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Cave Genesis and its relationship to surface processes: Investigations in the Siebenhengste region (BE, Switzerland)

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Foreword, Dedication, and Acknowledgements

Foreword

The present thesis is the first of its kind in Switzerland and deals with caves, their genesis and their sediments. Through observations in caves, tectonic information could also be extracted. This study thus reflects the kind of observations that can be made in caves, however biology, archeology, and climatology are not presented here. The general structure of the thesis is as follows:

Chapter 1 presents the aim of the thesis, the cave region of the Siebenhengste and its surroundings, and the most important caves for this study. The methods used are also summarised.

Chapter 2 deals with the tectonic and stratigraphic observations that can be made in caves. In ideal situations, not only the present structure of the rocks can be seen, but the structural evolution of the whole area may be retraced.

Chapter 3 presents observations of the underground waterways and their implication for the interpretation of tracing experiments. An overview of all tracing experiments performed in the region is made, and the 1996 multitracing experiment is described in detail.

Chapter 4: The interaction of rocks and water leads to the formation of caves which is described in Chapter 4. The specific position of the Bärenschacht permits the development of a speleogenetic theory that unifies two of the existing viewpoints.

Chapter 5 then describes the formation of speleogenetic phases and their relation to the paleovalley bottoms. A reconstruction of the paleogeography since the Mio/Pliocene is sketched.

Chapter 6: The dating of the phasology is described in Chapter 6. The position and succession of sediment profiles within the speleogenetic phases allows a relative chronology to be built which then is dated absolutely, retracing the events of the last 400‘000 years. Chapter 6 therefore is considered as the synthesis of this study.

Chapter 7 summarises the results and conclusions.

Chapters 2 to 6 are prepared as a base for papers. Therefore, some repetitions as well as missing cross-references to other chapters cannot be avoided completely, despite all care. Some photographs are not numbered in their legend. Those pictures were put for layout purposes and are not referred to in the text. Every chapter is preceded by a german *Zusammenfassung* and a french *résumé*. These summaries are provided for readers who are not familiar with the english language.

Dedication

The present thesis is dedicated to two scientists:

- Franz Knuchel, a school teacher in Interlaken, was a precise observer and a sharp thinker, and can therefore be named as the first scientist working in the Siebenhengste karst. His observations and his logical deductions are still stunning today. Franz died of a heart attack in the middle of the Siebenhengste karren field in 1974.
- Thomas Bitterli, geologist from Basel, was as precise in his observations as Franz. His main area of interest was speleogenesis and its relation to the spring. He always kept in mind the relations between the puzzle parts the single caves represent. An excellent topographer, he contributed considerably to the art of mapping caves. Thomas died in a waterfall in Faustloch cave in 1998.

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I am very grateful to Stein-Erik Lauritzen, who allowed me to go to Bergen University for the dating of the speleothems. These datings render the thesis interesting for an audience outside of the caving community. Thank you for being member of the Jury.
Christian Schlüchter wird seit vielen Jahren immer wieder mit Informationen aus Höhlen bombardiert. Vielen Dank dafür, dass er dennoch den Kopf nicht zu sehr schüttelte, sondern mich unterstützte und Teil der Jury ist.
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Martin Heller helped a great deal with the realisation of the 3D-Figures as well as with the cave-surveying software. Paco Saez and Silviu Constantin helped with the datings, K. Bieri-Steck analysed the pollen samples, and Maria-Angela Teodorescu did some sediment analyses. Rafael Ferreiro Mählmann kindly measured the vitrinite reflectance, and Heidi Haas measured the carbonate content.

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Peter Pfister ergrub nicht nur drei Sedimentprofile in der St. Beatus-Höhle. Die Familie von Anna, Agatha und Peter Pfister war für Beherbergung, Verköstigung, Diskussionen und Aufmunterung immer ein idealer Ort: herzlichen Dank!

Die Arbeit wäre ohne die Unterstützung der St. Beatus-Höhlen-Genossenschaft und ihrer Geschäftsleitung (Hans und Hanni Schild, Marie Schwaller), die uns Zugang zur Höhle bot, nicht möglich gewesen.

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Die Höhlen- und Oberflächenfotos wurden von den folgenden Personen aufgenommen: Peter und Anna Pfister, Daniel Burkhalter, Urs Widmer, Fabian Bels, Gavin Newman, Andreas Werthemann, Katja Schobert, Diego Sanz, Thomas Bitterli, Gregor Siegenthaler, Bernhard Voss, Frédy Fleury, Martin Otz, Ivo Baron, Franz Knuchel, Werner Janz, Stefan Näff, Marcel Briand und Markus Schafheutle. Ihnen allen herzlichen Dank für das Zurverfügungstellen der Bilder!

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Definitions (dictionary)

crawl(way): passage in a cave having a low ceiling.

diffluence: a cave stream that divides into two different streams. Phreatic diffluences are common, vadose diffluences more common than is usually assumed.

epiphreatic zone: the part of a cave that is regularly flooded.

Gault: the old name for Garschella formation (Upper Cretaceous).

karst water table: A “water table” such as in porous aquifers does not exist in karst systems, which are too heterogenous (vast voids with rapid flow in contrast to almost impermeable limestone). However, since we have seen that the water in the tubes behaves approximately like that of a normal water table, and also for simplicity’s sake, we still use the term “karst water table”, knowing that, in a strict sense, this is incorrect.

longitudinal section: map of a cave (passage) seen from the side. Zigzaging galleries are stretched in a longitudinal section (opposite: projected section).

looping passage: phreatic passages are not necessarily inclined downward or flat, they may move up and down along fractures or bedding planes. This up-and-down movement is called looping.

meander, meandering canyon: a gallery of vadose origin that is narrow but high and that very often has sharp bends, like the original fluvial meander.

phreatic: originally: under water. If referring to morphology, it means a gallery that has a circular to elliptic form that is attributed to a genesis under water. If attributed to water table, it means the parts that are perennially flooded.

piggyback transport: passive transport of a nappe on the back of another one. The main movement is at the base of the nappe pile.

plan: plan of a cave seen from above.

profile: cross-section across a gallery.

projected section: map of a cave (passage) seen from the side. Galleries perpendicular to the plan of view are not represented (opposite: longitudinal section).

Réseau Siebenhengste-Hohgant: proper name of the biggest cave system in the Siebenhengste region.

scallop: erosional feature on the rock walls that indicates flow direction and floodwater velocity. Scallops are mainly erosional, and corrosion only enhances the process, as can be seen with scallops developing in granite where no corrosion is possible.

shaft: part of a cave that is vertical and needs ropes for access. A shaft can be of phreatic or vadose origin.

sinter: comprehensive term for hardened chemical deopsits such as dripstones, helectites, draperies, flowstone etc.

soutirage: small phreatic galleries draining the epiphreatic zone towards the perennial watertable. They are only created within the epiphreatic zone.

speleogenetic phase: in contrast to other authors, we use *phase* instead of *level* or *stage*. The term “level” in particular may be misleading since the corresponding galleries usually are not levelled at all.

sump, siphon: a gallery that is filled with water.

transfluence: two cave streams that cross each other because they are in superposed galleries. The two streams do not necessarily connect later.

vadose: originally: shallow. If referring to morphology, it means a gallery that has a canyon-like, high but narrow form that is attributed to free-flowing water. If attributed to water table, it means the parts that are no longer water-filled.

windows: a) shaft windows: openings in the wall of a shaft that lead to another shaft or a gallery. b) galleries that lead down into the karst water table, without any continuation above the water table. c) An Apple a day keeps Windows away.

Summary

The Siebenhengste region is one of the most significant cave areas in the world. Its high density of cave passages that extend over 1500 m in altitude makes it a key site for the study of Alpine paleogeomorphology and paleoclimatology.

The present thesis concentrates on St. Beatus Cave and Bärenschacht at the southern rim of the cave region. The tectonics, hydrogeology, speleogenesis, paleogeography, and paleoclimatology are summarised as follows:

Tectonics and stratigraphy

The throw of the Hohgant-Sundlauenen fault (HSV) is around 1 km. The stratigraphical thickness of the Schrattenkalk and Hohgant series allow an examination of the synsedimentary activity of the HSV from the Lower Cretaceous up to the Eocene. A complicated history of faulting activity and sedimentation in this timespan is retraced. The Waldegg is found to be a Horst-Graben structure.

Hydrogeology

Observations in St. Beatus Cave have shown that karst waters not only can generate caves across and within impermeable formations; in addition vadose diffluences are common, and transfluences do not necessarily require an impermeable layer to form. These findings allow an explanation of complex results of water tracings to be formulated.

A tracing experiment permitted delineation of the catchment areas of St. Beatus Cave and Siebenhengste. A review of all tracing experiments performed in the Siebenhengste-Hohgant area is made, and allows an overview of the hydrogeologic systems to the north of Interlaken.

Speleogenesis

The passage morphology shows that in the present epiphreatic zone, temporal floodwater corrosion prevails over perennial low-water erosion, resulting in a phreatic morphology of the tubes within the epiphreatic zone. The transition from meandering canyon to tube-type passages occurs at the top of this zone, which is responsible for the latest stage of tube morphogenesis in Alpine caves. The speleogenetic phases are related to the top of the epiphreatic zone.

Soutirages empty the epiphreatic zone in low water condition. Their genesis is intimately connected to the existence of a floodwater zone.

The transition from one speleogenetic phase to another happens rapidly; however, equilibrium between passage size and total discharge most probably is reached only asymptotically and needs considerable time.

Reconstruction of paleogeography

Twelve speleogenetic phases of different age can be found. The spring responsible for their formation is thought to be related to an old valley bottom. Therefore, the speleogenetic phases should directly indicate the successive deepening of the valley. The six phases that are investigated in the present study are found at 558, 660, 700, 760, 805, and 890 m a.s.l. The statistical analysis of small caves near the surface supports the definition of these phases.

Morphologic and sedimentologic findings suggest the genesis of the oldest conduits at Siebenhengste to be contemporaneous with the last Molasse deposition in Mio-Pliocene, before the Aare valley existed.

Phase-dating and paleoclimatic information

Erosion always leaves some sedimentary traces within the cave, which therefore yields paleoclimatic information. Cave genesis and speleothem deposition occurs during warm periods, whereas during glaciations, speleogenesis stops. Instead, varved silts are deposited as a result of waterlevel rise.

Several sediment profiles are investigated, most of them within the St. Beatus Cave. The sedimentary succession allows a chronological reconstruction of events that, when combined with the speleogenetic phases, gives information about the relative age of each profile, and thus about the age of the speleogenetic phase.

The dating of this chronology then allows the estimation of ages for the speleogenetic phases and glacial advances and retreats. The results show six glaciations at >350 ka, 235-180 ka, 157-135 ka, 114-99 ka, 76-54 ka, and 39-16 ka. The speleogenetic phase 760 was present at >350-235 ka, phase 700 was active at 180-157 ka, phase 660 again at 135-39 ka, and the present phase 558 between 39 ka and today.

A comprehensive analysis of a cave system gives much more meaningful results than the analysis of single points and structures in a basically open system.

The present study was made possible by of the volunteer mapping efforts of generations of speleologists.

Zusammenfassung

Die Region der Siebenhengste ist eine der grössten Höhlengebiete weltweit. Ihre hohe Dichte an Höhlengängen, die sich über mehr als 1500 Höhenmeter erstrecken, machen sie zu einem idealen Ort zum Studium der alpinen Paläogeomorphologie und glazialen Paläoklimatologie.

Die vorliegende Arbeit konzentriert sich auf die St. Beatus-Höhle und den Bärenschacht, die sich am südlichen Ende der Höhlenregion befinden. Die Resultate über Tektonik, Hydrogeologie, Höhlenentstehung, Paläogeographie und Paläoklimatologie werden im Folgenden summarisch präsentiert.

Tektonik und Stratigraphie

Der Versatz der Hohgant-Sundlauenen-Verwerfung (HSV) liegt bei 1 km. Die stratigraphischen Mächtigkeiten des Schrattenkalkes und der Hohgantserie erlauben, eine synsedimentäre Aktivität der HSV bereits ab der Unterkreide bis zum Eozän zu belegen. Eine komplexe Geschichte der Bruchaktivität und Sedimentation dieses Zeitalters wird nachgezeichnet. Die Waldegg ist eine Horst-Graben-Struktur.

Hydrogeologie

Beobachtungen in der St. Beatus-Höhle haben gezeigt, dass Karstwässer auch innerhalb und quer zu undurchlässigen Schichten Höhlen bilden können. Zusätzlich sind vadose Diffluenzen sehr häufig, und Transfluenzen sind nicht auf Gebiete mit undurchlässigen Schichten beschränkt. Durch diese Beobachtungen können „seltsame“ Resultate von Färbversuchen erklärt werden.
Ein Färbversuch erlaubte die Abgrenzung der Einzugsgebiete der St. Beatus-Höhle von demjenigen der Siebenhengste. Eine Übersicht über alle je in der Region durchgeführten Färbversuche wurde erstellt und erlaubt einen Überblick über die hydrogeologischen Systeme nördlich von Interlaken.

Höhlenentstehung

Die Gangmorphologie zeigt, dass in der heutigen epiphreatischen Zone die zeitweilige Hochwasserkorrosion über die ständige Niederwassererosion dominiert, was eine phreatische Morphologie innerhalb der epiphreatischen Zone ergibt. Der Übergang Mäander-Röhre geschieht im Dach dieser Zone, welche für die letzte Morphogenese zumindest in alpinen Höhlen verantwortlich ist. Die speläogenetischen Phasen sind in Zusammenhang mit der epiphreatischen Zone.
Soutirages entleeren die epiphreatische Zone während Niederwasser. Ihre Genese ist von der Existenz einer Hochwasserzone abhängig.
Der Übergang von einer speläogenetischen Phase zur nächsten geschieht verhältnismässig schnell; ein Gleichgewicht zwischen Schüttung und Ganggrösse stellt sich jedoch sehr wahrscheinlich nur asymptotisch und nach einer sehr langen Zeit ein.

Rekonstruktion der Paläogeographie

Es wurden zwölf speläogenetische Phasen verschiedenen Alters gefunden, deren Quelle wohl in Zusammenhang mit einem alten Talboden steht. Aus diesem Grunde sollten die speläogenetischen Phasen die Abfolge der Taleintiefung darstellen. Die in der vorliegenden Arbeit besonders studierten Phasen liegen auf 558, 660, 700, 760, 805 und 890 m ü.M. Die statistische Analyse von Kleinhöhlen bestätigt diese Phasen. Morphologische und sedimentologische Befunde legen eine Entstehung der ältesten Gänge auf den Siebenhengsten zur Zeit der Molasseablagerung, also im Mio-Pliozän, nahe, bevor das Aaretal begann zu existieren.

Datierung der Phasen und paläoklimatische Informationen

Die Erosion verschont zumeist Überreste der Sedimente. Aus diesem Grund sind Höhlen zur Rekonstruktion des Paläoklimas geeignet. Höhlenentstehung und Tropfsteinablagerung geschieht während Warmzeiten, während Eiszeiten die Speläogenese behindern und wegen des Wasserspiegelanstiegs gewarvte Silte ablagern.
Einige Sedimentprofile, zumeist aus der St. Beatus-Höhle, wurden untersucht. Die sedimentäre Abfolge erlaubt eine chronologische Rekonstruktion von Ereignissen, die dann mit den spelägenetischen Phasen kombiniert wird und so Angaben über die relative Abfolge der Profile untereinander sowie über die Alterszusammenhänge der Phasen liefert.
Die Datierung dieser Chronologie erlaubt sodann die zeitliche Einstufung der speläogenetischen Phasen sowie der Eisvorstösse und -rückzüge. Die Resultate zeigen sechs Eisvorstösse bei >350 ka, 235-180 ka, 157-135 ka, 114-99 ka, 76-54 ka und 39-16 ka. Die speläogenetische Phase 760 war zwischen >350-235 ka aktiv, Phase 700 zwischen 180-157 ka, Phase 660 wiederum zwischen 135-39 ka, und die heutige Phase 558 seit 39 ka.
Eine Gesamtanalyse der Höhle ergibt sinnvollere Resultate als die punktuelle Analyse von Einzelproben in einem grundsätzlich offenen System.

Diese Arbeit war nur möglich dank der ehrenamtlichen Höhlenvermessung durch Generationen von Höhlenforschern.

Résumé

Du point de vue spéléologique, la région des Siebenhengste est l'une des plus importantes du monde. La densité exceptionnelle des galeries souterraines, qui s'étendent sur plus de 1500 m de dénivelé, en fait un site privilégié pour l'étude de la paléogéomorphologie alpine et de la paléoclimatologie glaciaire.

La présente thèse se concentre sur la grotte de St. Béat et le Bärenschacht, situés au sud de ladite région. Les résultats obtenus, qui concernent la tectonique, l'hydrogéologie, la spéléogenèse, la paléogéographie et la paléoclimatologie, sont présentés sommairement ci-dessous.

Tectonique et stratigraphie

Le rejet de la faille de Hohgant-Sundlauenen (HSV) est de l'ordre de 1 km. L'épaisseur stratigraphique du Schrattenkalk et de la série du Hohgant permet l'observation de l'activité synsédimentaire de la HSV à partir du Crétacé inférieur jusqu'à l'Eocène. L'histoire complexe de l'activité tectonique et de la sédimentation pendant cette période est esquissée. La Waldegg est une structure en Horst et Graben.

Hydrogéologie

Des observations dans la grotte de St. Béat ont démontré que les eaux du karst sont capables de former des cavités à l'intérieur et au travers de formations imperméables. De plus, les diffluences vadoses sont très courantes, et les transfluences ne nécessitent pas une couche imperméable pour leur mise en place. Certains résultats «étranges» des essais de traçage peuvent être expliqués par ces observations.
Un essai de traçage a permis de délimiter les bassins versants de la grotte de St. Béat et des Siebenhengste. Une revue de tous les traçages effectués dans la région des Siebenhengste-Hohgant est présentée et permet de faire une synthèse des systèmes hydrogéologiques au nord d'Interlaken.

Spéléogenèse

La morphologie des galeries dans la zone épiphréatique actuelle indique que la corrosion en temps de crue, bien que temporaire, prédomine sur l'érosion vadose pérenne, avec pour corollaire la forme phréatique des galeries qui se situent dans la zone épiphréatique. La transition méandre-tube se fait au toit de cette zone, qui est responsable de la dernière étape morphogénétique des cavités alpines. Les phases spéléogénétiques sont liées à la zone épiphréatique. Des soutirages vidangent la zone épiphréatique en temps d'étiage. Leur genèse est intimement liée à l'existence d'une zone de battement. La transition d'une phase à l'autre se fait assez rapidement. Par contre, un équilibre entre la taille des galeries et le débit total n'est atteint qu'asymptotiquement et après un temps considérable.

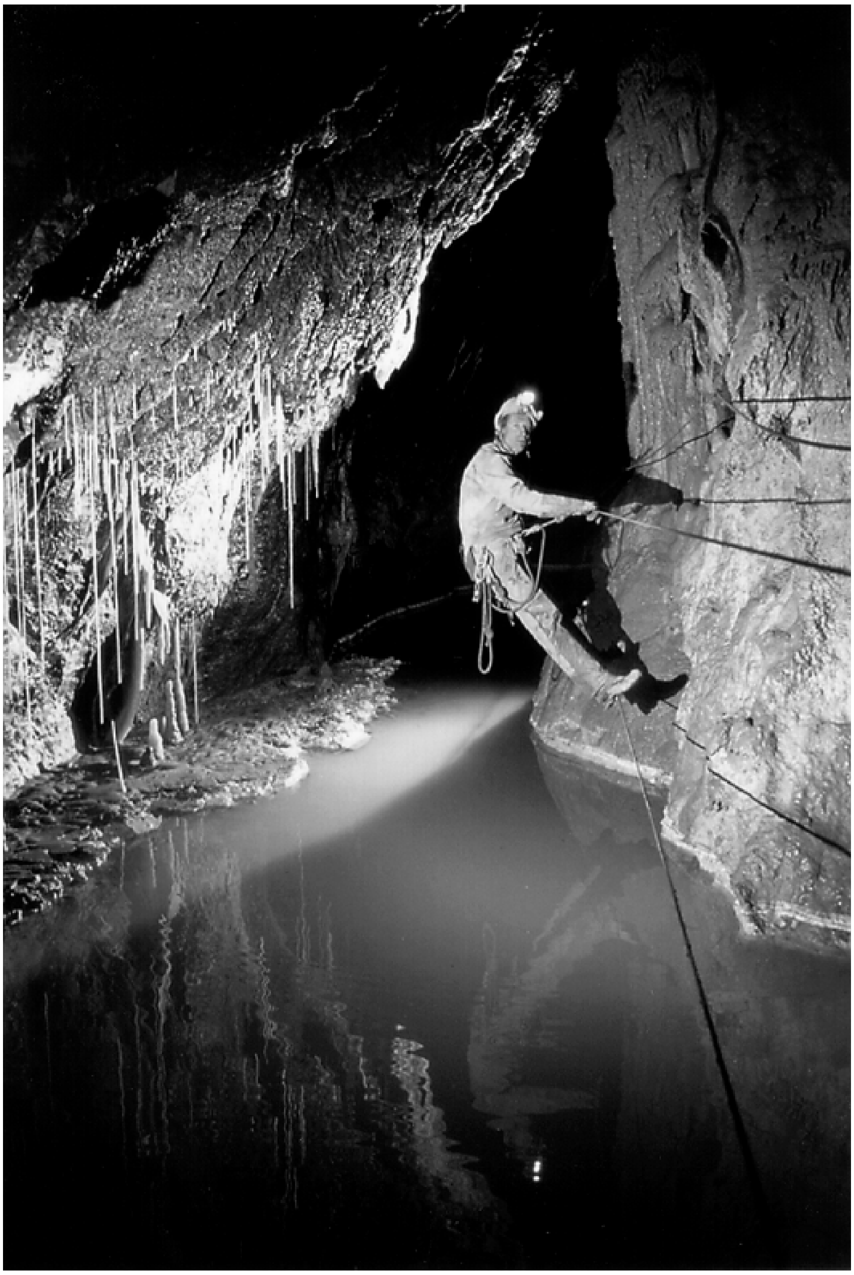
Reconstitution de la paléogéographie

On a trouvé douze phases spéléogénétiques, d'âges différents. On assume que leur source était en relation avec un ancien fond de vallée. Ainsi, les phases spéléogénétiques indiqueraient l'approfondissement progressif de la vallée. Les phases traitées dans le présent travail se situent à 558, 660, 700, 760, 805 et 890 m d'altitude. L'analyse statistique des petites cavités confirme ces phases.
Des observations morphologiques et sédimentologiques suggèrent une genèse des galeries les plus anciennes aux Siebenhengste pendant le dernier dépôt de molasse, au Mio/Pliocène, avant l'approfondissement de la vallée de l'Aare.

Datation des phases et information paléoclimatique

L'érosion laisse toujours des restes de sédiment à l'intérieur d'une cavité, que l'on peut utiliser pour une reconstitution du paléoclimat. La genèse des cavités et le dépôt de concrétions a lieu pendant les périodes chaudes, tandis que les glaciations causent l'arrêt de la spéléogenèse et le dépôt des limons varvés dus à l'ennoyement des galeries.
Plusieurs profils sédimentaires, principalement dans la grotte de St. Béat, ont été étudiés. La succession sédimentaire permet une reconstitution chronologique des évènements, combinée ensuite avec les phases spéléogénétiques. On obtient ainsi des indications sur l'âge relatif des profils et des phases spéléogénétiques correspondantes.
La datation de cette chronologie permet de retracer les phases spéléogénétiques et, en même temps, les avancées et retraits glaciaires. Les résultats montrent six avancées, à >350 ka, 235-180 ka, 157-135 ka, 114-99 ka, 76-54 ka et 39-16 ka. La phase spéléogénétique 760 était active à >350-235 ka, la phase 700 à 180-157 ka, la phase 660 à 135-39 ka, et la phase actuelle 558 entre 39 ka et aujourd'hui.
L'analyse intégrale d'un système souterrain fournit des informations paléoclimatiques bien plus significatives que l'étude d'échantillons isolés dans un système essentiellement ouvert.

La présente étude a été rendu possible grâce à la topographie souterraine bénévole effectuée par des générations de spéléologues.



The Ostergang of Faustloch. *Photo by Gavin Newman*

1. Introduction

Zusammenfassung: Einführung

Ziele und Struktur der Arbeit

Hauptziel der Dissertation ist, sedimentologische und morphologische Beobachtungen in Höhlen zur Rekonstruktion und Datierung der Taleintiefungen heranzuziehen. Zum Erreichen dieses Zieles müssen auch weitere Arbeiten durchgeführt werden. Die nachfolgende Liste erläutert die Bedeutung dieser Arbeiten und definiert gleichzeitig den Aufbau der Studie.

Die vorliegende Arbeit befasst sich nicht nur mit einzelnen Höhlen, sondern mit **Höhlensystemen**. Auf diese Weise sollen die zur Höhlenentstehung beitragenden Faktoren besser erkannt werden.
Eine Korrelation der Höhlen mit alten Talböden ist nur möglich, wenn wir sicher sind, dass keine geologischen Strukturen das Karstwasser abdämmen. Die nötigen **tektonischen Untersuchungen** erlauben Einsicht in die Struktur und geologische Geschichte der Region.
Hydrogeologische Beobachtungen in den St. Beatus-Höhlen führen zu einer Diskussion der allgemein beobachteten Resultate von Färbungen.
Die Einzugsgebiete der St. Beatus-Höhlen und der Siebenhengste wiesen keine klare Abgrenzung auf. Eine **Wasserfärbung** zeigte die Unabhängigkeit der Einzugsgebiete. Deshalb sind die beiden Höhlensysteme nur korrelierbar, wenn die Region der Quelle dasselbe Tal ist: die Abhängigkeit der Höhlen vom Tal wird gezeigt.
Der Flutungsmechanismus im Bärenschacht zeigte ein neues Modell der **Gangmorphogenese** auf, die zwei bisher existierenden Theorien in einem Kompromiss zusammenführt und eine bessere Definition der speläogenetischen Phasen erlaubt.
Die Erfassung der jungen **Phasen** im Detail erlauben eine Rückwärtsrechnung vom heutigen, bekannten Zustand an gegen die geologische Geschichte hin. Die Phasen in den Siebenhengsten sind von ihrer Quelle abhängig, die ihrerseits mit grosser Wahrscheinlichkeit im Talboden liegt. Somit sollte eine genaue Definition der **Höhlenphasen** unterschiedliche Talbodenstände rekonstruieren können.
Das **Alter der Taleintiefung** ist unbekannt. Mithilfe von Sedimentabfolgen – immer in Zusammenhang mit der Gangmorphologie – sollen sowohl die Sedimente wie auch die Phasen datiert werden können. Die Erarbeitung einer chronologischen Tabelle, die sedimentologische Befunde und morphologische Beobachtungen zusammenfasst, ist nötig.
Die **Datierung** dieser Tabelle erlaubt, eine komplette Abfolge von Taleintiefungen und Vergletscherungen in ihrer zeitlichen Abfolge zu erhalten. Dies sind die ersten Datierungen der Siebenhengste-Region und deshalb ein guter Abschluss dieser Arbeit.

Die Region

Die Höhlenregion der Siebenhengste befindet sich im Helvetikum nördlich des Thunersees. Von 558 m bis auf 2100 m gelegen, herrscht ein gemässigt-humides Klima mit deutlichen saisonalen Schwankungen der Temperatur.
Die stratigraphische Abfolge zeigt neben dem hauptsächlichen Karstaquifer des Schrattenkalkes (Kreide) noch weitere tertiäre (und kaum oberkretazische) Kalke, die auch Höhlen enthalten. Die allgemeine tektonische Lagerung ist einfach: eine mit 15-30° nach SE einfallende Platte wird von einer grossen SW-NE streichenden Verwerfung (Hohgant-Sundlauenen-Verwerfung HSV) und weiteren assoziierten Brüchen zerschnitten. SE der HSV bedeckt auf weite Teile ein Flyschpaket das Helvetikum und verhindert direkte Beobachtungen. Jüngere dextrale Blattverschiebungen sind vor allem im Bereich zwischen Gemmenalphorn und Grünenbergpass zu beobachten. Die tektonische Evolution der Waldegg wird im Kapitel 2 beschrieben.
Die Region ist in zwei Haupteinzugsgebiete geteilt, einerseits dasjenige der St. Beatus-Höhlen, das bis zum Gemmenalphorn führt, und andererseits dasjenige des Bätterichs/Gelberbrunnens, das über Bärenschacht, Faustloch, Siebenhengste und Hohgant bis zur 20 km entfernten, luzernischen Schrattenfluh reicht. Diese wurde wohl erst im Verlauf der letzten 200’000 Jahre an die heutigen Quellen angehängt. Eine Übersicht gibt Kapitel 3.
Verkarstungen der Region sind aus der Oberkreide sowie dem Tertiär belegt. Die heutigen Höhlen weisen zusammengenommen eine Länge von über 280 km und eine maximale Höhendifferenz von 1500 m auf, was das Gebiet zu einem der grössten weltweit macht. Das Réseau Siebenhengste-Hohgant, das aus dem Faustloch, dem Siebenhengste-Labyrinth und dem F1 besteht, weist beeindruckende Dimensionen auf: 148 km Länge und -1340 m Tiefe.

Die Geschichte der Höhlenforschung in den Siebenhengsten geht auf die Zeit des zweiten Weltkrieges zurück. Eine eigentliche Explosion der Forschung beginnt aber erst in den 70er Jahren. In den 80ern konnten F1 und Faustloch mit dem Réseau verbunden werden; in den 90ern erlebten Faustloch und Bärenschacht eine Blüte, während die St. Beatus-Höhlen komplett neu vermessen wurden. Die Arbeit ist jedoch noch lange nicht beendet. Die Koordination der Forschung wird durch die "Höhlenforschergemeinschaft Region Hohgant" HRH wahrgenommen, der momentan mehr als 10 internationale Vereine angehören. Zusammenarbeit über die ganze Region hinweg ist selbstverständlich.

Die wissenschaftliche Arbeit begann mit dem Pionier Franz Knuchel. Seine Arbeiten wurden aber oft nicht publiziert. Die ersten "streng" wissenschaftlichen Veröffentlichungen wurden erst ab den 80er-Jahren von Hof, Jeannin und Bitterli gemacht. Höhlenforschung ist in der Schweiz jedoch ein Hobby. Dies erklärt zum Teil, wehalb die Erkenntnisse aus Höhlen kaum in internationalen Fachzeitschriften publiziert sind.

Die ersten Theorien zur Entstehung des Réseaus wurden bereits 1984 gedruckt. Im heutigen Kenntnisstand umfasst das Gebiet 11 verschieden alte Phasen der Entstehung, wovon die sechs untersten (jüngsten) im Kapitel 5 beschrieben werden. Es wird angenommen, dass die Quellenhöhe ungefähr mit alten Talböden korrelierbar ist. Somit zeigen die Phasen alte Talstände an. Die obersten vier Phasen hatten ihre Quelle im Eriztal, was bedeutet, das zu dieser Zeit das Aaretal wohl noch nicht existierte. Die Phasengrenzen sind identisch mit Hochwasserständen, was im Kapitel 4 beschrieben ist. Das Alter der einzelnen Phasen war bislang unklar, einzig Sedimente auf den Siebenhengsten legten ein Alter von über 400 ka nahe. Weitere Sedimentuntersuchungen sind im Kapitel 6 beschrieben.

Die wichtigen Höhlen

Der Bärenschacht, 1965 entdeckt, weist heute eine Länge von 59 km bei 946 m Tiefe auf. Während der Eingangsteil aus Schächten und Kletterstellen besteht, zeigt das Labyrinth unterhalb phreatischen Charakter. Es entstand von den Wässern aus den Siebenhengsten und dem Hohgant. Da wegen des Flyschdeckels kaum Oberflächenwässer einfliessen, bietet der Bärenschacht einen ungestörten Einblick in das Verhalten eines tiefen Karstes.

Die St. Beatus-Höhlen sind seit alters her bekannt, und seit 1904 ist der erste von total 12 km (bei +353 m Höhendifferenz) ausgebaut. Die jüngste Nachvermessung ergab ein mustergültiges Planwerk und legte den Grundstein zu dieser Arbeit. Die Höhle zeigt vor allem Schlüssellochprofile, die nahe des Drusbergmergels verlaufen. Trotz scheinbar stetig absinkendem Gangverlauf können Entstehungsphasen ausgeschieden werden.

Das 1970 entdeckte Faustloch ist 14 km lang und 960 m tief. Leider können die tiefen Teile momentan nicht besucht werden, da ein Gang mit Sediment aufgefüllt wurde. Der Eingang besteht aus Schächten und Mäandern und ist hochwassergefährdet. Die anderen Teile des Faustlochs sind überwiegend phreatisch. Die Öffnung der Grabstelle würde erlauben, die im Bärenschacht und St. Beatus-Höhlen definierten Phasen bergwärts zu extrapolieren und mit den Siebenhengsten zu verbinden.

Methoden

Die Höhlensuche bildet den ersten Schritt zur Erstellung eines Inventars. Schachthöhlen müssen mit Seil eingerichtet werden. Dann müssen die Höhlen vermessen werden, und zwar in Grundriss, abgewickeltem Längsschnitt und Profilen. Ohne Einrichtung und Vermessung ist keine weiterführende Arbeit möglich.

Morphologische Beobachtungen weisen auf die Entstehungsbedingungen der Höhle hin. Im Gegensatz zur Stratigraphie sind die jüngsten Höhlen zumeist unten zu finden. Sedimentbeobachtungen erlauben, eine Abfolge von Erosion und Sedimentation zu skizzieren, die dann mit den Höhlenphasen in Zusammenhang gebracht werden kann. Sedimentanalysen wie Petrographie, Granulometrie, Calcimetrie, Tonmineralogie und U/Th-Datierung ergeben sodann im günstigen Fall Erkenntnisse über Ablagerungsbedingungen und -zeit.

Résumé: Introduction

Objectifs et structure de la thèse

L'objectif principal de la thèse est d'utiliser des observations sédimentologiques et morphologiques effectuées à l'intérieur des cavités pour retracer et dater l'approfondissement des vallées. Plusieurs études différentes ont été réalisées; la liste qui suit décrit les objectifs et définit en même temps la structure de ce travail.

La présente thèse ne concerne pas que des cavités séparées, mais aussi des **systèmes de cavités**. De cette manière, on reconnaîtra mieux les facteurs déterminant la spéléogenèse.

Une corrélation des grottes avec les fonds des anciennes vallées n'est possible que si on peut exclure une éventuelle interférence des structures géologiques. Les **travaux tectoniques** réalisés permettent d'éclairer la structure ainsi que l'histoire géologiques de la région.

Des **observations hydrogéologiques** menées dans la grotte de St. Béat sont suivies d'une discussion sur les résultats des colorations en général.

Les bassins versants de la grotte de St. Béat et des Siebenhengste n'avaient pas de délimitation claire. Un **essai de traçage** a démontré leur indépendance. Ainsi, ces deux cavités ne sont corrélables que si la région de la source est la même vallée: la relation des cavités avec les fonds de vallée est démontrée.

Le mécanisme de crue au Bärenschacht sert de base à un nouveau **modèle de morphogenèse** des galeries. Ce modèle est un compromis entre les deux théories existantes, et permet de mieux définir les phases spéléogénétiques.

L'analyse détaillée des phases récentes permet de remonter l'histoire géologique à partir de l'état actuel et connu. Les phases aux Siebenhengste dépendent de leur source, elle-même probablement liée à des fonds de vallée anciens. De cette manière, une définition des **phases spéléogénétiques** devrait permettre de reconnaître plusieurs anciens fonds de vallée.

L'âge de l'approfondissement des vallées est inconnu. Les successions sédimentaires – toujours en relation avec la morphologie des galeries – devraient permettre de dater et les sédiments et les phases. Ces observations sont réunies en un tableau chronologique, qui rassemble les données sédimentologiques et morphologiques.

La **datation** de ce tableau permet d'esquisser la succession des approfondissements de vallée et des glaciations. Ces datations sont les premières effectuées dans la région des Siebenhengste et constituent une bonne synthèse de cette étude.

La région

La région spéléologique des Siebenhengste se trouve au nord du lac de Thoune, dans les nappes de l'Helvétique. Située entre 558 et 2100 m d'altitude, elle subit un climat tempéré-humide avec des changements de température importants.

Outre l'aquifère principal du Schrattenkalk (Crétacé), la stratigraphie montre d'autres calcaires d'âge principalement éocène qui peuvent contenir des cavités. La structure tectonique générale est simple: une dalle monoclinale avec une inclinaison de 15-20°, coupée par une grande faille normale de direction SW-NE (la faille de Hohgant-Sundlauenen HSV) et d'autres failles associées. Au SE de la HSV, une nappe de Flysch couvre la majeure partie de l'Helvétique et les observations directes sont donc impossibles. Des décrochements dextres plus jeunes sont observés entre le Gemmenalphorn et la vallée de l'Eriz. L'évolution tectonique de la Waldegg est décrite au chapitre 2.

La région est divisée en deux bassins versants principaux. D'une part celui de la grotte de St. Béat, qui remonte jusqu'au Gemmenalphorn, d'autre part celui de Bätterich/Gelberbrunnen, qui comprend le Bärenschacht, le Faustloch, les Siebenhengste et le Hohgant ainsi que la Schrattenfluh, distante de 20 km. Celle-ci a probablement été raccordée au Bätterich il y a moins de 200'000 ans. Une vue d'ensemble des bassins versants est donnée au chapitre 3.

La karstification date du Crétacé supérieur et du Tertiaire. Les cavités actuelles ont une longueur cumulée de plus de 280 km et une dénivellation maximale de 1500 m, ce qui en fait une des plus importantes régions spéléologiques du monde. Le Réseau Siebenhengste-Hohgant, composé du Faustloch, du labyrinthe des Siebenhengste et du F1, a lui-même des dimensions impressionnantes: 148 km de long et 1340 m de dénivelé.

L'histoire de la spéléologie aux Siebenhengste remonte à la 2ème guerre mondiale. La recherche n'a cependant vraiment commencé qu'à partir des années 70. Dans les années 80, le F1 et le Faustloch sont reliés au Réseau, les années 90 voient l'apogée du Faustloch et du Bärenschacht, tandis que la grotte de St. Béat est retopographiée intégralement. Les explorations ne sont de loin pas terminées. La coordination des travaux sur toute la région est faite par la «Höhlenforschergemeinschaft Region Hohgant» HRH (Association des spéléologues de la région Hohgant), qui regroupe internationalement plus que 10 clubs.

Les premiers travaux scientifiques ont été réalisés par le pionnier de la recherche spéléologique, Franz Knuchel, qui, hélas, n'a pas publié tous ses résultats. Les premières publications “purement” scientifiques paraissent dans les années 80, par Hof, Jeannin et Bitterli. La spéléologie n'étant pas une profession en Suisse, beaucoup de résultats n'ont jamais été publiés dans des revues internationales reconnues.

Les premières théories sur la genèse du Réseau remontent à 1984. Aujourd'hui, on connaît 12 phases d'âges différents, dont les six plus profondes (jeunes) sont décrites au chapitre 5. On admet que l'altitude des sources correspondantes est liée aux anciens fonds de vallées. Les quatre phases les plus hautes avaient leur source dans la vallée de l'Eriz, ce qui signifie probablement que la vallée de l'Aare n'existait pas encore. Les limites des phases sont identiques à celle de la zone épiphréatique, phénomène décrit au chapitre 4. L'âge des phases était jusqu'alors inconnu, seuls quelques sédiments des Siebenhengste suggéraient un âge supérieur à 400 ka. Les analyses sédimentologiques sont décrites dans le chapitre 6.

Les cavités importantes

Le Bärenschacht, découvert en 1965, est actuellement long de 59 km et profond de -946 m. Tandis que la zone d'entrée comporte des puits et des ressauts, le labyrinthe profond a un caractère phréatique. Il a été creusé par les eaux venant des Siebenhengste et du Hohgant. Puisqu'il n'y a guère de circulations depuis la surface à cause de la couverture de Flysch, le Bärenschacht permet l'observation exceptionnelle du comportement d'un karst profond.

Les grottes de St. Béat, connues de longue date, ont subi en 1904 un aménagement du premier kilomètre (longueur totale 12 km, dénivellation +353 m). La retopographie récente a donné un plan exemplaire, qui sert de base au présent travail. Les galeries sont proches des marnes de Drusberg, avec un profil en trou de serrure. Malgré leur inclinaison apparemment uniforme, on peut distinguer des phases génétiques distinctes.

Le Faustloch, découvert en 1970, a une longueur de 14 km et une profondeur de -960 m. Suite au comblement par une crue d'une galerie dans la partie moyenne de la cavité, la zone profonde est actuellement inaccessible. L'entrée comporte des puits et méandres qui sont dangereux en crue. Les autres parties du Faustloch sont principalement de type phréatique. La désobstruction du colmatage permettrait d'extrapoler vers l'amont les phases décrites dans le Bärenschacht et la grotte de St. Béat, faisant ainsi le lien avec les Siebenhengste.

Méthodes

La prospection constitue le premier pas vers un inventaire des cavités. Les gouffres doivent être équipés à l'aide de cordes. Ensuite, une topographie complète est nécessaire, en plan, en coupe développée et avec des profils. Sans équipement ni topographie, aucun travail ultérieur n'est possible.
Des observations morphologiques permettent de déduire certaines conditions de spéléogenèse. Contrairement à la règle stratigraphique, les cavités les plus jeunes sont généralement en bas du massif. L'observation des sédiments permet de reconnaître les phases d'érosion et de sédimentation, en relation avec les phases spéléogénétiques. L'analyse de sédiments (pétrographie, granulométrie, calcimétrie, minéralogie des argiles et datation U/Th) permet souvent de tirer des conclusions sur les modes de dépôt et leur âge.

Photo by Fabian Bels

1.1. Aims and structure of the thesis

The cave region of the Siebenhengste has been explored for more than 50 years. Speleological knowledge increased exponentially with the application of the single-rope technique in caving in the early 1970s. The first scientific observations within the caves soon followed, but they only revealed a small part of the great potential that the cave system held. The present thesis continues in this way and represents another brick in the wall of knowledge.

The main aim of the thesis is to use in-cave observations in Bärenschacht and St. Beatus Cave to gain insight into valley deepening processes. This includes a description of the morphology and of the sediments in the cave, as well as dating methods to attribute absolute age to the deepening phases. To reach this aim, additional prerequisite work has been undertaken, which is explained in the following:

Cave systems versus single caves
Most of the scientific work that was made in the last 30 years dealt only with a particular cave instead of a cave system.
We assume that the study of cave systems gives much better insight into the governing processes of cave formation and sediment deposition.
Therefore, we want to establish a link between several caves within the studied region. This task is of course more time-consuming and complex than observations in a single cave.

Cave genesis processes and relation to tectonics
The correlation of caves with paleovalley bottoms is only possible if no geologic structure (such as folds or faults) is responsible for a damming of the karstwater.
We hypothesize that the speleogenetic phases found are not dependent on local tectonic features.
To check this, we have to undertake tectonic investigations in Bärenschacht and St. Beatus Cave. It is advantageous that the tectonic structure and history of the Waldegg region (where the Bärenschacht is) can be determined. This is not possible from the surface, since marls and Flysch cover most of the area.

Investigations of vadose waterways
Vadose flowpaths are often neglected in scientific studies of caves.
We assume that the behaviour of the vadose waterways is much more complex in caves than at the surface.
We want to use hydrogeologic observations in St. Beatus Cave to get new ideas about vadose flowpaths, and discuss the implication of the results for tracing experiments.

Catchment areas and relation to speleogenesis
The catchment areas of St. Beatus Cave and the Réseau Siebenhengste-Hohgant have no clear delimitation.
If we can prove that the catchment areas are different, then observed similarities of St. Beatus Cave and Bärenschacht have to have their origin in their common baselevel.
We therefore want to conduct a tracing experiment that permits this differentiation while answering other open questions.

Speleogenetic models
During fieldwork, it was seen that the two most widespread speleogenetic models don't completely fit the observations.
Our hypothesis is that a combination and completion improves the models and gives new insight into speleomorphogenetic processes.
We want to compare the two models with the observations made, and link the two models into one that fits better to the observed situation here as well as to other caves.

Speleogenetic phases and their link to the valley
Investigations in the last 15 years have shown that the Siebenhengste caves are a product of a complex multiphased history. St. Beatus Cave and Bärenschacht represent the lowermost (youngest) phases of the Siebenhengste region.
The phases in the Siebenhengste correlate with their respective paleospring. We suppose that the spring itself is related to old valley bottoms.
To test this, we want to characterize the phases in a way that indicates the progressive incision of the valley outside the cave. Remnants of old valley bottoms are usually eroded away outside.

Age of the valley incision
The age of the valley incision is largely unknown.
We hypothesize that the morphology and sediments are linked to valley deepening and paleoclimatic events.
We want to study the interrelation between morphology, sediments, and surface processes. Our main aim is to elaborate a table containing the relative chronology of events which should be able to answer those questions. Furthermore, we want to date some speleothems within the table mentioned above. Therefore, we should get a complete and dated succession of valley-deepening events and glaciations. The dating of speleogenetic phases in the Siebenhengste region has never been undertaken before. Therefore, we consider this to be the final conclusion and aim of the thesis.

1.2. The Cave Region of Siebenhengste

This chapter summarises the characteristics of the studied cave region. Some parts will be explained and discussed at length in other chapters of the present thesis.

Geography

The Siebenhengste cave region is part of the Helvetic border chain that is situated in the northwestern part of the Alps, adjacent to the Molasse basin (Fig. 1-1). Its southern end is at Lake Thun (Fig. 1-3), its western border is formed by the Justistal valley and the front end of the Helvetic domain. The northern and eastern delimitation is the Emmental and the Flysch nappes of the Habkern valley. The baselevel is formed by Lake Thun (558 m a.s.l.). The entire chain forms a roughly southeast-dipping slope, cut in the north and west by steep cliffs. The upper parts lie between 1950 m (Niederhorn) and 2190 m (Hohgant). The deepest interruption in this chain is formed by the Grünenberg pass (1550 m, Fig. 1-2).

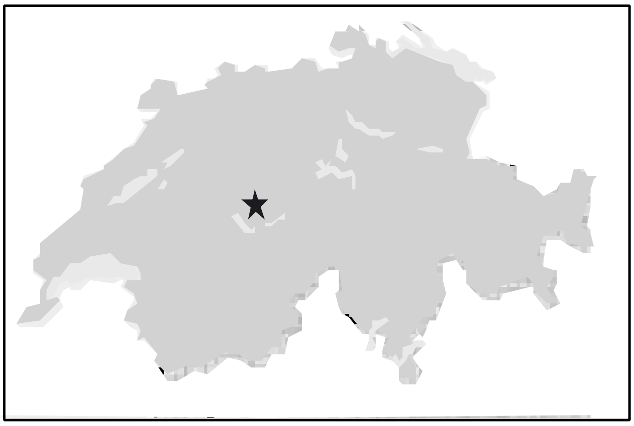


Fig. 1-1: Situation of the Siebenhengste cave region within Switzerland.

Lage der Höhlenregion Siebenhengste innerhalb der Schweiz.

Situation de la région des Siebenhengste en Suisse.

The areas below 1500 m are covered by vegetation and soils and are therefore farmed in most parts. Due to the relative steepness, agriculture is restricted to dairy-farming. Between 1500 and 1700 m, sandstone is predominant, and firs and grass patches grow on swampy ground. The area between 1700 m and 2100 m a.s.l. are either largely denuded and composed of limestone pavement or still covered with sandstone.

The climate is influenced mostly by westerly winds and is temperate humid. The average annual temperature is around 8°C at 600 m and 2°C at 1800 m, with seasonal differences between -35°C up to 40°C. The annual precipitation is between 1500 and 2000 mm, part of it as snow in winter.

Stratigraphy of the bedrock

The relevant stratigraphy (Fig. 1-4) for the karst configuration is as follows (from bottom to top):

- At its base is the Kieselkalk (silicious limestone, Lower Cretaceous) with a thickness of about 200 m. It is not well karstifiable, there are only some cave parts found. This is partly due to the superposed Drusberg marl.
- The Drusberg marl, which generally represents the impervious bottom layer, has a thickness of about 40 m. The uppermost parts show limestone banks.

- The marls are followed by about 200 m of Schrattenkalk (lower Cretaceous, herein also abbreviated as SK) which is easily karstifiable and thus the main aquifer. The Schrattenkalk can be divided into six sequences (Jeannin, 1989), which are usually distinguishable. However, their characteristics and their thickness may vary considerably.
  The Lower Schrattenkalk is almost not distinguishable from the Basal SK below, since the intermediate marly layers are often absent. Characteristic of both is an elevated content of pyrite, leading to sometimes spectacular secondary gypsum formations in the caves.
  The overlying Middle Oolithic Schrattenkalk smells oily when hammered on, proving the presence of organic rests. The following Upper Oolithic SK is a gray limestone with coarser shell clasts. Some oysters are found in the lower part. It is difficult to distinguish this limestone from the underlying one. A thin marly layer often marks the beginning of the Schrattenkalk s.str., a very bright limestone with many Rudist shells. The following Orbitolina marls are often not visible and may vary from slightly clayey limestone to a fine sandstone or marl. The topmost layer (Upper Schrattenkalk) consists of fossil-rich beds (Rudists and Turritelles) which contain brownish veins.

- Only in the Waldegg region (Fig. 1-3), some scarce traces of Upper Cretaceous Gault sandstone and Seewerkalk are found, both of them having a maximum thickness of no more than 15 m.
- A big sedimentary and erosional gap follows before the Eocene Hohgant series is deposited. The Hohgant series (thickness up to 200 m) consists of a complex succession of quartzitic sandstone, calcareous sandstone and locally even Lithothamnia limestone. The calcareous parts of the Hohgant series are often karstified and have caves

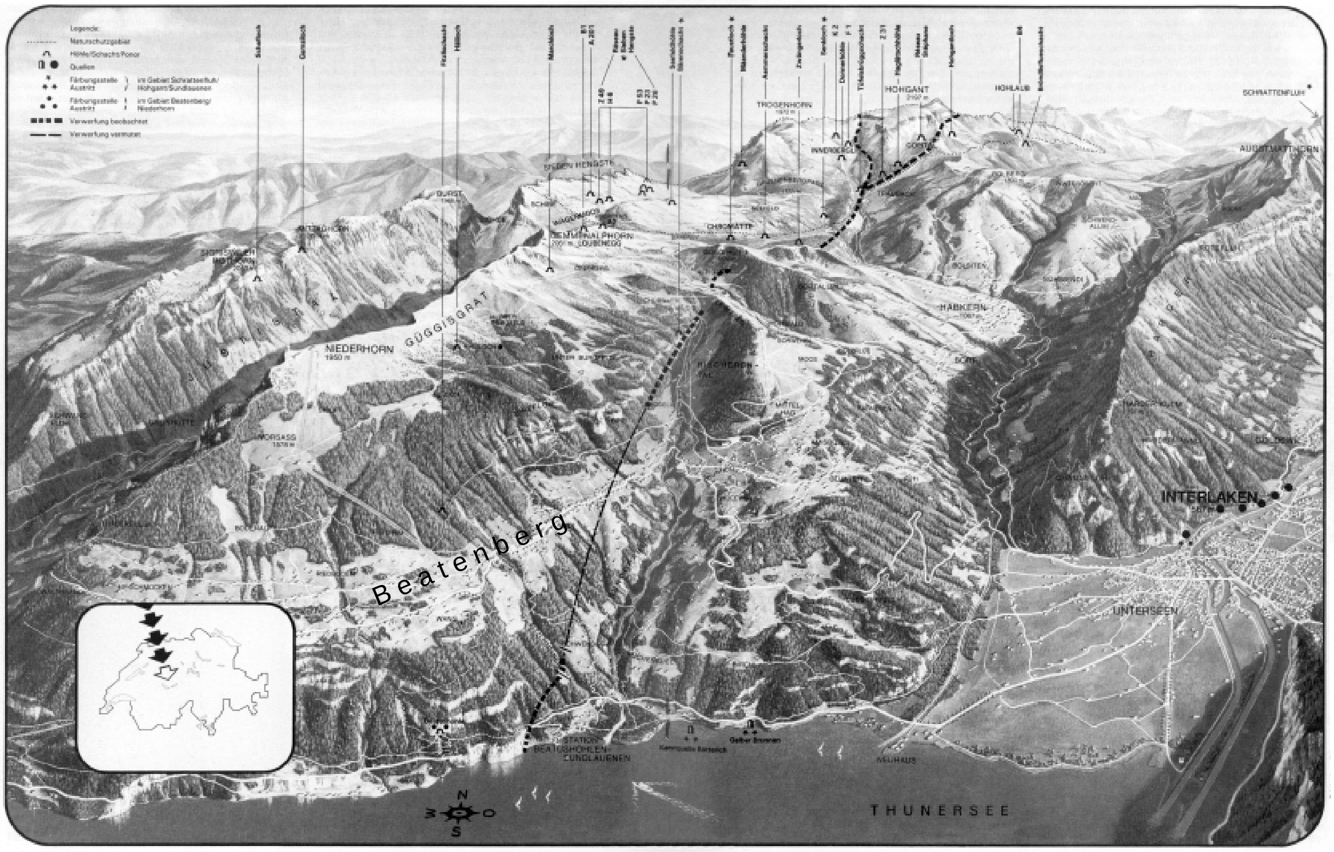


Fig. 1-2 (above):
Diagram showing the region, view towards the Northeast.

Diagramm der Region, Blickrichtung nach Nordosten.

Diagramme de la région, vue vers le nord-est.

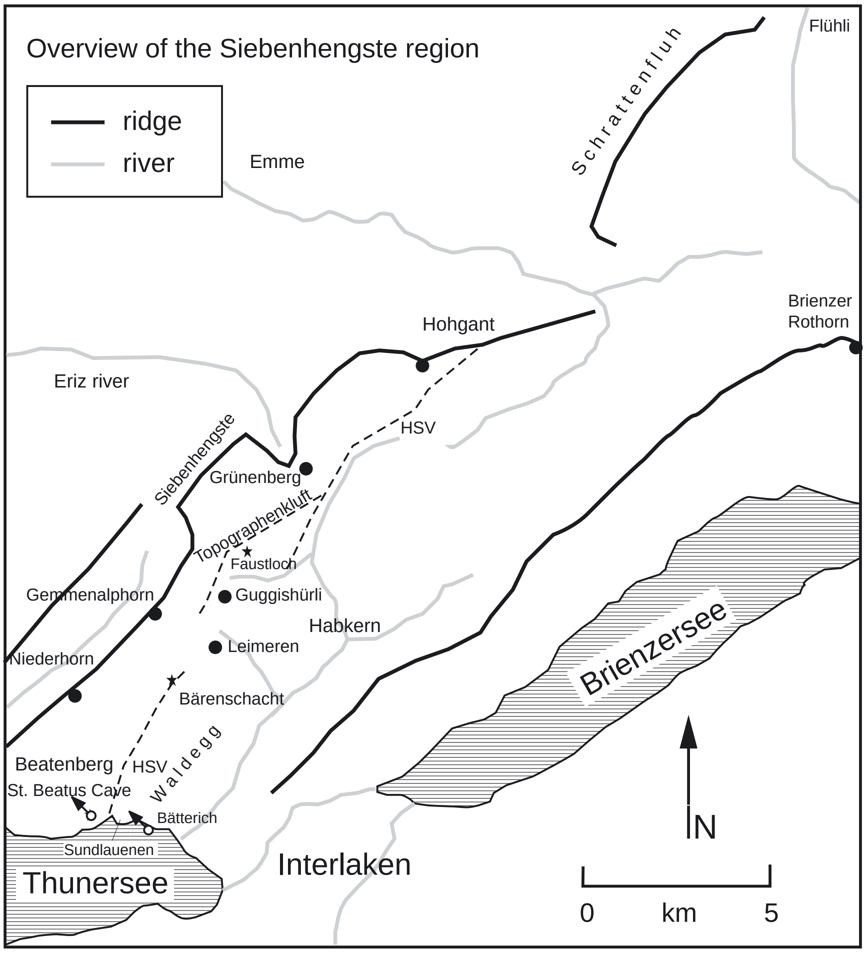


Fig. 1-3 (left):
Overview of the Siebenhengste region.

Übersicht über die Siebenhengsteregion.

Vue d’ensemble de la region des Siebenhengste.

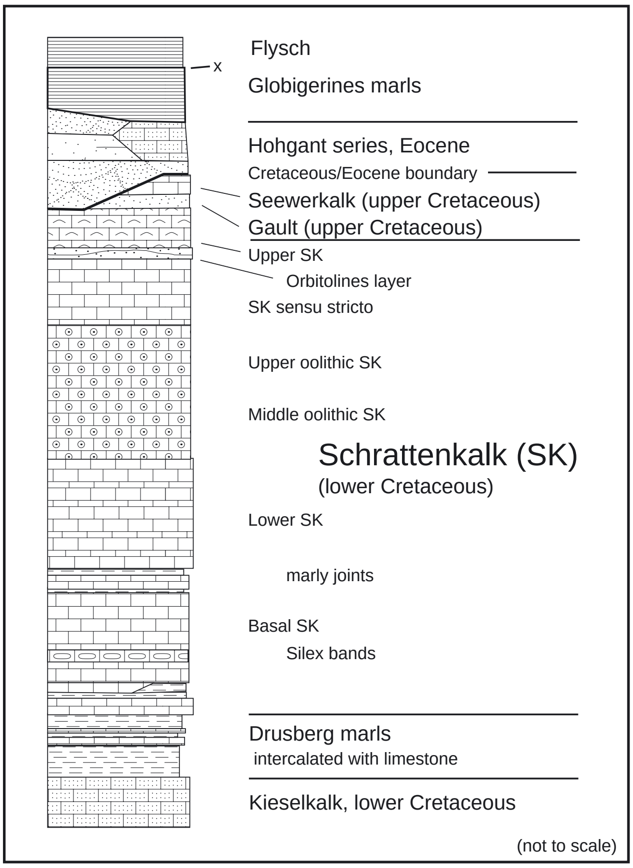


Fig. 1-4:
The stratigraphy of the Helvetic border chain.
Die Stratigraphie der helvetischen Randkette.
La stratigraphie de la chaîne bordière helvétique.

which can be longer than 1.5 km. However, many of those systems are hydrologically perched.

- The Hohgant series is followed by Globigerina marls which have a variable, tectonically influenced thickness.
- On top, a Flysch nappe is overthrust, which belongs to the Ultrahelvetic domain. The Flysch covers virtually all fractures of the Helvetic domain and hinders the investigation of the underlying strata.

Tectonics

The general tectonical features are simple (Fig. 1-5): a monoclinal slope, dipping to the southeast at about 15-30° that is interrupted by a large longitudinal normal fault, extending from Lake Thun up to the Schrattenfluh (Hohgant-Sundlauenen fault HSV). The throw of the fault is around 200 m in the Hohgant region and increases to more than 1000 m in Sundlauenen, thus interrupting the continuous dip of the Cretaceous and Eocene sediments. The HSV is accompanied by several other normal faults, the most important being the Topographenkluft-Faille de Bäreney (Fig. 1-3), and the Bärenkluft.

Southeast of the HSV, the geological features of the Helvetic domain are largely unknown, since the Flysch cover hinders direct surface observations. This part of the Helvetic domain is visible only in the southern part of Faustloch and in Bärenschacht. It seems to form an antiform structure that is cut by several normal and thrust faults of minor importance.
The other easily visible faults are dextral strike-slip faults that often have some vertical movement. They mainly occur between the Gemmenalphorn and the Grünenbergpass.
Observations indicate that the HSV and adjacent normal faults were already active synsedimentarily in the Lower Cretaceous and continued their activity to the Eocene.

The tectonic evolution of the Waldegg antiform structure (Fig. 1-3) will be discussed at length in Chapter 2.

Water catchments

The cave region is divided into two catchment areas (Fig. 1-6), the smaller one being the St. Beatus cave system, extending to northeast and west, up to the Gemmenalphorn, comprising an area of about 6 km^2. The other one extends from the springs called Bätterich and Gelberbrunnen at Lake Thun through Bärenschacht, Faustloch, Siebenhengste, and Hohgant up to the Schrattenfluh (Knuchel, 1972), therefore comprising three massifs. The Schrattenfluh, a massif that lies beyond the deeply incised valley of the Emme, lies 20 km away. It seems to have connected to the Siebenhengste catchment within the last 200 ka (see Chapter 5).

Most of the delimitations of the catchment areas have been determined by tracing experiments (see Chapter 3).

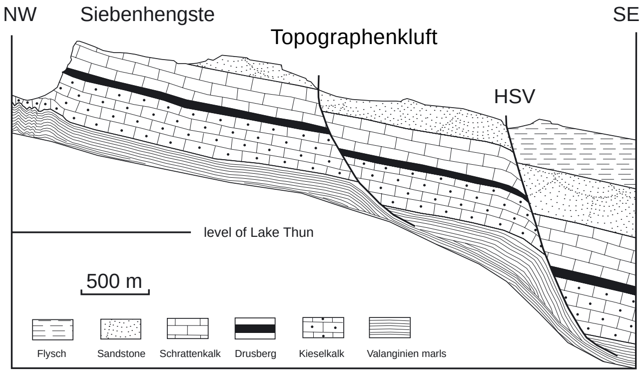


Fig. 1-5:
Geologic cross-section through the Siebenhengste.
Geologisches Profil durch die Siebenhengste.
Profil géologique à travers les Siebenhengste.
(from Jeannin 1989, modified)

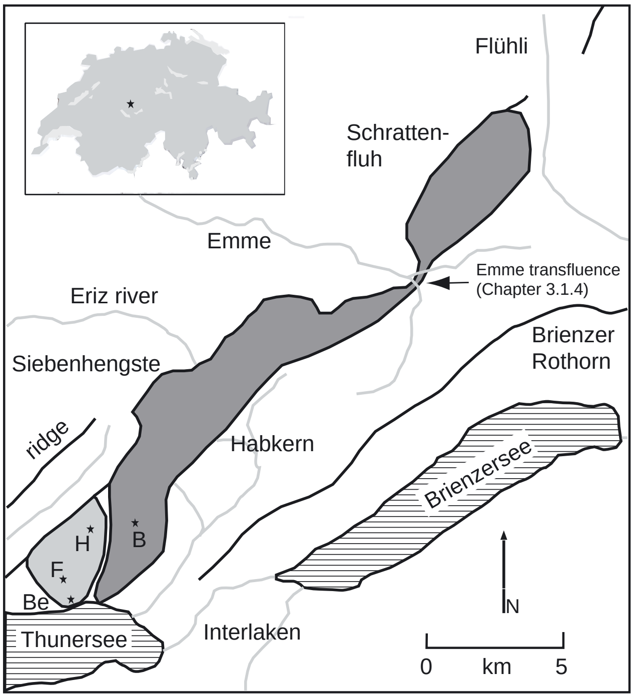


Fig. 1-6:
The water catchments as known prior to the tracing experiment of 1996. B=Bärenschacht, H=Häliloch, F=Fitzlischacht, Be=St. Beatus Cave.

Die Einzugsgebiete vor der Wasserfärbung 1996.

Délimitation des bassins versants proposée avant l'essai de traçage de 1996.

The cave system

The first traces of speleogenesis date back to the Upper Cretaceous. Paleokarsts found within the Schrattenkalk, which are filled with Upper Cretaceous Gault sandstone, prove a very early karstification. Another karstification took place in early Tertiary up to the Eocene transgression, however, only scarce traces are present (Jeannin 1989).

The cave's galleries known at present are over 280 km in length between 480 m and 2000 m a.s.l (Fig. 1-7 and 1-8). In the following section, we present the most important caves and their character. The key caves studied within this thesis – St. Beatus Cave, Bärenschacht, and Faustloch – are described in detail in Chapter 1.3.

The St. Beatus Cave represents the spring of a separate catchment (Fig. 1-6). Its entrance part is a show cave that attracts many tourists. The Fitzlischacht belongs to the St. Beatus catchment. It consists essentially of a fossil, phreatic tube along a fracture, that is cut by several younger shafts that are still active. The fossil tube might have been at least one of the old exits of the Siebenhengste area (see "Genesis of the Cave system" below).

The Bätterich, located in Lake Thun, represents today's major spring of the Siebenhengste catchment (Häuselmann et al. 2000). This phreatic tube goes down to 79 m below the level of the lake. No exit has yet been found. Estimations of the discharge give 500 l/s at extreme drought and about 10-15 m^3/sec at peak flood. To the north of the Bätterich is the Bärenschacht (Funcken et al. 2001), which is another major cave of the region.

The largest cave system, called Réseau Siebenhengste-Hohgant (148 km in length and -1340 m in depth), is composed of the labyrinth of Siebenhengste, the F1 at Hohgant and the Faustloch. It is almost impossible to give a general description of the Réseau, since its genesis is multiphased and complicated. Generally, it can be considered as a typical alpine cave system that begins with many shafts and narrow meandering canyons before reaching fossil tubes (generally between -200 and -500 m below the entrance) that are again cut by many recent meanders and shafts. From the labyrinth, huge meandering canyons follow dextral strike-slip faults and go down to the "Zone Profonde", where they again meet phreatic tubes. The F1 is different in the sense that most of the cave is developed near or at the Drusberg marls. Therefore it has a dendritic pattern, and many of the galleries (at least in the upstream parts) are meandering canyons. A more detailed description of the Réseau is given in Hof, Rouiller & Jeannin (1984), of Faustloch in Funcken et al. (2000), a synthesis of the whole region in Bitterli (1988).

Other important caves are A2 (11 km, Gerber et al. 1994), with a morphology comparable to the Siebenhengste labyrinth, and K2 (15 km, Rouiller 1983), that can be compared with F1. The downstream labyrinth of K2 consists of a complicated 3D-maze of phreatic galleries. The Mäanderhöhle – no doubt – consists mostly of meanders (Rouiller 1984) and has a length of about 2.5 km, whereas the Haglätschhöhle (5 km, SGHB 1980) superposes the K2 and is characterised by large fossil phreatic tubes. Haglätsch is a very interesting site to investigate the upper old phases of cave genesis.

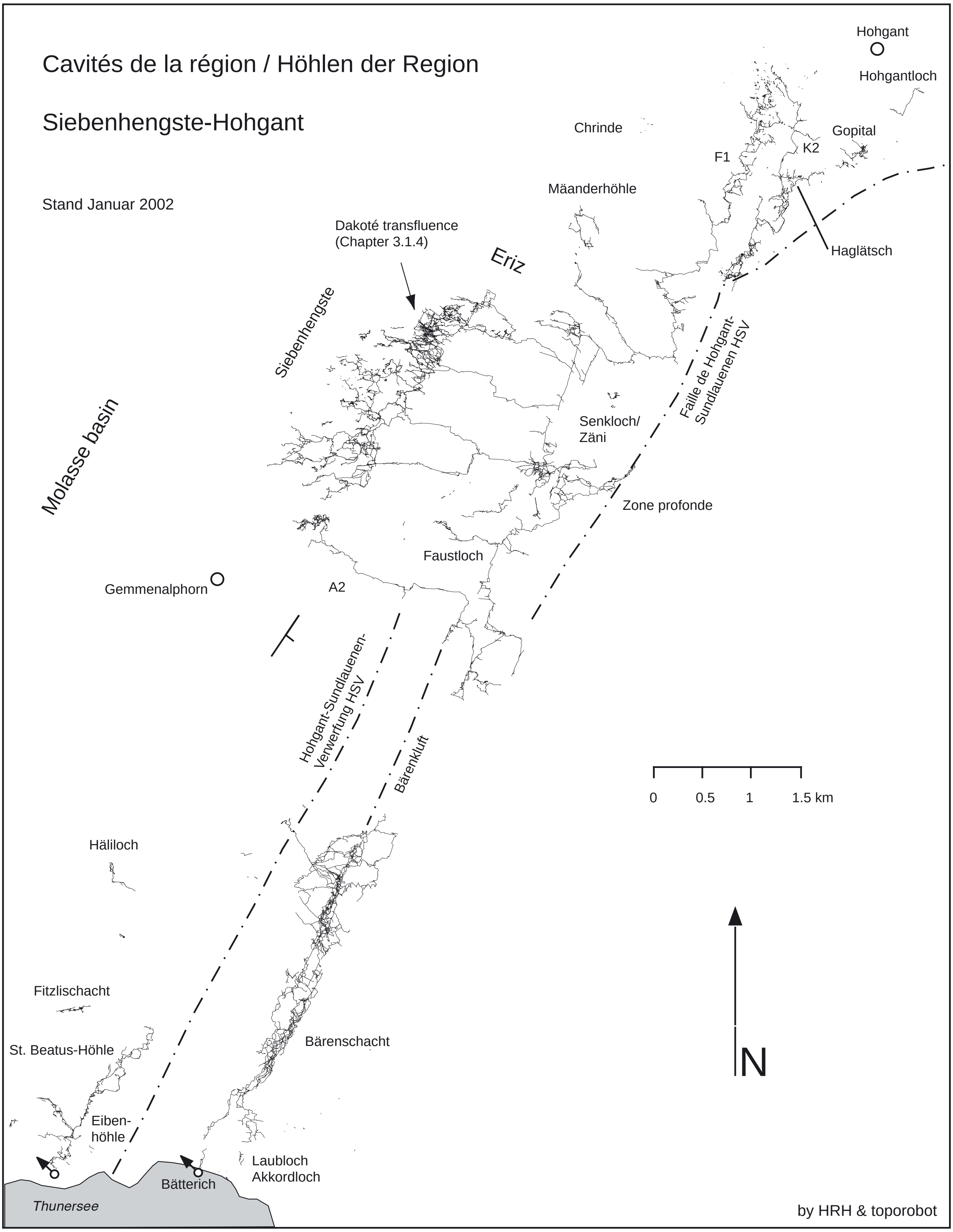


Fig. 1-7:
Overview of all the caves in the region Lake Thun-Siebenhengste-Hohgant.
Übersicht über alle Höhlen im Gebiet Thunersee-Siebenhengste-Hohgant.
Vue d'ensemble de toutes les cavités dans la région lac de Thoune-Siebenhengste-Hohgant.

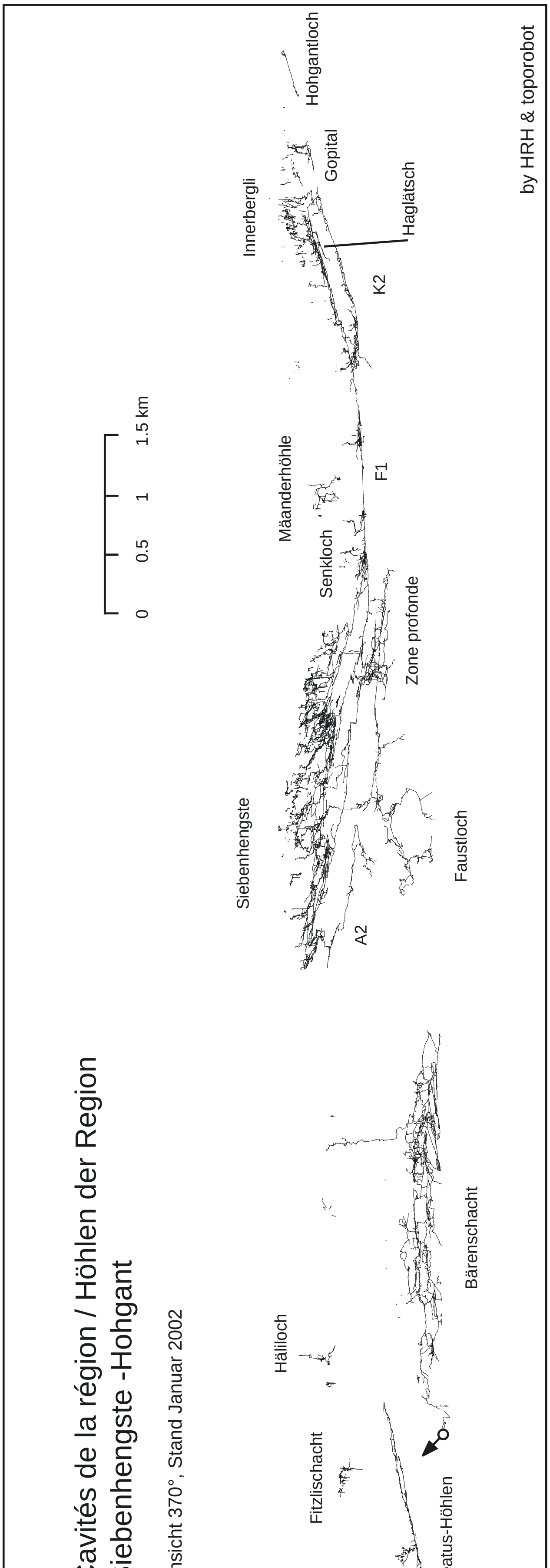


Fig. 1-8:
Projection of all the caves in the region. Projection along an axis with a view angle 370g.

Projektion aller Höhlen der Region. Projektion entlang einer Achse mit Blickrichtung 370g.

Coupe projetée de toutes les cavités de la région. Coupe projetée au long d'un axe avec un angle de vue de 370g.

History of speleological exploration

This paragraph is illustrated with Figs. 1-9 and 1-11, which give an idea of the evolution of speleologic knowledge.

The beginning of the well-documented speleological exploration in the Siebenhengste region was almost contemporaneous with the start of the Swiss Speleological Society SSS. 1945, the Häliloch was visited with a motor winch. This shaft, with an impressive diameter (10 to 50 m) and depth (100 m), was thought to connect with St. Beatus Cave. A dye trace was made in 1946 and proved this connection.

The St. Beatus Cave was also visited. Many new galleries were discovered, and important scientific observations were made by Franz Knuchel (see for example Knuchel 1963), pioneer and leader of the first Siebenhengste explorations. His interpretations are still true today. At the same time, other caves were visited, such as Waldheim cave, or Septemberschacht in the Innerbergli. Later, Fitzlischacht was discovered, almost at the same time as Bärenschacht. The latter, though, was not explored at depth.

1968, the SSS Interlaken and Berne went to the Siebenhengste and proceeded to prospect and map in detail a thin slab of karren field with great precision. However, they failed to discover an entrance to the Réseau, which at that time was just explored at some entrances by cavers from Neuchâtel, Lausanne, Belgium and Britain. After the entrances of the Réseau were found, its knowledge exploded, and the labyrinth of Siebenhengste was explored very rapidly in the beginning of the Seventies. This rapid growth caused dissensus between the caving groups that was only settled later.

The SSS Berne and Interlaken therefore moved out of the Siebenhengste properly, and proceeded to the exploration of the Bärenschacht, together with the SGH Basel and many individual cavers from all over Switzerland. They came to a stop at the sump at -565 m, that was considered impenetrable. The same group then continued to explore the Faustloch. This exploration was difficult due to the floods in the shaft part. In 1978, Haglätsch Cave was discovered and the systematic prospection of the Innerbergli that began in 1976 finally led to the discovery of F1 and K2, which "grew" one kilometer per expedition (duration often 30 hours…). Meanwhile, the Siebenhengste labyrinth was explored

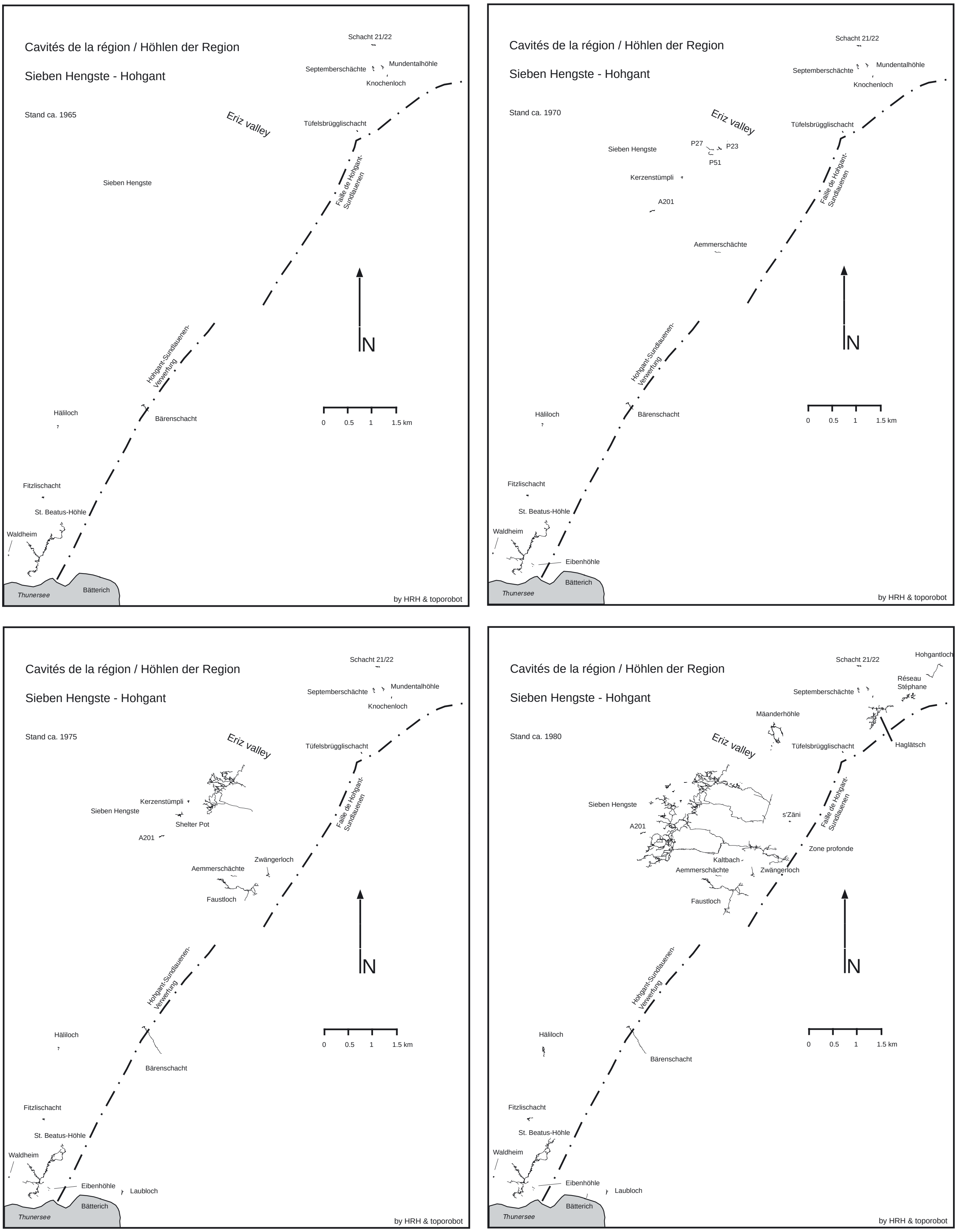


Fig. 1-9:
Development of speleological knowledge in the years between 1965 and 1980.
Entwicklung der speläologischen Kentnisse zwischen 1965 und 1980.
Développement des connaissances spéléologiques entre 1965 et 1980.

to its present form. The galleries that were discovered later mainly complicated the labyrinth more and more. In 1983, the junction between F1 and Siebenhengste could be mapped. In 1987, a huge devastating flood (Funcken & DeCannière, 1988) opened a sump and allowed connection between Faustloch and the Zone Profonde (Fig. 1-7).

The late 1980s was a lucky time. Not only was A2 explored behind a series of severe crawls, but the Bärenschacht sump was dived by the late Beat Brunold. This discovery started the saga of the Bärenschacht labyrinth that is far from being completed. Still today, some kilometers are discovered every year. Moreover, the differences between the groups were definitively eliminated and an association (HRH, described below) now groups all the cavers working in the Siebenhengste region.

The 1990s saw an important continuation of Faustloch and Bärenschacht, as well as the remapping of the complete St. Beatus Cave, which was the initial trigger for the present thesis.

The mapping and exploration of the caves is in full course, and many more galleries are waiting to be discovered.

“Höhlenforschergemeinschaft Region Hohgant”

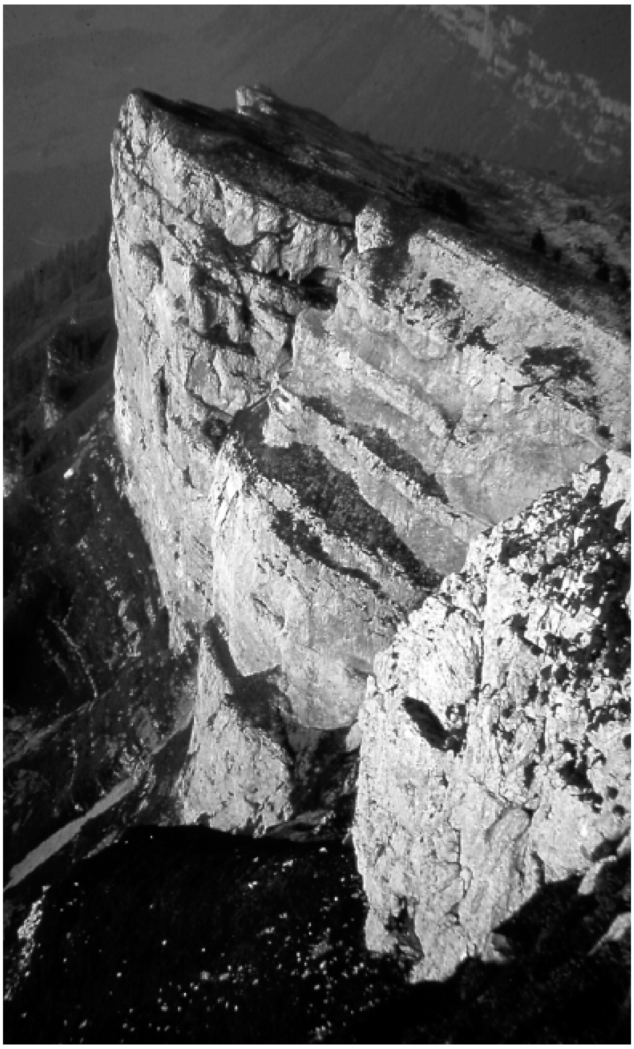
In 1973, the exploration of Bärenschacht was too complicated to be done by one single club. Therefore, the SSS sections of Interlaken, Bern and Basel joined in an organisation called “Aktion Bärenschacht”. The exploration was a success, and the quality of collaboration was proven. The same group, though less organised, then proceeded to Faustloch. This dangerous and difficult cave could then be explored, four years after its discovery. This success then led to the creation of the Höhlenforschergemeinschaft Region Hohgant HRH (Caver’s Association of the Hohgant Region, Fig. 1-10), which today coordinates and assists the work of more than ten international clubs working in the area. Through the HRH, interclub work is the rule.

