Zeitschrift: Eclogae Geologicae Helvetiae
Herausgeber: Schweizerische Geologische Gesellschaft
Band: 96 (2003)
Heft: 1

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DOI: https://doi.org/10.5169/seals-169004

0012-9402/03/010023-14
DOI 10.1007/s00015-003-1074-5
Birkhäuser Verlag, Basel, 2003

A review of the dye tracing experiments done in the Siebenhengste karst region (Bern, Switzerland)

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Key words: Dye tracing, karst, catchment area, St. Beatus Cave, Siebenhengste-Hohgant

ABSTRACT

This paper reviews and summarises 20 experiments to trace groundwater flow in the regions Beatenberg-Hohgant-Schrattenfluh and the Harder chain. We emphasize the water tracing experiment conducted in 1996 in the region Beatenberg / Gemmenalp, where the aim was to better delineate the catchment area of St. Beatus Cave, which extends to the Gemmenalphorn. The entrance of the Bärenschacht – a cave belonging to the Bätterich/Gelberbrunnen catchment – lies within this area. To the north lies a karstic zone within the Tertiary, in which water flows towards superficial brooks. The Bätterich/Gelberbrunnen catchment begins north of the line Gemmenalphorn – Bäreney. In addition, a map of the different dye tracings and of the catchment areas has been compiled.

ZUSAMMENFASSUNG

Dieser Artikel fasst die 20 in der Region Beatenberg-Hohgant-Schrattenfluh und der Harderkette durchgeführten Markierversuche zusammen. Ein besonderes Gewicht wird auf die im Jahre 1996 durchgeführte Wasserfärbung im Raume Beatenberg / Gemmenalp gelegt, die erlaubt, das Einzugsgebiet der St. Beatus-Höhle zu definieren. Dieses erstreckt sich bis zum Gemmenalphorn. Der Bärenschacht – der zum Bätterich/Gelberbrunnen-Einzugsgebiet gehört – befindet sich in diesem Gebiet. Nördlich dieses Einzugsgebietes folgt eine Karstzone innerhalb des Tertiärs, die aber oberflächlich in den Lombach entwässert. Erst nördlich der Linie Gemmenalphorn – Bäreney beginnt das Einzugsgebiet des Bätterich/Gelberbrunnen. Eine Übersichtskarte der Markierversuche sowie der Einzugsgebiete wird vorgestellt.

RESUME

L'article présente et résume 20 essais de traçage effectués dans la région Beatenberg-Hohgant-Schrattenfluh et dans la chaîne du Harder. Il met l'accent sur la présentation de l'essai de traçage effectué en 1996 dans la région Beatenberg / Gemmenalp, qui permet de préciser la délimitation entre les deux bassins versants de la St. Beatus-Höhle et de Bätterich/Gelberbrunnen. Le bassin versant de la St. Beatus-Höhle remonte jusqu'au Gemmenalphorn. Le Bärenschacht – qui appartient au bassin de Bätterich/Gelberbrunnen- s'ouvre pourtant dans ce bassin. Plus au nord, une zone karstique perchée dans le Tertiaire émerge dans des ruisseaux de surface. Ce n'est qu'au nord de la ligne Gemmenalphorn – Bäreney que le bassin versant de Bätterich/Gelberbrunnen commence. Une carte de synthèse des essais de traçage et des bassins versants de la région est présentée.

1. Introduction

After the second world war, a new water supply was required for the town of Interlaken. Temporary springs at the southern foot of the Harder chain near the town were investigated. Following precise observations of the spring behaviour, Franz Knuchel (a teacher in Interlaken) made the first tracing experiment, with a dye injection point in the Innerbergli karren field near Hohgant peak. The results of this experiment were not concluding. Therefore, further tracing experiments were conducted, in part by professionals, and in part by cavers. Many of the experiments are not published. The aim of this article is to review the results of this work spanning almost 50 years. Many data presented here were found in the archive of the research group "Höhlenforschergemeinschaft Region Hohgant" HRH. Since 1970, the Siebenhengste region has become one of the scientifically most important cave regions worldwide, comprising today more than 280 km of galleries. So, the dye tracing experiments were supported by direct underground observations.

The results of the past tracing experiments allowed a good delimitation of the different catchment areas and the effective waterways within the caves. However, several questions still persisted. In particular, the divide between the St. Beatus Cave catchment and the Siebenhengste catchment in the region of

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Tab. 1. Overview over the tracing experiments 1940–1995

No.	Date	Injection	Coordinates			Q l/s	Tracer	Amount	Time	Reappearance	Coordinates			Min flow time	Distance	Velocity m/h max.	Literature
1	17.4.46	Häliloch	626850	173550	1750	10	Fluoresceine	5 kg	13:00	Beatushöhle	626250	170450	690	30	3331	111	Archive HRH
2	28.4.53	Birenbach	627625	173025	1520	?	Fluoresceine?	?	11:10	Beatushöhle	626250	170450	690	18	3035	169	Archive HRH
										Haselegg	627700	171500	795	23	1690	73	
3	13.5.59	Septemberschacht	633490	181020	1740	?	Fluoresceine	19 kg	14:30	Bätterich	627744	170398	549	27	12135	449	Knuchel 1959
										Gelberbrunnen	628020	170330	561	27	12066	447	
										Ostbahnhof	633250	171350	570	22	9743	443	
										Niederried	637550	174600	660	170	7672	45	
4	1961	Kühlauenenbach	625900	170850	1020	0,5	Fluoresceine	750 g	11:20	Beatushöhle	626250	170450	690	7,6	626	82	Knuchel 1961
5	1961	Chrutbach	625875	170725	880	?	Fluoresceine	3 kg	?	Lerauquelle	626000	170250	600	23	565	25	Archive HRH
6	1959-1970	Senkloch	631950	178350	1400	?	Fluoresceine	20 kg	?	Bätterich	627744	170398	549	18	9036	502	Knuchel 1974
										Gelberbrunnen	628020	170330	561	18	8970	498	
7	6.6.70	Lagopèdes	640780	186380	1650	500?	Sulforhodamine	40 kg	17:20	Bätterich	627744	170398	549	38	20654	544	Knuchel 1972
										Gelberbrunnen	628020	170330	561	38	20533	540	
8	1970-1973	Bärenschacht	628575	173950	1505	?	Fluoresceine	5 kg	?	Bätterich	627744	170398	549	32	3771	118	Knuchel 1974
										Gelberbrunnen	628020	170330	561	78	3782	48	
9	26.5.73	Septemberschacht	633490	181020	1740	30	Uranine	20 kg		Gelberbrunnen	628020	170330	561	33	12066	366	Simeoni 1973
10	29.6.74	Faustloch	630175	177050	1530	?	Fluoresceine	?	17:10	Bätterich	627744	170398	549	15	7150	477	Archive HRH
										Gelberbrunnen	628020	170330	561	19	7123	375	
11	28.5.75	Doline Faustloch	630215	177020	1505	50	Sulforhodamine	10 kg	16:00	Gelberbrunnen	628020	170330	561	22	7104	323	Simeoni 1975
		Schluchhole	630700	179050	1593	50	Uranine	20 kg	14:00	Gelberbrunnen	628020	170330	561	24	9181	383	
12	10.7.77	Trogenmoos Dol. I	632375	179750	1600	500	Fluoresceine	160 g	14:35	Trogenbachh.	632450	179600	1550	0,25	175	700	Widmer/Rouiller 1978
		Trogenmoos Dol. II	632275	179650	1590	?	Fluoresceine	80 g	16:30	Trogenbachq.	632350	179525	1560	0,41	149	363	
13	9.6.80	Allgäuli	640250	180150	1670	50?	Fluoresceine	20 kg	10:30	Goldey	631600	171000	566	40	12640	316	WEA 1980
										Beau Rivage	632600	171140	568	40	11871	297	
14	6.7.82	Eisee	674475	182325	1960	?	Sulforhodamine	1 kg	11:00	Emmesprung	647950	183500	1440	4,5	1370	304	Wildberger 1982
15	15.12.84	Fitzlischacht	626550	172050	1400	?	Naphtionate	?	12:30	Beatus-NG	626700	171200	840	22	1029	47	Klötzli 1985
										Beatus-OG	626700	171200	840	22	1029	47	Archive HRH
										Beatus-HNG	626700	171200	840	23	1029	45	
		Häliloch	626850	173550	1750	?	Rhodamine B	?	13:30	Beatus-NG	626700	171200	840	37	2525	68	
										Beatus-OG	626700	171200	840	36	2525	70	
										Beatus-HNG	626700	171200	840	35	2525	72	
16	24.2.90	Beatus-Tschäderl.	626300	170775	750	0,1	Mud	--	22:00	Beatus-Bachgr.	626325	170550	720	1	228	228	Pfister 1990
17	29.2.92	Beatus-Erosionsg.	626100	170800	750	1	NaCl	5 kg	15:50	Beatus-Hauptb.	626250	170525	705	0,58	316	545	Pfister 1992
										Beatus-Spagh.	626250	170525	705	0,5	316	632	
18	8.3.92	Beatus-Nasser G.	626400	170550	730	0,1	NaCl	7 kg	12:10	unknown	?	?	?	--	--		Pfister 1992
20	1.4.01	Bärenschacht	628850	173608	1024	1	Fluoresceine	100 g	10:00	Bärenschacht	629020	173427	929	4	266	67	Isaac 2001

the Gemmenalphorn was still unclear. Additionally, the 1996 tracing experiment should show if the Bärenschacht entrance lies within the catchment area of the Bätterich spring.

