the Gouille Verte, and its feeding basin are proposed. Giffre River hydrologic basin doesn't match its geographic limits, which correspond to the border between France and Switzerland. Thus, precipitations falling on 4 km² of Swiss territory drain underground into France.

Simultaneously, temperature, conductivity and water flow rate have been measured during approximately 10 years. The results corroborate our transfer model. Finally, we made radiometric dating of concretions found in a high altitude cave, RU-1. Its age of greater than 400 000 years is not surprising if we look at the geomorphology around the cave: significant fluvio-glacial erosion has completely altered its drainage. From temperature measurements made in the cave, we determined the altitude of the 0°C isotherm in this region of the Alps to be 2570 m.

Keywords: *hydrogeology, tracer experiments, High Calcareous Alps, Valais, Haute-Savoie, Switzerland, France*

Résumé

Dix ans de recherches dans la région d'Emosson-Salanfe-Susanfe, Valais (Suisse), et Fer-à-Cheval (France) révèlent l'hydrogéologie de la région

Dix ans de recherches ont permis de comprendre l'hydrogéologie de la région frontière comprise entre le Valais (Suisse) et la Haute-Savoie (France), un secteur des Hautes Alpes calcaires. Les circulations souterraines se font principalement au sein du Malm. Un bilan est proposé tant au niveau des glaciers et de leurs résurgences, qu'à celui de la plus importante résurgence de la région, la Gouille Verte, et de son bassin d'alimentation. Le bassin du Giffre, qui était censé prendre naissance en Haute-Savoie, voit ses limites repoussées en Suisse. C'est ainsi environ 4 km² de territoire helvétique qui perdent leurs eaux au profit de la France.

Pour la Gouille Verte, la température, la conductivité et le débit ont été mesurés durant près de dix ans. Les résultats corroborent notre modèle de circulation. Enfin, une grotte d'altitude, RU-1, nous a livré des concrétions que nous avons fait dater. L'âge excède les limites de la méthode, soit plus de 400 000 ans. Cela n'est guère surprenant si l'on regarde le bassin d'alimentation de la grotte, dont la majeure partie a été détruite par l'érosion fluvio-glaciaire. Des mesures de température dans la grotte permettent de proposer une altitude de 2570 m pour l'isotherme 0°C dans cette région des Alpes.

Mots-clés: *hydrogéologie, traçages, Hautes Alpes Calcaires, Valais, Haute-Savoie, Suisse, France.*

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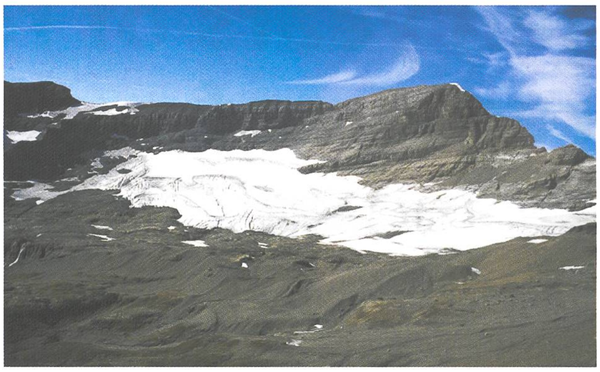
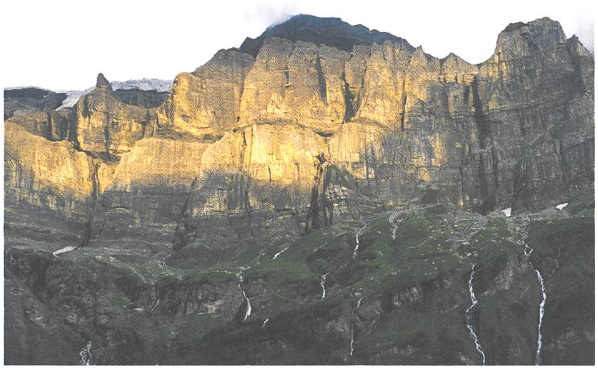
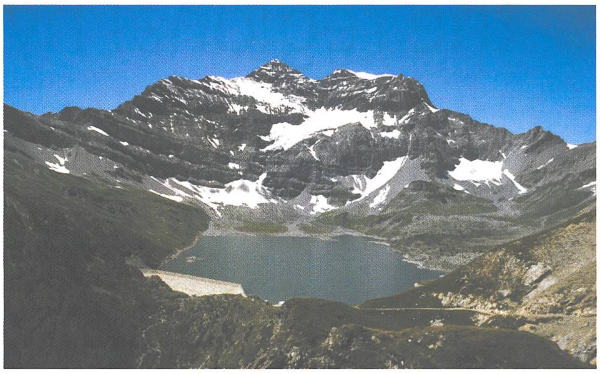
(a) The Emosson lake and the Mont Blanc massif, as seen from Tenneverge Peak.



(d) The glacier des Fonds with, on the right, the Mont Ruan.

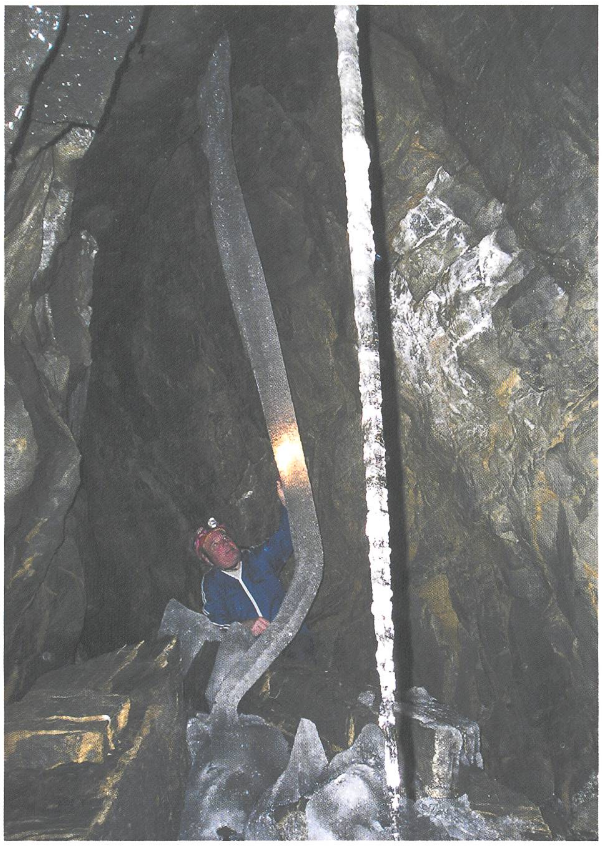


(b) Some of the Fer-à-Cheval springs. On the upper left, the Prazon glacier.