Fig. 1-10:
Logo of the HRH.

Das Logo der HRH.

Le logo de la HRH.

Höhlenforschergemeinschaft
HRH
Region Hohgant



The Siebenhengste are terminated by cliffs in the NW.

Das NW-Ende der Siebenhengste wird durch eine Fluh gebildet.

Le front NW des Siebenhengste consiste en une falaise impressionnante.

Photo by Urs Widmer

Fig. 1-11:
Development of speleological knowledge in the years between 1985 and 2000.
Entwicklung der speläologischen Kentnisse zwischen 1985 und 2000.
Développement des connaissances spéléologiques entre 1985 et 2000.

Scientific exploration

The scientific exploration of the region started with punctual observations and interpretations made by the teacher Franz Knuchel. However, his findings were only partially published, mainly in proceedings of the National Congresses of Speleology, and much of his work was never printed. This thesis will take into account much of the unpublished work of Franz Knuchel.

The first inferences about the cave genesis in Siebenhengste were published by Hof, Rouiller & Jeannin (1984). This work was followed by mainly tectonical and neotectonical observations within the caves (Jeannin, 1989, 1990), and the sediment successions in parts of the Siebenhengste (Jeannin, 1991). These were the first "truly scientific" papers published. Caving in Switzerland is a hobby and hobby cavers, if they have the knowledge, certainly have neither the financial means nor the time to publish in peer-reviewed journals. Therefore, the importance of the Siebenhengste caves only came to a wider audience by the publications of Pierre-Yves Jeannin and Thomas Bitterli, most of which were published during the 1990s.

Genesis of the cave system

Soon after cave exploration allowed the connection of the Siebenhengste labyrinth, the first observations suggested a genesis in distinct phases (Hof, Rouiller & Jeannin, 1984). With ongoing cave exploration, the model could be refined. Jeannin, Bitterli & Häuselmann (2000) describe the speleogenetic phases in detail.

The phases are recognised by following the looping phreatic tubes and observing vadose-phreatic transitions. Since there are no indications that the springs were dammed by surface or tectonic processes, it was hypothesized that they are in direct relation with the valley bottom. Therefore, the succession of the phases indicates a series of consecutive valley deepenings. The numbers below give the height of the respective springs in today's altitude. Because of the alpine uplift, they don't necessarily reflect the true height of formation of the phases.

The uppermost phases of cave genesis are found mainly in Siebenhengste, and to a lesser extent in the Hohgant area. The altitude of the springs was at 1950,

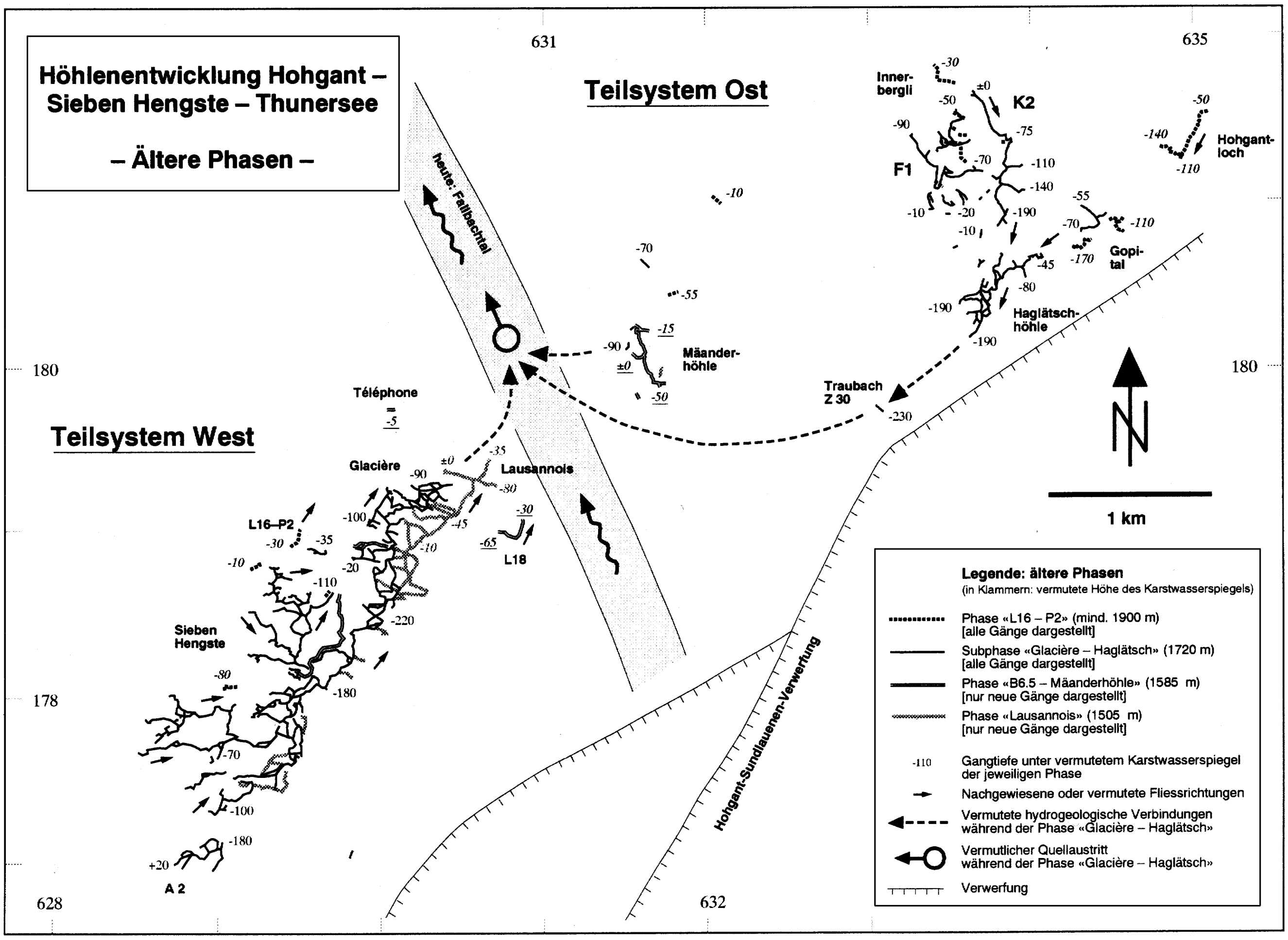


Fig. 1-12:
Genesis of the upper phases of the cave system (from Bitterli & Jeannin 1997).
Entstehung der oberen Phasen des Höhlensystems.
Genèse des phases supérieures du réseau spéléologique.

1720, 1585 and 1505 m a.s.l. respectively. The overall morphology indicates that the springs were located in Eriz valley (Fallbachtal in Fig. 1-12). We postulate that at this time, the Aare valley (Lake Thun) was not yet in existence and that maybe the Eriz was the riverbed of the Paleo-Aare.

The next series of phases had their springs in the Aare valley. So, an important geomorphic event has to be placed between the phases 1505 and 1440, turning the flow direction 180° and drying up the Eriz springs. The lower phases' springs were located at 1440, 890, 805, 760, 700, 660 and 558 m a.s.l. Of those, the lowermost six are investigated in further detail in the present thesis and are described in Chapter 5. The phase 1440 poses some problems if we assume its spring to be in the Bärenschacht region: this would mean a very deep karstification (≥500 m) and a conduit that had to cross thick masses of marls and Flysch. 3D investigations however allow a possible exit near Fitzlischacht. Figure 1-14 (from Bitterli & Jeannin 1997) reflects the knowledge at that time, all the other phases not represented in this figure are discussed in Chapter 5.

It was found that the phases reflect floodwater conditions, having inclinations of around 2 degrees. A detailed report on this floodwater problem is given in Chapter 4.

Chronology of the phases, age of the caves

Observations of glacial deposits in the "Grotte du téléphone" at 1600 m in the Siebenhengste permit the interpretation of an age superior than 400 ka for those deposits and galleries (Jeannin, 1991). However, since no work towards absolute dating had been undertaken, the age of the old phases of Siebenhengste remained unclear.

Since the Aare valley was subject to Quarternary glaciations, the base level lowering of the last phases is thought to have been caused by the glaciers. As part of the present study, a relative chronology of erosional and depositional events was established, and some cave deposits have been dated, indicating both a baselevel deepening by glaciers as well as ages above 350 ka already for phase 760. So we have to assume that the oldest galleries on top of the Siebenhengste are at least Lower Pleistocene, but a Pliocene or even Miocene genesis is also possible, since there is morphologic and sedimentologic evidence that the first galleries formed before the glaciations began.

The sedimentological findings, coupled with the morphology of the galleries, are described in detail in Chapter 6.

Fig. 1-13: The Siebenhengste seen from Haglätsch (see Fig. 1-14). The Eriz valley, where the ancient springs were, is to the right.

Die Siebenhengste von der Haglätsch aus (siehe Fig. 1-14), das Eriz mit seinen alten Quellen befindet sich rechts.

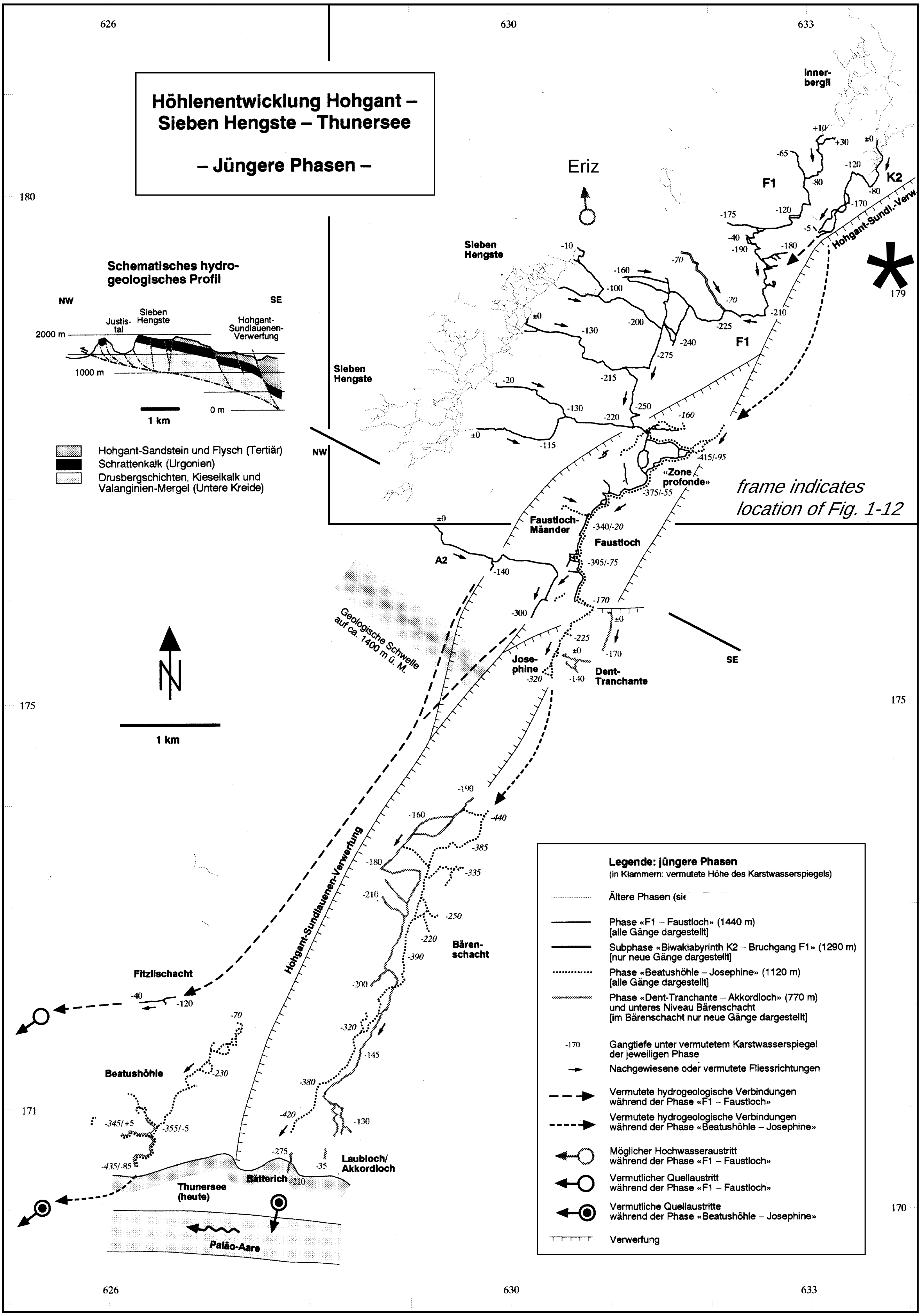
Les Siebenhengste vus depuis la Haglaetsch (voir Fig. 1-14). La vallée de l'Eriz avec ses anciennes sources se trouve à droite.
Photo T. Bitterli

Fig. 1-14 (right): Genesis of the lower phases. The star to the right indicates position of the Photographer of Fig. 1-13.

Entstehung der unteren Phasen. Der Stern links bezeichnet die Position des Photographen der Figur 1-13.

Genèse des phases inférieures. L'étoile à gauche est la position du photographe de la Fig. 1-13.

(from Bitterli & Jeannin, 1997)



frame indicates location of Fig. 1-12

1.3. The key caves for this study

Bärenschacht

History

The Bärenschacht was discovered in 1965 by two inhabitants of Beatenberg who were searching for a new water supply. Cavers then revealed a deep system that was explored in 1973 and 1974 by huge teams that reminded one of the conquest of a Himalayan summit in the 1950s. The exploration came to an end at -565 m at a sump that was considered to be impenetrable. Only in 1986 did the late Beat Brunold dive again and dig underwater, to free a very narrow flooded gallery that finally emerged again. A series of galleries and shafts then led to a huge 3D-labyrinth, going mainly north- and southward, whose exploration is not finished by far. In 1995, the sump was shunted by an artificial tunnel, making access possible also for non-divers. In order to preserve the climatic conditions of the cave and to control access, two doors were put into the tunnel.

Description

The Bärenschacht (Fig. 1-16) is described in detail by Funcken (1994) and Funcken, Moens & Gillet (2001). It is the second biggest cave in the area, being 59 km in length and 946 m in depth (January 2002).

The Bärenschacht has its name because of three bear skeletons that were found at the base of the first shaft.

Shafts and steeply dipping galleries are characteristic of the entrance part of this cave down to the labyrinth. Most of the shaft part is in a calcareous part of the Hohgant series. The following labyrinth consists of mainly phreatic, interconnected galleries of sometimes huge dimensions (Fig. 1-15). Some parts of the labyrinth are regularly flooded. The dry parts are richly decorated with dropstones and flowstones, gypsum crystals, and rare aragonite formations. Finding the way is very difficult.

Morphology and significance

The shaft zone is mainly of vadose origin. The galleries are quite large (average 3 m high and 1 m wide). Despite that, the shaft zone is merely a lateral gallery of minor inportance to the labyrinth, and given its position within the sandstone series, it may even be considered a speleogenetic accident.

Much of the surface above the Bärenschacht is composed of Globigerina marls and Flysch. Therefore, almost no input from the surface is observed within the labyrinth, which is almost entirely created by waters coming down from the Siebenhengste and Schrattenfluh. So, the Bärenschacht allows an unprecedented insight into the genesis and behaviour of an undisturbed deep karst. Bärenschacht is the link between the springs Bätterich and Gelberbrunnen and the upstream parts of the cave system (see Fig. 1-7).

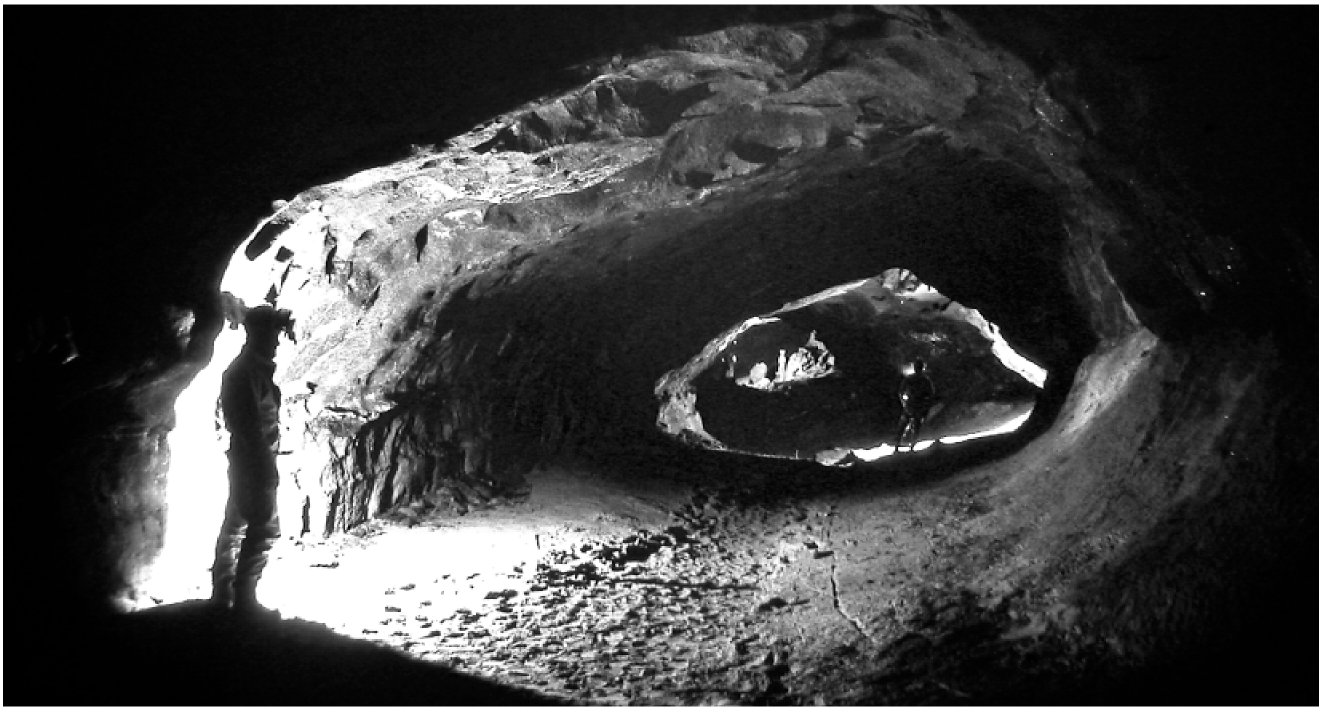


Fig. 1-15 : Typical phreatic tube of Bärenschacht.
Typische phreatische Röhre im Bärenschacht.
Tube phréatique typique du Bärenschacht.
Photo by Daniel Burkhalter

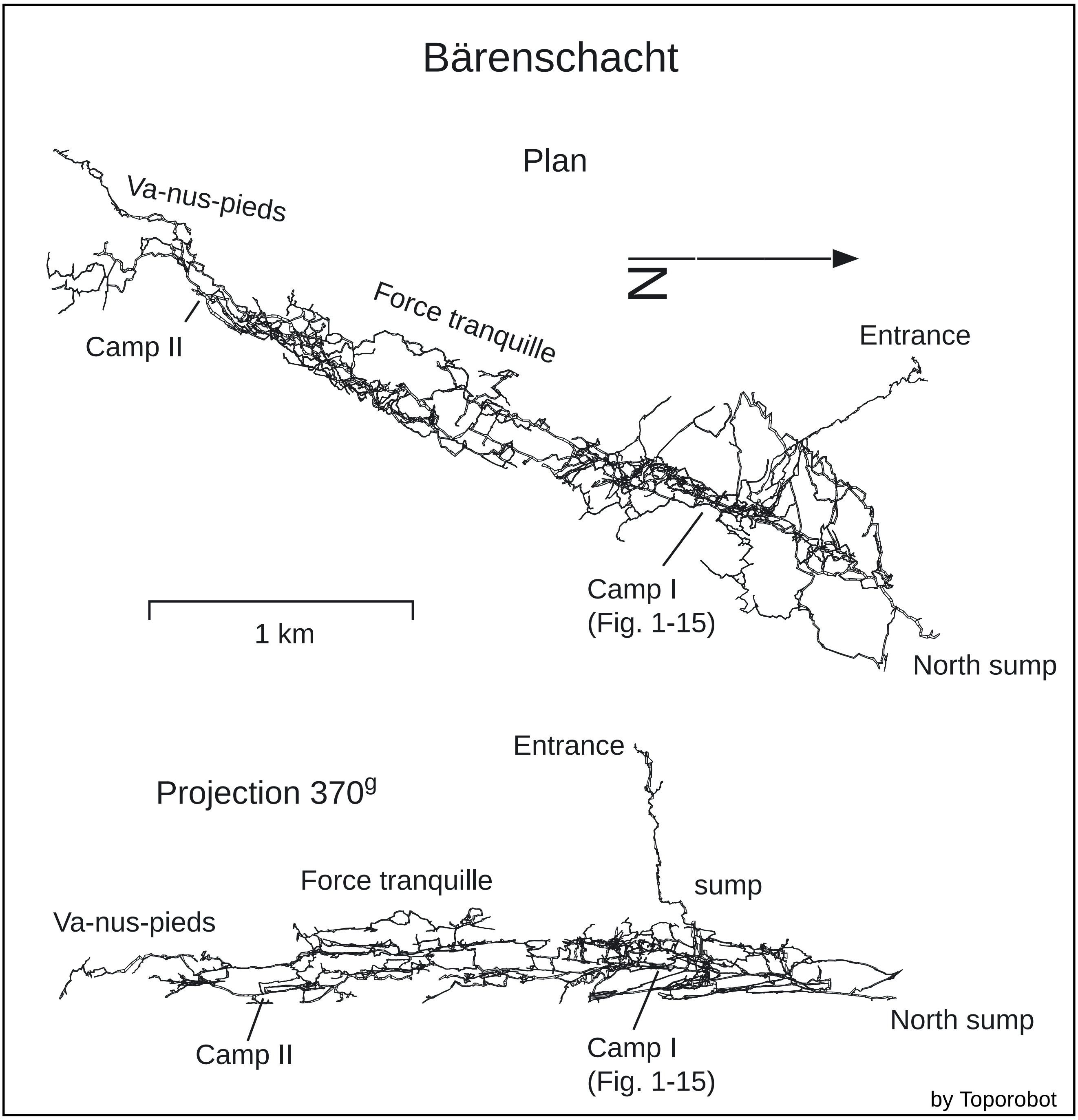


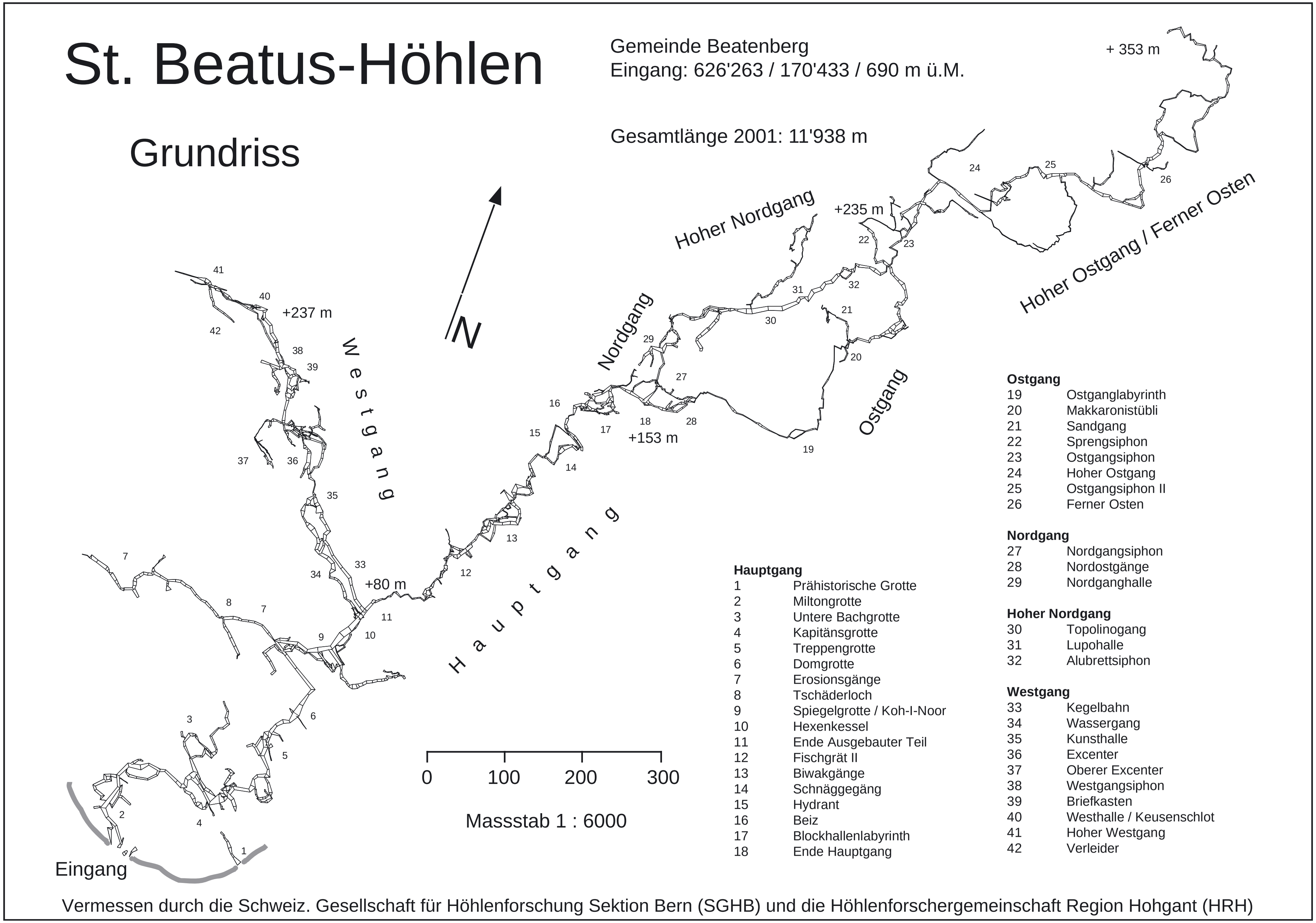
Fig. 1-16: Plan and projected section of Bärenschacht. Coordinates omitted for safety reasons.
Plan und Projektion des Bärenschachtes. Koordinaten aus Sicherheitsgründen weggelassen.
Plan et projection du Bärenschacht. Coordonnées omises à cause de la sécurité.

St. Beatus Cave

History

The entrance of St. Beatus Cave has been known since prehistoric times. According to legend, St. Beatus lived at the entrance. In the middle ages, it became a venerated place until the reformation.

The first explorations were made in the 19th century, but no one got very far. In 1903-1904, the first kilometer was arranged for tourists. At the same time, the cave was explored further. The first modern exploration started with the end of the 2nd World War with Franz Knuchel as leader. Since then, the St. Beatus Cave has been visited regularly by cavers. Because the modern maps were partially lost, and the quality of the old ones not satisfactory any more, the whole cave was remapped between 1993 and 1996. The result was the discovery of one kilometer of new galleries



St. Beatus-Höhlen

Grundriss

Gemeinde Beatenberg
Eingang: 626'263 / 170'433 / 690 m ü.M.

Gesamtlänge 2001: 11'938 m

Hauptgang	
1	Prähistorische Grotte
2	Miltongrotte
3	Untere Bachgrotte
4	Kapitänsgrotte
5	Treppengrotte
6	Domgrotte
7	Erosionsgänge
8	Tschäderloch
9	Spiegelgrotte / Koh-I-Noor
10	Hexenkessel
11	Ende Ausgebauter Teil
12	Fischgrät II
13	Biwakgänge
14	Schnäggegäng
15	Hydrant
16	Beiz
17	Blockhallenlabyrinth
18	Ende Hauptgang

Ostgang	
19	Ostganglabyrinth
20	Makkaronistübli
21	Sandgang
22	Sprengsiphon
23	Ostgangsiphon
24	Hoher Ostgang
25	Ostgangsiphon II
26	Ferner Osten

Nordgang	
27	Nordgangsiphon
28	Nordostgänge
29	Nordganghalle

Hoher Nordgang	
30	Topolinogang
31	Lupohalle
32	Alubrettsiphon

Westgang	
33	Kegelbahn
34	Wassergang
35	Kunsthalle
36	Excenter
37	Oberer Excenter
38	Westgangsiphon
39	Briefkasten
40	Westhalle / Keusenschlot
41	Hoher Westgang
42	Verleider

Vermessen durch die Schweiz. Gesellschaft für Höhlenforschung Sektion Bern (SGHB) und die Höhlenforschergemeinschaft Region Hohgant (HRH)

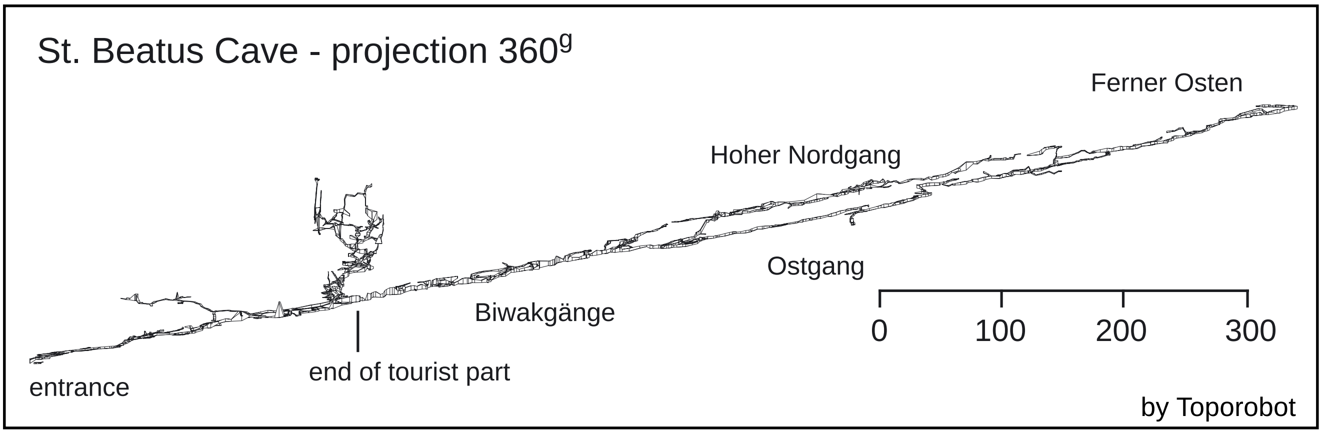


Fig. 1-18 (above):
Projection of St. Beatus Cave.

Projektion der St. Beatus-Höhlen.
Projection de la grotte de St. Béat.

as well as a complete high-quality map. Furthermore, the presence of interesting sediments and morphologies led to the present thesis.

Description
The St. Beatus Cave has a length of 11'938 m and a difference in elevation of +353 m (Häuselmann 2001). It represents the spring of a catchment area located to the west of the Siebenhengste that is perched above today's baselevel. The tourist part of St. Beatus Cave consists mainly of phreatic tubes with only minor vadose incision. They often divide into lateral tubes that go off the main passage. After the tourist part, the morphology changes: the galleries consist of inclined large keyhole passages that form a dendritic pattern. Shafts and chimneys are rare and mainly concentrated in the Westgang. Most of the galleries are on top of the Drusberg marls; however, some of them are within the limestone beds of this formation. Like Bärenschacht, St. Beatus Cave also continues to the north, but all galleries are obstructed by rockfall or sedimentary infill.

Significance
Despite its constant dip along the axis of a small syncline, there is evidence for a genesis in distinct phases. Especially the phase 760 (see Chapter 5) has its "type-locality" at the end of the tourist part of St. Beatus Cave, where the high meander of the upstream galleries turns into a phreatic tube. Furthermore, the phases 805 and 890 had been defined in St. Beatus Cave.

Fig. 1-17 (left):
Plan of St. Beatus Cave.

Plan der St. Beatus-Höhlen.

Plan de la grotte de St. Béat.

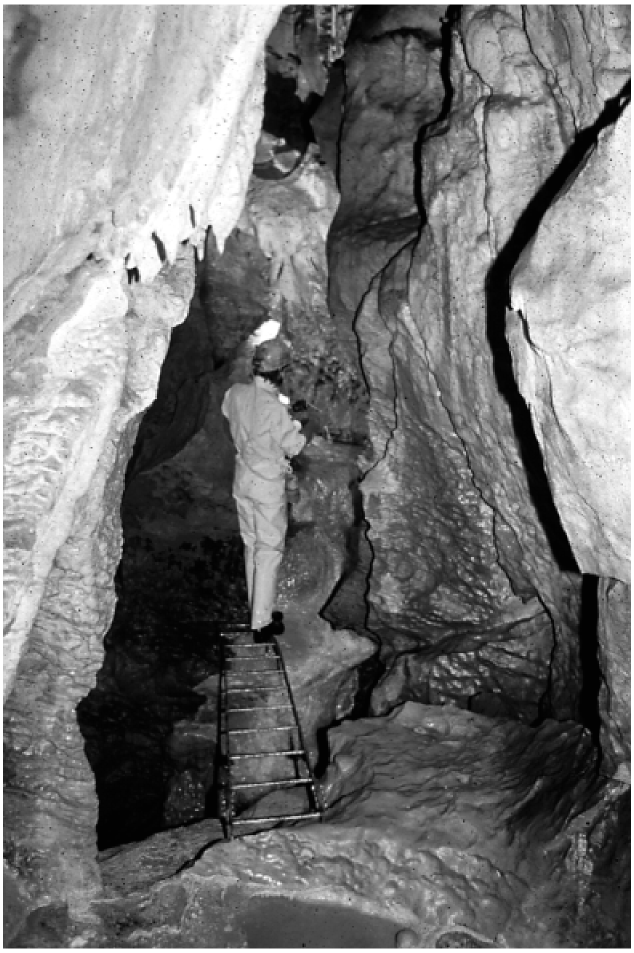


Fig. 1-19:
The main gallery of St. Beatus Cave is a meander.

Der Hauptgang der St. Beatus-Höhlen ist ein Mäander.

La galerie principale de la grotte de St. Béat est un méandre.

Photo by Daniel Burkhalter

Faustloch

History

The Faustloch was discovered in 1970 by Hugo Maler because of the airdraught in the entrance hole. It was then dug free, but the exploration of the shafts behind was difficult due to the brittle sandstone and the danger of flooding. So, it took many years and a huge effort to equip the shafts correctly. Then, from 1974 to 1978, the main passages of Faustloch were discovered. After that period, only marginal mapping work was conducted. The big flood of 1987 also flooded parts of the Ostergang and opened the connection to the Zone Profonde of the Réseau Siebenhengste-Hohgant. Then, the Belgierfrust at the southern end of the Faustloch was dug open in 1991. This success allowed to continue to the south and to reach the karst water table. Another dig in 1993 then opened the Meunina and its lateral galleries. In 1997, a flood closed the Belgierfrust again, closing 2 km of rope and two campsites. Several attempts to reopen failed due to bad weather, and in one of the attempts, Maja Köppel and Thomas Bitterli died in a flood in the shaft zone (Fig. 1-20).

Description

A recent description of Faustloch (Fig. 1-21) is made by Funcken, Moens & Häuselmann (2000). Its current length is 14 km, its depth -960 m. The entrance part of Faustloch lies in Hohgant sandstone. The 80m-shaft then joins the limestone, and the Drusberg marls are found in the following meander. The meander goes down to the Promenadengang-Ostergang, which represents the big fossil tube coming from F1-Zone profonde (see Fig. 1-7) and continues towards Pfingstgang-Bärenschacht. The mainly vadose Blumenkohlgang (Fig. 1-21) traverses the Drusberg marls and loses itself in the Kieselkalk. All the galleries south of the Belgierfrust, with the exception of the meandering Petit Pied-Guggishürliabstieg, are of mainly phreatic morphology. The Jojogang, of phreatic origin, seems to be a separate cave. The humidity there is very low and leads to the formation of Mirabilite (Na_2SO_4), and traces of paleokarst are supposed. Many parts of Faustloch are nicely decorated by dripstones and gypsum crystals.

Significance

The southern galleries of Faustloch are covered by Flysch and therefore have no input of water from the surface. The three main streams observed (entrance meander, Petit Pied, Jojogang) seem to have no connection to each other. The Faustloch is thought to be the link between the speleogenetic phases discovered in Bärenschacht/St. Beatus Cave and the upper parts of Siebenhengste. However, since the Belgierfrust is still closed, detailed observations could not be made until today. Thus, the speleogenetic connection is only hypothesized (Chapter 5).

Fig. 1-20:
The shaft zone of the Faustloch is famous for its hazardous floods.

Die Schachtzone des Faustlochs ist berüchtigt für ihre Hochwässer.

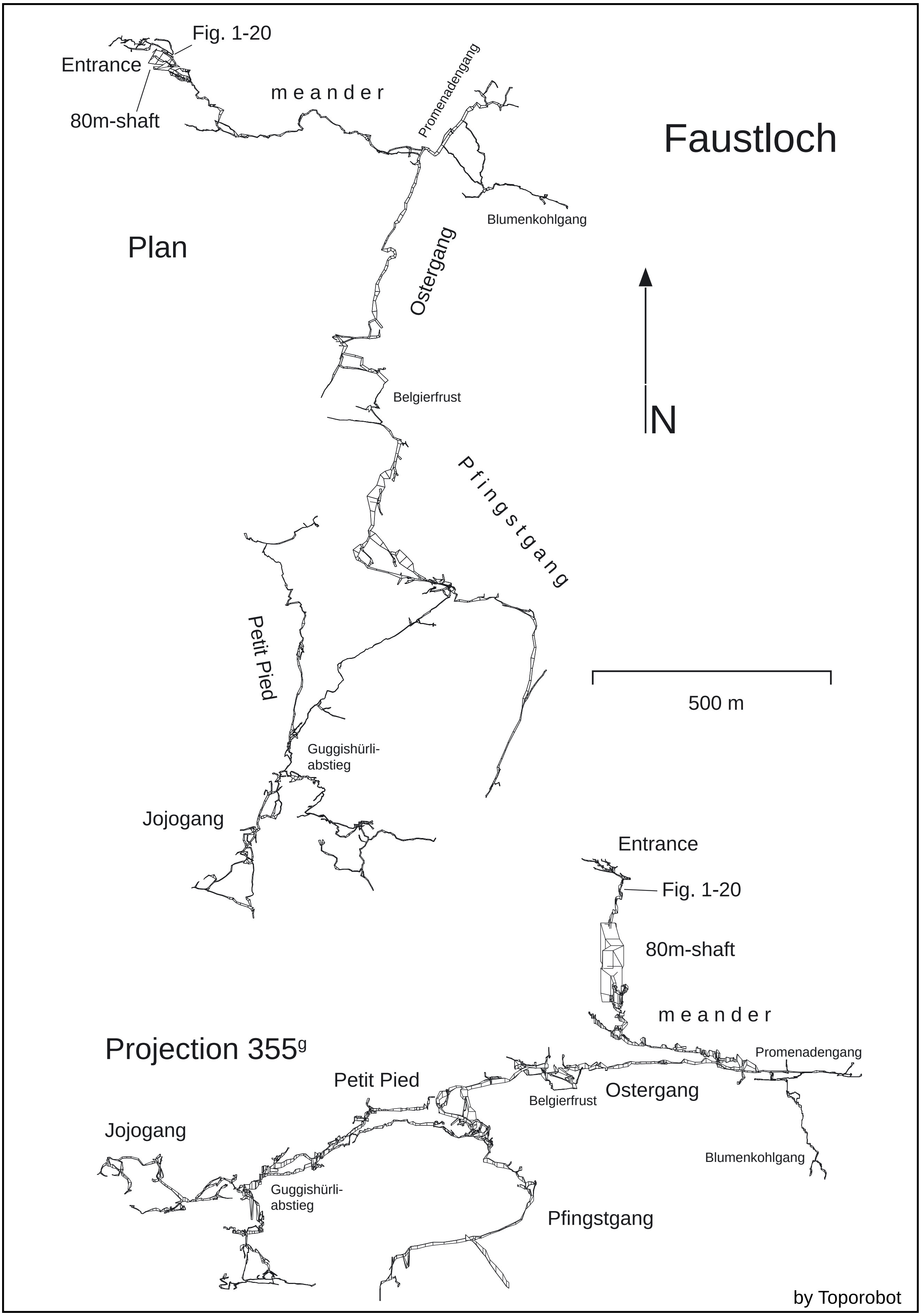
La zone des puits du Faustloch est connue pour ses crues dangereuses.

Photo by Diego Sanz

Fig. 1-21 (right):
Plan and projection of the Faustloch. Coordinates omitted for safety reasons.

Plan und Projektion des Faustlochs. Koordinaten aus Sicherheitsgründen weggelassen.

Plan et projection du Faustloch. Coordonnées omises à cause de la sécurité.


Faustloch
Plan
Fig. 1-20
Entrance
80m-shaft
m e a n d e r
Promenadengang
Blumenkohlgang
Ostergang
N
Belgierfrust
P f i n g s t g a n g
500 m
Petit Pied
Guggishürli-
abstieg
Jojogang
Entrance
Fig. 1-20
80m-shaft
m e a n d e r
Projection 355^g
Promenadengang
Petit Pied
Belgierfrust
Ostergang
Jojogang
Blumenkohlgang
Guggishürli-
abstieg
Pfingstgang
by Toporobot

1.4. Methods

Methods in caving

In the investigated area, by far not all caves are known. A systematic surface **search** has to be carried out. The resulting inventory is then published.

The Waldegg region has already been searched completely by the author, and a publication has been made (Häuselmann et al. 2000). The other zones are still under investigation.

Most of the studied caves require a complete domination of the vertical caving techniques.

Then, in order to allow observations within caves (and, depending on the system, just for orientation!), a **map** has to be made. Cave maps differ from surface maps in that they have to represent true 3D-objects instead of an undulating surface. Therefore, a cave map is more complicated to draw, especially since modern tools such as aerial photographs cannot be applied. A plan and a longitudinal section, together with profiles across the gallery, are compulsory.

The survey is done with decameter, compass and clinometer following the "Toporobot method” (Heller 1983). In addition, a sketch is made inside the cave, reporting characteristics of the conduit in plan and section. The numerical data is processed with the help of the computer program “Toporobot”, and a plan is then drawn to scale. A small excerpt of the plan of St. Beatus Cave (original scale 1:500) is shown in Fig. 1-22 and 1-23. The symbols presented within the drawing are standardised and can be found on the Web at http://www.karto.ethz.ch/neumann-cgi/cave_symbol.pl.

A written description complements the drawings. In this description, observations that cannot be drawn (such as the presence of bats, ideas about the genesis, danger of floods, rigging tips, etc.) are noted.

This work was done for St. Beatus Cave by the author (a publication is planned for 2003), and it is still in progress in Bärenschacht by Luc Funcken and Rolf Kummer.

Mapping is prerequisite before any geological and morphological observations in caves can be undertaken. This is often forgotten by the surface geologist. In this way, cavers are an invaluable help to scientists, and their work is worthy of more appreciation by the scientific community.

Throughout this thesis, projections of cave maps are presented. They represent a horizontal projection of the cave system along a defined axis (usually indicated in grades (400^g) and can directly be compared with a plan, which is a vertical projection of a cave along the z axis.

Methods applied within the cave

All methods applied within the caves were done by the author himself. The only literature that was accessible were conference proceedings and unpublished reports from Franz Knuchel concerning observations in the entrance parts of St. Beatus Cave.

Morphological observations in the galleries are used to determine if the respective gallery was formed above or below the watertable: a rounded, softly shaped elliptic gallery indicates formation below, a meandering canyon indicates formation above the water table. Both forms may be superposed. The tops of a looping phreatic tube indicate the minimum height of the watertable that was present at the time of the tube formation (Fig. 1-24).

The transition of a meandering canyon into a phreatic tube indicates the true elevation of the corresponding watertable. Thus, the interpretation of the morphology leads to the recognition of the different speleogenetic phases described in Chapter 5. In contrast to the laws of stratigraphy, the youngest cave phases are usually found in depth and the oldest are on top.

With the help of the plan, the location and characteristics of the **sediments** found are reported. The larger sediment profiles are drawn in the scale 1:50. An interpretation of the deposition chronology (classical stratigraphy: oldest strata at the bottom) is made. It is complicated by the several erosional cycles that sometimes leave some old sediments at the walls of the gallery, before younger sediments fill it from below again. A lateral correlation of the sediments and erosional cycles is attempted in Chapter 6.

Analytical methods

All analyses had been conducted and interpreted by the author himself, with the exception of the pollen analyses that had been contracted to K. Bieri-Steck.

Sediment analyses comprise **petrography** of the gravels. This method allows the determination of the percentage of material other than Helvetic rocks.

The **granulometry** (dry sieving and weighting) of the sediments permits an insight into flow velocity (Hjulström, 1939) and sedimentation mode. When laboratory data is absent, or when there is a bimodal sortation, the average size is taken into account.

The **calcimetry** (coulometric procedure) gives the carbonate content of the fine fractions (expressed in % $CaCO_3$). This has possible climatic implications: since a cave is enlarged by chemical corrosion of limestone, no fine-fractioned carbonate is supposed to endure. If there is such sediment found, this indicates that either the water is not corrosive enough, or that there is too

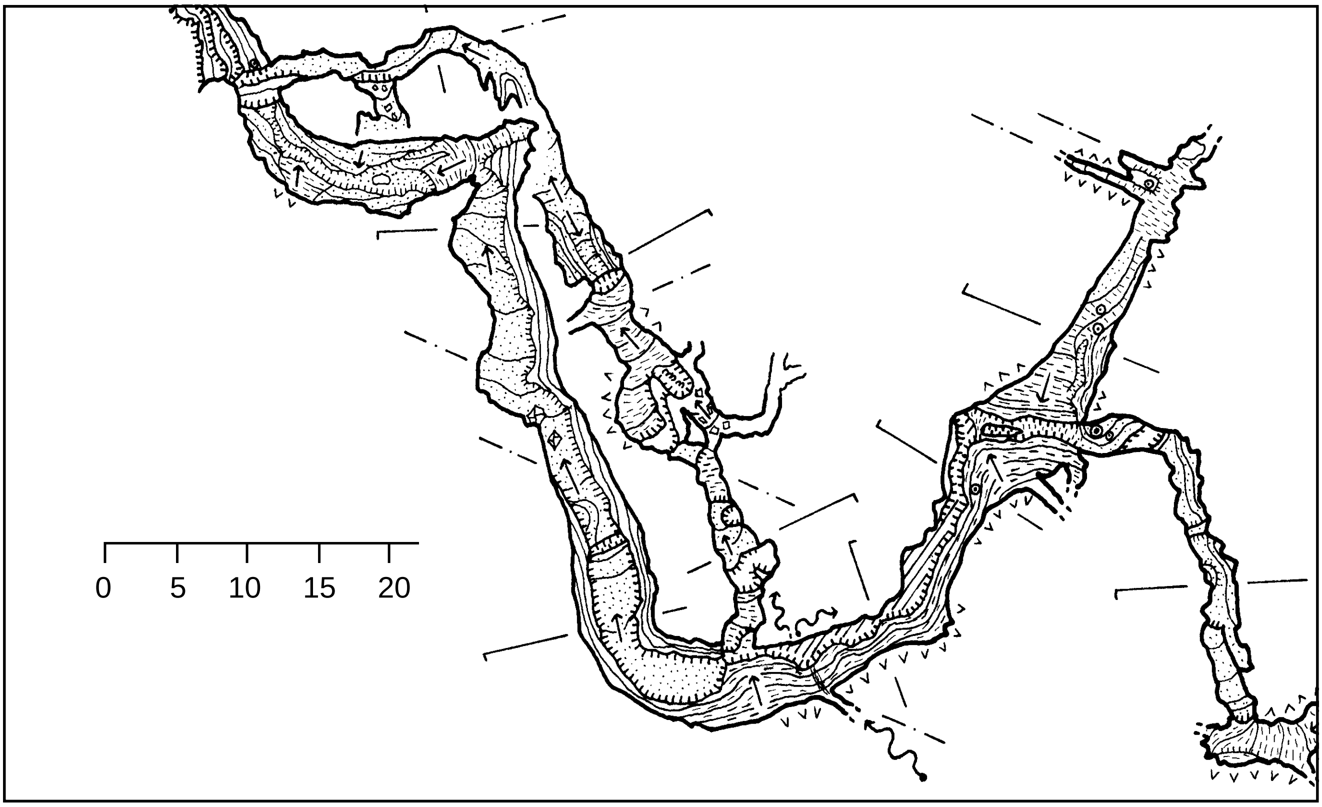


Fig. 1-22 (above): Excerpt of the detailed plan of St Beatus Cave (original by Ph. Häuselmann).
Ausschnitt des Detailplanes der St. Beatus-Höhlen.
Extrait du plan détaillé de la grotte de St. Béat.

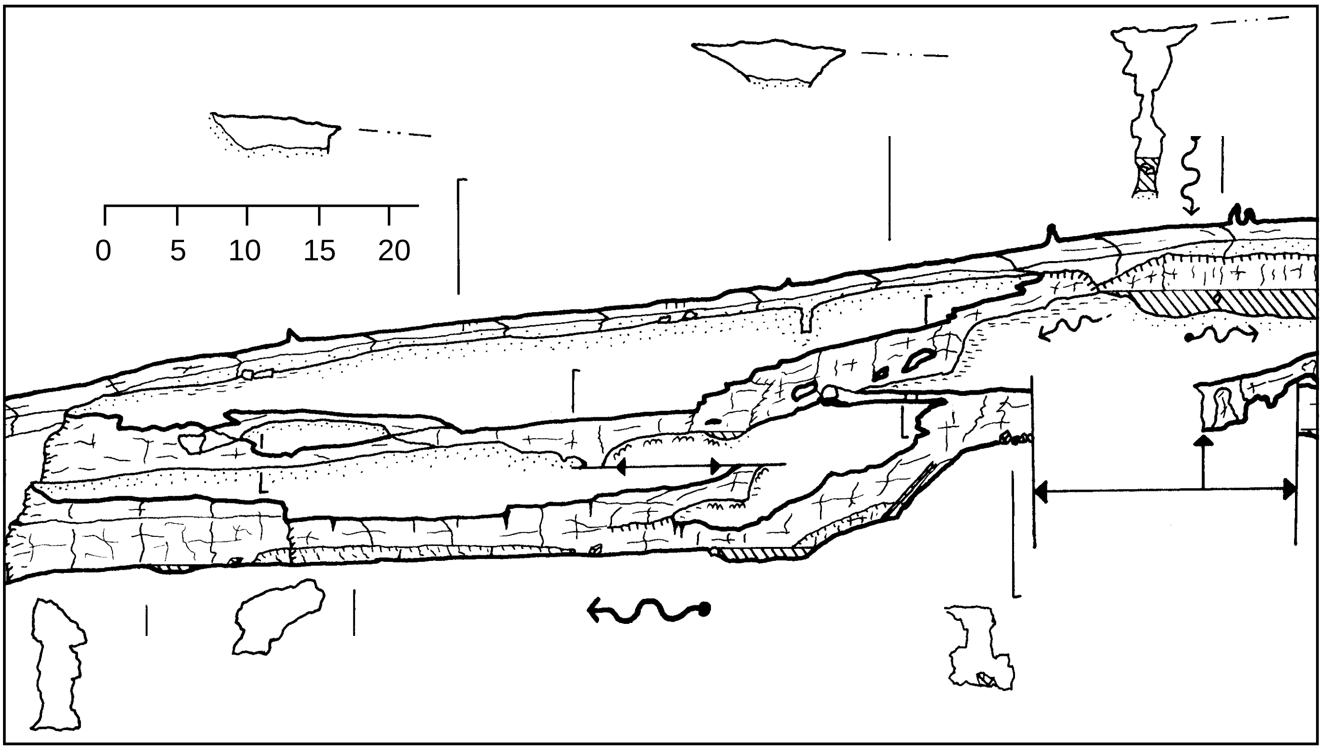


Fig. 1-23: Excerpt of the detailed longitudinal section of St. Beatus Cave (original by Ph. Häuselmann).
Ausschnitt des Detail-Längsschnittes der St. Beatus-Höhlen.
Extrait de la coupe développée détaillé de la grotte de St. Béat.

much carbonate flour. Both possibilities indicate a periglacial climate.

The **clay mineralogy** is done by separation of the fraction <2 μ in Atterberg cylinders, and xray of dried, glycoled and burnt (550°C) samples. It also may give some possible climatic information. Particularly, the content of smectites is thought to correlate with the presence of soils (Pochon, 1974).

The **U/Th datings** have been done in Bergen University (Norway) with the procedure of Lauritzen (1996). Dissolution of the sample, separation of U and Th by adsorption to resins, electroplating and counting by an alpha spectrometer was followed by an age calculation (decay age) using the programme 4U2U of S.E. Lauritzen. Careful inspection of the sample (recristallisation, hiatuses, dirt layers) was implicit.

The **pollen analysis** needed a dissolution of the calcitic and siliceous components of the investigated sample in HCl and HF and subsequent acetolysis and coloration of the pollen.

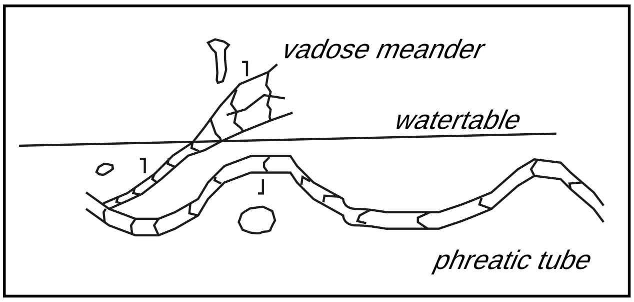


Fig. 1-24: An undulating phreatic tube is co-fed by a vadose meander, whose shape turns into a tube below the floodwater table.

Eine undulierende phreatische Röhre wird u.a. von einem vadosen Mäander gespiesen, dessen Form an der Hochwasserfläche in eine Röhre wechselt.

Une tube en montagnes russes est alimenté par un méandre vadose qui change de morphologie au top de la zone épiphréatique.

The St. Beatus Cave has a long history of research...

Die St. Beatus-Höhle hat eine lange Forschungsgeschichte...

La grotte de St. Béat a une longue histoire de recherche...

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The evolution of the landscape between the last glaciation and the Tertiary is obscured by clouds. Caves are one tool to unravel the fascinating history of the Alps.
Eiger, Mönch and Jungfrau seen from Burgloch.

Die Evolution der Landschaft zwischen der letzten Vergletscherung und dem Tertiär liegt im Nebel verborgen. Höhlen sind ein Werkzeug, um diese faszinierende Geschichte der Alpen zu entdecken.
Eiger, Mönch und Jungfrau vom Burgloch aus gesehen.

L'évolution du paysage entre la dernière glaciation et le tertiaire est inconnue. Les grottes sont un outil précieux pour découvrir un aspect fascinant de l'histoire des Alpes.
Eiger, Mönch et Jungfrau, vues depuis la sortie du Burgloch.

Photo by Peter Pfister

2. Tectonic and stratigraphic interpretation of the Waldegg structure by observations in caves

Zusammenfassung: Eine neue Interpretation der Waldeggstruktur durch Beobachtungen in Höhlen

Einführung

Eine strukturgeologische Analyse ist nötig, um sicherzustellen, dass der Karstwasserspiegel tatsächlich von der Quelle abhängt und nicht von dämmenden Falten oder Brüchen. Dieses Kapitel behandelt deshalb die Stratigraphie und Tektonik der Region zwischen Thunersee und den Siebenhengsten. Die Waldegg ist im Raum Thunersee berühmt für ihre Stratigraphie. Dahingegen war bislang eine Analyse der Bruchtektonik sehr schwierig, unter anderem wegen der dichten Vegetation. Einzig die Hohgant-Sundlauenen-Verwerfung HSV wurde als eozän synsedimentär beschrieben, ihr Versatz wurde auf 500-600 m geschätzt. Eine altersmässige Einstufung der Waldegg-Brüche sowie ihr Einfluss auf die Sedimentation gelang bisher nicht, da unter anderem die Gesteine der oberen Waldegg unter Globigerinenmergeln und Flysch verborgen liegen. Beobachtungen in Höhlen tragen dazu bei, diese Lücke zu füllen. Der Bärenschacht durchquert die HSV, führt auf 1.5 km Länge in der Hohgantserie weiter und gelangt durch die Bärenkluft wieder in den Kalk, wo sich die Höhle labyrinthisch entwickelt.

Die Stratigraphie und die Lage der Höhlengänge

Die Stratigraphie des Schrattenkalkes im Bärenschacht wird beschrieben. Die Mächtigkeit beträgt 320-340 m wegen der synsedimentären Aktivität der HSV. Die phreatischen Gänge bevorzugen nur einzelne Schichtfugen des Paketes. Aus diesem Grund ist die Prospektion nach neuen Höhlen am aussichtsreichsten, wenn sie entlang dieser Schichtfugen und falls möglich an der Intersektion von Schichtfugen und speläogenetischen Phasen stattfindet.

Beobachtungen von Brüchen und Stratigraphie

Die **HSV** ist der einzige Bruch, der an der Oberfläche gut sichtbar ist und von Sundlauenen via Hohgant (Versatz 200 m) gegen die Schrattenfluh zieht. Sie ist teilweise von Flysch bedeckt. Eine synsedimentäre Aktivität ist während des Eozäns bewiesen und während der Kreide vermutet. Beobachtungen im Bärenschacht, der die HSV quert, zeigen einen Versatz von rund 1025 m im Eingangsbereich des Bärenschachtes an und beweisen eine kretazische synsedimentäre Aktivität: der Schrattenkalk ist NW des Bruches 180 m mächtig, im SE davon aber minimal 340 m. Auch im Eozän war der Bruch synsedimentär, eine Ablagerungsmächtigkeit von sicherlich 640 m nimmt gegen SE stark auf geschätzte 215 m ab: der Mechanismus einer Schüttung in ein sich vertiefendes Becken ist angezeigt. Im NW zeigt das Eozän eine Mächtigkeit von max. 180 m.

Die geologische Stellung der **Bärenkluft** war lange Zeit nicht klar. Die Bärenkluft ist von SW her bis zum obersten Viertel des Bärenschachtes als inverser Bruch (Versatz um die 60 m) ausgebildet und wird im N des Bärenschachtes zum Normalbruch (Versatz 75 m). Dort begleitet eine meterdicke Lage aus Gaultsandstein den Bruch. Im Schrattenkalk SE davon sieht man eine Paläokarströhre, die ebenfalls mit Gault gefüllt ist. Die Mächtigkeit des Schrattenkalkes liegt bei ca. 330 m. Bei der Intersektion der Schachtzone mit der Bärenkluft findet man Brekzien von Schrattenkalk in Gault sowie brekziierten Seewerkalk. Somit kann eine Geschichte des Bruches rekonstruiert werden. Die wichtigste Erkenntnis ist, dass die Bärenkluft zeitgleich mit der HSV als Normalbruch angelegt wurde.

Die **Rampe** kann in gewissen Teilen des Bärenschachtes mit der Bärenkluft verwechselt werden. Es ist ein inverser Bruch mit einer Neigung von 40-60°, der ungefähr parallel zur Bärenkluft verläuft, einen Versatz von 50-100 m aufweist und im Norden sich mit der Bärenkluft vereinigt, wobei der Versatz vernachlässigbar wird. Die Schrattenkalkmächtigkeit SE der Rampe liegt ebenfalls bei 330 m.

Der **Barfüsser** (BF) genannte Bruch ist im Gegensatz zu Bärenkluft und Rampe an der Oberfläche sichtbar. Der im Bärenschacht beobachtete Versatz liegt bei 140 m; der Barfüsser ist ein Normalbruch mit einem WSW-Fallen. Die zeitliche Einstufung gibt etwas Probleme: Ist er zeitgleich mit HSV und Bärenkluft (und damit ein weiterer Zeuge der Horst-Graben-Struktur), oder entstand er erst während der Platznahme der helvetischen Decken?

Die **Längsbrüche an der Oberfläche** wurden von Colombi (1960) kartiert. Der «Doppelbruch» (Dop) wird als inverser Bruch von untergeordneter Bedeu-

tung interpretiert, dessen scheinbare kartographische Wichtigkeit auf spätere Querbrüche zurückzuführen ist. Der „SP"-Bruch zeigt einen Versatz von ca. 50 m, er bildet für einige 100 m die Ostgrenze des Seewerkalk- und Discusschicht-Auftretens und wird deshalb als synsedimentärer Bruch (zeitgleich mit der HSV und der Bärenkluft) interpretiert. Die Waldegg wird deshalb als Horst-Graben-Struktur gedeutet. Der „Kienbruch" weist einen Versatz von mindestens 20 m bei einem Fallen gegen NE auf. Weitere Beobachtungen sind wegen der Grösse des Aufschlusses (30*20 m) nicht möglich.

Die **Querbrüche an der Oberfläche** bestehen aus listrischen Abschiebungen mit einem Fallen gegen Süden. Geometrie und Versatz besagen, dass es sich um die jüngste Bruchgeneration handelt, die sich während der Platznahme der helvetischen Decken bildete. Die Frage, ob sie eiszeitliche Entlastungsbrüche darstellen, kann verneint werden.

Zusammengefasst wurden drei Bruchfamilien erkannt. Die erste Generation, SSW-NNE streichend, besteht aus kretazisch bis eozän synsedimentären Normalbrüchen und steht in Zusammenhang mit der Extension und Vertiefung der Thetys. Teilweise wurden sie während der Alpenbildung reaktiviert. Die zweite Generation mit demselben Streichen besteht aus inversen Brüchen und korreliert mit der Bildung und dem Transport der helvetischen Decken. Die jüngste Generation, normal mit einem E-W-Streichen, wird als Produkt der Platznahme der Decken gedeutet.

Chronologie der Ablagerungsgeschichte und Bruchaktivitäten zwischen Kreide und Eozän

Die oben gemachten Beobachtungen erlauben, eine schematische Chronologie der Ereignisse zu skizzieren, die in Figs. 2-9 und 2-10 dargestellt ist. In der Folge wird die Chronologe nur summarisch beschrieben.

- Nach der Ablagerung des Schrattenkalkes (synsedimentäre Aktivität der HSV) folgt eine Verkarstung desselben. Diese Hohlformen werden sodann mit Gaultsandstein gefüllt.
- Während der Gault-, Seewerkalk- und Discusschicht-Ablagerung ist die Bärenkluft (und später auch der SP-Bruch) synsedimentär aktiv; die Gesteine NW der HSV liegen oberhalb des Meeresspiegels.
- Die Eozäntransgression setzt ein und überflutet nach und nach die NW der HSV gelegenen Teile. Die HSV ist nach wie vor synsedimentär aktiv, die Bärenkluft sehr wahrscheinlich ebenfalls.
- Die letzten Hohgantsandsteinbänke im NW sind zeitgleich mit den ersten Ablagerungen der Globigerinenmergel im SE. Durch die fortschreitende Transgression greifen diese auf die gesamte Plattform über.
- Nach der Überschiebung der Flyschdecke wird auch das Helvetikum von der Kompression erfasst: die Bärenkluft wird reaktiviert und die Rampe entsteht.

Die heutige Struktur der Waldegg

Aufgrund der Informationen aus den Höhlen wurde ein 3D-Modell der Waldegg konstruiert. Hier werden nur geologische Profile (Fig. 2-8 und 2-11) längs und quer zur Waldegg vorgestellt. Im Folgenden die gemachten Annahmen: Die Intersektion des Barfüsserbruchs mit Bärenkluft und Rampe ist unbekannt. Der Versatz von SP und Dop ist in Fig. 2-8 stark überhöht gezeichnet, da ein Querbruch die Profillinie schneidet. Diese Figur versucht, die gegenwärtige Lage der Gesteine darzustellen; die Schrattenkalkmächtigkeit wurde hierbei auf 340 m festgelegt. Das puzzleartige Bild ist mit der zeitlich unterschiedlichen Aktivität der Brüche zu erklären. Fig. 2-11 zeigt den SP-Bruch nicht, da dessen Orientierung und Versatz gegen den N zu bislang unbekannt sind. Auch hier wird der Schrattenkalk mit 340 m Mächtigkeit angegeben. Die Kopplung einer Horst-Graben-Struktur mit einer Antiform ist in etwa kompatibel mit Hänni (1999), der den Bruch im Lombachtal mit der Bachli-Giesenen-Verwerfung korreliert.

Die Fortsetzung der Schichten gegen das Faustloch zu ist unklar, da in dieser Region bisher keine Höhlengänge gefunden wurden. Wir postulieren, dass das in Fig. 2-11c dargestellte Nordfallen durch einen quer zur HSV verlaufenden synsedimentären Bruch abgeschnitten wird. Ein Modell korreliert die HSV-Süd mit der Faille de Bäreney und Topographenkluft und erläutert die bisher bekannte Bruchtektonik in der Region des Faustlochs.

Schluss

Die Bedeutung von Höhlen für die Verfolgung und Interpretation von Brüchen darf nicht unterschätzt werden. Durch zusätzliche stratigraphische Beobachtungen kann die Bruchaktivität zeitlich bestimmt und der Aufbau der Region rekonstruiert werden. Die HSV war bereits in der Kreidezeit synsedimentär aktiv und zeigt im Raum Sundlauenen einen Versatz von rund 1 km. Mehrere andere Brüche waren gleichzeitig aktiv: die Waldegg ist eine Horst-Graben-Struktur. Weitere Brüche wurden während der Alpenfaltung und der Platznahme der Decken angelegt. Die heutige Struktur der Waldegg wird mithilfe von Profilen sichtbar gemacht. Eine Extrapolation der Brüche in die Region des Faustlochs wird versucht; Klarheit werden erst weitere Erforschungen bringen.

Es zeigt sich, dass die Karstwässer nicht geologisch abgedämmt werden. Aus diesem Grunde hängen die Wasserspiegel von der Quelle ab. Das nächste Kapitel befasst sich mit Karstwasser und erläutert die Fels-Wasser-Interrelation sowie die Abgrenzung der Einzugsgebiete.

Résumé: Nouvelle interprétation de la structure de la Waldegg par l’observation des cavités

Introduction

Toute structure géologique imperméable peut entraîner la formation d’une zone noyée perchée. Seule une analyse structurale permet d’affirmer qu’une zone noyée observée est en relation directe avec une source. Ce chapitre décrit la structure géologique de la région située entre le lac de Thoune et les Siebenhengste, la Waldegg. Sa stratigraphie est connue, voire célèbre dans la région du lac de Thoune, mais l’analyse de la fracturation est très difficile à cause de la végétation dense. Seule la faille de Hohgant-Sundlauenen (HSV) est décrite, synsédimentaire à l’Eocène, et son rejet est estimé à 500-600 m. Il n’existe aucune estimation de la chronologie des failles de la Waldegg ni de leur influence sur la sédimentation, parce que les roches de la Waldegg supérieure sont recouvertes de marnes et de Flysch. Les observations faites dans les cavités contribuent à combler cette lacune. Le Bärenschacht traverse la HSV, se développe sur 1.5 km dans la série du Hohgant, et retombe dans le calcaire par la faille de Bärenkluft.

La stratigraphie et la position des galeries

La stratigraphie du Schrattenkalk est décrite telle qu’on l’observe au Bärenschacht. La puissance du calcaire atteint 340 m à cause de l’activité synsédimentare de la HSV.

Les galeries phréatiques suivent préférentiellement certains joints de strate de la masse calcaire. Pour cette raison, la prospection de nouvelles entrées a de bonnes chances de succès si elle a lieu le long de ces joints de strate, et particulièrement à leur intersection avec les phases spéléogénétiques.

Observation des failles et de la stratigraphie

La **HSV** est la seule faille bien visible à la surface. Partiellement recouverte de Flysch, elle s’étend depuis Sundlauenen via le Hohgant (rejet 200 m) vers la Schrattenfluh. Une activité synsédimentaire est prouvée pour l’Eocène et supposée pour le Crétacé. Des observations au Bärenschacht dans la zone d’entrée indiquent un rejet de 1025 m, et témoignent d’une activité synsédimentaire crétacée: la puissance du Schrattenkalk au NW de la faille est d’environ 180 m, pour au moins 340 m au SE. Durant l’Eocène, la faille continua son activité synsédimentaire; la puissance de 640 m près de la faille passe à environ 215 m au SE, suggérant une sédimentation dans un bassin en subsidence. Au NW, les couches éocènes ont une puissance maximale de 180 m.

La géologie de la **Bärenkluft** fut longtemps un mystère. Cette faille est inverse dans la partie sud du Bärenschacht (rejet env. 60 m), et devient normale au N de la grotte (rejet de 75 m), où une couche métrique de grès du Gault l’accompagne. Dans le Schrattenkalk au SE, on observe un tube paléokarstique également rempli de Gault. La puissance du Schrattenkalk atteint 330 m. A l’intersection de la zone de puits avec la Bärenkluft, on observe des brèches de Schrattenkalk dans du Gault ainsi que du Seewerkalk fracturé. Ces éléments permettent de retracer l’histoire de la faille. Le résultat le plus important est que la Bärenkluft est considérée comme contemporaine de la HSV.

La **Rampe** peut être confondue avec la Bärenkluft dans certaines parties du Bärenschacht. Il s’agit d’une faille inverse d’une inclinaison de 40-60°, qui s’étend à peu près parallèlement à la Bärenkluft et présente un rejet de 50-100 m. Elle rejoint la Bärenkluft au nord, où son rejet devient négligeable. La puissance du Schrattenkalk atteint 330 m.

La faille nommée **Barfüsser** (BF) est, au contraire de la Bärenkluft et la Rampe, visible en surface. Le rejet observé au Bärenschacht est d’environ 140 m, le Barfüsser est une faille normale qui plonge en direction WSW. La datation n’est pas évidente: est-elle contemporaine de la HSV et de la Bärenkluft (elle serait donc un témoin de la structure en Horst-Graben) ou est-elle apparue lors de la mise en place des nappes de l’Helvétique?

Les **fractures longitudinales de surface** ont été cartographiées par Colombi (1960). Le «Doppelbruch» (Dop) est interprété comme faille inverse d’importance mineure, dont le rejet considérable visible sur la carte est dû aux failles transversales. La faille «SP» montre un rejet d’environ 50 m. Elle forme, sur quelques centaines de mètres, la bordure E des couches de Seewerkalk et Discussschicht, et est donc interprétée comme faille synsédimentaire contemporaine de la HSV et de la Bärenkluft. De ce fait, la Waldegg est considérée comme une structure en Horst-Graben. Le «Kienbruch» montre un rejet d’au moins 20 m et plonge vers le NE. Les observations sont limitées par la taille de l’affleurement (30*20 m).

Les **failles transversales de surface** sont des failles normales listriques qui plongent vers le sud. La géométrie et le rejet indiquent qu’il s’agit de la plus récente génération de fractures, apparues lors de la mise en place des nappe helvétiques. On peut affirmer qu’il ne s’agit pas de fractures de détente glaciaire.

En **résumé**, on distingue trois familles de fractures. La première génération, de direction SSW-NNE, consiste en failles normales synsédimentaires durant le Crétacé et l’Eocène, et en relation avec l’extension et l’approfondissement du bassin de la Thetys.

Elles ont été partiellement réactivées pendant le plissement des Alpes. La deuxième génération de failles concerne la même direction, mais ce sont des failles inverses, apparues simultanément à la formation et au transport des nappes helvétiques. Les failles les plus récentes sont normales et de direction E-W. Elles résulteraient de la mise en place des nappes.

Chronologie de la sédimentation et de l'activité des failles entre le Crétacé et l'Eocène

Les observations décrites ci-dessus permettent d'esquisser une chronologie schématique des évènements illustrés dans les Figs. 2-9 et 2-10. Elle est sommairement décrite ici:

- Après le dépôt du Schrattenkalk (activité synsédimentaire de la HSV), celui-ci est soumis à une karstification. Ce karst est ensuite rempli de grès du Gault.
- Lors du dépôt du Gault, du Seewerkalk et de la Discusschicht, la Bärenkluft (et plus tard aussi la faille «SP») sont synsédimentaires. Le bloc NW de la HSV est au-dessus du niveau de la mer.
- La transgression de l'Eocène commence par inonder peu à peu les parties NW de la HSV. Cette dernière poursuit son activité synsédimentaire, de même que la Bärenkluft probablement.
- Les derniers bancs de la série du Hohgant au NW sont contemporains des premiers dépôts de marnes à Globigerines au SE. Suite à la transgression, celles-ci se répandent sur toute la plate-forme.
- Après le charriage de la nappe de Flysch, le domaine helvétique est soumis à la compression lui aussi: la Bärenkluft est réactivée et la Rampe se crée.

Structure actuelle de la Waldegg

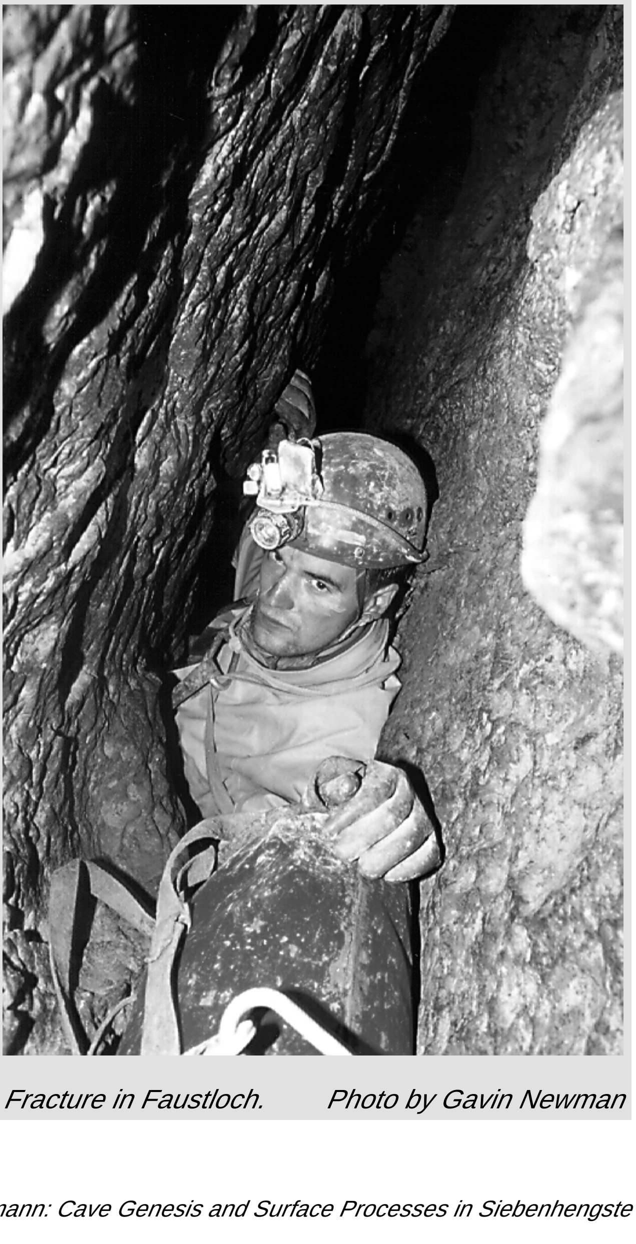
Un modèle 3D de la Waldegg a été élaboré à partir des observations souterraines. Seuls des profils géologiques (Fig. 2-8 et 2-11) à travers la Waldegg sont présentés ici. Les interprétations sont les suivantes: L'intersection du Barfüsser avec la Bärenkluft et la Rampe n'est pas connue. Le rejet de SP et Dop est exagéré dans la Fig. 2-8 à cause d'une faille transversale qui coupe le profil. Cette figure 2-8 tente de représenter la disposition actuelle des couches; la puissance du Schrattenkalk est fixée à 340 m. La structure en «puzzle» résulte des différentes générations de fractures. La Fig. 2-11 ne montre pas la faille SP, car son orientation et son rejet sont actuellement inconnus au nord. La puissance du Schrattenkalk est également fixée à 340 m. L'interprétation en une structure en Horst-Graben, couplée avec une antiforme, est compatible avec Hänni (1999), qui corrèle la fracture dans la vallée du Lombach avec la faille de Bachli-Giesenen.

Le prolongement des strates vers le Faustloch est incertain, car il n'y a pas de galeries connues actuellement dans cette direction. Nous postulons que les strates plongent vers le nord (Fig. 2-11c) et sont coupées par une faille synsédimentaire transversale à la HSV. Un modèle met la HSV-sud en relation avec la faille de Bäreney et la Topographenkluft, expliquant la fracturation de cette région telle qu'elle est connue à présent.

Conclusion

Il ne faut pas sous-estimer l'importance des cavités pour l'observation et l'interprétation des failles. Une étude stratigraphique permet d'organiser chronologiquement l'activité des failles, et de reconstruire la structure de la région. La HSV était synsédimentaire déjà pendant le Crétacé et montre un rejet d'un kilomètre dans la région de Sundlauenen. D'autres fractures étaient actives durant cette période: la Waldegg est une structure en Horst-Graben. D'autres fractures ont été mises en place lors du plissement des Alpes et de la mise en place des nappes. La structure de la Waldegg est illustrée par des profils géologiques.

Les nappes hydrologiques ne sont pas dépendantes de la géologie, mais de leur source. Le chapitre suivant traite des eaux karstiques, de l'interrelation eau-roche ainsi que des limites des bassins versants.



Fracture in Faustloch. *Photo by Gavin Newman*

2.1. Introduction

Paleowater levels can be observed in caves. It is aimed to link these with the spring levels. This can only be done if no significant geological barrier can be suspected to have dammed the water and created perched aquifers. Therefore a precise knowledge of the structural setting is important. The main aim of the present chapter is to study the geologic setting of the SW part of the Siebenhengste, mainly in the Waldegg region, which had been previously described as "Waldegg dome" because of its antiform structure.

It appeared that many geological observations could be carried out in the caves, providing information that is not available on the surface. This information is used to derive a model of the geologic history of the region, which is also presented in this chapter.

Previous investigations

The Küblisbad site near Neuhaus (Fig. 2-1) is famous for its stratigraphy (Herb et al. 1978). In a tight succession, Upper Cretaceous and Eocene strata overly the Schrattenkalk. Colombi (1960) mapped the front part of the Waldegg. Due to the thick vegetative cover, he couldn't completely map and understand the fractures, and his comment lapidarily says: "Relative Bedeutung, Sprunghöhe und Zeitfolge der alpinen Verstellung an Längs- und Querbrüchen scheinen (…) zu wechseln" (The relative importance, throw and temporal succession of the alpine movement at longitudinal and transversal faults seems (…) to vary). However, an Eocene synsedimentary movement of the Hohgant-Sundlauenen-Verwerfung HSV is described.

Schneeberger (1927) interpreted the Waldegg dome as an old basin, where the Upper Cretaceous rocks had been preserved from erosion. He also related fracture activity with sedimentation and erosion cycles. Ziegler (1967) mapped around Balmholz (Fig. 2-1) and interpreted the Balmholz fault as being synsedimentary during the Drusberg marl deposition; he positioned the Balmholz fault parallel to the HSV. This is in accordance with the findings of Schenk (1992) who described fractures and structural highs during the deposition of the Altmann member. However, no indication of some activity of the HSV is found. This is in contrast to Ischi (1978), who hypothesized that the HSV was active already during the deposition of the Kieselkalk. The throw of the HSV could never be determined correctly; the presence of Globigerina marls (downthrown side) in contact to Schrattenkalk at Sundlauenen allowed to estimate a minimum throw of 500 m, whereas at Hohgant the sandstone being in contact with Schrattenkalk indicated a throw of around 150 m.

Fig. 2-1:
A shaft of the Bärenschacht, seen from top.

Ein Schacht im Bärenschacht, von oben gesehen.

Un puits du Bärenschacht, vu du haut.

Photo by Daniel Burkhalter

A distinct relationship of the different temporal evolution of the various Waldegg fractures, as well as their influence on the sedimentation of the rocks, could not be established. This is mainly due to the limited outcrops at the surface. We will present some in-cave observations which partly help compensate for this lack of knowledge. Some information was already published (Häuselmann, Jeannin & Bitterli 1999) and will be only summarised here.