An overview of all dye tracing experiments done in the region is presented in Chapter 3 and Table 1.

2. Geographical and hydrogeological overview

The cave region of Siebenhengste is situated in the northwestern part of the Alps, adjacent to the Molasse basin (Fig. 1). From Lake Thun, it reaches up to Hohgant peak. The entire mountain chain forms a southeast-dipping slope, cut in the northwest by steep cliffs. The upper parts, between 1700 m and 2000 m a.s.l., are largely denuded and composed of limestone pavement. At lower altitudes, firs grow on swampy ground. The annual precipitation is between 1500 and 2000 mm (data from the Swiss Meteorological Service).

The region is divided into two water catchments (Fig. 1). The first drains Waldheim Cave, Fitzlischacht and Häliloch into the St. Beatus Cave and encompasses an area of about 6 km^2. The second catchment area contains Bärenschacht, the cave system called Réseau Siebenhengste-Hohgant (in this paper abbreviated as Réseau) and the surrounding caves, draining directly into Lake Thun via the Bätterich and Gelberbrunnen springs. The Réseau is made up of the F1 cave, the Siebenhengste labyrinth and Faustloch. Its current length is 148 km with 1340 m of altitude difference. In total, more than 280 km of cave passages have been explored, stretching from Lake Thun (558 m a.s.l.) up to the summit of Siebenhengste (1950 m a.s.l.).

The water catchment of the Bätterich/Gelberbrunnen springs extends even farther to the north, to the Schrattenfluh massif that lies beyond the deeply incised valley of the Emme.

The region lies in the Helvetic nappes of the Alps. The stratigraphy relevant to the karstic drains is represented in the overview in Fig. 1. Valanginien marls to Schrattenkalk are Cretaceous, the Hohgant series up to Globigerina marls are of Eocene age. The Drusberg marls usually form the impervious bottom layer of the thoroughly karstified Schrattenkalk, which constitutes the main aquifer. The Hohgant series ranges from quartzitic sandstone to pure limestone; all the calcareous members of it are usually karstified to some extent: more than 3 km of cave passages develop within the Hohgant series.

The rocks are thrust over the Molasse basin and form a monoclinal slope that is cut by some longitudinal normal faults and transverse dextral strike-slip faults (not visible on Fig. 1).

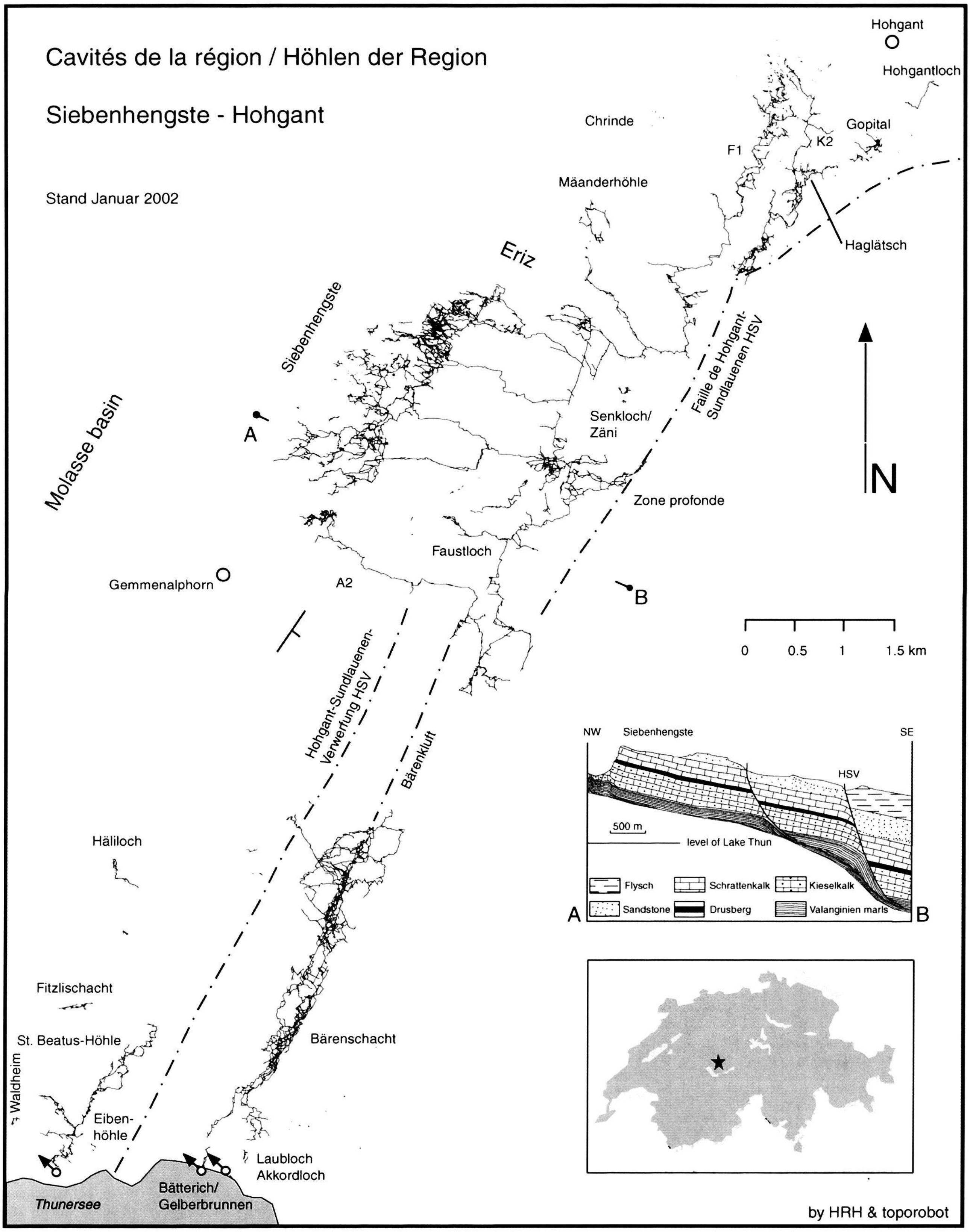

Fig. 1. The cave region of Siebenhengste with a geological cross-section.