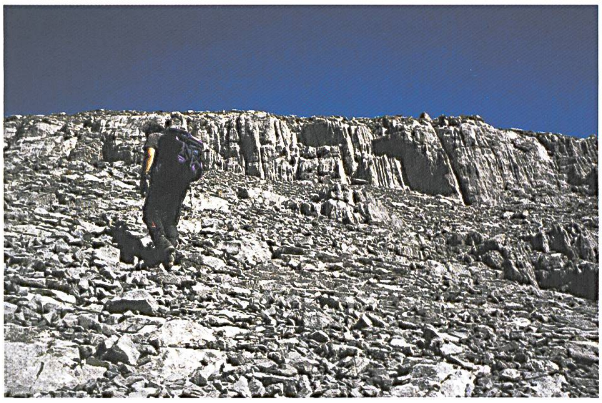


(e) The Salanfe lake and the Tour Sallière.

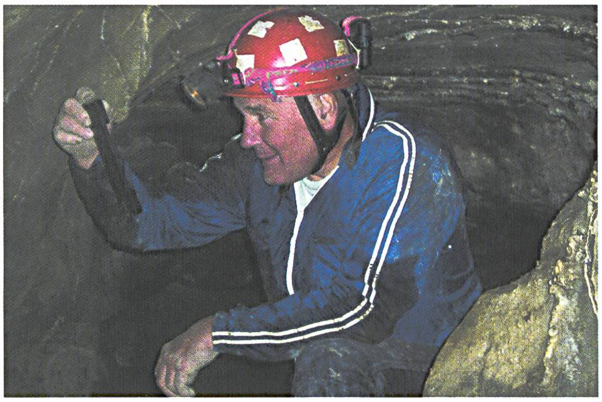
(c) Highly deformed ice stalactite in the RU-1 cave.



(f) A spring at the foot of the Malm cliff, on the Prazon ledge.

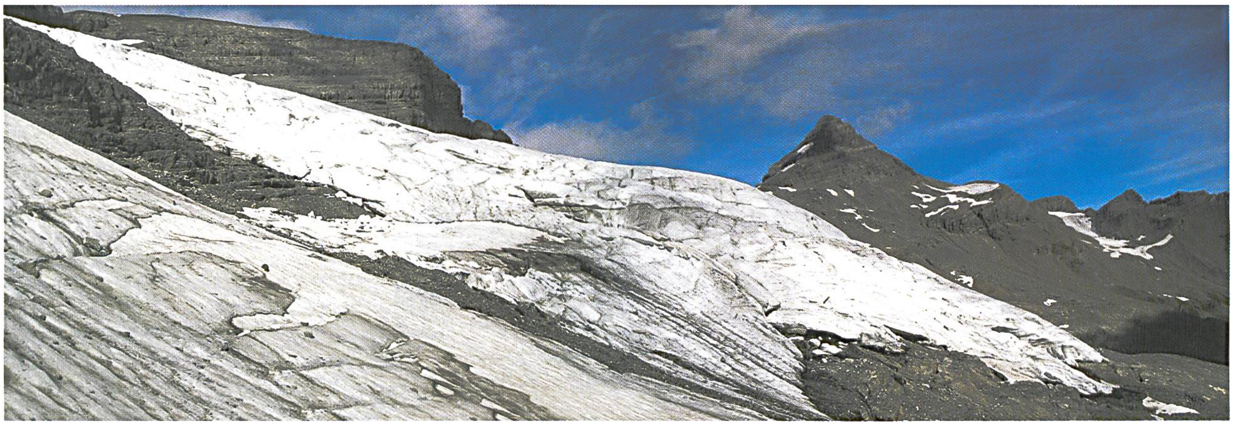


(g) The Malm limestone lapiazed surface on the Rosses Peak.



(i) Temperature measurements in the RU-1 cave.

(h) The glacier des Fonds, at left the Ruan and on the right, the Tour Sallière, as seen from the entrance of the RU-1 cave.



Introduction

For more than 10 years, we have studied the hydrogeology of the region between Haute-Savoie (France) and Valais (Switzerland). With altitudes ranging from 1000 to 3000 m a.s.l., i.e. from meadows to glaciers, the region has several valleys. The Barberine-Emosson valley, with an artificial lake, the Susanfe-Clusanfe valley, and the Salanfe valley, also occupied by an artificial lake, are all on the Swiss side of the border. The Fer-à-Cheval – Fond-de-la-Combe valley, on the French side of the border, lies in the Sixt Nature Reserve. The location of these units is shown in Fig. 1.

There are several reasons for our study taking many years. The local weather is very often poor and it is no coincidence that the area records the highest amount of precipitation in the western Alps. Additionally, working at altitudes between 2000 and 3000 m restricts fieldwork: the ground is normally free of snow at most 3 months per year, from mid-July to the end of October. Finally, the region on the French side is very steep, with cliffs more than 1000 m high and with deep gullies, leading to difficulties in going from one place to the other.

The reasons motivating this research are the following. Studies during the late 1980's and early 1990's of all natural lakes in Haute-Savoie and in the Emosson-Barberine valley (Sesiano 1993, 1994) show that some of them have underground drainage (Sesiano 1989a, 1989b, 1990). On the Swiss side of the border, glacial water does even not reach the lakes, sinking rapidly into the fractured limestone basement. Thus, we want to investigate the problem: Where does the water go?

Geology and tectonics of the area

The studied area is at the contact between the granite and gneiss cristalline basement of the Mont-Blanc – Aiguilles Rouges unit and its sedimentary autochthonous cover of Trias, Lias and Malm age. These formations are overthrusted by the Morcles nappe, which comprises Lias and lower Tertiary sediments. This region was named by Collet (1935) as the High Calcareous Alps. The deep glacio-karstic valley of Fer-à-Cheval – Fond-de-la-Combe is incised in the folded Jurassic core of the nappe, while the Barberine-Emosson one lies in its normal limb. The