Description of the tectonic setting of Bärenschacht

The entrance of Bärenschacht lies at the base of the Burgfeld cliffs that dominate the village of Beatenberg (Fig. 2-1). The Burgfeld cliffs are a product of the HSV. The Bärenschacht rapidly goes down to the Drusberg marl in a series of shafts (Fig. 2-1). In contrast to the

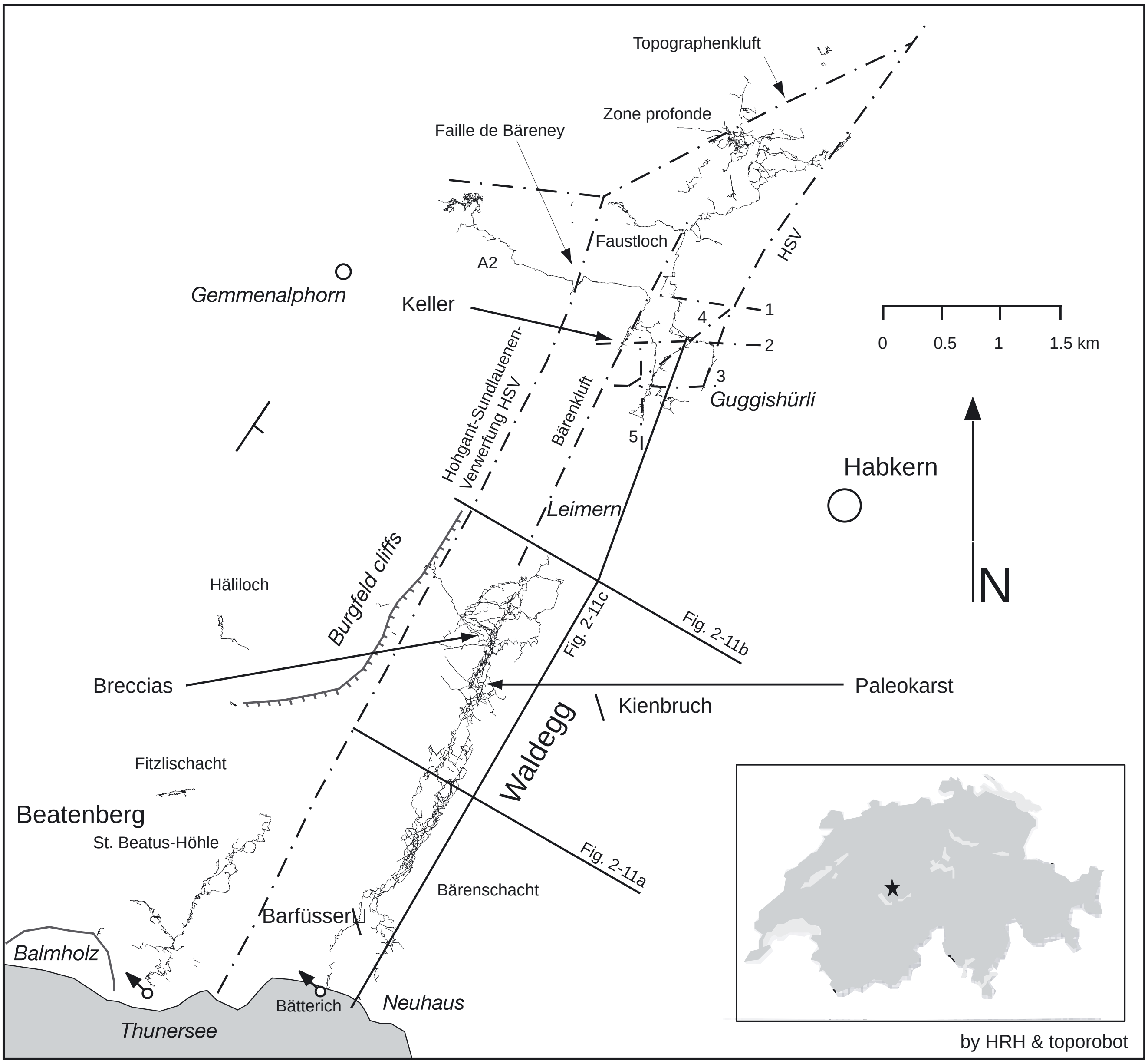


Fig. 2-2:
Setting of the localities and caves described.
Die Lage der beschriebenen Örtlichkeiten und Höhlen.
Situation des localités et cavités décrites.

general dip (SW) of the Schrattenkalk, the gallery is directed towards the HSV which then is crossed (Fig. 2-5). The cave continues within a thin calcareous bed of the Hohgant series, which is steeply dipping to the SE and intensely fractured (Bitterli, Funcken & Jeannin 1991). At 1.5 km from the entrance, at a depth of -565 m, the strata are folded and horizontalised, and a sump hinders progression within the cave. The sump was shunted in 1995. Behind it, a vast gallery steeply goes down along a fault zone. Due to one of these faults, the cave reaches the bottom of the Hohgant series and finally the Schrattenkalk again. There, a series of vast and deep shafts allow to reach the baselevel which consists of a complicated 3D-network of galleries. They represent the outflow parts of the Siebenhengste-Schrattenfluh catchment area. The labyrinth allows to follow the fractures and to observe them in three dimensions.

2.2. The stratigraphy and the position of cave passages

The Stratigraphy

The stratigraphy of the Schrattenkalk (SK, Fig. 2-3) observed in Bärenschacht varies from the one that can be seen in the Siebenhengste (Jeannin 1989, Fig. 1-4). In the following part, we describe a compilation of the observed lithologies. This observation is based on field studies alone, no thin slices were made. The overall thickness of the Schrattenkalk is 320 to 340 m (as compared to 160 to 220 m in Siebenhengste) because of the synsedimentary activity of the HSV.

- The Basal SK (Fig. 2-4) has a greyish to slightly brown colour and is often well-banded. Very characteristic for this lithology are the silex banks that are about 10 m above the Drusberg marls. The pyrite content is very high and leads to spectacular gypsum formations in caves. The total thickness is about 85 to 100 m. The marly layers separating the Basal from the Lower SK are only visible to the S of the Bärenschacht.
- The Lower Schrattenkalk is also well-bedded and has again much pyrite. It is quite difficult to distinguish from the overlying strata.
- The Middle Oolithic Schrattenkalk (MOSK) smells oily when hammered, proving the presence of organic rests. It is generally slightly brighter than the Lower Schrattenkalk, contains virtually no pyrite, and is less well bedded. Lower SK and MOSK have a thickness of about 85 m.
- The following Upper Oolithic SK (UOSK) consists of a gray limestone with coarser shell clasts. Some oysters are found in the lower part. It is difficult to distinguish this limestone from the underlying one; generally it is again brighter than the MOSK and contains irregular beds of 10-30 cm. The total thickness is about 35 m. Both MOSK and UOSK may contain microscopical dolomite spars within the rock mass.
- A thin marly layer often marks the beginning of the Schrattenkalk s.str. (SKSS), a very bright limestone with many Rudist shells that has a thickness of about 60-70 m. The following Orbitolina marls are often not visible and may vary from slightly clayey limestone to a fine sandstone or marl.
- The topmost layer (Upper Schrattenkalk) consists of fossil-rich beds (Rudists and Turritelles) which contain brownish veins. Often, some fractures seem to be filled with either Gault or Eocene sandstone, proving of an early karstification. Its thickness is about 50-60 m.

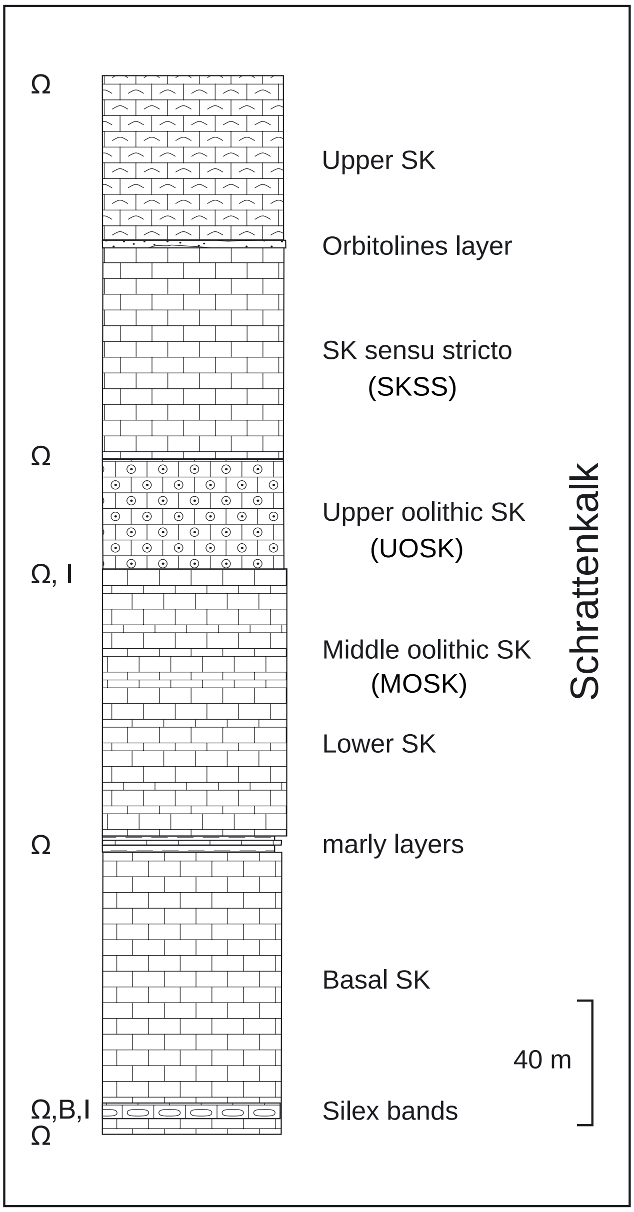


Fig. 2-3:
The detailed stratigraphy seen in Bärenschacht. The signs at the left side show the bedding planes where most of the cave passages are developed.

Die detaillierte Stratigraphie, beobachtet im Bärenschacht. Die Zeichen links zeigen die Schichtfugen mit den meisten Höhlengängen an.

La stratigraphie détaillée, observée dans le Bärenschacht. Les signes à gauche signifient les niveaux où il y a la plûpart des galeries.

The position of cave passages

While trying to define the stratigraphy by following the cave passages within the Schrattenkalk, it was found that most of the phreatic passages in the Bärenschacht labyrinth are primarily dependent on bedding planes instead of fractures or the big faults. It was observed that the passages prefer only some selected bedding planes. This observation is described in the speleo-inception theory (Lowe 1992). It is also observed in the Siebenhengste labyrinth, but a description of the different bedding planes is still to be done. In Bärenschacht (and, for some bedding planes, also in St. Beatus Cave), the cave passages develop mainly in the following strata:

- near the top of the Schrattenkalk
- along a marly layer that separates the SKSS from the UOSK that is only seen in Bärenschacht
- within a finely banked zone of Limestone. In Bärenschacht they were called the “oyster strata”, in Innerbergli and Haglätsch area, there are no oysters visible, but the fine beds are still very characteristic. This zone is interpreted as the transition between the MOSK and the UOSK, and it is a very important speleogenetic horizon.
- along the marly layers separating the Lower SK and the Basal SK. These layers are rarely visible.
- in the silex banks within the Basal SK. These strata are again very important for speleogenesis, virtually the whole phreatic tube of St. Beatus Cave as well as many passages in Bärenschacht are in the Silex layer.
- at or near the Drusberg marls. The importance of this layer is difficult to determine, because the Silex layer may influence the speleogenesis. However, Hohgantloch (Fig. 1-7), parts of the St. Beatus Cave (Chapter 3.1), as well as some passages of Bärenschacht, are in direct contact with the Drusberg marls.

The position of the respective layers is indicated on Fig. 2-3. An Ω indicates passages of Bärenschacht, a B additionally passages of St. Beatus Cave, and an I passages within the Innerbergli/Haglätsch region. Note that the thickness of of the profile is only valid for Bärenschacht.

The observation that phreatic cave passages tend to follow only selected bedding planes is very important for the “day-to-day”speleologist that is searching for caves. Huge cliffs therefore have to be abseiled by preference to places where the specific bedding planes crop out – the chance to find a cave is much higher at this place.

The ??Cave (Fig. 1-7) that is thought to be an old exit of St. Beatus Cave hasn’t been found yet. A passage **must** exist somewhere. The first place to look for this cave is – of course – the intersection of the respective speleogenetic phase (Chapter 5) with the corresponding bedding plane, in this case the Silex level. Unfortunately, the place there is densily forested, and there are also cliffs. A round spot of grass found in the middle of a cliff might represent the filled cave; until now no abseiling has been done to verify this theory. Anyhow, the intersections of speleogenetic bedding planes and phases is likely to give good chances for caves.

Fig. 2-4:
Rarely, nice ammonites are seen near the base of the limestone. This one is found within a calcareous layer of the Drusberg formation.

Selten sieht man schöne Ammoniten an der Basis des Kalkes. Dieser hier befindet sich in einem Kalkband der Drusbergformation.

Rarement, on voit de belles ammonites à la base du calcaire. Cet exemple se trouve dans un banc calcaire de la formation du Drusberg.

Siebenhengste labyrinth.
Photo by Gregor Siegenthaler

2.3. Observation of faults and stratigraphy of the rocks

The following description of the faults is based on observations within Bärenschacht, completed with information from the surface. The location of the faults and their interrelation is shown in Figs. 2-2 and 2-5. An overview of the current knowledge is followed by the description of the findings. An interpretation is then added.

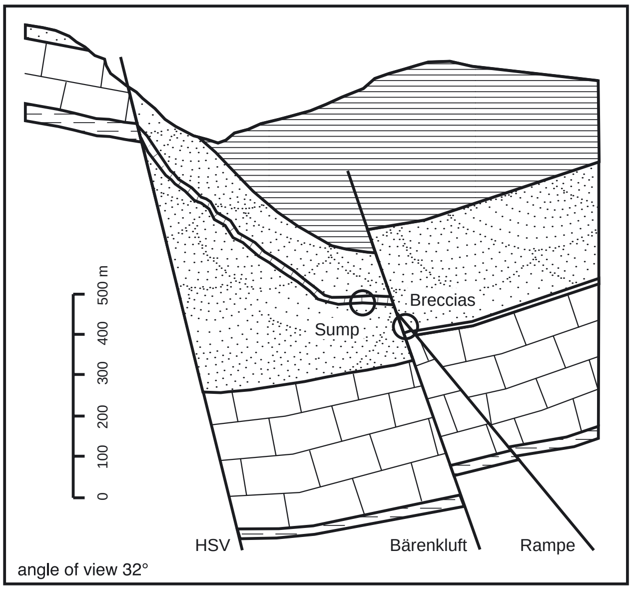


Fig. 2-5:
Cross-section through the entrance part of Bärenschacht (cave not shown). Bärenkluft, Rampe and the sediment thicknesses are shown to scale. Legend see Fig. 1-4.

Querschnitt durch den Bärenschachteingang (Höhle nicht dargestellt). Bärenkluft, Rampe und die Sedimentmächtigkeiten sind im Massstab.Legende siehe Fig. 1-4.

Profil à travers la zone d'entrée du Bärenschacht (cavité non dessinée). La Bärenkluft, la Rampe et l'épaisseur des sédiments sont à la même échelle. Légende voir Fig. 1-4.

The Hohgant-Sundlauenen normal fault HSV

The HSV is the only fault that is well visible at the surface. It was mapped from Lake Thun past Hohgant up to the Schrattenfluh, more than 20 km to the NNE. Its throw diminishes progressively from Lake Thun (more than 500 m) to Hohgant (150 m, Bayer et al. 1983). The HSV is covered by the Leimern and Guggershürli Flysch. Just in this region, the fault is split up into several perpendicular faults (Häuselmann, Jeannin & Bitterli 1999) which join again in the Siebenhengste region. Surface and in-cave observations indicate a present inclination of about 75° to the SE. Whereas a synsedimentary activity of the HSV in Eocene is clearly demonstrated (Menkveld-Gfeller 1995, Colombi 1960), a Cretaceous activity was only hypothesized by Steffen (1981).

The Schrattenkalk of the compartment between HSV and the neighbouring Bärenkluft (called “western compartment”) is first found in the shaft series after the Bärenschacht sump, at 775 m a.s.l. The stratal dip was measured in several places in the northern part of Bärenschacht. Its extrapolations towards the HSV allowed to estimate an elevation of the Schrattenkalk top at 675 m at the HSV. Thus, a throw of the HSV of at least 865 m is obtained. There is no indication about the presence of either Gault or Seewerkalk in the western compartment; Hohgant sandstone directly follow the Schrattenkalk.

Observations in the shaft zone region of Bärenschacht indicate a thickness of 90 m for the Upper Schrattenkalk and one of 35 m for the SK s.str. This information was then completed with the strata observed SE of the Bärenkluft in the middle parts of the cave. Like this, a total Schrattenkalk thickness of 340 m is obtained, 160 m more than observed NW of the HSV. Therefore we conclude that the HSV was already active during the Lower Cretaceous. The throw of the HSV amounts to 1025 m, more than double as estimated before.

As already described by Bitterli et al. (1991), the Bärenschacht follows a calcareous layer of the Hohgant series after having crossed the HSV. The first calcareous part found west of the HSV is a basal Nummulite layer, which is directly overlying the Schrattenkalk. Since this layer is described as being younger than the basal Discusschicht layer observed SE of the HSV (Menkveld-Gfeller 1995), we may assume that it is found in the middle of the Hohgant series SE of the HSV and that it is equal to the observed Nummulite layer of Bärenschacht. If this is true, the Eocene throw of this layer (after deposition) would be 180 m (Figure 2-5). This implies that a total of 640 m of underlying Hohgant series would have been deposited just near the HSV, compared to 45 m NW of it. The Nummulite limestone is also found at the sump of Bärenschacht. There, the total thickness of the underlying Hohgant series is only 215 m and indicates a decrease of 425 m in a horizontal distance of 575 m. This scenario is comparable with the findings of Menkveld-Gfeller (1995), giving a present surface angle of 32° and (after tilting back the Helvetic domain to horizontality) a sedimentation angle of about 15°. The Hohgant series on the northern wing of the HSV has a thickness of max. 180 m at Gemmenalphorn; this height was approximatively used in Figure 2-5 to estimate the amount of Hohgant overlying the Nummulite sandstone.

Jeannin (1989) described small normal faults parallel to the HSV within the Hohgant series, which would reduce both the inferred throw of the HSV and maybe also the deposition thickness. However, since the throw of those small faults cannot be determined exactly (a rough estimation can be inferred from Jeannin 1989 with 75 m), and since they are associated with the HSV, the presented interpretation is shown in Fig. 2-5.

Fig. 2-6:
The paleokarst tube found in Bärenschacht. The tube is filled with Gault sandstone.

Die Paläokarströhre im Bärenschacht, gefüllt mit Gaultsandstein.

Tube paléokarstique trouvé au Bärenschacht. Il est rempli de grès de Gault.

Photo by Bernhard Voss

The Bärenkluft

The Bärenkluft was first described by Bitterli et al. (1991). However, since no geologist was in the bottom part of Bärenschacht until the opening of the sump in 1995, the Bärenkluft is shown as a normal fault. Its distance from the HSV varies between 500 and 700 m in the Bärenschacht area.

Observations have shown that the reverse thrust of 60 m remains more or less constant towards the SW, whereas the Bärenkluft turns into a normal fault towards the NE (scissor movement), and has a throw of about 75 m in the region of the north sump. In the northern part of Bärenschacht, a meter-thick sandstone layer “fault gouge” is observed.

The stratigraphical sequence of the Schrattenkalk could be observed almost completely in the middle compartment that lies between Bärenkluft and Rampe. It shows a thickness of about 320 m. The middle compartment shows both Gault sandstone and Seewen limestone (Häuselmann et al. 1999), in addition, a paleokarstic void filled with Gault sandstone is found (Fig. 2-6). The Seewerkalk visible in the shaft zone (Fig. 2-5) laterally passes into a breccia visible only after the sump. There, a Schrattenkalk breccia in a Gault sandstone matrix is also visible (Fig. 2.7), whereas in the vicinity, there is no more Schrattenkalk.

Those observations allow us to interpret the history of the fault as follows (Häuselmann et al. 1999):

1. After the Schrattenkalk deposition sea level was lowered and karstification of the western and middle compartment (as well as NW of the HSV) took place. It is not known (yet) whether the Bärenkluft was already active then.
2. The next sea level rise drowned the system, and the fault began to be active. There are indications that at least a part of the “gouge” is Gault, so the fault must have been open. Gault sandstone was deposited on the SE part and within the karst voids. The top of the Schrattenkalk on the NW was brecciated, deposited onto the SW part and cemented with Gault.
3. During the first part of the Seewerkalk deposition, the fault appears to have been less active, allowing deposition on both sides of the fault.
4. An increase in activity during the last stages of deposition, leading to an uplift of the NW block and to erosion of the Seewerkalk, created the breccia that is contemporaneous with the last Seewerkalk deposition in the SE.
5. During the Eocene, the fault was active and synsedimentary. Here also, it seems to have been opened, leading to the infilling of the “gouge”.
6. During the formation of the Alps, the Bärenkluft was reactivated, and the SE block was upthrusted. It is very likely that the “gouge” acted as a lubricant aiding in the reactivation.

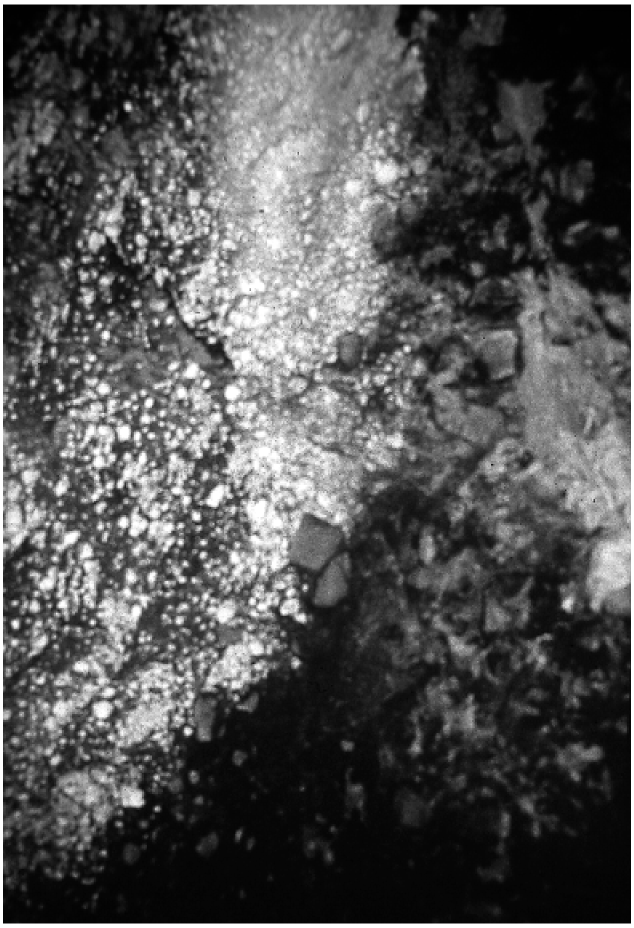


Fig. 2-7:
The breccia observed in the shaft zone of Bärenschacht. Below-right Schrattenkalk breccia, above-left Seewerkalk breccia. Picture height 2 m.

Die beobachtete Brekzie in der Schachtzone des Bärenschachtes. Unten und rechts Schrattenkalkbrekzie, oben Seewerkalkbrekzie. Bildhöhe 2 m.

Brèches observées dans la zone des puits du Bärenschacht. En bas et droite une brèche de Schrattenkalk, en haut et gauche une brèche de Seewerkalk. Hauteur de l'image 2 m.

Photo by Frédy Fleury

The Rampe

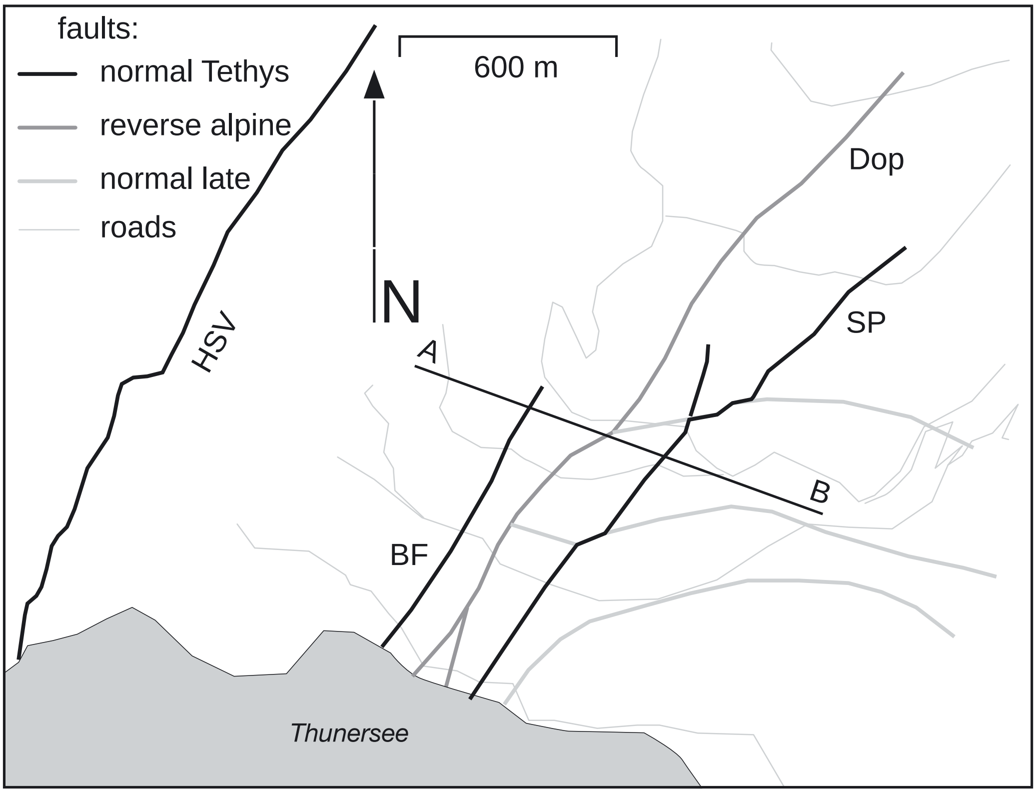
The Rampe is found in many parts of the Bärenschacht and can, depending on its situation, be confounded with the Bärenkluft. Its angle is between 40° (in the SW) and 60° (in the NE). The Rampe runs more or less parallel to the Bärenkluft, but due to its flatter angle, both faults join each other, as observed behind the sump. The bended character of the Rampe is also responsible for their joining north of Bärenschacht.
The Rampe is an inverse fault. Its thrust is negligible in the north of Bärenschacht (there also the Bärenkluft thrust is normal) and increases to a maximum of about 100 m in the middle of the Bärenschacht, decreasing towards the S to about 50 m.
The stratigraphic column of the compartment east of the Rampe could be followed almost completely and shows a thickness of also 320 m. It is assumed that the Rampe was created during the overthrust of the Helvetic nappes.

The Barfüsser fault

The Barfüsser fault (BF) is visible at the surface (Figure 2-8 – the profile of Fig. 2-8 is discussed in Chapter 2-5) and was mapped by Colombi (1960), although it was impossible to determine its throw. It is the same fault line that goes down to Bätterich, however, due to the transverse faults described below, the throw in this region is not the same as farther to the North. In Bärenschacht, it is only visible in the passage named Va-nus-pieds (Fig. 2-2). Its direction was calculated to be 14° to the NNW, thus it should intersect with both Bärenkluft and HSV, with a dip to the SW and a throw of about 140 m (normal fault, the SW compartment is lower) that was estimated by comparing the stratigraphy. There are two possibilities for the timing of the fault: either it was a normal fault during the HSV and Bärenkluft activities, or it was created in the last steps of the emplacement of the Helvetic nappes, adapting to the undulated thrust surface. There is no indication of a change in the stratigraphic column, but evidence is scarce.

Longitudinal faults at the surface

Some faults are only visible at the surface (Fig. 2-8). Two of them have been mapped by Colombi (1960). After revisiting the area, new ideas about the interconnection of the faults came up. The fracture named “Doppelbruch” (Dop) is thought to be a reverse fault of minor importance, with almost no thrust. The importance of the Doppelbruch seen at Lake Thun is due to the transverse faults (see below).
The SP fault has a throw of about 50 m in the southern parts of Waldegg, the dip (towards the NW) cannot be calculated exactly. Seewerkalk, Gault and the Eocene Discusschicht are present west of the SP fault, whereas only Gault is visible in the East. Only after some 100 m, the Seewerkalk appears and gradually thickens. The Discusschicht is not present. We therefore conclude that the SP fault is synsedimentary at least during the deposition of Seewerkalk and Discusschicht, and thus belongs to the same generation as HSV and Bärenkluft. Therefore, the Waldegg structure seems to represent a Horst-Graben structure at the Thetys margin.



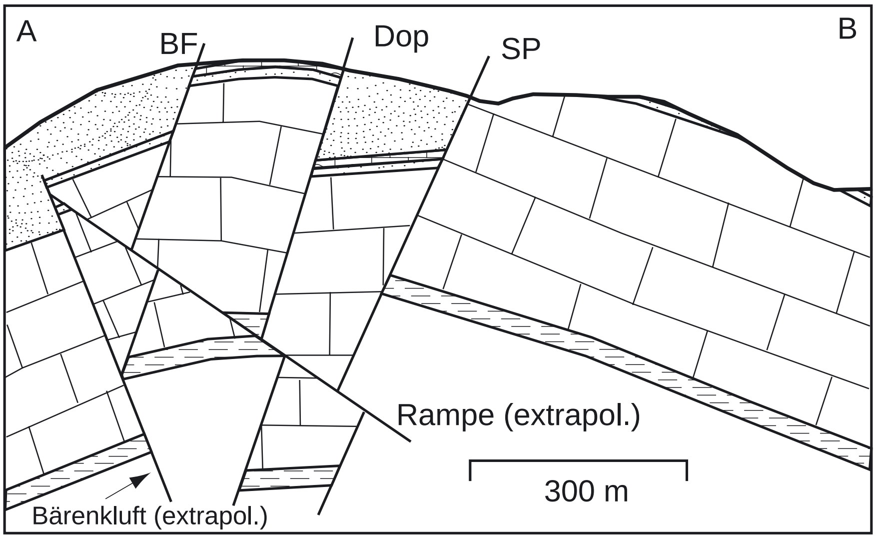


Fig. 2-8:
Top: The fractures visible north of Lake Thun, as mapped and reinterpreted.
Bottom: The profile shows a big displacement at Doppelbruch (Dop) and SP, which is due to the transverse fault to the north of the profile line. BF=Barfüsser. Bärenkluft and Rampe are extrapolated to the profil line and are not visible at surface due to the Globigerins marls.

Oben: Die an der Oberfläche sichtbaren Brüche wurden kartiert und neu interpretiert.
Unten: Das Profil zeigt einen grossen Versatz an Doppelbruch (Dop) und SP an, der durch den Querbruch nördlich der Profillinie bedingt ist. BF=Barfüsser. Bärenlkuft und Rampe sind extrapoliert und an der Oberfläche wegen der Globigerinenmergel nicht sichtbar.

En haut: Les failles visibles en surface au nord du lac de Thoune ont été cartographiées et réinterprétées.
En bas: Le profil montre un déplacement majeur au Doppelbruch (Dop) et SP, ce qui est dû à la faille transversale au nord de la ligne de profil. BF=Barfüsser. Bärenkluft et Rampe sont extrapolés et pas visibles à la surface en raison de la présence des marnes à globigérines.

Another longitudinal fault (Kienbruch) was observed in the middle of the forest towards Habkern (Fig. 2-2). This Kienbruch has a throw of at least 20 m, and it dips to the NE. Because of limited outcrop size (30*20 m), further observations are not possible.

Transverse faults at the surface

In the front part of the Waldegg towards Lake Thun (Fig. 2-8), several faults trending E-W have been mapped by Colombi (1960), but they have not been interpreted. They are all listric faults showing a dip towards the south. Geometrical considerations as well as their throw help to interpret them as being the last (normal) fracture sets that were created during the placement of the Helvetic nappes at the present location. The question whether they could be relaxation fractures related to the deglaciation, or normal faults due to the deepening of Lake Thun, arose. A geologic profile across Lake Thun and Waldegg showed clearly that all those fractures reach much deeper than the rock bottom of Lake Thun (which was assumed to be at Sea level, Sturm & Matter 1972).

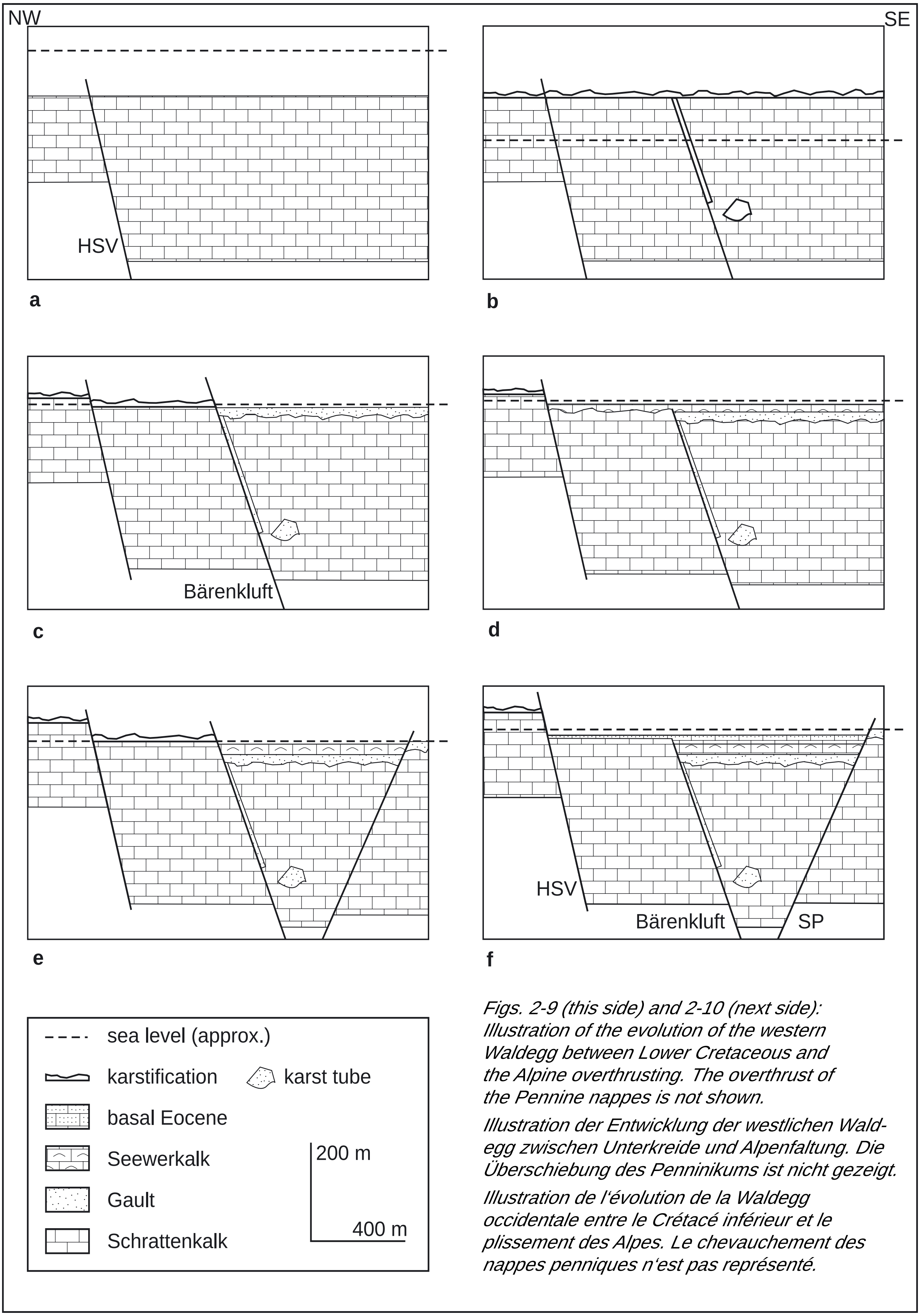
Conclusion

We presented evidence for the existence of three fault generations. The first generation, stretching roughly SSW-NNE to S-N, is normal and synsedimentary from Lower Cretaceous to the Eocene. Parts of this generation have been reactivated during the Alpine orogenesis. The second generation, stretching again SSW-NNE, is related to the Alpine compression during the formation and transport of the Helvetic nappes, and is therefore composed of inverse faults. The third and last generation, with an E-W direction, is attributed to the emplacement of the Helvetic nappes at their present location. They are normal listric faults.

2.4. Chronology of the deposition and fault activity between Lower Cretaceous and Eocene

Our observations and conclusions allowed to draw a schematic chronology of the events, naturally still incomplete. Figures 2-9 and 2-10 illustrate the different evolutionary steps. The schemes are made along the line 2-11a (Fig. 2-2). The Bärenschacht is not visible for reasons of clarity. Possible interpretational problems are aborded in the following text. The letters at the beginning of each paragraph refer to the corresponding figure.

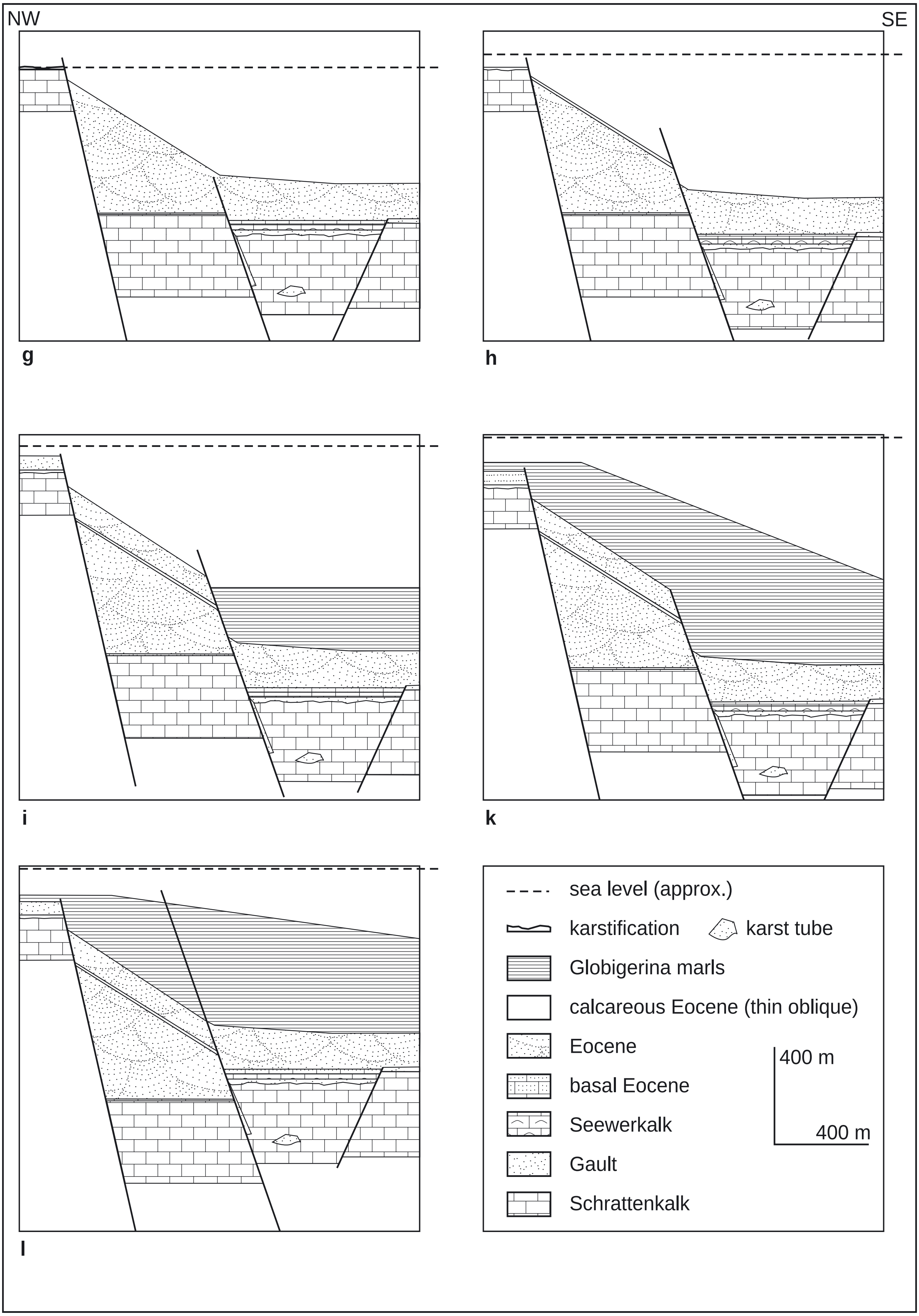
a) During the deposition of the upper Schrattenkalk layers, the HSV was active. Its real beginning cannot be timed in our region.
b) A big drop in sea level induced the karstification of the uppermost parts of the Schrattenkalk. Caves were dug. It is possible that the paleokarst tube found in Bärenschacht was created along the halocline. This hypothesis has the advantage that the sea level need not be lowered more than 200 m, as it should be the case if we assume that the cave was created by normal meteoric water. We time the beginning of the Bärenkluft activity in this period, however, it might have been active also before, associated with the HSV.
c) At Gault deposition (Upper Cretaceous), the NW parts of the Bärenkluft are still above sea level and karstified. The activity of the Bärenkluft is seen in the shaft zone of Bärenschacht: a Schrattenkalk breccia is deposited on the SE wing, proving an erosion of Schrattenkalk at the same time as Gault deposition. In parallel, the Bärenkluft, which is open, is filled with Gault sandstone, as is the karst tube presented above.
d) A relative sea level rise permitted the deposition of Seewerkalk in both wings of the Bärenkluft, whereas the NW block of the HSV might still be above sea level. The relative proximity of the sea level is documented by the absence of Seewerkalk near the SP fault which begins its synsedimentary activity. It is possible that the Seewerkalk was deposited at both sides of the SP fault, however, clear indications for an erosional event are missing until now.
e) During the last stages of Seewerkalk deposition, a lowering of the sea level induced the erosion of the Seewerkalk that was deposited on the NW wing of the Bärenkluft, and its cementation as a breccia on the SE part near the fault. Parallel to that, the Seewerkalk deposition went on in the SE part.



Figs. 2-9 (this side) and 2-10 (next side): Illustration of the evolution of the western Waldegg between Lower Cretaceous and the Alpine overthrusting. The overthrust of the Pennine nappes is not shown.

Illustration der Entwicklung der westlichen Waldegg zwischen Unterkreide und Alpenfaltung. Die Überschiebung des Penninikums ist nicht gezeigt.

Illustration de l'évolution de la Waldegg occidentale entre le Crétacé inférieur et le plissement des Alpes. Le chevauchement des nappes penniques n'est pas représenté.


NW
SE
g
h
i
k
l
sea level (approx.)
karstification
karst tube
Globigerina marls
calcareous Eocene (thin oblique)
Eocene
basal Eocene
Seewerkalk
Gault
Schrattenkalk
400 m
400 m

f) The following timespan is not documented. We assume that the activity of the faults as well as the sedimentation were low. The next documented event already falls into the Eocene: The deposition of the basal Discusschicht is assumed to have happened at a time when the NW wing of the HSV was still dry (Menkveld-Gfeller 1995). The SE limb of the SP fault is assumed to have risen close to or above the sea level, since the Discusschicht is missing.

g) The sea level continuously rose (and the HSV and Bärenkluft were active, respectively), and the main part of the Hohgant sands were deposited near the HSV.

h) The following deposition of the nummulitic sandstone (where the Bärenschacht galleries between the HSV and the sump lie) is thought to be parallel to the deposition of the basal Discus layer found in the Sieben Hengste ("Basalpriabone Discusschicht" sensu Schumacher 1948). If this deposit was synchronous or if it reflects the progressive transgression of the sea level, and is therefore asynchronous, is unknown yet. A study of the foraminifera association should be able to resolve this question.

i) Other banks of Hohgant layers are contemporaneous with the first Globigerina marl deposition in the south (Menkveld-Gfeller 1995).

k) The ongoing transgression causes the deposition of Globigerina marls in the whole region. The Pennine nappes and the Flysch between were later overthrust (not shown in Fig. 2-9). The Flysch is not cut by the HSV activity (Herb et al. 1978), therefore this thrusting has to be younger. It is possible that the thrusting occurred contemporaneously with, or after, the reactivation of the Bärenkluft (below).

l) The next event recorded is the reactivation of the Bärenkluft and the creation of the Rampe (not shown on Fig. 2-9). Both function as inverse thrust faults during the overthrust of the Helvetic nappes. The transverse normal faults created during the emplacement is not visible in the figures.

2.5. Today's setting of the Waldegg

A 3D-model of the situation of the Waldegg has been made. Here, we rely on conventional geologic profiles (Figs. 2-8, 2-11a-c) to visualize the setting. The position of the profiles is indicated on Fig. 2-2 and 2-8. The following text indicates how interpretative problems had been solved for the reconstruction of the profiles.

The Barfüsser fault (Fig. 2-8) is interpreted with the data available, and represented as a normal fault without synsedimentary activity, since the stratigraphical data are missing. It is unclear how and where it exactly intersects the Bärenkluft, the proposed interpretation seems to be the most probable.

The intersection of the Rampe with the Bärenkluft in the northern part of Bärenschacht is given, however, the continuation of the Rampe towards the south is unknown. It most probably is partly intersected also with the Barfüsser. The SP and Dop fault's displacement is highly exaggerated due to one of the transverse normal faults that lies north of the profile line on Fig. 2-8. The profile of Fig. 2-8 tries to represent the present location of the rocks, assuming an overall thickness of the Schrattenkalk of 340 m. The BF and SP faults (normal synsedimentary) are later cut and upthrusted by the Bärenkluft and Rampe.

In Fig. 2-11, the SP fault is not shown, since its displacement and orientation towards the north is unknown. The Kienbruch is also not shown since its correct orientation and throw is unknown.

The Schrattenkalk over the whole Waldegg area – for simplicity – is assumed to have a thickness of 340 m, which comes very near to the probable value estimated above.

The resulting picture shows a syn- and antiform structure. This is in agreement with the findings of Hänni (1999). Geological mapping by the author in the region of the Lombach canyon indicates that the separation of the Harder chain from the Waldegg is really due to a thrust fault, as also indicated by Hänni, who further postulates that this thrust fault (Bachli-Giesenen-Verwerfung) was active as a synsedimentary fault already during the sedimentation of the Valanginien marls that are situated below the Kieselkalk. This is in agreement with the present data.

Fig. 2-11 (right):
Profiles illustrating the present setting of the Waldegg. For location see Fig. 2-2, legend Fig. 1-4.

Profile zur Illustration des heutigen Aufbaus der Waldegg.

Profils de la structure actuelle de la Waldegg.

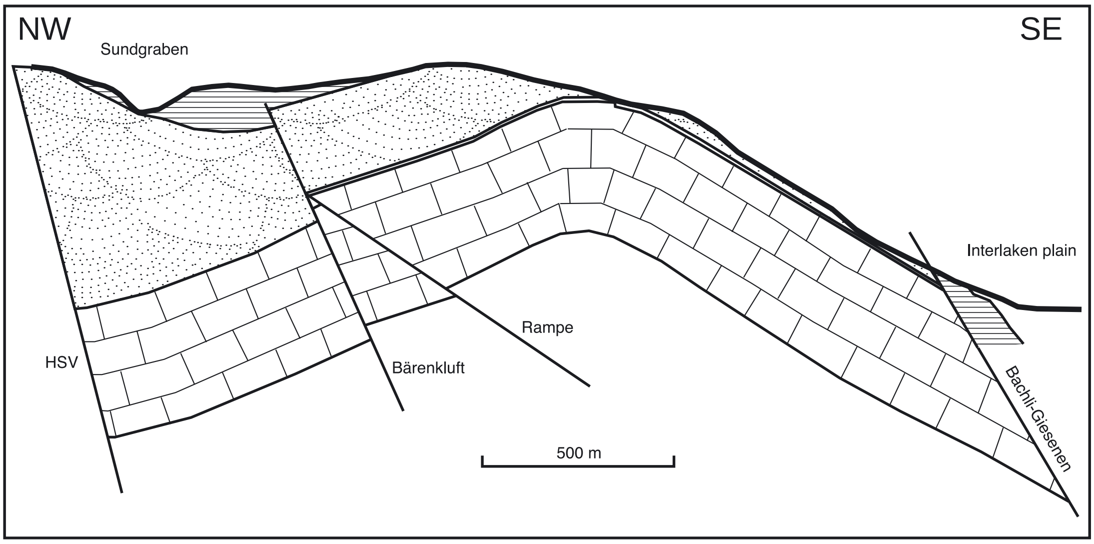


Fig. 2-11a

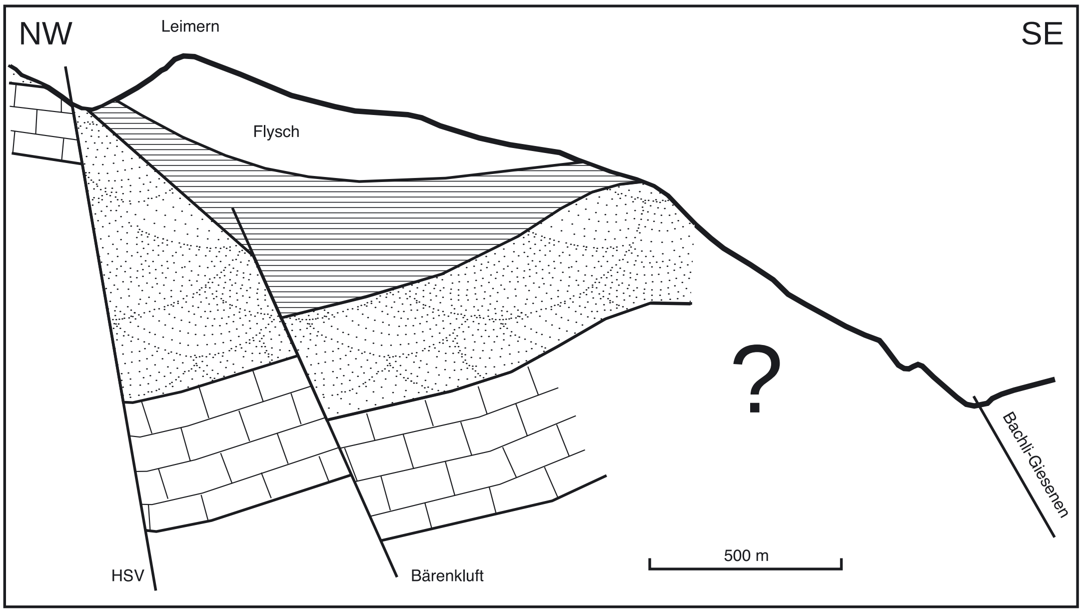


Fig. 2-11b

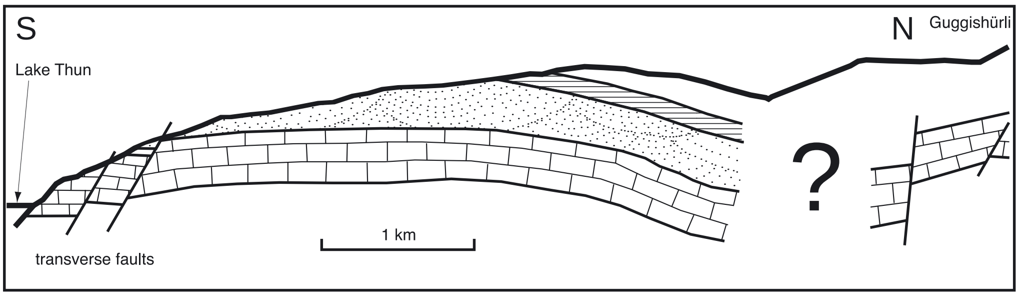


Fig. 2-11c

The continuation of the strata to the north, towards Faustloch, is unclear. The observed dip, as indicated by Fig. 2-11c, is likely to be interrupted, since the Schrattenkalk again reappears in Faustloch (strata approximatively drawn in the N of Fig. 2-11c). This whole area is covered by Flysch, any information therefore has to be extracted from observations in caves. We suggest that the interruption of dip is due to a normal (synsedimentary) fault perpendicular and contemporaneous to the HSV. The HSV that is observed north of the Faustloch is not observed in Waldegg any more and therefore has to be translated to the west, where it reappears again (see below).

Interpretation of the observations in Faustloch: the continuation towards the North

Due to the obstruction of a passage in Faustloch, the presented hypothesis is based on published data (Gerber et al. 1994), some observations and memory. There is a very complicated set of fractures that are more or less perpendicular to the HSV (Fig. 2-2). This region is covered by the Flysch nappe, therefore the observations of the fractures is only possible in caves.

We postulate that the HSV coming from the south continues as Faille de Bäreney (the fault crossing A2 cave) and then as Topographenkluft (crossing the Zone profonde, before joining the northern HSV again. This northern HSV (throw estimated 300-400 m) loses some of its throw to the Topographenkluft, but continues southward until it meets the perpendicular faults 1 and 2 of Faustloch. Fault 1 seems to be of minor importance, whereas fault 2 seems to be a dextral strike-slip fault with a dip to the S and a throw of estimated 150 m in Faustloch. Fault 3 is again a normal fault with a minimal throw of 200 m. Fracture 4 is interpreted as a very oblique normal fault (throw at least 50 m) and fracture 5 has neither observed throw, nor is its orientation and interrelation well known. It is within Fig. 2-2 for reason of completeness.
In this model, the Bärenkluft (described below) is related to the Keller fault of A2 and, due to its dip, to the fault visible in Ostergang of Faustloch. The estimated throw, the direction and the dip is in agreement. The completion of this model is only possible after the reopening of the Faustloch passage and probably the finding of additional cave passages between Faustloch and Bärenschacht.

2.6. Conclusions

The interpretion of fractures and their genesis was possible by observations in Bärenschacht. Stratigraphical observations helped to date the fault activity, and to resolve the buildup of the Waldegg. The Hohgant- Sundlauenen fault is proven to be synsedimentary in the Lower Cretaceous, and it has a throw of about 1000 m. Several other faults were active in the same time. The Waldegg is considered to be a Horst-Graben structure. During the overthrust of the Helvetic domain, thrust faults were created, and other normal faults were partially reactivated. At the emplacement at its present position, a third generation of faults fitted the nappe to the substratum.
The present structure of the Waldegg is made visible by geologic profiles and permits to gain new insight into parts that had hitherto never been observed.
An interpretation of the observations made in Faustloch is made. This interpretation is hypothetical due to the obstruction of a passage in Faustloch; however, it allows to get an idea about the tectonic setting of the region.

The investigations have shown that all the faults present had been cut by the karstwater. The morphology of the passages indicates no hanging watertable behind a fault, therefore we can conclude that the geologic structure is not responsible for a damming of the karstwater. Therefore, the observations of karst water tables indicate the height of the paleospring, and can be used for the temporal evolution of the cave system. The next chapter deals with the karstwater and explains the catchment delimitations as well as the interrelation between rock and water.

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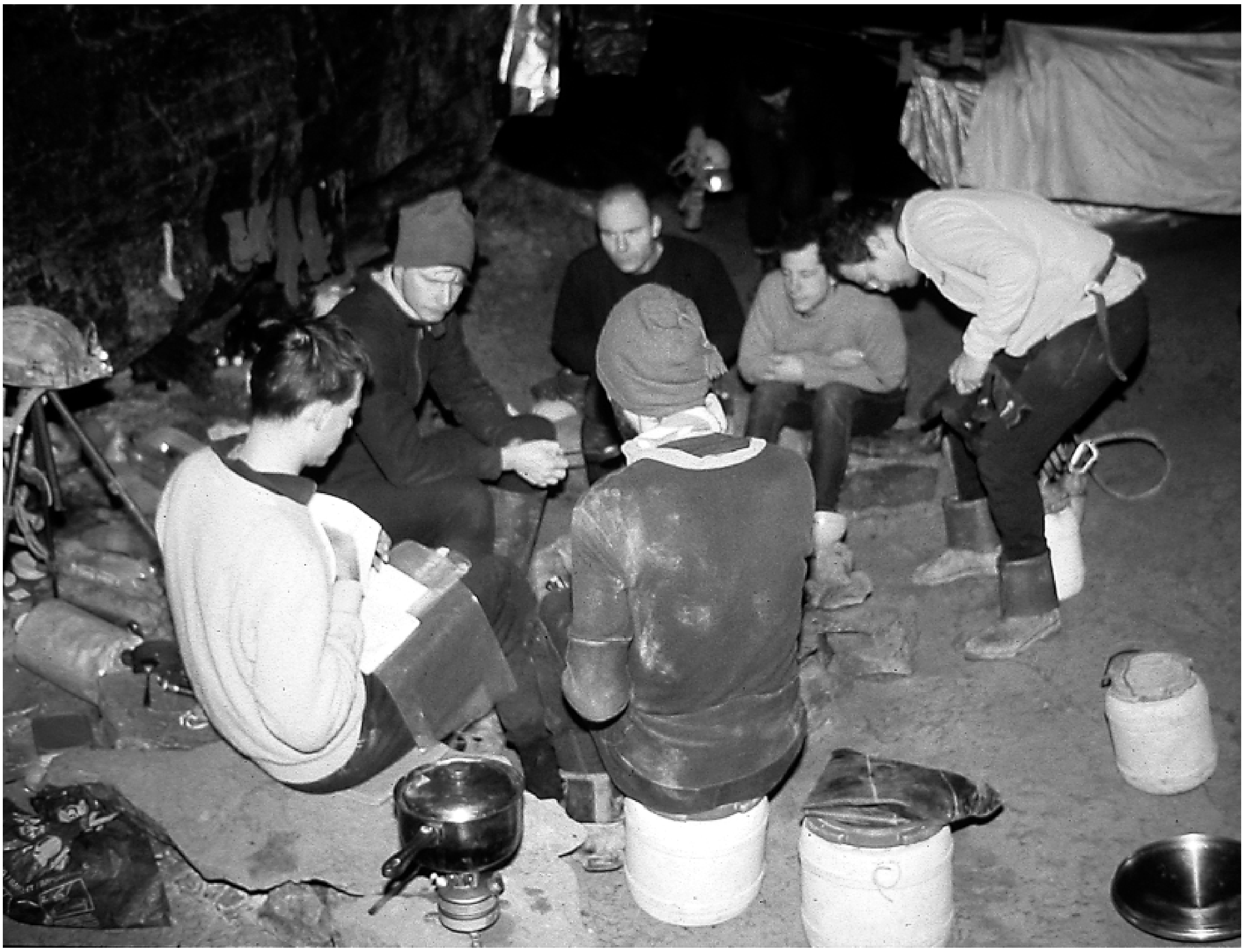


Bivouac in the Bärenschacht. *Photo by Daniel Burkhalter*
Biwak im Bärenschacht.
Bivouac au Bärenschacht.

3. Hydrogeology around the St. Beatus Cave and Bärenschacht

Dieses Kapitel befasst sich mit den unterirdischen Wasserwegen in der Region der St. Beatus-Höhlen und des Bärenschachts.
Kapitel 3.1 beschreibt drei Fliessmöglichkeiten im vadosen Raum, die praktisch alle Resultate von Färbversuchen erklären können. Die St. Beatus-Höhle zeigt alle drei Möglichkeiten. Speziell die Diffluenzen werden zur Erklärung von Färbversuchsresultaten, die im Kapitel 3.2 vorgestellt werden, herangezogen.
Kapitel 3.2 beschreibt alle im Raum Siebenhengste vorgenommenen Färbversuche und geht speziell auf den bislang unpublizierten Versuch von 1996 ein.
Das Ziel der Färbversuche war die Unterscheidung der Einzugsgebiete. Es zeigt sich, dass die St. Beatus-Höhle und das Réseau der Siebenhengste getrennte Einzugsgebiete haben. Aus diesem Grunde sollten die Höhlen sich unabhängig voneinander entwickeln. Beobachtungen zeigen aber, dass dies nicht der Fall ist: ein Zusammenhang besteht in der Region der Quelle, im Aaretal, wohin beide Systeme entwässern. Somit ist der Nutzen der Analyse von Höhlensystemen (statt einzelnen Höhlen) sowie die Abhängigkeit der Höhlen vom Tal bewiesen.

Ce chapitre traite des écoulements souterrains dans la région de la grotte de St. Béat et du Bärenschacht.
Le chapitre 3.1 décrit trois types d'écoulement dans la zone vadose qui peuvent expliquer quasiment tous les résultats de traçages. La grotte de St. Béat connaît les trois types. Les résultats des traçages décrits dans le Chapitre 3.2 sont en particulier interprétés en termes de diffluence.
Le chapitre 3.2 décrit tous les essais de traçage effectués dans la région des Siebenhengste. L'accent est mis sur le traçage de 1996, pas encore publié.
Le but de ces traçages est la délimitation des bassins versants. Il est prouvé que la grotte de St. Béat et le Réseau des Siebenhengste ont des bassins indépendants. Ainsi, les cavités seraient indépendantes. Cependant, les observations montrent des similarités: il doit exister un lien entre elles dans la région de la source, dans la vallée de l'Aare, qui draine les deux systèmes. On prouve l'utilité d'analyser des systèmes de cavités (au lieu de cavités isolées), ainsi que la dépendance des cavités avec le fond des vallées.

This chapter deals with the underground waterways in the region of St. Beatus Cave and Bärenschacht.
Chapter 3.1 deals with cross-formational flow, diffluence and transfluence. All three possibilities are often seen in the vadose parts of a cave and may explain all results of tracing experiments. The St. Beatus Cave contains all three possibilities of flow and may therefore be regarded as a hydrogeological model. Especially the diffluences are used to explain partially the results of some tracing experiments presented in Chapter 3.2.
Chapter 3.2 then describes all the tracing experiments undertaken in the Siebenhengste region and the surrounding karst areas. The last tracing experiment, conducted in 1996, was not published until now and is therefore described in detail.
The aim of this chapter is to present the tracing experiments made for the delimitation of the different catchment areas. It is found that the St. Beatus and Siebenhengste catchments are independent. Therefore, there should be no similarities between the caves. But both morphological and sedimentological observations (presented in Chapters 5 and 6) show that there are similarities: so there has to be a link. This link is the area of the spring, the Aare valley into which both cave systems drain. Thus, we evidence the interest of the study of cave systems (versus single caves) as well as the dependency of the caves from the valley.

A cave diver in a sump.

3.1. Cross-formational flow, diffluence and transfluence observed in St. Beatus Cave and Siebenhengste

Zusammenfassung: Cross-formational flow, Diffluenzen und Transfluenzen in den St. Beatus-Höhlen und den Siebenhengsten

Färbversuche im Karst zeigen oft seltsame Fliesswege. Viele dieser Resultate wurden bislang nur theoretisch erklärt, da kein natürliches Analogon beobachtet wurde. Wir haben solche Analoga gefunden, wobei wir uns vor allem auf die vadose Zone des Aquifers konzentrieren. Generell nimmt man an, dass diese Zone mehr oder weniger vertikal durchflossen wird, bis das Wasser auf einen Aquicluden stösst, entlang dessen es dann abfliesst. Der erste Eindruck der St. Beatus-Höhlen bekräftigt dieses Bild (Fig. 3-1); detaillierte Beobachtungen enthüllen aber einige Unterschiede. Die Resultate werden im Kapitel 3.2 verwendet.

Cross-formational flow
Im oberen Bereich des Drusbergmergels sind durch unterschiedliche Sedimentation Kalkbänke eingeschaltet, in denen Höhlengänge verlaufen. Die erste Erklärung für das Vorhandensein der Gänge ist in Fig. 3-3 gezeigt. Diese mag jedoch nicht zu befriedigen, da die Gänge (Fig. 3-4) zwischen den einzelnen Kalkbänken oszillieren. Diese Oszillation wurde bereits im Phreatischen angelegt. Wir finden in St. Beatus-Höhle und Bärenschacht sogar Gänge, die inmitten der Mergel liegen.
Diese Beispiele zeigen, dass Höhlenentstehung auch im phreatischen Bereich durchaus innerhalb, unterhalb und quer zu „Aquicluden“ verlaufen kann.

Diffluenzen
Das dendritische System unserer Oberflächenflüsse (der kleine Bach, der sich mit den anderen zum Fluss verbindet, der nach einem Zusammenfluss als Strom ins Meer mündet) ist wohlbekannt. Vor allem Hydrogeologen wissen, dass dies nicht die einzige Lösung von Wasserflüssen ist, da im Phreatischen das Wasser dem hydraulischen Gradienten folgt und somit eine Einspeisstelle mehrere Quellen haben kann. Nun aber ist vergleichbares Fliessverhalten auch aus Bereichen bekannt, wo die phreatische Zone weit unterhalb der geologischen Schwellen liegen müsste. Falls kein „undurchlässiges“ Gestein wie oben beschrieben verkarstet wurde, muss eine andere Erklärung gefunden werden. Eine mögliche Lösung liegt in der Tatsache, dass vadose Diffluenzen (Verzweigungen flussabwärts) in Höhlen durchaus häufig sind; nur schon in der St. Beatus-Höhle wurden deren gleich sieben gefunden, des weiteren sind vadose Diffluenzen aus Kaltbachhöhle, Senkloch, K2, Bärenschacht und dem Labyrinth der Siebenhengste (Fig. 1-7) bekannt, allesamt hängen sie nicht von der Geologie, sondern von der Ausprägung des Karstes ab. Ein extremes Beispiel ist am Eingang des Bärenschachtes zu finden (Fig. 3-7), wo drei Einzugsgebiete auf kleinstem Raum anzutreffen sind.

Transfluenzen
Es ist bekannt, dass in Gegenden, wo Karst von einer undurchlässigen Schicht bedeckt ist, oft die Karstwässer in eine andere Richtung fliessen als die Oberflächenflüsse einige Meter darüber. Weniger bekannt ist, dass dasselbe auch passieren kann, wenn keine undurchlässige Schicht vorhanden ist. Die Emme hinter dem Hohgant fliesst durch eine Schlucht im Schrattenkalk, in dem – etwas weiter unten – die Wässer der Schrattenfluh just in die andere Richtung, nämlich gegen den Thunersee hin, fliessen. Die Emme scheint jedoch kein Wasser zu verlieren. Es ist klar, dass in gelogischen Zeiträumen die Emme angezapft werden könnte; in geschichtlichen Zeiträumen (und deshalb auch für Färbversuche) ist jedoch der aktuelle Zustand massgebend.
Transfluenzen kommen auch innerhalb der St. Beatus-Höhlen (Hoher Nordgang, der den Ostgang überlagert) und des Labyrinths der Siebenhengste vor.

Schluss
Alle hier präsentierten Beobachtungen dienen als Analoga zur Erklärung der Resultate von Färbversuchen. Da in der St. Beatus-Höhle alle drei Fälle vorkommen, bildet die Höhle ein beobachtbares „hydrogeologisches Modell“.
Cross-formational flow, Diffluenzen und Transfluenzen erklären praktisch alle seltsamen Resultate von Färbversuchen. Wo die direkte Beobachtung in situ nicht möglich oder die Stratigraphie nicht genau bekannt ist, ist allerdings eine Bestimmung der Ursache oft nicht möglich.

Résumé: Cross-formational flow, diffluences et transfluences observées dans la grotte de St. Béat et les Siebenhengste

Les essais de traçage montrent souvent des résultats inattendus. Beaucoup de ces résultats n'ont des explications que théoriques, à défaut de phénomène naturel analogue. Nous en proposons plusieurs, qui concernent surtout la zone vadose de l'aquifère. Généralement, on admet que celle-ci est parcourue plus ou moins verticalement avant que l'eau ne bute sur un aquiclude, qu'elle suit alors suivant le pendage. A première vue, la grotte de St. Béat en est un bon exemple (Fig. 3-1), même si des observations détaillées apportent quelques nuances. Les résultats décrits ici sont utilisés dans le chapitre 3.2.

Cross-formational flow

La partie supérieure des marnes de Drusberg contient des bancs de calcaire, dans lesquels on trouve des galeries. La Fig. 3-3 propose une première hypothèse à la présence de ces galeries. Elle n'est cependant pas satisfaisante, parce que les galeries oscillent entre les différents bancs calcaires (Fig. 3-4). Cette oscillation est apparue en régime phréatique. De plus, certaines galeries de la grotte de St. Béat et du Bärenschacht se développent entièrement dans les marnes.

Ces exemples démontrent que la spéléogenèse en milieu phréatique peut très bien avoir lieu au sein, au-dessous et en travers des «aquicludes».

Diffluences

On connaît bien le système dendritique des rivières de surface (confluence de ruisseaux en rivière, puis de rivières en fleuve, qui se jette finalement dans la mer). Cependant, les hydrogéologues savent que ce n'est pas la seule situation; en milieu phréatique, l'eau suit le gradient hydraulique. Ainsi, une perte peut avoir plusieurs sources. Des situations comparables se présentent aussi lorsque la zone phréatique devrait se situer nettement en contrebas du seuil géologique. A défaut d'une karstification des «aquicludes» décrite ci-dessus, on peut trouver des diffluences vadoses (bifurcations des rivières vers l'aval). Ce phénomène est courant dans les cavités; pour la seule grotte de St. Béat, on en a trouvé sept exemples; il a été décrit en outre dans la Kaltbachhöhle, le Senkloch, le K2, le Bärenschacht et dans le labyrinthe des Siebenhengste (Fig. 1-7). Ces diffluences ne dépendent pas de particularités géologiques, mais du développement spécifique des galeries. On trouve un exemple extrême dans la zone d'entrée du Bärenschacht (Fig. 3-7), à la jonction de trois bassins versants sur une superficie très réduite. La taille de ces bassins dépend du débit de l'eau.

Transfluences

Lorsque le calcaire est coiffé de strates imperméables, on sait que les écoulements karstiques peuvent avoir une autre direction que ceux de surface situés quelques mètres au-dessus. Cela peut être le cas même en l'absence de strate imperméable. Au-delà du Hohgant, la gorge de l'Emme est creusée dans le Schrattenkalk, dont l'écoulement souterrain, en provenance de la Schrattenfluh, s'écoule vers le Lac de Thoune, soit dans la direction opposée. L'Emme ne subit pas de soutirage actuellement (à l'échelle historique, concernée par les traçages). Il est possible qu'elle ait eu des soutirages à l'échelle géologique.

Des transfluences ont été observées dans la grotte de St. Béat (le Hoher Nordgang est superposé à l'Ostgang), et dans le labyrinthe des Siebenhengste.

Conclusion

Les observations souterraines que nous présentons ici le sont en tant que situations exemplaires, à mettre en relation avec différents résultats de traçage. La grotte de St. Béat, véritable «modèle hydrogéologique» de terrain, contient des exemples de trois types de situation décrits.

Cross-formational flow, diffluences et transfluences peuvent expliquer quasiment tous les résultats étranges des essais de traçage. Cependant, une détermination exacte de la cause sera souvent impossible, là où l'observation in situ n'est pas possible et la stratigraphie n'est pas bien connue.

3.1.1. Introduction

Tracing experiments in karst often evidence unexpected flowpaths. Many of these results have had hitherto only theoretical explanations and no directly observable analogon. Observations in caves provide nice examples explaining this type of "strange" behaviour. We will mainly concentrate on the vadose parts of a karstic aquifer. As a general rule, water flowpaths in the vadose part are considered as being vertical to subvertical, until they reach either the phreatic parts or an aquiclude rock, on which they then flow towards the spring. The first impression of St. Beatus Cave matches exactly this rule (Fig. 3-1). However, detailed observations show that there are many differences to it, which shall be explained here. The results are partially used to explain the water tracings presented in Chapter 3.2.

3.1.2. Cross-formational flow

If a water course flows across a formation that is considered as hardly penetrable for water, then this is termed cross-formational flow. Such a flow is observed in St. Beatus Cave, it is described and interpreted here. The boundary between Drusberg marls and Schrattenkalk is not a sharp one (Fig. 3-1). Especially in St. Beatus Cave, but also in the Siebenhengste labyrinth (Bitterli 1990), we observe three beds of lime-

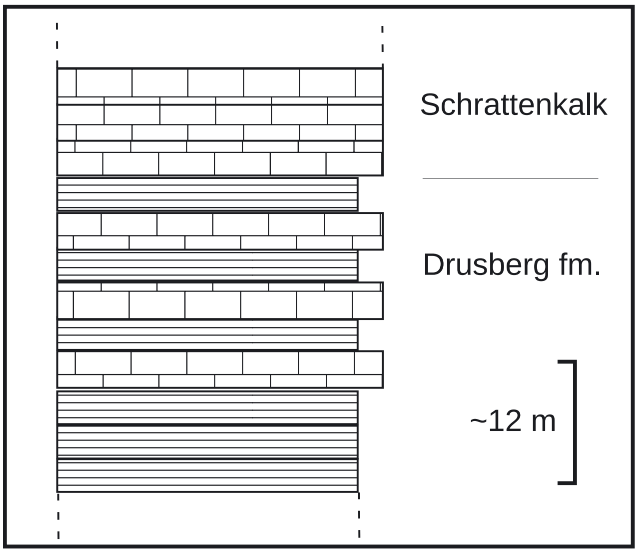


Fig. 3-2:
The interfingering of limestone and marly beds within the Drusberg formation.

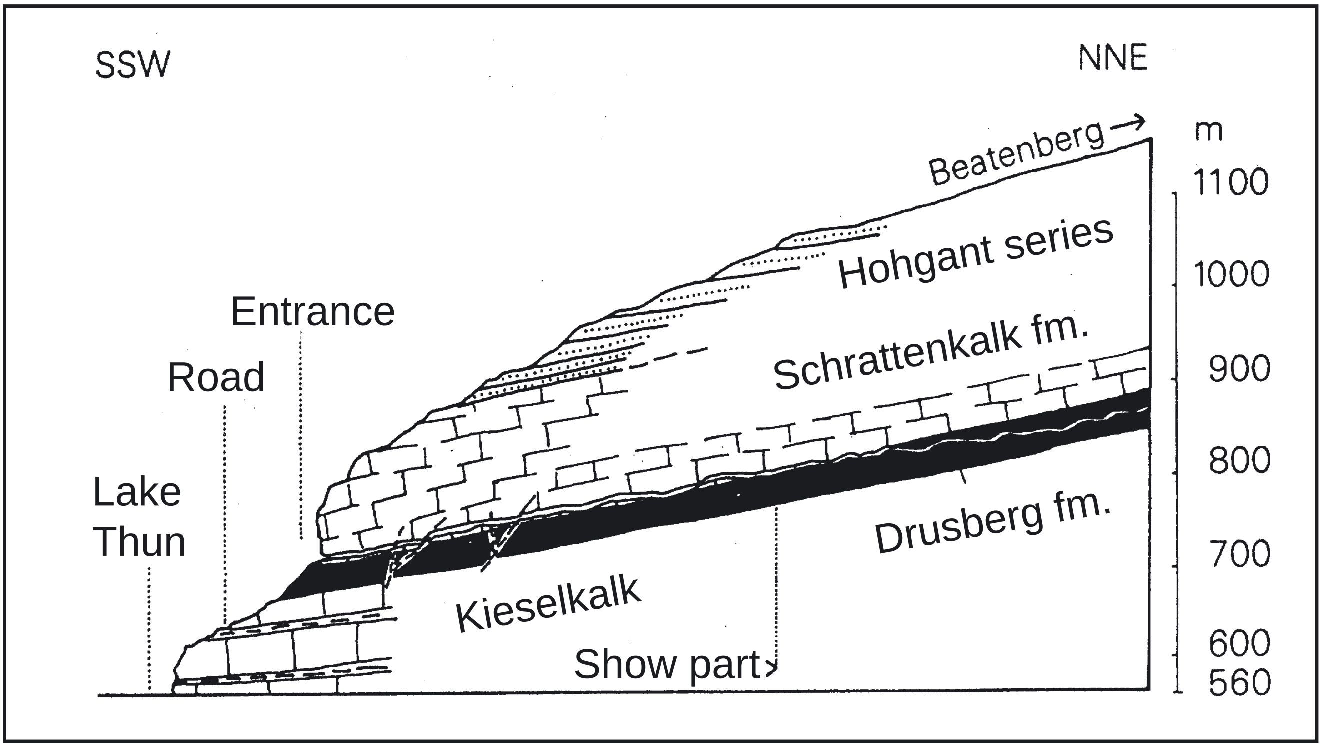
Die Wechsellagerung von Kalk und Mergel innerhalb der Drusbergformation.

Imbrication des bancs calcaires et marneux dans la formation de Drusberg.

Fig. 3-1:
Longitudinal section through the St. Beatus Caves (after Heim 1909).

Geologische Projektion durch die St. Beatus-Höhle.

Coupe géologique dans le secteur de la grotte de St. Béat.



stone within the uppermost Drusberg layers (Figure 3-2). This interbedding is due to the changes in sea level and consequent sediment deposition. At least one of those limestone layers disappears towards the entrance of St. Beatus Cave.

The observations of those different interlayers has been possible because there are several cave passages in them, that alternate between the limestone parts. Why are passages there? One possible explanation would be that the sedimentation of Schrattenkalk and Drusberg interfingers (as shown schematically in Fig. 3-3), and that the different water courses flowing towards the exit of the cave are then trapped between Drusberg layers. Whereas this might be a possibility for the initial capturing of the waters, observations show repeated jumping between the layers, which cannot be explained any more by simple trapping. Fig. 3-4 sketches schematically the observed conduits of St. Beatus Cave within the rock layers. The jumping observed is sometimes due to fractures, but often, this is not the case. For example, it is unclear why the water jumps up at Ostgangsiphon I, only to jump down the strata some 40 m further downstream, creating a shaft on a fracture.

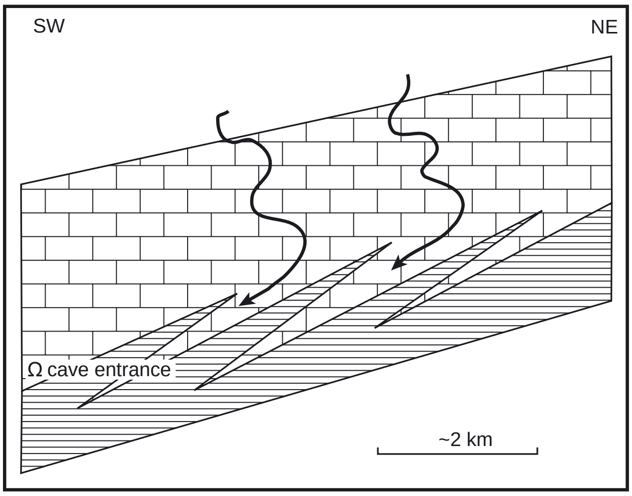


Fig. 3-3:
Possible explanation for the primary origin of the different water courses.

Eine mögliche Erklärung für das Entstehen von verschiedenen Wasserläufen.

Une explication possible pour la génération des écoulements différents.

It is well known that relatively thin aquicludes can be cut by the erosional forces of a vadose stream, allowing the water to flow into the strata below, as is the case in the Faustloch meander in Siebenhengste (for location see Fig. 1-7). The morphology of the galleries of St. Beatus Cave, however, show that the jumping (both up and down the strata!) already occurred in phreatic state. There are even some small parts of St. Beatus Cave that developed entirely within the marly parts of the "aquiclude”. The same thing is observed in nearby Bärenschacht, where most of the “Galerie des mille visages” (Fig. 3-7), about 200 m long, developed straight across the Drusberg marls on the left side of a thrust fault. Some tens of meters farther down, a phreatic gallery again crosses an upthrusted Drusberg block without any sign of following the limestone that lies some meters higher.

Those examples show that cave genesis is well possible within, below and across “aquicludes” under phreatic conditions. Therefore, geologically “impossible” results of tracing experiments are karstologically possible in both phreatic and vadose conditions.

3.1.3. Diffluences

The dendritic river pattern is ubiquitous on Earth’s surface. Hydrogeologists, however, know that under phreatic conditions, water flows according to its head, and that a karst region might have several springs connected to one injection point (see the example of Totes Gebirge in Austria by Maurin & Zötl 1964). So far, so good. Now, we know that diffluences also are proved by tracing experiments in regions where the phreatic realm should be much lower than the geologic barriers (for example in some parts of the Swiss Jura, Herold, pers. comm.). If we can exclude the above mentioned possibility of aquiclude karstification, another answer to this behaviour must be found.

One possible answer lies in the fact that vadose diffluences (rivers parting and taking two different ways) also exist and that they are much more numerous that one might think. In the St. Beatus Cave, we found at least six proven diffluences (Fig. 3-5).

1. The first one can be seen just behind the entrance to the cave. There, the water course divides from a lake dammed by sinter and breakdown. The two branches join again only at the surface.
2. The second is the brook fed by the sewage station from Beatenberg. It is met as a whole in the far end of Erosionsgang and later divides, reappearing in Bachgrotte and Spaghettigrotte.
3. The third, small one is a seepage in Erosionsgänge that divides on sinter floor.
4. The fourth one is found in Alibaba, where a waterfall partly splashes into Alibaba gallery (!) and partly into the main gallery of Westgang.
5. The fifth one is in Biwakgänge, where a lake, dammed by sinter, is emptied through both sides, since the inflow is coming from the ceiling of the cave.
6. The sixth one at the entrance of Der Vermisste, where the water divides on Sinter floor.
7. There is even a seventh one in the Tourist part, that divides only under flood conditions.

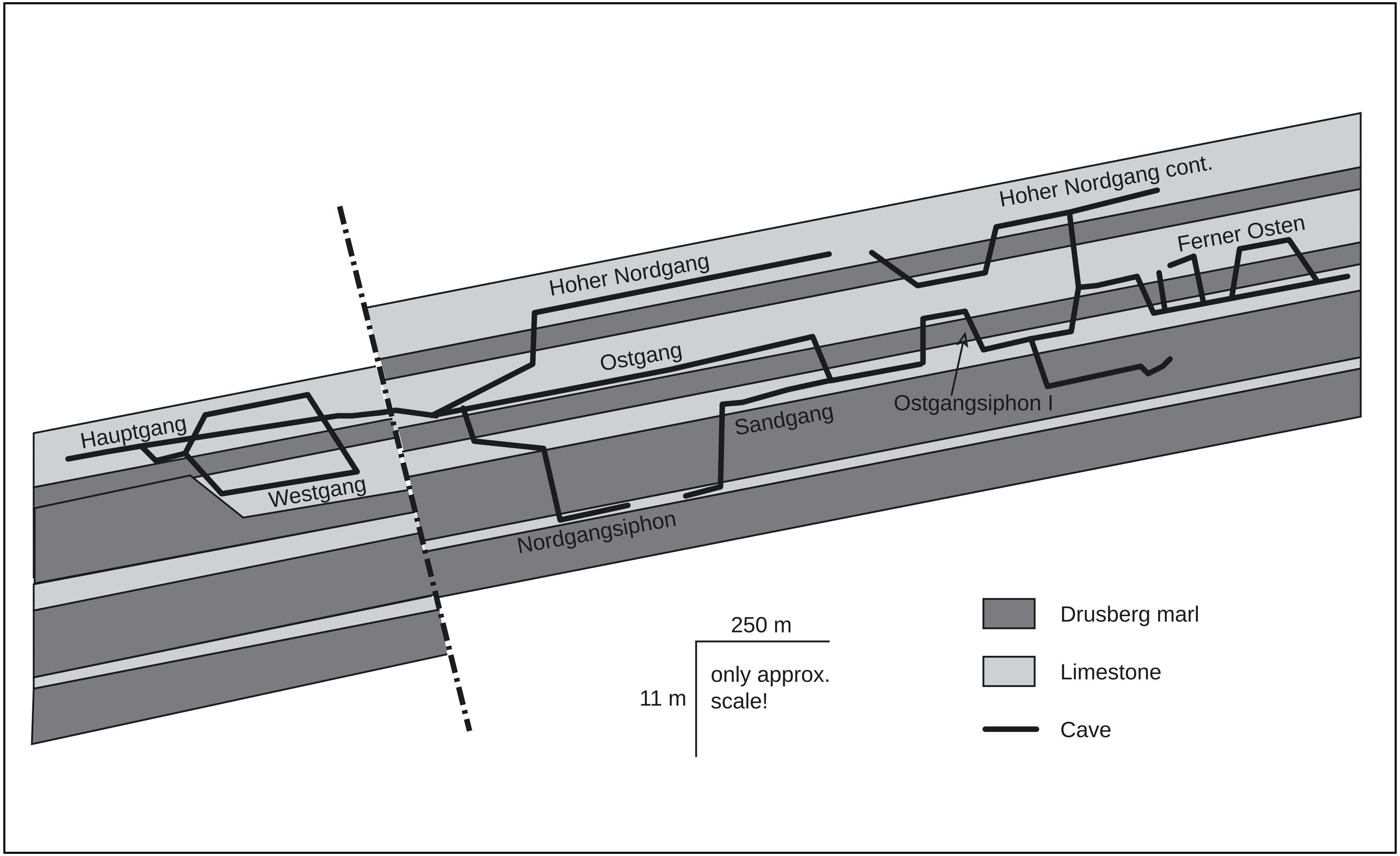


Fig. 3-4:
Schematic sketch through St. Beatus Cave with the location of the galleries in the stratigraphic column.