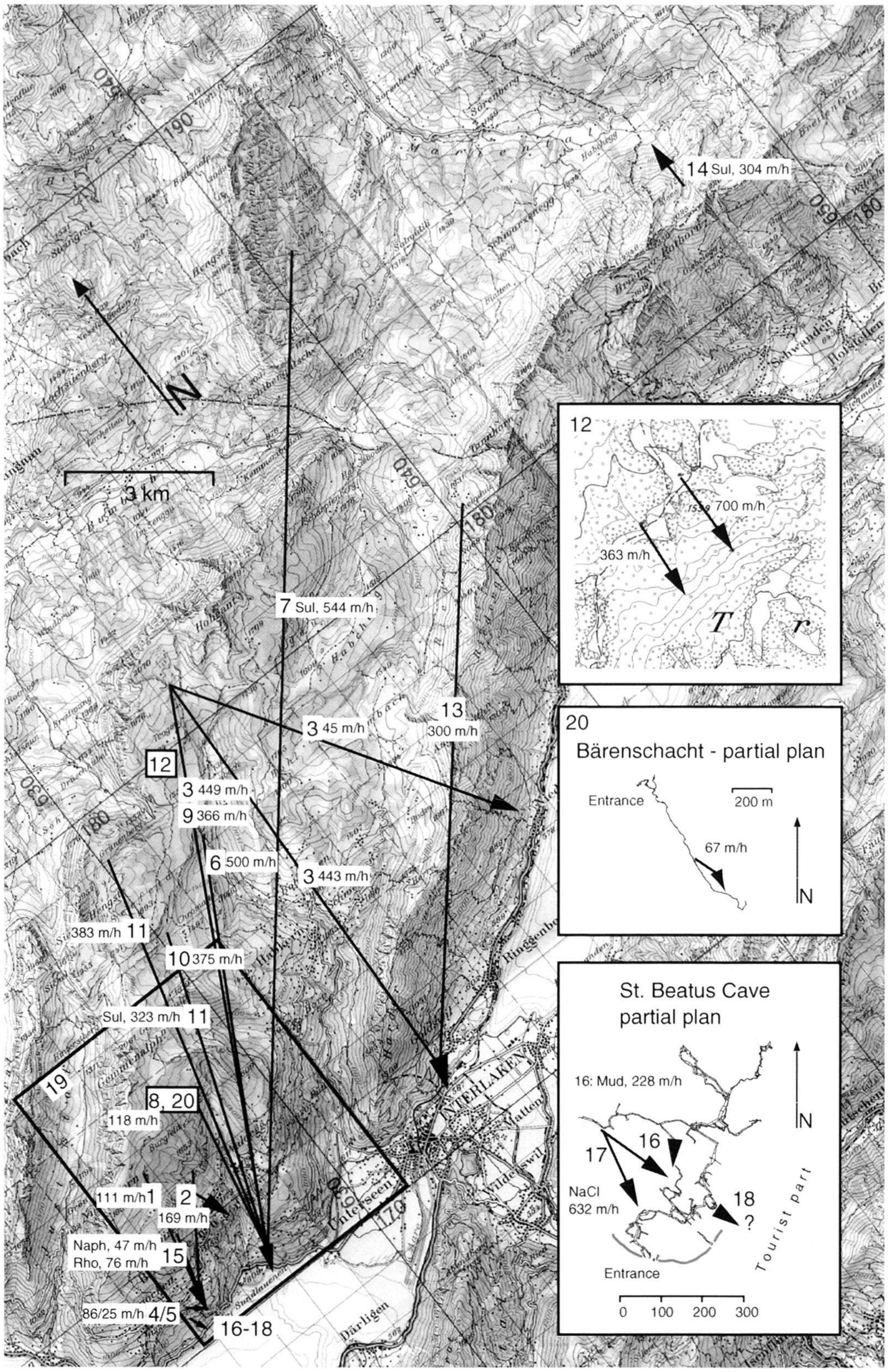

Fig. 2. Map of the region with the various tracing experiments presented in chapter 3. Small maps are inserted for the tracing experiment No. 12 (Trogenmoos), 16-18 (St. Beatus Cave), and 20 (Bärenschacht). The frame shows the location of Fig. 3 for the tracing No. 19 (results are not presented here). Abbreviations: Rho=Rhodamine B; Sul=Sulforhodamine; Naph=Naphtionate; all other tracings were done with Fluoresceine/Uranine.
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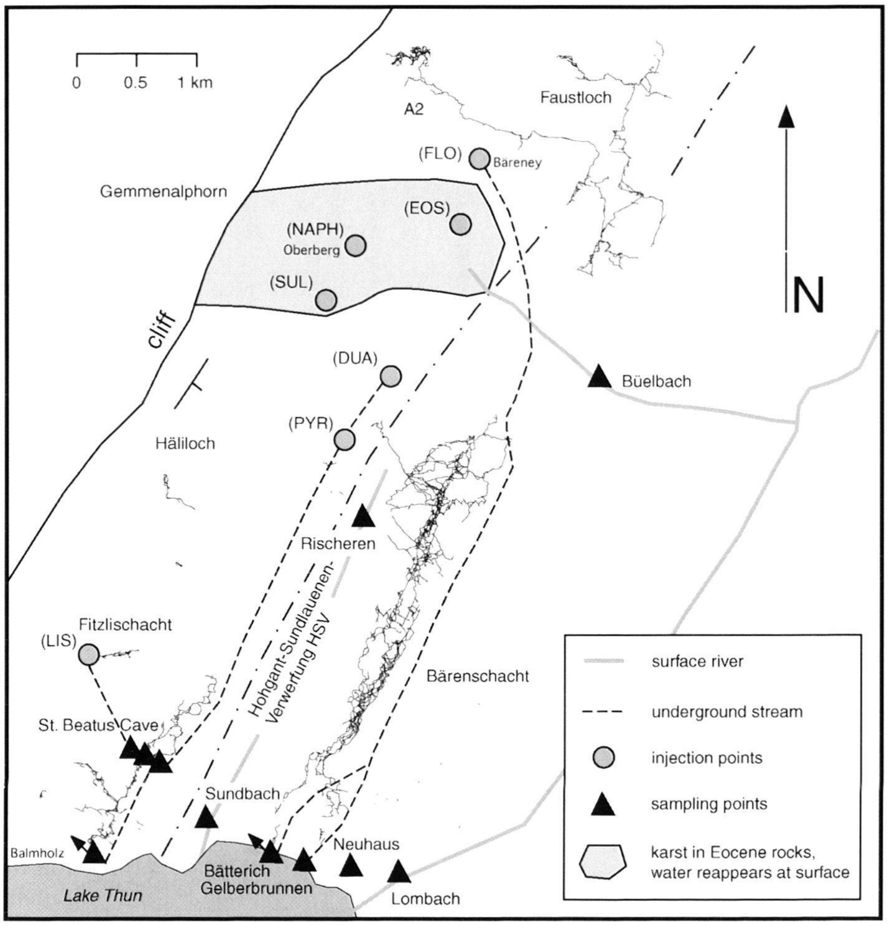

Fig. 3. Detailed map showing the injection and sampling locations of the tracing experiment No. 19 of 1996.

The most important normal fault is the Hohgant-Sundlauenen fault (HSV), having a throw of about 200 m in the Hohgant region and more than 600 m at Lake Thun. The HSV separates the catchments of St. Beatus Cave to the west and Bärenschacht-Siebenhengste to the east.

An overview of the cave system is given in Bitterli (1988), its genesis is described in Jeannin et al. (2000), and the stratigraphy and tectonic features are explained in Häuselmann et al. (1999).

3. Water tracing experiments between 1946 and 2001

To our knowledge, no water tracing experiments were conducted prior to 1946. In the following text, we summarise the tracing experiments in chronological order. Table 1 and Fig. 2 give more detailed information. An eventual interpretation is given also.

During the last 50 years, the techniques of dye tracer detection have considerably changed, no constant policy was maintained in the Siebenhengste area. We will describe the detection methods wherever we have an indication of them.

In the past, the main aim was to detect the flow direction and sometimes the maximum velocity of the underground streams; no attention was paid both to the peak arrival time and to the analysis of the breakthrough curves. Therefore, some data of importance are missing in many old tracing reports. In an attempt to uniformise the data, the missing flow velocities were calculated by the direct distance divided by the time of the first dye detection. Flow velocities therefore are usually approximative, unless otherwise stated. Still, for comparison purposes, we thought it useful to include the flow velocities.

Tracing No. 1, 1946: Häliloch – St. Beatus Cave (Na-Fluoresceine). This is the first water tracing experiment done in the region, after some trials with sawmill powder. 17 springs were observed: the Na-Fluoresceine was clearly visible in St. Beatus Cave after 30 hours (visual detection only). The colour came from two rivers within St. Beatus Cave (Fig. 3), the flow velocity (111 m/h) was rather low for free-flowing karst water. There is only secondary literature available (handwritten manuscript by Franz Knuchel).

Tracing No. 2, 1953: Birenbach – St. Beatus Cave and Haselegg (Na-Fluoresceine). This tracing is poorly documented. We assume that the dye was injected in the brook just above the Bire cliffs (as indicated by the given coordinates) and that the brook disappeared completely in the debris below the cliffs. The colour was clearly visible in both St. Beatus Cave (after 18 h, 169 m/h) and the Haselegg spring (visual detection only). The first appearance in Haselegg after 23 h could not be determined precisely, because no observer was present, therefore the calculated velocity of 73 m/h is very approximative. Teachers P. Grossniklaus and F. Knuchel with their school classes led the experiment. Literature is only present in form of a typewritten sheet by Franz Knuchel.

Today's interpretation is that the water from Birenbach infiltrates the debris and moraines of Beatenberg. Parts of this water continue through fissures towards St. Beatus Cave, while the other part continues within the scree towards the Haselegg spring. This interpretation corresponds well with the flow velocity.

Tracing No. 3, 1959: Septemberschacht – Bätterich / Harder springs / Niederried (Na-Fluoresceine). The weather situation as well as the springs observed are clearly documented (Knuchel 1959). The first appearance of colour at the Harder springs at Ostbahnhof Interlaken after 22 hours (443 m/h) is proved by reports and pictures (visual detection only). Only 5 h later the dye also appeared at Bätterich/Gelberbrunnen (449 m/h). One week later dye was reported from a spring in Niederried (45 m/h). Franz Knuchel (1959) led the experiment.