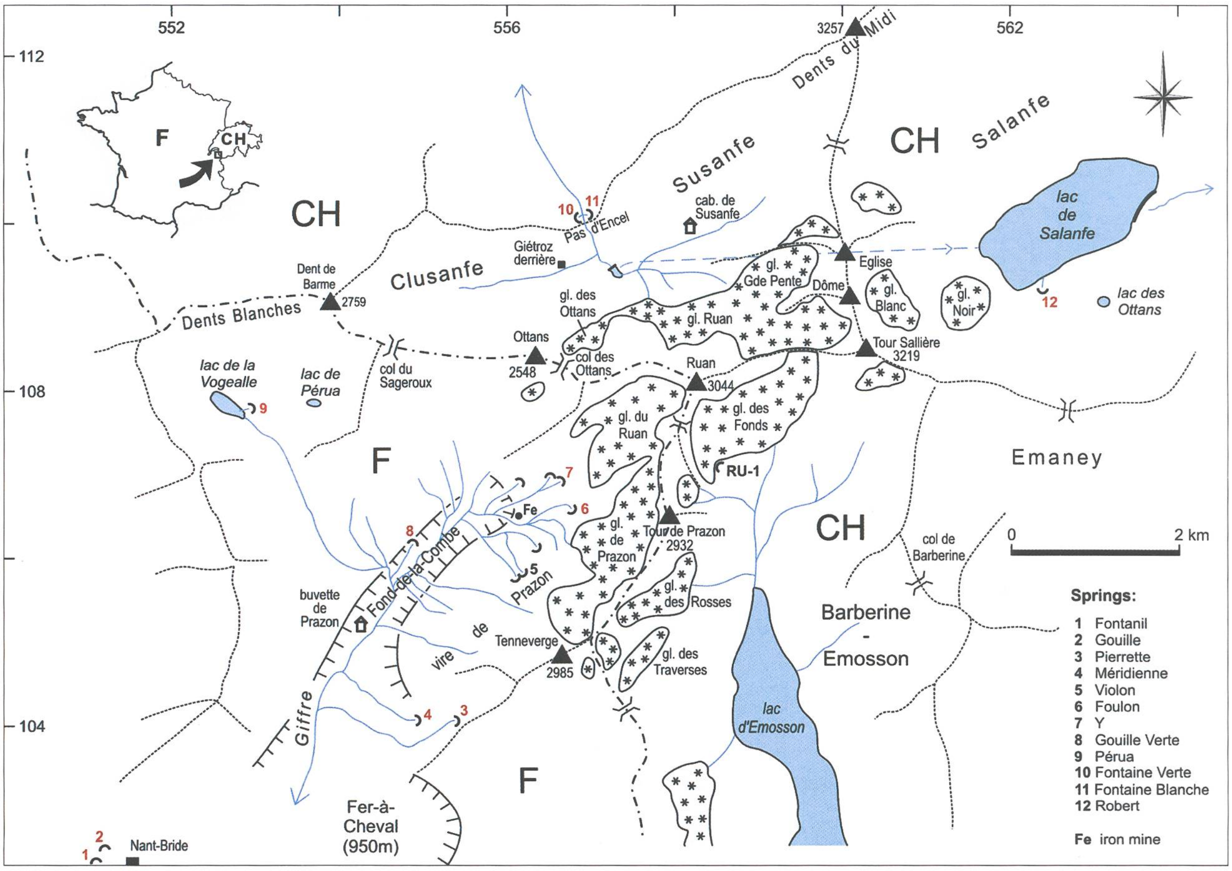


Fig. 1. Location of the studied zone in the Swiss-French Alps.

basement and its cover dip at an angle of about 30° to the NW. Slices of gneissic mylonites between the sedimentary cover and the base of the Morcles nappe can be observed in the Fer-à-Cheval (Pellys) and the Salanfe (Emaney) areas. While late deformations of the nappe from Pontian to the present have joints representing typical alpine directions (NE-SW), Hercynian directions (rather meridian) are found not only in the basement, but also in its cover and the nappe, where faults have been recently reactivated (Lombard, 1968).

Concerning the stratigraphy, we observe that the Malm or Tithonic (= Sequanian-Portlandian) limestone is the most karstifiable rock. It is compact and blue-grey with a thickness reaching 150 m. However, in Tenneverge Mountain, it is overfolded several times to reach a total thickness of more than 1000 m and has thin Berriasian layers separating disharmonic folds. The Malm limestone is very pure with more than 98% $CaCO_3$. It reacts to deformation by obtaining a dense net of joints, which are enlarged by corrosion to give a much higher secondary permeability than a primary one. The Argovian is less favourable to chemical dissolution, with about 95% $CaCO_3$. It is a black limestone, 50 to 60 m thick, found mostly in the upper part of the Barberine-Emosson glacial valley. Impervious strata are argillaceous layers from Lias, Bajocian, Callovo-Oxfordian marls and Berriasian. They outcrop largely at Fond-de-la-Combe, on the French side of the border. Together with the main joint directions given above, the dip and the direction of the Malm strata guide the underground drainage.

Background information about our research area can be found in Lombard (1932), Collet (1943), Pierre et Uselle (1966), and in geological maps of the region, i.e. sheets No 525 Finhaut (1952) and No 483 St Maurice (1934). The coordinates given in our study are from the Swiss national map, sheet No 1324 Barberine, with a scale of 1/25.000.

Tracer experiments

In August 1993, we made our first tracer dye experiment at an altitude of 2500 m in the upper part of Barberine valley. Glacial meltwater flows into an inverse fault in the Malm limestone, which is parallel to the frontal part of the glacier des Fonds. From the dip and direction of strata, it was tempting to believe that this water would reappear in the French Fer-à-Cheval – Fond de-la-Combe valley, some 1400 m lower to W-SW. This valley is drained by the Giffre River, the regional base level. The dye, fluorescein (uranin), was detected the following day by active charcoal bags (fluocaptors) placed in the river, but we could not say more accurately from which waterfalls or resurgences it came from.

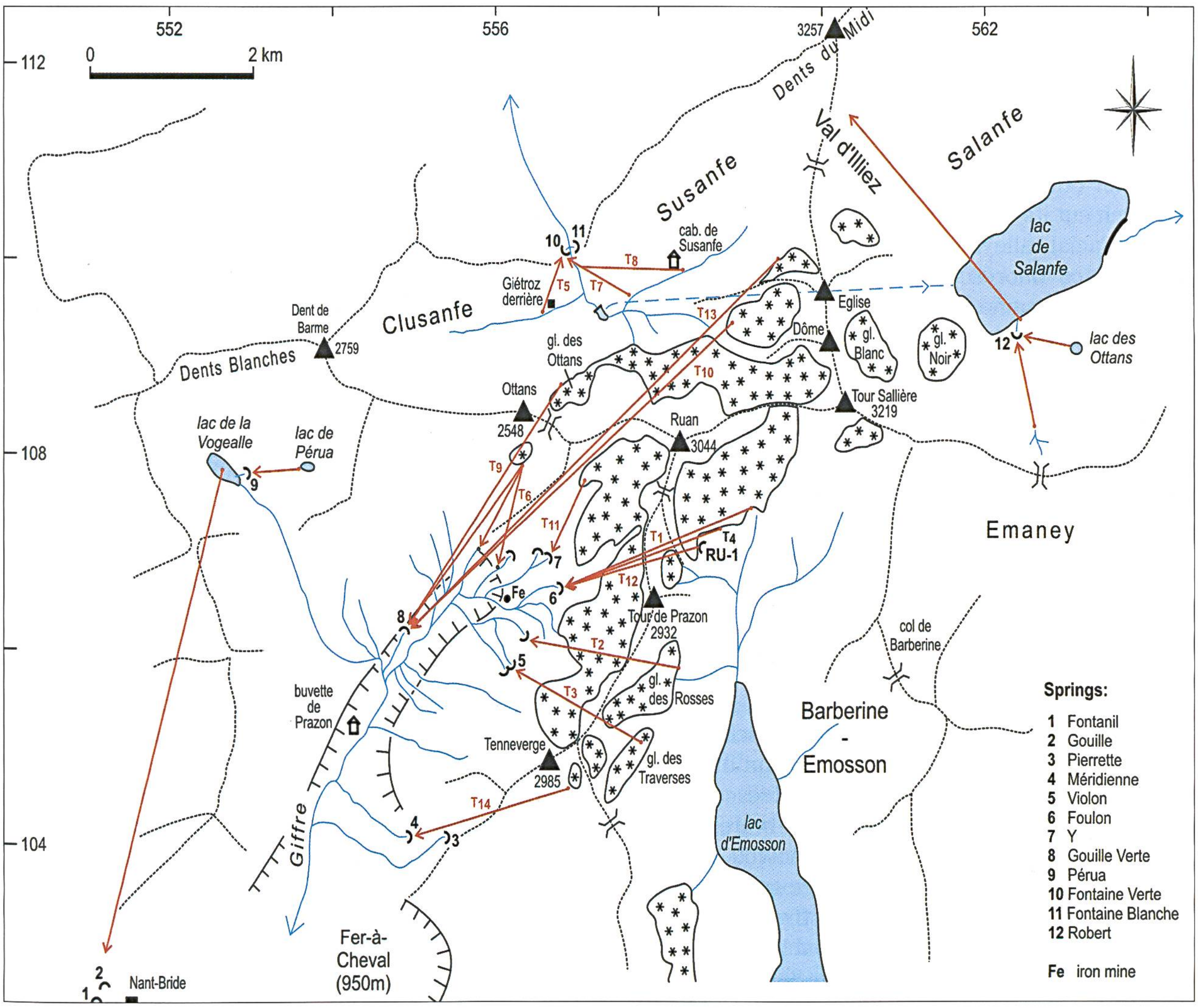
When repeating the experiment one week later, a large diffuse spring (several rises), at an altitude of 2000 m on the Prazon ledge of the Malm- Oxfordian interface, became brightly colored 3.25h after the dye injection (transit T1 in Fig. 2). The velocity was close to 1 km/h, a high value for an alpine environment, but quite similar to the one found by Favre (1976) in another limestone massif, some 10 km to the west. Such speed denotes a well-developed karstification. None of the other fluocaptors placed elsewhere showed any dye.