Schematische Projektion durch die St. Beatus-Höhle mit der Lokalisation der Gänge in der stratigraphischen Kolonne.

Projection schématique à travers la grotte de St. Béat, avec localisation des galeries dans la colonne stratigraphique.

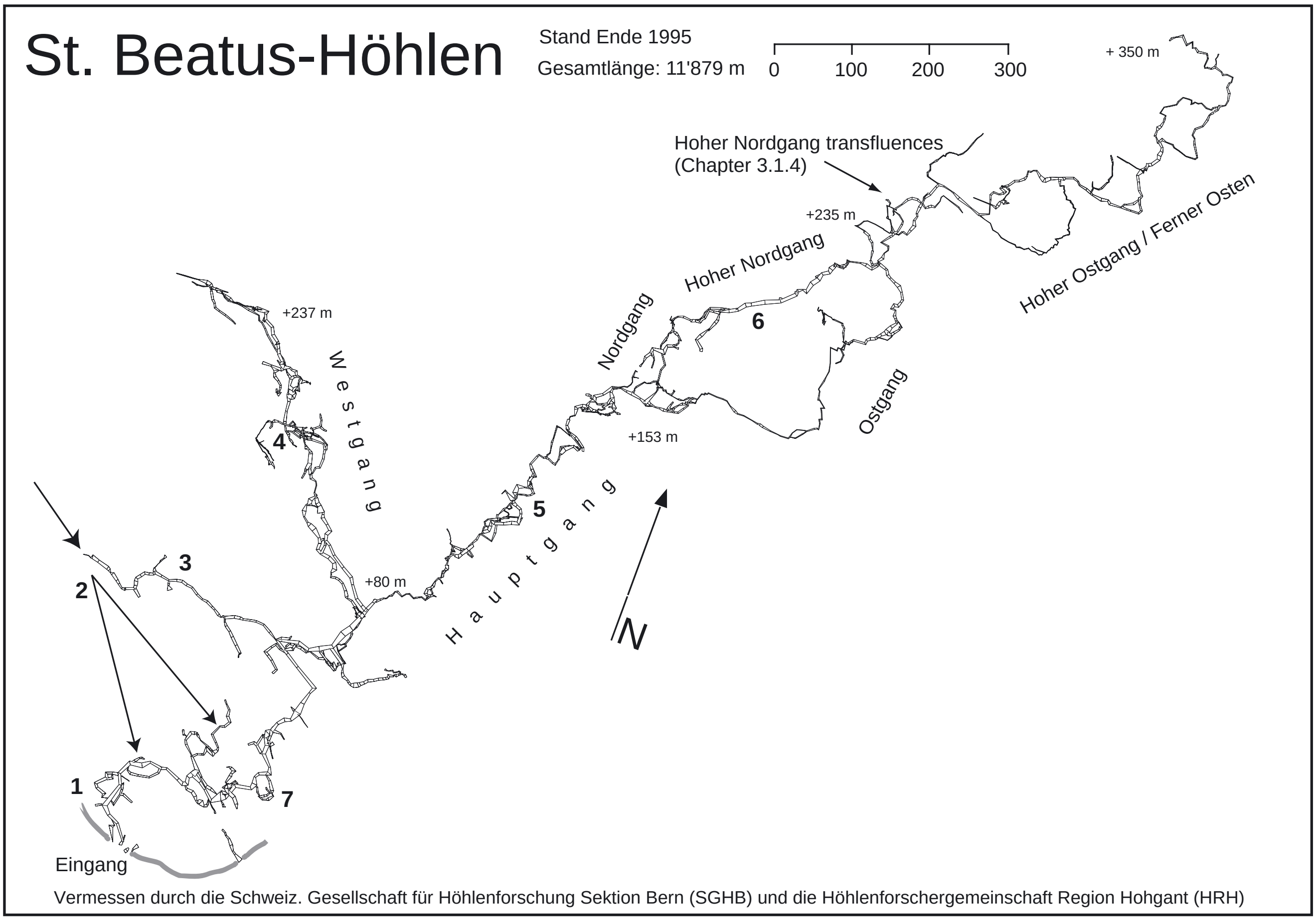


Fig. 3-5: Plan of the St. Beatus Cave with the location of the several diffluences. Tht numbers refer to the text.
Plan der St. Beatus-Höhlen mit den Fundstellen der Diffluenzen. Die Zahlen beziehen sich auf den Text.
Plan de la grotte de St. Béat avec la location des diffluences décrites. Les chiffres sont commentés dans le texte.

Other vadose diffluences are found in Kaltbachhöhle, Senkloch, K2, Bärenschacht, and the labyrinth of Siebenhengste. This enumeration is by far not complete. All cited examples are **not** dependent on local geology, but inherent to karstological features such as damming sinter (1, 5, 7), deposited sediments (Kaltbach), breakdown or gallery shape (2), flat gallery floors (3, 6, Senkloch, Bärenschacht), or simply by pure coincidence (4).

In all of the examples cited above, the water finally reappears at the same spring. But, of course, this is by no means obligatory, and depending on the voids encountered, flowpaths divided in vadose conditions might join quite different springs:

An extreme case of division is encountered near the entrance of Bärenschacht (Fig. 3-6 and 3-7). The small river disappearing just before reaching Bärenschacht entrance flows into Beatus cave (Häuselmann & Otz 1997 and Chapter 3.2). If there is high flood, it rushes down past Bärenschacht and flows down on the surface. Every water falling to the left side of this brook, within some 1000 m^2, will join Bärenschacht and therefore Bätterich spring.

As a conclusion, it seems that vadose diffluences are not as rare as assumed, but seem to be quite a common feature for underground rivers.

3.1.4. Transfluences

If karst rocks are overlain by impermeable caprocks, it is known that the surface streams often flow in another direction than the karstic flowpaths below. It is less known that the same thing may happen even if there's no caprock present. The Emme river flows through a gorge between Hohgant and Schrattenfluh, and this gorge is cut into the Schrattenkalk (Fig. 1-6). In the same Schrattenkalk, the waters coming from the Schrattenfluh (through cave passages) flow in direction of Lake Thun, so almost the opposite way. There is, at least in normal conditions, neither indication of waterloss in the Emme gorge nor indication

of cave forming processes. It is well possible that this Emme crossing is temporary and that the river may later dry up in profit of the subterranean system. However, today's state is important for tracing experiments.

Transfluences are also observed in St. Beatus Cave (Fig. 3-5). The Hoher Nordgang and the Ostgang were created at the same time and in phreatic conditions. They are divided by the uppermost Drusberg intercalation (see Fig. 3-4). Today, flow in both galleries is essentially vadose. The Hoher Nordgang river crosses the Ostgang several times without loss of water, until they eventually join to form the main gallery. Here, the division is due to geologic structure.
Another transfluence is known in Siebenhengste labyrinth, where a small brook from the Dakoté entrance of the Réseau (NE part of the labyrinth, Fig. 1-7) flows in southeast direction, whereas a rivulet in Blatersystem, some 150 m below, flows in southwestern direction (Hof, pers. comm).

Fig. 3-6:
The entrance of Bärenschacht seen from the brook flowing at the surface.

Der Eingang des Bärenschachtes vom Bächlein aus, das an der Oberfläche fliesst.

L'entrée du Bärenschacht à partir du ruisseau qui alimente la surface.

Photo by Peter Pfister

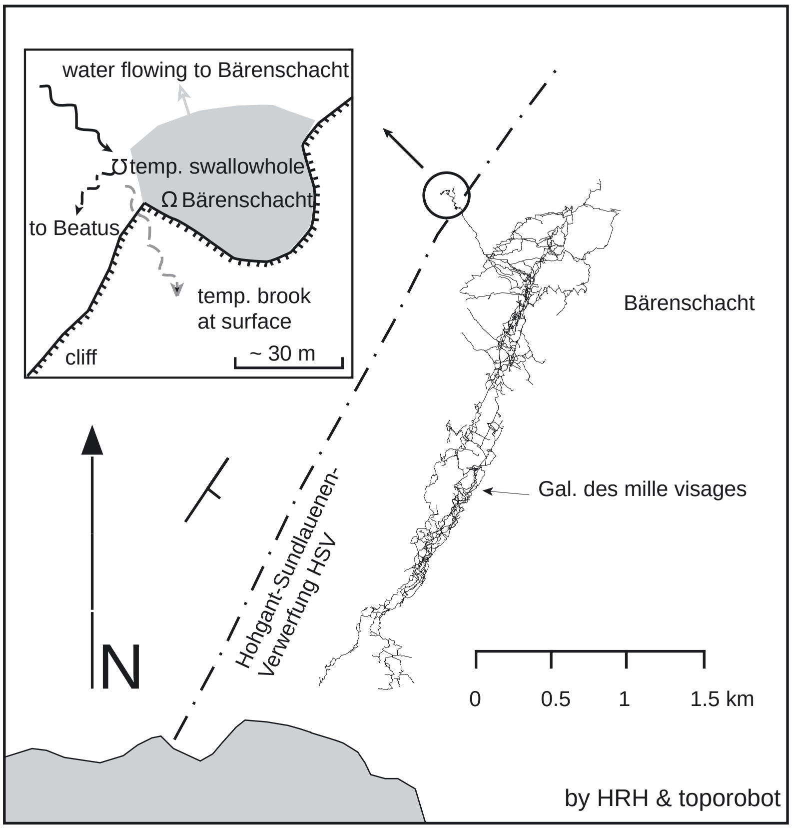


Fig. 3-7:
Illustration of the three different catchments at the entrance of Bärenschacht.

Illustration der drei verschiedenen Einzugsgebiete beim Bärenschacht-eingang.

Illustration des trois bassins versants différents autour de l'entrée du Bärenschacht.

3.1.5. Conclusion

It is demonstrated that cross-formational flow exists both in the phreatic as well as in the vadose zone, and that the karstification of marls is well possible. Vadose diffluences are very common in caves, in contrast to the river systems at the surface. Transfluences don't necessarily need a geologic barrier, therefore they are also possible within pure limestone.

All the observations presented here help to better understand the behaviour of tracing experiments. Especially in St. Beatus Cave, we observed all three cases of flow, therefore the cave represents a kind of a "hydrogeological model" that is observable *in situ*. It is important to note that all the three types of flow are basically independent on the evolution (single- or multiphased) of the cave system.

Cross-formational flow, diffluences and transfluences may therefore explain all "strange" results of tracings in karst regions. One problem, however, still exists: It will often be quite impossible to tell which of those three types is dominant and responsible for the result of the tracing experiment.

The diffluences will be used to explain unexpected results obtained in the tracing experiment of 1996 that is presented in Chapter 3.2.

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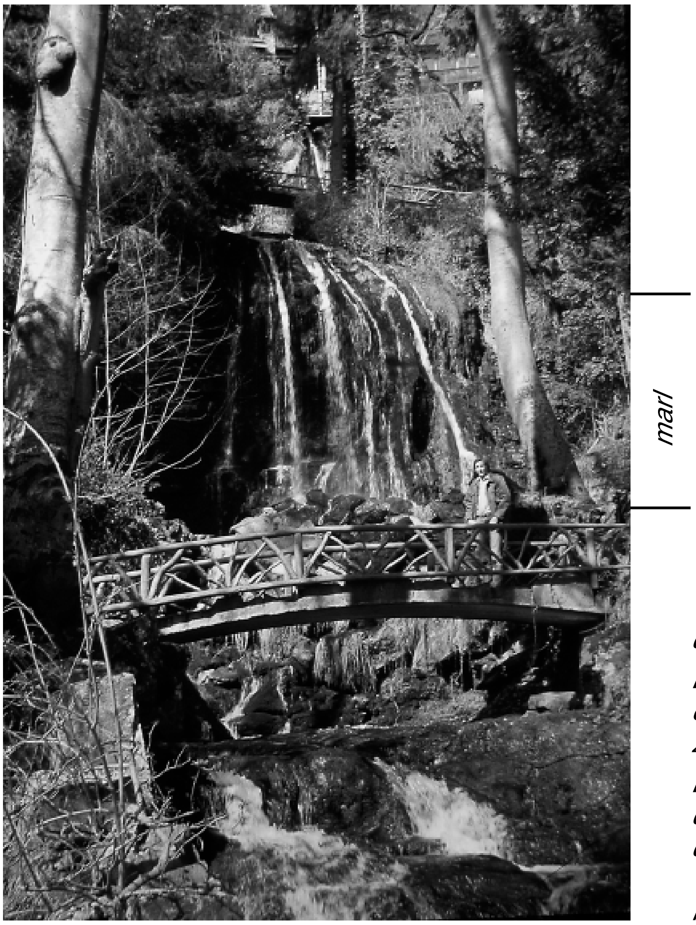


The waterfall at the entrance of St. Beatus Cave is due to marly strata between two limestone banks.

Der Wasserfall beim Eingang der St. Beatus-Höhle entstand wegen einer mergeligen Schicht zwischen zwei Kalkbänken.

La cascade à l'entrée de la grotte de St. Béat est due à l'interstratification d'un banc marneux entre deux bancs calcaires.

Photo by Anna Pfister

3.2. A review of the dye tracing experiments done in the Siebenhengste karst region

Zusammenfassung: Überblick über die Färbversuche im Karstgebiet der Siebenhengste

Dieses Kapitel behandelt alle in der Region der Siebenhengste durchgeführten Färbversuche. Ziel ist, die Unabhängigkeit der Einzugsgebiete von Bätterich/ Siebenhengste einerseits und von der St. Beatus-Höhle (und somit der Höhlen selbst) andererseits nachzuweisen.

Nach dem 2. Weltkrieg benötigte Interlaken eine bessere Trinkwasserversorgung. Die Goldeyquellen am Fuss des Harders wurden untersucht, bald die ersten Färbversuche unternommen. Da diese jedoch teilweise von Höhlenforschern gemacht wurden, sind sie häufig nicht publiziert. Das Ziel dieses Kapitels ist, eine komplette Übersicht über alle je in der Region gemachten Färbversuche zu geben. Der letzte grosse, 1996 durchgeführte Versuch wird im Detail beschrieben.

Färbeversuche zwischen 1946 und 2001

Es werden in chronologischer Reihe die Färbeversuche in der näheren und weiteren Umgebung der Siebenhengste präsentiert und teilweise auch interpretiert. In dieser Zusammenfassung werden nur die offenen Fragen dargelegt. Die Dokumentation vieler Versuche befindet sich im HRH-Archiv.

Färbversuch Nr. 3, 1959: Das Auftreten von Farbe in Interlaken ist zweifelsfrei nachgewiesen. Da im späteren Färbversuch Nr. 9 keine Farbe mehr auftrat, wurde das alte Resultat als Fehler interpretiert. Tatsächlich aber muss dieses korrekt sein; als Erklärung ist die 1959 sehr starke Schneeschmelze möglich. Auf alle Fälle ist eine Verbindung Innerbergli-Harder nachgewiesen.

Färbversuch Nr. 9, 1973: Nebst der in unseren Augen falschen Interpretation der Verbindung Innerbergli-Harder besteht bei genauerem Hinsehen eine Inkonsistenz im übergebenen Rapport: es werden zwei unterschiedliche Zeiten für das erste Auftreten von Farbe im Gelberbrunnen angegeben.

Färbversuch Nr. 15, 1984: Die angegebenen Resultate sind nicht in Übereinstimmung mit den physikochemischen Parametern der Wässer, darüber hinaus werden zwei unterschiedliche Zeiten für das erste Auftreten von Farbe angegeben. Aus diesem Grunde wurde dieser Versuch 1996 teilweise wiederholt.

Das Resultat dieser 20 Färbversuche führte zur Ausarbeitung einer Karte der Einzugsgebiete (Fig. 1-6).

Der Färbeversuch 1996

Während die Abgrenzung des Einzugsgebietes der St. Beatus-Höhlen von SE über SW bis NW recht klar ist, existiert keine morphologisch sichtbare Grenze gegen die Siebenhengste zu. Deshalb wurde der Färbversuch 1996 gestartet. Gleichzeitig wurden offene Fragen im Fitzlischacht und um den Bärenschacht herum angegangen.

Eine detaillierte Beschreibung der Planung und Durchführung des Versuchs findet sich in Häuselmann (1997). Sieben Eingabepunkte wurden ausgewählt; nebst den Quellen wurden auch die Oberflächenbäche beprobt, um eine lückenlose Dokumentation zu erhalten. Wegen des temporären Charakters einiger Bäche musste das Wetter stimmen, was am Wochenende des 12./13. Oktobers 1996 der Fall war. Dennoch musste an zwei Orten nachgewässert werden. Die Beprobung wurde zu Beginn häufig durchgeführt, die Intervalle wurden danach allmählich verlängert, bis am Ende (fünf Wochen nach Eingabe der Farbe) nur noch alle drei Tage beprobt wurde.

Die Bestimmung der Farbstoffe wurde fluorometrisch durchgeführt. Nach der Erstellung einer Eichkurve wurde die erhaltene Farbstoffmenge quantitativ bestimmt. Da die Schüttung der Quellen nur geschätzt wurde, sind die angegebenen Mengen ebenfalls approximativ. Für gewisse Farbstoffe ist eine Peak-Überlappung nicht auszuschliessen, deshalb wurde mit HPLC die Farbstoffart nachkontrolliert.

Die Resultate sind wie folgt: Die Farbe des Fitzlischachtes gelangte wie erwartet in die St. Beatus-Höhlen; allerdings zeigte der Ostgang keine Farbe an. Die Bäche oberhalb des Bärenschachtes kamen ebenfalls in der St. Beatus-Höhle zum Vorschein. Die in der Region der Gemmenalp eingegebenen Farbstoffe verschwanden im Karst der Hohgant-Serie, traten weiter unten wieder an die Oberfläche und gelangten somit via Büelbach und Lombach in den Thunersee. Die Doline in der Bäreney, auch in der Hohgantserie gelegen, entwässerte in den Bätterich.

Die im Folgenden wiedergegebenen Interpretationen zeichnen summarisch die wichtigsten Ideen nach.

Die langsame Fliessgeschwindigkeit Fitzlischacht-St. Beatus-Höhlen kann mit einer (karstologisch) jungen

Verbindung erklärt werden. Das Nichtauftreten von Farbe im Ostgang ist nur mit dem herrschenden Niedrigwasser erklärbar, das eine Farbstoffdiffluenz in unbegehbaren Teilen der Höhle verunmöglicht. Dahingegen spricht eine Diffluenz des Hohen Nordgangs in den Nordgangsiphon hinunter für das beobachtete Auftreten von Farbe an beiden Orten. Berechnungen der physikochemischen Parameter des unbekannten, zusätzlich nötigen Gewässers unterstützen diese Hypothese.

Die in der Gegend oberhalb des Bärenschachtes in die Bäche eingegebenen Farben erscheinen in der St. Beatus-Höhle. Dies beweist die besondere Stellung des Bärenschachteinganges im Einzugsgebiet der St. Beatus-Höhle (Fig. 3-7). Die langsame Fliesszeit ist durch die karstologisch junge Verbindung leicht erklärbar.

Das Wiederauftreten der im Raume Gemmenalp eingegebenen Farbstoffe im Büelbach ist nicht sehr erstaunlich, wenn man dem komplexen Aufbau der Hohgant-Serie Rechnung trägt. In diesem Sinne verhalten sich die Ponore dieser Region wie diejenigen des Trogenmooses (Färbversuch Nr. 12).

Die Verbindung Bäreney-Bätterich ist angesichts der ähnlichen Lage innerhalb der Hohgantserie schon eher erstaunlich. Allerdings ist diese Zone tektonisch stark beansprucht (HSV und Faille de Bäreney), und deshalb ist ein Hindurchsickern der Farbe eher möglich. Die Konzentrationsdifferenzen zwischen Bätterich und Gelberbrunnen können mit verschiedenen Szenarien befriedigend erläutert werden.

Das Nichtauftreten von Farbe in der Quelle Neuhaus bestätigt die Annahme Knuchels, dass diese Quelle von lokalem Karst der Waldegg gespiesen wird. Wieviel das Gundwasser der Interlakner Ebene zur Schüttung beiträgt, ist unklar.

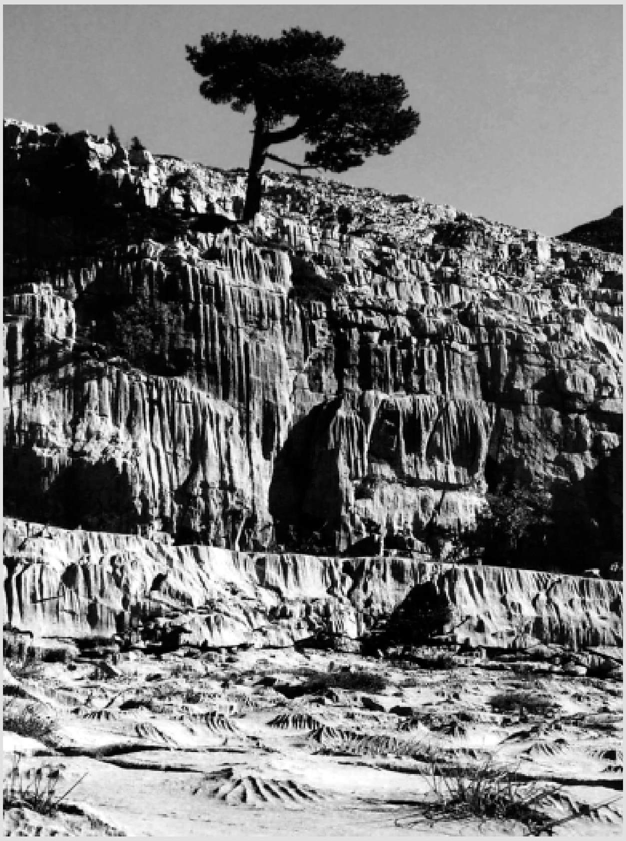
Schlussfolgerung

Der Färbversuch 1996 beantwortet einige wichtige Fragen. Zusammen mit der Analyse der unpublizierten Resultate kann nun eine neue Karte der Einzugsgebiete (Fig. 3-20) gezeichnet werden.

- Das Einzugsgebiet der St. Beatus-Höhle reicht weiter nordwärts als bisher angenommen.
- Der Eingang des Bärenschachtes liegt innerhalb des Einzugsgebietes der St. Beatus-Höhlen. Einzig das lokale Fallen in Richtung SE, gekoppelt mit dem Versatz der HSV, der eine kalkigere Varietät der Hohgantserie an die Basis des Schrattenkalkes bringt, erlaubt die Genese des Bärenschachtes in Richtung Réseau.
- Die Region Gemmenalp entwässert via Hohgantkarst schliesslich oberflächlich.
- Siebenhengste, Hohgant und Schrattenfluh entwässern in Bätterich und Gelberbrunnen. Der Hohgant zeigt bei grossen Hochwässern eine Verbindung zu den Harderquellen.
- Diese werden zur Hauptsache vom Einzugsgebiet entlang des Streichens gespiesen.
- Der Emmesprung NE davon markiert wohl das Ende des Harder-Einzugsgebietes und grenzt somit auch das Brüniggebiet im W ab.
- Die Quelle Neuhaus ist von Lokalkarst gespiesen.

Die Resultate zeigen, dass die Einzugsgebiete von St. Beatus-Höhle und Bärenschacht unabhängig voneinander sind. Aus diesem Grunde müssen allfällige Ähnlichkeiten von der Quellregion und somit vom Tal abhängen. Das nächste Kapitel behandelt die Morphogenese von Höhlengängen. Die Resultate werden sodann zu einer Definition der speläogenetischen Phasen benutzt.

Selbstverständlich sind noch Fragen offen. Die Abgrenzung des Einzugsgebietes SW der St. Beatus-Höhle ist genauso unbekannt wie dessen Quelle, die im Thunersee liegen muss. Weiter ist unklar, ob die gesamte Schrattenfluh in den Bätterich entwässert. Ein Färbversuch ist jedoch in Planung. Schliesslich ist die Begrenzung des Emmesprung-Einzugsgebietes gegenüber demjenigen des Harders und des Brünigs unbekannt.



The Innerbergli karren field. Photo by Ivo Baron
Das Karrenfeld des Innerberglis.
Le lapiaz de l'Innerbergli.

Résumé: Synthèse des essais de traçage dans la région karstique des Siebenhengste

Ce chapitre passe en revue tous les essais de traçage réalisés dans la région des Siebenhengste. Notre objectif est de prouver l'indépendance des bassins versants du Bärenschacht et de la grotte de St. Béat. Après la 2ème guerre mondiale, Interlaken avait besoin d'une alimentation supplémentaire en eau potable. Les sources de Goldey au pied du Harder ont été observées, et bientôt les premiers essais de traçage ont été entrepris. Les essais de traçage ont été souvent faits par des spéléologues, et tous ne sont pas publiés. Le second objectif de ce chapitre est de passer en revue tous les traçages réalisés dans la région. La dernière grande campagne (1996) est notamment décrite en détail.

Essais de traçage entre 1946 et 2001

Les essais de traçage dans la région des Siebenhengste sont présentés dans un ordre chronologique, et partiellement interprétés. Le résumé français ne présente que les questions restées ouvertes. On trouvera la documentation de plusieurs essais de traçage dans les archives de la HRH.

Essai de traçage no. 3, 1959: L'apparition du colorant à Interlaken est indiscutable. Vu que ce phénomène ne s'est pas reproduit lors de l'essai no. 9, la réapparition a été contestée. Actuellement, ce résultat est validé, une explication possible en étant la crue majeure suite à la fonte des neiges en 1959. La liaison Innerbergli-Harder est prouvée indubitablement.

Essai de traçage no. 9, 1973: A part l'interprétation de la liaison Innerbergli-Harder discutée ci-dessus, à nos yeux injustifiée, on relèvera une incohérence: dans le rapport, on signale deux heures différentes pour la première apparition du colorant au Gelberbrunnen.

Essai de traçage no 15, 1984: Les résultats décrits ne correspondent pas aux paramètres physico-chimiques des eaux; de plus, on signale à nouveau deux heures différentes pour la première apparition du colorant. C'est pour cette raison que l'essai a été partiellement répété en 1996.

Les résultats de ces 20 essais de traçage ont permis l'élaboration d'une carte des bassins versants (Figure 1-6).

La campagne de 1996

Tandis que la délimitation SE-SW-NW du bassin versant des grottes de St. Béat est relativement claire, il n'y a pas de frontière nette du côté des Siebenhengste. C'était l'objectif principal de l'essai de traçage de 1996, qui concernait également le Fitzlischacht et le Bärenschacht.

Pour une description détaillée de l'organisation et de l'exécution du traçage, on consultera Häuselmann (1997). Sept points d'injection ont été choisis; en plus des sources, plusieurs ruisseaux de surface ont été surveillés pour obtenir une documentation exhaustive. Vu le caractère temporaire de quelques ruisseaux, la météo jouait un rôle important. Le week-end du 12 au 13 octobre 1996, le traçage commença, et deux sites durent être arrosés. L'intervalle d'échantillonnage, court au début, a été prolongé peu à peu, jusqu'à la fin de l'essai (cinq semaines après l'injection, tous les trois jours).

La détermination des colorants a été faite par fluorométrie. Une fois une courbe de calibration établie, on détermina le dosage. Les débits des sources étant seulement estimés, les dosages sont approximatifs. Pour certains colorants, on ne pouvait exclure une superposition des pics, et la détermination des colorants a été vérifiée par HPLC.

Les résultats sont les suivants: on retrouve le colorant du Fitzlischacht dans la grotte de St. Béat comme prévu. Il ne réapparaît cependant pas dans l'Ostgang. Les ruisseaux proches du Bärenschacht réapparaissent également dans la grotte de St. Béat. Les colorants injectés dans la région de la Gemmenalp pénètrent dans le karst de la série du Hohgant pour sortir en aval et s'écouler en surface via le Büelbach et le Lombach. La doline de la Bäreney, située elle aussi dans la série du Hohgant, est drainée vers la résurgence du Bätterich.

Voici une synthèse sommaire des interprétations:

La faible vitesse d'écoulement entre le Fitzlischacht et la grotte de St. Béat est peut-être due à une relation (karstologiquement) jeune. L'absence de colorant dans l'Ostgang n'est explicable que par l'étiage qui éviterait une diffluence dans une zone inconnue de la cavité. Par contre, la réapparition dans le Nordgang et le Hoher Nordgang peut être facilement expliquée par une diffluence du dernier vers l'aval. Le calcul des paramètres physico-chimiques d'un hypothétique affluent inconnu confirme cette hypothèse.

Les colorants injectés dans les ruisseaux en amont du Bärenschacht réapparaissent dans la grotte de St. Béat, prouvant ainsi la position privilégiée de l'entrée du Bärenschacht dans le bassin versant de la grotte de St. Béat (Fig. 3-7). La faible vitesse d'écoulement s'expliquerait par une liaison karstologiquement jeune.

La réapparition au Büelbach des colorants injectés dans la région de la Gemmenalp n'est pas étonnante, compte tenu de la stratigraphie complexe de la série du Hohgant. Dans ce sens, les ponors de cette région se comportent de la même manière que ceux du Trogenmoos (essai de traçage no. 12).

La liaison Bäreney-Bätterich est plus intéressante, étant donné que la position de la doline dans la série du Hohgant est comparable. Cette zone est sujette à des tensions tectoniques importantes (HSV et faille de Bäreney), et le passage du colorant le long des fractures est envisageable. Les différences de concentration entre Bätterich et Gelberbrunnen sont expliquées par différents scénarios.

L’absence de colorant dans la source de Neuhaus confirme l’hypothèse de Knuchel, selon laquelle cette source serait alimentée par le karst local de la Waldegg. La contribution de la nappe de la plaine d’Interlaken ne peut pas être quantifiée.

Conclusion

L’essai de traçage de 1996 répond à plusieurs questions importantes. Nous proposons une nouvelle carte des bassins versants, tenant compte des résultats non publiés (Fig. 3-20).

- Le bassin versant de la grotte de St. Béat s’étend plus au nord que ce que l’on supposait antérieurement.
- L’entrée du Bärenschacht se situe dans le bassin versant de la grotte de St. Béat. Seul le pendage local vers le SE, couplé avec le rejet de la HSV mettant en contact une couche calcaire de la série du Hohgant et des marnes du Drusberg, permettent le développement du Bärenschacht vers le Réseau.
- La région de la Gemmenalp est drainée vers la surface par le karst de la série du Hohgant.
- Siebenhengste, Hohgant et Schrattenfluh s’écoulent vers Bätterich et Gelberbrunnen. Le Hohgant communique avec les sources du Harder en temps de crue.
- Celles-ci sont principalement alimentées par leur bassin versant, qui s’étend le long des strates.
- Au NE, l’Emmesprung marque probablement la limite du bassin versant du Harder et délimite ainsi le bassin versant du Brünig à l’W.
- La source de Neuhaus est alimentée par un karst local.

Ces résultats prouvent que les bassins versants du Bärenschacht et des grottes de St. Béat sont indépendants. Les éventuelles similitudes ne peuvent dépendre que de la source – autrement dit, de la vallée. Le prochain chapitre traite de la morphogenèse des galeries, qui permettra de définir des phases spéléogénétiques.

La délimitation du bassin versant qui s’étend au SW de celui de la grotte de St. Béat n’est pas connue, tout comme sa source qui doit se trouver dans le lac de Thoune. Par ailleurs, on ne sait pas si l’ensemble de la Schrattenfluh s’écoule vers le Bätterich. Un essai de traçage est prévu. Finalement, la limite entre les bassins versants de l’Emmesprung et ceux du Harder et du Brünig n’est pas encore déterminée.

The St. Beatus Cave river in flood troubles Lake Thun.

Der Fluss der St. Beatus-Höhlen bei Hochwasser trübt den Thunersee ein.

La rivière de la grotte de St. Béat en crue trouble le lac de Thoune.

3.2.1. Introduction

This chapter presents all the tracing experiments ever conducted in the Siebenhengste region. The aim is to prove that the Bätterich/Bärenschacht catchment and the St. Beatus Cave catchment are independent from each other. Thus, any similarities observed within the caves are dependent on their spring region.

After the 2nd world war, the town of Interlaken needed a better water supply. So, temporary springs ("Harder springs", Fig. 3-20) at the southern foot of the Harder chain near the town were investigated. Following precise observations of the spring behaviour, Franz Knuchel, teacher in Interlaken, made the first tracing experiment, with a dye injection point in the Innerbergli karren field near Hohgant peak. The result left more questions than answers. Therefore, many more tracing experiments were done, partly by professionals (Universities), partly by cavers. Many of the experiments are not published. The second aim of this chapter is to review the results of this long-lasting work. Many data presented here have been found in the archive of the research group "Höhlenforschergemeinschaft Region Hohgant" HRH.

The results of the past tracing experiments allowed a good delineation of the different catchment areas (Fig. 1-6) and about the effective waterways within the caves. However, several questions still persisted. Especially the differentiation between the St. Beatus Cave catchment and the Siebenhengste catchment in the region of the Gemmenalphorn was still unclear. Additionally, the 1996 tracing experiment should evidence if the Bärenschacht entrance lies within the catchment area of the Bätterich spring.

3.2.2. Water tracing experiments between 1946 and 2001

To our knowledge, no water tracing experiment was conducted prior to 1946. In the following text, we summarise the tracing experiments in chronological order. Table 1 and Figure 3-8 gives more detailed information. An eventual interpretation is also given here.

Tracing No. 1, 1946: Häliloch-St. Beatus Cave (Fluoresceine). This is the first water tracing experiment done in the region, after some trials with sawmill powder. 17 springs had been observed, the Fluoresceine was clearly visible in St. Beatus Cave after 30 hours, some suppositions in Gelber Bunnen later proved wrong. The colour came from both Nordgang and Ostgang of St. Beatus Cave (Fig. 3-11), the flow velocity (111 m/h) was rather low for free-flowing karst water. There is only a handwritten manuscript by Franz Knuchel available.

Tracing No. 2, 1953: Birenbach-St. Beatus Cave and Haselegg (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. The first appearance in Haselegg after 23 h could not be determined precisely, since no observer was present, therefore the calculated velocity of 73 m/h is very approximative. The experiment was led by teachers P. Grossniklaus and F. Knuchel with their school classes. 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 (Fluoresceine). The weather situation as well as the springs observed are clearly documented (Knuchel 1959). The first appearance of colour at the Harder springs after 22 hours (443 m/h) is proved by reports (Fig. 3-9) and pictures. 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). The experiment was led by Franz Knuchel, who also wrote an unpublished report (Knuchel 1959).

The proved appareance of dye in the Harder springs 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 the Harder springs. A reason for the dye appearance might be the very high floods (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, to our opinion, the traverse of the Habkern syncline is proved, 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

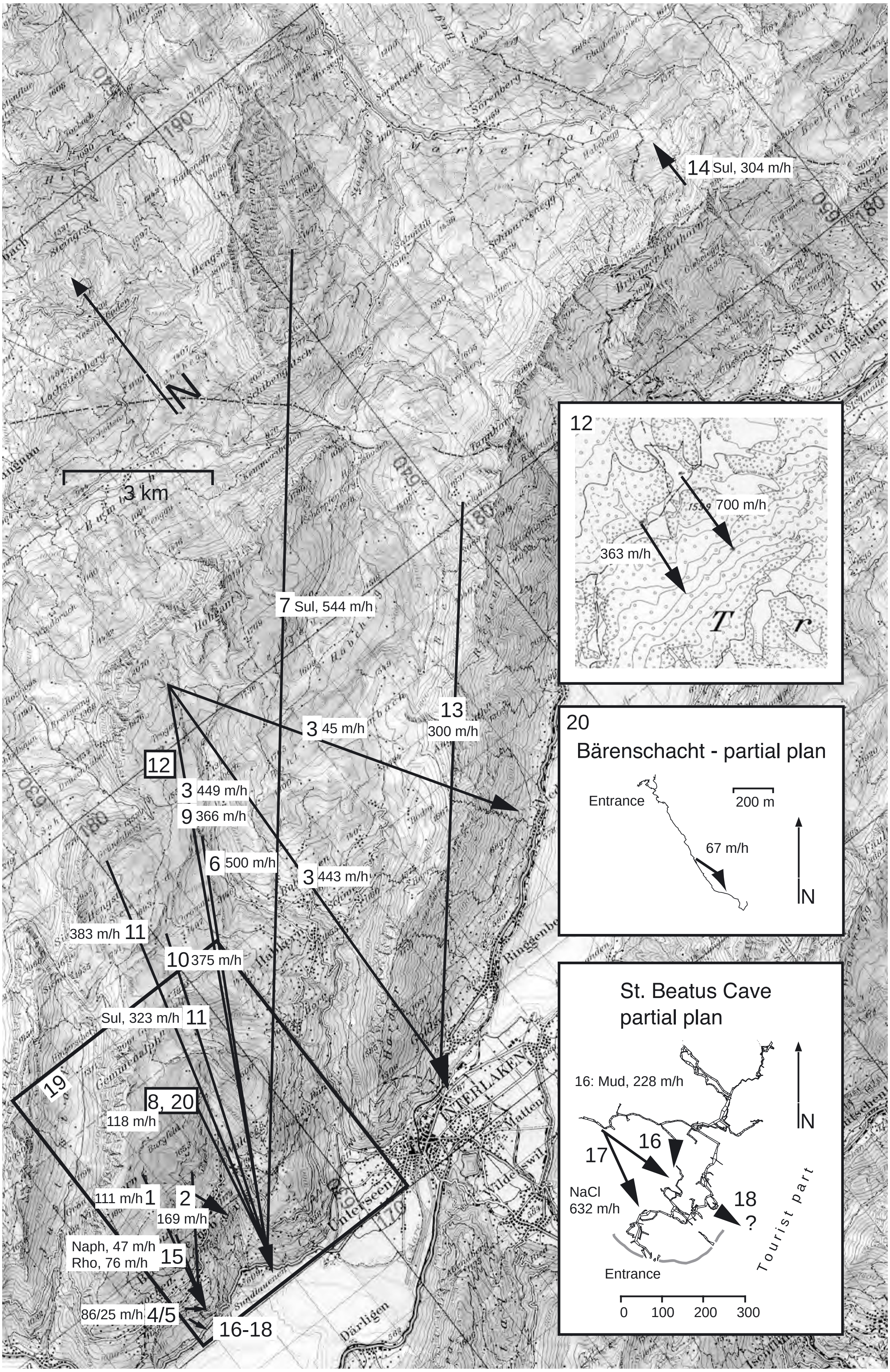

14 Sul, 304 m/h
N
3 km
7 Sul, 544 m/h
13
300 m/h
3 45 m/h
12
3 449 m/h
9 366 m/h
6 500 m/h
3 443 m/h
383 m/h 11
10 375 m/h
Sul, 323 m/h 11
19
8, 20
118 m/h
111 m/h 1
2
169 m/h
Naph, 47 m/h
Rho, 76 m/h 15
86/25 m/h 4/5
16-18
12
700 m/h
363 m/h
20
Bärenschacht - partial plan
Entrance
200 m
67 m/h
N
St. Beatus Cave
partial plan
16: Mud, 228 m/h
16
17
NaCl
632 m/h
18
?
N
Tourist part
Entrance
0 100 200 300

Fig. 3-8 (left):
Map of the region with the various tracing experiments. Small maps are inserted for the tracing experiment No. 12 (Trogenmoos), 16-18 (St. Beatus Cave), and 20 (Bärenschacht). The large frame shows the location of Fig. 3-13 for the tracing No. 19 whose results are not represented here. Abbreviations: Rho=Rhodamine B; Sul=Sulforhodamine; Naph=Naphtionate; all other tracings were done with Fluoresceine/Uranine or NaCl.

Karte der Region mit den verschiedenen Färbversuchen. Kleine Karten sind eingefügt für die Versuche Nr. 12 (Trogenmoos), 16-10 (St. Beatus-Höhle) und 20 (Bärenschacht). Der Rahmen hat die Grösse der Fig. 3-13 des Färbversuches Nr. 19, dessen Resultate hier nicht dargestellt sind. Abkürzungen: Rho=Rhodamin B; Sul=Sulforhodamin; Naph=Naphtionat; alle anderen Versuche wurden mit Fluorescein/Uranin oder NaCl durchgeführt.

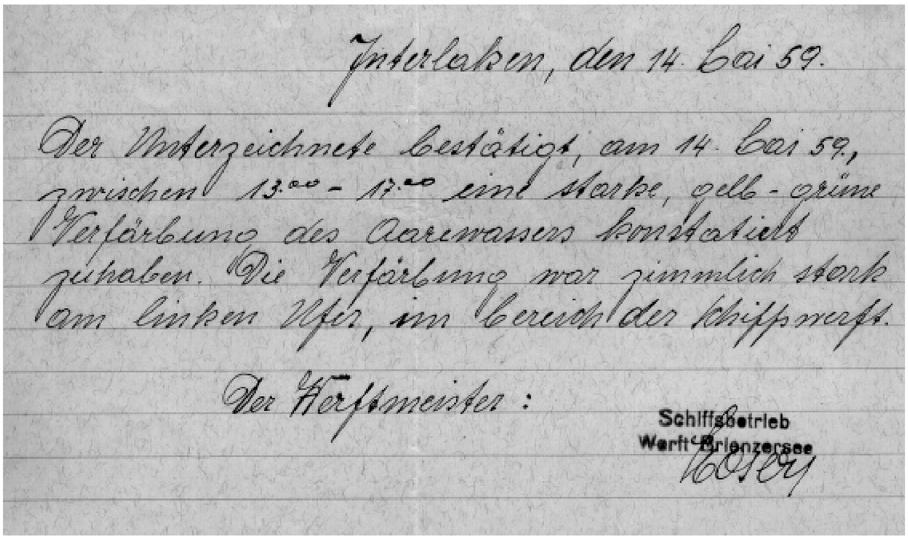
Carte de la région avec les différents essais de traçage. Des petites cartes sont insérées pour les essais no. 12 (Trogenmoos), 16-18 (grotte de St. Béat) et 20 (Bärenschacht). Le cadre représente la Fig. 3-13 du traçage no. 19, dont les résultats ne sont pas représentés ici. Abbréviations: Rho=Rhodamine B; Sul=Sulforhodamine; Naph=Naphtionate; tous les autres essais de traçage ont été faits avec Fluorésceine/Uranine ou NaCl.
Reproduced by permission of the Swiss Federal Office of Topography (BA024093).

(which seems to be an overflow spring such as the Harder springs), but that they discharged only after the next floodwater pulse. A long residence time for the Niederried waters is indicated by its temperature, which is 1°C warmer than the other springs that are around 7.5°C.

Tracings No. 4/5, 1961: Chüelauenen - St. Beatus Cave / Chrutbach - Lerau (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, following 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) until reaching the St. Beatus Cave is unexpected, since 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. The low flow velocity (23 h, 25 m/h) is explained by the water flowing through scree.

Tracing No. 6: Senkloch - Bätterich (Fluoresceine). This tracing experiment is roughly documented by Knuchel (1974). It was realised in between 1959 and 1970 (the exact date 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 famous tracing experiment, organised by Franz Knuchel, is well documented (Knuchel 1972). Almost all springs around the Schrattenfluh have been sampled, however, the dye



Interlaken, den 14. Mai 59.

Der Unterzeichnete bestätigt, am 14. Mai 59.,
zwischen 13^{00} - 17^{00} eine starke, gelb-grüne
Verfärbung des Aarewassers konstatiert
zu haben. Die Verfärbung war ziemlich stark
am linken Ufer, im Bereich der Schiffswerft.

Der Werftmeister :

Schiffsbetrieb
Werft Brienzersee

Fig. 3-9 (right):
Letter of confirmation that dye was visible at the Harder springs after the tracing experiment 1959.

Bestätigung, dass nach dem Färbversuch 1959 Farbstoff bei den Harderquellen sichtbar war.

Lettre d'attestation confirmant la présence de colorant dans les sources du Harder après l'essai de 1959.

Table 1: Overview over the tracing experiments 1940-1995

No.	Date	Injection	Coordinates			Q	Tracer	Amount	Time	Reappearance	Coordinates			Min flow time		Velocity	Literature
						l/s									Distance	m/h max.	
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	0.3	175	700	Widmer/Rouiller 1978
		Trogenmoos Dol. II	632275	179650	1590	?	Fluoresceine	80 g	16:30	Trogenbachq.	632350	179525	1560	0.4	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	0.6	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

reappeared only at Bätterich and Gelberbrunnen after 38 h, giving a flow velocity of 544 m/h. 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 mostly free-flowing conditions, however, it might be primarily given by the snowmelt conditions that prevailed during the tracing experiment.

Tracing No. 8: Bärenschacht - Bätterich (Fluoresceine). This very roughly documented experiment (Knuchel 1974) was conducted between 1970 and 1973 (the exact date is 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 much lower still (78 h, 48 m/h).

Tracing No. 9, 1973: Septemberschacht - Gelberbrunnen (Uranine). This tracing 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, 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. 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 may 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 (Figure 3-10) to the Harder springs. A close observation of Simeoni's report showed two different first reappearance times of dye at Gelberbrunnen. We chose to present the very first appearance here, however, we do not know if this is fully correct.

Tracing No. 10, 1974: Faustloch - Bätterich (Fluoresceine). This experiment was conducted by the cavers Ricka and Pfister (unpublished HRH report 1974). Three springs (Bätterich, Gelberbrunnen, Goldey) were sampled, 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 / Uranine). This tracing experiment was conducted 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. 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 (Fluoresceine). Two small tracing experiments are documented (Widmer & Rouiller 1978). In the region of Trogenmoos several sinkholes were thought to connect to springs downstream without having a direct relation to the Bätterich spring. The dye from the first sinkhole appeared in Trogenbachhöhle 20 min later (700 m/h), the dye from the second sinkhole in an unnamed spring 25 min later (363 m/h).

Fig. 3-10:
The Innerbergli at Hohgant.

Das Innerbergli am Hohgant.

L'Innerbergli au Hohgant.

Photo by Daniel Burkhalter

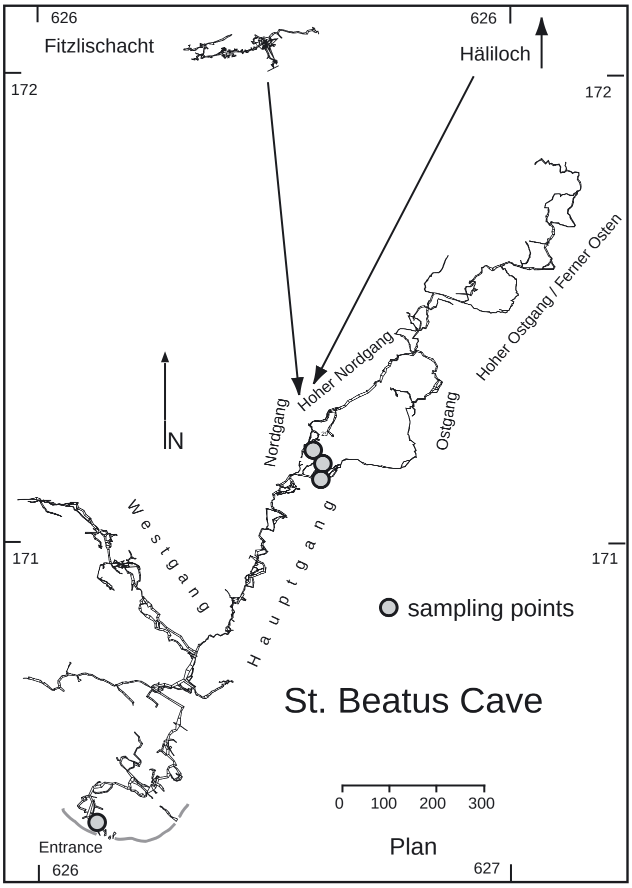


Fig. 3-11 (left):
Plan of St. Beatus Cave with sampling locations and results of the tracing experiment No. 15.

Plan der St. Beatus-Höhle mit Probenahmestellen und Resultaten des Färbversuches Nr. 15.

Plan de la grotte de St. Béat avec les points d'échantillonage et les résultats du traçage no. 15.

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 at small scale. This karst is developed within a calcareous layer of the Hohgant series, a direct connection to the Schrattenkalk systems is not proved.

Tracing No. 13, 1980: Allgäuli-Harder springs (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, giving a flow velocity of 316 m/h.
The conclusion of Wildberger, Gruner & Siegenthaler (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). This tracing (Wildberger, Gruner & Siegenthaler 1982) is useful to be included 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 sinkhole reappeared at Emmesprung 4.5 h later (velocity 304 m/h).

Tracing No. 15, 1984: Fitzlischacht/Häliloch-St. Beatus Cave (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 (Nordgang, Hoher Nordgang, Ostgang) within the cave (Fig. 3-11) were sampled.
The Naphtionate of Fitzlischacht reappeared after 22 h (47 m/h) in all three rivers, with high amounts (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 (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, conductivity, hardness, ion concentration) of the three rivers show that Hoher Nordgang and Ostgang are relatively similar, whereas Nordgang is completely different (Höchli 1995). This contradiction to the tracing results was inconclusive and caused a retracing experiment of Fitzlischacht during the experiment of 1996 (No. 19). The review of the different reports and analyses of tracing No. 15 reveals inconsistencies.

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-Unt. 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 Unt. Bachgrotte (545 m/h). 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. The question risen by Pfister (1992a) whether the traced river divides, is answered by now: the Erosionsgang river shows a vadose diffluence in unreachable parts of the cave. This observation was possible due to the visible pollution (Fig. 3-12) of this river by the sewage water of the Beatenberg clarification plant.

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 doesn't reappear in the main river.

Tracing No. 19, 1996: Gemmenalp. In this paper, we focus on this last multitracing experiment done (see below).

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 flow time of maximal 4 h (67 m/h). An exact flow time cannot be determined since the sampling was done with active carbon. The results are in accordance with flow rate measurements.

3.2.3. The tracing experiment of october 1996

Whereas the SE to NW boundaries of the catchment of the St. Beatus Cave can be limited quite well (the HSV in the SE, the Balmholz in the SW and cliffs in the NW, Fig. 3-13), there is no distinct morphological boundary towards the Siebenhengste in the NE. Therefore, one way to determine the catchment area is to do 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. Since an unnamed brook disappears just 20 m before reaching the entrance of the Bärenschacht, it was interesting to see if this rivulet (and others nearby) join St. Beatus Cave (as supposed by the geology) or the Bärenschacht resp. the Bätterich spring. The other injection points towards the Siebenhengste (Fig. 3-13) had the aim to delineate the two catchment areas.

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. 3-13) 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 sinkholes and continue on the surface. In the weekend of 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 (Fluoresceine) was injected at 8:50. Injection of dye and sampling was of course made by different persons to eliminate the risk of contamination. In the sinkhole at Oberberg (SUL in Fig. 3-13), 2 m^3 of water had been added (Fig. 3-14). In Bäreney (FLO in Fig. 3-13) the sinkhole was also dry, therefore water from a nearby fountain was added two hours before the injection. The addition continued for two days, the complete water added amounts to about 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.

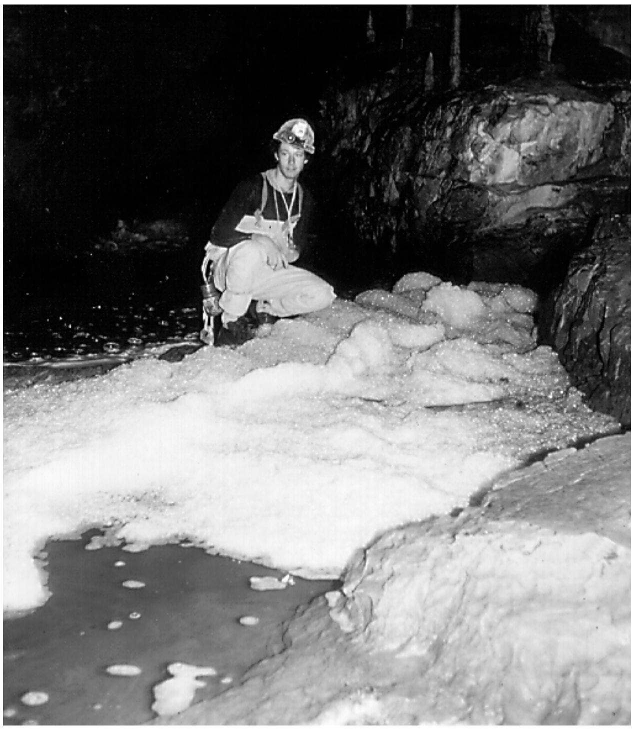


Fig. 3-12:
During flood, the pollution of the St. Beatus Cave can be impressive.

Während Hochwässern kann die Verschmutzung der St. Beatus-Höhle beeindruckend werden.

Pendant les crues, la pollution de la grotte de St. Béat peut être impressionnante.

Photo by Peter Pfister

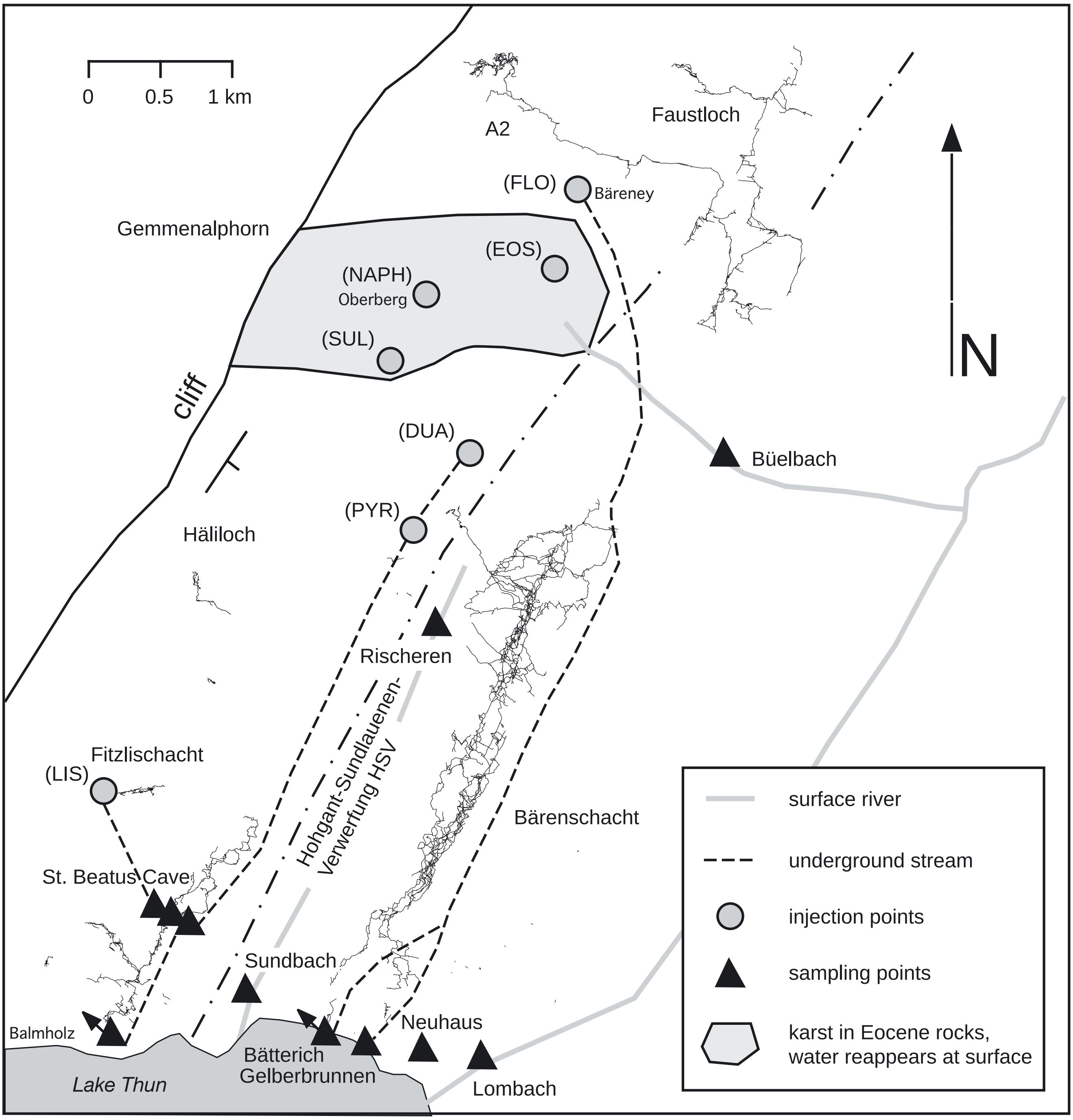


Fig. 3-13 (above): Detailed map showing the injection points and sampling locations of the tracing experiment No. 19 of october 1996.

Detailkarte der Eingabepunkte und Probenahmestellen des Färbversuches Nr. 19 vom Oktober 1996.

Carte détaillée montrant les points d'injection et d'échantillonage du traçage no. 19 d'octobre 1996.

The measurements of the dyes were done by fluorometry: With a Perkin Elmer Fluorometer LS-2B, every sample was searched. The samples with high peaks were checked by the double scanning method with a "Shimadzu RF5001-PC". The representations were made in a concentration/time diagram. Then, quantitative determinations were made: A calibration curve for every dye was made with the LS-2B. The detection limit of the LS-2B is at 10 $\mu g/m^3$ for Lissamine, Fluoresceine, Eosine, Sulforhodamine, 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 we might find the used dyes (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

Table 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 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

Fig. 3-14 (left):
The watering of a sinkhole is surely a rare view...

Das Nachwässern einer Doline ist gewiss ein seltener Anblick...

L'addition d'eau dans une doline n'est certainement pas une opération courante...

Photo by Martin Otz

their retention times instead of their characteristic wavelength. That enabled us to prove the presence of the inoculated dyes.
The measured values were subtracted by the blind values and then transformed into recovery masses. To get the recovery masses, the concentration has to be multiplied with the flow rate at the time of sampling. Since this flow 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 below 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 eventually appearing multiple dyes.

Results

Results are summarised in Table 3 and drawn in Figs. 3-13 and 3-15.

The Lissamine of 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 were regained.

The Pyranine injected into Brook 1 (Fig. 3-13) was also found at St. Beatus Cave. The sampling within the cave was already stopped when the dye appeared. At the entrance of the cave (Fig. 3-15), a total of 26 g 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 appeared.

The Sulforhodamine B injected in the sinkhole at Oberberg did not appear in any cave; after 83.5 h the first traces of a total of 105 g appeared in Bühlbach creek, after 93 h, the dye (total amount recovered 150 g) 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 recovered).
The same is valid for the 200 g of Eosine injected in a sinking brook, it was found in Bühlbach after 12 h (102 gr) and in Lombach after 19 h (124 g).

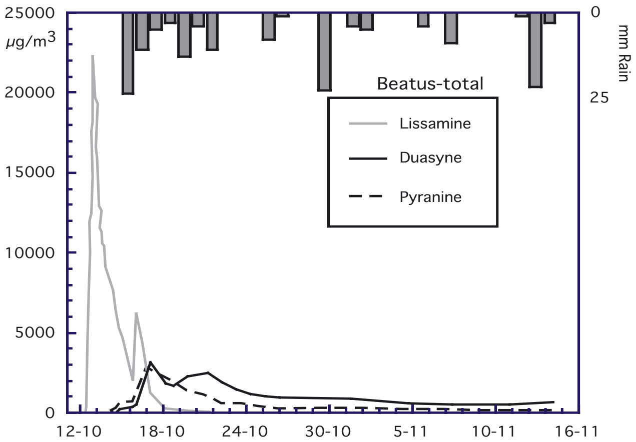
The Uranine injected in the Bäreney sinkhole appeared in the Bätterich spring after 16.5 h. Five hours later, the concentration went back to zero, only after 54 h the main peak appeared, which was detectable for some days (maximum after 130 h). In total, 482 g appeared.
The Gelberbrunnen, which is the second spring of the Réseau, wasn't sampled at first time because there was no obvious discharge. Along the sampling period, a total of 294 g of Uranine was recovered in Gelberbrunnen.

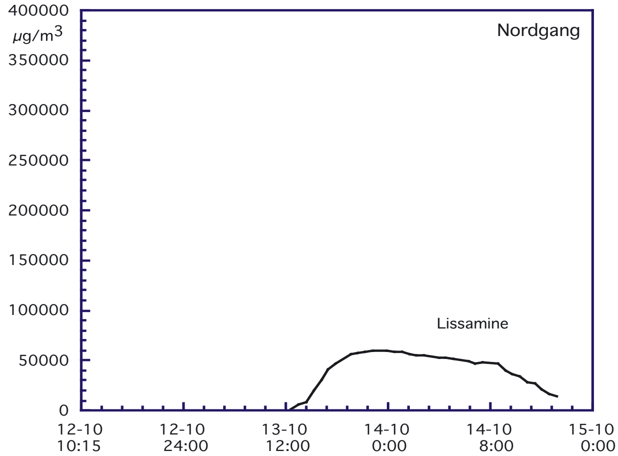
Interpretation

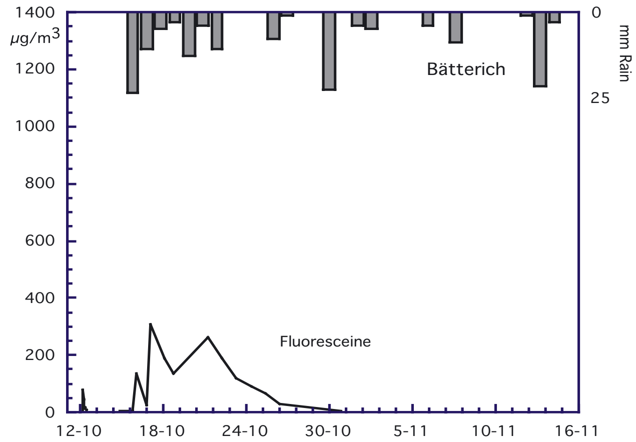
Fitzlischacht-St. Beatus Cave
The connection of the two caves was already shown by Klötzli (1985). In 1984, the tracer needed 22 h, in contrast it took 15 h in 1996. However, in both cases the flow velocity of 45 to 67 m/h is quite slow compared to other experiments in the region. Since there is a fracture 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.

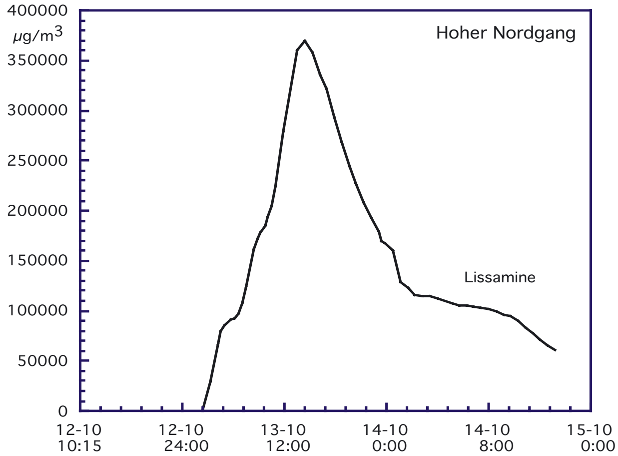
Table 3: Results, tracing experiment of 1996

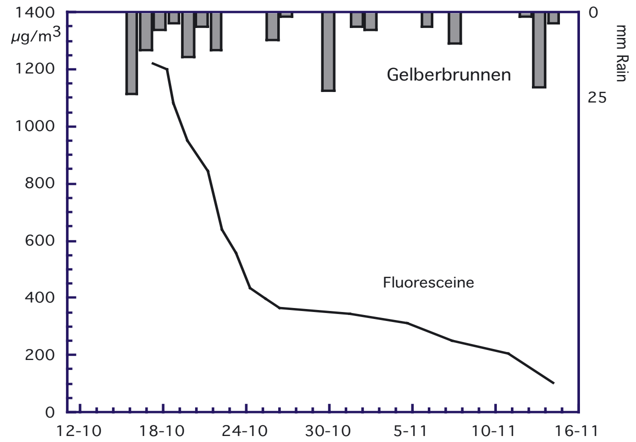
Location	Q (l/s)	Dye	first arrival	Peak	Distance	flow velocity		recovery		
	estimated		(h)		(m)	max (m/h)	Peak (m/h)	(g)	(%)	
B-Wasserfall	0.3	--	--	--	--	--	--	--	--	
B-Beiz	2	--	--	--	--	--	--	--	--	
B-Ostgang	5	--	--	--	--	--	--	--	--	
B-Nordgang	5	Lissamin	25.6	35	1001	39	29	24 g	12%	
B-Ho. Nordgang	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!

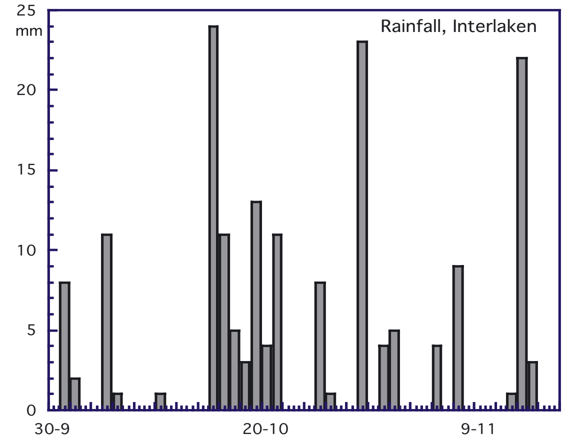

Beatus-total
25000
µg/m3
20000
15000
10000
5000
0
12-10
18-10
24-10
30-10
5-11
10-11
16-11
0
25
mm Rain
Lissamine
Duasyne
Pyranine

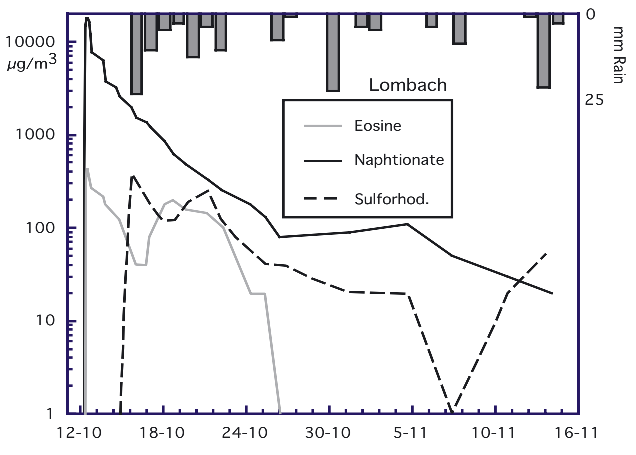

Nordgang
400000
µg/m3
350000
300000
250000
200000
150000
100000
50000
0
Lissamine
12-10 10:15
12-10 24:00
13-10 12:00
14-10 0:00
14-10 8:00
15-10 0:00


Bätterich
1400
µg/m3
1200
1000
800
600
400
200
0
Fluoresceine
12-10
18-10
24-10
30-10
5-11
10-11
16-11
0
25
mm Rain


Hoher Nordgang
400000
µg/m3
350000
300000
250000
200000
150000
100000
50000
0
Lissamine
12-10 10:15
12-10 24:00
13-10 12:00
14-10 0:00
14-10 8:00
15-10 0:00


Gelberbrunnen
1400
µg/m3
1200
1000
800
600
400
200
0
Fluoresceine
12-10
18-10
24-10
30-10
5-11
10-11
16-11
0
25
mm Rain


Rainfall, Interlaken
25
mm
20
15
10
5
0
30-9
20-10
9-11


Lombach
10000
µg/m3
1000
100
10
1
Eosine
Naphtionate
Sulforhod.
12-10
18-10
24-10
30-10
5-11
10-11
16-11
0
25
mm Rain

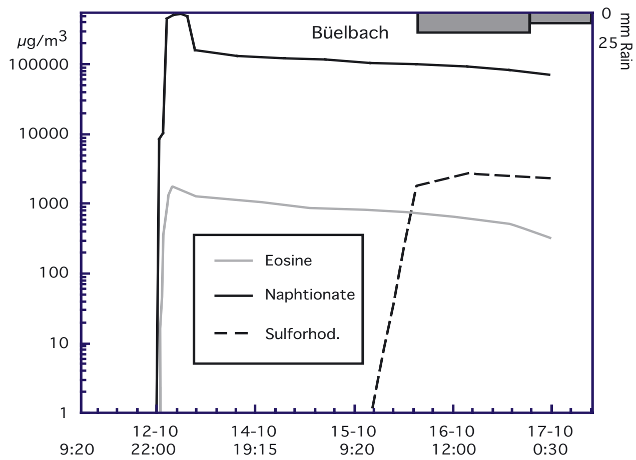

Büelbach
µg/m3
100000
10000
1000
100
10
1
Eosine
Naphtionate
Sulforhod.
9:20
12-10 22:00
14-10 19:15
15-10 9:20
16-10 12:00
17-10 0:30
0
25
mm Rain

Fig. 3-15 (left):
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.

Durchbruchskurven (Konzentrationen) der Farbstoffe an den Probenahmestellen. Der Niederschlag während des Färbversuches (Station Interlaken der Schweiz. Meteorologischen Anstalt) ist eingefügt. Der Injektionszeitpunkt ist am Beginn der Graphen.

Courbes d'apparition (concentrations) des colorants aux points d'échantilonnage. Les précipitations pendant le traçage (station Interlaken du Service Météorologique Suisse) sont prises en compte. L'heure d'injection se trouve à l'extremité gauche des graphiques.

The 1984 appareance of dye in all three main galleries of St. Beatus Cave couldn't be solved completely so far. In 1996, the Ostgang hadn't dye at all; the Nordgang sump had five times less dye than the Hoher Nordgang. This discrepancy with the results of 1984 can only be explained partially: 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 the part behind the Nordgang sump (Fig. 3-16): Speleological research behind the sump revealed that the gallery divides into a gallery with a brook (situated approximatively 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, tempe-

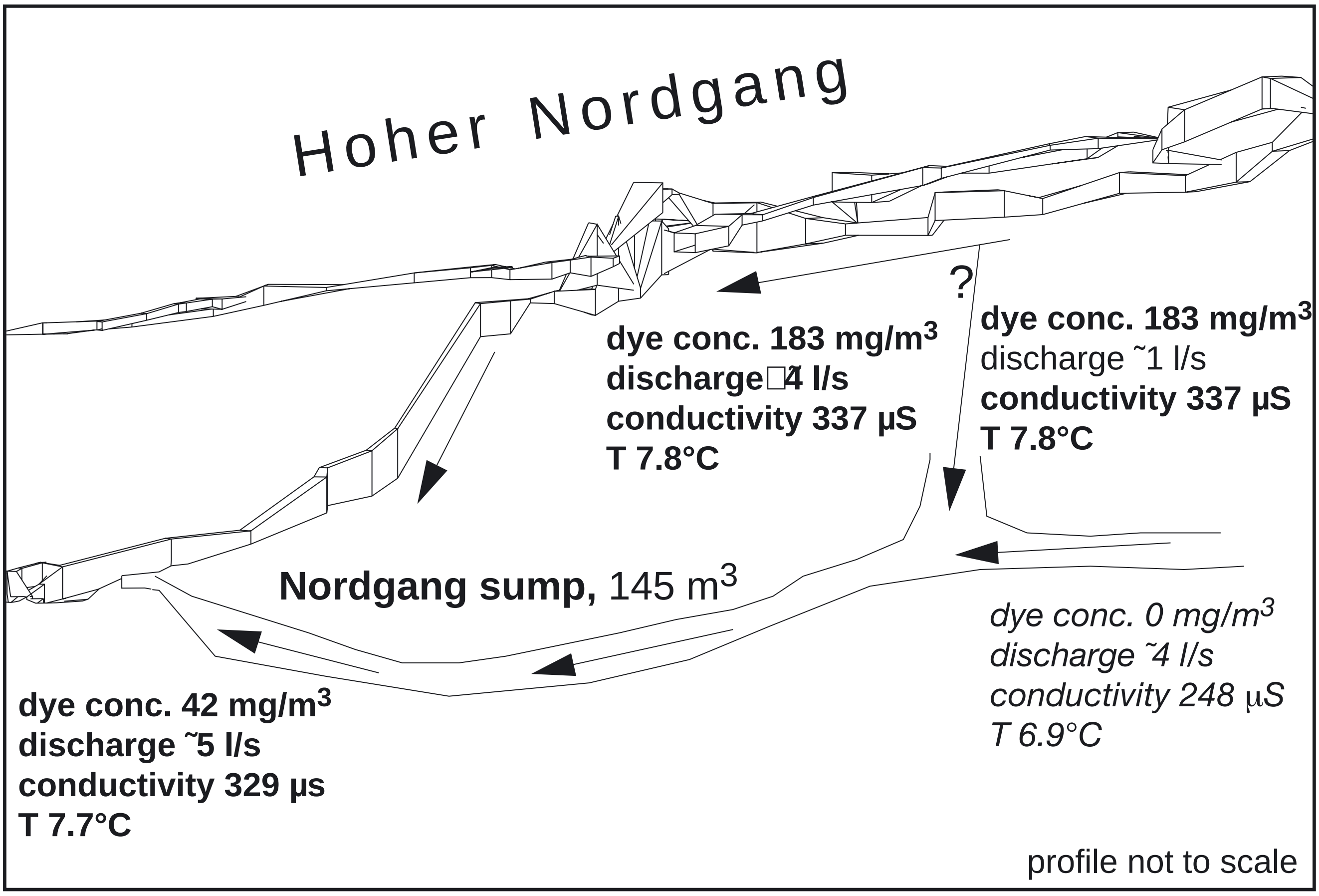


Fig. 3-16 (above):
Sketch of a possible explanation for the diffluence in the Hoher Nordgang of St. Beatus Cave. The measured values are in bold, hypothetic values are in normal, and calculated values in italic letters.

Schema der möglichen Erklärung der Diffluenz vom Hohen Nordgang der St. Beatus-Höhle. Die gemessenen Werte sind fett, die hypothetischen Werte normal, und die berechneten Werte schräg gedruckt.

Schéma d'une explication possible de la diffluence dans le Hoher Nordgang de la grotte de St. Béat. Les données mesurées sont en caractères gras, les données assumées en normale, et les données calculées en italique.

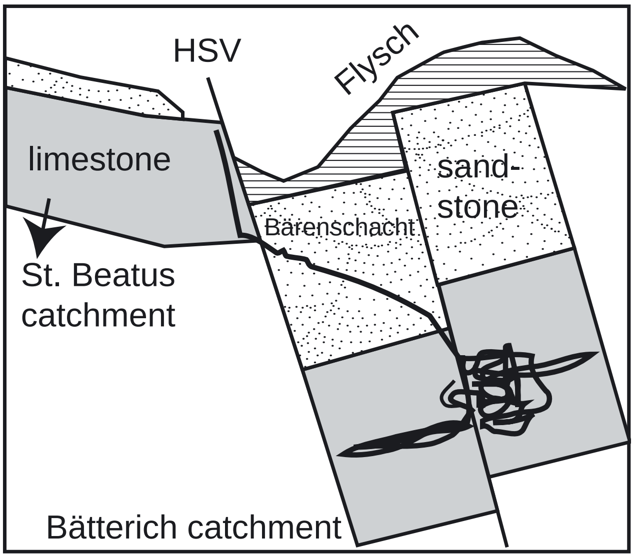


Fig. 3-17:
Schematic projection across the Bärenschacht entrance, illustrating its unique position with respect to the St. Beatus and Bätterich catchments.

Schematische Projektion durch den Bärenschacht-eingang zur Verdeutlichung seiner einzigartigen Lage in Bezug auf die Einzugsgebiete der St. Beatus-Höhle und des Bätterichs.

Projection schématique à travers l'entrée du Bärenschacht pour illustrer sa position unique en relation avec les bassins versants de la grotte de St. Béat et du Bätterich.

rature), we calculated the parameters of the hypothetical water before mixing. The results show that the parameters still lie within a normal karst water (Figure 3-16), therefore we assume that such a mixing would be possible. The absence of dye in the Ostgang can only be explained by the smaller discharge in 1996, which caused that a floodwater diffluence in unexplored parts of the cave was not active at all.

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 sinkhole 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) the supposition was raised that the water flowed towards St. Beatus Cave (Fig. 3-17). This was tested during the tracing experiment of 1996.
The flow velocity of the Duasyne and Pyranine injected in those brooks, 63 respectively 65 m/h, 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, respectively 25 % of Duasyne). 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 has been higher. The reason for such long tails could be related to a poorly connected flowpath between the sinkhole and the cave stream (young and distal flowpath). The bimodality of the Duasyne could be explained by a second rainfall, whereas the Pyranine seems to be more buffered, since no second peak is visible.
Since the brooks completely infiltrated into the sinkholes, no dye was detected in Sundbach.

Sinkholes 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 very astonishing. It seems that waters from Oberberg infiltrate into the top layer of the Hohgant series, which is a 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 % respectively 87 %).
The Sulforhodamine B injected into a sinkhole within the 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 flows into Bühlbach, too. The slow 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 of the tracer (no natural flow, 2 m^3 of water added).

Sinkhole Bäreney-Bätterich/Gelberbrunnen
The sinkhole 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 sinkholes above was expected. The region of Bäreney is quite fractured and located near the A2 cave (Fig. 1-7), which is known to be connected with the Bätterich spring. Therefore, a flow

Fig. 3-18:
The "boiling" Bätterich after a huge flood. Such events are very rare.

Der „kochende" Bätterich nach einem grossen Hochwasser. Solche Ereignisse sind sehr selten.

Le Bätterich «bouillonnant» après une grosse crue. De tels évènements sont très rares.

Photo by Peter Pfister

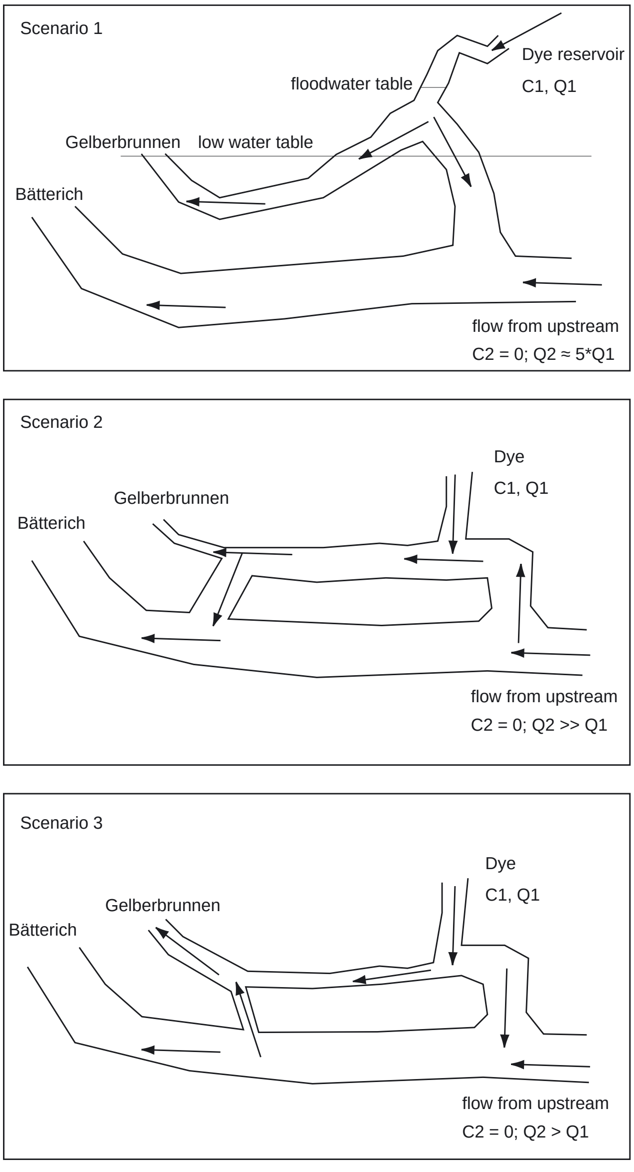


Fig. 3-19 (left):
Illustrations for the three scenarios described in the text.

Illustration zur Verdeutlichung der drei im Text beschriebenen Szenarien.

Illustrations pour la clarification des trois scénarios décrits dans le texte.

through the underlying sandstone into the Schrattenkalk has been proved by the tracing experiment. A first 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 (Fig. 3-18) and Gelberbrunnen, although the latter seems to be the overflow of the other. Bätterich received the tracer first (at low water), at that time the Gelberbrunnen was not flowing visibly. 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. Our interpretation of this response is the following (see also Fig. 3-19):

Scenario 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.

Scenario 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 narrow passages, the dye first appears in Bätterich, and only in flood situation, the Gelberbrunnen begins to react clearly.

Scenario 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 narrow passages, the Gelberbrunnen only reacts at flood.

Considering that the injection point is located close to the springs (compared to the size of the whole catchment), these scenarios seem reasonable. More connecting passages between the main conduits are possible. The key factors are that 1) at least one link presents flow downwards (resp. sidewards), and 2) a diffluence is connected with this conduit.

Other hypotheses may probably explain the observed responses as well. The scenarios 2 and 3 are most compatible with the network style observed in Bärenschacht (see also Chapter 4) and are therefore favorised. 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 supposition by Knuchel (unpublished), saying 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 unclear yet whether the Neuhaus spring is co-fed by the groundwater within the Interlaken plain.