The proved appearance of dye in Ostbahnhof and Niederried was later rejected as being impossible because of the experiments of 1973 and 1980 (see below) and geologic assumptions about the Habkern syncline (partly revised by Hänni 1999). However, dye was present at least at Ostbahnhof. One possible explanation for the dye appearance might be the very high floods at the time (all the Harder springs were active at the day of tracing): the waters somehow traverse the Habkern syncline.

The discovery of dye at Niederried is ambiguous. Whereas, in our opinion, the traverse of the Habkern syncline is proved (be it within the karst or through other formations), the week elapsed since the tracing experiment is quite long. The only solution we see is that parts of the dye went towards Niederried spring (which seems to be an overflow spring as are the Harder springs), but that they discharged only after the next floodwater pulse. Its temperature indicates a long residence time for the Niederried water, which is 1°C warmer than the other springs which have a temperature of approximately 7.5°C.

Tracings No. 4/5, 1961: Chüelauenen – St. Beatus Cave / Chrutbach – Lerau (Na-Fluoresceine). These tracings were made in order to study the possibility of a canalisation outlet for the village of Beatenberg. The location of the Lerau spring is unknown, given the situation of Lerau Castle just below St. Beatus Cave, we assumed that this spring mainly contributes water for these houses, and is located below the road. The unpublished report (Knuchel 1961) is moderately detailed.

The first tracer was injected in Chüelauenenbach between the two cliffs. The low flow velocity (7.6 h, 86 m/h) between the injection site and St. Beatus Cave (visual detection only) is unexpected, because the water infiltrates through open fissures in the host rock.

The second injection was made at the base of the cliffs. The dye reappeared in Lerau spring (visual detection only). In this case, the low flow velocity 23 h, 25 m/h) is explained by the water flowing through scree.

Tracing No. 6: Senkloch – Bätterich (Na-Fluoresceine). This tracing experiment is roughly documented by Knuchel (1974). It was performed between 1959 and 1970 (the exact date and detection method is unknown), and the dye appeared in Bätterich and Gelberbrunnen after 18 h, giving a rapid flow velocity of about 500 m/h. This flow velocity is comparable to the one from Schrattenfluh in 1970 (No. 7).

Tracing No. 7, 1970: Schrattenfluh – Bätterich (Sulforhodamine). This tracing experiment, organised by Franz Knuchel, is well documented (Knuchel 1972). Almost all springs around the Schrattenfluh were sampled (water samples analysed by fluorometry at Bern University), however, the dye reappeared only at Bätterich and Gelberbrunnen after 38 h, giving a flow velocity of 544 m/h (precise determination by sample analysis). This proves that the water from Schrattenfluh, distant more than 20 km, underflows the Emme valley to reappear in the Bätterich spring.

The rapid conduit flow velocity is thought to be an expression of free-flowing conditions, however, it might be primarily a result of the snowmelt conditions that prevailed during the tracing experiment.

Tracing No. 8: Bärenschacht – Bätterich (Na-Fluoresceine). This very roughly documented experiment (Knuchel 1974) was conducted between 1970 and 1973 (exact date and detection method unknown). The dye reappeared in Bätterich and Gelberbrunnen. Due to low-flow conditions the flow velocity to Bätterich (32 h, 118 m/h) was relatively low, and the one to the Gelberbrunnen was even lower (78 h, 48 m/h).

Tracing No. 9, 1973: Septemberschacht – Gelberbrunnen (Na-Fluoresceine). This experiment was organised by the Centre d'hydrogéologie of Neuchâtel University (CHYN). It is documented in an unpublished report (Simeoni 1973). The experiment repeated tracing No. 3 from 1959, and it was also conducted under snowmelt conditions. The Bätterich spring was not observed, but all other springs in Lake Brienz region and Interlaken were sampled (detection method: samples of the main springs and active carbon in the others, all analysed by spectrofluorometry at Neuchâtel University). The dye only reappeared in Gelberbrunnen after 33 h (366 m/h).

This tracing experiment was used to reject the results from the 1959 tracing. As discussed above, those results are proven and can not be rejected easily. Therefore we assume that under normal flood conditions, the Hohgant region is connected only to the Bätterich spring, whereas under exceptional snowmelt conditions, there may be a connection from Hohgant to the Harder springs. A close observation of Simeoni's report showed two different first reappearance times of dye at Gelberbrunnen, indicating some possible problems.

Tracing No. 10, 1974: Faustloch – Bätterich (Na-Fluoresceine). This experiment was conducted by the cavers Ricka and Pfister (unpublished HRH report, 1974). Three springs (Bätterich, Gelberbrunnen, Harder) were sampled (water samples taken, analysed by fluorometry); the dye only reappeared in Bätterich (15 h, 477 m/h) and Gelberbrunnen (19 h, 375 m/h).

Tracing No. 11, 1975: Faustloch/Schluchhole – Bätterich (Sulforhodamine B / Na-Fluoresceine). This tracing experiment was done and documented by the CHYN (Simeoni 1975). A total of 23 springs and rivers were observed, extending from St. Beatus Cave to the springs at Lake Brienz (detection method: samples of the main springs and active carbon in the others, all analysed by spectrofluorometry at Neuchâtel University). Two injection points with different dyes were used, the dyes both reappeared at Gelberbrunnen after 22 h (Faustloch) and 24 h (Schluchhole), indicating flow velocities of 323 m/h (Faustloch) and 383 m/h (Schluchhole), respectively.

The results are comparable with the previous tracing experiment (No. 10) at Faustloch.

Tracing No. 12, 1977: Trogenmoos (Na-Fluoresceine). Two small tracing experiments are documented (Widmer & Rouiller 1978). In the region of Trogenmoos several swallowholes were thought to be connected to springs downstream without having a direct relation to the Bätterich spring. The tracing experiments supported this hypothesis. The dye from the first swallowhole appeared in Trogenbachhöhle 20 min later (700 m/h, visual detection only), the dye from the second swallowhole in an unnamed spring 25 min later (363 m/h).

The rapid flow velocity in the first case is caused by snowmelt, free-surface flow and high discharge. Trogen represents a minikarst region, where almost every karst feature is visible in small scale. This karst is developed within a karstified calcareous layer of the Hohgant series; a direct connection to the Schrattenkalk systems has not been proven.

Tracing No. 13, 1980: Allgäuli – Harder springs (Na-Fluoresceine). This tracing is documented in a report of the "Wasser- und Energiewirtschaftsamt des Kantons Bern" (WEA 1980). A total of 42 springs between Sundlauenen and the canton of Obwalden were sampled. The dye reappeared after 40 h at the Harder springs (only one spring is indicated on Fig. 3; water samples taken, analysed by fluorometry), giving a flow velocity of 316 m/h.

The conclusion of Wildberger et al. (1982) was that the catchment area of the Harder springs is sufficient in size for the flow rate of the springs.

Tracing No. 14, 1982: Eisee – Emmesprung (Sulforhodamine B). It is worthwile to include this tracing (Wildberger et al. 1982) here, as it marks the transition between the Harder/Bätterich region to the west and the Brünig region to the east. The dye injected in an active swallowhole reappeared at Emmesprung 4.5 h later (velocity 304 m/h; visual detection only).

Tracing No. 15, 1984: Fitzlischacht/Häliloch – St. Beatus Cave (Na-Naphtionate / Rhodamine B). The dyes were injected with 3.5 h difference in Häliloch and Fitzlischacht (Klötzli 1985). At this time, only St. Beatus Cave and the three most important rivers within the cave (Fig. 3) were sampled.

The Na-Naphtionate of Fitzlischacht reappeared after 22 h (47 m/h, precise determination by sample analysis) in all three rivers (water samples taken, analysed by fluorometry), with high concentrations (16 mg/m^3) in Nordgang and Ostgang, and much less (2.6 mg/m^3) in Hoher Nordgang. The water from Häliloch was detected after 35 h (72 m/h) mainly in Hoher Nordgang, in traces at the detection limits (0.01 mg/m^3) also in the other rivers.

Klötzli (1985) interpreted that the three rivers meet in the inaccessible parts of the cave. However, physical as well as chemical parameters (pH, T, electric conductivity, hardness, ion concentration) of the three rivers show that Hoher Nordgang and Ostgang are relatively similar, whereas Nordgang is completely different (Höchli, pers. comm.). As a result of this contradiction to the tracing results, the experiment was partly repeated in 1996 (No. 19). The review of the different reports and analyses of tracing No. 15 reveals inconsistencies, for instance the first appearance of Rhodamine B from Häliloch was described as being after 43 h, whereas the data available show the first apparence after 35 h.