A water chemical analysis was made at the sinkhole and at the resurgence. It shows a sharp increase in total hardness from 1.94 to 8.36°F, from 8.4 to 27.8 mg/l for Ca, from 0.2 to 4.1 for Mg and from 3 to 15.4 for sulfates. An agressive cold water explains the conductivity (i.e. mineralization) increase from 37 to 175 μS/cm. The presence of pyrite in the limestone leads to the sulfate increase.

A similar setting prevails under the frontal part of the glacier des Rosses, 2 km south of the glacier des Fonds. A large joint in the Malm-Argovian limestone floor gathers the water, so in 1994 a dye was injected into the joint. Less than 6 hours later, the dye appeared on the French side of the border, at the same interface between the Malm limestone and the Oxfordian argillaceous schists (T2 in Fig. 2). The water issued from a small cave, less than 1 m² in area and 3 m above the ledge. In September we made another tracer experiment in the small glacier des Traverses. It is located 1 km to the south of the glacier des Rosses in a closed glacio-karstic depression. The tracing was also successful (T3 in Fig. 2).

In October, we performed a final experiment, again in the frontal part of the glacier des Fonds but several hundred meters south of T1, i.e. in the Argovian

Fig. 2. The 14 dye-tracing experiments that were performed (T1-14).



fissured limestone. Fluorescein reappeared less than 20 h later at the same place as for T1. The water probably followed a joint that leads to the same major water-collector fault. The transit time was much longer due to the unfavourable conditions in late autumn with very little ice melting (T4 in Fig. 2). In 1995, no tracer experiments were made since the snow cover was too thick, but field investigations continued as well as research in RU-1, a cave discovered the previous year (see Fig. 1 and further down).

At this point, it is worth noting that all the dyed waters flowing out of Swiss glaciers towards France would seem to feed the Emosson artificial lake. Instead, they escape under the border and feed the spectacular waterfalls of the French Fer-à-Cheval valley. This means a net loss of hydroelectric power for Switzerland, but it is relatively low, corresponding to about 2 days of production.

In 1996, the experiment T2 was repeated to locate more accurately the water resurgence. Then in autumn, we started to investigate the Susanfe-Clusanfe area, at the SW foot of the Dents du Midi range in Valais, Switzerland. A small stream originates on the eastern slopes of the Dent de Barme, and flows along the Clusanfe valley. It then feeds, through a man-made channel and a tunnel, the artificial lake of Salanfe. By building a small dam in the Clusanfe valley, we temporarily diverted the stream towards an inactive sinkhole. It was probably the valley water output several thousand years ago, before the ditch cut its way through the riegel, at the mouth of this glacial valley.

Injection of fluorescein showed that water reappeared on the same side of the border, at the bottom of the deep Encel gorge and 100 m below the path leading to the Susanfe valley. The spring, whose sinter deposits are covered with mosses, is called «Source Verte». Just across the stream flowing in that gorge, the Saufla, is another spring called «Source Blanche», which has no mosses.

While the water sinkhole is located in highly tectonized Valanginian rocks, the resurgence lies in the Nummulitic reversed limb of the frontal part of the Morcles nappe (T5 in Fig. 2).

In 1997, we worked back on the French side of the range, at the foot of the Tête des Ottans (2548 m). One can observe there a large dissolution pan, whose bottom is littered with Berriasian calc-schist debris fallen from above. Several dolines in the underlying Malm dot the floor. After pouring fluorescein into a small stream from melting snow, some waterfalls and springs in the Fond-de-la-Combe showed the presence of the tracer, including the large spring «Gouille Verte», a major affluent of the Giffre River (T6 in Fig. 2). The diffluence was probably due to high waters after a heavy rainstorm. In September, fluorescein was injected into a trickel of water in the RU-1 cave. It flowed under the border into France, but the resurgence could not be defined more accurately.

Early 1998 marks the beginning of the field fluorimeter measurements. The instrument, developed by the Geomagnetism Group of the University of Neuchâtel (Switzerland), is fed by 1 (or 2) 12 V battery, which last 10 (or 20) days. An analysis of the water tracer (fluorescein or sulforhodamin) with a detection threshold of $5 \cdot 10^{-11}$ gr/ml, is made every 4 s or 4 min and recorded on a memory card. The fluorimeter accurately determines the time for the dye to flow from the sinkhole to the rise, allowing to plot the dye concentration curve against time (restitution curve). We could then make hypothesis about the degree of maturity of the karstic system from the shape of the curve, the transit duration, etc.