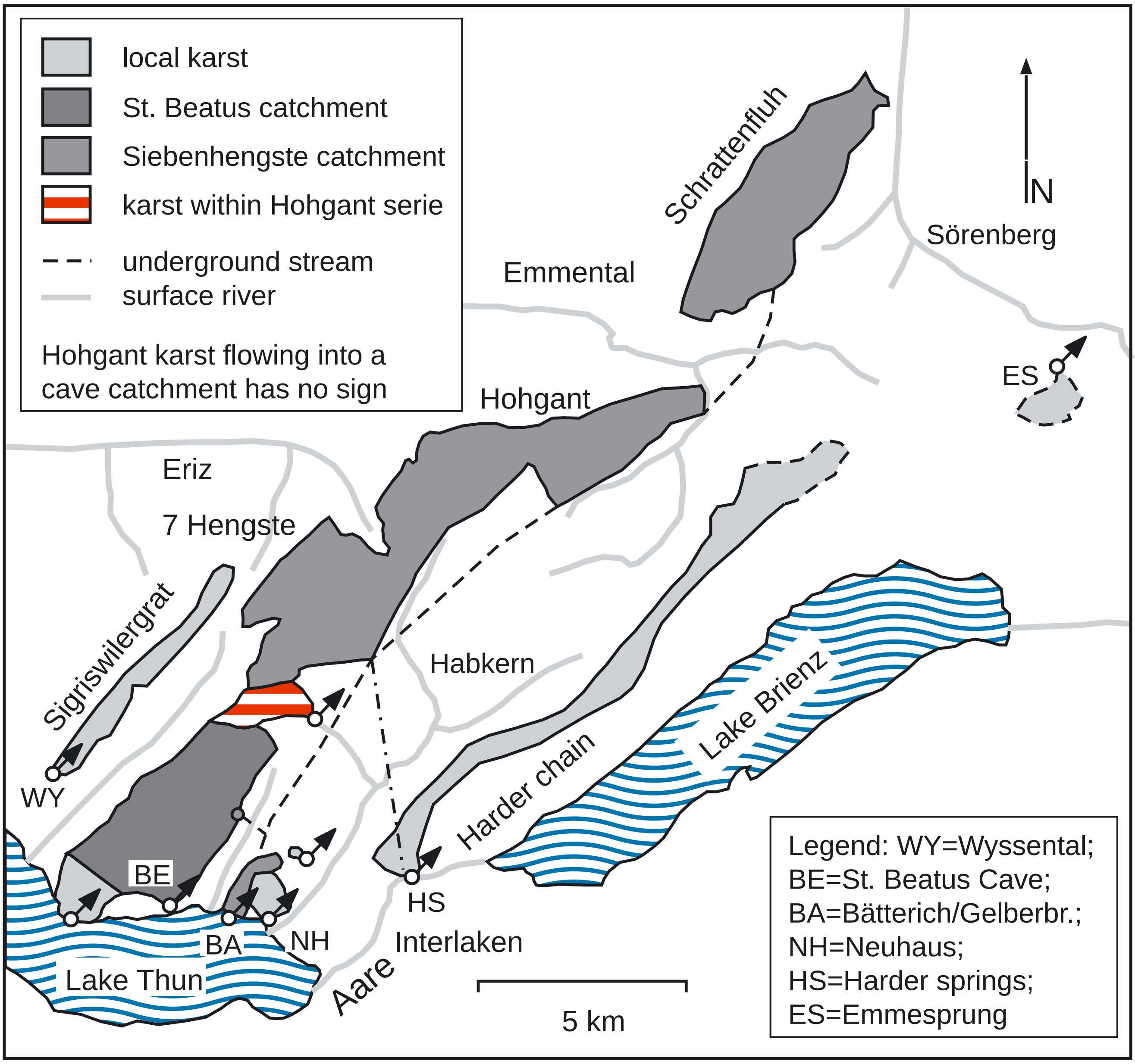


Fig. 3-20: Proposed catchment delimitations of the region between Lake Thun and Schrattenfluh.
Ein Vorschlag zur Begrenzung der Einzugsgebiete zwischen Thunersee und Schrattenfluh.
Proposition de délimitation des bassins versants entre le lac de Thoune et la Schrattenfluh.

3.2.4. Conclusion

The analysis of unpublished results, combined with the tracing experiment of 1996, makes it possible to delineate catchments of most of the springs in the region (Fig. 3-20).

- The catchment area of St. Beatus Cave reaches further 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 (Fig. 3-7). 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-Häreney-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 between the Hohgant region and aquifers in the Harder chain.
- The Harder springs are mainly fed by 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.

The results prove that the catchments of St. Beatus Cave and Bärenschacht are independent. So, possible similarities must depend on the spring area and therefore on the Aare valley bottom. The next chapter deals with the morphogenesis of cave passages. The results are later used to define the different phases.

Open questions

Of course, several open questions remain. One of them is the delimitation of the catchment SW of the one of St. Beatus cave (Fig. 3-20), which is as unknown as its spring which has to be in Lake Thun. Then, the question remains whether the whole Schrattenfluh connects to Bätterich, as suggested in Figure 3-20. A tracing experiment is in preparation. Finally, the exact delimitation of the Emmesprung basin towards the Harder and Brünig (east of the Emmesprung) is unknown.

Proof of the presence of dye in the Aare at Interlaken after the 1959 tracing experiment.
Beweis des Auftretens von Farbstoff in der Aare bei Interlaken nach dem Experiment von 1959.
Preuve de la présence de colorant dans l'Aare à Interlaken après le traçage de 1959. Photo by Franz Knuchel

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4. Role of epiphreatic flow and soutirages in conduit morphogenesis: the Bärenschacht example

Zusammenfassung: Die Rolle von Überflutungszonen und Soutirages in der Gangausbildung: das Beispiel des Bärenschachtes

Einführung

Dieses Kapitel behandelt die Gestein-Wasser-Wechselwirkung und deren Einfluss auf die Höhlenentstehung. Beobachtungen des Flutungsmechanismus geben Einblick in die speläomorphogenetischen Prozesse, die für das Verständnis der in Kapitel 5 beschriebenen Phasen wichtig sind.

Diverse Theorien zur Höhlenentstehung wurden im Laufe der letzten zwei Jahrhunderte formuliert und verfeinert. Höhlenentstehung ist das Produkt des Zusammenwirkens von chemischen Faktoren, Grenzbedingungen, der Geologie und des Klimas. Jeder dieser Faktoren für sich erklärt nur einen Teil; ein allgemeingültiges Modell muss alle Relationen einbeziehen. Im vorliegenden Kapitel konzentrieren wir uns auf die Genese von begehbaren Höhlen. Wir untersuchen also nicht die Entstehung von Beginn an, sondern die Formgebung von reifen Gängen.

Das eine der beiden anerkannten Modelle zur Höhlenbildung ist das klassische „Four state model“ von Ford & Ewers (1978). Dieses Modell setzt die Charakteristika von phreatischen Röhren (Undulationen, Tiefe der Verkarstung unter dem Karstwasserspiegel) in Zusammenhang mit der Häufigkeit von Brüchen und Diskontinuitäten. So soll eine tiefgehende Verkarstung mit grossen Undulationen in massiven, wenig zerbrochenen Kalksteinen vorkommen, während in intensiv zerbrochenen und beanspruchten Kalken eine praktisch horizontale „Wasserstandshöhle“ die Regel sei.

Das andere Modell ist von Audra (1994). Er hinterfragt die Entstehung der Gänge von phreatischer Morphologie und zeigt, dass die wohlgerundeten Röhren ein Produkt der Hochwasserzone seien, dies auch aus lösungskinetischen Gründen. Aus diesem Grunde stellt er auch die Existenz der speläogenetischen Phasen in Frage.

Das vorliegende Kapitel präsentiert die Beobachtungen im Bärenschacht und erstellt damit ein neues Modell, das die beiden vorhandenen Theorien miteinander verbindet und die Widersprüche auflöst.

Die Beobachtungen

Die morphologischen Charakteristika der Gänge erlauben die Bestimmung von einzelnen speläogenetischen Phasen. Die Undulation der Röhre muss im phreatischen Raum erfolgen und definiert deshalb die minimale Höhe des zugehörigen Karstwasserspiegels. Ein Mäander, der in eine phreatische Röhre übergeht, zeigt die exakte Höhe an (Fig. 4-1). Auf diese Weise wurden drei Phasen definiert, deren zugehöriger Wasserspiegel stark (1.3 bis 2.1°) gegen die Quelle zu geneigt ist. Die Neigung ist nicht auf tektonische Effekte zurückzuführen. Die zugehörigen Quellenhöhen liegen auf 700, 760 und 890 m ü.M. (Fig. 4-2).

Beobachtungen in der heutigen Flutungszone zeigen, dass das Anwachsen des Hochwassers nicht uniform von unten her erfolgt, sondern dass das System im „Füllen-Überfliessen“-Modus (Fig. 4-3) funktioniert. Das heisst, dass das Wasser von Norden her kommend diese Gänge füllt, bevor es in die nächste Senke abfliesst und diese ihrerseits füllt. Das System wird nach dem Hochwasser von kleinen, meist unbegehbaren Gängen geleert. Sowohl Fliessfacetten wie auch zerstörte Einrichtungen zeugen von einem starken vadosen Strom vor der Füllung; dennoch ist die Gangmorphologie phreatisch. In der Region des Glücksschachts (Fig. 4-4) ist ein Mäander sichtbar, der im Dach der epiphreatischen Zone in eine phreatische Röhre übergeht. Aus diesem Grund schliessen wir, dass in der Hochwasserzone die phreatische Korrosion dominiert und die vadose Erosion in den Hintergrund tritt. Ähnliche Beobachtungen werden auch in der nächstälteren Phase in der Region des Biwaks I gemacht (Fig. 4-5).

Die Entstehung der Soutirages

Während der Flut ist die epiphreatische Zone wassererfüllt. Die Gänge, durch die sie geleert wird, heissen Soutirages und sind kleine phreatische Gänge, welche zum perennierenden Wasserspiegel hinabgehen.

Während der Flut sind alle aktiven Gänge hydraulisch verbunden, und der hydraulische Gradient ist relativ flach. Nach der Flut jedoch wird der Gradient steiler (Fig. 4-7), also sucht sich das Wasser einen Weg nach unten. Aus lösungskinetischen Gründen entstehen die Soutirages am tiefsten Punkt der Gänge. Unterhalb des Wasserspiegels verbinden sie sich und tragen zum Entstehen des perennierend phreatischen Ganges bei (Fig. 4-9). Die Figur 4-10 zeigt das Funktionieren während der Phase 760. Der untere horizontale Wasserspiegel (Niederwasser) und der geneigte Hochwasserspiegel treffen an der Quelle aufeinander. In schwarz der Hauptgang der Phase, bergwärts epiphreatisch, wo auch die Soutirages auftreten (hellgrau) und sich mit dem perennierend phreatischen Gang (dunkelgrau) vereinigen. In der perennierenden Zone fliesst ein Teil des Wassers in den Hauptgang zurück (Pfeile); diese Gänge zeigen Fliessfacetten gegen oben (im Gegensatz zu den Soutirages). So ist ein wichtiges Merkmal der Soutirages, dass sie sich nur im epiphreatischen Bereich bilden können.

Interpretation

Beobachtungen haben ergeben, dass die Phasen der Speläogenese geneigt sind. Die phreatische Korrosion ist gegenüber der vadosen Erosion bedeutender, selbst in Gängen, in denen immer Wasser fliesst. Der Übergang vadoser Mäander – phreatische Röhre geschieht im Dach der Hochwasserzone. Diese ist zwar in ihrer Höhe variabel; Beobachtungen zeigen aber eine Höhe, die häufig erreicht und kaum übertroffen wird, und wo die oben beschriebenen Wechsel auftreten. Als Schlussfolgerung können wir nun die beiden Modelle von Audra (1994) und Ford & Ewers (1978) miteinander verbinden:

- Initialgänge bilden sich unterhalb des perennierenden Karstwasserspiegels. Reife Höhlengänge von phreatischer Morphologie bilden sich ober- und unterhalb dieses Spiegels.
- Die Definition einer speläogenetischen Phase ist durch die Quellenhöhe und das Dach der Hochwasserzone gegeben.
- Dieser Schwankungsbereich ergibt sich aus „normalen“ Hochwässern wie Schneeschmelze und Sommerregen.
- Soutirages entwässern die epiphreatische Zone gegen die perennierende Zone hin, wo sich neue Gänge bilden.

Die Hauptaussage des neuen Modells ist, dass „phreatische Röhren“ sich sowohl im klassischen phreatischen Bereich als auch in der Hochwasserzone bilden. Deshalb ist der Übergang phreatisch-vados im Dach dieser Zone anzusiedeln. Die Unterscheidung zwischen Gängen der phreatischen und der epiphreatischen Zone ist nur anhand der Röhren nicht möglich. Einen guten Hinweis bildet das Vorhandensein von Soutirages, die sich nur im Epiphreatischen bilden. Auf alle Fälle muss die Bestimmung der speläogenetischen Phasen nach dem klassischen Muster erfolgen. Unser Modell ist für alpine Höhlen gültig und könnte unter Umständen auch auf andere Höhlen zutreffen.

Die gemachten Beobachtungen erklären die starke Neigung der speläogenetischen Phasen und beantworten die Frage nach dem Einfluss der Überflutungen. Die genaue Definition der speläogenetischen Phasen erfolgt in Kapitel 5.

Bemerkungen zum Four state Model und zum Phasenübergang

Das four state Model weist einige Mängel auf, die begründet werden:

- „State“ (Zustand) impliziert, dass die Höhlen im Laufe ihrer Existenz die vier Zustände durchlaufen; dieses wird in der Literatur nicht eindeutig verneint. Ich zweifle aber, dass sich die Bruchhäufigkeit in Karst-Zeiträumen bedeutend verändert.
- Der Bärenschacht zeigt Undulationen des Zustands 2, während die Bruchhäufigkeit mindestens bei Zustand 3 ist: ein Widerspruch.
- Für einige 100 Meter liegt ein Gang mitten im Mergel, während 30 m daneben Kalk vorliegt. Dies zeigt, dass die Bruchhäufigkeit nicht Fliesswege bestimmt, sondern höchstens beeinflusst.
- Das Modell trägt zwei andern Parametern zuwenig Rechnung: der Zeit und der Schüttung: Eine Höhle des Zustands 4 ist häufiger in ausgeglichen regenreichen Klimata, während undulierende Gänge in Regionen mit ausgeprägten Hochwasserschwankungen auftreten.

Das Four state model war ein grosser Schritt zum Verständnis der speläogenetischen Prozesse, da es Geologie und Hydrologie verbindet. Heutzutage ist es jedoch nicht mehr möglich, alle Höhlen auf dieses Modell zu reduzieren, da viel mehr Parameter in Betracht gezogen werden müssen.

Oft wird eingewendet, dass ein geneigter Karstwasserspiegel ein Zeichen sei, dass sich das Höhlensystem im Übergang von einer Phase in die andere befinde. Deshalb hier einige Definitionen:

- Übergang heisst, dass das untere Niveau nicht alles Wasser schlucken kann, der perennierende Niederwasserspiegel ist geneigt. Dieser Zustand dauert generell (siehe Berechnungen von Dreybrodt (2000) und Palmer (2000)) nur kurze Zeit.
- Nach dem Übergang ist der Niederwasserspiegel horizontal und der Hochwasserspiegel geneigt. Deshalb ist noch kein Gleichgewicht erreicht, das erst dann beginnt, wenn mittlere Hochwässer den Wasserspiegel nicht mehr signifikativ heben. Dies heisst, dass die unteren Gänge durch eine Schüttung in der Grössenordnung der Flut gebildet wurden, was seinerseits nur während weniger Wochen im Jahr möglich ist. Aus diesem Grunde dauert es sehr viel länger (und asymptotisch), bis das Gleichgewicht erreicht ist. Zumeist befinden sich die Gänge nur im Gleichgewicht bezüglich des Nieder- und Mittelwassers.

Alle Phasen des Bärenschachtes und des Réseaus sind nicht mehr im Übergang, aber noch nicht im Gleichgewicht gewesen, als der nächste Phasenübergang stattfand.

Résumé: Le rôle de la zone épinoyée et des soutirages pour la morphogenèse des galeries: l'exemple du Bärenschacht

Introduction

Ce chapitre traite de l'interaction entre roche et eau et de son influence sur la spéléogenèse. L'observation des crues fournit des indices sur les processus spéléomorphogénétiques importants pour la compréhension des phases décrites dans le chapitre 5.

Depuis deux siècles, il existe différentes théories sur la formation des cavités. La spéléogenèse résulte de l'interaction des facteurs chimiques, géographiques, géologiques et climatiques. Chacun de ces facteurs n'explique qu'une partie de la spéléogenèse; un modèle général doit prendre en compte toutes les relations. Dans ce chapitre, nous discuterons la genèse des cavités pénétrables. Il ne s'agit donc pas du début du développement des cavités, mais de la morphogenèse des galeries à leur maturité.

L'un des deux modèles de spéléogenèse est le «four state model» classique de Ford & Ewers (1978). Ce modèle met en relation le caractère des conduits phréatiques (ondulations, profondeur de la karstification au-dessous de la nappe) et la densité des fractures et des discontinuités. Ainsi, un calcaire massif et peu fracturé serait le siège d'une karstification profonde avec des conduits en «montagnes russes» importantes, tandis que dans les calcaires densément fracturés se développeraient en règle générale des galeries subhorizontales de type «ligne d'eau».

Audra (1994) propose un autre modèle de genèse phréatique. Les conduits de formes bien arrondies seraient un produit de la zone épiphréatique, pour des raisons de cinétique de dissolution. Il remet ainsi en cause la notion d'étage spéléogénétique.

Ce chapitre présente les observations faites dans le Bärenschacht et propose un nouveau modèle qui relie les théories existantes.

Les observations

La morphologie des galeries permet d'identifier plusieurs phases spéléogénétiques. Les ondulations ont lieu en milieu phréatique et permettent de déterminer l'altitude minimale de la nappe. Un méandre qui se transforme en tube en définit l'altitude exacte (Fig. 4-1). Trois phases ont été identifiées. La nappe est fortement inclinée (1.3° à 2.1°) vers la source. Cette inclinaison ne dépend pas de facteurs tectoniques. L'altitude respective des sources est de 700, 760 et 890 m (Fig. 4-2).

Dans la zone épinoyée actuelle, l'eau ne monte pas uniformément, mais le système fonctionne en «remplissage-déversoir» (Fig. 4-3): L'eau provient du nord, elle remplit ces galeries avant de se précipiter dans le prochain point bas, en le remplissant aussi. Après la crue, le système est vidangé par des galeries de petite dimension, souvent impénétrables. Les cupules d'érosion sur les parois et la destruction de l'équipement témoignent d'un courant vadose puissant avant le remplissage total, malgré une morphologie phréatique. Dans la région du Glücksschacht (Fig. 4-4), on observe un méandre qui se tranforme en tube phréatique au toit de la zone épinoyée. Nous en concluons que dans la zone épiphréatique, la corrosion phréatique prédomine sur l'érosion vadose. D'ailleurs des observations similaires ont été faites dans la région du bivouac I (Fig. 4-5).

La genèse des soutirages

En période de crue, la zone épiphréatique est noyée. Les galeries de vidange sont nommées soutirages. Ce sont des conduits phréatiques de petites dimensions qui descendent vers la nappe pérenne.

Pendant la crue, l'eau ennoie toutes les galeries, et le gradient hydraulique est relativement faible. Après la crue, le gradient devient raide (Fig. 4-7), et l'eau cherche à descendre. Pour des raisons de cinétique de dissolution, les soutirages se forment au point bas des ondulations. Sous le niveau de la nappe pérenne, les soutirages se rejoignent et forment la galerie phréatique pérenne (Fig. 4-9). La figure 4-10 illustre le fonctionnement pendant la phase 760. La nappe horizontale (étiage) et la nappe de crue (inclinée) se rejoignent à la source. La galerie principale en noir, et sa zone épiphréatique en amont ont des soutirages (gris clair) qui communiquent avec la galerie phréatique pérenne (gris foncé). Dans la zone pérenne, une partie des eaux remonte vers la galerie principale (flèches); ces galeries montrent des cupules d'érosion orientées vers le haut, au contraire des soutirages, dont la formation n'a lieu que dans la zone épinoyée.

Interprétation

Les nappes des phases spéléogénétiques sont inclinées. La corrosion phréatique prime sur l'érosion vadose, même s'il y a un écoulement pérenne. La transition méandre vadose – tube phréatique a lieu à la limite supérieure de la zone épiphréatique. L'altitude est variable, mais il existe généralement un seuil maximum. C'est à ce niveau que l'on observe les changements de morphologie. En définitive, ces assertions sont en accord avec le modèle de Ford & Ewers (1978) et celui de Audra (1994):

- Les conduits initiaux apparaissent sous le niveau de la nappe pérenne. Plus tard, des galeries matures de morphologie phréatique se forment audessous et au-dessus de ce niveau.
- Une phase spéléogénétique est définie par l'altitude de la source et le toit de la zone épiphréatique.

- On entend par battement de la nappe les oscillations des crues «normales», telles que la fonte des neiges ou les pluies d'été.
- Les soutirages drainent la zone épiphréatique vers la zone phréatique, où se forment de nouvelles galeries.

L'innovation principale de ce modèle est que les tubes de morphologie phréatique se forment aussi dans la zone épinoyée, fixant la transition phréatique-vadose au toit de cette zone. La distinction des zones phréatiques et épiphréatiques est impossible par la seule observation des galeries. Les soutirages sont un indice de la zone épiphréatique. Mais on observera les règles classiques pour déterminer les phases spéléogénétiques. Notre modèle est validé pour les cavités alpines et peut probablement être appliqué à d'autres types de cavités.

Les observations au Bärenschacht expliquent l'inclinaison notable des phases spéléogénétiques et éclaircissent le rôle des crues sur les phases. Les phases sont décrites en détail dans le chapitre 5.

Remarques concernant le «four state model» et les transitions de phases

Le «four state model» présente quelques défauts:

- «state» (stade) implique que les cavités transitent les états au cours de leur existence. Ce fait n'est nulle part mis en doute dans la littérature. Je serais surpris que la fracturation évolue significativement à l'échelle de temps de la karstification (quelques centaines de milliers d'ans).
- Le Bärenschacht montre des ondulations de stade 2, tandis que la fracturation,de stade 3, est en contradiction.
- La fracturation ne détermine ni les écoulements ni la corrosion, elle ne fait que les influencer. Ainsi, une galerie se développe sur quelques centaines de mètres au milieu des marnes, mais 30 mètres à côté se trouve le calcaire.
- Le modèle ne tient pas compte de deux paramètres importants: le temps et la recharge: on trouvera une cavité de stade 4 plutôt sous un climat humide et régulier, tandis que les galeries en montagnes russes se forment sous un climat à précipitations contrastées.

Le «four state model» marque un progrès dans la compréhension des processus spéléogénétiques puisqu'il réunit géologie et hydrologie. Nous proposons un modèle qui va au-delà, en tenant compte de davantage de facteurs.

On peut dire que la nappe est inclinée car le système est en transition d'une phase à l'autre. Voici quelques précisions à ce sujet:

- Le système est en transition lorsque le niveau inférieur ne peut pas absorber toute l'eau, et la nappe d'étiage est inclinée. En général (voir les calculs de Dreybrodt (2000) et Palmer (2000)) cet état ne dure qu'un temps très court.
- Après la transition, la nappe d'étiage est quasiment horizontale et la nappe de crue est inclinée. L'équilibre n'apparaît que lorsque les crues moyennes ne contribuent plus à faire monter la nappe. Ainsi, les galeries inférieures sont formées sous un débit comparable à celui de crue, situation que l'on ne rencontre que durant quelques semaines de l'année. Pour cette raison, l'équilibre n'est atteint qu'asymptotiquement et après un temps très prolongé. En général, seules les galeries d'étiage sont en équilibre.

Nous estimons que les phases du Bärenschacht et du Réseau n'étaient déjà plus en transition, mais pas encore en équilibre, au moment de la transition suivante.

Hanging sump in Bärenschacht.

Hangender Siphon im Bärenschacht.

Siphon suspendu au Bärenschacht.

Photo by Daniel Burkhalter

4.1. Introduction

This chapter deals with the rock-water interaction and its effects on speleogenesis. Observations of the flooding behaviour and the resulting morphologies are used to gain better insight into speleomorphogenetic processes, which are important for the understanding of the phases described later in Chapter 5.

Since the solubility of limestone in acidic water (mainly carbon dioxide) is known, karst and cave formation is more or less explained. As more underground exploration progressed, more theories of cave formation developed to fit observations, from Davis (1930) to Bögli (1978) to today's views that are best expressed in the comprehensive work of Ford & Williams (1989). Recent work is more focussed on modeling and kinetics of cave genesis, like for example Groves & Howard (1994), Palmer (2000) or Dreybrodt & Gabrovsek (2000).

Cave genesis is a process of dissolution and transport. Dissolution is strongly linked to water and rock chemistry (e.g. Bögli 1978) and geology (e.g. Lowe 1992), transport is linked to boundary conditions (e.g. Jeannin 1996) and climate (e.g. Maire 1990). Therefore many models exist to describe formation processes. All of them are valid approaches, but in order to explain cave genesis as a whole, they should meet in the same place.

In the classical model of cave genesis by Ford & Ewers (1978), looping passages are attributed to the phreatic realm, whereas the theory of Audra (1994) suggests that they form in epiphreatic conditions (see also next section). This chapter compares the observations in Bärenschacht to the models, discusses problems and proposes a new model linking the two most widespread ones. We concentrate on the genesis of penetrable cave systems. We don't take into consideration the very beginning of cave formation, but instead try to explain how the "mature" cave forms. Our model is based on many different observations in caves and their comparison with existing literature.

Within the Siebenhengste-Hohgant cave system (Fig. 1-7), we focus on Bärenschacht cave, which forms the southernmost cave and develops directly upstream from the main springs of the system (Bätterich).

4.2. Genesis of cave passages

Palmer (1991) states, "The question posed by early workers (…) to whether caves originate above, at, or below the water table is not pertinent. (…) The water-table concept must be used with caution at the scale of individual passages, yet it is nearly always possible to tell from passage morphology whether a particular reach of cave originated under vadose or phreatic conditions."

The two most widespread models of passage formation

The classical model of passage formation is the most widely accepted "four state model" (Ford & Ewers 1978). The four state model puts the characteristics of the passage (loops in the phreatic realm, depth of karstification below the karst water table) in relation to the fissure frequency of the karstic massif. Therefore, this model predicts deep phreatic karstification and huge loops only in a thickly bedded limestone wich has small fractures, and an "ideal" water table cave in karst massifs that are thoroughly fractured and highly permeable.

Another more recent model is from Audra (1994). He puts a main question mark behind the notion of "phreatic passages", saying that most of the well-known, rounded passages that generally are attributed to having been created below the water table, are in fact produced in the epiphreatic zone. His reasoning is that only in the epiphreatic zone is corrosion sufficiently strong to provide effective solubility. His theory is supported by the fact that in many alpine caves, "phreatic" passages slope down for several hundreds of meters and don't have classical loops, an unlikely situation with a very high water table. Therefore, a question also exist about the notion of "cave phases". Audra (1994) infers that virtually all cave passages are created in the epiphreatic zone.

In the following chapter, we present observations in Bärenschacht cave which may give insight into how cave passages form. These observations allow to link the two different models presented above.

4.3. The observations in Bärenschacht

Our first aim was to determine the possible phases of cave genesis. Cave levels have been recognised by following the ascending and descending phreatic tubes that have been created by the same stream. The top of the tubes indicates the minimum height of the corresponding water table. The transition of vadose meandering canyons into phreatic tubes gives an absolute indication of the watertable height (Fig. 4-1). Three superimposed, now inactive, phases of cave genesis are identified within Bärenschacht using the principles and observations of Fig. 4-1. The other phases discussed in Chapter 5 and following had been

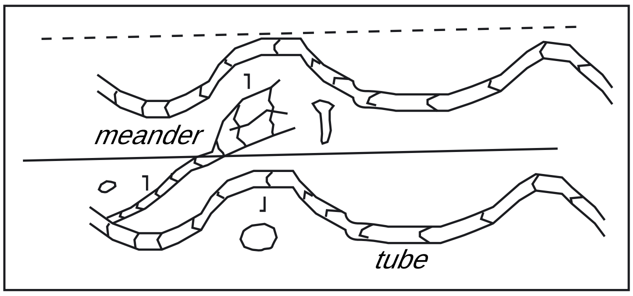


Fig. 4-1: Schematic sketch illustrating the identification of speleogenetic phases. Loops of phreatic passages (top) give the minimum height of the watertable (dotted), whereas a transition canyon-tube (below) gives the absolute watertable height (straight line).

Schematische Skizze zur Erkennung der speläogenetischen Phasen. Undulierende phreatische Röhren (oben) ergeben die Minimalhöhe des Wasserspiegels (gestrichelt), während der Übergang Mäander-Röhre (unten) die absolute Höhe (Linie) ergibt.

Dessin schématique illustrant l'identification des phases spéléogénétiques. Les ondulations (en haut) indiquent l'altitude minimale de la nappe (ligne interrompue), alors que la transition méandre-tube (en bas) en donne l'altitude exacte (ligne continue).

Fig. 4-3 (right): Schematic sketch of the northern part of Bärenschacht to illustrate the flooding mechanism. For explanation see text.

Schematische Skizze des nördlichen Teiles des Bärenschachts zur Illustration des Flutungsmechanismus. Zur Erklärung siehe Text.

Dessin schématique à travers la partie nord du Bärenschacht, illustrant le méchanisme de crue. Pour l'explication voir dans le texte.

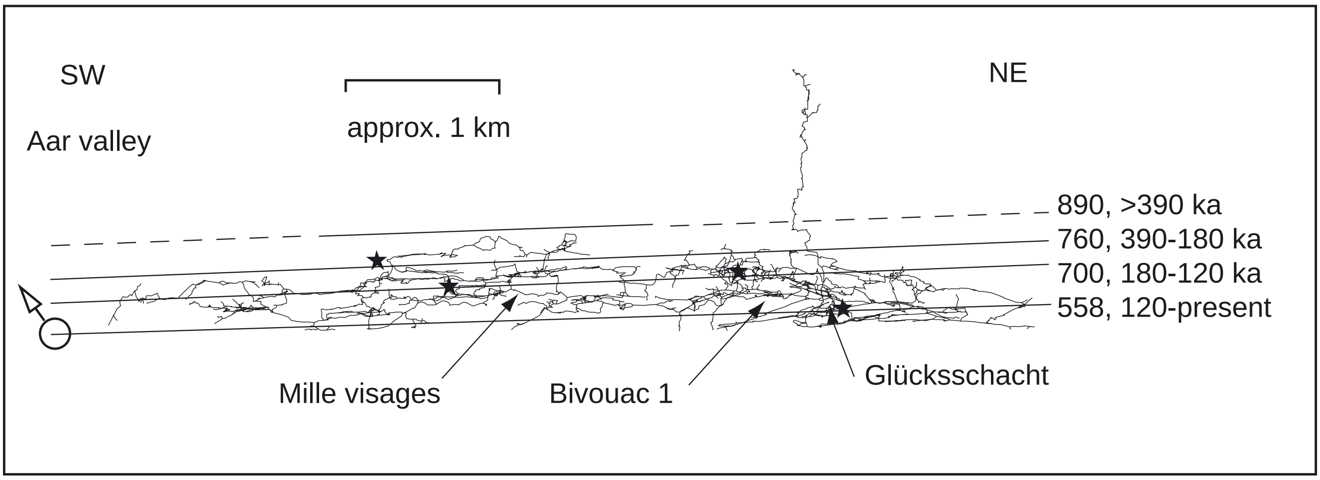
recognised in either St. Beatus Cave or other small caves in the region, and in Faustloch. For each phase, the loops of the phreatic passages are higher with increasing distance from the spring. The height of the watertable given by canyon-tube transitions (Appendix) correlates well with the height inferred from the top of the loops as described above. The canyon transitions show a clear inclination of the water table (1.3 to 2.1 degrees – 2.25 to 3.65 %). The definition of the corresponding height is attributed to the presumed spring level because of the watertable inclination: Phases at 700, 760, and 890 m a.s.l. are recognised (Fig. 4-2).
The observations further showed that the watertable inclination is not due to structural and/or tectonic effects: there are no limiting factors such as impervious layers or faults.

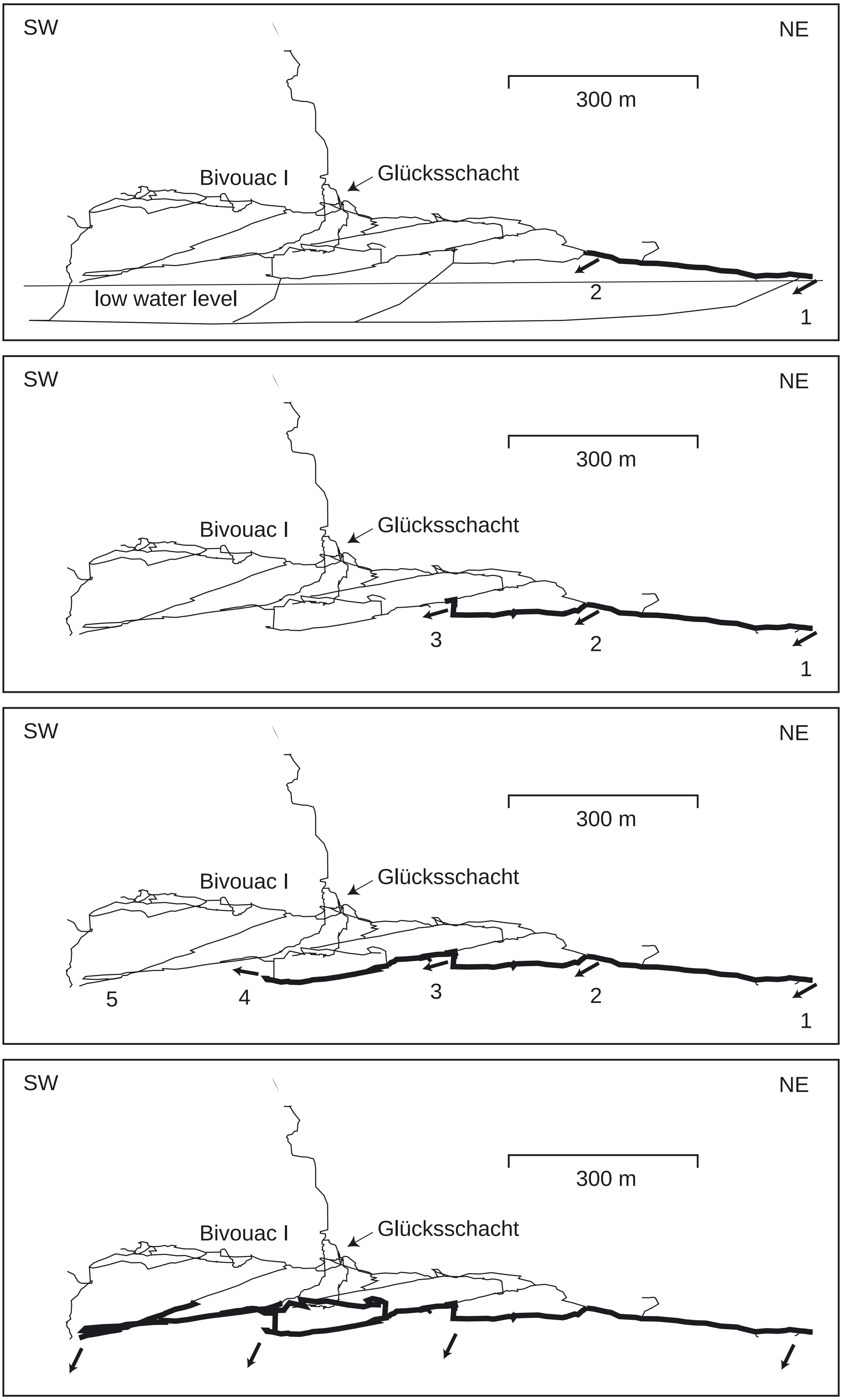
Observations in today's active phase (Fig. 4-2 Phase 558) allow to describe the flooding mechanism as well as the passage formation. First, in a low water situation, all galleries visible below Phase 558 (which represents the flood situation) are dry. Sedimentological observations as well as destroyed equipment (ruptured ropes etc.) show that when flooding occurs, the water is not rising uniformely from the lower, permanently flooded galleries, but instead the system functions in the "filling-overflow" manner (Fig. 4-3). This means that the water coming from the North sump first fills up the northernmost galleries until it reaches the departure of the "Zone nord basse" (Fig 4-3 top

Fig. 4-2 (below): Projected profile through the Bärenschacht with the four recognised phases. 558 is the active water table in flood situation. Stars indicate observed transitions from canyons to tubes.

Projektion durch den Bärenschacht mit den vier erkannten Phasen. 558 ist der aktive Wasserspiegel bei Hochwasser. Sterne bezeichnen die beobachteten Übergänge Mäander-Röhren.

Coupe projetée à travers le Bärenschacht avec les quatre phases reconnues. 558 est le niveau de la nappe actuelle en crue. Les étoiles localisent les transitions méandre-tube observées.



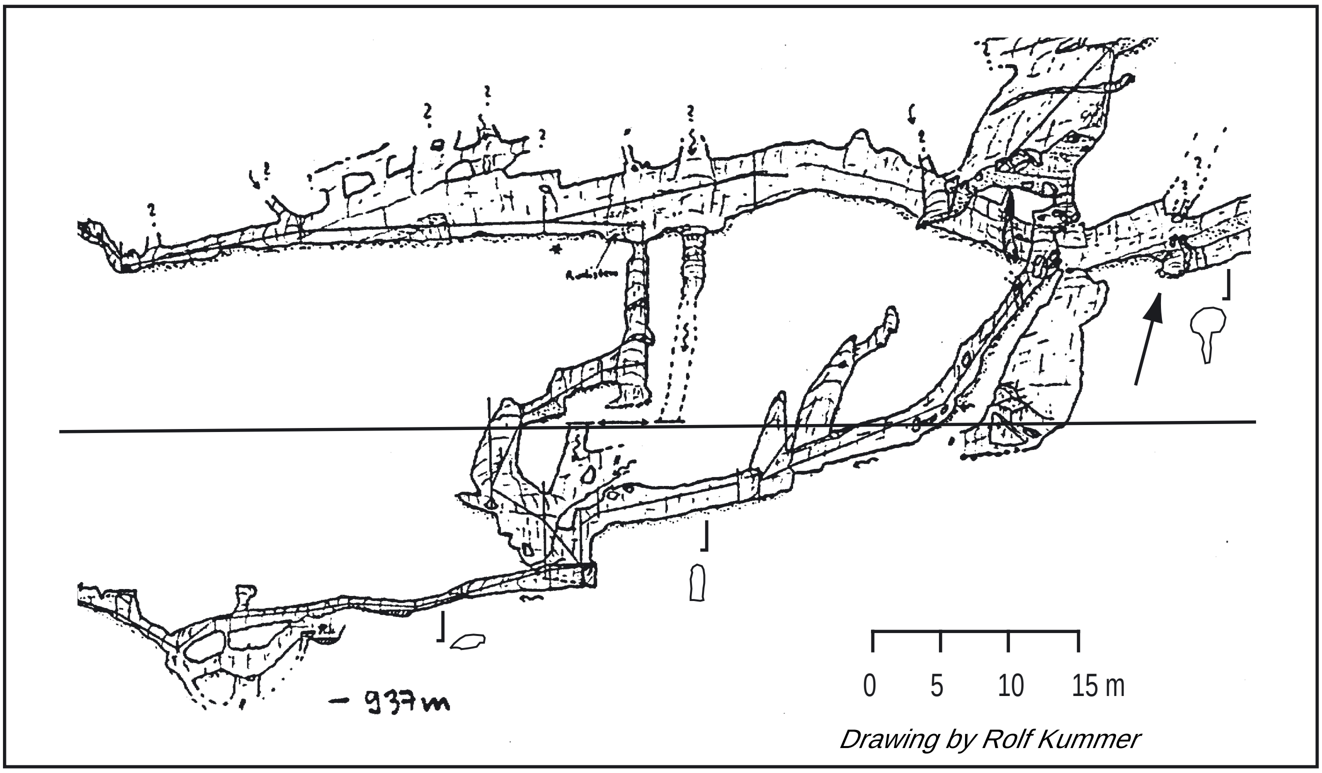

SW
NE
300 m
Bivouac I
Glücksschacht
low water level
2
1
SW
NE
300 m
Bivouac I
Glücksschacht
3
2
1
SW
NE
300 m
Bivouac I
Glücksschacht
5
4
3
2
1
SW
NE
300 m
Bivouac I
Glücksschacht

graph, No. 2). Then, a considerable vadose flow is injected into this zone (No. 2-3) which in turn gets flooded. One of the main exits for the water is the P20 (a 20 m deep shaft, No. 3) which is filled from below. When the water reaches the top of the shaft, it rushes down the adjacent galleries of the “Longs couteaux” (No. 3-4) in vadose conditions, until the Longs couteaux are filled (Fig 4-3 third graph). The escape route is again a shaft (No. 4); the water finally also fills the Karstwasserlabyrinth (Fig. 4-3 third and fourth graphs, No. 4-5). At this moment, the inclination of the watertable is 1.3 degrees. After the flood, the whole system is emptied through small galleries which connect with the perennial water table (Fig 4-3 base graph). Those galleries are usually not penetrable for humans. This type of flooding mechanism has also been observed in other caves such as Hölloch (Jeannin 2001).

Sediments remaining only at the rims of the vadose riverbed and elongated high-velocity scallops at the gallery’s base prove that there are huge vadose flows. The whole passage morphology, however, is phreatic, in spite of the sometimes considerable vadose conditions prevailing. Therefore, it seems that phreatic corrosion is dominant over vadose corrosion and erosion.

Research in the Glücksschacht region, which is approximately at the top of the present epiphreatic zone, shows that the vadose canyons flowing down this zone transform into phreatic tubes at the top of the epiphreatic zone (Fig. 4-4). Therefore, the observation that below the epiphreatic zone, phreatic corrosion is predominant and vadose entrenchment negligible, is confirmed.

Observations in conduits of phase 700 have shown that the same filling-overflow mechanism was most likely working during this older phase. Before reaching Bivouac I one sees a phreatic tube which has a sandy bottom. At the top loop of the tube, sand is absent and only some boulders are present. The descent then



Drawing by Rolf Kummer

Fig. 4-4:
Extended profile through the lower part of Glücksschacht. The subhorizontal line represents the average present high-water level. At right, a canyon (arrow) that would continue to the floodline, but is obstructed. The cross-sections show clearly the vadose-phreatic transitions.

Längsschnitt durch den unteren Teil des Glücksschachtes. Die subhorizontale Linie stellt das aktuelle Hochwasserniveau dar. Rechts befindet sich ein Mäander (Pfeil) dessen Fortsetzung gegen unten zusedimentiert ist. Die Profile zeigen klar den vados-phreatischen Übergang.

Section longitudinale à travers la partie profonde du Glücksschacht. La ligne subhorizontale représente le niveau de crue récent. A droite se trouve un méandre (flèche) dont la suite vers le bas est fermé par des sédiments. Les profils montrent clairement la transition vadose-phréatique.

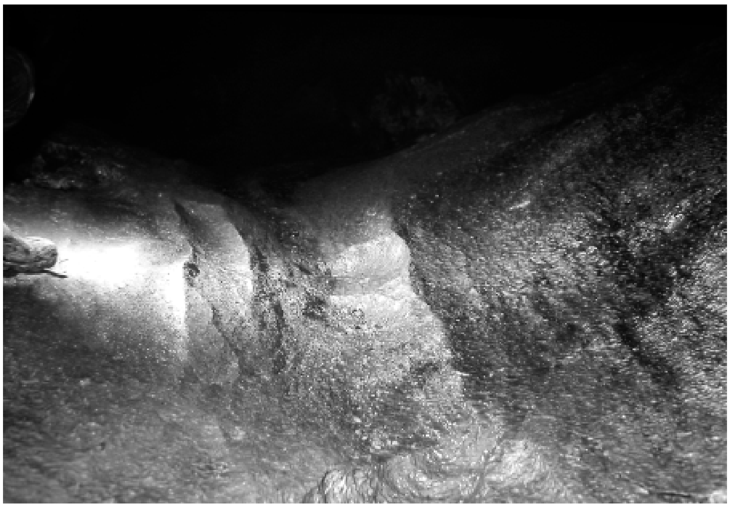


Fig. 4-5:
High-discharge scallops at the base of the gallery just upstream the lake of Bivouac I (see Fig. 4-6). Caver's boot for scale.

Fliessfacetten am Gangboden oberhalb des Sees beim Biwak I (siehe Fig. 4-6). Stiefel als Massstab.

Cupules à la base de la galerie en amont du lac du bivouac I (voir Fig. 4-6). Une botte donne l'échelle.

Photo by Bernhard Voss

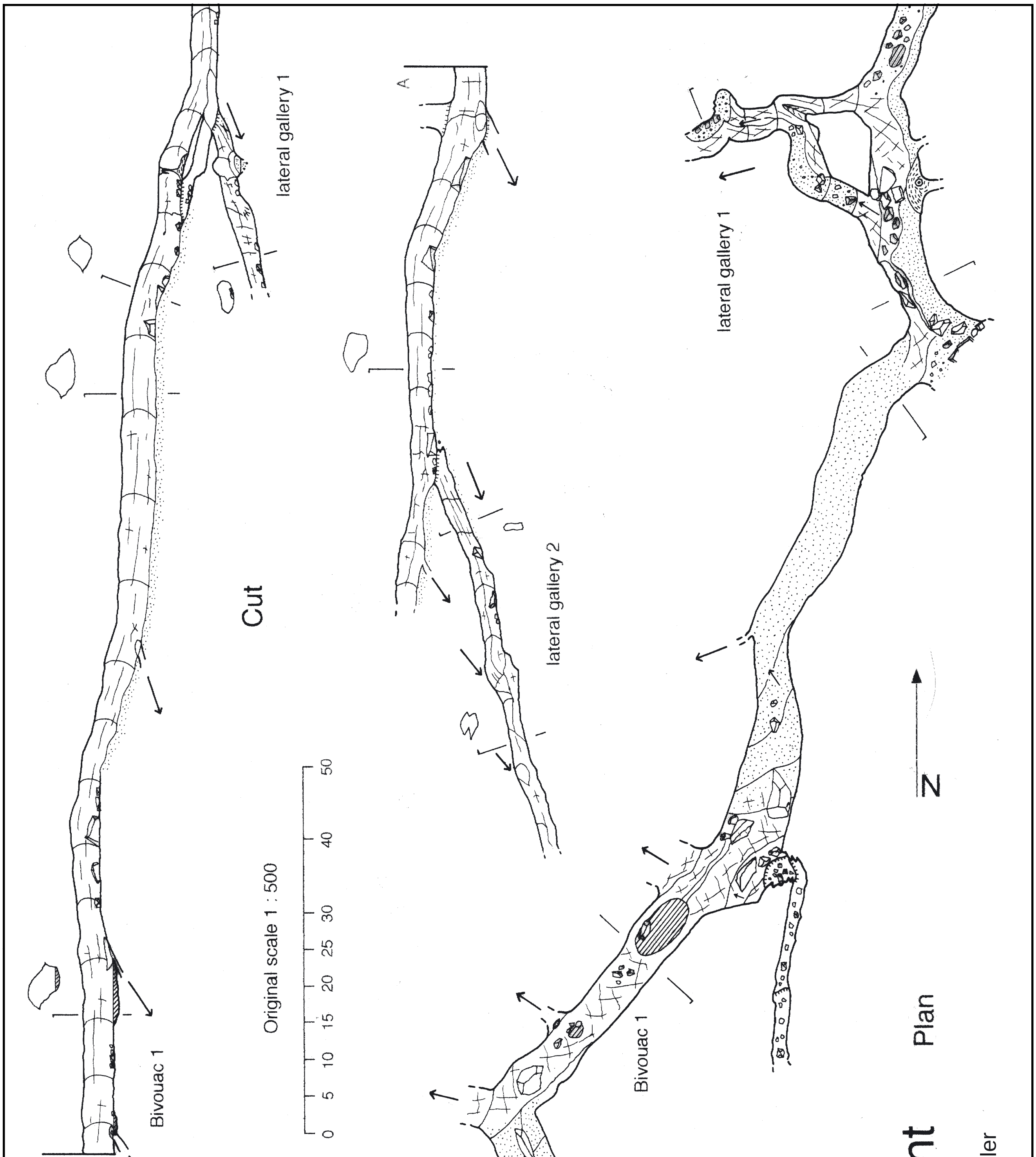
shows high-discharge scallops at the bottom (Figure 4-5), before the next sandy ground marks the beginning of the next rise. Taking flow rates into consideration, it shows clearly that the water was slowly rising until reaching the top of the loop, before flowing down and filling the next depression, eventually flooding all galleries. Small passages at the base of the loops (the so-called soutirages) emptied the galleries again during low water.

4.4. The genesis of the Soutirages

During flood events, the galleries are filled with water to the top of the loops. At low water stages, the loops are empty, therefore an outflow must exist at the bottom of the loops. These outflow passages are well known and are called soutirages (Hof, Rouiller & Jeannin 1984, Funcken 1994, Lismonde 1997)
The soutirages are small galleries that go down in the direction of the present water table (Fig. 4-6, arrows). Soutirages are observed in the present epiphreatic zone as well as in fossil loops. They always have a phreatic morphology and are much smaller than galleries which form the loops.

During a flood, all galleries of the active phase become flooded and hydraulically connected. Thus, the hydraulic gradient is more or less uniformly inclined towards the spring. After a flood, however, the water in the loops is perched above the original watertable, the gradient becomes steep (Fig. 4-7). The water reaches lower levels by seeping through unconformities (or proto-tubes as in Fig. 4-8) in the bedrock, in the downward-springward direction. Assuming uniform initial apertures, this seeping first occurs as diffuse flow over the whole height of the loop. However, the uppermost parts of the loop will first loose water, whereas the dissolution and erosion of the host rock still persists in the lower parts. In those parts, and logically at the lowestmost position, corrosion is long-lasting, creating the biggest voids. During the next flood, those voids are able to absorb more water, therefore corrosion and erosion are enhanced. Finally, a soutirage is created. Since the soutirage becomes the fastest path for reaching the original watertable, some other soutirages may connect to it, creating a sort of “main soutirage” (Fig. 4-6 lateral gallery 2). After connecting with the other soutirages, this type of gallery progressively becomes the perennial phreatic main gallery.

Where does the water from the soutirages flow, once it reaches the watertable? We postulate that simultaneously with the soutirages, phreatic passages are created in the direction of the spring. They form below the perennial water table and are also looped. Since the gradient is much flatter, but still pointing towards the spring, all those galleries possibly will join together, creating a phreatic network of galleries that drains the karst system in low-water conditions (Fig. 4-9).
Fig. 4-10 shows the functioning of the system in phase 760. There are two watertables, a lower one, approximately horizontal, which represents low-water conditions, and an upper one, inclined, which represents flood conditions. They converge at the spring. The gallery drawn in black is the main drain of phase 760. It is epiphreatic in its upstream part. This upstream part also shows soutirages (light grey) that connect with the perennial phreatic drain which is also active in low-water conditions (dark grey). Some of the water again joins the main drain where it gets perennially flooded (arrows), so that the main outflow is still the main spring at 760 m. The upflow-galleries are instantly abandoned once the watertable lowers, and therefore are preserved from reshaping. The upflow-galleries always have a small diameter (proving of low-water conditions), perfect phreatic morphology and scallops pointing upward (in contrast to the soutirages).



Bärenschacht

HRH - Drawing: Ph. Rouiller

Fig. 4-6 (left):
Plan and extended profile of the Bärenschacht at Bivouac 1 (location see Fig. 4-2). The main gallery extends from north to south (=paleoflow direction) and is emptied by small soutirages going in a general southwestern direction (arrows). In the lateral gallery 2, small soutirages combine to form a bigger gallery going down to the perennial water table.

Plan und Längsschnitt des Bärenschachtes beim Biwak 1 (Lage siehe Fig. 4-2). Der Hauptgang erstreckt sich von Nord nach Süd (alte Fliessrichtung) und wurde durch kleine Soutirages mit einer generellen SW-Richtung (Pfeile) geleert. Im Seitengang 2 kommen mehrere Soutirages zusammen und bilden einen grösseren Gang in Richtung des perennierenden Wasserspiegels.

Plan et coupe longitudinale du Bärenschacht au bivouac 1 (situation voir Fig. 4-2). La galerie principale s'étend du nord au sud (direction de l'écoulement ancien) et est vidangée par de petits soutirages orientés généralement SW (flèches). Dans la galerie latérale 2, des soutirages se combinent pour former une galerie plus grande qui rejoint plus tard la nappe pérenne.

Fig. 4-7 (right):
The genesis of the soutirages. A: the situation after a flood event. The water is perched above the low-water table and seeks his way down. B: Since the water stays longer at the base of the loop, the probability of soutirage forming is higher. C: in low-water conditions, the soutirage leads to the water table and further down to the perennial phreatic gallery. Of course, the genesis of the soutirages needs many cycles.

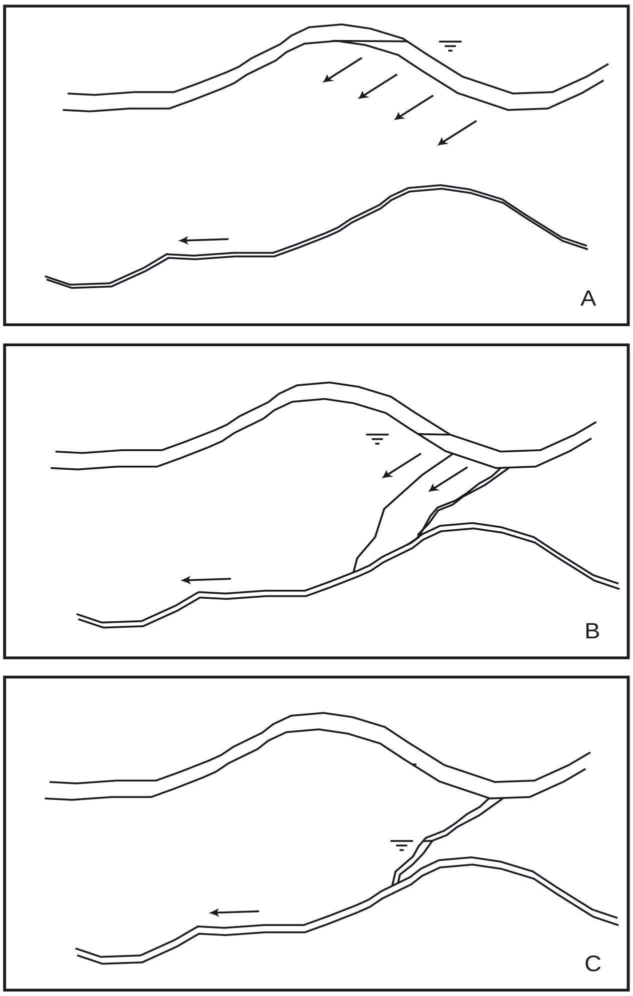
Die Entstehung der Soutirages. A: Die Situation nach einem Hochwasser. Das Wasser ist oberhalb des Niederwasserspiegels gestaut und sucht sich seinen Weg nach unten. B: Da das Wasser an der Basis des Ganges länger liegen bleibt, ist die Wahrscheinlichkeit einer Soutirage dort höher. C: Bei Niederwasser führt die Soutirage zum Wasserspiegel und zum perennierend phreatischen Gang. Natürlich werden viele solcher Zyklen für die Entstehung der Soutirages benötigt.

Genèse des soutirages. A: La situation après une crue. L'eau est perchée au-dessus de la nappe d'étiage et cherche son chemin vers le bas. B: L'eau reste plus longtemps à la base de l'ondulation, la probabilité d'un soutirage est donc élevée. C: En étiage, le soutirage est connectée à la nappe et continue vers la galerie phréatique pérenne. Bien sûr, un grand nombre de cycles est nécessaire.

The dark-grey passages are small compared with the epiphreatic ones (otherwise the full flood could pass through) and attain a final shape and size only at the next phase 700.

The soutirages in loops close to the spring may develop earlier than the more distant ones, thus emptying the downstream loops earlier and creating a jump in head and watertable as shown in Hölloch (Jeannin 2001, Fig. 2). This schematic possibility is shown in Fig. 4-11, however, in Bärenschacht, there is no evidence for such a mechanism. Of course, deepening of the spring level may cause soutirage formation in the upper galleries.

Soutirages can only form in the epiphreatic zone, because the waters in the phreatic realm would continue to flow in the big phreatic tube – there is no steep hydraulic gradient in the phreatic realm. Observations in Bärenschacht show (Fig. 4-10) that, especially in the downstream section, the main tubes experience perennial phreatic conditions and the epiphreatic flooding occurs only in the upstream section. This is confirmed by the fact that in the downstream (flooded) tubes, soutirages do not exist.



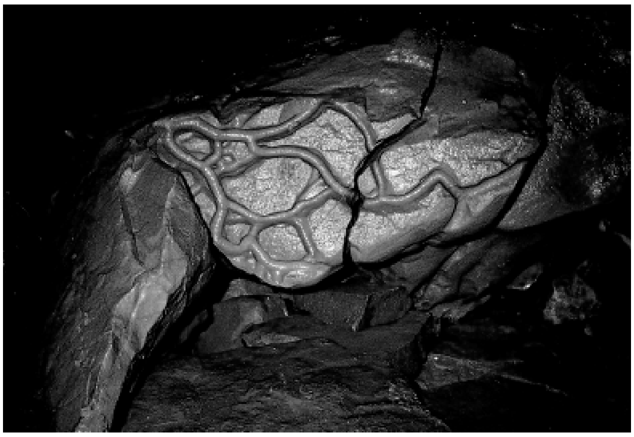


Fig. 4-8 (left):
Protoconduits in the Glücksschacht region (diameter approx. 5 cm).

Protogänge in der Glücksschachtregion.

Prototubes dans la région du Glücksschacht.

Photo by Werner Janz

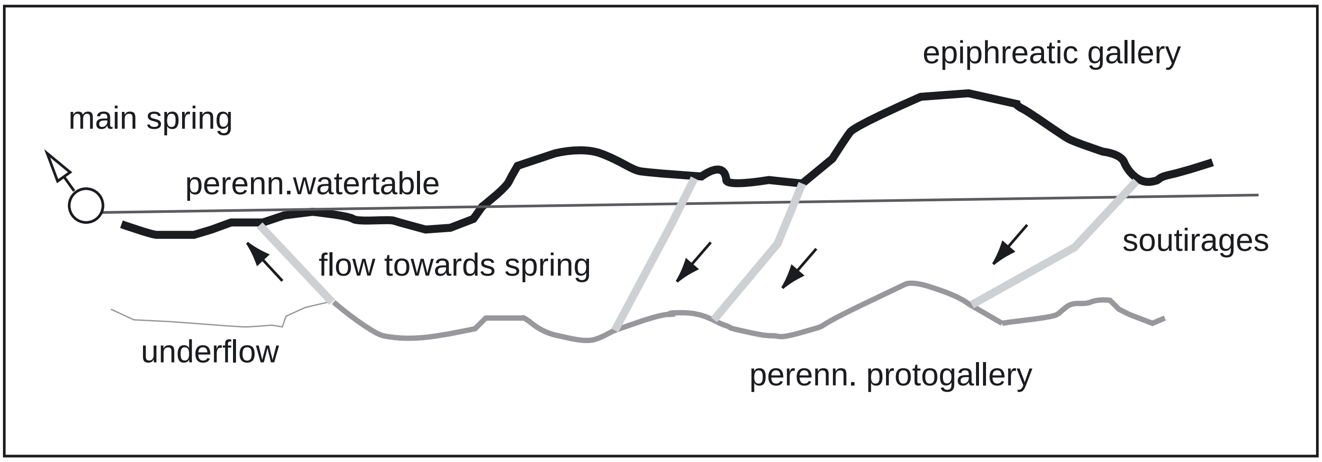


Fig. 4-9 (above): Schematic flow system. Black=main gallery; light grey=soutirages (downward) and upflow (upward); dark grey=perennial phreatic conduit. For further explanation see text.

Wasserflussschema. Schwarz=Hauptgang; hellgrau=Soutirages (abwärts) und Rückbringer (aufwärts); dunkelgrau=perennierend phreatischer Gang. Weitere Erklärung im Text.

Schéma du courant d'eau. Noir=galerie principale; gris clair=soutirages (flot descendant) et remontées (flot remontant); gris foncé=galerie phréatique pérenne. Pour plus d'explications,voir dans le texte.

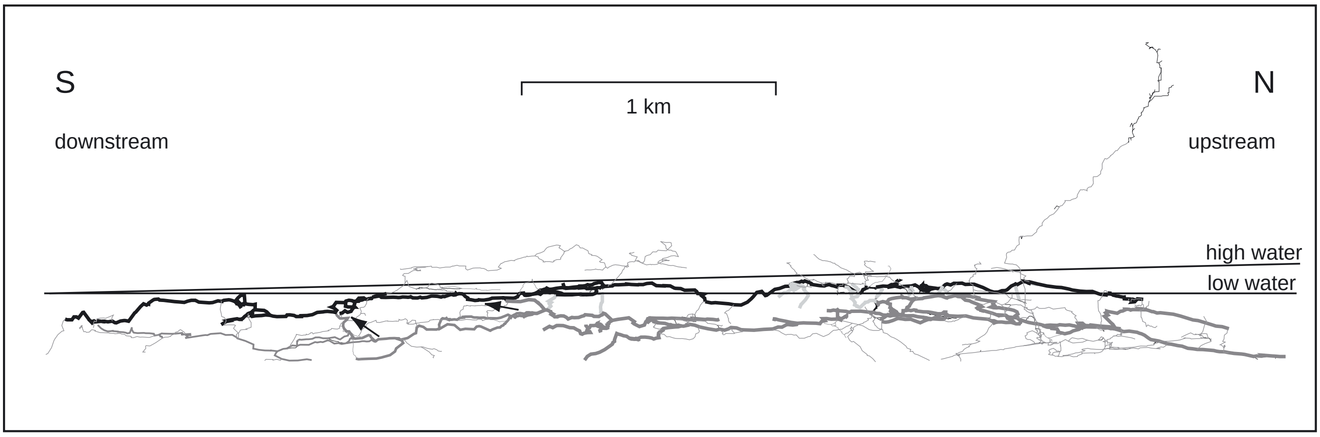


Fig. 4-10: The galleries of the Bärenschacht in phase 760. The schema 4-9 is applied, the legend of colours are the same.

Die Gänge des Bärenschachtes in der Phase 760. Das Schema 4-9 ist angewendet, die Farblegende bleibt dieselbe.

Les galeries du Bärenschacht dans la phase 760. Le schéma 4-9 est appliqué, la légende des couleurs est la même.

4.5. Further interpretation

Observations of the cave genesis phases have shown that they are inclined. Further, phreatic corrosion is predominant over vadose corrosion and erosion within the epiphreatic zone. This not only in galleries which have temporary water flow, but also in galleries which have perennial streams (Glücksschacht).
The transition canyon-phreatic tube occurs at the top of the epiphreatic zone. Therefore, we conclude that those transitions, formerly attributed to the perennial water table, reflect the height of the epiphreatic zone.

This epiphreatic zone, which naturally is defined by inflow-outflow balance, is variable in height. Observations of flood behaviour show that heavy rain as well as snowmelt raises the flooded zone to an "average height" which seldom is surpassed. This may be due to overflow over loops, as well as other constraints. For example, the amount of water stored in the epiphreatic zone is not only given by outflow capacity, but also the feeding galleries have a limited capacity. The change of vadose canyons towards passages which resemble phreatic ones occurs (see the example of Glücksschacht above) at the average height of flood. The setting of the main phreatic passages shows that near the spring, the passages often stay flooded even in low-water conditions (Fig 4-10), and only in the upstream sections, the epiphreatic model holds true. The same is valid for Hölloch cave (central Switzerland), as shown by Jeannin (2001).

Passage morphology, sedimentology and observations of the soutirages are concordant and lead to a new model of cave morphogenesis that links both models of Ford & Ewers (1978) and Audra (1994):

1. Initial passages form below the water table. The mature cave passages of phreatic morphology form below and above the perennial water table.
2. The definition of cave phases is given by its spring and the height of the epiphreatic zone.
3. This height is given by "normal" high-water events such as spring snowmelt and heavy summer rain.
4. Soutirages drain the water from the epiphreatic zone towards the perennial flooded zone, in which new galleries form.

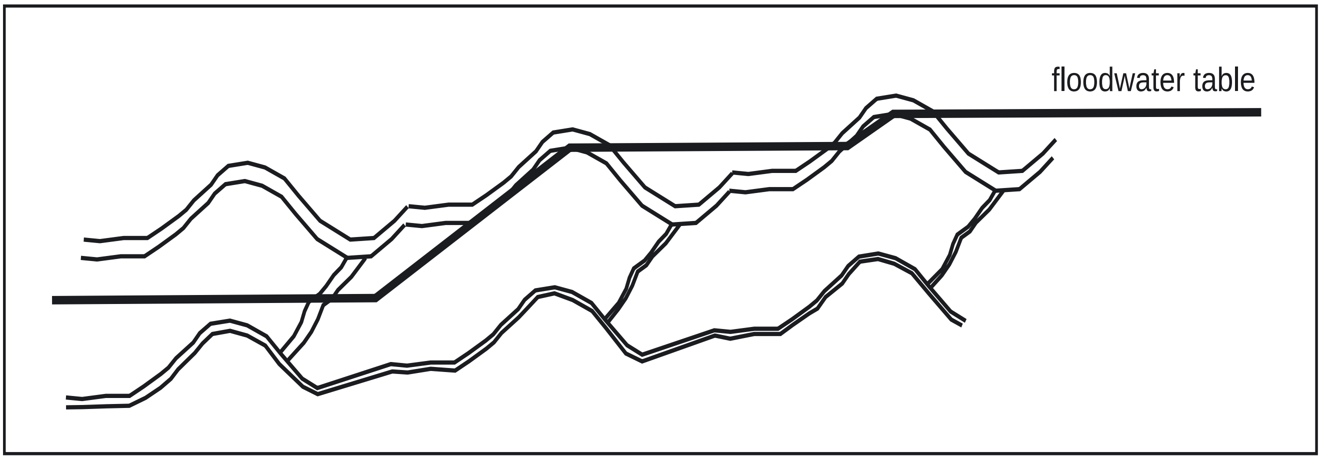


Fig. 4-11: Possibility of change of the floodwater table with time due to successive widening of soutirages. The one to the left is already wide enough to let pass all water, whereas the other two are still in creation. Since the head is bigger for the middle one, it will widen quicker.

Die Möglichkeit eines Spungs der Flutungszone durch sukzessives Erweitern der Soutirages. Diejenige links ist bereits gross genug, um alles Wasser passieren zu lassen, während die anderen sich noch erweitern. Da der Gradient für die mittlere Soutirage grösser ist, erweitert sie sich schneller.

La possibilité d'un changement de la nappe en crue dû à une croissance successive des soutirages. Le soutirage de gauche est déjà suffisamment large pour laisser passer les eaux, alors que les autres sont encore en voie de formation. Le gradient étant élevé pour le soutirage du milieu, celui-ci va s'élargir plus vite.

4.6. Comparison with literature

Calculations of Curl (1974) and Lauritzen, Ive & Wilkinson (1983) show that floodwater corrosion is predominant: the formula relating scallop measurements with flow velocity indicate that scallops form generally during annual floods (see also Jeannin 2001). Therefore, our observation that phreatic floodwater corrosion is predominant, is likely true. Another supporting fact is that floodwater has not only a higher flow rate, but in general also a higher suspension load (more erosion and corrosion). In addition, it is less in chemical equilibrium with the host rock, thus enhancing the corrosion.

Palmer (1987) writes that “The point at which these changes (vadose canyon-phreatic tube, auth.) take place has been called the “piezometric limit” by Palmer (1972), implying that it is the upstream limit for the effects of hydrostatic pressure on passage morphology. This term is applied to a single point (or, rather, a short zone) within a specific passage (…) and does not imply the presence of a continuous piezometric surface.” However, in a later passage, he states “passages fed by large recharge areas can be subject to severe flooding to heights considerably above base level. They do not have the sharply defined transition.” In Bärenschacht (Glücksschacht) such a sharp transition exists. The remaining question is, if our model only holds true for Bärenschacht and Siebenhengste, or if it may be generally applied. The theory of Audra (1994) indicates that the epiphreatic zone is important for the genesis of mature caves. His study was carried out in alpine Austrian caves which are comparable to ours. Observations of Audra about the importance of epiphreatic passage genesis are similar to ours. The main difference is that for caves such as St. Beatus cave, Audra would postulate a genesis in a huge epiphreatic zone reaching from the entrance up to the far end of the cave at +350 m. In contrast, observations in St. Beatus cave show that the inclination is due to geologic structure, and that the passage is composed of several superimposed galleries of different age, thus still creating the phases of cave genesis. Therefore, our model fits better the observations and would probably also fit Audra’s ones.

What about caves in non-alpine areas? Palmer (1972) describes Onesquethaw Cave (NY, USA) in detail: The cave morphology is mainly phreatic (with the exception of the entrance meander), however the cave may get flooded completely. These observations seem to fit quite well the model presented here, although Palmer (1972) only states that passage genesis in epiphreatic conditions is observed.

In Mammoth Cave (KY, USA), flooding is not very significant (Palmer, pers. comm.) and the low discharge waters are aggressive, therefore it seems that in Mammoth Cave, the canyon-tube-transitions are adjusted to the low watertable. However, this is still coherent with our model: if there is (almost) no flooding, it is clear that the transitions form at low-water level.

4.7. Conclusions

Observations in Bärenschacht cave north of Lake Thun, which represents the outflow of the current and some past epochs of Siebenhengste region, permit the development of a new, comprehensive model for the genesis of mature, penetrable caves. The model has as advantage to link the classical four-state model by Ford & Ewers (1978) with the newer model of Audra (1994), therefore providing a new approach to the problem of cave genesis in general. Perhaps the most striking feature of the model is that “phreatic tubes” are created in the phreatic realm as well as in the epiphreatic zone. Therefore, the classical “piezometric limit”, derived from the morphological transition of vadose meanders into phreatic tubes, reflects the annual average height of the epiphreatic flood zone. The distinction between the phreatic and the epiphreatic states is not possible by observing the tubes alone, which have the same morphology. The absence or presence of soutirages, which only form in the epiphreatic zone, may be a good indication. However, the determination of cave genesis phases must still follow the classical procedure: determining the minimum (epiphreatic) water table height by following the tubes and observing vadose-phreatic transition. Extrapolating the water table to the spring determines an average spring position. All galleries connected to that spring, but existing at lower elevations, are perennial phreatic and show no soutirages.
Our model is applicable to Bärenschacht, and most likely also to alpine caves in general. It still needs to be confirmed if this model can be transferred to fit low-dip cave systems other than Onesquethaw and Mammoth Caves.

Following our model, the top of the epiphreatic zone indicates the limits of a speleogenetic phase. This explains the observed inclination of those phases, and it answers the question whether flooding would affect the distinctive phase boundaries as well. The exact definition of the speleogenetic phases and their location within Bärenschacht follows in Chapter 5.

4.8. A remark on the four state model and the phase transitions

The Four state model

Based on observations and ideas developed in this chapter, it appears that the widely accepted four state model of Ford & Ewers (1978) presents some flaws which are discussed here below. The following remarks are a result of an exchange of thoughts with Derek Ford.

1. “state” implies for the reader that the caves transit, during their lifetime, the four states. This possibility is not explicitly excluded in Ford & Ewers (1978). However, I think that we can reliably enough exclude that the fissure frequency used as a base for the four state model will differ significantly in karst timespans (here: some 100‘000 years in the maximum) within a given cave region. This criticism deals with semantics and understanding and is therefore somehow subjective.
2. The galleries of Bärenschacht (and most of the Siebenhengste labyrinth) have an undulation of more than 70 m, which would be State 2. We are in an Alpine thrust belt with many fractures and beddings (State 3 at least), so also a state 3 or even 4 cave should be observed, which is not the case.
3. Another observation in Bärenschacht shows that for some 100 m in length, the gallery “Mille visages” (Fig. 4-2) is dug within the marl (which was considered impossible some time ago, see Chapter 3.1). If it moved 30 m to the right, it would have enjoyed pure fractured limestone. This example shows that fractures and corrosion do not determine pathways, they only influence it, the main controlling factor being the local hydraulic gradient.
4. The four state model doesn’t take into account other important parameters: time and recharge. I believe that if the difference in discharge between low water and flood water is small (p.ex in a rainy climate, or if an allogenic stream is retained by a lake), the watertable cave is quite common (Mammoth Cave), but if the difference is big (alpinotype: huge snowmelts and thunderstorms, sometimes no rain for one month), looping passages will develop, regardless of the fracturation. This is mostly due to the difference between transition and equilibrium that is discussed below.

I think the four state model was a very big step forward towards an understanding of speleogenetic processes, since it tries to link geological and hydrological parameters which have a big influence on karstification. Therefore I think the four state model still retains some validity, but it is no more possible to reduce all caves to this model. There are much more parameters influencing speleogenesis and even more parameters acting upon morphogenesis.

The notion of transition versus equilibrium

A remark I often heard when I presented the above ideas was that the system is still in transition from an upper phase towards the present one. I think it is useful to put forward some definitions of transition versus equilibrium.

- Transition means that the lower level cannot absorb all lower and intermediate waters, thus the perennial watertable is inclined measurably. This state is during usually only a very short time (see the calculations of Dreybrodt (2000) and Palmer (2000) for the growth time of galleries).
- After transition, the low waters have nearly flat watertables, while intermediate and floodwater rises the watertable (in slant angle) considerably. Therefore, equilibrium is not yet attained. Equilibrium is only reached when intermediate and high waters don’t rise the watertable significantly any more. Since the equilibrated galleries can take all the flood, this means that they are formed by a discharge equivalent to the flooding. Since in our regions this discharge is only rarely available, the time required to reach equilibrium is very long, and most probably a complete equilibrium is only reached asymptotically after a very long period of time. This time will not be reached in Alpine regions, since the landscape outside the cave evolves geologically before the equilibrium can be reached. Most usually, only in low-and intermediate flow the galleries are in equilibrium state.

All the phases of Bärenschacht and the whole rest of the Réseau, in our opinion, was no more in transition, but not yet in complete equilibrium, when the transition to the next lower phase occurred.

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5. Reconstruction of Alpine Tertiary paleorelief through the analysis of Caves at Siebenhengste

Zusammenfassung: Rekonstruktion des tertiären Paläoreliefs der Alpen durch die Analyse von Höhlen der Siebenhengste

Dieses Kapitel behandelt die Überlegungen, denen zufolge die Höhlen und Talböden zusammenhängen. Danach werden die Beobachtungen in den Höhlen sowie zusätzliche Beweise präsentiert. Zuletzt wird eine Extrapolation der Phasen gegen die Siebenhengste zu versucht. Dieses Kapitel hängt die Geologie (Kap.2), Wasserfärbungen (Kap. 3.2) sowie Gestein-Wasser-Wechselwirkung (Kap. 4) zu einem Modell zusammen.

Speläogenese und deren Beziehung zu Tälern

Die Eintiefung der Alpentäler wurde schon längere Zeit diskutiert. Die Quantifizierung der sukzessiven Eintiefung ist jedoch schwierig, da beobachtete Terrassen oft von der Geologie abhängen und die verbliebenen Sedimente zumeist von der jüngsten Vergletscherung abtransportiert wurden oder – falls vorhanden – über mehrere Kilometer verstreut auseinanderliegen. Durch die Höhlenanalyse kann ein besserer Einblick gewonnen werden.

Die grundlegenden Faktoren der Höhlenentstehung können hier aus Platzgründen nur summarisch erläutert werden; das Buch „Speleogenesis – Evolution of Karst Aquifers“ bietet eine sehr gute Übersicht. Während Wasser der vadosen Zone nur Boden und allenfalls Wände eines Ganges korrodiert (und so einen Mäander schafft), wirkt das Wasser in der phreatischen Zone auf den gesamten Gangquerschnitt: eine rundliche Röhre entsteht. Die Gangmorphologie gibt also Aufschluss über die Entstehungsbedingungen.

Dadurch können oft speläogenetische Phasen erkannt werden: In einem ersten Schritt werden die ab- und aufsteigenden phreatischen Röhren, die vom gleichen Fluss stammen, verfolgt. Deren höchster Punkt ergibt den minimalen zugehörigen Karstwasserspiegel. Ein Übergang Mäander-Röhre definiert dessen Höhe exakt. Der so beobachtete Karstwasserspiegel ist oft mit 1-2° geneigt; die Höhenangabe erfolgt daher an der vermuteten Quelle. Der Begriff „Wasserspiegel“ ist im Karst eigentlich inkorrekt, da Röhrenfliessen mit praktisch undurchlässigem Gestein kontrastiert. Der Einfachheit halber belassen wir diesen Term.

Die im Kapitel 4 beschriebenen Beobachtungen zeigen, dass der obige geneigte Karstwasserspiegel das Dach des epiphreatischen Raumes darstellt, und dass darunter phreatische Korrosion immer über vadose Erosion dominiert.

Falls der Karstwasserspiegel nicht von geologischen Strukturen abgedämmt wird, so muss er von der Quelle abhängen. Falls die Tieferlegung der Quelle (die ihrerseits zumeist vom regionalen Wasserspiegel des Talbodens abhängt) graduell erfolgt, passt sich auch das Höhlensystem dahinter graduell an, es werden keine Phasen gebildet. Falls die Tieferlegung rasch erfolgt und von einer ruhigen Zeit abgelöst wird, passt sich auch die Höhle rasch (innerhalb einiger 10‘000 Jahre) an die neuen Gegebenheiten an: es entstehen Phasen.

Der Eintiefungsmodus des Tales reflektiert sich deshalb in der Ausbildung der Höhle. Wir gehen davon aus, dass die in den Siebenhengsten beobachteten speläogenetischen Phasen eine etappenweise Taleintiefung (hier durch Gletscherwirkung) widerspiegeln und deshalb ein wichtiges Werkzeug zur Rekonstruktion des Paläoreliefs darstellen.

Neuere Forschungen beweisen die Vermutung, dass die Speläogenese zu Zeiten der Vergletscherung kaum aktiv war, und sich in Interglazialen resp. Interstadialen die Hohlraumschaffung intensivierte. Da die Gletscher in unseren Breiten temperiert sind, bewirkt eine Vergletscherung des Tales eine Hebung des Wasserspiegels, die Ersäufung alter Gänge und die Ablagerung von feinkörnigem Gletschermilch-Sediment. Die am Ende einer Vergletscherung einsetzende Erosion bewirkt in aller Regel nur ein teilweises Ausräumen der Silte: die Höhle wird zum geologischen Archiv.

Die jüngsten speläogenetischen Phasen der Siebenhengste-Region

Bärenschacht und St. Beatus-Höhle, zusammen mit dem Faustloch die tiefstgelegenen Höhlen des Gebietes, haben ihre Quellen im Aaretal. Da keine geologische Ursachen für eine Abdämmung gefunden wurden, kann die Eintiefungsgeschichte des Tales deshalb mithilfe der beiden Höhlen untersucht werden. Oberflächeninformationen zur Taleintiefung fehlen bislang fast vollständig, da wohl die jüngste Vergletscherung alle Spuren auslöschte. Die Höhe

der im Folgenden angegebenen Phasen bezieht sich auf ihre Quelle, wegen der Alpenhebung sind diese Höhen nicht diejenigen zum Zeitpunkt ihrer Bildung. Die Phase 558 ist die aktuelle Phase, gegeben durch den Thunerseespiegel. Es bestehen Anzeichen dafür, dass der See nacheiszeitlich 30 m (resp. davor sogar einmal 80 m) tiefer lag. Die Phase 700 ist im Basissystem des Bärenschachtes zu sehen, es sind grosse Gänge mit 25 m^2 Querschnitt und einem Minimalalter von 160 ka. Die Phase 760 ist in der St. Beatus-Höhle gut ausgebildet; die dazugehörigen Gänge im Bärenschacht sind deutlich kleiner (12 m^2). Das Minimalalter beträgt 260 ka. Die Phase 805 ist in der St. Beatus-Höhle sichtbar, von untergeordneter Bedeutung und älter als 350 ka. Die Phase 890 ist hingegen wieder in beiden Höhlen vorhanden und als gesichert einzustufen.
Das Inventar der Kleinhöhlen der Waldegg wurde statistisch ausgewertet. Die Kleinhöhlen zeigen sehr deutlich dieselben Phasen wie oben beschrieben und zusätzlich eine Phase bei 660 m.

Die deutliche Differenz der Querschnitte der Gänge der Phasen 660 und 760 erklären wir mit dem zu diesem Zeitpunkt erfolgten Anschluss der Schrattenfluh an das System. Die Ganggrösse ist nämlich, sofern die chemischen Gegebenheiten dieselben bleiben, von Schüttung und Zeit abhängig. Die Datierungen zeigen dass die Hohlraumvergrösserung mit der Schüttung erklärt werden muss, was in diesem Fall am ehesten mit dem Anschluss eines neuen Einzugsgebietes erklärt werden kann.
Wir versuchen eine Extrapolation der Phasen gegen das Faustloch zu, dessen tiefer Teil momentan unzugänglich ist. Deshalb sind die hier gegebenen Indikationen mit Vorsicht zu geniessen. Die Phase 558 ist bei Hochwasser in ungefähr der extrapolierten Höhe zu finden; deshalb schliessen wir, dass in erster Näherung die Neigung der Phasen nicht ändert. Die Phase 660 ist im Faustloch gut zu sehen und kann deshalb als gesichert angenommen werden, ganz in Gegensatz zu den höher gelegenen Phasen, wo noch beträchtliche Unsicherheiten herrschen. Die Verbindung Bärenschacht-Faustloch ist eminent wichtig für das Verständnis der älteren, vom Aaretal abhängigen Phasen (bis 1440).
Zusammenfassend lässt sich sagen, dass sechs Phasen in den Höhen 558, 660, 700, 760, 805 und 890 m gefunden wurden, und dass die Analyse von Kleinhöhlen diese Phasen bestätigte. Diese Erkenntnis ist von Nutzen in Gebieten, wo kaum grosse Höhlensysteme gefunden wurden.