Tracing No. 16, 1990: St. Beatus Cave (Tschäderloch – Untere Bachgrotte). This tracing was the first one made directly in a cave (Pfister 1990). Pfister simply traced the waters with mud, observed the turbidity and estimated the flow velocity (228 m/h).

Tracing No. 17, 1992: St. Beatus Cave (Erosionsgang – Untere Bachgrotte / Spaghettigrotte). Pfister (1992a) did a salt dilution test using NaCl in the cave. The salt was injected in the river coming from Chüelauenenbach (tracing No. 4), was measured with an EC-meter after 30 min in the Spaghettigrotte (632 m/h) and after 35 min in the Untere Bachgrotte (545 m/h).

Tab. 2. Injection and sampling points, tracing experiment of 1996

A. Injection points									
Place	Coordinates			Q (l/s) (12.10., estimated)	cond. (µS/cm)	Temp. °C	Dye	Amount	Time of injection
Fitzlischacht	626600	172060	1400	0,1	--	--	Lissamin	200 g	10:20
Brook 1	628120	173835	1590	0,5	1276	4,8	Pyranin	200 g	9:55
Brook 4	628870	174265	1570	0,5	214	5,1	Duasyne	200 g	9:35
Doline Oberberg	628275	175120	1830	2 m2 added	--	--	Sulforhodamin	200 g	10:25
Fountain Ob'bg	628560	175335	1810	0,5	313	5,7	Naphtionat	2 kg	10:55
Brook Bäreney	629350	175660	1640	1	212	7	Eosin	200 g	11:15
Doline Bäreney	629440	176025	1680	24 m3 added	--	--	Fluorescein	1 kg	8:50

B. Sampling points						
Place	Coordinates			Q (l/s) (12.10., estimated)	Cond. (µS/cm)	Temp. °C
Beatus-Portal	626250	170450	690	40	333	9,8
B-Wasserfall	626404	170651	742	0,3	--	--
B-Beiz	626629	171159	838	2	--	--
B-Ostgang	626708	171196	842	5	--	--
B-Nordgang	626712	171224	851	5	--	--
B-Ho. Nordgang	626705	171230	852	5	--	--
Sundbach	627375	170725	610	10	299	10,3
Rischeren	628650	173390	1260	5	295	--
Bätterich	627725	170375	558	2000	199	--
Gelberbrunnen	628100	170350	558	300	--	--
Neuhaus	628650	170225	562	20	350	10,3
Büelbach	630285	174575	1280	30	284	6,3
Lombach	628940	169980	565	800	314	8,6

The high flow velocity (632 m/h) is probably due both to the short distance and high discharge (several l/s) in an essentially free-surface flow regime. The question raised by Pfister (1992a) whether the traced river divides, has subsequently been answered: the Erosionsgang river shows a vadose diffluence in unreachable parts of the cave and the water reappears in both places. This observation was possible due to the visible pollution of this river by the sewage water from the waste water treatment plant of Beatenberg.

Tracing No. 18, 1992: St. Beatus Cave (Versteinerter Wasserfall). This tracing experiment by Pfister (1992b) was made using NaCl and a conductivity meter. There was no result; it seems that the water from this region of the cave does not reappear in the main river.

Tracing No. 19, 1996: Gemmenalp. This last multitracing experiment is examined in detail in chapter 4.

Tracing No. 20, 2001: Bärenschacht (entrance part). This tracing experiment was conducted in Bärenschacht cave (Isaac 2001). It revealed that the disappearing stream of the entrance part reappears in the sump at -565 m after a minimal flow time of 4 h (67 m/h, detection: water samples and active carbon, analysed by fluorometry). An exact flow time cannot be determined because the dye was fixed in activated carbon.

4. The tracing experiment 1996

Whereas the SE to NW boundaries of the catchment of the St. Beatus Cave can be delimited quite well (the HSV in the SE, the Balmholz in the SW and cliffs in the NW, Fig. 3), there is no distinct morphological boundary towards the Siebenhengste in the NE. Therefore, one way to determine the catchment area is to perform a dye tracing experiment. In order to solve the questions raised by the tracing in 1984 (No. 15, above), a coloration of the Fitzlischacht was done at the same time. Because an unnamed brook disappears just 20 m before reaching the entrance of the Bärenschacht, it was of interest to determine if this rivulet (and others nearby) join St. Beatus Cave (as supposed by the geology) or the Bärenschacht and the Bätterich spring.

4.1. Planning and execution

A detailed description of the planning, execution, and organisational problems is given by Häuselmann (1997). In order to outline the entire watershed, seven injection points (Fig. 3) were chosen. The tracers and their quantity were selected following criteria of adsorption and the expected dilution factor. In order to maximise knowledge, all karst springs and the surface brooks were sampled (Table 2).

The dye tracing had to be timed: In dry time, the brooks are dried up, whereas in big floods, some brooks overflow the swallowholes and continue on the surface. In the weekend of

Tab. 3. Results, tracing experiment of 1996

Location	Q (l/s) estimated	Dye	first arrival (h)	Peak	Distance (m)	flow velocity max (m/h)	Peak (m/h)	recovery (g)	(%)	
B-Wasserfall	0.3	--	--	--	--	--	--	--	--	
B-Beiz	2	--	--	--	--	--	--	--	--	
B-Ostgang	5	--	--	--	--	--	--	--	--	
B-Nordgang	5	Lissamin	25.6	35	1001	39	29	24 g	12%	
B-Ho. Nordgang	5	Lissamin	15	27	1001	67	37	124 g	62%	
Beatus-Portal	40	Lissamin	3.6	6	920	255	153	171 g	85%	velocity Nordgang to Entrance
Beatus-Portal	40	Pyranin	62.5	81	3971	64	49	26 g	13%	
Beatus-Portal	40	Duasyne	72.5	82	4711	65	57	49 g	24%	
Sundbach	10	--	--	--	--	--	--	--	--	
Rischeren	5	--	--	--	--	--	--	--	--	
Bätterich	2000	Fluorescein	16.3	130	6010	369	46	482 g	48%	
Gelberbrunnen	300	Fluorescein	?	?	6010	?	?	294 g	29%	sampling started late
Neuhaus	20	--	--	--	--	--	--	--		
Büelbach	30	Sulforhodamin	83.5	97	2154	26	22	105 g	52%	
Büelbach	30	Naphtionat	11	17	1958	178	115	1420 g	71%	
Büelbach	30	Eosin	12	17	1477	123	87	102 g	51%	
Lombach	800	Sulforhodamin	9.5	9.5	4841	510	510	150 g	75%	flow velocity
Lombach	800	Naphtionat	6	6	4841	807	807	1770 g	88%	from Büelbach into
Lombach	800	Eosin	7	8	4841	692	605	124 g	62%	Lombach!

12./13. October 1996, the conditions were acceptable. The weather was dry, the average flow rate of the brooks was between 0.5 and 1 l/s. On each sampling point a background sample was taken prior to any dye injection. The first dye (Na-Fluoresceine) was injected at 8:50. Injection of dye and sampling was made by different persons to eliminate the risk of contamination. In the swallowhole at Oberberg (SUL in Fig. 3), 2 m^3 of water had been added. In Bäreney (FLO in Fig. 3) the swallowhole was also dry, therefore water from a nearby fountain was added by a tube 2 hours before the injection. The addition continued for two days, the total quantity of water added was approximately 24 m^3.

After 9:00, the surface brooks and the karst springs were sampled in 0.5h- to 2h-intervals. During the experiment, the intervals were progressively prolonged, during the last two weeks of sampling (of a total of five weeks), samples were taken every third day.

The measurements of the dyes were done by spectro-fluorometry: Every sample was examined using a Perkin Elmer Fluorometer LS-2B. The samples with high peaks were checked by the synchro-scanning method with a "Shimadzu RF5001-PC". The representations were made in a concentration/time diagram. Then, quantitative determinations were made by constructing a calibration curve for each dye with the LS-2B. The detection limit of the LS-2B is at 10 $\mu g/m^3$ for Lissamine, Na-Fluoresceine, Eosine, Sulforhodamine B, and Duasyne, and around 100 $\mu g/m^3$ for Pyranine and Na-Naphtionate.

Using synchroscans in spectro-fluorometry we might encounter fluorescence peaks at the same wavelength as the dyes used (Käss 1998). To prove that the peaks are in fact caused by our dyes and not by any other organic substance, we used HPLC. With this analytic technique, the dyes are determined by their retention times instead of their characteristic wavelength.