In July, the instrument was used for the first time in the Susanfe valley, where a snow melt stream sinks into a crack on a path leading to the Susanfe hut. Water reappeared at Source Verte with a velocity of only 25 m/h during snow melt, denoting a phreatic regime in a poorly developed karstic system of the Neocomian strata (T7 in Fig. 2). The restitution curve showed the first fluorescein detection 39 hours after injection, with a peak of 0.8 ppb 13 hours later. Then, we observed several daily peaks (24 h period) corresponding to the snow melt. We had a second major peak one week later at 1 ppb, because of violent rain storms which expelled part of the tracer stored in the system. Active charcoal bags put elsewhere (Swiss and French sides of the border) did not show any tracer.

In the same month, we made another experiment in the WC effluents of the Susanfe hut, which sink into a joint in the Neocomian limestone. Fluorescein was detected at Source Verte, with the same velocity as for T7. Dye concentration was higher (11.5 ppb) and had a sharp peak, even though the tracer amount (0.5 kg) was the same as for T6. It seemed that the hut drainage reached the collector more directly, but still with a phreatic circulation; 25% of the dye was recovered (T8 in Fig. 2). We obtained more proof of the link between the hut effluents and Source Verte : water samples from that spring were analysed for bacteria and a high contamination by Escherichia coli. (i.e. fecal germs) was found.

In late July, a very small stream flowing from the Glacier des Ottans on the Swiss side of the range and sinking into a joint in a Malm lapiaz outcrop (alt. 2250 m), was dyed. The fluorimeter was turned on at the Gouille Verte spring, on the French side, at the altitude of 1050 m. Fluorescein appeared 22.5 h after injection, with a peak 11 h later. A slow decrease followed for 10 days, with daily peaks around 18 h (summer time) and less intense every day (T9 in Figs. 2, 3). The modal velocity was 150 m/h. We inferred that the first part of the transit

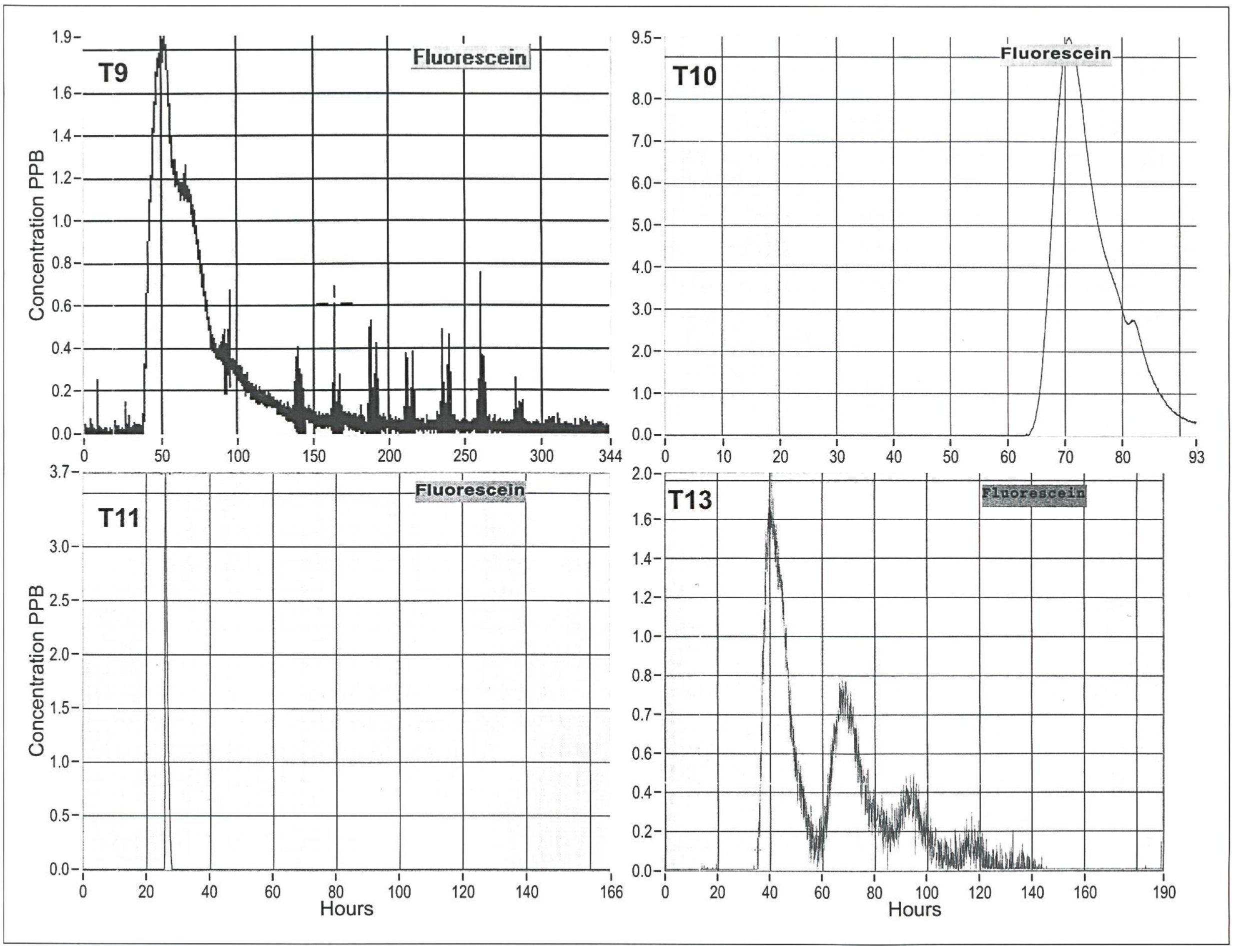


Fig. 3. Typical fluorimeter signals from some of our tracer dye experiments.

is vadose (strong gradient), while the latter is phreatic (the rises come from a small Malm outcrop whose base is hidden by talus debris at valley level; locally, the glacial trough is filled with fluvio-glacial deposits less than 100 m thick, and the water table lies close to the ground surface).

In September 1999, we poured fluorescein into a stream (5 to 10 l/s) coming out of the glacier de la Grande Pente, on the western slopes of the Eglise and Dôme, in the Tour Sallière massif (Valais). As the extremity of the glacier lies in a glacio-karstic basin (Malm) at an altitude of 2460 m and has no water outlet, there must be sink holes or a joint system under the glacier. The first signal was detected at Gouille Verte spring 42.5 h after injection, with a peak (9.5 ppb) 5 h later (T10 in Figs. 2, 3). The modal velocity was 130 m/h, close to that of the Ottans glacier, thus the water follows the collector. Shortly afterwards, we injected dye into a stream flowing and falling into a crevasse on the surface of the western tongue of the French Ruan glacier. The glacier moves across the karstified subhorizontal Malm strata. The dye appeared 3 h later, about 800 m lower in a stream traversing several cliffs, just beside an old iron mine (chamosite, an oolite in the Dogger) at an altitude of 1550 m. A high velocity of 1 km/h, and a narrow response peak (Fig. 3) imply a well-developed karstic vadose system in the upper Tithonic (T11 in Figs. 2, 3).