Schematische Entwicklung der Paläogeograpie des Siebenhengste-Gebietes vom Tertiär bis heute
Die speläologische Forschung auf den Siebenhengsten zeigte die Existenz von vier Phasen (auf 1950, 1720, 1585 und 1505 m) auf, die ins Eriztal entwässerten. Die nächsten Phasen (1440 und 1150 m) hingegen flossen in Richtung Aaretal.
Lage und Grösse der ältesten fossilen Gänge legen eine Entstehung vor der Entstehung des Justistals nahe, es ist auch möglich, dass das Aaretal zu diesem Zeitpunkt kaum existierte und dass das Eriztal als „Proto-Aaretal“ fungierte.
Im F1 gefundene Kohle zeigte eine Vitrinit-Reflektanz, wie sie für das Penninikum üblich ist. Sollten zum Zeitpunkt dieser Ablagerung noch die penninischen Decken vorhanden gewesen sein, wäre der Beginn der Verkarstung auf den Siebenhengsten zeitgleich mit der jüngsten (heute bereits wieder erodierten) Molasseablagerung. Nach der Erosion des resistenten Penninikums wurden die weichen Flysch- und Mergelschichten freigelegt; die Erosion folgte deshalb eher dem Streichen der Schichten. Die Theorie von Beck (1954) besagt, dass vor der Entstehung des heutigen Aaretals die „Alpenaare“ via Brünigpass abfloss und die „Thun-Aare“ aus Kander und Simme in Richtung Bern floss. Dies ist nicht in Widerspruch mit den Befunden aus den Höhlen. In dieser Zeit setzten die Eiszeiten ein und das Aaretal wurde sukzessive eingetieft. Inwieweit die Täler eingetieft oder aber die Alpen gehoben wurden, lässt sich mit der Höhlenanalyse allein nicht quantifizieren. Eine schematische Skizze zur Landschaftsentwicklung ist auf den Figuren 5-10 bis 5-12 abgebildet.

Höhlen sind also wertvolle Werkzeuge für die Rekonstruktion der Paläogeographie, da sie Formen und Sedimente erhalten, die an der Oberfläche längst wegerodiert sind. In Ermangelung von Grosshöhlen können nun auch Kleinhöhlen zur Phasenrekonstruktion herangezogen werden.
Diese Rekonstruktion der Paläogeographie ist jedoch noch nicht datiert, Zusammenhänge mit Vergletscherungen fehlen. Dies wird das Ziel des Kapitels 6 sein, das Sedimente und Morphologie zusammenhängt.

Résumé: Reconstitution du paléorelief tertiaire alpin par l'analyse des cavités de la région des Siebenhengste

Ce chapitre commence par un exposé sur la relation entre les cavités et les fonds de vallée. Nous présentons ensuite nos observations dans les cavités, ainsi que d'autres éléments. Finalement, nous proposons une extrapolation des phases aux Siebenhengste, en un modèle évolutif. Ce chapitre fait le lien entre géologie (voir Chap. 2), traçages (voir Chap. 3.2) et la relation eau-roche (voir Chap. 4).

Spéléogenèse et relation avec les vallées

On discute de longue date l'approfondissement des vallées. Il est difficile de quantifier l'approfondissement successif, parce que les terrasses observées sont souvent dépendantes de la géologie, les sédiments érodés ou dispersés sur plusieurs kilomètres par la glaciation la plus récente. Dans les cavités, les conditions d'observation sont meilleures.

Nous ne répéterons que sommairement les facteurs principaux de la spéléogenèse; on se référera avec profit à l'ouvrage «Speleogenesis – Evolution of Karst Aquifers». En zone vadose, l'érosion ne concerne que le fond et parfois les parois des galeries, créant des méandres, alors que dans la zone phréatique, l'action de l'eau s'exerce sur tout le diamètre, créant un conduit de section elliptique. Ainsi, la morphologie des galeries indique les conditions de leur formation.

C'est ainsi que l'on distingue des phases spéléogénétiques. On commence par suivre les tubes en «montagnes russes» créés par le même cours d'eau. Leur point le plus haut définit l'altitude minimale de la nappe de ce cours d'eau. Une transition méandre-tube en donne l'indication exacte. La nappe ainsi extrapolée est souvent inclinée de 1-2°; on lui donne alors comme altitude de reférence celle de la source présumée. L'utilisation du terme «nappe» dans le karst n'est pas exacte, car le courant dans les gros tubes contraste avec la roche mère quasiment pas perméable. Afin de simplifier, nous continuerons à utiliser ce terme.

Les observations décrites au chapitre 4 démontrent que la nappe inclinée est le toit de la zone épinoyée, et que dans cette zone, la corrosion phréatique prévaut toujours sur l'érosion vadose.

Lorsque la nappe n'est pas retenue dans une structure géologique, elle est en relation avec la source. Si l'altitude de la source (qui dépend généralement de la nappe régionale dans le fond de la vallée) diminue peu à peu, le système spéléologique en amont se développe graduellement: il n'y a pas de phases marquées. Si l'approfondissement est brusque et suivi d'une période calme, la cavité elle aussi évolue rapidement (en quelques dizaines de milliers d'années): il se forme ainsi des phases spéléogénétiques.

Le mode d'approfondissement de la vallée se reflète donc dans la formation de la cavité. Nous supposons que les phases spéléogénétiques observées aux Siebenhengste reflètent le creusement des vallées par étapes. Elles sont, de ce fait, un outil précieux pour la reconstitution du paléorelief.

De récentes études attestent que la spéléogenèse n'était guère active pendant les glaciations, et que le creusement s'intensifie pendant les périodes interglaciaires et/ou pendant les interstades. Puisque les glaciers de nos latitudes sont tempérés, un englacement de la vallée provoque une surrection de la nappe, l'inondation des galeries anciennes et le dépôt de sédiments de granulométrie fine provenant de la farine glaciaire. L'érosion qui fait suite à une glaciation n'élimine en général pas tous les sédiments: la cavité devient une archive géologique.

Les phases spéléogénétiques les plus récentes de la région des Siebenhengste

Le Bärenschacht et la grotte de St. Béat sont avec le Faustloch les grottes les plus basses en altitude de cette région et ont leurs sources dans la vallée de l'Aare. En l'absence de retenue d'eau par des facteurs géologiques, l'histoire de l'approfondissement de cette vallée peut être étudiée dans ces cavités. A ce jour, il n'y a aucune information en surface, car la dernière glaciation a effacé probablement toutes les traces antérieures. L'altitude des phases décrites ci-dessous se refère à la source; elle ne correspond cependant pas à l'altitude lors de la formation des galeries, à cause de la surrection alpine.

La phase 558 est la phase actuelle, son niveau est celui du lac de Thoune. Des indices prouvent que le niveau du lac était 30 m plus bas après la dernière glaciation. La phase 700 est bien visible dans le système basal du Bärenschacht, ce sont de grandes galeries (25 m^2 de section) d'un âge minimal de 160 ka. La phase 760 est bien développée dans la grotte de St. Béat, les galeries correspondantes du Bärenschacht sont plus petites (12 m^2), leur âge est d'au moins 260 ka. La phase 805 n'est observable que dans la grotte de St. Béat, d'une importance mineure et plus ancienne que 350 ka. La phase 890 apparaît à nouveau nettement dans les deux cavités.

L'inventaire des petites cavités de la Waldegg a été traité par des méthodes statistiques. Ces cavités montrent très clairement les phases décrites ci-dessus, et une phase supplémentaire à 660 m.

On peut expliquer la différence marquante du diamètre des galeries entre les phases 660 et 760 par la jonction de la Schrattenfluh durant la période 660. En effet, pour des conditions chimiques inchangées, la taille des galeries dépend du débit et du temps. Les datations indiquent que la phase 760 fut la plus longue, ainsi l'accroissement lors de la phase 660 ne peut être que fonction d'un changement de débit, fait plausible si l'on admet l'annexion d'un nouveau bassin versant.

Nous avons tenté d'extrapoler les phases au Faustloch. La partie profonde en est actuellement inaccessible et les indications données ici sont à prendre avec précaution. En crue, la phase 558 correspond assez bien à l'altitude extrapolée; nous en déduisons, pour une première approche, que l'inclinaison des phases reste inchangée vers l'amont. Bien visible, la phase 660 est identifiée au Faustloch de manière sûre. En contrepartie, les phases supérieures sont très incertaines. La jonction Bärenschacht-Faustloch serait très profitable à la compréhension des phases plus anciennes, mais dépendantes de la vallée de l'Aare (jusqu'à 1440 m).

En résumé, six phases ont été trouvées, aux altitudes de 559, 660, 700, 760, 805 et 890 m, découverte confirmée par l'analyse des petites cavités. Cette dernière possibilité d'analyse sera principalement appréciée dans les régions dépourvues de grands réseaux souterrains.

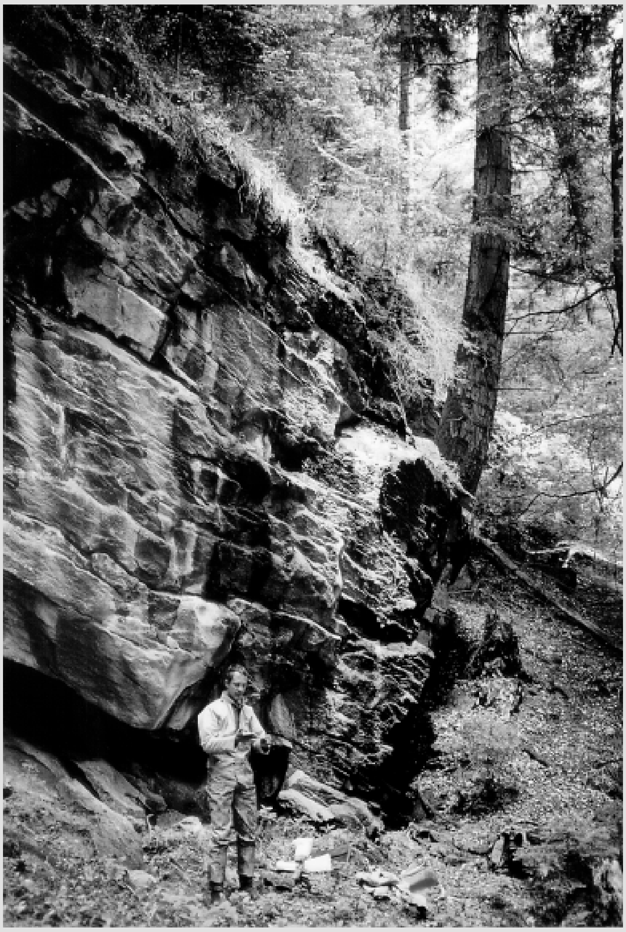
Evolution schématique de la paléogéographie de la région des Siebenhengste du Tertiaire jusqu'à présent

L'exploration spéléologique des Siebenhengste a permis de découvrir quatre phases (à 1950, 1720, 1585 et 1505 m) dont les sources se situaient dans la vallée de l'Eriz. Les phases suivantes (1440 et 1150) sont creusées en direction de la vallée de l'Aare. Si l'on prend à témoin leur position et leur taille, les galeries fossiles les plus anciennes sont apparues avant la formation du Justistal: la vallée de l'Aare n'existait pas, et la vallée d'Eriz est à considérer comme une «proto-vallée de l'Aare».

Du charbon trouvé dans la partie supérieure du F1 présente une réflectance de vitrinite typique des nappes penniques. Si ces nappes étaient présentes lors du dépôt de ce charbon, le début de la karstification des Siebenhengste serait contemporain du dépôt de molasse le plus récent, dépôt entièrement disparu aujourd'hui. Après l'érosion des solides nappes penniniques, les strates moins résistantes de Flysch et de marnes furent mises au jour, et l'érosion suivit ces couches. La théorie de Beck (1954) propose que, avant que la vallée de l'Aare actuelle n'existe, «l'Aare alpine» coulait par le col du Brünig dans le lac des Quatre Cantons, tandis que «l'Aare de Thoune», composée de la Simme et la Kander, se dirigeait vers Berne. Cette théorie n'est pas en contradiction avec les indications trouvées dans les cavités. C'est alors que les glaciations commencèrent et la vallée de l'Aare s'approfondit par étapes successives. Les parts respectives de l'approfondissement des vallées et de la surrection alpine ne peuvent être estimées par la seule analyse des cavités. Les figures 5-10 à 5-12 représentent schématiquement l'évolution du paysage.

Les grottes sont des éléments précieux pour la reconstruction paléogéographique, parce qu'elles renferment des formes et des sédiments qui ont été érodés depuis longtemps à la surface. Faute de réseaux, même les petites cavités peuvent être utilisées pour la reconstruction des phases.

Cette reconstruction paléogéographique n'est cependant pas encore datée, car il manque le lien avec les glaciations. Ceci sera le but du chapitre 6, qui traite à la fois des sédiments et de la morphologie.



A small cave in the Waldegg.
Eine Kleinhöhle der Waldegg.
Une petite cavité de la Waldegg.

Photo by Stefan Näff

5.1. Speleogenesis and its relationship to valleys

Introduction

The incision of the Alpine valleys has been a topic of intensive debate (e.g. Beck 1954, Müller 1995). The evaluation of the successions of valley elevations, however, is made very difficult at the surface due to the following problems:

- Several terrasses, formerly attributed to older valley bottoms, seem to be controlled by geology (strike and dip, different rock types, faults).
- There is almost no trace of (valley) sediments left, since the youngest glaciations eroded most of the deposits that were once present. Moreover, their scarce traces are often obscured by vegetation.
- If evidence for an old valley bottom is undeniable, the different sites are often scattered over several km along the valley. A correlation of those sites is very difficult since the old valley bottom might have been inclined more steeply than the present one.

The cave system north of Lake Thun was studied in order to solve some of these problems and to quantify the different steps of valley deepening.

This chapter first describes the theories which allow a link between speleogenetic phases and valley bottoms. It then presents the phases observed in Bärenschacht and St. Beatus Cave as well as additional evidence for a valley deepening in distinctive phases. In a last step, an extrapolation of the phases towards the old systems is drawn schematically. Here, Geology (Chapter 2), tracing experiments (Chapter 3.2) and the rock-water interaction (Chapter 4) are combined into an evolutionary model.

Genesis of caves and morphology of passages

The topic of cave genesis, in relation to climate, geology, dissolution kinetics, and other related fields, has been a subject of interest for many decades (see Chapter 4 for a reference list). To discuss the basics of cave genesis in detail is beyond the scope of this work. Instead, the reader is referred to the most comprehensive and up-to-date work “Speleogenesis: Evolution of Karst Aquifers” (Klimchouk et al. 2000), which presents all necessary elements for the understanding of speleogenetic processes.

Water flowing onto limestone corrodes and erodes the rock. Driven by gravity and geological structure, it flows down more or less vertically, until it reaches either the karstwater level or impermeable strata. Then it continues flowing towards the spring, collecting water from other lateral passages.

Water flowing in the vadose, unsaturated zone can only erode and corrode the floor of a gallery. Therefore, with time, a meandering canyon is created (Fig. 5-1). On the other hand, water flowing within the saturated zone can corrode a passage over its whole cross-section, so that an ideally rounded passage forms (Fig. 5-2). Those morphologies that are preserved once the water courses have been abandoned give information about the prevailing position of the phreatic zone during the genesis of the galleries.

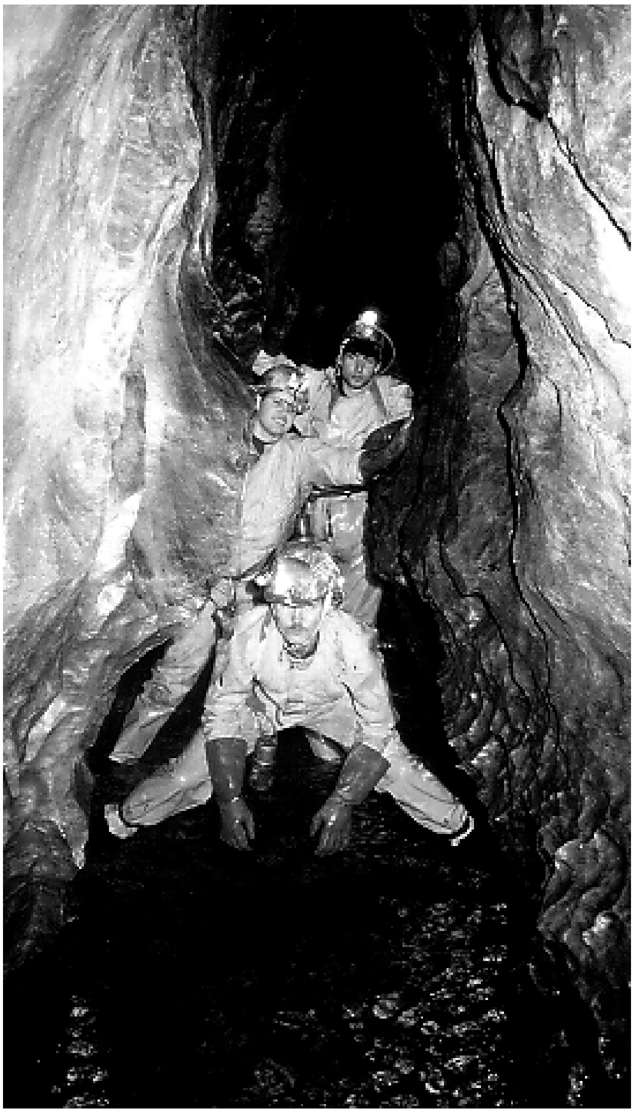


Fig. 5-1: A meander with flowing water.
Ein Mäander mit fliessendem Wasser.
Un méandre avec de l’eau courante.

Photo by Daniel Burkhalter, St. Beatus Cave

Fig. 5-2:
Phreatic tubes in F1 forming a sharp bend.

Phreatische Röhren im F1, die eine scharfe Kurve vollführen.

Tube phréatique au F1, avec un virage serré.

Photo by Werner Janz

Recognition of speleogenetic phases, relation to the spring

With the help of the gallery's morphology, speleogenetically distinct phases can often be recognised. In a first step, the ascending and descending phreatic tubes (loops) that have been created by the same waterflow are followed. The top of these tubes indicates the minimum elevation of the corresponding water level. Then, the transition of vadose canyons into phreatic tubes gives an absolute indication of the karstwater level. This level is usually in perfect accordance with the top of the loops. One often observes an inclination of the water table in the order of 1 to 2 degrees (2.5-3.6 %). Because of this inclination, the definition of the water level is difficult. For obvious reasons the given elevation should be the one of the presumed spring level.
A "water table" such as in porous aquifers does not exist in karst systems which are too heterogenous (vast voids with rapid flow in contrast to almost impermeable limestone). However, since we have seen that the water in the tubes behaves approximately like that of a normal water table, and also for simplicity's sake, we still use the term "karstwater level", knowing that, in a strict sense, this is not correct.
In order to ascertain that the observed paleowatertables are really controlled by spring position and not by geological structure (impervious barriers such as folds or faults), it is necessary to investigate the tectonic setting of the caves.

Perennial vs. floodwater table

Observations in Bärenschacht as well as in Hölloch (Jeannin 2001) show that when flooding, the water does not rise uniformly from the lower, permanently flooded galleries, but that the system functions in the "filling-overflow" manner (Chapter 4). The whole system is emptied, after the flood, through small galleries reaching the perennial water table. Those galleries are usually not directly accessible for observations. The overall morphology of all galleries is phreatic, in spite of the vadose torrents sometimes prevailing. Recent research also showed that meandering canyons transform into phreatic tubes just at the top of the epiphreatic zone. Therefore, we conclude that in the epiphreatic zone, phreatic corrosion is predominant and vadose entrenchment is negligible.

Since the transition from meandering canyon to phreatic tube takes place at the top of the epiphreatic zone, thus creating the above mentioned inclination, those transitions, formerly attributed to the perennial water table, indicate the elevation of the epiphreatic zone (Chapter 4). Both the perennial as well as the epiphreatic regime converge at the spring level.

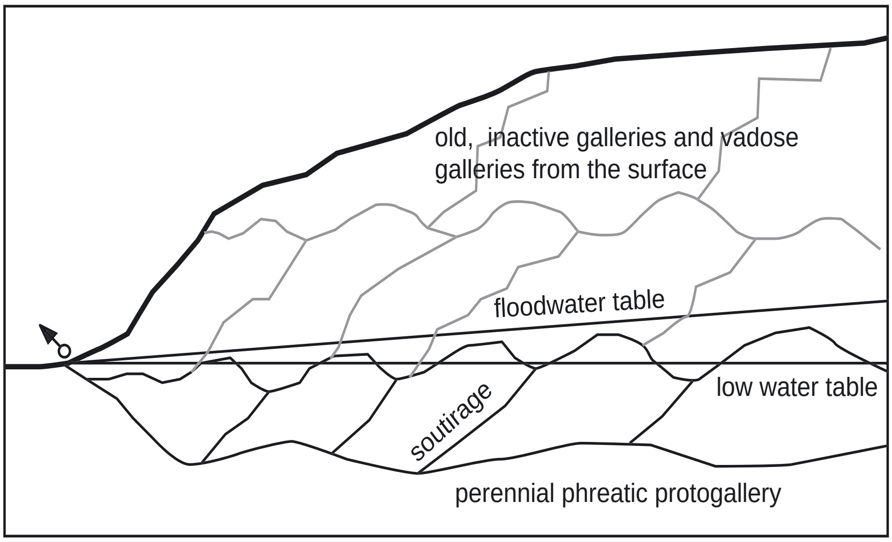
Succession of speleogenetic phases

If the lowering of the spring occurs rapidly, followed by a time of relative stability, the flowpath readjustment in the cave system also occurs rapidly. Calculations have shown that, once a small paleo-conduit is formed, caves may evolve rapidly, i.e. within a few 10'000 years, to reach penetrable size (Palmer 2000). Through preexisting or newly created soutirages (Chapter 4), the water reaches the spring level and creates a new karst water table, which then controls the evolution of the next phase (Fig. 5-3).

Fig. 5-3:
Sequential genesis of cave passages, drawn schematically. The epiphreatic zone is only shown for the phase currently forming.

Schematische Sequenz der Entstehung von Höhlengängen. Die epiphreatische Zone ist nur für die in Bildung begriffene Phase dargestellt.

Séquence schématique de la genèse des galeries. La zone épiphréatique n'est representée que pour la phase actuellement en formation.



Connection to the valley

If there is no evidence that the karstwater level is controlled by geological structure, then it has to be connected with the level of the spring. The spring elevation itself is usually determined by the regional water level related to the valley floor (Figs. 5-4 and 1-8), as evidenced also in Chapter 3.2.
If valley incision would be caused by continuous fluvial erosion, then signs of progressive spring deepening and gradual (mainly vadose) deepening of the corresponding speleogenetic phase would be observed. If there are no such signs, the valley deepening must have happened by a rapid process, followed by a time of long relative stability, in which the next speleogenetic phase developed. In the present alpine valleys, the most probable agents of a quick valley deepening are the quarternary glaciers.
We hypothesize that the speleogenetic phases reflect the deepening of the valleys in time. Therefore, observations of the speleogenetic phases give information about both the relative elevations of the valley bottom as well as their succession in time and provide an effective tool for the reconstruction of paleorelief. Equivalent information at the surface is usually no longer present, due to the erosion by the youngest glaciations.

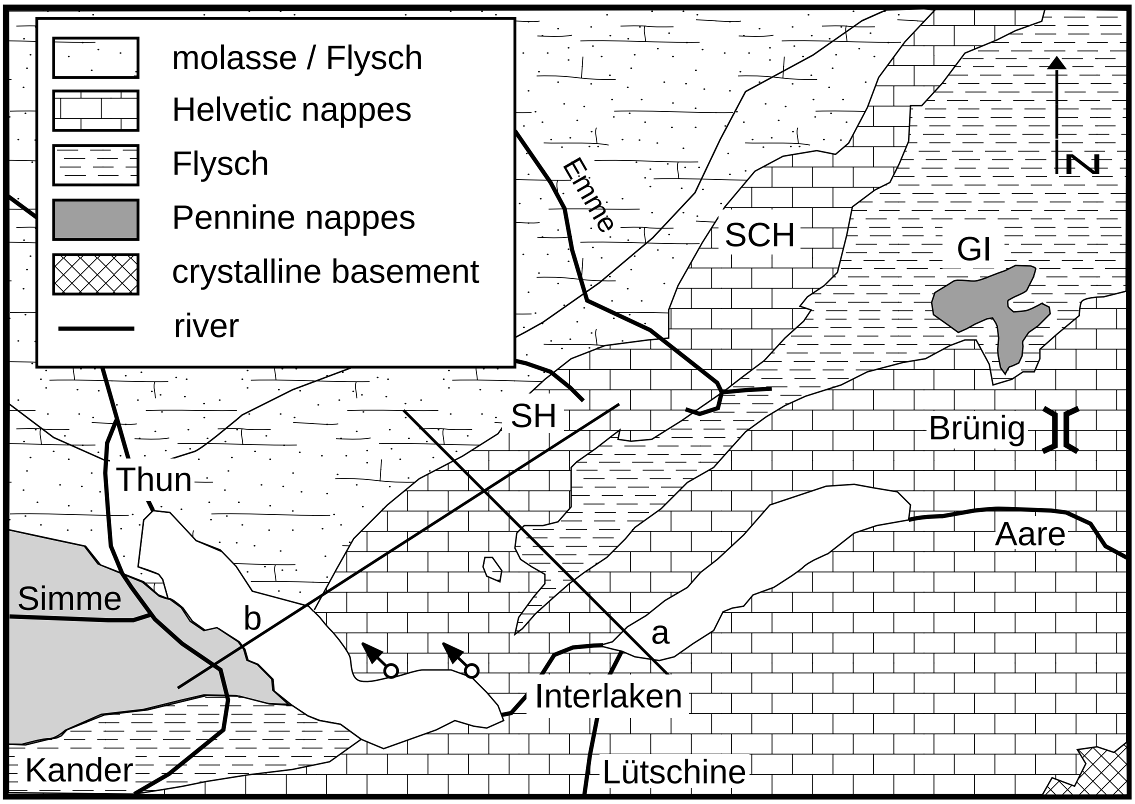
The role of the glaciers

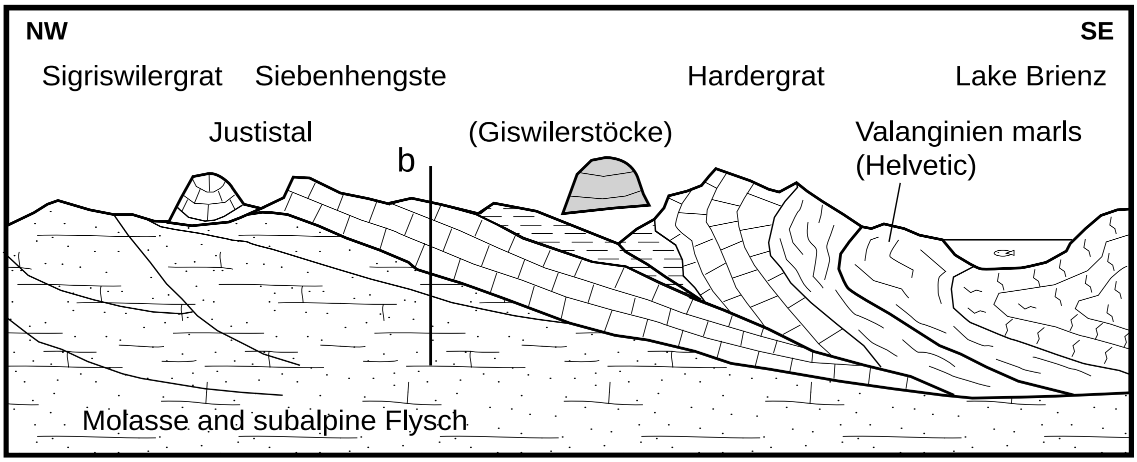
In accordance with Audra (2001), the glaciation usually does not affect the speleogenesis itself very much, and the creation of new voids mainly occurs in interglacials and/or interstadials.
Glaciers in our area were temperate with flowing water. A huge glacier body in the valley sometimes raised the karstwater level to considerable elevations and in addition, the ice itself and the moraines were prone to obstruct the preexisting springs. Both effects caused the water table inside the mountain to rise. A rising karstwater level invading older conduits caused small flow velocities and therefore deposition of fine-grained sediments that are often observed in caves. Those

Fig. 5-4: *Photo by Peter Pfister*
The Gelberbrunnen in flood.

Der Gelberbrunnen bei Hochwasser.

Le Gelberbrunnen en crue.


molasse / Flysch
Helvetic nappes
Flysch
Pennine nappes
crystalline basement
river
N
Emme
SCH
GI
SH
Brünig
Thun
Aare
Simme
b
a
Interlaken
Kander
Lütschine


NW
SE
Sigriswilergrat
Siebenhengste
Hardergrat
Lake Brienz
Justistal
(Giswilerstöcke)
Valanginien marls
(Helvetic)
b
Molasse and subalpine Flysch

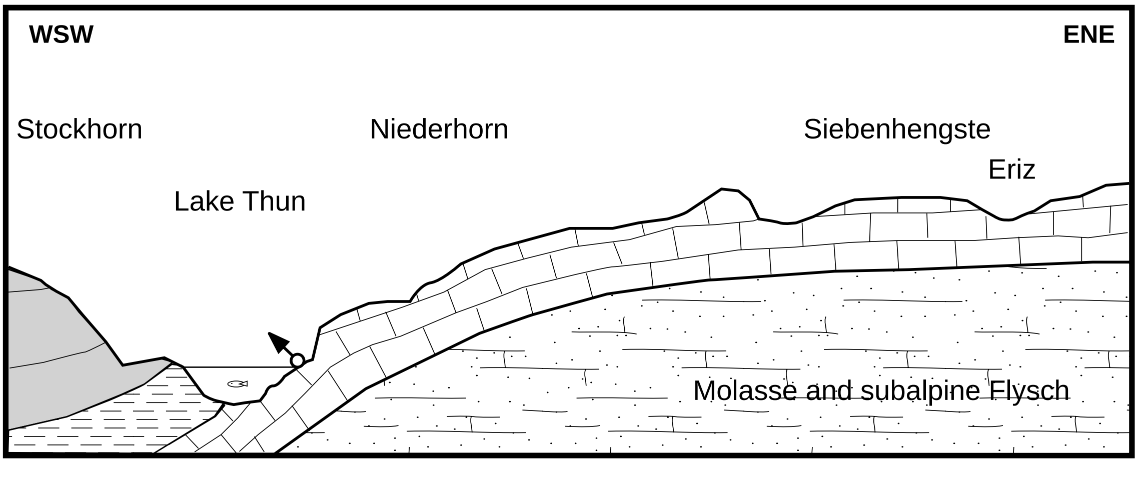

WSW
ENE
Stockhorn
Niederhorn
Siebenhengste
Eriz
Lake Thun
Molasse and subalpine Flysch

Fig. 5-5 (left): Present simplified tectonic sketch of the region. Picture width approximatively 50 km. HSV=Hohgant-Sundlauenen fault; GI=Giswilerstöcke; SH=Siebenhengste; SCH=Schrattenfluh; line a)=cross-section of Fig. 5-5a (width approx. 16 km); line b)=cross-section of Fig. 5-5b (width approx. 25 km).

Aktuelle, vereinfachte tektonische Skizze der Region. Bildbreite ca. 50 km. HSV=Hohgant-Sundlauenen-Verwerfung; GI=Giswilerstöcke; SH=Siebenhengste; SCH=Schrattenfluh; Linie a)=Profillage der Fig. 5-5a (Bildbreite ca. 16 km); Linie b)=Profillage der Fig. 5-5b (Bildbreite ca. 25 km).

Esquisse tectonique actuelle et simplifiée de la région. Largeur environ 50 km. HSV=faille de Hohgant-Sundlauenen; GI=Giswilerstöcke; SH=Siebenhengste; SCH=Schrattenfluh; ligne a)=profil de la Fig. 5-5a (largeur env. 16 km); ligne b)=profil de la Fig. 5-5b (largeur env. 25 km).

sediments come often from the glacier itself (glacier milk) and contain a high amount of carbonate flour. This carbonate flour could not be dissolved by the natural aggressivity of the water. Therefore, a karstification of the walls around the cave is very improbable, and the only means to enlarge the cave would be by abrasion.

The high discharge of waters towards the end of a glaciation would be very effective for the re-erosion of the deposited sediments. But, since those sediments were deposited in phreatic conditions and were therefore spread all over the cave, to parts where a vadose river cannot reach, many of them survive in the caves, together with the older sediments which are proof of an even earlier history.

Summary

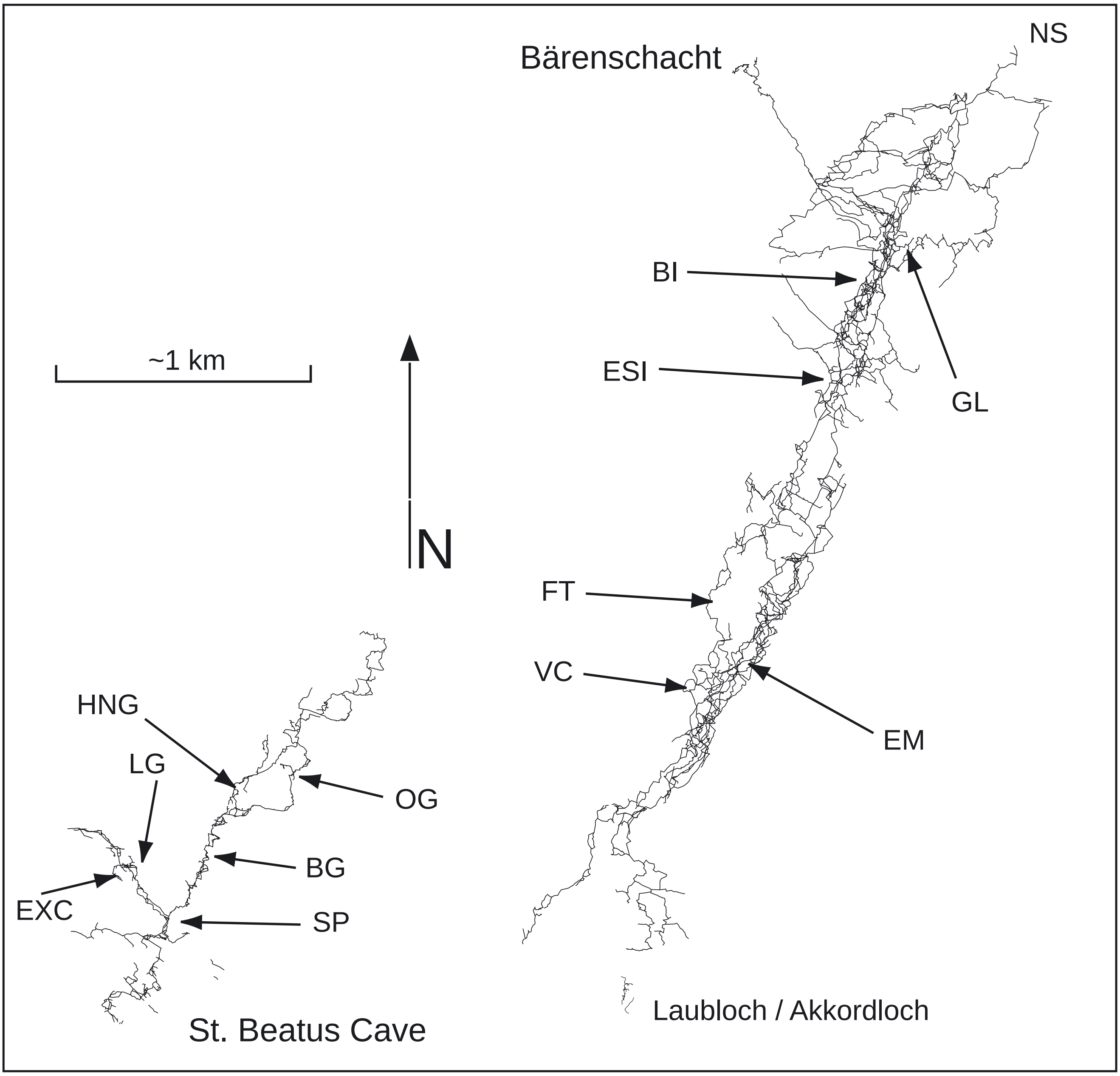
Many morphologic indications in caves show that cave genesis is strongly linked to the corresponding spring (Ford & Williams 1989), which in turn is dependent on the valley where it resurfaces. Several distinct phases of cave genesis can so be attributed to different valley bottom elevations, and may therefore be good indicators for a reconstruction of the paleorelief of the region in question.
The ideas presented here are applied to the youngest cave phases of the Siebenhengste system (the geology of which is presented in Fig. 5-5). In section 5.3, an attempt to reconstruct the Tertiary paleorelief and the forces acting upon it is presented.

5.2. The most recent speleogenetic phases of the Siebenhengste region

Observations in Bärenschacht and St. Beatus Cave

Here we present speleogenetic phases that have been recognised in Bärenschacht and St. Beatus Cave. With the help of those phases, an evolution of the valley deepening can be drawn.
Both Bärenschacht (Funcken 1994, Funcken, Moens & Gillet 2001) and St. Beatus Cave, which have different catchment areas, have their spring in the Aare valley. Therefore, following the principles described above, they both reflect the deepening of the Aare valley.
Observations in both caves gave no indications that the old karstwater levels had been influenced by geological barriers, therefore they are considered as being in relation to the valley floor. The present exit (690 m a.s.l.) of St. Beatus Cave is geologically perched high above the current waterlevel of the valley (Lake Thun, 558 m), therefore, phreatic conduits of the two most recent phases are no longer visible in St. Beatus Cave. Still, the older phases are observable. Surface information for each of the phases described below (such as shoulders at valley flanks, or flattened surfaces at higher elevations) has not been found until now. Most probably, the youngest glaciation erased all traces and left only some moraines.
In some phases we describe the sediment found. This sediment has a maximum age that is equivalent to the phase, but it might also be much younger.

In the next parts, we illustrate the different findings in each speleogenetic phase and discuss possible problems. The names of the phases are given after the level of the spring in m a.s.l. (Fig. 5-6). Since the


NS
Bärenschacht
BI
ESI
GL
~1 km
N
FT
VC
EM
HNG
LG
OG
BG
EXC
SP
St. Beatus Cave
Laubloch / Akkordloch

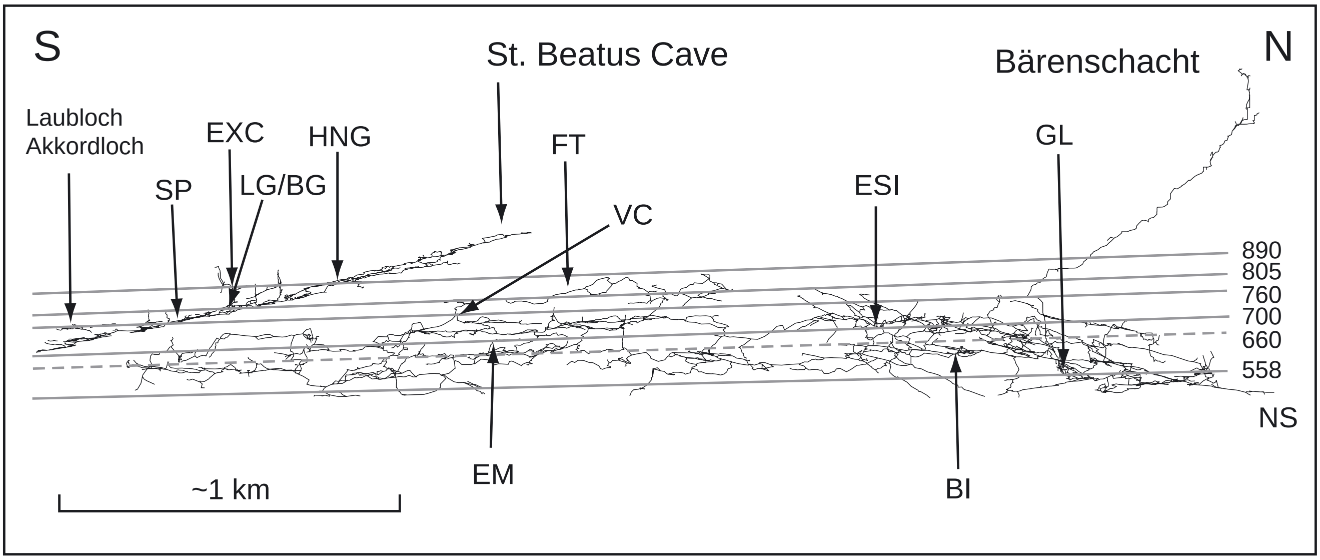

S
St. Beatus Cave
Bärenschacht
N
Laubloch
Akkordloch
EXC
HNG
FT
GL
SP
LG/BG
ESI
VC
890
805
760
700
660
558
NS
EM
BI
~1 km

Fig. 5-6 (left): Plan (above) and N-S-projection (below) of Bärenschacht and St. Beatus Cave, with localities and the recognised phases. The phase 660 discussed later is dotted. For explanations see text.

Grundriss (oben) und N-S-Projektion (unten) des Bärenschachtes und der St. Beatus-Höhle, mit Lokalitäten und den erkennbaren Phasen. Die Phase 660 wird weiter unten diskutiert. Erläuterungen finden sich im Text.

Plan (en haut) et projection N-S (en bas) du Bärenschacht et de la Grotte de St. Béat, avec les localités et les phases reconnues. La phase 660 est décrite plus loin dans le texte. Les explications se trouvent également dans le texte.

Alps are still uplifting, this altitude does not necessarily reflect the true level of the active spring at the time of formation.

Phase 558: Present

The present phase is the easiest to determine. Its base level is given by Lake Thun. In Bärenschacht, several galleries go down to the karstwater level. The perennial phreatic galleries belonging to this phase are not dived in Bärenschacht, but the current springs Bätterich (486 m long / -79 m deeper than the lake level) and Gelber Brunnen (140 m long / -68 m deep) have been dived (Häuselmann et al. 2000). The delimitation of this phase (i.e. of the epiphreatic zone) is well exposed in “Glücksschacht” (GL).
Some authors (e.g. Bodmer et al. 1973) propose that the level of Lake Thun rose at least 30 m after the last glaciation. This was due to the infilling of the lower Aare valley (between Thun and Berne) with alluvium. There is morphological data in Bätterich (observations of Karren, see Schafheutle, in Häuselmann et al. 2000, and Fig. 5-7) supporting this theory.
An even older and deeper phase of Lake Thun, around 80 m deeper than the present level, is in hypothesis. The sublacustrine platform in the Bödeli area of Interlaken, as well as Karren at over 70 m depth in Bätterich and Gelber Brunnen, support this idea.

Phase 700:
Main system of Bärenschacht

This phase is defined by two transitions of vadose meandering canyons into phreatic tubes, the one in “Empire du Milieu” (EM) and the other in “Ecoulements symmétriques interconnectés” (ESI). The corresponding phreatic tubes are well known and lie within the karstwater levels defined by the transitions. Observations of the galleries’ morphology (Chapter 4) indicate epiphreatic behaviour in the Bivouac I sector (BI). The size of the phreatic gallery is considerable, with a cross-section as large as 25 m^2. Its spring is not known with certitude, however, the Akkordloch at 703 m a.s.l. is a very strong possibility. It may be that there were other lateral springs, since there are many phreatic entrances in the region.
With the exception of syngenetic sands, some boulders and flowstone, sediment deposition within the galleries of this phase is restricted. Dating of speleothems by U/Th series (alpha counting method) gave a minimal phase age of 160 ka.

Phase 760: St. Beatus Cave – Show part

The phase 760 is defined by two meandering canyon-tube transitions, the one being in the end of the show part of St. Beatus Cave (SP), the other one being in “Voûte céleste” of Bärenschacht (VC). Both transitions

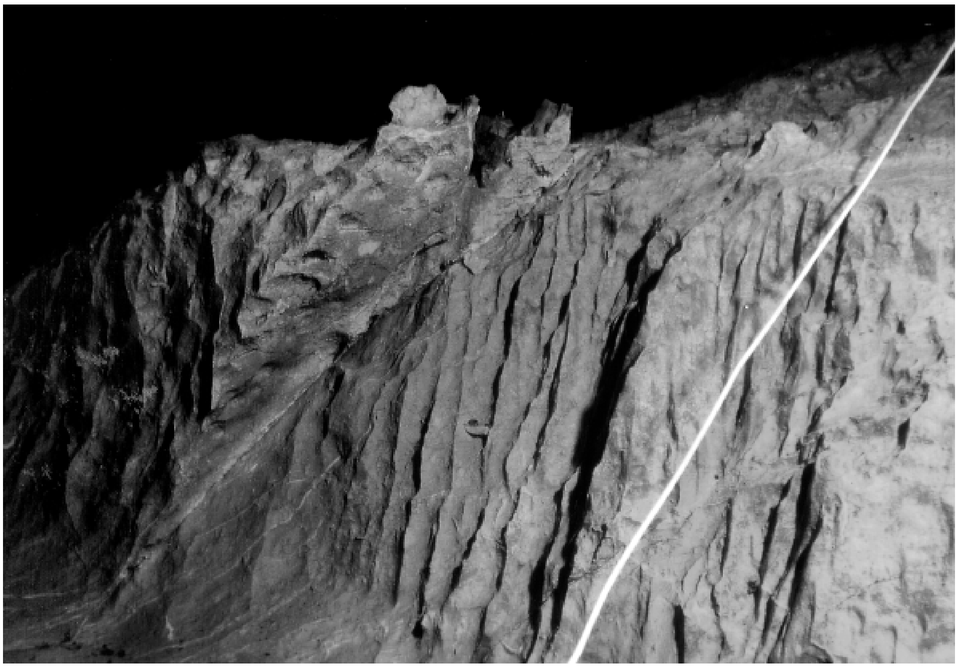


*Fig. 5-7:
Karren at -30 m below the level of Lake Thun in Bätterich.*

Karren auf -30 m unter dem Thunerseespiegel im Bätterich.

Lapiaz au Bätterich, -30 m en-dessous du niveau du lac de Thoune.

Photo by Markus Schafheutle

are in perfect accordance with the corresponding phreatic tubes. This illustrates that the phase elevation was defined by a common valley level. The size of the phreatic gallery in Bärenschacht is smaller than the one of phase 700, with an average cross-section of 12 m^2. Its spring is also not well known. It is very possible that the Laubloch was one of the main springs. However, the size of its gallery is still too small. In St. Beatus Cave, the spring is thought to be still Eibenhöhle. The Bärenschacht gallery of this phase can be recognised throughout the cave.

The Bärenschacht galleries are richly decorated by dripstones and partly filled with silty sediments as well as pebbles. The St. Beatus Cave only shows some traces of old fillings that have mostly been eroded again, with the exception of silt accumulation near the top of the phase. Dating of speleothems gave a minimal phase age of 260 ka.

Phase 805: St. Beatus Cave – Biwakgänge

This phase is defined by two transitions in St. Beatus Cave, the one being in Biwakgänge (BG), the other one in Lehmgänge (LG). Both transitions are clearly visible, but of minor morphogenetic importance. Therefore, the corresponding valley elevation is presumed not to have lasted long and was perhaps caused by an interstadial. In Bärenschacht, no evidence has been found until now, since there are not so many galleries found at this altitude, but exploration continues. The spring of St. Beatus Cave would probably have been Eibenhöhle (see Fig. 1-7), whereas in Bärenschacht region no spring is known.

The galleries of this phase in Bärenschacht show fewer dripstones than those of phase 760, and there are more silty deposits found. St. Beatus Cave shows sediment of every type. Dating of speleothems gave a minimal phase age of more than 350 ka.

Phase 890: Force Tranquille / Murgelergang

The definitions of this phase are difficult to place. In St. Beatus Cave's Excentergang (EXC), a corrosion notch in an otherwise fossil gallery, with many silt deposits below, is a first indication. The elevation of this zone falls just into the Sandgang-Ostgang diffluence (OG). At the same time, this phase was responsible for the creation of the lower Hohe Nordgang (HNG) below the older Murgelegang.

The recent speleological explorations in the "Force Tranquille" (FT) of Bärenschacht reveal the existence of big phreatic galleries within the postulated phase. However, morphological analyses of these parts are still to be done. The spring of Bärenschacht is not known, the one of St. Beatus Cave would probably be "??Cave" in Fitzligrabenregion (see Fig. 1-7 for location) for the Hoher Nordgang system and Eibenhöhle for the Ostgang system. The age of this phase is unknown, but older than 350 ka.

Comparison with small caves

The springs of the phases listed above are expected to have been located close to the valley bottom. The waters of the valley may also corrode the limestone at their contact. Therefore, we can imagine the existence of many small caves or shelters (see for example Blanc 1992). A detailed speleological inventory for the area has been made (Häuselmann et al., 2000). The caves were classified into phreatic, vadose, and tectonic caves. Then, a plot was made containing the elevation a.s.l. of the phreatic caves only (in 10m intervals), with respect to their numbers. This plot was complemented with data from the Swiss Cave Inventory (SSS, internal paper) for caves around Lake Thun. A total of 96 caves were plotted (see Fig. 5-8).

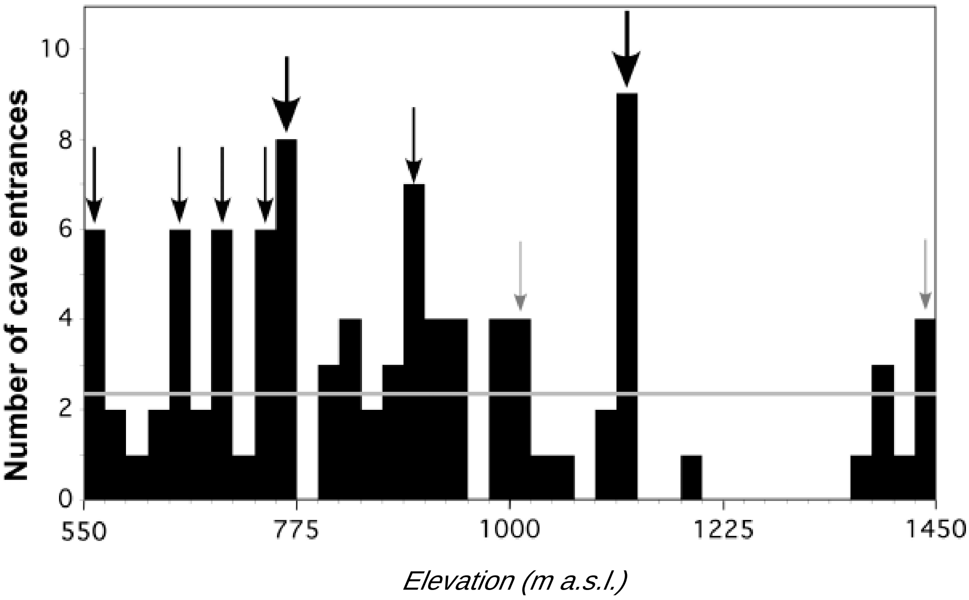


Fig. 5-8:
Graph of the altitudinal frequency of entrances of the small phreatic caves around Lake Thun.

Graph der höhenabhängigen Häufigkeit der Eingänge der phreatischen Kleinhöhlen um den Thunersee.

Graphe de la fréquence altitudinale des entrées des petites cavités phréatiques autour du lac de Thoune.

A statistical analysis, based on the hypothesis of an uniform distribution of cave entrances (grouped into 40 classes: mean 2.45±1.55), had been undertaken. The results show that the distribution is not uniform, with families identified with a confidence of more than 95 % at 560, 660, 695, 765, and 900 m a.s.l. Therefore, the small caves reflect very well the phases described above. The class at 660 m has no correspondent phase defined in Bärenschacht. The next most important classes match the 700, 760, and 890 phases perfectly.

Discussion and interpretation

The observation of karren below phase 558 has to be treated with care, since karren-like features that originated underwater are also known, mostly due to sediment effects (Murphy & Cordingley 1999). However, the karren reported by M. Schafheutle (in Häuselmann et al. 2000) aren't likely to be created underwater because of their very sharp forms. Therefore, in accordance with Bodmer et al. (1973), we think that there was a watertable equivalent to or lower than 530 m a.s.l. after the last glaciation.

If there was an even deeper level at 480 m, as suggested by the karren in Gelberbrunnen and sublacustrine platforms in Interlaken and Gwatt (S Thun) areas, this would mean that the Aare level in Berne would also have had to be at least 30 m deeper than it is today. This is possible, as some infilled old channels have been found around Berne (Schlüchter, pers. comm), but these would have formed long before the last interglacial.

The phase 660, which is suggested by the small caves, was not visible in Bärenschacht, however, the latest speleologic research (January 2002) indicates a meandering canyon-tube transition at this height. Further, closer look at the passages therein reveals that most of the biggest galleries are found just below this phase. This is not sufficient to postulate a phase 660, however, there is also no contradiction to it. An extrapolation of the different phases towards Faustloch (see below) reveals that a phase 660 is very probable. Therefore, we suggest that this phase did exist.

The phases 700 and 760 are clearly visible and give no problems. The phase 805, however, is not visible with the small caves. Since the observations in St. Beatus Cave indicate that this phase is subordinate, the missing indications in the small caves aren't astonishing.

The following phase 890 is clearly visible.

The hydrological connection of the Schrattenfluh to Bätterich spring

Currently, the Bätterich spring drains not only Siebenhengste-Hohgant, but also the Schrattenfluh. For geological and geomorphological reasons, the galleries coming from Zone profonde-Faustloch (see Fig. 1-8) couldn't have been the drain of Schrattenfluh, this massif had to be "connected" to the Bärenschacht/Bätterich system later. Do we see evidence of a possible connection in the morphology or size of the galleries?

The size of a cave gallery is dependent on many factors. Aggressivity of water and composition of the bedrock are chemical constraints. Water discharge and therefore water velocity, as well as erosion rates, are dependent on catchment size and/or climatic changes. Finally, time is also important.

In Bärenschacht, the composition of the limestone is roughly the same as in other parts of the massif, with the exception of some granular dolomite grains present in the oolithic parts in the middle of the stratigraphic column (Jeannin 1989). We assume that the aggressivity of the water does not change, since all the waters involved have already undergone a long subsurface traveltime, and mixing corrosion effects are excluded since there are no contributing rivers. Therefore the chemical constraints should be the same throughout the Bärenschacht.

Worthington (1991) has shown that the size of a conduit is dependent mainly on time and water discharge rate: In the enlarging phase, flow velocity is rapid, causing erosion and corrosion at the same time. When the passage size increases, the flow velocity drops, until there is no more fast flow. Consequently, sediment deposition on walls and floor also slow the corrosion and the passage almost doesn't grow any more: equilibrium is reached. The size of the passage then depends only on flow rate. Worthington (1991) further cites that most of the active karst springs (and therefore the galleries connected to them) are in "equilibrium state" sensu Worthington, a hypothesis that is confirmed by theoretical studies (Dreybrodt 1988, Dreybrodt 1996).

If we assume that the main Bärenschacht galleries are past the transition state (see end of Chapter 4), the size should depend only on flow rate and therefore on climatic conditions and/or catchment size. We have seen above that the size varies: The galleries at 760 m have a cross-section of about 12 m^2 (and correspond quite well with the Zone profonde-Faustloch axis), whereas those at 660 m are at least 25 m^2. Dating of flowstone with the U/Th method has given an age of 180 to 157 ka for the 760 phase, and of 135-39 ka for the 700 phase. We may assume that the overall climatic conditions were not very different for these periods of time (Burga & Perret 1998, p. 713). Therefore, we postulate that the Schrattenfluh was connected to Bätterich at the time of the 660 phase.

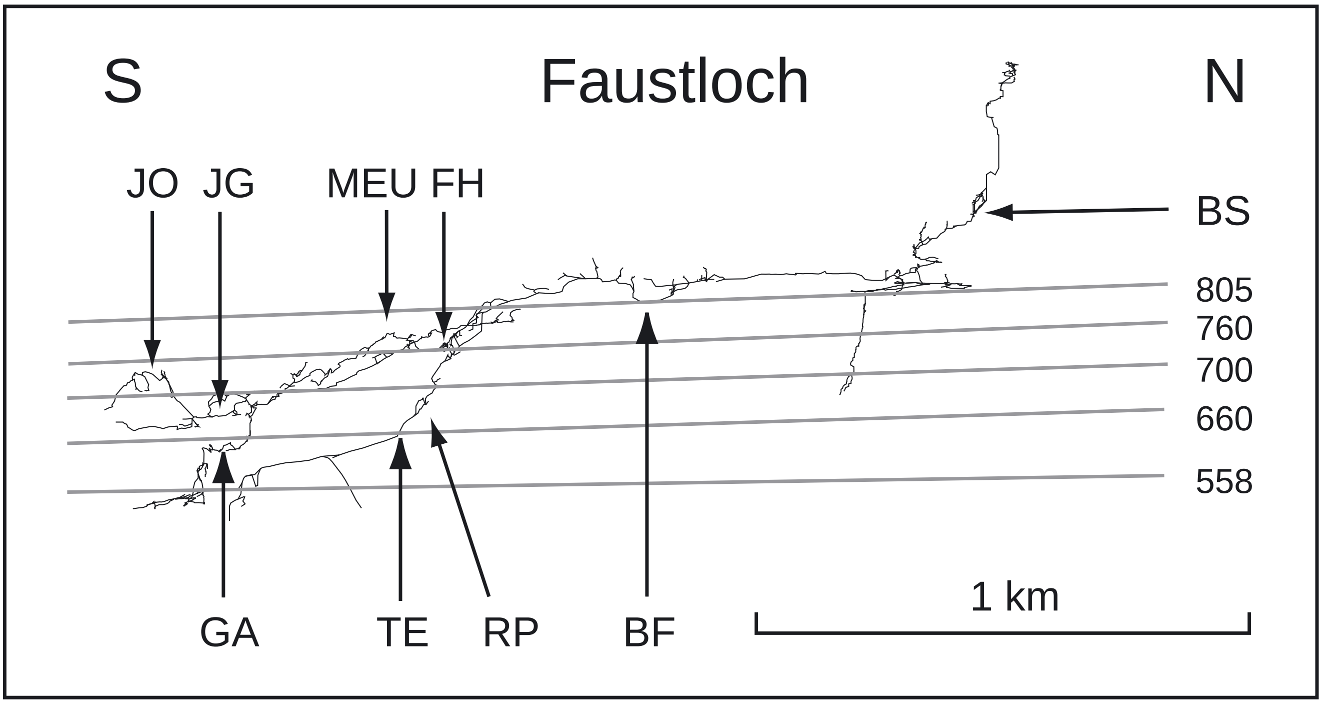


Fig. 5-9: N-S-projection through the Faustloch with the localities. For explanation see text.
N-S-Projektion durch das Faustloch mit den angegebenen Lokalitäten. Zur Erklärung siehe im Text.
Projection N-S à travers le Faustloch, avec les localités indiquées. Pour l'explication voir dans le texte.

Extrapolation of the phases towards Faustloch

An upstream extrapolation of the phases defined in Bärenschacht and St. Beatus region is difficult. First of all, the phases do not represent subhorizontal phreatic, but inclined epiphreatic conditions. Depending on tectonic accidents between Bärenschacht and Faustloch, the inclination may decrease or increase, or there might even be non-uniform inclination between the different phases. Second, the deep parts of the Faustloch have been closed in 1997 because a flood closed the Belgierfrust passage (BF, Fig. 5-9). Therefore the galleries are not accessible at the moment. The only "access" for an extrapolation is thus based on cave maps and personal memory. However, I think that it is worth to try and correlate the phases to have a base for future work.

Phase 558: Present
The present karst water table is found in three places in Faustloch. In flood situation, it rises about 10-15 m, so that the water level is about 10 m deeper than the one extrapolated (with constant inclination) from Bärenschacht. Therefore, we assume that constant inclination can be used in a first step. An interesting fact is that the perennial water table is 50 m above the North Sump (NS) of Bärenschacht, therefore, if the mapping is correct, a geologic accident has to be present between the two caves to make Faustloch karstwater level perched. This is in agreement with the tectonic data collected so far. It is interesting that flood situations seem to correspond with Bärenschacht.

Phase 660: Small caves-Guggershürliabstieg
Whereas there is no direct evidence for a phase 660 in Bärenschacht, in Faustloch we observe a nice transition from a meandering canyon into phreatic tubes, the present water course passing into small, recent galleries (GA).
Below the rather meandriform Puits Très Echelles (TE), we observe a big phreatic gallery that has huge sediment masses at its beginning. We examined the possibility that both those hypothetical transitions in Faustloch correspond to either 558 or 700. For evident reasons, 558 can be rejected. For the phase 700, there are also problems, since behind Bärenschacht, the water table had to be absolutely horizontal (respectively slightly inclined towards the upstream part), which is not very probable. Then, the next indications for phases correspond well with the spacing observed in Bärenschacht.

Phase 700: Bärenschacht-Ressaut de la prière
In contrast to the phase 660, the one at 700 m is not clearly defined. At Ressaut de la prière (RP) there's a hint that at this place might have been a waterlevel, since there is accumulation of fine-grained lacustrine-

type sediments below a clean gallery. This corresponds well with the entrance galleries of Jojogang (JG), however, there is no evidence of a transition. Those observations are not situated at the exact altitude of the the extrapolated water level, but lie within the errors.

Phase 760: St Beatus Cave-Joséphine

This phase also is not well defined. The first indication is the height of the Josephine gallery (JO), indicating a minimum level of the corresponding karstwater level. The labyrinthic buildup of phreatic galleries at “Fromage helvétique” (FH) might be connected to it.

Phase 890: Force tranquille-Murgelergang-Blumenkohlgang

The definition of this phase is also poor. The maximum height of Meunina (MEU) indicates the minimum level of the phase. The northernmost end of Faustloch coincides roughly with this phase. Another hypothesis would be that those poor indications point to the phase 805.

Implications for flowpaths

If we assume that the phasology described above is correct, then, we have to revise the propositions presented by Bitterli & Jeannin (1997). Especially, their phase 1120 then clearly matches the phase 890 of the model presented here and has to be renumbered. This has no consequences for the direction of flowpaths yet.

The next phase of Bitterli & Jeannin is the one at 1440 m, which was defined in the NE part of the Siebenhengste labyrinth. Now, if we assume constant inclination of the karstwater level, this would mean that this phase crosses Faustloch around the base of the shafts (BS) and continues towards the lowest part of A2 (Fig. 1-7), where it reaches the height of 1240 m asl. Assuming a flow through unknown parts of Faustloch and Bärenschacht, the spring would be at 1145, which corresponds roughly to a number of small caves in the Waldegg region on one hand and to Underholz plateau on the other hand. The problem is that the geologic structure both in the northern part of Bärenschacht and in the southern part of Faustloch indicate that the limestone was considerably deeper, which would result in an artesian Karst. The possibility depicted in Bitterli & Jeannin (1997) that the water flow could traverse the Hohgant-Sundlauenen fault and continue in its southwestern part, is not possible any more, since the karst water table in the region in question is already deeper than the minimum height required for reaching the limestone on the northern part of the HSV.

Therefore the question where the waters of the old phase 1440 flow, and if this phase can really be connected with the one at 1145 in Bärenschacht area, needs considerable work in the Zone profonde of the Sieben Hengste and on the deep part of F1, K2 and A2 (for location see Fig. 1-7).

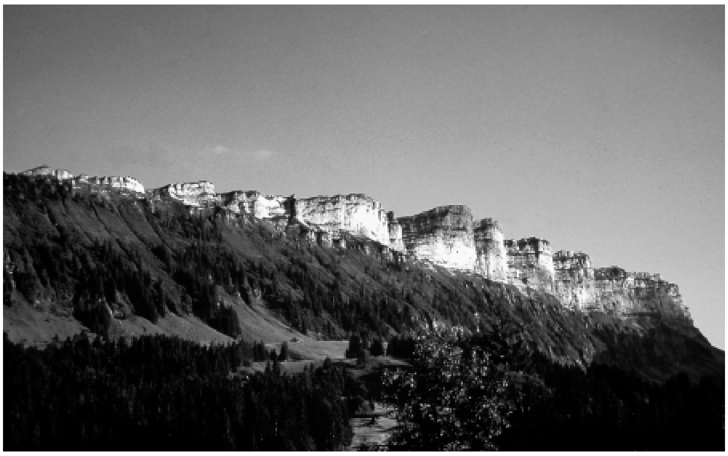
Conclusion

Inclined cave levels with spring elevations at 558, 660, 700, 760, 805, and 890 m a.s.l. are identified. These phases are supported by statistical analysis of small caves in the spring region. We conclude that entrances of small (or even impenetrable) caves are a reliable help to define phases in regions where no big cave system has been found yet. However, this method must be used with care until further evidence (be it from surface or from in-cave observations) confirm the inferred phases.

We hypothesize that all those phases correspond to ancient valley bottoms and represent therefore stages of the paleogeographic evolution of the Aare valley in time.

Dating results give ages of 390-240 ka for phase 760, and 240-180 ka for phase 700. Cross-section comparisons within the cave system suggest that the hydrological connection of the Schrattenfluh happened during phase 660. An attempt to extrapolate the phases towards the inner parts of Faustloch-Siebenhengste gives some results that need to be refined with fieldwork in Faustloch.

The section 5.3 will now use the available information from caves to draw a schematic evolution of the paleogeography of the Siebenhengste region.



The Siebenhengste.
Photo by Urs Widmer

5.3. Schematic evolution of the paleogeography of the Siebenhengste region from the Tertiary to the present

Speleogenetic phases of the Réseau Siebenhengste-Hohgant

Speleologic research provided evidence for several speleogenetic phases (Hof, Rouiller & Jeannin, 1984). Four phases are found in the Siebenhengste labyrinth, corresponding to a present-day altitude of 1950, 1720, 1585, and 1505 m a.s.l. (Jeannin, Bitterli & Häuselmann, 2000). All those phases had their exit in the Eriz valley (Fig. 1-7). The next phase, found in Siebenhengste region at 1440 m, comprises the lower parts of F1, the Zone profonde and Faustloch. The flow direction changed 180° and was then directed to Lake Thun. The influence of today's Aare valley therefore became predominant. The spring of this old phase is not yet well known. Since there was a thick impermeable cover in Bärenschacht region, a geologically possible solution would be that the water was flowing out in the Fitzlischacht region (Fig. 1-7) as proposed by Jeannin et al. (2000).
A next phase, found at 1145 m as well as all the younger phases described in Chapter 5.2, had their springs also in Lake Thun area. For those phases, the spring always had to be in the Bärenschacht region, and the Aare valley had to be in existence.

The surrounding landscape

The evolution of the landscape of Siebenhengste cannot be detached from both the foreland (where the rivers flow to) and the hinterland (where recharge and the glaciers come from). In the following section, we try to give some ideas for the evolution of the surrounding environment.

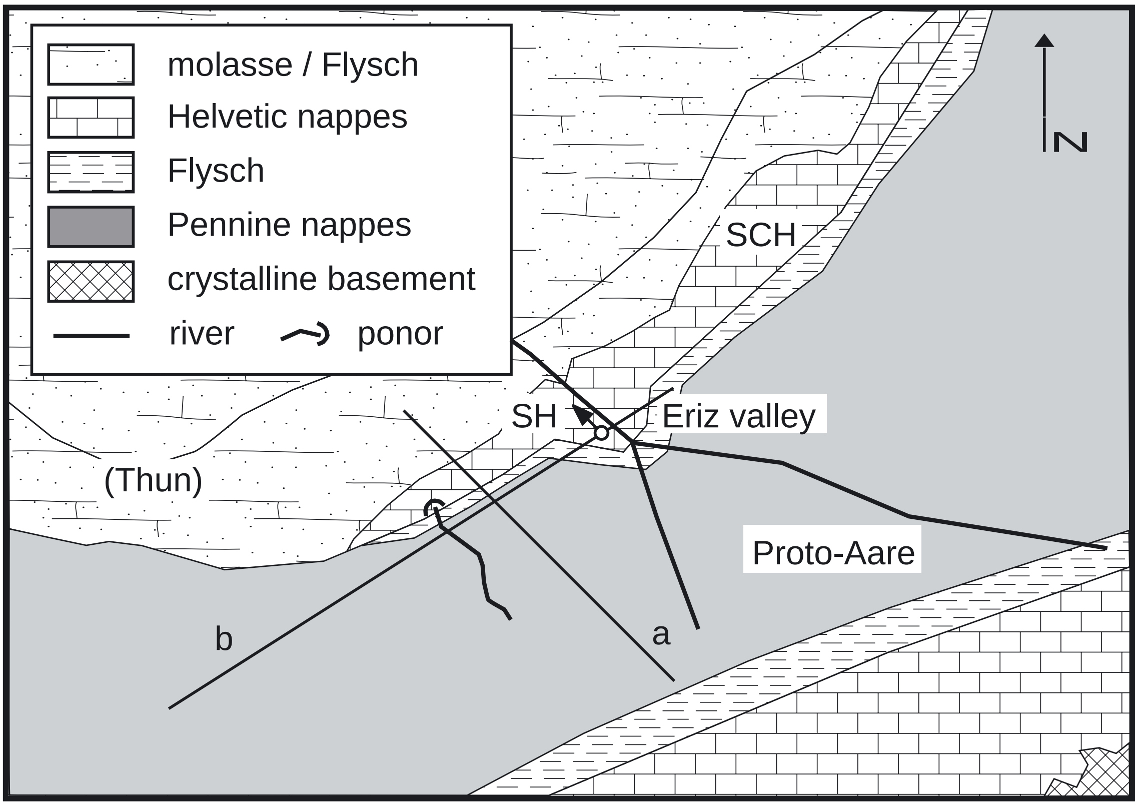
Old phases (1950, 1720, evtl. 1585)
The position of the oldest (and maybe also the second oldest) phreatic galleries near the top crest of Siebenhengste and in the middle of the limestone sequence has implications for the genesis of Justistal (see Fig. 5-5). If this valley was already in existence, phreatic galleries at this position would not have been possible. Therefore, we conclude that at least the phase 1950 predates the anticline erosion of the Helvetic front. This coincides with (a few) galleries found in this region which are too big for today's catchment area; therefore, the catchment had to be more extended to the southwest or west, towards the presently eroded parts. The fact that the waters of the old phases didn't flow towards the Aare valley is interesting. Of course, the plunge of the Helvetic nappes at Lake Thun induces that there are thick, impermeable series present. Therefore, a flow towards this region seems improbable. The question is where the proto-Aare valley was located at this time, and whether the Eriz valley could be the "Proto-Aare". The fact that there were springs present in different timespans in Eriz valley means that Eriz was an important baselevel. Therefore, it might be possible that a river came from the Pennine nappes or behind (see Fig. 5-10). We suggest that this river was the "Proto-Aare", and that the Habkern and Aare valley were not in existence.

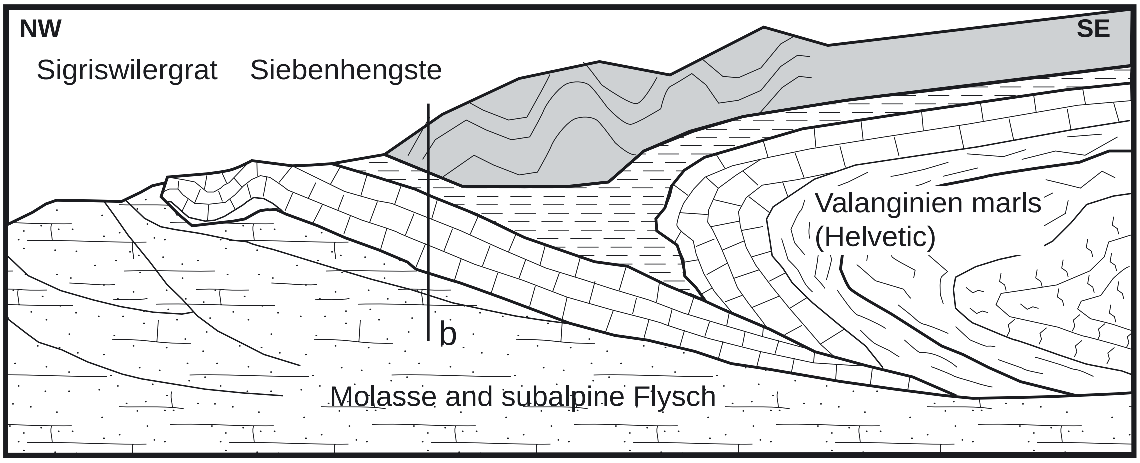
Coal can be measured for its vitrinite index, which gives an idea of the metamorphic/diagenetic grade and therefore about burial depth of the rocks that originally contained the coal. In the Helvetic border chain, the measured reflectances do not exceed 1 % (Burkhard & Kalkreuth 1989). Coal found in the upper parts of F1 reveals an Rmax of 1.3 %. Therefore, we can exclude an authochthonous source. Reflectances of around 1.3 % are found either in the external parts of the pennine Klippendecke, or (theoretically, since no measurements have been made) in the more internal parts of the Helvetic domain (Burkhard & Kalkreuth 1989). If we assume that the coal in question came from the internal Helvetic, a transport by either glacier or river was needed. However, in Innerbergli region where the coal was found, there is no indication for either possibility: neither allochthonous gravels nor Aare glacier traces are observed. A pennine origin is possible, since the Pennine nappes were overlying the Helvetic border chain. This would imply that during formation of the old phases of Siebenhengste, some remains of overlying Pennine elements were still present.
The erosion of Pennine nappes on the northern Helvetic domain is commonly regarded as being con-

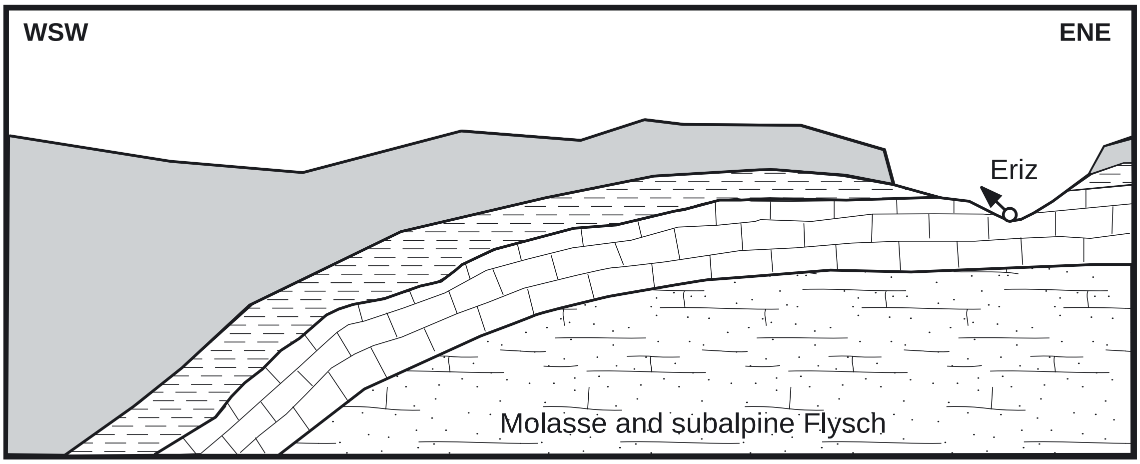
Fig. 5-10 (right): Presumed situation at the genesis of the oldest caves (Miocene to Pliocene?). Picture width approx. 50 km. SH=Siebenhengste; SCH=Schrattenfluh. The lines indicate the the location of the profiles displayed below.

Angenommene Situation zur Zeit der Entstehung der ältesten Höhlen (Miozän/Pliozän?). Bildbreite ca. 50 km. SH=Siebenhengste; SCH=Schrattenfluh. Die Linien geben die Lage der unten abgebildeten Profile wieder.

Situation présumée pendant la genèse des cavités les plus vieilles (Miocène à Pliocène?). Largeur de l'image env. 50 km. SH=Siebenhengste; SCH=Schrattenfluh. Les lignes indiquent la situation des profils montrés en bas.


molasse / Flysch
Helvetic nappes
Flysch
Pennine nappes
crystalline basement
river
ponor
N
SCH
SH
Eriz valley
(Thun)
Proto-Aare
b
a


NW
SE
Sigriswilergrat
Siebenhengste
Valanginien marls
(Helvetic)
b
Molasse and subalpine Flysch


WSW
ENE
Eriz
Molasse and subalpine Flysch

temporaneous to the molasse deposition time. This now implies that firstly, a cone of Molasse boulders should be present at the outflow of Eriz valley, and secondly, that the Alps were still uplifted an/or overthrust after this period. Discussions with molasse geologist Fritz Schlunegger, who was working in this area (Schlunegger 1991, Schlunegger 1995), gave the result that a molasse cone around Eriz would have been possible, but that it most probably has been eroded away by now, and that at best only some remnants could be found. The existence of a Molasse river is proven for older periods (Berger 1996), therefore the idea might not be irrealistic.

The Eriz river had to flow into the molasse foreland, which today is at much lower elevations than the Siebenhengste. The modern Eriz valley is adapted to today's water discharge. Therefore we can assume that both the original valley as well as the molasse hills surrounding it have been eroded, lowering the molasse plateau considerably with respect to the Siebenhengste. The erosion of most of the Molasse foreland is in accordance with the fact that no molasse fan originating from Eriz was found.

The re-erosion of the youngest molasse deposits and the incision of the rivers into this basin is regarded by Schlunegger (1995) as being the consequence of the piggyback transport of the molasse basin at the time of the Jura folding. This would mean that the oldest galleries of Siebenhengste would be older than this event.

Intermediate phases
(evtl. 1585, 1505, 1440, evtl. 1145)

Once the relatively resistant pennine nappes were eroded, the much softer Habkern Flysch and the Valanginien marls (in Lake Brienz area) were attacked. Beck (1954) found evidence for old valley remnants at about 1600 m, which he called "Simmenfluhniveau". He already indicated the possibility of a first "Thun-Aare" valley which contained the waters from Simme and Kander (see Fig. 5-11 for location), and another "Alpine-Aare" flowing from Grimsel region over the Brünigpass towards Lake Lucerne. Therefore Knuchel (unpublished) infers that the Lütschine might have crossed today's Aare valley and flown out through Eriz. The next phase described by Beck (1954) is called Burgfluhniveau, and is situated around 1000 m. There, the Thun-Aare is joined by the Lütschine, whereas the Alpine-Aare still flow over Brünig towards Lake Lucerne. Following Beck, the glaciations began at about the same time as this Burgfluhniveau and began to erode the Valanginian marls separating the two Aare rivers, finally breaking through and deviating the Alpine-Aare to join the Thun-Aare at Interlaken. Until now, clear evidence of an onset of glaciations only after this Burgfluhniveau has not been found; evidence of old glaciations (Jeannin 1991) in heights of more than 1600 m do not necessarily imply that the corresponding valley had to be at the same height.

However, it is clear that between the two phases described by Beck (1954), a big change had to happen, able to produce the observed turn in flow direction of the cave waters towards the Aare valley. Was this due to the fact that the Thun-Aare simply eroded most of the sandstone and Flysch near today's springs, or was a bigger morphogenetic event in the alpine foreland (as described by Schlüchter & Müller-Dick 1996) responsible for that change?

Recent phases
(evtl. 1145, 890, 805, 760, 700, 660, 558)

During the recent phases, the Aare valley was in full existence, and the deepening of it is thought to be a product of the glaciations. All those phases are described above. The age of phase 760 is older than 350 ka.

Uplift vs. valley deepening

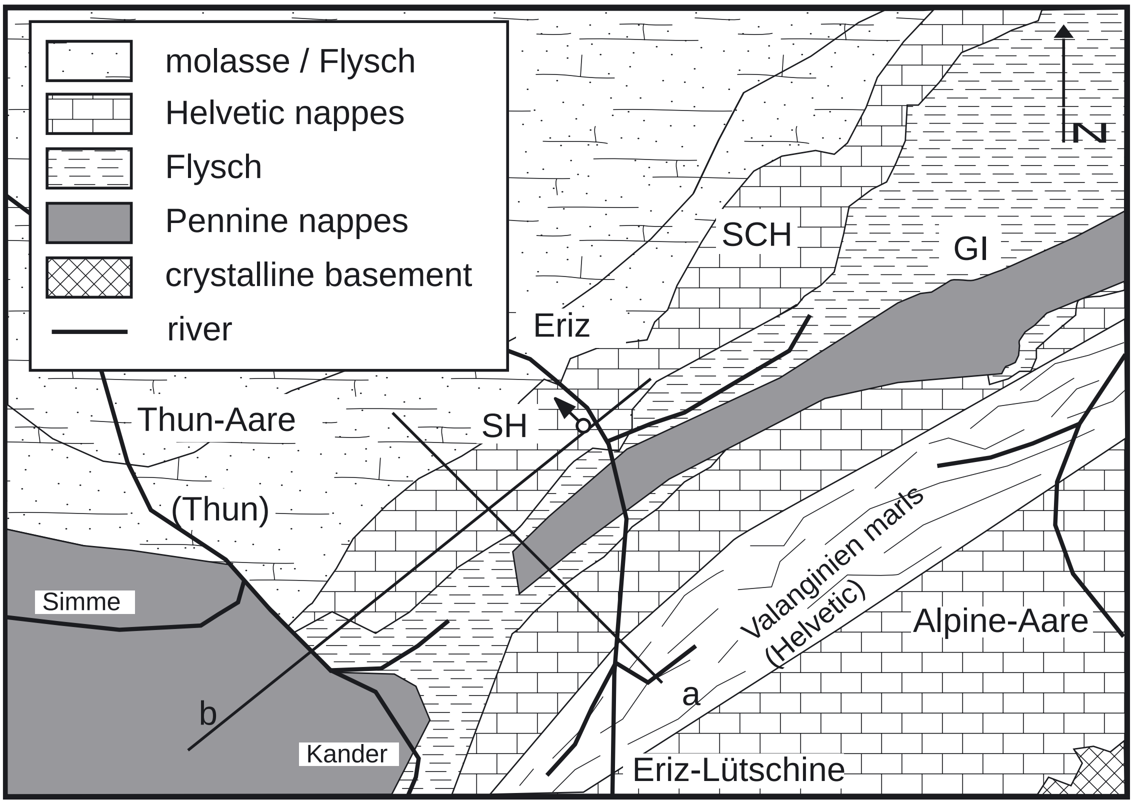
As to the question of uplift, no answer has yet been found. Imprecise measurements of paleowaterlevels in old phases have shown no inclination within the same cave passage, meaning that uplift/overthrust was uniform (no tilting). There is also no indication about how effective the uplift process was and whether it affected both the molasse and the helvetic domain (as suggested above), or if uplift was restricted to the Helvetic.