The measured values were subtracted from the blind values and then transformed into recovery masses. To get the recovery masses, the concentration has to be multiplied with the discharge rate at the time of sampling. Since this discharge rate could be determined only by estimations, the quantity of dye that reappeared at the spring (Table 3) is an approximation.

The Bätterich spring leads directly into Lake Thun, 9 m under the lake's surface. Due to the uncertainty encountered at this point we used spectro-fluorometry and HPLC for all water samples to separate clearly between the appearance of multiple dyes.

4.2. *Results*

The results of the tracing experiment are summarised in Table 3 and drawn in Figs. 3 and 4.

The Lissamine from Fitzlischacht was found only in St. Beatus Cave. The first dye appeared after 14.8 h in Hoher Nordgang and after 25.6 h in Nordgang. In contradiction to the experiment of 1984 no dye was found in the Ostgang. The quantity of regained dye is 24 g in Nordgang and 124 g in Hoher Nordgang.

The first dye appeared at the entrance of St. Beatus Cave after 18.6 h, in total, 171 g (85 %) were regained.

The Pyranine injected into Brook 1 (Fig. 3) was also found at St. Beatus Cave. The sampling within the cave had already ceased when the dye appeared at the cave entrance. At the entrance of the cave, a total of 26 g (13 %) arrived after 62.5 h of flow time.

The Duasyne from Brook 4 also appeared in St. Beatus Cave. After a flow time of 72.5 h, a total of 49 g (25 %) appeared.

The Sulforhodamine B injected in the swallowhole at Oberberg did not appear in any cave; after 83.5 h the first

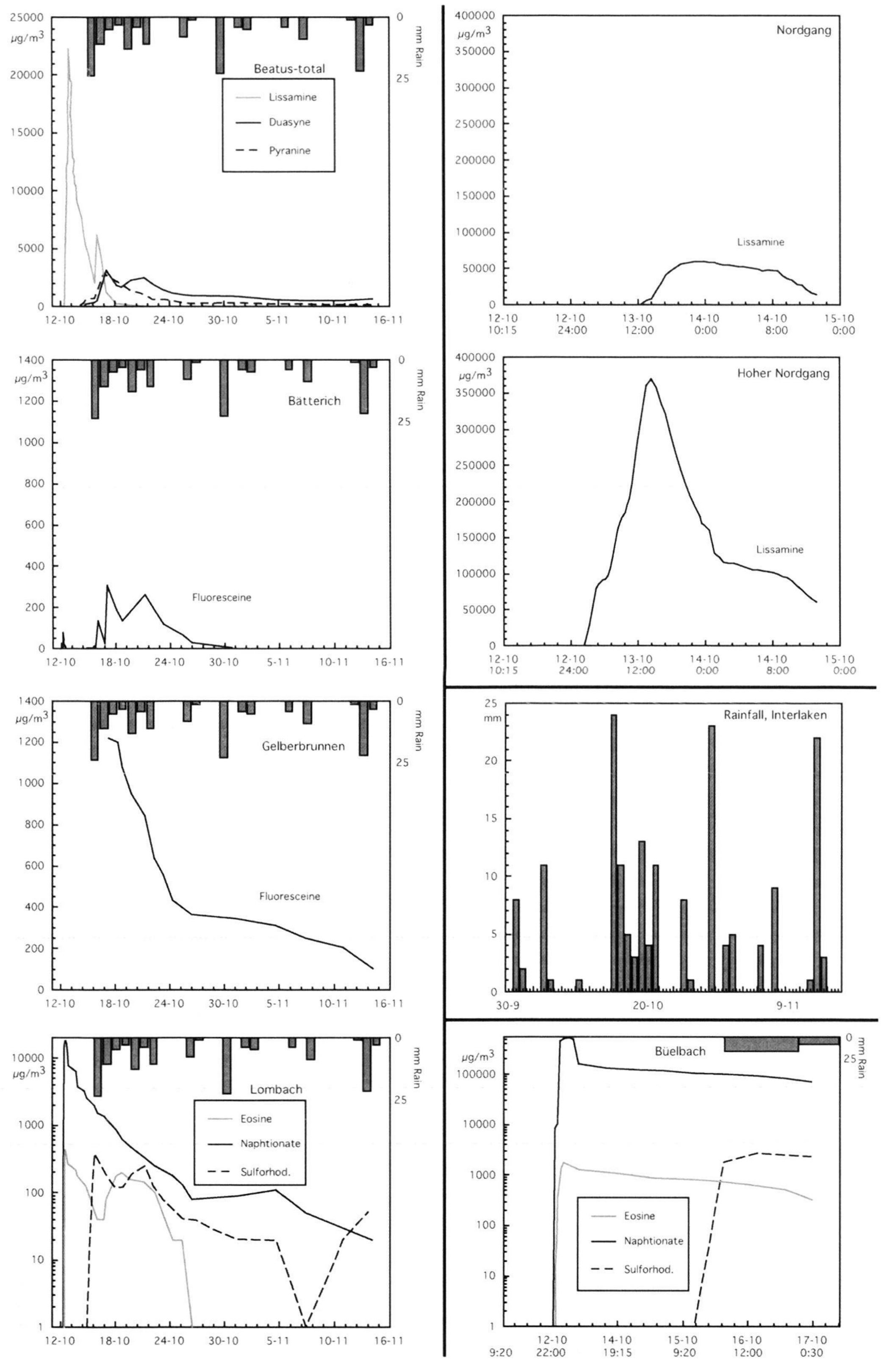

Fig. 4. Breakthrough curves (concentrations) at the different sampling locations. The precipitation during the tracing experiment (station Interlaken of the Swiss Meteorologic Service) is inserted. The injection time is at the beginning of the graph.

traces of a total of 105 g appeared in Bühlbach creek, after 93 h, the dye (total amount recovered 150 g, 75 %) was found also in Lombach creek.

The Na-Naphtionate injected in a sinking brook also reappeared in Bühlbach after 11 h (1420 g recovered) and therefore also in Lombach after 17 h (1770 g, 88 % recovered).

The same observation is valid for the 200 g of Eosine injected in a sinking brook, it was found in Bühlbach after 12 h (102 g) and in Lombach after 19 h (124 g, 62 %).

The Na-Fluoresceine injected in the Bäreney swallowhole appeared in the Bätterich spring after 16.5 h. Five hours later, the concentration returned to zero, only after 54 h the main peak appeared, which was detectable for several days, with a maximum after 130 h. In total, 482 g (48 %) appeared.

The Gelberbrunnen, which is the second spring of the Réseau, wasn't sampled at first time because there was no obvious discharge. A total of 294 g (29 %) of Na-Fluoresceine was recovered in Gelberbrunnen.

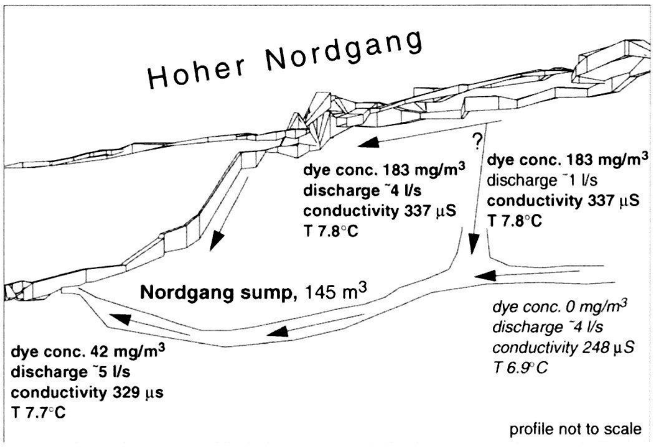

Fig. 5. Sketch of a possible explanation for the diffluence observed in the Hoher Nordgang of St. Beatus Cave. The arrow with a "?" indicates the hypothetic diffluence coming from Hoher Nordgang into Nordgang behind the sump.

4.3. Interpretation

Fitzlischacht-St. Beatus Cave

The connection between these two caves had already been demonstrated by Klötzli (1985). In 1984, the tracer required 22 h, in contrast it took 15 h in 1996. However, in both cases the flow velocity of 45 to 67 m/h is quite slow compared to other experiments in the region. Since there is a fracture between Fitzlischacht and St. Beatus Cave, a sump zone may be present and could slow down the tracer. This is supported by the Fitzlischacht morphology indicating that the connection Fitzlischacht – St. Beatus Cave is karstologically young.