In 2000, we repeated the experiment in the RU-1 cave. The dye showed up 7.25 h later in the same place as for T1 and T4 (500 m altitude drop) with a 130 ppb peak 1 h later. The pre-experiment background-noise level was recovered the following day. An average velocity of 400 m/h seems quite low compared to that of T1. Obviously, the first part of the transit was slow (only 0.1 l/s in the cave) before the collector was reached (T12 in Fig. 2). The rest of the year was spent in the Salanfe valley where an experiment, repeated in 2001, showed the connection between water lost at the Salanfe artificial lake and the Val d'Illiez thermal springs (Sesiano, 2003).

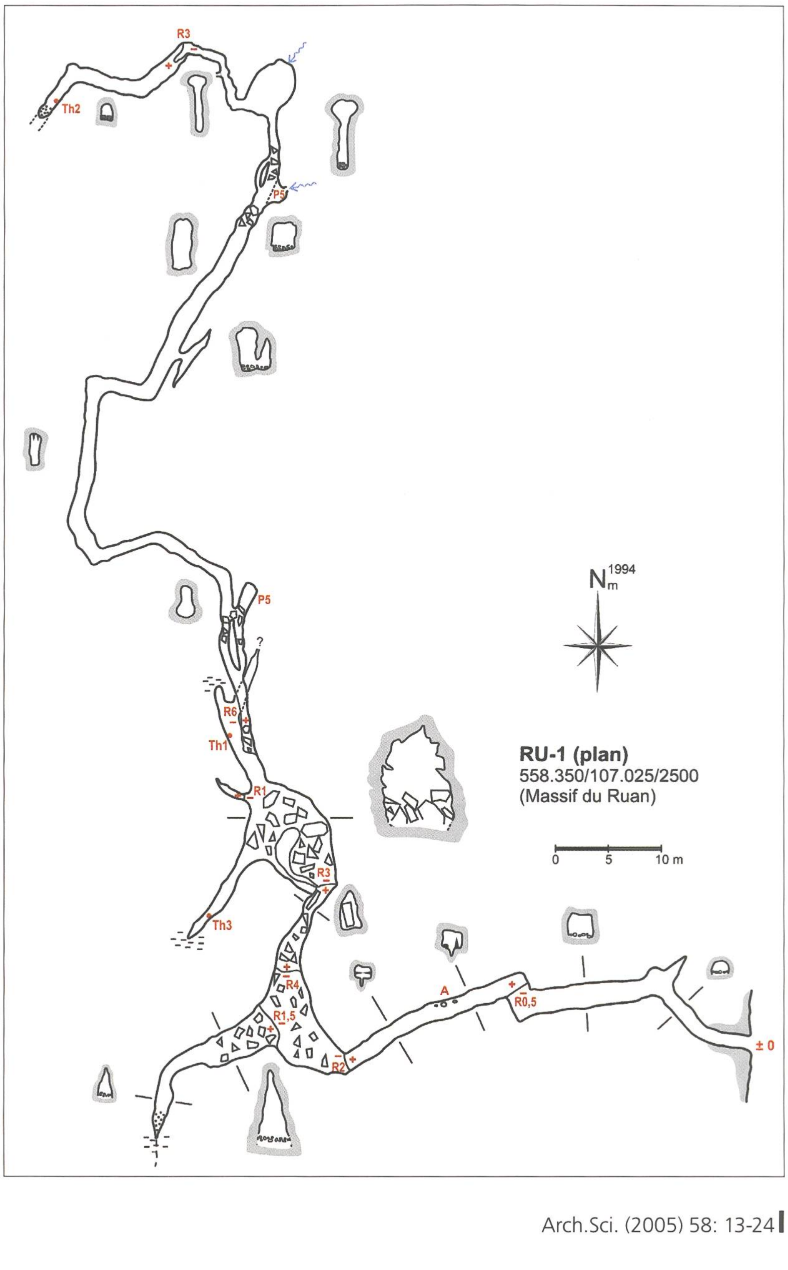
Finally, in 2002, we wanted to localize the furthest point reached by the Giffre drainage basin. On the northern slopes of the Eglise summit (3077 m), we noticed a glacier devoid of aerial emission, although water could be heard flowing in shallow crevasses, 1 m below the surface (coordinates: 559.650/110.000 and 2570 m altitude). Fluorescein was poured into a crevasse, while the fluorimeter was turned on at

Gouille Verte spring and charcoal bags were placed at different locations. The only signal (2 ppb) appeared on the instrument 47 h after injection. One week later, the daily peaks disappeared (T13 in Figs. 2, 3). The velocity of 130 m/h indicates a poorly developed underground drainage, especially at the head of the basin. According to the restitution curve, about 25% of the fluorescein was recovered.
A final experiment was performed in August 2004 on the southern face of the Tenneverge peak, at an altitude of 2680 m. Fluorescein was detected at the Meridienne waterfall 9 h after injection. The dye followed numerous stacked Malm folds before coming out of a joint in the center of the Dogger cliff (T14 in Fig. 2).

The RU-1 cave

The RU-1 cave was is located on the eastern slopes of the Ruan massif, on the Helvetic side of the border, close to the glacier des Fonds. Its coordinates are 558.350/107.025, and its altitude is 2500 m. The opening, about 1.5 m high, lies at the foot of a 10-m-high limestone cliff that was cut by a subvertical joint. Several thin sections made from samples taken at the entrance and in the cave, show an age of Upper Tithonic.
This cave was discovered during our fieldwork. Its recent discovery is explained by the typical 5 to 6 m of snow piling up at the foot of the cliff. But in autumn, we have seen the entrance either totally hidden or, aboveall in recent years, completely free of snow, depending on the yearly snow fall. This area also has an air current entering or leaving, depending on the hour at that time of the year (August to October), in agreement with the « chimney effect » (Lismonde, 2001).
The cave is subhorizontal, as the surrounding bedding. Major joints cause several abrupt changes in the cave's direction (Fig. 4). The galleries are mainly phreatic ; vadose ones are observed only near the entrance. A few old-looking concretions cover the walls and are sometimes found on the floor. Corrosion often affects them. Here and there, trickles of water percolate from the ceiling. They arise from snow melt on the lapiaz, some 30 to 50 m above. Although small rooms were created by floor collapses, the original phreatic tube can still be observed at the ceiling.
Fine sand-clay deposits become increasingly abundant the deeper we penetrate the cave, even reaching the ceiling at its extremity. Samples from the cave-floor deposits show a very fine and uniform grain-size distribution, indicating glacial abrasion of Argovian marls (Dr. J. Martini, pers. comm.).
A broken piece of a massive in situ stalagmite (A, Fig. 4) weighing some 15 kg, was taken for an age determination. Palaeomagnetism was the first technique attempted, but we failed to get any result due to the low amount of iron oxides. A U/Th age determination was the next step. The first sample, a slice

Fig. 4. The RU-1 cave map.
Th: thermometer. - R (xm): a x m high step - (-: low side; +: high side).
P(xm): a x m deep pit. - A: dated stalagmite.



from the concretion, showed to have been geochemically opened through detritic elements or external colloïds. That was not too surprising since the stalagmite presented a somewhat corroded surface. But due to the fact that the ratio U^{234}/U^{238} was equal to 1, its age was estimated to be probably more than one million years. A second sample, from the heart of the same stalagmite, showed the same problem. Finally, from a deeper wall concretion, which was not geochemically opened, an age greater than 400.000 years (the age limit for that technique) was obtained.