Different uplift rates in Molasse and Alps (as observed today) are likely to have happened also during the recent phases. However, it is still impossible to assess their importance with respect to the valley's erosion rate, and this is therefore not taken into account.

Fig. 5-11 (right): Presumed situation before the change of flow direction, just before the first glaciations began (late Pliocene). The Emme valley begins to be dug. Picture width approx. 50 km. HSV=Hohgant-Sundlauenen fault; SH=Siebenhengste; SCH=Schrattenfluh. The lines indicate the the location of the profiles displayed below.

Angenommene Situation vor dem Wechsel der Fliessrichtung, knapp vor dem Einsetzen der Eiszeiten (spätes Pliozän). Die Emme beginnt sich einzutiefen. Bildbreite ca. 50 km. HSV=Hohgant-Sundlauenen-Verwerfung; SH=Siebenhengste; SCH=Schrattenfluh. Die Linien geben die Lage der unten abgebildeten Profile wider.

Situation présumée avant le changement de direction de l'écoulement, juste avant les glaciations (Pliocène supérieur). L'Emme commence de s'enfoncer. Largeur de l'image env. 50 km. HSV=faille de Hohgant-Sundlauenen; SH=Siebenhengste; SCH=Schrattenfluh. Les lignes indiquent la situation des profils montrés en bas.


molasse / Flysch
Helvetic nappes
Flysch
Pennine nappes
crystalline basement
river
N
SCH
GI
Eriz
Thun-Aare
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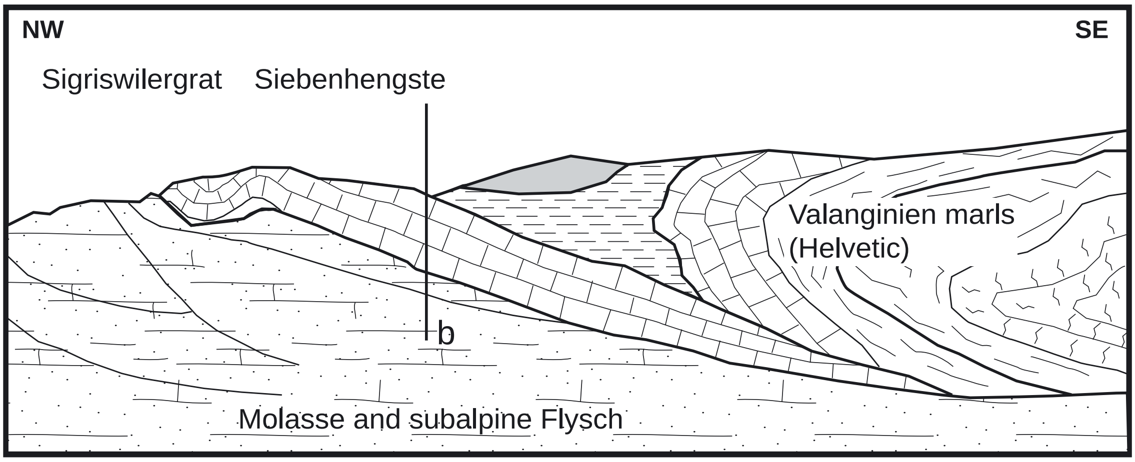
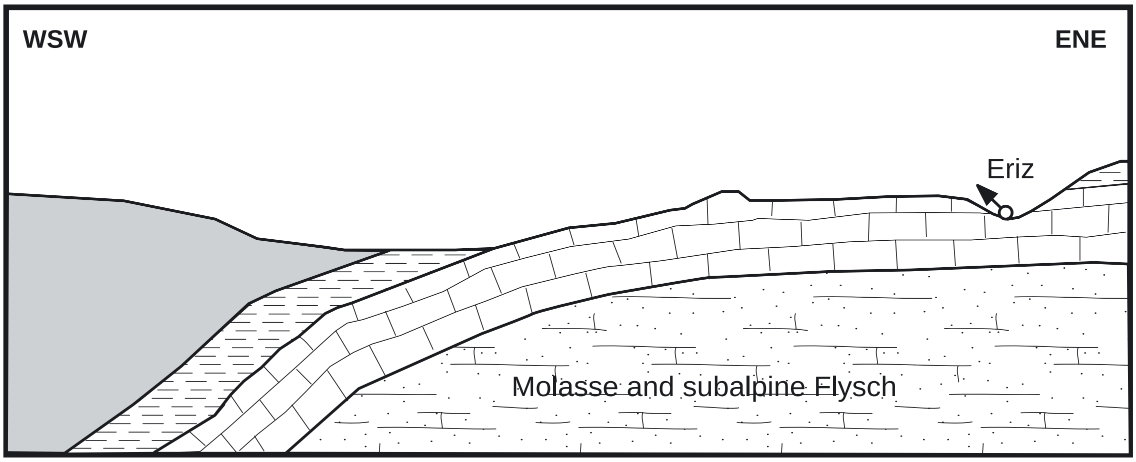
(Thun)
Simme
Valanginien marls
(Helvetic)
Alpine-Aare
a
b
Kander
Eriz-Lütschine


NW
SE
Sigriswilergrat
Siebenhengste
Valanginien marls
(Helvetic)
b
Molasse and subalpine Flysch


WSW
ENE
Eriz
Molasse and subalpine Flysch

The schematic evolution – a discussion

We try here below to depict the evolution of the landscape between Schrattenfluh, Brienz, Interlaken and Thun in chronological order, taking into account the different findings and interpretations presented above. The phases that might be correlated to the respective epoch are numbered in brackets.
In St. Beatus Cave and Bärenschacht, the datings revealed that the phase 760 had already begun before 350 ka, therefore all the upper levels have to be considerably older, which is in accordance with Jeannin (1991). The presence of Pennine coals in the upper galleries indicate a Tertiary age of the oldest phases of Siebenhengste, which are therefore probably of Pliocene or even Miocene age.

During the Miocene (Fig. 5-10), the Aare valley did not yet exist, whereas the Eriz valley was active. The anticline at Justistal was intact, and at least remnants of the Pennine nappes existed. Small rivers fed the Siebenhengste labyrinth and continued underground towards the Eriz valley river, which contributed to the molasse accumulation (alluvial fan). The last movements of the Jura folding then uplifted both the Helvetic and the Molasse basin, and therefore the molasse began to be eroded again (Phases 1950 and evtl. 1720).

In the Pliocene (Fig. 5-11), the last Pennine remnants were disappearing. The Thun-Aare began to erode the boundary between the Pennine and Helvetic nappes. The Justistal anticline was still present, but was also attacked. This timespan corresponds with Beck's Simmenfluhniveau (Phase 1585-1505).
The big change in underground flow direction and the connection of Lütschine to the Thun-Aare is not documented in Fig. 5-11. It is well possible that the glaciations already began at this time, still in the Pliocene. This timespan corresponds to Beck's Burgfluhniveau (Phases 1440-1145).

In Plio/Pleistocene (Fig. 5-12), waterflow and glaciations continued to attack the softer Valanginien marls and Habkern flysch. Therefore, the Alpine-Aare was deviated along the strike and joined the Thun-Aare at Interlaken, where it cut across the Harder riegel. The Siebenhengste were still reached by big glaciations, as today's morphology (roches moutonnées, allochthonous morainic deposits) proves. Due to combined water and ice attack at the fissures at the top of the Justistal anticline, this was eroded away. Also, the Emmental was in existence (Phase 1145-890).

In the Pleistocene and Holocene (Fig. 5-5), the deepening of the Aare valley and its tributaries continued. The Eriz valley is now fully fossilized (with respect to karst springs!) and the anticline of Justistal cut open (Phase 890-558). It is this timespan that has been mostly described in Part II of the present paper. All the upper (older) phases still are under investigation.

Conclusions

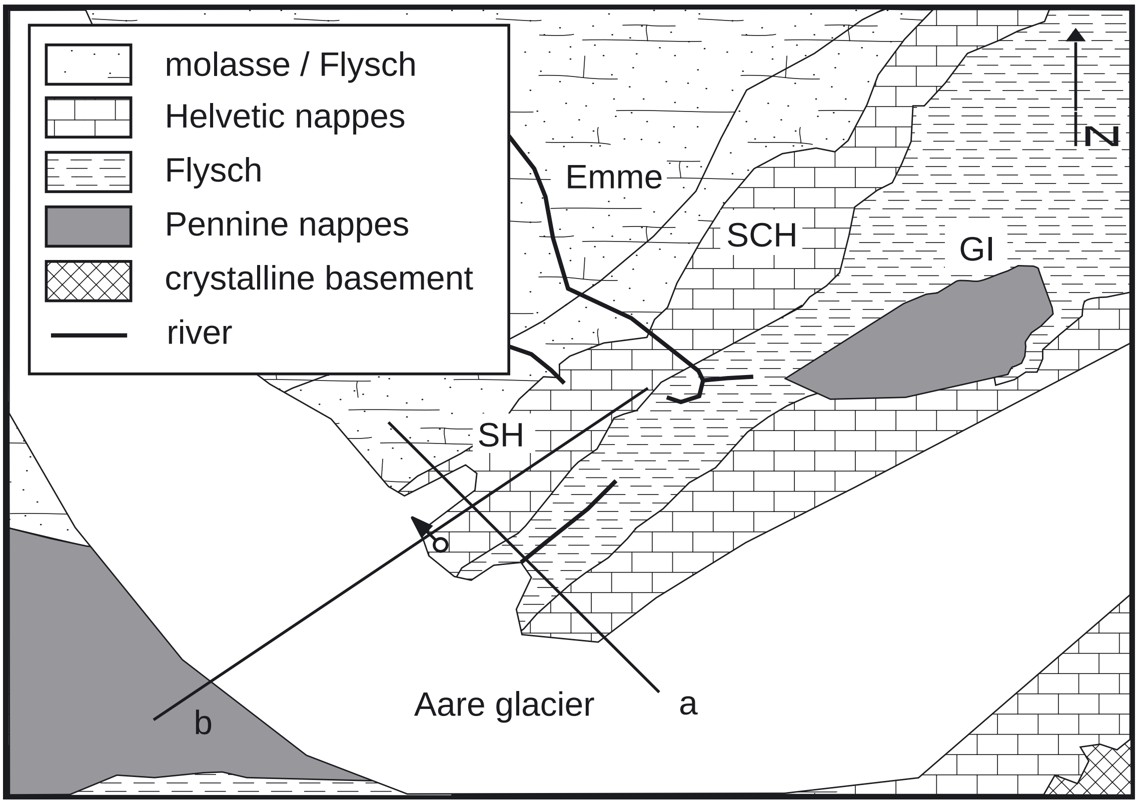
Caves are precious tools for the reconstruction of the paleogeographic evolution of the Alps. They preserve forms and sediments which are quickly eroded at the surface and are therefore archives for past processes. This work, in agreement with Blanc (1992), shows that at least phase reconstructions can be made also in regions where the caves are either too small or inaccessible.

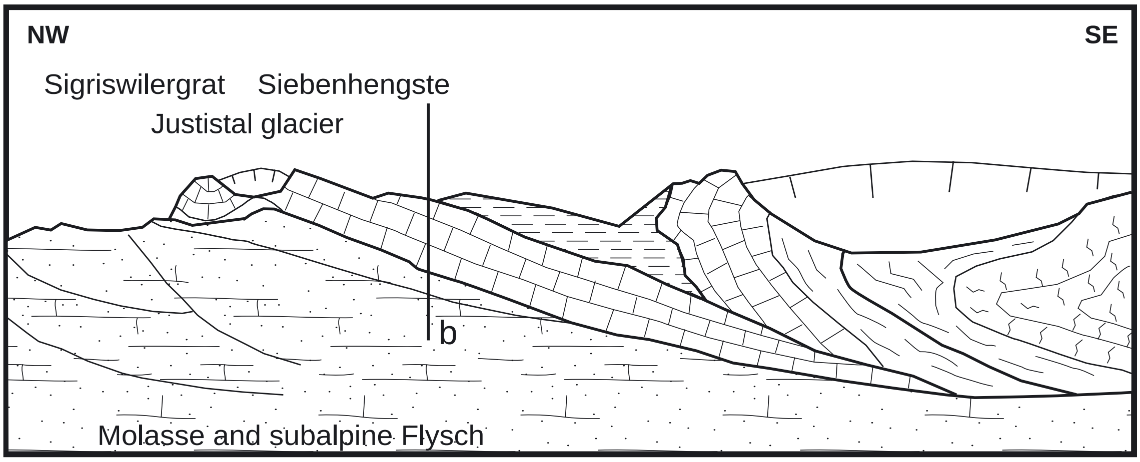
We have deciphered the progressive deepening of the Aare valley in six distinct steps, reaching from today's level at 558 m a.s.l. over 660, 700, 760, and 805 to 890 m. Three levels could be dated. Level 558 is the present one, level 700 was active between 160 ka and 100 ka and level 760 was active between 390 ka and 160 ka.
This phasology and its extension towards the upper phases results in a tentative reconstruction of the Alpine paleogeography from Mio/Pliocene to today. This reconstruction may be regarded as the final synthesis. But the absolute datations and the correlation with glaciations are still missing. This will be the aim of Chapter 6, which deals in detail with sedimentary and morphological successions and their dating, and finalises therefore the thesis.

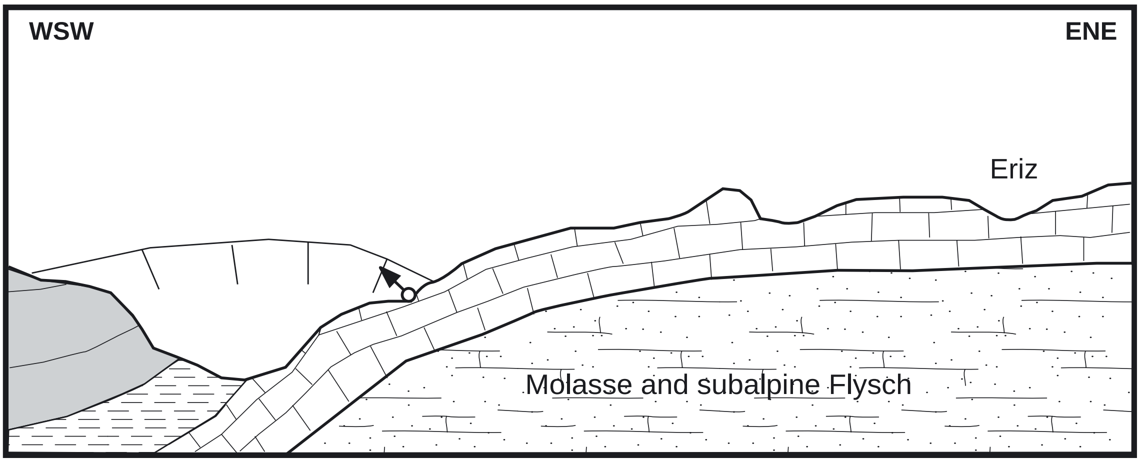
Fig. 5-12 (right): Presumed situation in Plio-Pleistocene. The Pennine nappes are almost completely eroded away, the Aare valley is at about 1100 m a.s.l. (uncorrected). The Eriz springs are dry, the Emme valley is in existence. Picture width approx. 50 km. GI=Giswilerstöcke; SCH=Schrattenfluh. The lines indicate the the location of the profiles displayed below.

Angenommene Situation im Plio/Pleiszozän. Die penninischen Decken sind fast komplett erodiert, das Aaretal liegt auf ca. 1100 m ü.M. (unkorrigiert). Die Quellen im Eriz sind versiegt, das Emmental existiert. Bildbreite ca. 50 km. GI=Giswilerstöcke; SCH=Schrattenfluh. Die Linien geben die Lage der unten abgebildeten Profile wieder.

Situation présumée au Plio/Pléistocène. Les nappes penniques sont à peu près érodées, la vallée de l'Aare se trouve à env. 1100 m (non corrigé). Les sources de l'Eriz sont fossiles, la vallée de l'Emme existe. Largeur de l'image env. 50 km. GI=Giswilerstöcke; SCH=Schrattenfluh. Les lignes indiquent la situation des profils montrés en bas.


molasse / Flysch
Helvetic nappes
Flysch
Pennine nappes
crystalline basement
river
N
Emme
SCH
GI
SH
Aare glacier
a
b


NW
SE
Sigriswilergrat
Siebenhengste
Justistal glacier
b
Molasse and subalpine Flysch


WSW
ENE
Eriz
Molasse and subalpine Flysch

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6. Paleoclimatic and paleogeographic information obtained from the study of cave sediments

Zusammenfassung: Paläoklimatische und paläogeographische Informationen aus Höhlensedimenten

Einführung

Dieses Kapitel befasst sich mit den Höhlensedimenten. Nach einer Übersicht über die möglichen Sedimentationsarten werden die in der St. Beatus-Höhle gefundenen Sedimentprofile vorgestellt. Die Resultate der Analysen werden interpretiert und eine chronologische Tabelle erstellt. Das Resultat ist eine Synthese der paläogeographischen und paläoklimatischen Evolution während der letzten 400‘000 Jahren. Die meisten Studien über die Vergletscherungsgeschichte der Alpen wurden im Vorland durchgeführt, da in den Alpentälern die Erosion durch den jüngsten Eisvorstoss ältere Spuren zumeist verwischte. Morphogenetische Studien sowie Datierungen sind schwierig durchzuführen. Die alpine Geschichte ist jedoch wichtig für das Verständnis der Eiszeiten, da eine Freilegung der Alpentäler ein deutliches Klimasignal benötigt und dieses unter Umständen auch besser auflösbar ist. Im Gegensatz dazu ergeben die Aufschlüsse im Vorland oft keine gute Klimainformation her. Da gutes Material an der Oberfläche kaum gefunden werden kann, bieten sich Höhlensedimente als sinnvolle Alternative an. Da es sich um offene Systeme handelt, sind sie jedoch auch der Erosion ausgesetzt. Das vorliegende Kapitel zeigt auf, dass diese im Allgemeinen nur einzelne Teile der Sedimentabfolge erfasst und dass somit Höhlen ein ausgezeichnetes Mittel zum Studium von Vergletscherungen und Taleintiefung darstellen.
Höhlen entstehen durch Korrosion von Kalkstein durch Kohlensäure. Diese ist durch Bodenaktivität sehr stark angereichert, aus diesem Grunde ist während Warmzeiten und Pflanzenbewuchs sowohl die Höhlenenstehung wie auch die Bildung von Tropfsteinen im vadosen Raum (durch erneutes Entgasen von Kohlendioxid) stark beschleunigt.

Die Gletscher der Alpen sind temperiert und enthalten deshalb Wasser. Während einer Vergletscherung der Täler wird somit der Wasserspiegel im Tal stark angehoben: die älteren Höhlenteile werden ersäuft und reaktiviert. Einhergehend mit dem geringeren Abfluss (der Niederschlag fällt zumeist als Schnee) hat dies eine starke Abnahme der Fliessgeschwindigkeit in den Höhlengängen zur Folge. Durch das Mitführen von karbonatischer Gletschermilch wird zudem noch die Korrosion verlangsamt: Höhlenbildung ist also während Eiszeiten kaum aktiv, während die Ablagerung von rhythmisch geschichteten karbonathaltigen Silten (Warven) die Regel ist.

Die Sedimentprofile

Die einzelnen Sedimentprofile (die alle in der St. Beatus-Höhle zu finden sind) werden vorgestellt und sind auf den Figuren 6-5 und 6-9 gezeichnet. Nach einer Beschreibung sowie den Resultaten der Laboranalysen folgt eine Interpretation der Profilgenese.

Interpretation der Labordaten

Die Präzision der **U/Th-Datierung** ist wegen des hohen Gehalts an U zufriedenstellend. Speziell in den jungen Proben kann der Gehalt an detritischem Th hohe Werte annehmen, da vor allem Bodensinter statt Stalagmite beprobt wurden. Durch die Auswahl von alten Sintern ist ein Auswaschen von U durch Hochwässer (das zu hohe Alter ergibt) ein Problem, das durch die Entnahme von Bohrkernen und die Beprobung von alterationsfreien Sintern minimiert wurde. Die erhaltenen Daten müssen in jedem Fall mit der Ablagerungschronologie übereinstimmen. Tabelle 1 zeigt die erhaltenen Daten. Einige Problemfälle zeitigen als Resultat, dass UAT wohl mit ziemlicher Sicherheit ebenfalls älter als 350 ka ist, dass die Datierung von „KE2, Mäanderboden, WGBoden, STI und Rätsel“ wegen des hohen Gehaltes an detritischem Th unbrauchbar ist, WGU ein U-Leaching aufweisen könnte, und dass „KH3 und Empire“ wegen detritischen Thoriums nur als Indikation zu gebrauchen sind.

Die Frage, ob die **Tonmineralogie** Aussagen über das Klima machen kann, scheint – zumindest im Falle von Höhlensedimenten – verneint werden zu müssen. Gemäss Literaturangaben ist die Bildung von Tonmineralien eher von der Gesteinsart und der Wasserchemie abhängig als vom Klima. Des weiteren finden sich in den analysierten Proben z.B. verhältnismässig viel Kaolinit, der oft als Indikator für tropische Lateritverwitterung hinhalten muss, was in unserem alpinen Klima doch eher unwahrscheinlich

ist. Der Kaolinit ist deshalb entweder als detritisches oder geochemisches Produkt zu deuten.

Die **Pollenanalyse** zeitigt magere Resultate in Übereinstimmung mit Befunden aus dem Hölloch und Jochloch. Es scheint, dass die interpretierten kaltzeitlichen Bedingungen zum Zeitpunkt der Ablagerung der Feinsedimente die Vegetation reduzierten, und dass die verbliebenen Pollen im Untergrund dann noch weiter umgelagert wurden. Wir schliessen daraus, dass in alpinen Höhlen die Pollenanalyse von Feinsedimenten im Allgemeinen wenig sinnvoll ist, und dass einzig die Analyse von im Sinter gefangenen Pollen Resultate ergeben könnte.

Die **Geröllanalyse** gibt Aufschluss über die Gesteinsarten, die in die Höhle gewaschen wurden. So ist das Vorhandensein von helvetischem Sand- und Kalkstein nicht verwunderlich. Die Präsenz von Kristallin zeigt oft Moränenmaterial an. Umgelagerter Sinter beweist das Vorhandensein von mindestens einer Versinterungsphase vor der erfolgten Umlagerung.

Die **Korngrössenanalyse** gibt Aufschluss über die Fliessgeschwindigkeit und die Sedimentationsart. Sedimentation in einem Fluss resultiert in einer guten Sortierung der Ablagerung, während Sedimentation von Moränen oder Murgängen (resp. in Höhlen Flutablagerungen) keine Sortierung bewirken. Gemäss dem Diagramm von Hjulström kann die mittlere Korngrösse zur Bestimmung der Fliessgeschwindigkeit benutzt werden. Es wurde nur die Fraktion 0.064 bis 4 mm analysiert. Die meisten Proben zeigen eine recht gute bis sehr gute Sortierung und erlauben deshalb näherungsweise die Bestimmung der Fliessgeschwindigkeit.

Entstehung der Höhle, Lage der Profile

Die Entstehung von St. Beatus-Höhle und Bärenschacht ist im Kapitel 5 beschrieben. Aufgrund der Lage am Aaretal werden die Höhleneintiefungsphasen als Produkt der glazialen Taleintiefung gedeutet. Die Frage ist nun: Wann geschahen diese Taleintiefungen? Die Datierung ist nur mithilfe der Sedimente, speziell des Sinters, möglich. Da Sinter im Allgemeinen in der vadosen Zone abgelagert wird, bedeutet das erste Erscheinen von Sinter in einer phreatischen Röhre den spätestmöglichen Zeitpunkt deren Trockenfallens. Somit ergibt diese Sinterdatierung das Minimalalter der nächsttieferen Phase und das Maximalalter der Phase, als der beobachtete Gang noch unter Wasser stand. Aus diesem Grunde ist es nötig, die oben beschriebenen Sedimentprofile in den phasologischen Rahmen zu stellen (Fig. 6-3) und die Gangmorphologie mit der Sedimentabfolge zu korrelieren. So kann eine relative Chronologie erstellt werden. Die Datierung von Sintern ergibt dann Absolutalter innerhalb dieser Chronologie, als Resultat erhält man eine Tabelle (Tabelle 3), die Phasenübergänge (=Taleintiefungen), Sedimentationen und Erosionen sowie die Datierungen enthält. Diese Tabelle ist in dem Sinne korrekt, als die Abfolgen und Alter logisch zusammenhängen; die Schwierigkeit besteht in der Alterszuweisung von Lockergesteinen zwischen zwei datierten Sintern.

Interpretierte Chronologie der Taleintiefungen und Vergletscherungen

In diesem Abschnitt wird die Tabelle 3 interpretiert. Zu den Phasen oberhalb 805 können keine Sedimente zugeordnet werden. Während der Phase 805 wurden die Gerölle MU5 (der Ausgang der St. Beatus-Höhlen war zu dieser Zeit in der „??Cave“) und später die Tropfsteine EXC1 und EXC2 abgelagert, dies alles vor über 350 ka. Durch die nächste Vergletscherung wurden diese mit Silt bedeckt, und die Phase 760 entstand. Danach wurde wiederum Geröll (BG1) abgelagert, das nach einer weiteren Klimaerwärmung übersintert (KOH, EXC5) wurde, was ebenfalls vor über 350 ka bis 325 ka geschah. Ein humideres Klima bewirkte eine Erosion von Sinter und Fels auf 2 m Tiefe. Eine trockenere Phase sedimentierte den Tropfstein BG23 vor 238 ka. Die nächste graduelle Klimaverschlechterung brachte zuerst Sand und Gerölle ein (BG1-BG13) und verstopfte den in Ansätzen ausgebildeten Ausgebauten Teil: der Ausgang der St. Beatus-Höhlen war zu jener Zeit die Eibenhöhle. Die Klimaverschlechterung kulminierte in einer neuen Eiszeit (BG15-BG17), welche den Talboden auf 700 m absenkte. Während dieser Phase war der grösste Teil der St. Beatus-Höhle bereits in der vadosen Zone, deshalb ist die Phase als solche im Bärenschacht zu sehen, wo die „Voûte céleste“ ein Alter von 157 ka angibt. Einige Sedimentationsereignisse sind aber auch in der St. Beatus-Höhle zu sehen: BG20 und BG25 zeigen 161-170 ka an, wahrscheinlich war dieselbe Generation für die Zementierung des Ausgebauten Teils verantwortlich. Eine nächste Siltlage zeigt die Eintiefung auf 660 m verursachende Vergletscherung an, die ebenfalls für die Verstopfung der Eibenhöhle und das Ausräumen des Ausgebauten Teils verantwortlich war. Einige Sinter (EXC3, Bärenschacht) belegen die nächste wärmere Zeit, der ein Gletschervorstoss von untergeordneter Bedeutung sowie eine nächste Warmzeit (EXC4, KH2) folgte. Dieser Zyklus wiederholte sich noch zweimal.

Zusammenfassung

In dieser Zusammenfassung wird nur die Abfolge von Kalt-und Warmzeiten beschrieben, das Zusammenspiel Sedimente, Sedimentart und Morphologie ergibt aber zusätzlich noch weitere Informationen über die vermutete Temperatur und Durchflussrate, die in Fig. 6-18 gezeigt werden.

- Eintiefung auf 805 m, vermutlich durch eine Vergletscherung, vor über 350 ka
- eine Warmzeit ebenfalls vor 350 ka
- Eintiefung auf 760 m durch einen Gletscher, vor über 350 ka

- eine warmzeitlich/humide Abfolge zwischen >350 ka und 235 ka
- Eintiefung auf 700 m durch einen Gletscher, zwischen 235 und 180 ka
- eine Warmzeit zwischen 180 und 157 ka
- Eintiefung auf 660 m durch einen Gletscher, zwischen 157 und 135 ka
- eine Warmzeit zwischen 135 und 114 ka
- eine Vergletscherung zwischen 114 und 99 ka
- eine Warmzeit zwischen 99 und 76 ka
- eine Vergletscherung zwischen 76 und 54 ka
- eine Warmzeit zwischen 54 und 39 ka
- Eintiefung auf 530 m durch eine Vergletscherung zwischen 39 und 16 ka (Maximalalter der Eintiefung 114 ka)
- eine Warmzeit zwischen 16 ka und heute.

Die Altersangaben wurden ohne Fehlerkorrektur angegeben: Falls die sedimentäre Abfolge zwingend eine Vergletscherung zwischen zwei Sintern vorschreibt, muss diese auch dann stattfinden, wenn sich die korrigierten Alter der Versinterungen überlappen sollten.

Ein Vergleich mit der Literatur ergab eine recht gute Übereinstimmung.

Schluss

Seit langem werden Tropfsteine zur Analyse von stabilen Isotopen gewonnen, aber andere Informationen aus Höhlen werden, oft wegen der Offenheit des Systems, nicht beachtet. Die vorliegende Arbeit beweist, dass sich eine enorme Vielfalt von Informationen aus den Höhlen extrahieren lässt. Die Gesamtuntersuchung von offenen Systemen erbringt eine Gesamtübersicht über die Bildungsbedingungen und -prozesse, während Einzeluntersuchungen naturgemäss nur Einzelresultate zeitigen.

Dieses Kapitel zeigt Befunde, die die Rekonstruktion der Taleintiefungs- und Vergletscherungsereignisse in einem absoluten zeitlichen Rahmen erlauben. Aus diesem Grunde bildet es den Abschluss der vorliegenden Arbeit.

Résumé: Informations paléoclimatiques et paléogéographiques obtenues par l’étude des sédiments des cavités

Introduction

Ce chapitre concerne les sédiments conservés dans les cavités. Nous passons en revue les modes de sédimentation et décrivons les profils sédimentologiques trouvés dans la grotte de St. Béat. L’interprétation des résultats permet de construire un tableau chronologique. Cette synthèse de l’évolution paléogéographique et paléoclimatique s’étend sur une durée de 400’000 ans.

L’histoire des glaciations alpines a été surtout étudiée dans l’avant-pays, car la glaciation la plus récente a érodé les traces antérieures dans les vallées alpines. Les études morphogénétiques et les datations sont difficiles à effectuer. L’histoire alpine est cependant importante pour la compréhension des glaciations: de légères variations de température peuvent provoquer d’importantes avancées et retraits de la langue glaciaire dans l’avant-pays, tandis que le dégel d’une vallée alpine nécessite un signal climatique nettement plus marqué. Vu la rareté du matériel de surface, les sédiments souterrains sont une véritable aubaine. On sait depuis longtemps que les grottes sont en quelque sorte des archives géologiques, même si, en tant que système ouvert, elles sont soumises à l’érosion. Le présent chapitre indique que l’érosion n’attaque généralement que partiellement la masse des sédiments. Les grottes sont donc un lieu privilégié pour l’étude des glaciations et du creusement des vallées.

Les grottes se créent par corrosion du calcaire par l’acide carbonique. Sa concentration dans l’eau est favorisé par la présence de sol végétal. Ainsi, la spéléogenèse et la formation des concrétions (par dégazage de dioxide de carbone) sont fortement accélérées pendant les périodes chaudes où la végétation prospère.

Les glaciers des Alpes sont tempérés, puisqu’ils renferment de l’eau liquide. Pendant une glaciation, lorsqu’une vallée est envahie par la glace, la nappe régionale monte fortement, et les cavités anciennes sont ennoyées et réactivées. Les précipitations tombant principalement sous forme de neige, le débit dans les grottes est faible. La corrosion chimique est également ralentie par la présence dans l’eau de farine carbonatée («lait glaciaire»). Pendant les glaciations, la spéléogenèse est presque inactive; en règle générale, ces périodes correspondent à des dépôts de limons varvés.

Les profils sédimentologiques

Différents profils sédimentologiques (tous de la grotte de St. Béat) sont décrits (voir Figs. 6-5 et 6-9). Nous présentons les résultats des analyses de laboratoire et proposons une interprétation. Nous renonçons à une traduction détaillée ici.

Interprétation des données du laboratoire

La précision des **datations U-Th** est très satisfaisante grâce à la teneur élevée en U. Dans les échantillons récents, la concentration en Th détritique peut être élevée elle aussi, parce que nous avons échantillonné des planchers stalagmitiques plutôt que des stalagmites. Le choix délibéré des concrétionnements les plus anciens pose le problème du lessivage de U par les eaux de crue (il en résulte un âge trop élevé). Ce problème a été minimisé par l'échantillonnage de carottes et de concrétions sans altération visible. De toute manière, les données obtenues doivent correspondre à la chronologie relative du dépôt. Le tableau 1 présente les données obtenues. Quelques cas litigieux sont discutés: UAT est très probablement plus ancien que 350 ka; par ailleurs, la datation de «KE2, Mäanderboden, WGBoden, STI et Rätsel» est impossible car trop contaminée par le Th détritique; WGU en revanche pourrait présenter un lessivage de U, et finalement «KH3 et Empire» ne sont utilisables qu'à titre indicatif, car contaminées par le Th détritique.

Dans le cas des sédiments de cavités, la **minéralogie des argiles** ne semble pas fournir d'indications climatiques. Selon la littérature, la formation des minéraux argileux dépend davantage de la nature des roches et de la chimie des eaux que du climat. Nos échantillons contiennent beaucoup de kaolinite, minéral souvent interprété comme indicateur d'une altération sous climat tropical (latérites). Cette hypothèse est peu probable dans nos latitudes, et on peut expliquer la présence de kaolinite soit comme matériau détritique, soit comme produit géochimique, mais sans rapport avec le climat.

Les résultats de l'analyse des **pollen** sont maigres et en accord avec les analyses du Hölloch et du Jochloch. Les conditions climatiques froides qui régnaient lors du dépôt des sédiments fins devaient inhiber la végétation, et la plupart du pollen sédimenté a été détruit. Nous en concluons que l'analyse des pollens est d'un intérêt limité dans les sédiments détritiques des cavités alpines. En revanche, l'analyse des pollens pris dans le concrétionnement pourrait donner de bons résultats.

L'**analyse des galets** met l'accent sur la nature des roches transportées à l'intérieur de la grotte. Le gravier de l'Helvétique n'est pas une surprise. Les galets cristallins sont issus de matériel morainique, et les galets de sédiment de grotte attestent d'une phase de sédimentation antérieure au dépôt définitif.

La **granulométrie** renseigne sur la vitesse d'écoulement et le mode de sédimentation. Une sédimentation en rivière donne un bon tri des galets, tandis qu'un dépôt de moraine ou de lave torrentielle (dans les grottes: dépôt de vagues de crue) n'est pas trié du tout. Suivant le diagramme de Hjulström, on peut connaître la vitesse d'écoulement d'après la granulométrie moyenne des sédiments. Les limons étant peu indicatifs, nous n'avons analysé que la fraction 0.064 à 4 mm. La majeure partie des échantillons présente un assez bon tri, ce qui nous permet d'estimer la vitesse d'écoulement.

Genèse de la cavité, situation des profils

La genèse de la grotte de St. Béat et du Bärenschacht est décrite au chapitre 5. Vu la situation de ces cavités par rapport à la vallée de l'Aare, les phases spéléogénétiques sont interprétées comme résultat de l'approfondissement glaciaire de la vallée. Reste à savoir quand cette dernière a eu lieu. Une datation n'est possible qu'à l'aide des sédiments et plus spécialement du concrétionnement. Les concrétions ne se forment que dans la zone vadose, ainsi, la première apparition de concrétions dans un tube phréatique indique l'époque du début de son assèchement. En définitive, la datation d'une concrétion dans une galerie donnée indique l'âge minimal de la phase inférieure, tout comme l'âge maximal de la phase qui a formé cette galerie. Il s'agit donc de placer les profils décrits ci-dessus dans le contexte phasologique (Fig. 6-3), et de corréler la morphologie des galeries avec la succession des sédiments pour obtenir une chronologie relative. La datation du concrétionnement donne ensuite des âges absolus dans cette chronologie. Le tableau 3 résume les transitions de phases (=approfondissement de vallée), la sédimentation, les types d'érosion et les datations. Même si les évènements et les âges se succèdent dans un ordre logique, il est difficile d'estimer l'âge d'un sédiment meuble déposé entre deux concrétions datées.

Interprétation de la chronologie des approfondissements de vallée et des glaciations

Dans ce paragraphe, nous interprétons le tableau 3. Il n'y a pas de sédiments clairement liés aux phases au-dessus de 805. Pendant cette dernière, voilà plus de 350 ka, ont été déposés les galets MU5 (la sortie de la rivière de St. Béat était à cette époque à la «??Cave») et plus tard les stalagmites EXC1 et EXC2. Pendant la glaciation suivante, tout a été recouvert de limons, et la phase 760 était créée. Ensuite, les galets BG1 ont été déposés, puis cimentés (KOH, EXC5) entre 350 ka et 325 ka. Un climat plus humide entraîne alors une érosion de 2 m (roche et concrétionnement), puis une phase plus sèche voit le dépôt de la stalagmite BG23 il y a 238 ka. Lors d'une détérioration climatique ultérieure, des sables et des galets (BG1-BG13) colmatent la partie amenagée de la grotte de St. Béat, dont la principale sortie était à cette époque la Eibenhöhle. La détérioration climatique culmine en une nouvelle glaciation (BG15-BG17) qui abaisse le fond de vallée à 700 m. Durant cette phase, la majeure partie de la grotte de St. Béat se situait en zone vadose, et l'on voit la phase 700 dans le Bärenschacht, où la «Voûte céleste» donne un âge de 157 ka. Quelques évènements sédimentaires sont malgré cela visibles dans la grotte de St. Béat: BG20 et BG25 indiquent un âge de 161-170 ka. C'est probablement la même génération de concrétionnement qui a cimenté la partie aménagée. Ensuite, une couche de limon marque la prochaine glaciation, responsable de l'approfondissement de la vallée à 660 m. Ladite glaciation est responsable de l'obstruction du trajet St. Béat-Eibenhöhle et de la décolmatation de la partie aménagée. Par la suite, quelques concrétions (EXC3, Bärenschacht) témoignent d'une période chaude, suivie d'une glaciation de moindre importance, puis d'une période chaude (EXC4, KH2). Ce cycle se repète deux fois, la dernière période chaude étant l'Holocène.

Résumé

Dans ce résumé, nous ne décrivons que la succession de périodes froides et chaudes. L'interaction des processus sédimentaires, des types de sédiment et de la morphologie donnent des informations supplémentaires sur la température et le débit (voir figure 6-18).

- Approfondissement de vallée à 805 m, probablement à cause d'une glaciation, il y a plus de 350 ka
- une période chaude, également antérieure à 350 ka
- approfondissement jusqu'à 760 m par une glaciation antérieure à 350 ka
- une période chaude et humide entre >350 ka et 235 ka
- approfondissement jusqu'à 700 m par une glaciation, entre 235 et 180 ka
- une période chaude entre 180 et 157 ka
- approfondissement jusqu'à 660 m par une glaciation, entre 157 et 135 ka
- une période chaude entre 135 et 114 ka
- une glaciation entre 114 et 99 ka
- une période chaude entre 99 et 76 ka
- une glaciation entre 76 et 54 ka
- une période chaude entre 54 et 39 ka
- approfondissement jusqu'à 530 m par une glaciation, entre 39 et 16 ka (âge maximal de l'approfondissement: 114 ka)
- une période chaude entre 16 ka et aujourd'hui

Les datations sont indiquées sans marge d'erreur. En effet, si la succession sédimentaire prescrit une glaciation entre deux phases de concrétionnement, elle doit avoir lieu même si l'âge corrigé des concrétions se superpose.

Une comparaison bibliographique donne une bonne cohérence, même s'il n'y a pas beaucoup de datations dans le milieu continental.

Conclusion

On prélève de longue date des stalagmites pour l'analyse des isotopes stables, mais les autres sources d'information que recèlent les cavités sont en général négligées, sous prétexte que ces dernières sont un système ouvert. Le présent travail prouve qu'il y a une multitude d'informations à extraire des grottes. Nous proposons – à part les analyses très utiles des stalagmites – d'analyser le système comme un tout, car seule une synthèse permet d'obtenir des conclusions globales sur les conditions et les processus qui ont régné lors de la spéléogenèse et de la sédimentation.

Ce chapitre contient les premières datations jamais faites dans la région des Siebenhengste. Ces datations permettent une reconstitution chronologique de l'approfondissement des vallées et des glaciations. De ce fait, cette étude constitue la synthèse de tous les chapitres précédents.

An interesting Bärenschacht sediment contains snail shells.

Ein interessantes Bärenschachtsediment besteht aus Schneckenschalen.

Un sédiment intéressant du Bärenschacht contient de nombreuses petites coquilles d'escargots.

Photo by Bernhard Voss

6.1. Introduction

While most of current knowledge about glaciations in the Alpine Belt comes from the study of sites such as river terraces and gravel pits in the foreland (for example Penck & Brückner 1909, Schlüchter & Röthlisberger 1995), there is very little data from the inneralpine valleys. This is mainly due to the fact that the alpine area was (and still is) a region where erosion prevails over accumulation of sediments. Therefore, most traces of glaciations and valley deepening are derived from morphogenetic studies (such as Beck 1954). Such studies are difficult to conduct for the older glaciations, because erosion by the youngest one usually erased most of the older traces. Moreover, the dating of events is possible only with the aid of suitable sediments, which are either lacking or cannot be attributed to one specific glaciation.

However, inneralpine valleys are very important for the understanding of glaciation and deglaciation processes (Schlüchter 1988). Whereas the glacier tongues in the foreland can advance and retreat substantially with small climatic changes, deglaciation of the inneralpine valleys requires a considerable change in climate. Therefore, the presence or absence of glaciers gives direct evidence about the climate prevailing at a given time.

Because high quality information cannot be found at the surface, cave sediments represent a suitable alternative. Caves have been recognized as archives that respond to some of the changes occurring at the surface (Campy 1990, Jeannin 1991, Burns et al. 2001, Müller 1995). Caves, however, are open systems. Erosional events do not usually affect the whole cave, therefore the geologic record may be preserved in parts of the cave unaffected by erosion. We want to investigate cave sediments in order to obtain information on glaciation and valley deepening processes.

After an overview of the possible sedimentation modes, the sediment profiles found in St. Beatus Cave are presented. The results of the sediment analyses are then interpreted, and together with the phases described in Chapter 5, a chronological table is constructed. The result is a synthesis of paleogeographic and paleoclimatic changes that happened during the last 400'000 years.

The dependence of caves and cave sediment on climate

Caves are a product of limestone dissolution. To dissolve limestone, there has to be enough water and acidic substances, usually CO_2. Water is directly related to precipitation and climate. CO_2 dissolves more easily in cold water, therefore one could expect higher CO_2 concentrations in cold (periglacial) climate and therefore enhanced speleogenesis. However, in most cases the source of CO_2 is the soil present at the surface, which may considerably increase the CO_2 content of the water (Bögli 1978). Soils are dependent on plants, which in turn depend on a moderate to warm climate. A high CO_2 content in the water has two effects: first, the creation of voids (the proper dissolution) occurs more quickly and secondly, when the waters reach an airfilled cave in the vadose zone, the CO_2 is usually degassed again, causing speleothem growth (Fig. 6-1).

Glaciers in the Alps are temperate and usually have flowing water at their base. When a glacier advances in a valley, it raises the water table considerably: the formerly airfilled caves are drowned and the older galleries are reactivated. In a cold climate, much of the precipitation falls as snow, and as a result, discharge into the cave is small. Both effects cause a drastic drop in flow rate, and erosion is minimal. If the water flowing through the cave carries finely ground limestone ("glacier milk"), then corrosion of cave walls is no longer possible, because the waters are already

Fig. 6-1: The Hoher Nordgang of St. Beatus Cave. Photo by Peter Pfister

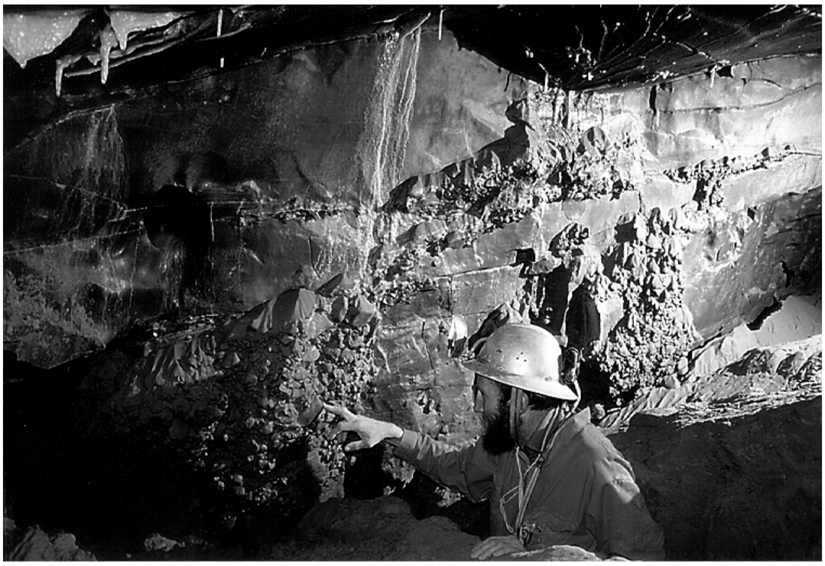


Fig. 6-2:
The Murgelegang in St. Beatus Cave shows old gravelcemented to the wall.

Der Murgelegang der St. Beatus-Höhle zeigt alte, an diei Wand angesinterte Gerölle.

Le Murgelergang dans la grotte de St. Béat montre des galets vieux, cimentés au paroi.

Photo by Peter Pfister

saturated. Therefore, a glaciation will most likely stop cave growth, and carbonated silt will be deposited throughout the waterfilled part of the cave (Audra 2001).
We conclude as a general rule that moderate to warm climate is responsible for speleogenesis and precipitation of speleothems, whereas glaciations slow down speleogenesis and result in the deposition of silt.

6.2. The sediment profiles

The sediment profiles (scale 1:50) described in this chapter are reported in Fig. 6-3 and illustrated in Figs. 6-5 and 6-9 (Legend in Fig. 6-6). All of the profiles are situated in St. Beatus Cave. In the following text, we first describe the setting and aspect of the sediment profile, then present laboratory results, and finally interpret the genesis of the profile.

Hoher Nordgang (HNG, Fig. 6-5)

The relatively large (2*3 m) gallery shows first a phreatic genesis, followed by vadose entrenchment. A huge accumulation of flowstone fills the gallery almost completely. Only the lower- and uppermost parts of it have a solid laminated aspect, all the other flowstone mass is palisadic and porous. In the lower part of the flowstone, some limestone blocks are found.

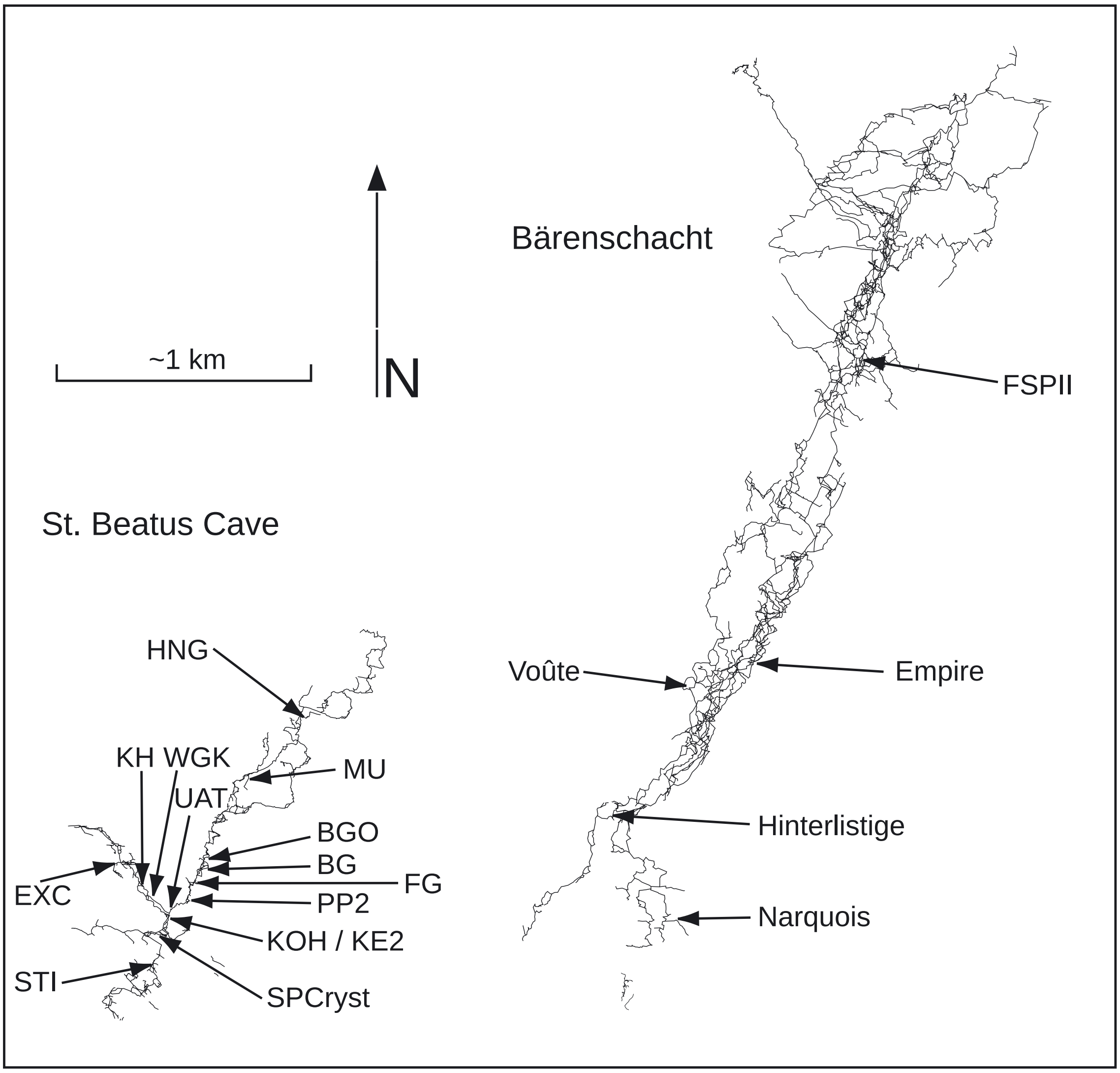
Dating of the different layers gave ages of 325 ka (+50/-35) for HNG1, 166 ka (+18/-16, corrected for detritic Th) for HNG5, and 81 ka (±12, corrected) for HNG7.

Comparisons up- and downstream indicate that the main volume of the gallery was excavated in the vadose domain. The origin of the flowstone is unknown, but it is most probably a local phenomenon. The blocks indicate a breakdown of the ceiling. With the exception of the upper- and lowermost members of the flowstone, it was deposited in or near a lacustrine environment, as is shown by the porous and palisadic macrocrystals, as well as the cauliflower-type flowstone lying above the boulders. This flowstone mass acted as a dam, slowing down the velocity of the water coming from upstream, therefore causing a sandy deposit in the gallery and a detritic input into the flowstone.

Murgelegang (MU, Fig. 6-5)

The Murgelegang presents a huge, almost quadratic section but 2/3 of the gallery's volume is filled with sediment (Fig. 6-2). At the right wall, coarse gravel is cemented to the wall. The sediment profile was dug by P. Pfister. It consists mainly of fine sand and silt that is layered in some places, only on the left side, some matrix-supported pebbles are found. A very thin sinter layer is found within the silts.

The cement of the gravels could be dated to 262 ka (+25/-21). The gravel petrography indicates 17 % sandstone, 72 % limestone, 7 % cristalline rocks, and 4 % reworked cave sediment. The granulometry of MU2 indicates a coarse silt (interpreted mean grain-size 0.04 mm), clay mineralogy yields 8 % of smectites and chlorite, 6 % kaolinite, and 78 % illite, with some illite/smectite mixed layers. Calcimetry of MU4 indicates 15 % carbonate. The pollen analysis of MU4 revealed that the sample is sterile.
The morphology of the gallery proves that it was mainly dug within the phreatic domain, and only a minor, not easily quantifiable amount of the gallery could be dug by a vadose stream. The gallery was then filled with coarse gravel (MU5) that was later cemented to the walls. The deposition of the gravel may have happened in phreatic conditions, however, the cementation by


Bärenschacht
~1 km
N
FSPII
St. Beatus Cave
HNG
Voûte
Empire
KH WGK
MU
UAT
BGO
BG
FG
EXC
PP2
KOH / KE2
STI
SPCryst
Hinterlistige
Narquois

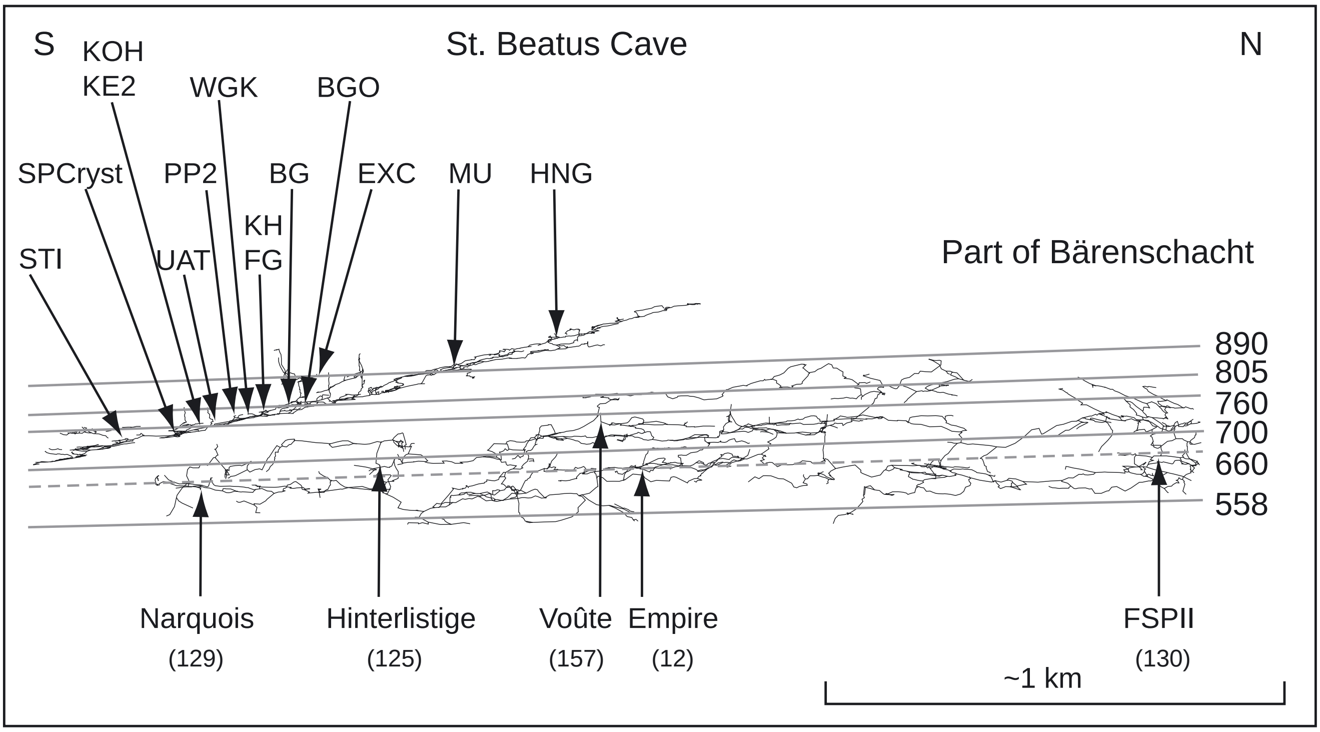

S
St. Beatus Cave
N
KOH
KE2
WGK
BGO
SPCryst
PP2
BG
EXC
MU
HNG
KH
FG
STI
UAT
Part of Bärenschacht
890
805
760
700
660
558
Narquois
(129)
Hinterlistige
(125)
Voûte
(157)
Empire
(12)
FSPII
(130)
~1 km

Fig. 6-3 (left):
Location of the sections in St. Beatus Cave and the dated samples (Bärenschacht), above plan view, below N-S projection. The dates are given in brackets in the projection.

Lage der Profile (St. Beatus-Höhle) und der datierten Proben (Bärenschacht), oben im Grundriss, unten als N-S-Projektion. Die Alter sind in Klammern in der unteren Grafik angegeben.

Situation des profils (grotte de St. Béat) et des échantillons datés (Bärenschacht), en haut en plan, en bas en projection N-S. Les âges sont indiqués entre parenthèses en bas.

sinter was in the vadose zone. The gravel, with an average diameter of 2-3 cm, indicates a flow velocity of more than 100 cm/sec. Assuming a vadose regime, a flow of some tens of l/s might be sufficient. For phreatic conditions, a minimum of 2.1 m^3/sec (average flood conditions) would be needed. A large erosional event after cementation then emptied the gallery almost completely, with a flow velocity of over 200 cm/sec. The subsequent deposition of fine sand and silt (MU2, fining upward into MU3) happened in a slow, almost stagnant regime (0.2-0.6 cm/sec), with the fining upward indicating a gradually slower flow rate ("stagnant water"). Water can only be stagnant in this position if there is a blockage at the outflow. A breakdown of the gallery's ceiling would not cause such a significant halt to circulation. A blockage of the outflow path is attributed to either a glacier raising the valley waterlevel, or glacial sediments pressed into the outflow gallery. An erosive discordance then cuts those layers, washes in some small pebbles, and a very fine flowstone layer indicates vadose conditions. A next set of layered silt (MU4) coarsens upward into fine sand. The carbonate content of the sample MU4 as well as the absence of organic matter supports the hypothesis of a glaciogenic origin.

Biwakgänge oben (BGO, Fig. 6-5)

Fig. 6-5 reports only the sediment succession in this gallery, which shows a (comparatively) small elliptic top and about 2 m of vadose entrenchment. Following this entrenchment, pebbles (BGO1, Fig. 6-4) were deposited and then cemented by sinter. The next flowstone layers are quite dirty and mixed with sand (BGO5). After an erosional event, another more recent flowstone deposition (BGO-Jung) follows. A more recent waterfill is proven by silt deposits.

Dating of BGO5 gave 190 ka (+22/-18), and dating of BGO-Jung gave 54 (±4) ka, both corrected for detritic Th.

The pebble size of about 3 cm indicates a peak flow velocity of more than 100 cm. The water depositing the following flowstone washed down some of the clay that had been deposited on the upper parts of the gallery. The following erosion preceding BGO-Jung must have been quite significant, since it destroyed the thick flowstone layer.

Biwakgänge unten (BG, Fig. 6-5)

The lower part of the Biwakgänge consists essentially of a passage with keyhole morphology. Its meander section is mostly filled with sediment. A profile was dug by P. Pfister in 1973. At the base of the profile,

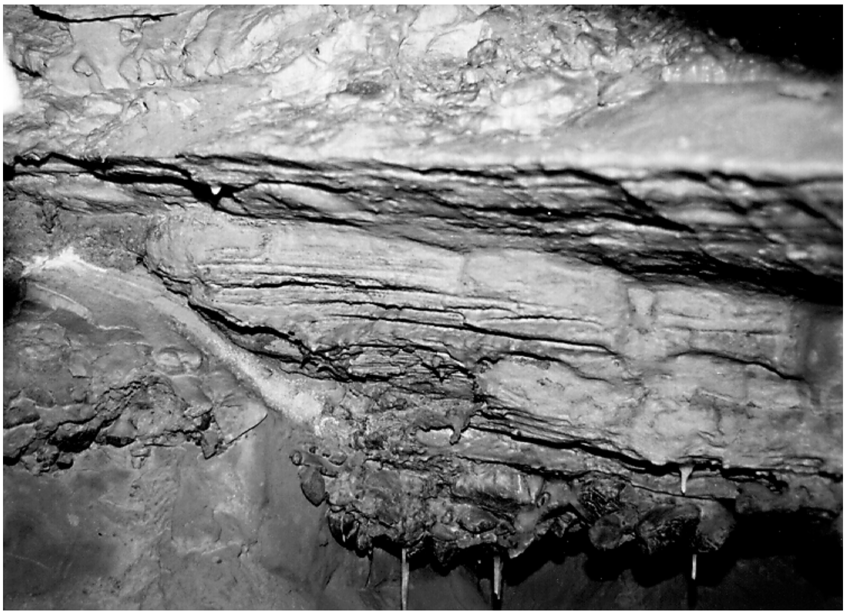
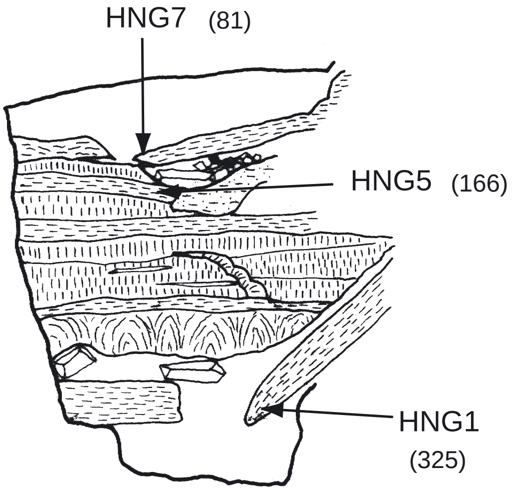


Fig. 6-4:
A part of the BGO profile.

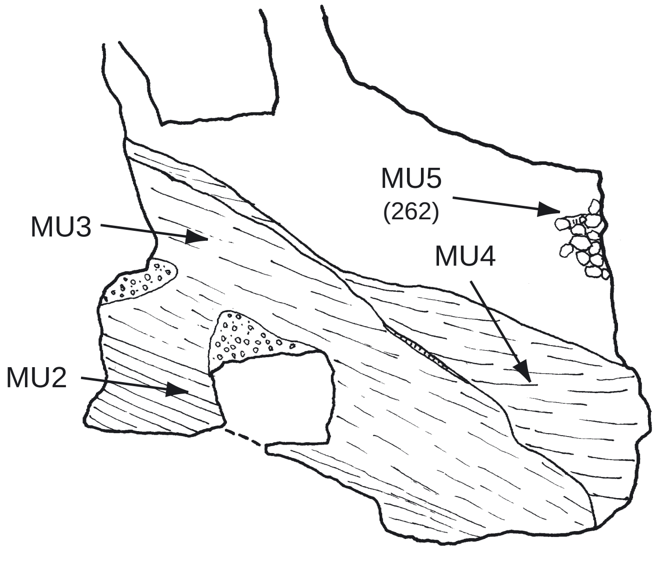
Ein Teil des BGO-Profils.

Une partie du profil BGO.

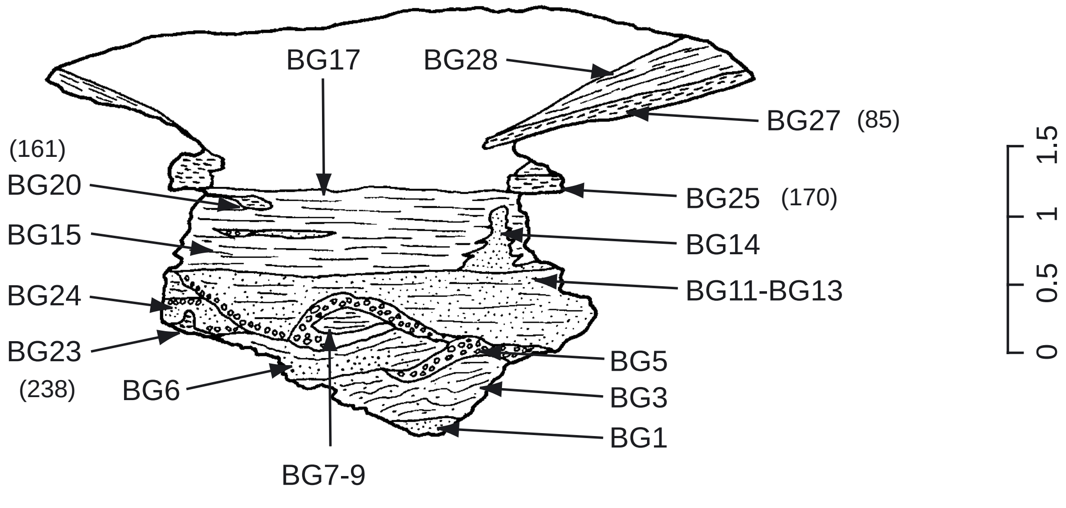
Photo by Daniel Burkhalter



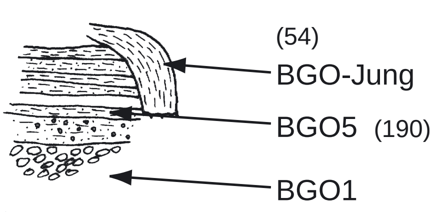
Hoher Nordgang HNG

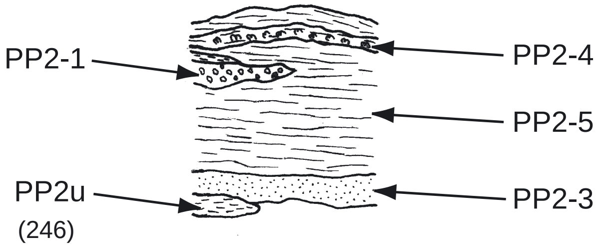


Murgelegang MU



Biwakgänge unten BG





Biwakgänge oben BGO

PP2

Fig. 6-5 (left):
Sediment profiles of Hoher Nordgang, Murgelegang, Biwakgänge oben and unten, PP2. The numbers in brackets indicate ages obtained. The profile legend is shown in Fig. 6-6.

Sedimentprofile vom Hohen Nordgang, Murgelegang, Biwakgänge oben und unten, PP2. Die Zahlen in Klammern sind gemessene Alter. Eine Legende zeigt Fig. 6-6.

Profils sédimentaires du Hoher Nordgang, Murgelegang, Biwakgänge unten et oben, PP2. Les chiffres entre parenthèses indiquent les âges obtenus. Une légende est présentée à la Fig. 6-6.

red sand (BG1) is overlain by quite a complicated interbedding of sands, silts and small matrix-supported pebbles (BG1-BG9). At the left side, a stalagmite (BG24) was sampled. The complicated sequence is overlain by fine sands (BG11-BG13), which in turn are succeeded by a layered silt deposit (BG15) that is partially interbedded with coarse sand (BG14) and sinter (BG20). The sequence is rimmed by other sinter deposits (BG25). On the shoulder of the ellipse, sinter (BG27, Fig. 6-7) is overlain by layered silt (BG28).

Dating of the stalagmite BG23 gave ages of 236 (+15/-13) ka at the top and 238 (+19/-16) ka at the base. Sinter BG20 gave 161 ka (+14/-13), corrected for detritic Th), Sinter BG25 gave an age of 170 ka (+14/-13), and sinter BG27 gave an age of 85 (±5, corrected) ka.
Granulometry of BG1 indicates a well-sorted medium sand with a mean grainsize of 0.25 mm, BG3, BG17 and BG28 a medium-sorted coarse silt (0.04 mm), BG5 a heterogenous mixture of sand and gravel (mean size 1.5 mm), BG12 a medium-sorted sand (0.45 mm), BG24 a very well-sorted sand (0.6 mm), and BG15 a poorly sorted coarse silt (0.02 mm).
Petrographic analysis of BG1 indicates 96 % sandstone and 4 % reworked sinter, BG5 shows 48 % sandstone, 31 % limestone, 10 % crystalline rocks, and 11 % reworked cave sediment (about the same is present in BG12).
Clay mineralogy of BG1 (and BG17) indicates 17 % chlorite, 68 % illite, and 15 % kaolinite, BG28 contained 6 % smectite, 15 % chlorite, 69 % illite and 10 % kaolinite.
Calcimetry of BG28 indicates a carbonate content of 20 %, whereas BG17 had 11 %, and BG8 and BG15 both had 25 % carbonate.
The pollen analysis of BG15 gave the following pollen: 8 Pinus, 1 Alnus, 1 Juniperus, 3 Poaceae, 6 Artemisia, 3 Asteraceae, 1 Chenopodiaceae, and 4 trilete spores.

An initial phreatic genesis of an ellipse is soon followed by a deposition of the gravel (BG31, not visible on Fig. 6-5) that presumably happened under vadose conditions, with a flow rate of about 100 cm/sec. The following sinter (not visible either on Fig.) precedes an important erosion. Most probably the sinter BG23 was deposited before the following gravel-sand-erosion layers (BG1-6, BG24, BG7-13) that reflect vadose conditions and a free-flowing small stream, with velocities varying from 5 to 100 cm/s. A quite distinct change was the flooding of the gallery, which caused the silt deposition BG15, that was contemporaneous to the sands BG14, which fell down from the ellipse shoulder during phreatic conditions due to gravity. The position of the gallery indicates that this flooding was very probably caused by a glacial blocking of the exit, as is also indicated by the calcimetry of

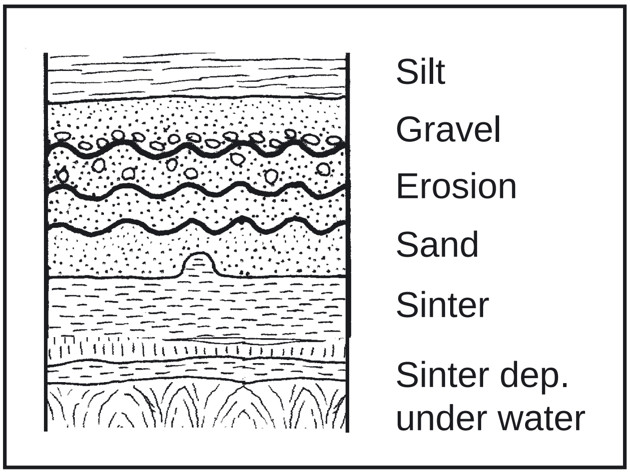


Fig. 6-6: Legend to Figs. 6-5, 6-9, 6-18
Legende zu den Figuren 6-5, 6-9 und 6-18
Légende des figures 6-5, 6-9 et 6-18

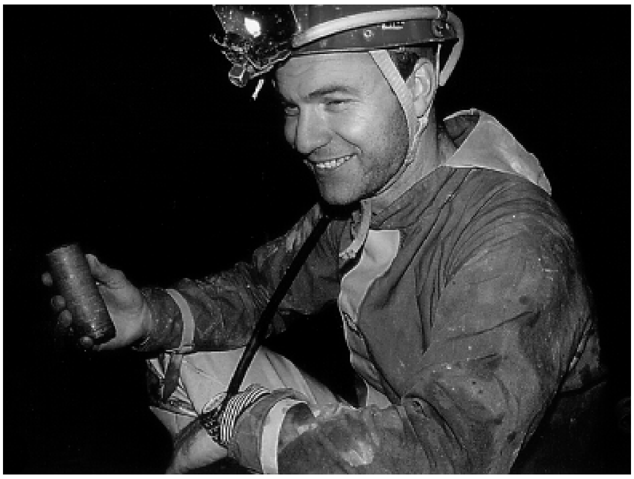


Fig. 6-7: A cored sinter sample. Photo by Peter Pfister
Ein Bohrkern aus Sinter.
Une carotte de concrétionnement.

sample BG15 and the poor pollen assemblage suggesting a rather cold climate. A break in silt deposition gave room for the sinter BG20 which falls in the same timespan as sinter BG25, both preceding sinter BG27 which is deposited before a last (unimportant) erosion and the sedimentation of the glacially induced silts BG17 (which is also seen on the ellipse shoulder: BG28).

Profile PP2 (Fig. 6-5)

The small profile, dug by P. Pfister, is near the top of the main ellipse. The succession begins with a sinter layer that is covered by sands and silts. Towards the top, a gravel layer precedes another sinter deposition, which is followed by silts and a layer of moonmilk clasts. A silt layer marks the end of the sedimentation.

Dating of the lower sinter (PP2u) gave 246 ka (+34/-26, corrected).
The gravel petrography of PP2-1 gave 12 % sandstone, 59 % limestone, 23 % crystalline rocks, 5.5 % reworked cave sediments and 0.5 % other material. Granulometry of PP2-3 indicates a poorly sorted coarse silt (0.02 mm). Clay mineralogy on PP2-4 gave 18 % chlorite, 68 % illite and 14 % kaolinite. The calcimetry of PP2-5 gives a very low value of 4 % carbonate.

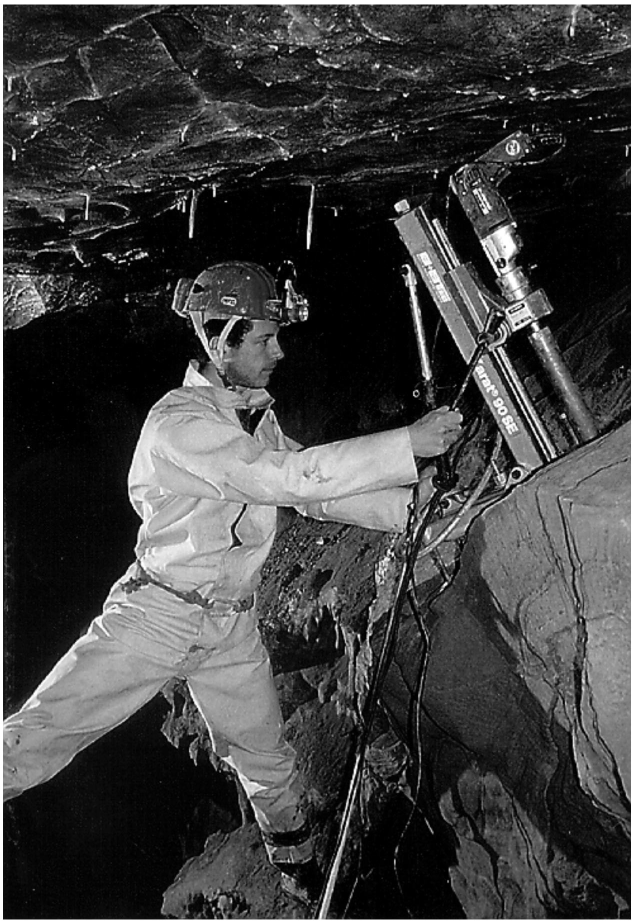


Fig. 6-8:
Coring at FG.

Kernbohrung bei FG.

Carottage à FG.

Photo by Peter Pfister

Fig. 6-9 (right):
Sediment profiles of Excenter, Kegelbahn, Kunsthalle. The numbers in brackets indicate ages obtained. The profile legend is shown in Fig. 6-6.

Sedimentprofile von Excenter, Kegelbahn, Kunsthalle. Die Zahlen in Klammern sind gemessene Alter. Eine Legende zeigt Fig. 6-6.

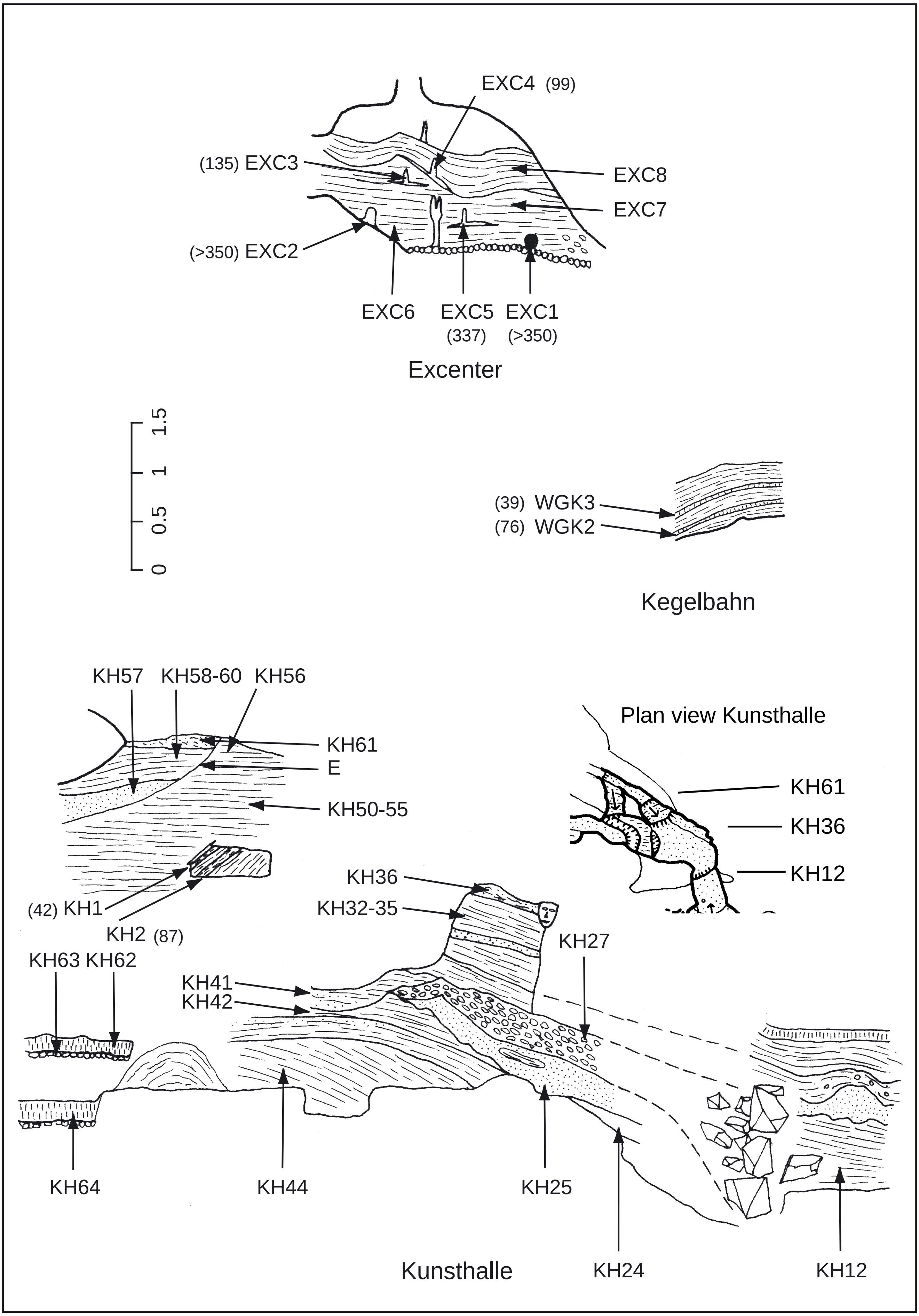
Profils sédimentaires du Excenter, Kegelbahn, Kunsthalle. Les chiffres entre parenthèses indiquent les âges obtenus. Une légende est présentée à la Fig. 6-6.

Presumably the sediments were deposited when the first vadose entrenchment was already active. The bottom sinter deposition falls in the same timespan as the dripstone of the Biwakgänge profile described above. This is followed by a succession of sand, silt and gravel (flow velocity not more than 50 cm/sec for the gravels). The following moonmilk clasts are supported by a silty environment. This shows an erosion of a preceding moonmilk with currents that were not very strong. The low carbonate content of PP2-5 indicates deposition under carbonate-dissolving conditions, which is difficult to explain when trying to correlate it with a glacier blocking the entrance (see discussion in part 6.1). It may be that this sediment was deposited before the onset of the next cold period.

Tourist Part and surroundings

In the region above PP2, and continuing down towards the end of the tourist part of the St. Beatus Cave, a sinter coming from an obstructed lateral gallery is deposited in the initial phreatic ellipse before entrenchment of the meandering canyon. This flowstone deposit, named FG (Fig. 6-8), UAT and KOH successively, begins before 350 ka (limit of alpha counting U/Th) and partially grows up to 276 ka (+98/-55, corrected). $^{234}U/^{238}U$ ratio calculations give an estimated age of about 390 ka for the beginning of the deposit.

The deposition and erosion cycles in the tourist part of the cave are generally only visible by lateral correlation of single deposits. A huge contribution in this respect was made by Knuchel (1968).


EXC4 (99)
(135) EXC3
EXC8
EXC7
(>350) EXC2
EXC6
EXC5
(337)
EXC1
(>350)
Excenter
0
0.5
1
1.5
(39) WGK3
(76) WGK2
Kegelbahn
KH57
KH58-60
KH56
KH61
E
KH50-55
(42) KH1
KH2 (87)
Plan view Kunsthalle
KH61
KH36
KH12
KH36
KH32-35
KH27
KH63
KH62
KH41
KH42
KH64
KH44
KH25
KH24
Kunsthalle
KH12

Excenter (EXC, Fig. 6-9, right)

One of the most interesting sediment successions is a gallery found in the Upper Excenter that is almost completely filled with a succession of silt and dripstones.

Datings of the different dripstones gave ages older than 350 ka for EXC1 and 2, 337 (+52/-35) ka for EXC5, 135 (±6) ka for EXC3, and 99 (±3) ka for EXC4. Calcimetry of EXC6 gave 27 % carbonate, and EXC8 yields 24 %. Clay mineralogy of EXC6 indicates 13 % Chlorite, 78 % Illite, and 9 % Kaolinite. The pollen analysis of EXC6 revealed that the sample is sterile, only some organic components were found.

After the initial phreatic genesis of the cave, a dripstone generation (EXC1 and 2) formed. A later flooding of the gallery deposited silt, the gallery then fell dry and the next generation of dripstone (EXC5) was deposited. This cycle is repeated three times.The position of the Excenter profile (along a horizontal passage that represents the top of a phreatic loop) indicates that a flooding by breakdown or sediment deposition in other parts of the gallery is very improbable. Therefore, it is assumed that the flooding of the galleries causing the silt deposition, was made by a glacier flooding the entrance. The calcimetry and pollen analysis again supports this hypothesis.

Kunsthalle (KH, Fig. 6-9)

The Kunsthalle is the third key section, and it is also the most complicated one. Much of the temporal and spatial succession presented here is interpretative, because erosion has broken important links between the sediment masses.