The 1984 appearance of dye in all three main galleries of St. Beatus Cave can not be completely explained. In 1996, no dye was observed at Ostgang; while the Nordgang sump had five times less dye than the Hoher Nordgang. This discrepancy can only be partially explained: The scarce traces of Lissamine that appeared late in Nordgang sump can be explained by the sump itself (diluting the dye and reducing the flow velocity due to its volume (145 m^3) and to a probable diffluence in the Hoher Nordgang, deviating a small part (~20 %) of the waters towards behind the Nordgang sump (Fig. 5): Speleological research behind the sump revealed that the gallery divides into a gallery with a brook (situated approximately below the Hoher Nordgang) and into a gallery with lakes. If some water from Hoher Nordgang joins the Nordgang sump, there would be mixing of two different waters. Based on the measured physical and chemical parameters (hardness, temperature), we calculated the parameters of the hypothetical water before mixing. The results show that the parameters still lie within a normal karst water (Fig. 5), therefore we assume that such a mixing is possible.

The flow velocity of 255 m/h for the distance Nordgang-Entrance is within the velocities measured in the region; this further indicates that the previous interpretation of free-surface flowing rivers within the Réseau is correct.

The dye recovery rate of 85 % is relatively high and shows the absence of any significant sorption or degradation process. The difference between the entrance and the galleries is explained with the limited sampling time within the cave. The bimodality of the curve observed at the entrance is most probably due to the onset of rain just before the arrival of the second peak.

Rivers at Bärenschacht – St. Beatus Cave

On a rainy day, it was observed that 20 to 30 l/s disappeared in a swallowhole situated just some tens of meters above the entrance of the Bärenschacht. This water, however, has not been found in Bärenschacht down to the sump at -565 m below the entrance. Because of the geologic situation of Bärenschacht (traversing the HSV and continuing in Eocene sandstone) it was suggested that this water flows towards St. Beatus Cave (Fig. 6). This was tested during the tracing experiment of 1996.

The flow velocity of the Duasyne and Pyranine injected in those brooks, 63 and 65 m/h respectively, is comparable to the one from Fitzlischacht. Here, it is even clearer that the subterranean flow path has to be karstologically young: if flow rate is too high, the brooks continue on the surface. The recovery rates are low (13 % of Pyranine and 25 % of Duasyne respectively). The breakthrough curves show very long tails: at the last day of sampling, a month later, there still was dye detected. This means that the real recovery was higher. The reason for such long tails could be related to a poorly connected flowpath between the swallowhole and the cave stream (young and distal flowpath). A second rainfall could explain the bimodality of the Duasyne, whereas the Pyranine seems to be more buffered, because no second peak is visible.

Since the brooks completely infiltrated the swallowholes, no dye was detected in Sundbach.

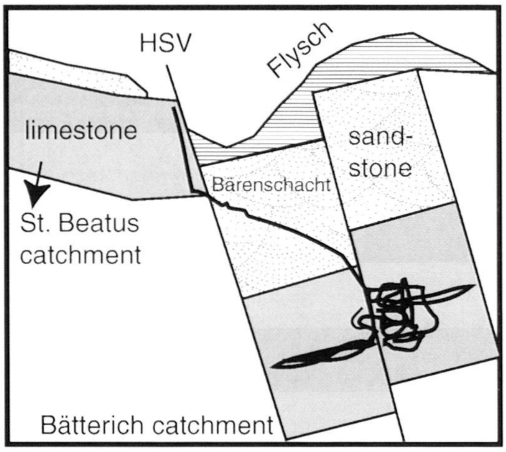

Fig. 6. Schematical projected profile across Bärenschacht entrance. This illustrates its unique position with respect to the catchment areas of St. Beatus Cave and Bätterich.

Swallowholes Oberberg / brooks Oberberg – Bühlbach

The injection points in the karstified parts of the Hohgant series had been chosen in order to cover the region. The recovery of Naphtionate and Eosine in the Bühlbach surface creek is not surprising. It seems that waters from Oberberg infiltrate into the karstified top layer of the Hohgant series, which is sandstone with calcite cement. The underlying quartzitic sandstone of Hohgant appears to be an effective aquiclude for those waters in this particular area. The flow velocity (123-178 m/h) is quite typical for low-water conditions. The amount of dye recovered is high (60 % and 87 % respectively).

The Sulforhodamine B injected into a swallowhole within the karstified Lithothamnia limestone (which is the uppermost layer of the Hohgant series) was expected to flow towards St. Beatus Cave, following the dip of the strata. This is not the case, as it also flows into Bühlbach. The flow velocity is slow (26 m/h) and the amount of dye recovered is high 75 %. This suggests a calm flow (phreatic domain or lakes) along the underground path. A part of the low velocity can be related to the injection mode of the tracer (2 m^3 of water added), because the waterways are not thoroughly wetted and rinsed.

Swallowhole Bäreney – Bätterich/Gelberbrunnen

The swallowhole at Bäreney is situated at the Flysch border within the Lithothamnia limestone. It swallows about 50 l/sec during thunderstorms. A similar response as the three swallowholes above was expected. The region of Bäreney is quite fractured and located near the A2 cave (Fig. 1), which is connected with the Bätterich spring. Therefore, a flow through the underlying sandstone into the Schrattenkalk has been proved by the tracing experiment. An initial tiny peak indicates a flow velocity of 368 m/h, which is very fast, but consistent with several tracing experiments in the region. The main peak appeared later, after a rainfall event.

The breakthrough curves are significantly different at Bätterich and Gelberbrunnen, although the latter seems to be the overflow of the other. Bätterich received the tracer first (at low water), and at that time, the Gelberbrunnen was not visibly flowing. As soon as the Gelberbrunnen started to flow after the rain event of October 16th, the tracer was found in much higher concentrations than in Bätterich. There are several hypotheses (see also Fig. 7):

Hypothesis 1: At low water, most of the tracer is trapped in the vadose zone close to the injection point, and only a few percent of the tracer reaches Bätterich. With the rainfall, the tracer is mobilised, but at the same time the whole system gets flooded. Thus, the Gelberbrunnen begins to react visibly.

Hypothesis 2: The dye enters the phreatic zone. The water coming from upstream mixes with the dye waters. A diffluence divides the waters again. Due to constrictions, the dye first appears in Bätterich, and only under flood conditions does the Gelberbrunnen begin to react.

Hypothesis 3: Again the dye enters the phreatic zone, but mixes with the main waters only after the diffluence. The high flow rate towards Bätterich causes the first peak to be visible quickly. Again due to constrictions, the Gelberbrunnen only reacts under flood conditions.

Considering that the injection point is located close to the springs (compared to the size of the whole catchment), these hypotheses seem reasonable. More links between the conduits are possible. The key factors are that 1) at least one link directs flow downwards (respectively sideways), and 2) a diffluence is connected with this conduit.

There may be other hypotheses which explain the observed responses equally well. However, hypotheses 2 and 3 are most compatible with the network style observed in Bärenschacht and are therefore favored. Furthermore, they are consistent with observations and models developed for other similar cave systems such as Hölloch (Jeannin 2001).

In Neuhaus spring, no dye was found. This was expected and proves a suggestion made by Knuchel (unpublished), that the catchment area of this spring is located in the slope directly above the spring (Waldegg). In this area, two independent karst aquifers (upper Cretaceous Seewerkalk and Hohgant series) are present. This system is much more complicated than the main system situated just below within the Schrattenkalk. It is still unclear whether the Neuhaus spring is co-fed by the groundwater within the Interlaken plain.

5. Conclusion

The tracing experiment of 1996 answers some important questions regarding the extent of the different water catchments of the Beatenberg region, and the analysis of unpublished results makes it possible to delineate catchments for most of the springs in the region (Fig. 8).

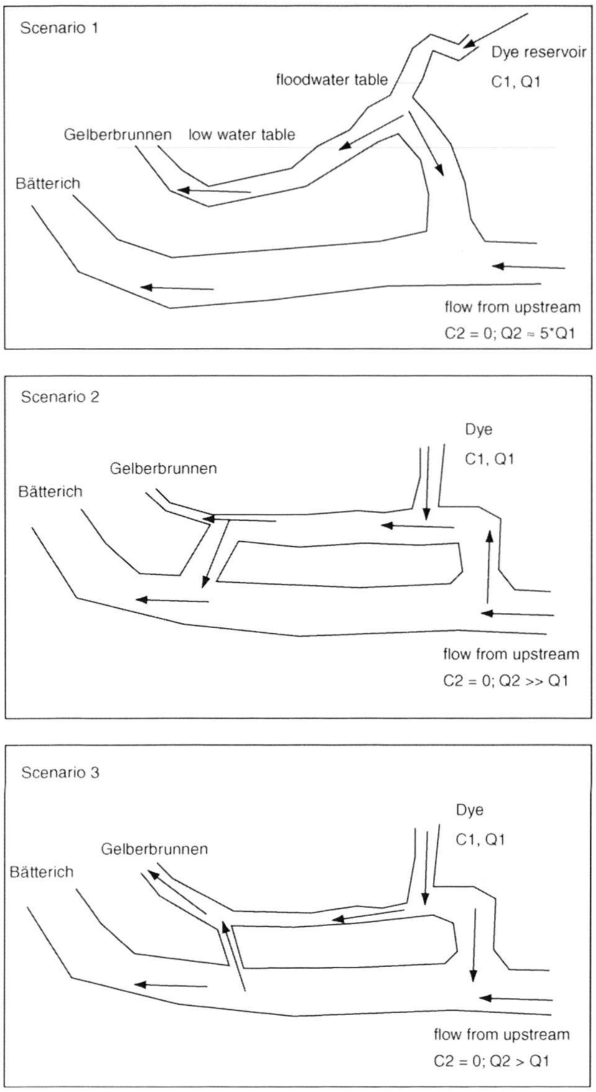

Fig. 7. Illustrations for the three scenarios of flow within the saturated zone between Bäreney and Bätterich. For details see text.