In 1995, we put 3 minimum-maximum thermometers in the cave, either on the ground (Th2 and Th3) or against the wall (Th1) (Fig. 4). They were set in portions of the cave apparently devoid of air circulation from the surface. We expected that the measurement to be representative of the average yearly local temperature as the distance to the outside cliff and to the surface, some 40 m, was large enough to dampen the seasonal variation. Generally in September, the reading was done and then set to 0. Extreme values of –0.5°C to +2°C were observed, with a trend of the yearly averages toward positive values over the last years.

The altitude of the 0°C annual isotherm in the Swiss and the northern part of the French Alps is quite different among various authors. Vivian (1975), in his intensive study of northern Alps glaciers, finds 2800 m. Gauthier (1973), however, estimates an altitude of 2580 m in our region, and Maire (1990, p. 22) calculates 2050 m. Borreguero (2002), in the central part of Valais, finds 2200 m, and Trüssel (1993) finds the same value in the Prealps (Obwald canton).

From our measurements, it looks as though we are very close to the 0°C isotherm, in fact 60 to 80 m below, i.e. that line would stand around 2570 m in that region of the Alps.

The environment of the RU-1 cave is typically glacial. The front part of the glacier des Fonds lies at the same altitude as the cave, some 300 m to the NE, while a (dead?) ice tongue flows 100 m below the cave. The Milchbach cave, just next to the Grindelwald glacier (Stettler, 1999), has a similar situation but with an altitude 1000 m lower.

Numerous gelifracts affect the first 10 m or so of the gallery, but they can also result from a decompression effect. A small moraine, some 50 cm high, lies across the entrance and probably dates back to the Little Ice Age. According to photos taken in the early and middle 20th century (Perret, 1911), the cave entrance was hiden at that time by the glacier des Fonds and the cave represented a swallow hole for the glacier melt water (evidenced by scours on the cave walls). During phreatic conditions, galleries were completely filled with fine-grained deposits. Presently, they are slowly being washed away by new water circulation cutting across the ancient galleries.

The geomorphology around the cave, the dip of the Argovian and Malm strata, and the possibility of having 150-200 m of rock eroded by a glacier in a million years (Audra 1994; 1997, p.338), all indicate that the entire head of the cave disappeared through the glacier des Fonds action. On the other hand, it is unclear how massive concretions, such as those used for the radiometric dating, could form at an altitude where present conditions are very unfavourable: low temperature, lack of vegetation and thus CO_2. According to our dating and to the uplift rate in that part of the Alps of 1 mm/y, the region must have been some 1000 m below its present altitude early in the Quaternary. During the interglacial period, with temperatures similar or higher than the present ones, there was plenty of CO_2 in the ground for a high rate of corrosion, thus for calcite deposition in the cave.

The Gouille Verte spring

The Gouille Verte lies on northwest side of the Fond-de-la-Combe valley (8 in Fig. 1). The adjective «Verte» is used in order to avoid any confusion with the «Gouille spring», which is further down the same valley (2 in Fig. 1). This spring is a resurgence of the water lost in Vogealle Lake, located on the same side of the valley but 1000 m higher than the Gouille Verte (Sesiano, 1989a). The coordinates of the Gouille Verte are 554.800/106.000 and its altitude is 1050 m. As mentioned above, the water comes out of a talus debris at the foot of the glacial trough cliff, through several rises that are situated at the contact between the Argovian-Malm limestone and the upper Bajocian argillaceous limestone strata (Lombard 1932, p. 194-5).

Since 1995, we operated a limnigraph at this site (3 weeks autonomy). During the winter of 1998-99, large amounts of snow led to avalanches, and only with the help of a fluxgate gradiometer could we locate the instrument the following spring, under 2 m of snow. It was removed, after 4 years of recording. In the same place, a scale with cm divisions has been in operation since 1995. Every 2 or 3 weeks, a visit was made to the Gouille Verte to check the instrument and to change the paper. Simultaneously, we measured temperature, conductivity and pH and estimated the flow rate of the spring (Fig. 5).

We observe that the spring regime is nivo-glacial, with a minimum water level in January and February and a maximum one in May and June, followed by a slow decrease. However, the rise of the curve in springtime is much more rapid than its automnal decrease. It tends to show that large amounts of water are stored in the joints and galleries of the karstic system, above all in its phreatic part (probably below the water table of the valley). The low average velocity of the dye, despite an