The profile presented in Fig. 6-9 is not across a gallery, but in a longitudinal section. Therefore, the gallery walls are not shown. The first sediments described below are not visible in the figure, but have been included for completeness.
Pebbles at the base of a phreatic gallery are held in place by a relatively thick sinter layer (WGU, not visible on figure) that precedes the next vadose erosion.

The following sediment succession (upper left side of figure) begins with a silt layer that was deposited near the walls. A sinter layer (KH2) precedes a silt layer and another sinter layer (KH1). The next silty/clayey layers are important and fill most of the room (KH50-55). They are again eroded by a channel (labelled E on figure). This channel is filled with the sand KH57, fining upward into silts (KH58-61).
The downstream sediment succession is very close by (middle of figure), however, there is no direct link between these sediments. The deposition of silty sands (KH44-42) precedes two erosions with subsequent va-

Fig. 6-10: The Kunsthalle gets its name from the head modelled into the silts in 1964. Photo by Katja Schobert
Die Kunsthalle hat ihren Namen wegen des 1964 in die Silte modellierten Kopfes.
La Kunsthalle porte son nom grâce à la tête modelée dans les limons en 1964.

Fig. 6-11:
Fine sand and warved Silt.
Feinsand und Silt, gewarvt.
Du sable fin et du limon warvé.

Picture height approx. 70 cm
Photo by Daniel Burkhalter

dose deposition of sands (KH25) and gravel (KH27), before the next cycle of flooding is marked by the silt succession (“Moritz-Silts”) KH41-36 (Fig. 6-10).

Dating of flowstone WGU gave an age of 178 ka (+17/ -15, corrected), whereas KH2 gave 87 (±3) ka, KH1 had 42 ka (±2, corrected), and KH3 had 41 ka (±7, corrected).
Petrography of KH27 indicated 36 % sandstone, 38 % limestone, 21 % crystalline rocks, 3 % reworked cave sediments, and 2 % other material.
The granulometry of KH25 indicates a well-sorted sand with 0.4 mm mean grainsize; whereas KH57 also indicates an extremely well-sorted fine sand, with a mean size of 0.1 mm.
Calcimetry of KH57 gave 3.3 % carbonate content, KH12, KH41 and KH44 contained 8 %, KH24 had 9 %, KH58 showed 19 %, whereas KH53 and KH56 had 27 % and 14 % respectively, and KH33 as well as KH60 contain an astonishing 33 %.
Clay mineralogy of the sample KH12 indicates 9 % Smectites, 14 % Chlorite, 68 % Illite, and 9 % Kaolinite, with Smectite/Illite mixed layers; KH24 and KH44 had 15 % Chlorite, 73 % Illite, 12 % Kaolinite, and also mixed layers. KH34 has 36 % Chlorite and 64 % Illite, KH52, KH58, and KH61 all show comparable values between 4-7 % Smectites, 18-21 % Chlorite, 58-62 % Illite, and 12-17 % Kaolinite, with some mixed layers. The pollen analysis of KH58 gave the following pollen: 1 Picea, 1 Pinus, 1 Pocaceae, 4 Asteraceae. KH42 contained 4 trilete spores and 5 Asteraceae.

Repeated sinter-silt-erosion successions are proof of an active history. The phreatic phase followed by a stream input of pebbles that are cemented again is not very unusual. The position of the room with respect to the downstream gallery is not clear enough to tell whether the floods were caused by obstructions or by a glacier. The thin silt layers below and between KH1 and KH2 are proof of a (probably short) flood and sinter deposition under “dry” conditions between. The next important silty/clayey layers (KH50-55) are most probably deposited during a glaciation. They are again eroded by a channel (E on Figure 6-9). This erosion is followed by a stable phase with sinter deposition (KH3, not visible on Figure 6-9), before the next succession of silty sands (KH44-42) is deposited: the silt indicates a blockage of the entrance by a glacier, while the relatively low carbonate content and the pollen infer a moderately cold climate. Two erosions with subsequent vadose deposition of sands (KH25) and gravel (KH27) follow, before the next cycle of flooding is marked by the silt succession KH41-36 which also fills the channel (KH57-61) and generally shows (with the exception of the sand KH57) a pleniglacial environment. Interestingly enough, in this succession a Picea pollen was found, indicating a climate comparable to today. However, the presence of one pollen makes no summer yet. Another very important erosional event as a result of the pre-existing connection to today’s Westgang river, empties the room almost to today’s aspect. Probably at the same time, gravel (KH63) was deposited and cemented by basin sinter (KH62). Another erosional event destroys most of this sinter. The remaining gravel was again cemented by basin sinter (KH64), before more recent waters underflew this sediment again, losing themselves in narrow obstructed passages.

Kegelbahn (WGK, Fig. 6-9)

The Kegelbahn profile is placed in an essentially phreatic gallery that has seen some vadose entrenchment before having been filled again with sediment. A varved silt layer precedes a thin sinter layer (WGK2), a varved silt (Fig. 6-11) again follows the next sinter layer (WGK1), which is capped by the last silt. The whole succession was then eroded by a vadose stream.

Dating gave 76 (±3) ka for WGK2, 39 ka (±3, corrected) for WGK3, and 10 (±8, corrected) ka for KE2 (not visible on Figure 6-9).

Knuchel (1963) made observations in other parts of the Kegelbahn gallery and found the following succession: A phreatic gallery underwent a vadose deposition of pebbles that later were cemented together by sinter. This sinter is overlain by the silt-sinter succession described above and the postdating erosion. Another sandy deposition at the bottom of the gallery is followed by sinter deposition. This sinter is then destroyed by floods that precede the last sinter generation (pool sinter, KE2). After the pools were emptied, dripstones grew in them.

Bärenschacht

Because of the perched nature of St. Beatus Cave, investigations of the three most recent phases has to be conducted in Bärenschacht. This huge cave presents only few interesting sediment profiles. In addition, the mapping of this cave is still underway. Therefore, only a few sinters have been sampled, whose position (see Figure 6-3) with respect to the cave genesis (see below) is clear. The dating of those sinters gave the following ages: For the phase 700, 129 ka (+7/-6, corrected) for Narquois, 125 (±4) ka for Hinterlistige, 130 (±5) ka for FSPII, and 12 (±3, corrected) ka for Empire. The only dating for Phase 760 gives an age of 157 ka (+12/-11, corrected) for Voûte céleste. These dates are important for the interpretation of the youngest phases, however, more detailed work in Bärenschacht is required.

6.3. Interpretation of the laboratory data

Reliability of the datings (Table 1)

The precision of the dates was greatly enhanced by the high U contents. However, especially in young samples, the content of detritic Th can reach high levels. This is mainly because flowstone (where clay from the river is deposited as well) was sampled instead of stalagmites. The reason for the sampling of flowstone is simple: a relative chronological order of the sediments is much easier or only possible with layered and not punctual sinters (this term will be used throughout the paper to denote a chemical precipitate of calcite, be it dripstone or flowstone). The problem of differential leaching of U (giving apparent ages older than real) when the sinter is flooded after deposition is a large potential source of error for dating, especially in this context where the oldest sinters have been chosen. To minimize this problem, sinter parts as far away from the surface as possible (by taking cores) and presenting no visible alteration fronts were taken for dating. The position of the sinters then give a relative chronology of deposition which must match the dates found (e.g. top younger than base). The Table 1 gives the samples, dates and errors (1sigma).

The reliability of the dates is important for the correct position of the chronologic table that is presented below and therefore for a correct interpretation of the paleoclimatic and -geographic information.

First, every dated sample was carefully inspected to detect hiatuses or corrosional features. All data within a defined stratigraphy match this chronology. This suggests that the data are reliable. In the following paragraph, some of the more difficult samples (Table 1, Fig. 6-13) are discussed.

The two samples BG25 and BG27 have a position (Fig. 6-5) that was first thought to be older (or at least contemporaneous) than the meandering canyon incision. However, the dates indicate that they are considerably younger. This is not in contradiction to the stratigraphy because of their lateral position with respect to the main sediment. In addition, the ages lie within a range often measured. Therefore, we postulate that these dates are also correct.

Fig. 6-12:
Coring in the river...

Kernbohrung im Fluss...

Carottage dans la rivière...

Photo by Peter Pfister

Results of the U/Th datings																	
UIB No	Name	Yield U	Yield Th	conc U	234/238	±	234/238	±	230/234	±	230/232	Age	+	-	Age, corr.	+	-
					U/U ratio		initial		Th/U ratio		Th/Th ratio	ka			for det. Th		
2354	HNG1	65.5	37.6	0.399	1.188	0.02	1.467	0.05	0.999	0.02	10000.00	325	50	35			
2449	HNG5	73.1	44	0.108	1.265	0.05	1.427	0.08	0.825	0.04	35.00	170	18	16	166	18	16
2355	HNG7	57.8	45.3	0.134	1.276	0.05	1.393	0.07	0.713	0.03	2.91	126	10	9	81	12	12
2356	HNG-SU	70.6	36.3	0.683	1.44	0.02	1.697	0.03	0.829	0.02	235.93	165	7	7			
2357	HNG-SO	67.1	37.4	0.317	1.316	0.02	1.441	0.03	0.693	0.02	195.77	120	6	5			
2364	MU5	61.8	36.8	0.439	1.51	0.03	2.06	0.07	0.998	0.03	397.00	262	25	21			
2409	BGO-JUNG	67.1	38.4	0.235	1.312	0.04	1.366	0.05	0.414	0.02	24.35	57	4	4	54	4	4
2466	BGO5	66.1	42	0.239	1.225	0.04	1.389	0.07	0.869	0.03	26.00	195	21	18	190	22	18
2392	BG20	51.2	21.6	0.47	1.225	0.02	1.373	0.04	0.845	0.02	6.54	182	13	12	161	14	13
2394	BG23 Top	79.2	31.4	1.232	1.244	0.01	1.471	0.03	0.932	0.02	180.05	236	15	13			
2395	BG23 Base	61.4	18.3	1.252	1.248	0.01	1.482	0.03	0.935	0.02	10000.00	238	19	16			
2407	BG27	69.1	37.2	0.441	1.266	0.03	1.343	0.04	0.581	0.02	15.51	91	5	5	85	5	5
2408	BG25	72.3	38.8	0.239	1.365	0.04	1.587	0.07	0.835	0.03	10000.00	170	14	13			
2448	PP2u	30.5	54.7	0.569	1.114	0.04	1.231	0.08	0.928	0.03	22.65	252	33	26	246	34	26
2396	FG1	50.4	41.4	0.193	1.164	0.06	(1.417)		1.14	0.06	6.14				.(376)		
2412	UAT	64.5	40.6	0.19	1.223	0.05	1.513	0.12	0.989	0.05	6.43	298	95	52	276	98	55
2413	KOH	55.7	36.3	0.222	1.19	0.04	(1.5705)		1.067	0.04	6.76				.(388)		
2411	HG1-M'bodn	62	19.9	0.184	1.533	0.06	1.628	0.07	0.428	0.03	1.90	58	5	5	16	9	9
2431	SPCryst	77.2	37.5	0.22	1.236	0.04	1.273	0.05	0.391	0.02	16.75	53	4	4	49	5	4
2432	STI	52.3	9.5	0.157	1.083	0.06	1.12	0.08	0.7179	0.08	1.74	134	35	27	32	54	50
2433	Ratsel2	25.3	31	0.163	1.426	0.09	1.48	0.1	0.331	0.02	1.61	43	4	4	4	8	8
2428	WGBoden1	56.8	32.3	0.165	2.012	0.06	2.113	0.07	0.277	0.01	1.93	34	2	2	9	3	3
2429	WGBoden5	61.6	40.3	0.177	1.439	0.05	1.47	0.06	0.205	0.01	4.03	25	2	2	16	3	3
2430	KE2	59.1	27.7	0.222	1.525	0.06	1.6	0.07	0.366	0.03	1.82	48	4	4	10	8	8
2358	EXC9	60.8	33.1	0.712	1.106	0.02	1.146	0.02	0.658	0.02	255.31	114	5	5			
2359	EXC1	57.1	22.6	1.923	0.937	0.01			1.114	0.03	1640.25						
2360	EXC2	55	27.6	2.571	0.912	0.01			1.06	0.03	1069.00						
2361	EXC3	60.2	26.9	1.051	1.091	0.01	1.133	0.02	0.721	0.02	10000.00	135	6	6			
2362	EXC4	73.2	33.9	0.712	1.145	0.01	1.191	0.02	0.606	0.01	412.33	99	3	3			
2363	EXC5	71	32.8	1.497	0.994	0.01	0.993	0.02	0.955	0.02	10000.00	337	52	35			
2365	WGU	37.6	34.7	0.341	1.325	0.04	1.557	0.07	0.878	0.03	8.48	193	16	14	178	17	15
2397	KH1	68.7	37.3	0.453	1.525	0.03	1.593	0.04	0.336	0.01	36.77	43	2	2	42	2	2
2378	KH2	66	33.5	1.934	1.292	0.01	1.372	0.02	0.565	0.01	248.74	87	3	3			
2406	KH3	71.6	43.7	0.186	1.259	0.04	1.323	0.05	0.529	0.02	2.56	79	5	5	41	7	7
2367	WGK2	64.2	38.5	0.571	1.281	0.02	1.347	0.03	0.515	0.01	757.67	76	3	3			
2368	WGK3	50.3	28.9	0.384	1.257	0.04	1.29	0.05	0.331	0.02	14.56	43	3	3	39	3	3
2379	BS-Narquois	64.3	36.9	1.107	1.046	0.02	1.068	0.02	0.719	0.02	16.89	136	6	6	129	7	6
2380	BS-Hinterl.	81.3	33	3.58	0.904	0.01	0.864	0.01	0.672	0.01	2329.80	125	4	4			
2381	BS-FSPII	80	30.4	5.047	0.907	0.01	0.866	0.01	0.687	0.01	464.22	130	5	5			
2390	BS-Voute	75.8	40.3	0.335	1.522	0.04	1.828	0.06	0.835	0.03	14.71	165	11	10	157	12	11
2391	BS-Empire	60.5	31.7	0.196	1.476	0.04	1.515	0.05	0.231	0.01	2.44	28	2	2	12	3	3

Table 1:
The table of the datings obtained in the Bergen Laboratory.

Die Tabelle der Datierungen aus dem Labor in Bergen.

La tabelle des datations du laboratoire de Bergen.

FG1, UAT, and KOH are all thought to be parts of the same very dirty flowstone that was sampled by coring. The only age obtained (UAT, 276 +98/-55 ka) has a large analytical error, and FG and KOH are older than the age limit. Therefore we conclude that the deposition of this sinter happened before 350 ka, which is also within the error of the date obtained.

The next series, HG-Mäanderboden up to KE2, represents young samples cored within the Tourist Part of St. Beatus Cave or at the bottom of the present meandering canyon (WGBoden, Mäanderboden, Figure 6-12). The latter must be very young because of their position; they are thought to have formed after the last glaciation. The ages are in accordance with this theory, but because they are also very dirty, the error is high, and no precise dating can be given. The same holds true for the Rätsel and KE2 sinters. The age of sinter SPCryst is acceptable, whereas STI is unusable.

In the series from Westgang (WGU to WGK3), WGU is relatively dirty, and a leaching of U is not excluded: the sample was not cored. The other samples all seem reliable, with the exception of KH3, that has a lot of

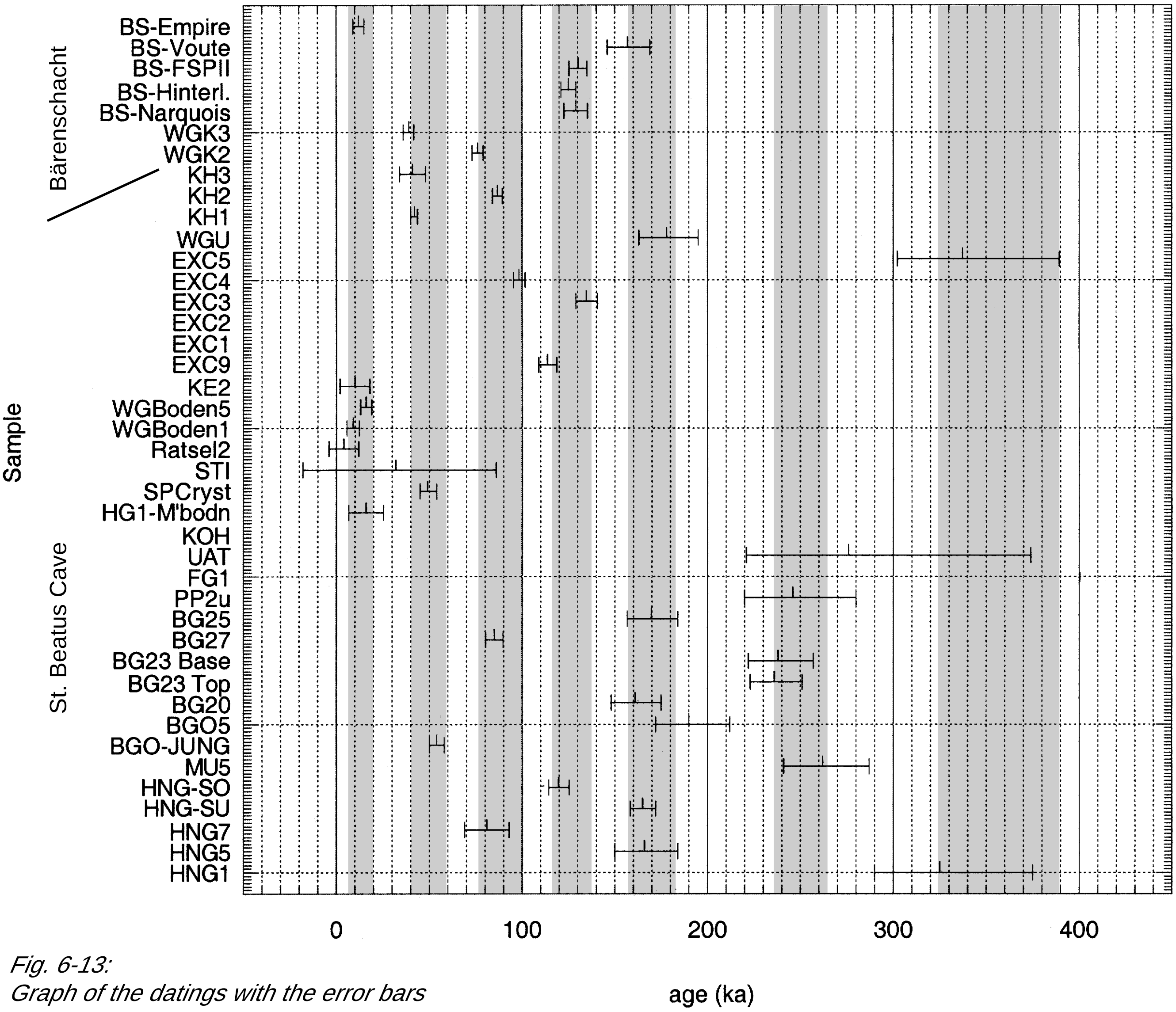


Fig. 6-13:
Graph of the datings with the error bars (1sigma). In grey the main growth periods.

Graph der Datierungen mit den Fehlerbalken (1sigma). Grau die hauptsächlichen Wachstumszeiten.

Graphique des datations avec les marges d'erreur (1sigma). En gris les principales périodes de croissance.

detritic Th and is therefore of only limited usefulness. Of the Bärenschacht samples, only the Empire has high detritic Th. In addition, it is quite a porous sample and therefore, the age obtained is only approximate.

Clay mineralogy (Table 2a)

Clay minerals have been found mostly in the silty-clayey deposits, however, some sands were washed and the residue analysed for clay minerals. The aspect of the sediments indicates that the clay minerals were probably deposited as residuum, because there is no direct evidence of neoformation.

Clay minerals are present in virtually every cave sediment. However, almost no analyses have been conducted; one of the only publications is Jeannin (1991). It is difficult to assess the extent to which clay mineralogy might clarify the climate prevailing during deposition. If we assume that the clay is insoluble residue of the limestone (or, in our case, of the Drusberg marl), there is no possible correlation. Otherwise, Pochon (1974) indicated that the smectites content could be related to the presence of soils at the surface (and that the Illite content should decrease). However, Deer, Howie & Zussman (1962) indicate that the genesis of clay minerals can also be related to chemical properties of the surrounding rocks and fluids, without direct influence of the climate: Illite would result from the weathering of acidic Al/K bearing rocks under alcaline conditions, whereas Kaolinite would form under acidic conditions. Smectites are interpreted as being a weathering product of mostly (but not necessarily) basic rocks with high Ca and Mg and low K content

Clay mineralogy, in %													
	MU2	**BG1**	**BG17**	**BG28**	**PP2-4**	**EXC6**	**KH12**	**KH24**	**KH34**	**KH44**	**KH52**	**KH58**	**KH61**
Smectites	8	0	0	6	0	0	9	0	0	0	4	7	5
Chlorite	8	17	14	15	18	13	14	15	36	15	21	19	18
Illite	78	68	75	69	68	78	68	73	64	75	58	62	62
Kaolinite	6	15	11	10	14	9	9	12	0	10	17	12	15
mixed layers	ML	(ML)			(ML)		ML	ML		ML	ML	ML	

Table 2a: Clay mineralogy / Tonmineralogie / Minéralogie des argiles

under alkaline conditions. Kaolinite is often mistaken as indicator for tropical (lateritic) weathering at the surface – which, in our case, is highly improbable.

Bolt (1982) indicates that the stability of the different clay minerals varies greatly as a function of the geochemical properties of the surrounding sediment and water. Therefore, the presence or absence of a clay mineral is only interpretable if the geochemical conditions in its surroundings are known. This information is supported by N. Waber (pers. comm.).

Kaolinite is present in every sample measured in ratios between 6 and 17 %. Almost all of the silts are interpreted as having been deposited in a glacial environment, which would exclude tropical weathering. Therefore we conclude that the presence of Kaolinite is either detrital or due to geochemical conditions rather than to a different climate.

Smectites are not present in every sample and range from 4 to 8 %, where present. All these samples are thought to have been deposited in a glacial or even pleniglacial context with no (or at least no important) soil present. Therefore, the formation of the Smectites more likely reflects the above mentioned geochemical conditions, and not climatic ones.

Pollen analysis

Of the five analysed samples, two were sterile, and of the other three samples, only BG15 had a pollen content that was satisfactory. These low pollen counts reflect the findings of Groner, who observed only few broken pollen in Hölloch cave (Groner 1990) and in Jochloch on Jungfraujoch (Groner, pers. comm.).

It seems that the interpreted glacial conditions during the deposition of the sediments already impede dense vegetation, and according to Groner (1990), the remaining pollen are mostly destroyed during their underground transport and deposition. We might therefore conclude that palynologic analyses in soft sediments in alpinotype caves do not usually provide much information. The only possibility for future studies may be to analyse pollen trapped within the sinters (Bastin 1990).

Petrography of the gravels (in %)						
	MU5	**BG1**	**BG5**	**BG12**	**PP2-1**	**KH27**
Sandstone	17	96	48	45	12	36
Limestone	72	0	31	36	59	38
Crystalline	7	0	10	5	23	21
rew. sediment	4	4	11	14	5	3
other	0	0	0	0	1	2
total	100	100	100	100	100	100

Table 2b: Gravel petrography

Gravel petrography (Table 2b)

The gravel petrography indicates the type of rocks that were washed into the cave. In our geological setting, we expect sandstone and limestone as main components of the gravels. They constitute between 71 and 96 % of the total pebbles. Crystalline rocks suggest that till material was washed inside the cave. Only BG1, which is a coarse red sand, contains no crystalline rocks. Because this sand contains almost no pebbles, this result may well be due to the limited quantity of material sampled. The reworking of cave sediment demonstrates that there were parts of the cave that had been destroyed by the river, therefore another

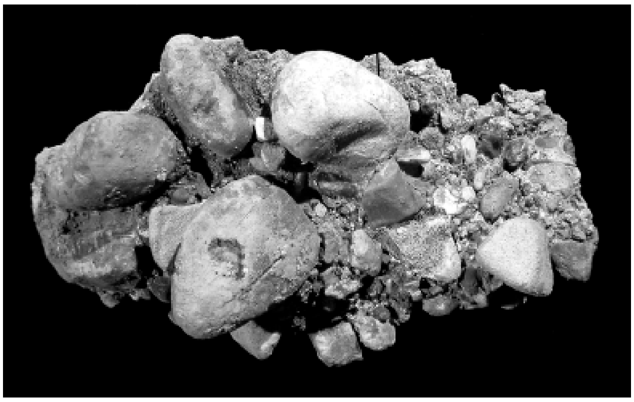


Fig. 6-14: Photo by Andreas Werthemann
The gravel MU5 before it was analysed.

Der Schotter MU5 vor der Analyse.

Les galets MU5 avant l'analyse.

Granulometry, weight %												
	MU2	**BG1**	**BG3**	**BG5**	**BG12**	**BG15**	**BG17**	**BG24**	**BG28**	**PP2-3**	**KH25**	**KH57**
Fraction												
-4	0.00	3.70	0.00	34.60	1.57	1.29	0.00	0.00	0.00	0.00	0.00	0.00
-2	0.06	1.11	0.06	7.34	2.01	2.19	0.00	1.09	0.00	0.41	0.38	0.07
-1.4	0.04	0.66	0.09	3.02	2.54	1.17	0.03	1.66	0.03	0.30	0.53	0.07
-1	0.14	1.20	0.49	4.26	7.41	2.10	0.05	11.24	0.05	1.10	3.57	0.06
-0.7	0.44	3.10	1.35	6.52	14.72	3.45	0.10	26.70	0.06	2.98	16.01	0.12
-0.5	0.76	9.58	1.48	7.25	16.19	2.88	0.15	25.70	0.11	3.56	22.60	0.15
-0.35	0.67	14.61	0.99	5.01	10.42	1.25	0.11	12.35	0.06	2.31	12.46	0.06
-0.25	0.65	16.85	1.23	4.90	10.07	1.65	0.21	7.52	0.08	2.40	8.77	0.36
-0.175	0.41	16.60	1.12	4.16	8.65	1.20	0.38	3.68	0.13	2.51	5.02	3.20
-0.125	1.92	13.78	1.67	4.30	8.64	2.35	1.48	2.53	0.88	3.97	4.87	28.60
-0.088	6.24	7.61	4.26	4.12	6.97	5.81	5.51	2.21	4.05	4.51	4.77	33.35
-0.063	13.14	3.73	15.88	2.91	4.59	7.64	14.89	1.25	11.07	5.94	4.99	19.89
-0.02	75.54	7.48	71.38	11.62	6.22	67.00	77.09	4.06	83.47	70.02	16.03	14.06
<0.002	3.08	7.86	8.20	16.58	5.38	-	-	11.93	5.17	14.01	12.65	9.89

Table 2c: Granulometry in wt% / Granulometrie in Gewichts% / Granulométrie en % du poids

sedimentologic phase has to precede the deposition of the pebbles. Generally, the petrography of the gravel matches our expectations (Fig. 6-14).

Granulometry (Table 2c)

The granulometry of a sediment indicates the velocity of the flow transporting the sediment, as well as the sedimentation mode. Sedimentation in a river usually results in the deposition of a well sorted sediment. In contrast, flood sedimentation on river sides often causes bimodal sorting. If the sediment is not sorted at all, it can be related to passive transportation (till) or to a debris flow.

The Hjulström diagram relates grain diameter to flow velocity. For example, a velocity of 10 cm/s causes silt to be eroded and sand to be transported, whereas gravel above 2 mm in size is deposited. A well sorted sediment therefore indicates deposition in a river with a given flow velocity. Since a cave passage represents a tube, the flow velocity in the phreatic state can be multiplied by the cross section of the passage to obtain a discharge, which is indicated above for some sediments. In most cases, the discharge is attributed to flood conditions.

Because most of the sediments are of silty and sandy type, and because the flow velocity depositing the silt fraction does not show large variations (Hjulström 1939), we concentrated on the analysis of the fraction from 0.064 to 4 mm in size. Generally, the granulometric curves presented in Fig. 6-15 are medium to well sorted and therefore reflect deposition within a river. The only exception is BG5 which is poorly sorted. We interpret this deposit to have formed during a large flood event that reworked much material upstream and deposited it without grading in its present location. This interpretation is supported by the channel-like form of deposit BG5, that was later eroded laterally.

Because the other sediments are medium to well sorted, they can be used to estimate flood velocity. The erosion of such sediments again allows an estimation of the velocity needed with the aid of the Hjulström diagram. Because of the specific channel / tube form of a cave passage, the flow velocity is directly

MU4	15
BG8	25
BG15	25
BG17	11
BG28	20
PP2-5	4
EXC6	27
EXC8	24
KH12	8
KH24	9
KH33	32
KH41	8
KH44	8
KH53	27
KH56	24
KH57	3.3
KH58	19
KH60	33

Table 2d:
Calcimetry of the samples, carbonate content in %.

Calcimetrie der Proben, Karbonatgehalt in %.

Calcimétrie des échantillons, contenu en carbonate en %.

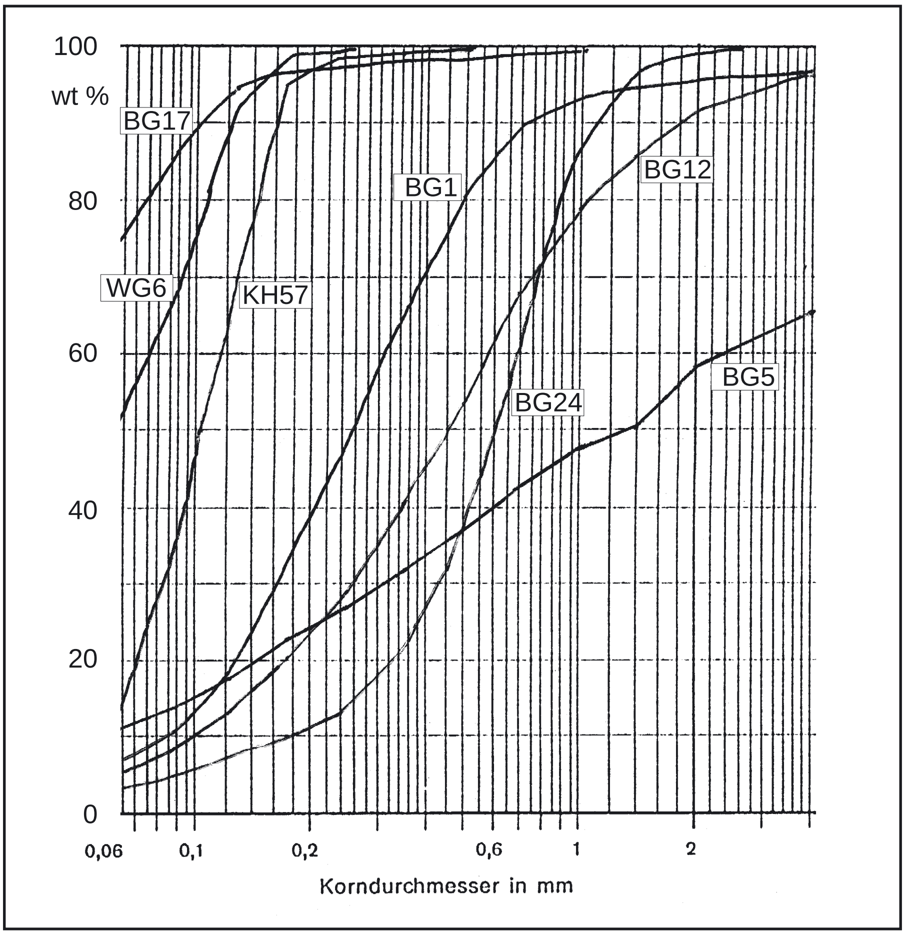


Fig. 6-15:
Some granulometric curves from sediments from St. Beatus Cave.

Einige Kornsummenkurven von Sedimenten aus der St. Beatus-Höhle.

Quelques courbes granulométriques de sédiments de la grotte de St. Béat.

connected to discharge: the sediment present or eroded gives an indication of the climate. For example, the gravel BG31 is thought to have been deposited after glaciation: the surface was free of retaining vegetation and scattered with cryoclasts and moraine material debris that was likely washed into the cave as the melting glaciers released huge amounts of water.

6.4. Link between speleogenesis and sediment profiles

The genesis of the caves is presented in Chapter 5. The Aare valley is thought to have controlled the position of the springs. As this is a glacial valley (Schlüchter 1995), it is assumed that the deepening of the valley is directly related to ice advances. Consequently, the speleogenetic phases should reflect the glaciomorphologic evolution of the Aare valley. There is evidence for six phases (see Fig. 6-3), that are labeled with the present-day altitude of the corresponding spring. Due to uplift processes, this altitude may not reflect the true altitude at the time of formation. The youngest phase, 558, is the present one (level of Lake Thun), additional phases are found at 660, 700, 760, 805, and 890 m a.s.l.

By combining the chronology of the sediments and the phase chronology, a relative chronological order is constructed (see for example Fig. 6-16). On this basis, the dating of some sinter can be undertaken. These dates (if interpreted correctly) put constraints on the relative timeframe. The final result is a chronological table (Table 3) that indicates both phase transitions (and therefore valley deepening), sedimentation and erosional events, coupled with the dates. Table 3 is explained in the figure caption. It is then used to indicate the timing of the valley deepening, and, in our inneralpine context, to date some of the glaciations.

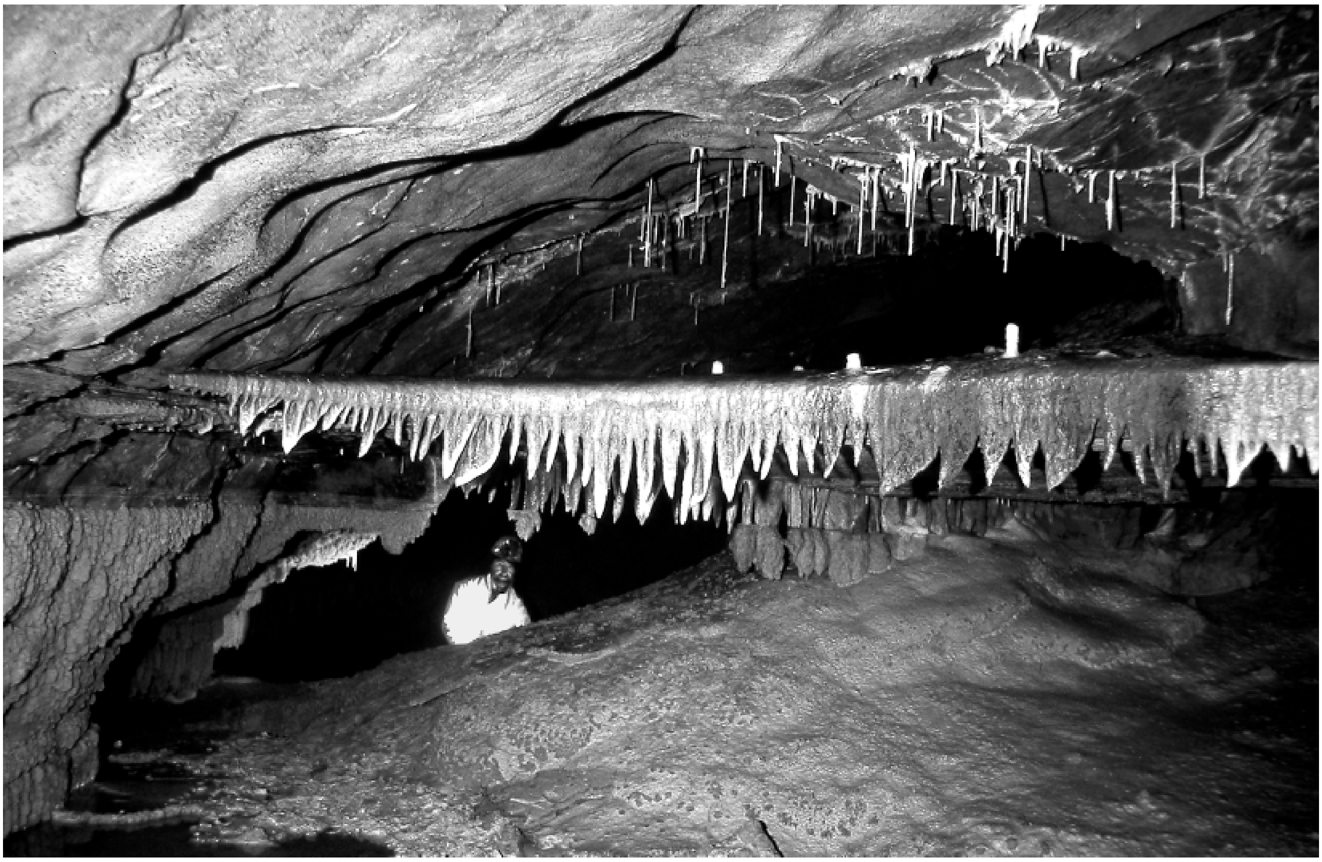


Fig. 6-16:
A phreatic gallery that was later filled with sediment which was covered by sinter. The sediment then was washed away and a lake formed before all got dry and the last sinter grows.

Ein phreatischer Gang wurde mit Sediment gefüllt, das mit Sinter überzogen wurde. Das Sediment wurde dann ausgewaschen, ein See bildete sich, bevor alles trockenfiel und die letzte Sintergeneration wächst.

Galerie phréatique ayant été remplie de sédiment, couvert à son tour de concrétions. Le sédiment a alors été lessivé et un lac s'est formé. Enfin le tout s'est asséché et la dernière génération de concrétionnement s'est formée.

Bärenschacht. Photo by Daniel Burkhalter

6.5. Interpreted chronology of valley deepening, climatic changes and glaciations

Here, the chronological Table 3 is used to get some information about the timing of valley deepening and the glaciations (see also Fig. 6-13 for datings). Table 3 is accurate in the respect that the observed sedimentological successions and the dates are in correct order. However, the insertion of an undated sediment may cause difficulties. They were solved by chronologically inserting those sediments in places where the other profiles have similar, but better defined, deposits.

Hoher Nordgang, Hoher Ostgang, and the top of the Excenter gallery were created during a phase above 890 m a.s.l, whose elevation is not yet definitively known. There are no sediments that can be attributed with certainty to this phase. The same holds true for phase 890.

While phase 805 was active and 890 was above the watertable, gravel was deposited by a fast-flowing river in Murgelegang. This river still had its exit in ??Cave (see Fig. 1-7 for location). After this fast-flowing river (which may indicate a deglaciation environment and a washing-in of the unconsolidated gravel remaining at the surface) waned and the climate became warmer,

sinter deposition began, placing dripstones EXC1 and 2 in the Excenter. These dripstones are all older than 350‘000 years.
As the next glaciation progressed and filled the Aare valley, the water level rose and deposited a layer of varved silt (EXC6) in Excenter. This glacier was also responsible for the deepening of the valley to 760 m a.s.l.

While phase 760 was active, gravel was deposited in the galleries belonging to phase 805, both in Kunsthalle/Kegelbahn and in Biwakgänge. After a climate warming, a thick sinter (FG, KOH) was deposited in the ellipse downstream of Biwakgänge. Both sinters are older than 350 ka. Another change in climate, probably towards a slightly wetter one than our climate today, induced a huge flow rate and therefore the re-erosion of both sinter and bedrock to a depth of about two meters. A following drier phase was responsible for the deposition of the dripstone BG23 that has an age of 237 ka.
A deterioration of climate then led to the deposition of a sand-gravel succession, that is truncated at least two times by other (eventually minor) erosions. This succession was responsible for the filling up of the tourist part of St. Beatus Cave with gravel; the exit of the cave was in Eibenhöhle at that time (Fig. 1-7). The sand is then capped by another varved silt deposit that indicates the onset of the next glaciation. This succession is also well visible in the profile PP2, where the sinter has an age of 246 ka.
The next dated dripstone found in Excenter has an age of 337 ka, and most probably can be connected to the warm climate that deposited the FG and KOH sinters described above. Also in Excenter, a varved silt layer marks the onset of the next glaciation, which was responsible for the deepening of the valley to 700 m.

During phase 700, most of the St. Beatus Cave was already under vadose conditions, due to the geological perching of this cave. Therefore, this phase is mainly visible in Bärenschacht (see Chapter 5). There, the sinter in Voûte céleste (157 ka) indicates the timing of the 700 phase. However, several sedimentation/ erosion events of St. Beatus Cave can also be attributed to this timespan. After the deglaciation and some erosion, a warm period was responsible for the deposition of sinter BG20 and BG25 in Biwakgänge (161-170 ka). It is probable that the same sinter was responsible for the cementation of the filled Tourist Part of St. Beatus Cave. An erosional event, followed by a deposition of varved silt, marks the onset of the next glaciation.
The oldest sinter in Kegelbahn and Kunsthalle has about the same age as sinter BG20 (178 ka). The following silt deposition is thought to be due to the next glaciation which also was responsible for the deepening of the valley to 660 m. This assumption is based on a “best fit”, with no direct evidence available in the field. However, a comparison of morphology and dating indicate that this change must have happened between 160 and 100 ka.

After the phase 660 began, and the glacier (which was responsible for the obstruction of the junction Walhalla-Eibenhöhle) receded, a huge erosional event emptied the tourist part of St. Beatus Cave (leaving behind large gravel accumulations with a size of more than 10 cm) and was also responsible for an erosion in Excenter. The next sinter deposition in Excenter has an age of 135 ka. This warm period is also visible in Bärenschacht, where three sinters between 125 and 135 ka in age were found, that may have been deposited during phase 660. This period was followed by a glacial advance that was likely of minor importance. The following warmer period deposited sinter EXC4 (99 ka) as well as many flowstones in Kunsthalle, Kanonenrohr and Hoher Nordgang (76-87 ka). The next varved silt deposition is attributed to another advance of a glacier, that was succeeded by a warmer period with new sinter deposition, mainly found in Kunsthalle and the tourist part (39-49 ka). The next varved silt deposition in Kunsthalle is huge (Fig. 6-17), but is truncated by several erosional events, and can possibly be correlated to the last pleniglacial. Another erosion and gravel deposition marks the beginning of today’s 558 phase. A sinter-erosion cycle is again followed by the last sinter deposition, visible at the bottom of the Hauptgang meandering canyon and behind Kunsthalle, taking place between 16 and 4 ka, that is currently being eroded away by the river. The last stage in the evolution of St. Beatus Cave, dated precisely, is the building of the tourist part in 1903.

6.6. Summary

In the following summary (compare Fig. 6-18), the climatologic and morphogenetic events are listed in chronological order. Because of gaps in the sediment records or morphologic data, some of the timespans indicated may vary. In brackets, we present the minimum and maximum ages for the event attributed to a given time. This chronology is almost exclusively based upon observations in Bärenschacht and St. Beatus Cave. The only information obtained from the surface is the deepening of the Aare valley to 530 m a.s.l. (Bodmer et al. 1973) and the deviation of the Kander in 1713.

1. deepening of the valley bottom to 890 m a.s.l., before 350 ka
2. deepening of the valley bottom to 805 m a.s.l., before 350 ka, probably due to a glaciation.
3. deposition of gravel at the end of the presumed glaciation

Table 3: Overview of the datings and events around Beatenberg

bold = morphologic event, *italic* = dated event

	Beatus Cave																Bärenschacht				Interpretation	
Text N	HWG	WGPost	EXC	KH	Kanonen	HNG	HMu	Block	BGoben	BGunten	FG	PP2	Walhalla	Dom	UBGr	ATvorn	Force	CdS	EM	Basis	Age	Interpretation
			>890Ø			**>890Ø**	**>890Ø**															**->890**
1	**890Ø**		**890Ø**					**890Ø**	**890Ø**								**890Ø**					**->805**
2																						
				805Ø	**805Ø**	**805v**	**805Øv**	**805v**	**805v**	**805Ø**	**805Ø**	**805Ø**	**805Ø**									
3							Geröll	Geröll														
4			*EXC1+2*					Sinter													*>350*	
5			Silt6																			**->760**
		805760v		**760v**	**760v**		**760v**		**760v**	**760v**	**760v**	**760v**	**760vØ**	**760Ø**	**760Ø**	**760Ø**		**760Ø**				
6				UGeröll	Geröll					Geröll	Geröll											
		Versturz																				
										G'sinter	*FG*		*KOH*UAT								*>350*	
7			*EXC5*			*Bodensi.*															*325-337*	
8								**Erosion**	**Erosion**	**Erosion**	**Erosion**	**Erosion**										
	Sa/Silt								Geröll	BG1-6												
9						Sinter	*Sinter*		Sinter	*BG23*		*PP2u*	*UAT*								*236-262*	
										BG24		Sand										
										BG22		Silt										
10										BG7-9 G		Geröll	Stopfg.	Geröll								
										BG11-13												
11			Silt7							BG15 Silt												**->700**
12									**Erosion**	**Erosion**												
13		Tropfs.		*WGU*	Sinter	*5/SchU*			*Sinter*	*BG20/25*		Sinter	Kroksi	Sinter				*Voute*			*157-190*	
									SiSand													**->660**
14																						
15		VersBlo					**Erosion!**		**Erosion**	**Erosion**			**EroSto!**	**EroVer!**	**Versturz**							
													Geröll	**Geröll**	**Geröll**							
16			*EXC3/9*			*SchO*								Sinter	Sinter	Sinter		*Hinter*	*Narquois*	*FSPII*	*114-135*	
17			Silt8	Silt	Silt					BG17		Silt										
			Erosion																			
18	*WGO1*		*EXC4*	*KH2*	*WGK2*	*SiEnde*				*BG27*											*76-99*	
19	SaSilt			Silt	Silt																	
	(Erosion)																					
				KH1					*Sinter*				*SPCr/StI*								*42-54*	
20				*KH3*	*WGK3*		Sinter														*39-41*	
				50-55			SiltSand															
				Erosion																		
	Silt		Silt	44-42-12			Silt					Mmlage										
				(Erosion)																		
				25/13																		
21																						
				Erosion						**Erosion**												
				27-1 Ger.																		
				Erosion																		
				41/18/15								Silt										
				22/19																		
		Silt		30-57																		
22				36-61-8	Silt				Aufstau	BG28			MnSilt									**->558**
				Erosion!	**Erosion!**								**Erosion**	**Erosion!**	**Erosion!**	**Erosion!**						
				Geröll																		
		Sinter		Sinter	Sinter																	
																Frostbruch						
				EroGer	**ZusSchub**																	
23				Sinter	*BodenBe*								*MäBod.*	Bachsi		Bachsi					*16*	
					Kegelb										Bachsi				*Empire*		*10-12*	
					BodenEn								*Rätsel*								*3-8*	
					BeStal																	
25													**Ausbau**	**Ausbau**	**Ausbau**	**Ausbau**					**1903 A.D.**	

Table 3: Overview of the datings and events around St. Beatus Cave and Bärenschacht. First the numbers correlating to the text, then from the right to the vertical line several profiles of St. Beatus Cave, then events in Bärenschacht, to the left the ages obtained and the phase interpretation. A ->700 means that at this time the phase 700 entered its activity and maintained it until the ->660 sign. Since caves usually develop from top to bottom, the "stratigraphic order" is reversed here. The ages are decay ages BP.
bold: *a morphological event (valley deepening, erosion), italic: dated sinter. Undated sinter has normal lettering. A Ø means that the gallery was in the phreatic zone after the valley deepening event, a v means that the gallery was in the vadose zone.*

Übersicht über die Datierungen und Ereignisse um St. Beatus-Höhle und Bärenschacht. Zuerst die Nummern, die im Text erwähnt werden, danach von links bis zur Linie einige Profile der St. Beatus-Höhlen, danach Ereignisse im Bärenschacht, zuletzt erhaltene Alter und Phaseninterpretationen. Ein ->700 heisst, dass zu dieser Zeit die Phase 700 aktiv wurde und bis zum ->660 auch blieb. Da Höhlen sich zumeist von oben nach unten entwickeln, ist die "stratigraphische Ordnung" umgekehrt. Die Alter sind Zerfallsjahre BP.
fett: *ein morphologisches Ereignis (Taleintiefung, Erosion), schräg: ein datierter Sinter (undatierte in Normalschrift) Ein Ø heisst, dass der Gang nach der Taleintiefung in der phreatischen Zone lag, ein v bedeutet in der vadosen Zone.*

Vue d'ensemble des datations et évenements dans les environs de la grotte de St. Béat et le Bärenschacht. Les nombres de la 1ère colonne se rapportent aux évènements présentés dans le texte, suivi de quelques profils de la grotte de St. Béat, puis des évènements dans le Bärenschacht, enfin des âges obtenus et l'interprétation de la phasologie. Un ->700 veut dire que la phase 700 commençait son activité et la maintenait jusqu'au signe ->660. Puisque les cavités se développent généralement du haut vers le bas, "l'ordre stratigraphique" est inversé. Les âges sont des âges de decomposition BP.
gras: *un évenement morphologique (approfondissement, érosion), en italique un concrétionnement daté. Un Ø signifie que la galerie se trouvait dans la zone phréatique après l'approfondissement, un v signifie qu'elle se situait dans la zone vadose.*

Fig. 6-17:
The huge silt succession in Kunsthalle. A bended unconformity line is visible in the upper left side.

Die mächtige Siltabfolge in der Kunsthalle. Eine gekrümmte Erosionslinie ist oben links sichtbar.

La succession puissante de limons dans la Kunsthalle. Une courbe d'érosion est visible dans la partie supérieure gauche.

Photo by Daniel Burkhalter

4. a warm period with sinter, before 350 ka
5. deepening of the valley bottom to 760 m a.s.l., before 350 ka, by a glacier.
6. deposition of gravel at the end of the glaciation
7. a warm period with sinter, between 390 and 325 ka
8. an erosion indicating a humid climate, between 325 and 260 ka.
9. a deposition of sinter between 260 and 236 ka
10. a succession of gravel and sands, indicating a progressively deteriorating climate, ending in a glaciation, between 236 and 180 ka. (max. 190 ka)
11. deepening of the valley bottom to 700 m a.s.l., between 236 and 180 ka.
12. an erosion at the end of this glacial cycle
13. the deposition of flowstone, between 180 (max. 190) and 157 ka
14. deepening of the valley bottom to 660 m a.s.l., between 157 and 135 ka
15. erosion of the tourist part of St. Beatus Cave, gravel deposition
16. deposition of flowstone, between 135 and 114 ka
17. the deposition of silt, indicating a glaciation, probably of minor importance, between 114 and 99 ka
18. deposition of Sinter, between 99 and 76 ka
19. silt deposition indicating another glaciation, between 76 and 54 ka.

20. sinter deposition between 54 and 39 ka
21. a next silt deposition attributed to the last pleniglacial, between 39 and 16 ka.
22. deepening of the valley bottom to 530 m a.s.l., between 39 and 16 ka (maximal age of this deepening 114 ka, minimal age 16 ka)
23. deposition of the most recent sinter, between 16 and 3 ka
24. successive filling of the Aare valley by Kander and Zulg gravel, levelling Lake Thun at 558 m a.s.l., between 16 ka and 1713 A.D.
25. building of the tourist part in St. Beatus Cave, in 1903/1904.

The ages indicated both above and in Fig. 6-18 are the measured values without taking the errors into consideration. This is due to the following: If we have a succession like that seen at Kegelbahn (WGK, Fig. 6-9), and if we agree that silt deposition is due to a glacier, then inevitably a glaciation must have occurred in between the two flowstone layers. If the errors are high and the datings overlap, the glaciation in between must still occur, and the ages cannot be the same despite the measurement. For this reason we thought it wiser to present the age “as is”.

6.7. Comparison with literature

In order to verify the temporal glacial succession presented above, a literature search was conducted. There is almost no comparable data from caves available in Switzerland, therefore we have to rely on data presented by quarternary geologists.

Schlüchter (1995) indicates the final collapse of ice occurred around 14 ka, which would correspond roughly with our youngest dates. Our dating of the preceding glaciation (isotopic stage 2) is around 16-39 ka. The finding of a brown bear in Melchsee-Frutt (Central Alps) at 1800 m a.s.l. that was dated to ~33 ka (Morel et al. 1997), indicates that around this time, the glacier limits were high up, in places corresponding to the present state. This implies that St. Beatus Cave would have been deglaciated at 33 ka, which is possible.

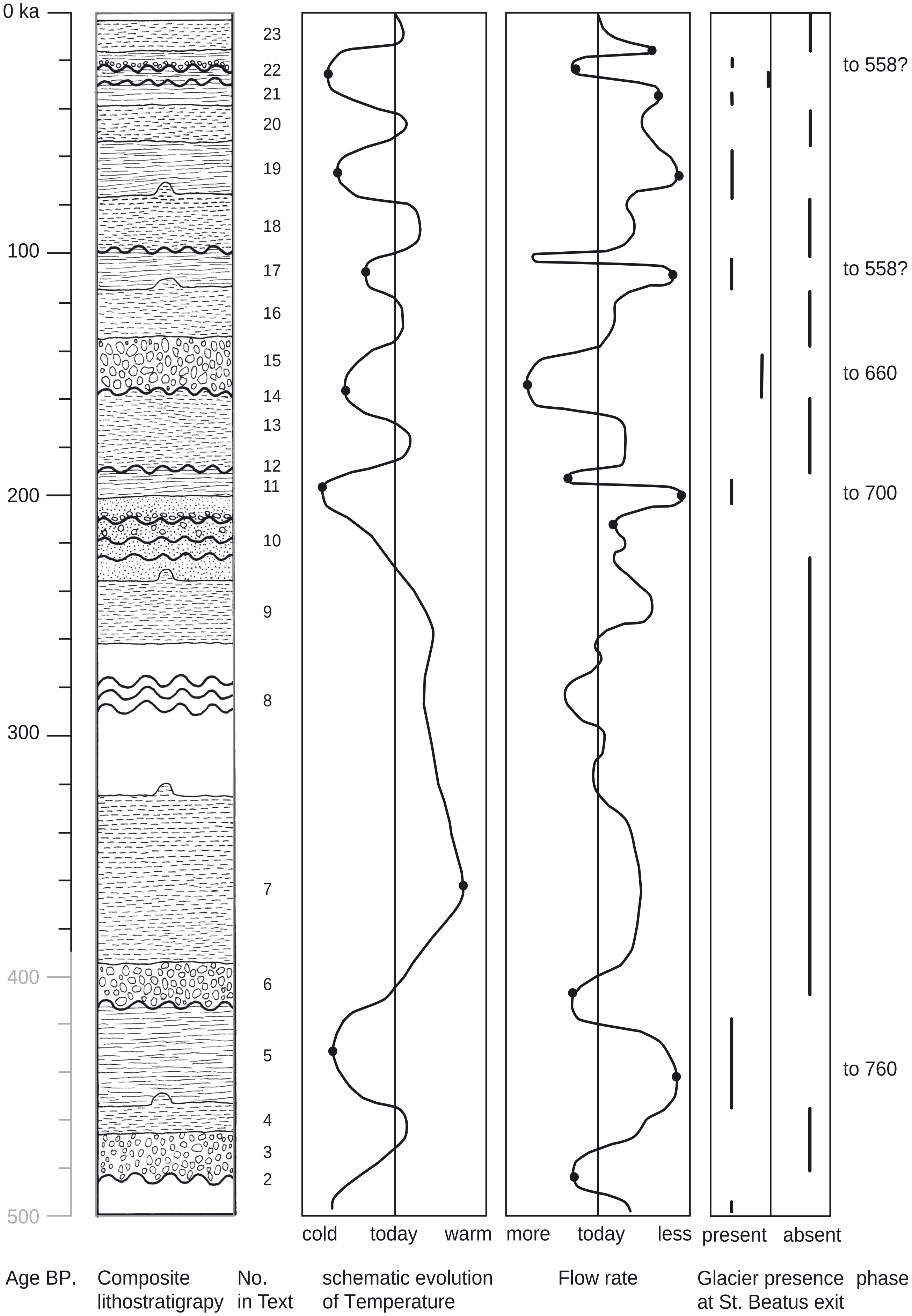
Schlüchter (1995) states that the alpine foreland was free of ice for a long time during the last glaciation cycle, at least between 28 and 60 ka. This would correspond with the sinter generation found in the Tourist Part of the St. Beatus Cave (39-54 ka). The preceding glacial advance is proven in the Swiss plateau and corresponds to isotopic stage 4.

The preceding warmer period found in the cave, around 76-99 ka, has almost no corresponding dates in the Swiss plateau (Schlüchter & Müller-Dick 1996). A single date at 86 ka would correspond to an interstadial (Wegmüller 1992). This interstadial is reflected in ocean cores (Bradley et al. 1985) and corresponds to isotopic stage 5a (Weichsel- or Würm-Glaciation). The preceding ice advance between 99 and 114 ka, would correspond to isotopic stage 5d and is currently under debate. Recent dating in the Gossau profile (Swiss plateau, Preusser 1999) strongly support the idea of an important glacial advance during stage 5d. The preceding warm period, around 114-135 ka, is also found in ocean cores (isotopic stage 5e) as well as in the plateau at Gondiswil (Wegmüller 1992), where the average of the dates obtained give an age of 115 ka (94-144 ka). These dates correspond well with the data from St. Beatus Cave and indicate the “Eemian” interglacial. The preceding, big glaciation, that is attributed to the “Riss”, has no timeframe (Schlüchter & Müller-Dick 1996), however, a summary of the quarternary deposits of Germany (Eissmann, unpublished), indicates the “Saale” glaciation between 125 and 150 ka. This is preceded by another warm period (Holstein), where no more dates are given. In our estimation, this ends around 180-190 ka. All the other glaciations found in the plateau have no direct age information.

Fig. 6-18 (right):
A suggestion for a reconstruction of the paleoclimate based on the sediments analysed. Dots indicate places of higher accuracy.

Ein Vorschlag einer Paläoklimarekonstruktion aufgund der analysierten Sedimente. Punkte zeigen Orte höherer Genauigkeit.

Proposition de reconstitution paléoclimatologique basée sur les sédiments analysés. Les points indiquent les événements définis avec une précision élevée.


0 ka
100
200
300
400
500
23
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21
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11
10
9
8
7
6
5
4
3
2
to 558?
to 558?
to 660
to 700
to 760
cold
today
warm
more
today
less
present
absent
Age BP.
Composite lithostratigrapy
No. in Text
schematic evolution of Temperature
Flow rate
Glacier presence at St. Beatus exit
phase

6.8. Conclusions

This chapter presents the first dating ever undertaken in the Siebenhengste region. This dating permits the construction of a chronology of valley deepening as well as of glaciations. We see this chapter as the conclusive syn-Thesis of all the work that has been described within this study.

We present evidence for at least six glacial advances that obstructed the exit of St. Beatus Cave and Bärenschacht. The timing of those advances was possible by dating flowstones that were deposited before and after the glacial cycles. We thus have dated, in a much more precise way, several old glacial advances that hitherto could not be dated in continental Switzerland. Glacial advances occurred at around: above 350 ka, 325-276 ka, 235-190 ka, 157-135 ka, 114-99 ka, 76-54 ka, and 39-16 ka.

For some years, caves have proven to be precious tools for the reconstruction of the paleoclimate by the analysis of stable isotopes from flowstone (Burns et al. 2001). Other geoscientific applications were often regarded as either not possible due to low resolution, or dangerous because of the openness of the cave system. The investigations presented above have shown that despite those true objections, caves have a great potential for both paleoclimatic and paleogeographic reconstructions that are no longer possible at the surface.
It is our wish that more studies are carried out in caves, in order to study their genesis and their sediments. We are sure that this comprehensive approach would extract much more information than the simple analysis of stable isotopes in some selected stalagmites, which of course remains a great source of information.

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The end of a cave life is illustrated with this picture. The roof of the cave is eroded away, and only stalagmites are left over.

Das Ende eines Höhlenlebens wird mit diesem Bild illustriert. Die Decke der Höhle ist wegerodiert, und nur noch Stalagmiten bleiben übrig.

La fin de vie d'une cavité est illustrée par cette photo. Le plafond de la grotte est érodé, et il n'y a que les stalagmites qui restent.

Brezstropa jama (Slovenija)

7. General conclusions

Zusammenfassung: Allgemeine Schlussfolgerung

Höhlenentstehung

Wir zeigen, dass in der heutigen epiphreatischen Zone die zeitweilige Hochwasserkorrosion über die ständige Niederwassererosion dominiert, was eine phreatische Morphologie innerhalb der epiphreatischen Zone ergibt. Der Übergang Mäander-Röhre geschieht im Dach dieser Zone, welche für die letzte Morphogenese zumindest in alpinen Höhlen verantwortlich ist. Die speläogenetischen Phasen sind in Zusammenhang mit der epiphreatischen Zone.

Soutirages entleeren die epiphreatische Zone während Niederwasser. Ihre Genese ist von der Existenz einer Hochwasserzone abhängig.

Der Übergang von einer speläogenetischen Phase zur nächsten geschieht verhältnismässig schnell; ein Gleichgewicht stellt sich jedoch sehr wahrscheinlich nur asymptotisch und nach einer sehr langen Zeit ein.

Rekonstruktion der Paläogeographie

Es wurden speläogenetische Phasen gefunden, deren Quelle wohl in Zusammenhang mit einem alten Talboden steht. Aus diesem Grunde sollten die speläogenetischen Phasen die Abfolge der Taleintiefung darstellen. Deren Höhen liegen bei 558, 660, 700, 760, 805 und 890 m ü.M. Die statistische Analyse von Kleinhöhlen bestätigt diese Phasen.

Morphologische und sedimentologische Befunde legen eine Entstehung der ältesten Gänge auf den Siebenhengsten zur Zeit der Molasseablagerung, also im Mio/Pliozän, nahe, bevor das Aaretal begann zu existieren.

Datierung der Phasen und paläoklimatische Informationen

Die Untersuchungen haben gezeigt, dass die Offenheit der Höhlen kaum ein Problem darstellt, da die Erosion zumeist Überreste der Sedimente verschont. Höhlenentstehung und Tropfsteinablagerung geschieht während Warmzeiten, während Eiszeiten die Speläogenese behindern und wegen des Wasserspiegelanstiegs gewarvte Silte ablagern.

Einige Sedimentprofile, zumeist aus der St. Beatus-Höhle, wurden untersucht. Die sedimentäre Abfolge erlaubt eine chronologische Rekonstruktion von Ereignissen, die dann mit den spelägenetischen Phasen kombiniert wird und so Angaben über die relative Abfolge der Profile untereinander sowie über die Alterszusammenhänge der Phasen liefert.

Die Datierung dieser Chronologie erlaubt sodann die zeitliche Einstufung der speläogenetischen Phasen sowie der Eisvorstösse und -rückzüge. Die Resultate zeigen sechs Eisvorstösse bei >350 ka, 235-180 ka, 157-135 ka, 114-99 ka, 76-54 ka und 39-16 ka.

Die Analyse der Höhle als Gesamtes ergibt einiges mehr an Paläoklimainformation her als die alleinige Analyse von stabilen Isotopen.

Stratigraphie und Tektonik

Der Versatz der Hohgant-Sundlauenen-Verwerfung HSV liegt bei 1 km. Die stratigraphischen Mächtigkeiten des Schrattenkalkes und der Hohgantserie erlauben, eine synsedimentäre Aktivität der HSV bereits ab der Unterkreide bis zum Eozän zu belegen. Eine komplexe Geschichte der Bruchaktivität und Sedimentation dieses Zeitalters wird nachgezeichnet. Die Waldegg ist eine Horst-Graben-Struktur.

Hydrogeologie

Karstwässer können auch innerhalb und quer zu undurchlässigen Schichten Höhlen bilden. Zusätzlich sind vadose Diffluenzen sehr häufig, und Transfluenzen sind nicht auf Gebiete mit undurchlässigen Schichten beschränkt. Auf diese Weise können „seltsame“ Resultate von Färbversuchen erklärt werden. Ein Färbversuch erlaubte die Abgrenzung der Einzugsgebiete der St. Beatus-Höhle von demjenigen der Siebenhengste. Eine Übersicht über alle je in der Region durchgeführten Färbversuche wurde erstellt und erlaubt einen Überblick über die hydrogeologischen Systeme nördlich von Interlaken.

Die vorliegende Arbeit belegt die Vielzahl von Informationen, die in Höhlen verborgen liegen. Höhlen sind geologische Archive, die Einblick in die tektonische Geschichte einer gesamten Gegend geben, über vergangene und aktuelle Wasserläufe Aufschluss geben, die geomorphologische Entwicklung einer Landschaft reflektieren, und die datierbare Sedimente und damit paläoklimatische Informationen über eine bislang unbekannte geologische Periode enthalten. Höhlen sind Juwelen des Untergrundes – nicht nur wegen ihrer Schönheit, sondern wegen ihrer simplen Existenz.

Résumé: Conclusion générale

Spéléogenèse

Dans la zone épiphréatique actuelle, la corrosion en temps de crue, bien que temporaire, prédomine sur l'érosion vadose pérenne, de telle sorte que les galeries de la zone épiphréatique ont une forme phréatique. La transition méandre-tube se fait au toit de cette zone, responsable de la dernière étape morphogénétique des cavités alpines. Les phases spéléogénétiques sont liées à la zone épiphréatique.

Des soutirages vidangent la zone épiphréatique en temps d'étiage. Leur genèse est intimement liée à l'existence d'une zone de battement.

La transition d'une phase à l'autre se fait assez rapidement. Par contre, l'équilibre n'est atteint qu'asymptotiquement et après un temps considérable.

Reconstitution de la paléogéographie

Nous avons trouvé des phases spéléogénétiques, dont la source correspond au niveau d'un ancien fond de vallée. Par conséquent, les phases spéléogénétiques pourraient indiquer l'approfondissement progressif de la vallée. Nous avons trouvé des phases à 558, 660, 700, 760, 805 et 890 m. L'analyse statistique des petites cavités confirme ces phases.

Des observations morphologiques et sédimentologiques attestent de la genèse des galeries les plus anciennes des Siebenhengste pendant le dernier dépôt de la molasse, soit au Mio/Pliocène, avant que n'apparaisse la vallée de l'Aare.

Datation des phases et informations paléoclimatiques

Les recherches ont démontré que le caractère ouvert des cavités ne pose généralement pas de problème, puisque l'érosion laisse toujours des traces de sédiment à l'intérieur de la cavité. La genèse des cavités et la formation des concrétions ont lieu pendant les périodes chaudes, tandis que les glaciations freinent la spéléogenèse et créent des dépôts de limons varvés, suite à l'ennoyement des galeries.

Plusieurs profils sédimentaires ont été étudiés, principalement dans la grotte de St. Béat. La succession sédimentaire permet une reconstitution chronologique des évènements, que l'on peut alors combiner avec les phases spéléogénétiques. On peut ainsi non seulement connaître la succession des profils dans le temps, mais aussi déterminer l'âge relatif de chaque phase spéléogénétique.

La datation de cette chronologie permet alors d'attribuer une période à chaque phase spéléogénétique, ainsi qu'aux diverses avancées et retraits glaciaires. Nos résultats indiquent six avancées, à >350 ka, 235-180 ka, 157-135 ka, 114-99 ka, 76-54 ka et 39-16 ka. Finalement, l'analyse de la grotte dans son ensemble fournit beaucoup plus d'informations paléoclimatiques que la seule étude des isotopes stables.

Stratigraphie et tectonique

Le rejet de la faille de Hohgant-Sundlauenen HSV est d'environ 1 km. L'épaisseur stratigraphique du Schrattenkalk et de la série du Hohgant attestent d'une activité synsédimentaire de la HSV dès le Crétacé inférieur jusqu'à l'Eocène. Nous esquissons l'histoire compliquée de l'activité tectonique et de la sédimentation durant cette période. La Waldegg est une structure en Horst et Graben.

Hydrogéologie

Nous expliquons que les circulations karstiques peuvent creuser des cavités à l'intérieur et à travers des formations imperméables. De plus, les diffluences vadoses sont très courantes, et les transfluences ne nécessitent pas une couche imperméable pour leur mise en place. On peut expliquer de la sorte certains résultats de traçage «étranges» ou inattendus.

Un essai de traçage a permis de différencier le bassin versant de la grotte de St. Béat de celui des Siebenhengste. Nous avons passé en revue tous les traçages effectués dans la région des Siebenhengste-Hohgant et proposons une synthèse des systèmes hydrogéologiques au nord d'Interlaken.

Cette thèse atteste de la multitude d'informations à tirer des cavités. Les grottes sont de fabuleuses archives géologiques: elles renferment l'histoire tectonique de toute une région et celle des circulations d'eau passées et présentes; elles reflètent l'évolution géomorphologique du paysage, et conservent des sédiments et des informations paléoclimatiques sur une époque géologique quasiment inconnue. En définitive, les grottes sont de véritables joyaux souterrains – non seulement grâce à leur beauté, mais surtout du simple fait de leur existence.

La présente étude aurait été irréalisable sans le travail de topographie souterraine effectué par des générations de spéléologues bénévoles.

7.1. Results

The final aim, a dated succession of valley deepening and glaciation cycles, was only attained after the completion of other work. Tectonic investigations (Chapter 2) reveal that the karstwater was never dammed by geologic structures. Observations within the St. Beatus Cave reveal the flow of waters in the vadose zone (Chapter 3.1), which then is used to explain some water tracings (Chapter 3.2). The results of the water tracing reveals that the catchment areas of St. Beatus Cave and Siebenhengste are separate, therefore the cave should develop independently. The importance of the epiphreatic zone (Chapter 4) is underlined and helps to identify the speleogenetic phases (Chapter 5). Those phases are the same in St. Beatus Cave and Bärenschacht, therefore the caves don't develop independently as suggested in Chapter 3.2. They have to have a link in the Aare valley where they drain to. Sedimentary successions (Chapter 6) then allow to schedule a chronological table that is dated by U/Th and allows to reach the final aim. The following lines summarise shortly the results obtained. The findings of general importance are followed by the ones of regional or only specific interest.

Speleogenesis

The northern part of Bärenschacht is undisturbed by inflows from the surface and therefore gives exceptional insight into the behaviour of a deep karst. We can show that in the present epiphreatic zone, temporal floodwater corrosion prevails over perennial low-water erosion, resulting in a phreatic morphology of the tubes within the epiphreatic zone. The transition meandering canyon-tube is easily visible and occurs at the top of this zone that is inclined between 1.3 to 2.1° (2.25 to 3.65 %). We conclude that the epiphreatic zone is responsible for the latest stage of tube morphogenesis in Alpine caves, whereas the initial formation of the tubes happens in the perennial phreatic zone. The speleogenetic phases are related to the epiphreatic zone.

Soutirages are small phreatic galleries that empty the epiphreatic zone in low water condition. Their genesis is intimately connected with the existence of a floodwater zone, therefore their presence in fossil tubes indicates a past epiphreatic morphogenesis.

The transition from one speleogenetic phase to another one happens rapidly; however, once the transition achieved, the system is still not in equilibrium. This equilibrium is most probably reached only asymptotically and needs considerable time.

Reconstruction of paleogeography

By following the tubes of phreatic morphology and the observation of meander-tube transitions, speleogenetic phases can be found. The spring responsible for their formation is thought to be related to an old valley bottom. Therefore, the speleogenetic phases should directly indicate the successive deepening of the valley. The levels found are at 558, 660, 700, 760, 805, and 890 m a.s.l.

The statistical analysis of small caves near the surface supports these phases. Therefore, such phase reconstruction should also be possible in karst regions where no big cave systems have been found.

Morphological and sedimentological findings allow ideas about the age and evolution of the Siebenhengste karst system and its surroundings to be formed. We suggest the genesis of the oldest conduits at Siebenhengste are contemporaneous with the last Molasse deposition in Mio/Pliocene, before the Aare valley came into existence.

Phase dating and paleoclimatic information

Information about the glaciations is obtained only with difficulty in the Alpine valleys, since the last glaciation destroyed most older traces. The paleoclimatic meaning of glaciation-deglaciation cycles, however, is much more important in the Alps than in the Foreland. Investigations in St. Beatus Cave and Bärenschacht have shown that the fact that caves are open systems usually doesn't negate their usefulness, because erosion always leaves some sedimentary traces within the cave.

It is shown that cave genesis and speleothem deposition occurs during warm periods, whereas glaciations stop speleogenesis and deposit varved silts due to the waterlevel rise.

Several sediment profiles are investigated, most of them within St. Beatus Cave. The sedimentary succession allows a chronological reconstruction of events. The location of the sediment profiles within the speleogenetic phases gives indications about the relative timing of each profile with respect to the other. Moreover, it informs about the timing of the speleogenetic phase: a comprehensive relative chronology can be made.

This chronology then allows dating of both the speleogenetic phases and glacial advances and retreats. The results are as follows:

Age in ka	event	valley deepening phases
>350	glaciation	deepening to 760 m
>350-235	warm period	
235-180	glaciation	deepening to 700 m
180-157	warm period	
157-135	glaciation	deepening to 660 m
135-114	warm period	
114-99	glaciation	
99-76	warm period	
76-54	glaciation	
54-39	warm period	
39-16	glaciation	deepening to 530 m
16-today	warm period	

It is shown that the analysis of a cave as a whole gives much more paleoclimatic information than the analysis of stable isotopes alone. It is our wish that more such studies be undertaken.

Stratigraphy and tectonics

The throw of the Hohgant-Sundlauenen fault HSV could be determined by observations in Bärenschacht. It measures around 1 km. Moreover, the different stratigraphic thicknesses of the Schrattenkalk and Hohgant series allowed a demonstration of synsedimentary activity of the HSV from the Lower Cretaceous up to the Eocene. Breccias in the upthrusted side of the Bärenkluft permitted us to retrace a complicated history of faulting activity and sedimentation. Together with observations of Upper Cretaceous rocks at the surface, a schematic evolution of the Waldegg Horst-Graben structure could be drawn.
Furthermore, the investigations in Bärenschacht gave insight into the present buildup of the Waldegg. The relationship with the mapped fractures at the surface could be established.

Hydrogeology

It could be shown that the karst waters can not only generate caves across and within “impermeable” formations, but furthermore, vadose diffluences are very common, and transfluences don’t necessarily require an impermeable layer to form. All these examples are found in St. Beatus Cave, which is proposed as a hydrogeological model at scale 1:1. Virtually all “strange” results of water tracings now can be explained. However, the determination of the real cause might still be tricky.

A tracing experiment permitted us to delineate the catchment areas of St. Beatus Cave and Siebenhengste. A zone with local karst within the Hohgant series lying between the two catchments finally has its outflow to the surface. The entrance of Bärenschacht lies within the catchment of St. Beatus Cave. A review of all tracing experiments performed in the Siebenhengste-Hohgant area was made, and this gave an overview of the hydrogeologic systems north of Interlaken. Hohgant and Harder are proven to be connected in high floods.

Speleology

The observation that only some of the bedding planes are preferred for speleogenesis can be used in the search for new caves. Particularly, the intersections of “speleoinception” bedding planes with the old valley floors are very interesting places to look for caves: the Eibenhöhle for example is exactly at such an intersection.

7.2. Open questions

A modelling study to quantify the time needed until a cave system reaches equilibrium would be an exciting, but difficult task. Nevertheless, such studies help towards a better understanding of speleogenetic processes.

Geochemical work aimed at clarifying the neoformation, decomposition, and alteration of clay and associated minerals is a very interesting task. Such a study could use – and be of use for the understanding of – the possible paleoclimatic information the clay minerals contain. A link with pedologists would be very interesting.

The way is open for the continuation of speleochronological work with sediment profiles and their datings. Since the U/Th method is out of range even for the exact determination of the phase 760, another method has to be found. We hope that the analysis of cosmogenic isotopes fulfils the expectations and that in the future, we will be able to date the whole Siebenhengste system, in order to get a complete chronology of a timespan largely unknown to geologists and geomorphologists.

The tectonic buildup between Bärenschacht and Faustloch is unclear, since no conduits have been found yet. Only thorough speleological exploration may reveal the hidden faults. The structure of the Habkern syncline, which has been proven to be permeable for karst water, remains the big mystery. When will cavers be able to follow the waterways between Schrattenfluh, Hohgant and Harder?

The delimitation of a small catchment area SW of the St. Beatus catchment is yet unknown. Since no prospection has been undertaken in this area (as is the case for most of the Siebenhengste region outside of the karren fields), there is still much preliminary work to be done. It is not known if the whole Schrattenfluh connects to Bätterich; a tracing experiment is planned.

The connection of the speleogenetic phases recognised in Bärenschacht with the ones presumed in Faustloch is fundamental to the understanding of the Siebenhengste karst evolution. The opening of the obstructed gallery in Faustloch should permit us to tackle the questions which will allow the connection of the whole system.

7.3. Finale

The present thesis shows the multitude of information that is hidden in caves. Caves are geological archives that give insight into the tectonic evolution of a whole region, inform about past and present waterways, reveal the geomorphical evolution of a landscape, and contain datable sediments and therefore paleoclimatic information about a hitherto unknown geological period.
Especially these last factors make caves the jewels of the underground – not only because of their beauty, but also by their simple existence.

The present study was made possible by the volunteer mapping efforts of generations of speleologists. I am in awe of the volume of their work, and wish them to be recognised by the academic world as valuable contributors to “real science”. I think cavers should be regarded as a section of the Federal Office of Topograpy – hidden in the beauty of the underground world.

Photo by Fabian Bels

Appendix: Description of phase transitions

This Appendix describes the phase transitions observed in St. Beatus Cave, Bärenschacht, and Faustloch in a better detail. With the help of the figures, the places should be recognisable, if the desire to visit the places arises. Since the detailed maps are not published and continue to evolve, we decided to not show them. However, they are available upon request from the author or another responsible HRH caver (http://www.sghbern.ch/hrh.html).

Phase 558 is easiest to observe, since it is the present phase. The type locality of this phase is in the Glücksschacht region of Bärenschacht. There, a labyrinth of initially phreatic galleries was occupied in some parts by a river that created a meandering canyon. This canyon (1.5 m deep and 20 cm wide) disappears just in the area where the epiphreatic zone begins. The present small river (currently coming down from a vadose chimney) also disappears in phreatic tubes. A longitudinal section is presented in Fig. 4-4 (p. 102).

Phase 660 has its type-locality in the Guggershürliabstieg in Faustloch (see Fig. 5-9, p.124). There, a big, active meandering canyon (at least 4 m high, 1 m wide) loses its river in very narrow passages that are impossible to follow, the main volume of the meander continues as a phreatic, slightly undulating passage along a fracture, before dropping down into a shaft of phreatic origin.
The other locality in Faustloch is not distinct. The Puits Très Echelles has a meandriform shape, but continues as a clearly phreatic gallery (half filled with sediments) downwards. The change in of morphology is at the exact altitude, but no thorough morphological analysis has been conducted so far.
A very recently discovered gallery in Bärenschacht supports this phase as well.

Phase 700 has its type-locality in the “Ecoulements symétriques interconnectés” of Bärenschacht (Fig. 5-6, p. 120). A huge passage (8*1.5 m) of clearly vadose (but complicated) origin has a slightly smaller outflow that gradually turns into a clearly phreatic passage.
The other locality in “Empire du Milieu” consists of a small (1*1 m) keyhole passage with an even smaller meander (30*10cm), extending very horizontally, before encountering a fracture, and continuing downwards along this fracture as a fully phreatic shaft.

Phase 760 has its type-locality at the end of the tourist part of St. Beatus Cave (Fig. 5-6). The active main meander, with a size of 8”1.5 m, divides into two passages wich get a phreatic morphology, the upper within the tourist part (Hexenkessel-Walhalla), the lower just below. We assume that the meander was already vadose when the St. Beatus exit was still in Eibenhöhle (Fig. 1-7 for location, p. 24).
The transition in Bärenschacht, at “Voûte céleste”, is very clear, but small: a huge phreatic gallery (3*3 m) shows a partially obstructed small (1 m*30 cm) meander that disappears just below the transition zone. The meander length is not more than 10 m.

Phase 805 has its locality in the Biwakgänge of St. Beatus Cave (Fig. 5-6, p. 120). A meander (3*1.5 m) continues straight as phreatic tube, the transition being just at the 1954 campsite (longitudinal section at the right end of Fig. 1-23). The currently active waterway is a soutirage belonging to the phase 805. The galleries below are phreatic for a moderately short distance, before they join the top tube.
The other transition in Lehmgänge of St. Beatus Cave is discrete. A meander (3*1.5 m) divides into a meandriform smaller gallery (2*1 m) and a phreatic passage which shows some clay deposits. The continuation of the gallery after joining again shows clearly a bigger phreatic tube than before.

The phase 890 has, until now, no type-locality, because the indications are not very clear up to now. In Bärenschacht, all the big passages found in “Force tranquille” are below this phase. In St. Beatus Cave, the lower Hohe Nordgang (below the Murgelergang, HNG in Fig. 5-6) is thought to have been created mostly during this phase, as well as the lower Ostgang. However, with the exception of a corrosion notch in the Upper Excenter, clear indications are missing yet.

Curriculum vitae

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1978-1986	8 years primary and secondary school, Bern
1986-1990	4 years high school Kirchenfeld, Bern
1990	Matura, Type B (languages)
1991-1997	studies of Mineralogy and Geology, University of Bern (see list attached)
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Languages:

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Jobs:

1990-1991	Employee at Information Center of the Town of Berne, for software installation and troubleshooting
1992-1995	Responsible for the entries of the Mineralogic-Petrographic Institute (MPI) of Berne University into the geochemical database "Terdat".
1994-1997	Assistant (~15 %) at MPI Uni Bern, mainly for practical courses for undergraduates
1994-2001	Assistant (25 %) of the Earth Sciences Departement of Natural History Museum Bern. Jobs: care taking of the collection, updating the database, determination of Minerals, Microprobe work, sample treatment for geochemistry.
1997-1998	Assistant (25-50 %) at the Geologic Institute Uni Bern, for fluid inclusion studies on diagenetic cements, as well as assistance for practical courses.
1998-2002	Assistant at University of Fribourg (PhD student)

Research (done):

- Diploma (1994-1997): "Zur Geologie des Val Vergeletto (TI)":
  Observation and interpretation of the tectonic situation
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  estimations about pressure and temperature of the eoalpine metamorphosis (Microprobe analysis and thermobarometric calculations)
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- Hydrogeology (1996): Organisation and execution of a tracing experiment in the region St. Beatus Cave-Gemmenalp (Bernese Oberland) to delineate the catchment of St. Beatus Cave.