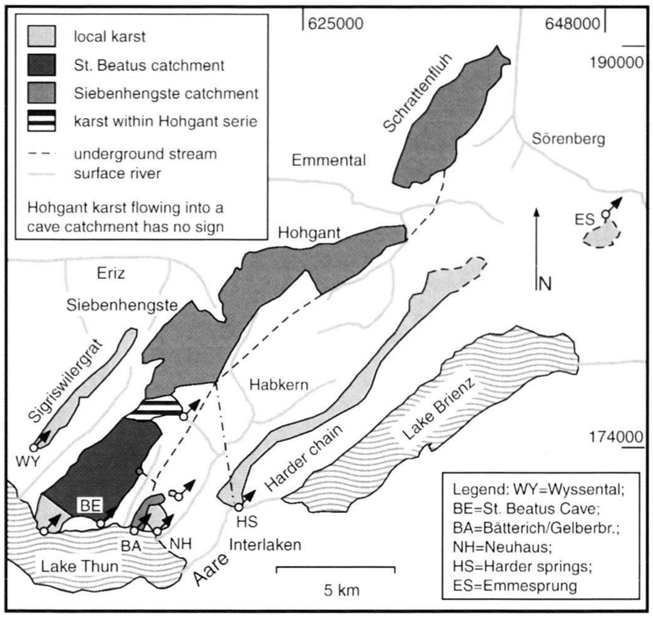

Fig. 8. Proposed catchment delimitations of the region between Lake Thun and Schrattenfluh.

- The catchment area of St. Beatus Cave reaches farther to the North than previously assumed. The connection Fitzlischacht-St. Beatus Cave has been confirmed.
- The entrance of the Bärenschacht is situated within the catchment area of St. Beatus Cave. Only the local dip to the southeast, coupled with the throw of the HSV, which placed a calcareous layer of the Hohgant series at the side of the Schrattenkalk, permitted the development of the Bärenschacht entrance part to the other side of the HSV.
- In the region Oberberg-Bäreney-Gemmenalphorn, the waters flowing into the karst of the Hohgant series reappear in surface brooks and join the Bühlbach-Lombach creeks.
- The waters of the whole Siebenhengste, Hohgant, and Schrattenfluh region flow towards the Bätterich/Gelberbrunnen springs. The appearance of dye at the Harder springs during a high flood proves a hydrological connection of the Hohgant region and aquifers in the Harder chain.
- The Harder springs are mainly fed by the waters of a catchment area extending NE along the strike for several kilometers.
- The Emmesprung is fed by the Eisee and is most probably located east of the watershed of the Harder springs.
- The Neuhaus spring is fed by local karst from the Waldegg.

Acknowledgements

Without the generous support of the enterprise "Otzhydro" in Bellmund, this tracing experiment wouldn't have been possible. The clubs of the "Höhlenforschergemeinschaft Region Hohgant" (HRH) helped financially and with manpower. The population of Beatenberg helped both practically and financially and were interested in our work. B. Müller and M. Monbaron are thanked for discussions and ideas. The Swiss Meteorologic Service SMA provided precipitation data. The elaboration of this article was financially helped by the Swiss National Science Foundation (grant no. 2100-053990.98/1). Reviews by. H. Hötzl, P. Milanovic and K.-P. Seiler considerably improved the manuscript. Linguistic corrections of M. Hobbs are warmly thanked.

REFERENCES

Bitterli, T. 1988: Das Karstsystem Sieben Hengste-Hohgant-Schrattenfluh, Versuch einer Synthese. Stalactite 38, 10–22.

Hänni, R. 1999: Der geologische Bau des Helvetikums im Berner Oberland. Unpubl. PhD thesis, Univ. of Bern.

Häuselmann, Ph. 1997: Wasserfärbung 1996: Die Organisation. Jber Schweiz. Ges. Höhlenforschg. Sekt. Bern 45, 82–92.

–, JEANNIN, P.-Y. & BITTERLI, T. 1999: Relations between Karst and tectonics: The case-study of the cave system north of Lake Thun (Bern, Switzerland). Geodinamica Acta 12, 377–388.
HRH-ARCHIVE: a collection of geologic and hydrologic data of the region Beatenberg-Hohgant. Contact: SGH Bern, 3000 Bern.
ISAAC, R. 2001: Rapport de coloration, Gouffre du Bärenschacht, Canton de Bern, Suisse. Unpubl. report, Univ. Cathol. Louvain.
JEANNIN, P.-Y., BITTERLI, T. & HÄUSELMANN, PH. 2000: Genesis of a large cave system: the case study of the North of Lake Thun system (Canton Bern, Switzerland). In: Speleogenesis: Evolution of Karst Aquifers (Ed. by KLIMCHOUK, A., FORD, D.C., PALMER, A.N. & DREYBRODT, W.). NSS publication, Huntsville, USA, 338–347.
– 2001: Modeling flow in phreatic and epiphreatic karst conduits in the Hölloch cave (Muotatal, Switzerland). Water Resources Research 37, 191–200.
KÄSS, W. 1998: Tracing techniques in geohydrology. Rotterdam, A.A. Balkema.
KLÖTZLI, U. 1985: Wasserfärbung. Jber. Schweiz. Ges. Höhlenforschg. Sekt. Bern 33, 47–50.
KNUCHEL, F. 1959: Bericht über die Wasserfärbung 1959 im Hohgantgebiet zum Nachweis der Herkunft der Karstquellen am Hardersüdfuss. Unpubl. report, Interlaken.
– 1961: Betrifft Kanalisationsableitung in den Chrutbach: Bericht über die Untersuchung der Versickerungsverluste und deren Wiederauftritte. Unpubl. report, Interlaken.
– 1972: Färbung des unterirdischen Abflusses der Schrattenfluh. Supplement à Stalactite 7.
– 1974: Die 5 grossen Färbversuche im Karstgebiet nördlich von Thuner- und Brienzersee. Akten des 5. Nationalen Kongresses für Höhlenforschung, Interlaken.
PFISTER, P. 1990: Tourenbericht Bachtrübung Tschäderloch. Jber. Schweiz. Ges. Höhlenforschg. Sektion Bern 38, 34–35.
– 1992a: Tourenbericht und Diagramme zur Salzung des Erosionsgangbaches. Jber. Schweiz. Ges. für Höhlenforschung Sekt. Bern 41, 69–76.
– 1992b: Tourenbericht zur Salzung des Nassen Ganges. Jber Schweiz. Ges. Höhlenforschg. Sektion Bern 40, 69–70
SIMEONI, G.P. 1973: Etude de la region alimentaire de la nappe de la plaine du Bödeli – Essai de coloration au Septemberschacht dans le massif du Hohgant (BE). Rapport du CHYN Neuchâtel.
– 1975: Etude des regions alimentaires de la plaine du Bödeli (Interlaken) et des sources du pied SE du Harder. Rapport du CHYN Neuchâtel.
WEA 1980: Zwischenbericht Bödeli. Wasser- und Energiewirtschaftsamt des Kantons Bern.
WIDMER, U. & ROUILLER, PH. 1978: 1. Internationales Speleo-Camp Interlaken: Lagerbericht. Höhlenforschergemeinschaft Region Hohgant HRH, Interlaken.
WILDBERGER, A., GRUNER, U. & SIEGENTHALER, U. 1982: Markierversuche und weitere hydrologische Untersuchungen im Karst des Brienzergrates und des Brünigpasses. Akten des 7. Nationalen Kongresses für Höhlenforschung, Schwyz, 249–267.

Manuscript received April 11, 2002
Revision accepted October 28, 2002