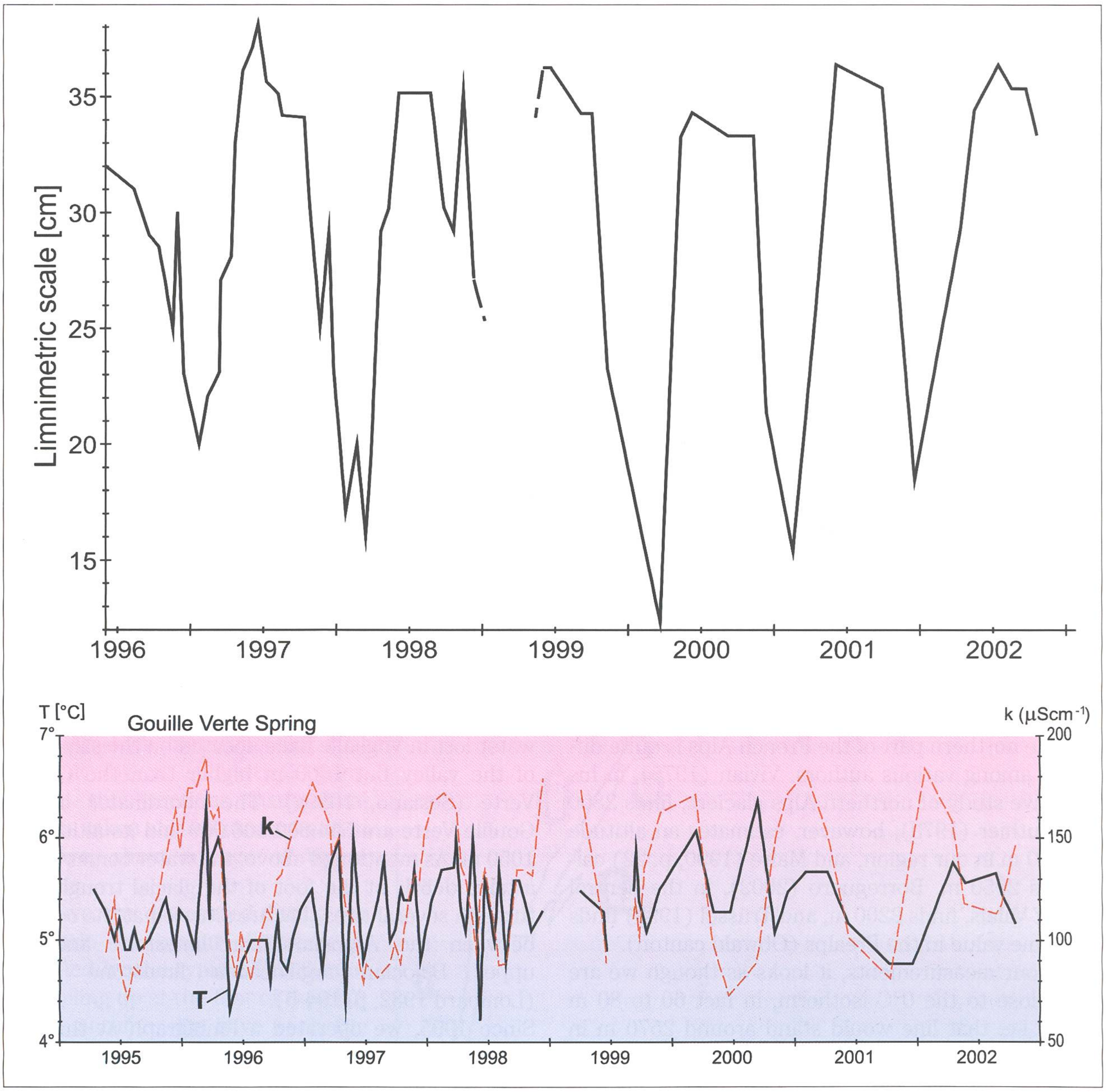


Fig. 5. The temperature (T), conductivity (k) and water flow regime (from a limnimetric scale in cm), of the Gouille Verte spring during a 6-7 year period.

alpine environment with high gradients, tends to prove this. However, in winter we can have a very rapid transition to high water levels, whenever the 0°C isotherm rises temporarily and is accompanied with rains at high altitude.

Daily oscillations from snow melt, are observed between 10 h and 18 h, the rise being again more rapid than the decrease. Their amplitude is highest from April to June. Because of fresh snow falls and the lack of melting from November onwards, they do not show up later. We have no data for January, February and early March, since the limnigraph lies under the snow cover.

Concerning the temperature, we notice an amplitude from 4.5 to 6.5°C, during 8 years of measurements, while recording 20°C for a neighbouring surface stream. This is the result of a strong damping due to deep and slow water circulation under phreatic conditions. The average yearly temperature of the spring is 5.5°C. It represents fairly well the average temperature of the place of emergence. That value can be compared with the one obtained from another deep spring studied in the 1980's, the Vivier (Sesiano, 1989b). It is fed by an altitude basin, lower than the one studied here and without any glacial or even perennial snow. The spring, at an altitude of 500 m near Magland in the Arve valley, has a yearly average temperature of 8.7°C, with an amplitude of 1°C. This represents the average temperature in that deep alpine valley.

Another graph shows the relation between temperature and conductivity, i.e. water mineralization. At time of low level water (January-February), we note that «warm» and mineralized water is expulsed, after a «long» stay in the system (piston-flow effect). More water coming out in spring means rapid transit, thus with lower temperature and mineralization (less time for corrosion). This behaviour can be interrupted by a short episode of colder weather, rain at high altitude or even fresh snow.

The lowest temperatures are reached in July-August, completely out of phase with the outside air temperature. The conductivity of the Vivier spring (Sesiano, 1989b) is much higher (500 µS/cm) than in our case (125 µS/cm), which can be explained by lower altitude basin (Lepiller, 1984): in our case, the paucity of the vegetation signifies less CO_2 available and thus less agressive water, even if its temperature is lower. The variability of the conductivity is quite low, about 80 µS/cm. It shows once more that the karstification is still underdevelopped, as confirmed by the low dye transit velocities (Mondain, 1983).

Due to the absence of a gauge station, we made estimates of the volume of water flowing out of the Gouille Verte spring, by using either a millwheel or by measuring width, depth and velocity in a straight and flat section of the river bed. The lowest amount of water is observed from January to early March, with about 100 l/s. A rapid increase follows with 200 l/s in April, 300 in May, 400 in June and 500 in July and August. Then begins a slow decrease with 400 l/s in September, 300 in October, 200 in November and 150 in December. These are approximate values, subject to significant variations following various meteorological events such as winter warm spells with rain at high altitude over fresh snow, heavy summer thunderstorms, variable snow thickness, etc. The annual module is thus estimated to be 270 l/s, which is used in our water balance.

The Gouille Verte has a large nivo-glacial basin: it covers the surface west (from T10 data) and north (T13) of the ridge Tour-Sallière – Dôme – Eglise. It also gets water from the glacier des Ottans s.l. (T8) and partly from the Ottans karst, on the French side (T6). All that amounts to 4 km^2. Even if a certain amount of water flows out of the glacier du Ruan (Swiss side) to reach, by a tunnel, Salanfe Lake (35 l/s correspond to an annual drainage of 0.5 km^2), we are left with 3.5 km^2 for the Gouille Verte drainage basin.

Assuming a value of 2.7 m/y for precipitation (data from various neighbouring pluviometers) and a 15% evapotranspiration (from the Turc and Coutagne formula, in Maire, 1990), we are left with 2.3 m to infiltrate underground. This corresponds to a yearly outflow of 250 l/s, very close to the estimates from our observations.

Conclusions

Our research answers the following questions: Where does the water feeding all the waterfalls of the Fer-à-Cheval – Fond-de-la-Combe valley come from? Why is there such a poor surface drainage in the upper part of the Barberine-Emosson valley and in the Susanfe valley?

However, we cannot pinpoint the origin of a famous resurgence of the Fer-à-Cheval, the Pierrette, and we determine only part of the drainage basin of the Méridienne (T14). The former probably originates from water sinking into Malm cracks, near the Tenneverge summit. The latter, flowing like a faucet in the center of a high Dogger cliff in the lower Tenneverge, probably drains also part of the floor of the glacier de Prazon. We will try to prove it once the ice melts.

On the other hand, valuable data have been collected about temperature, conductivity and hydrological behaviour of the main resurgence of the area, the Gouille Verte. A satisfying balance could be drawn between input (precipitation) and output (evapotranspiration, surface and underground drainage). We also prove that the Giffre, a famous Haute-Savoie river, originates in Switzerland and not in France, as was previously believed.

Finally, observations in RU-1 cave show that it is an old drainage system, even though recent water circulation disturbs the original flow direction by cutting through the galleries. Except in the head of the drainage basin, where high gradient and rapid transit predominate (vadose circulation), the water circulation is slow and phreatic, the system is underdeveloped and often disturbed by glacial deposits.

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