Glacier advances during the last 400 ka as evidenced in St. Beatus Caves (BE, Switzerland)

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Abstract

While stalagmites within caves are commonly used to obtain information about past climate change, little attention has so far been given to the cave, its morphology, and many other types of deposits contained in it. The discontinuous nature of cave sediments and the possibility that caves are re-shaped by more recent water circulations has discouraged many researchers, despite the fact that it is just this intimate relationship between the cave and surface conditions that makes caves such valuable archives. This article presents a method of determining a relative chronology which can then be dated numerically. Information from St. Beatus Cave and other nearby caves provides evidence of glacial advances that occurred within the following time windows: >350, 235–180, 160–135, 114–99, 76–54, and 30–16 ka. It also describes the following dated periods of valley deepening: 805–760 m a.s.l. (>350 ka), 760–700 m a.s.l. (235–180 ka), 700–660 m a.s.l. (160–135 ka), and 660–560 m a.s.l. (30–16 ka). These dates are new for this part of the Alpine Arc.

1. Introduction

Caves are well known as recorders of environmental change. ∂18O variations within speleothems (Burns et al., 2001; Spötl et al., 2002) are now widely used to reconstruct climatic changes that can also be directly dated. However, normal karstic caves are also intimately linked to landscape evolution, especially valley deepening and subsequent spring lowering (Ford and Williams, 2007). They are also linked to climatic changes in a much wider way than only by speleothems: water forming the cave is derived from rainwater or meltwater, glaciers damming the spring cause sediment deposition within the caves (Bini et al., 1998), and the vegetative cover also influences the sediment deposition mode (Audra, 1994, 2001).

The speed at which a valley is deepened by glaciers remains poorly understood. It has been suggested from both short-term sediment budgets (Hallet et al., 1996) and

long-term regional exhumation rates from thermochronology (Farley et al., 2001; Shuster et al., 2005) that glacial erosion can outpace fluvial erosion. However, it remains debated whether the growth of glacial valleys occurs quickly or gradually, because, until recently, there has been no long-term record of glacial valley incision. Caves may be useful in interpreting phases of valley deepening as well as the deepening rate in terrains that are either unglaciated (Stock et al., 2005) or glaciated (Häuselmann et al., 2007).

Such information is particularly useful in areas where the surface record is absent due to erosion. This is the case in most mountain belts, where net erosion almost always prevails over accumulation (Kühni and Pfiffner, 2001; Schlunegger and Hinderer, 2003), and where repeated glacial advances effectively obliterated older accumulations (Beck, 1954; Schlüchter, 2004). Therefore, most of the current knowledge of glaciations in the Alpine Belt in central Europe has been obtained from river terraces and gravel pits in the foreland (Preusser, 1999).

In the Alps, a glaciation is defined as a glacial advance beyond the Alpine front into the foreland (Schlüchter, 2004). Therefore, the rim of the Alps is a crucial area for

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distinguishing glacial from non-glacial conditions. In Switzerland, this rim mostly consists of karstifiable limestone, and thus there are many caves that might record geomorphic changes and thus improve our understanding of Alpine glaciation.

This article presents evidence for climatic change obtained from St. Beatus Cave and neighboring Bärenschacht, near Lake Thun, Switzerland. In the first section, we present a general model of cave formation, sediment deposition, and their relationship. Then we describe the different stages of cave genesis of St. Beatus Cave and the sedimentary profiles observed. Finally, with the aid of U/Th dating, we construct a composite profile that is used to retrace climatic variations and phases of valley deepening over the past 400 ka.

2. Setting

The region of Siebenhengste is situated north of Lake Thun, adjacent to the Molasse basin (Fig. 1). The mountain chain forms a southeast-dipping slope, dissected in the northwest into steep cliffs. The upper parts, between 1700 and 2000 m a.s.l., are largely free of soil and are composed of limestone pavement. At lower altitudes, firs grow on swampy ground. The annual precipitation is 1500–2000 mm.

The St. Beatus Cave represents the outlet for a small catchment area located to the southwest of the Siebenhengste. It is perched above today's base level and consists mainly of inclined keyhole passages that form a dendritic pattern. The Bärenschacht (Funcken et al., 2001) represents the downstream part of the Siebenhengste catchment area. It is characterized by a huge three-dimensional labyrinth of galleries with elliptical cross sections.

Both caves are located on the northern rim of the Swiss Alps, in the Helvetic nappes. At this location, the altitude of the Last Glacial Maximum (LGM) was around 1400 m a.s.l. (Schlüchter, 2004), so both caves were below the glacier surface. Today, the glacier has retreated about 50 km from the caves (Fig. 1).

2.1. Geology

In the Helvetic nappe, the following strata are of interest: On top of the Kieselkalk (siliceous limestone) lie the impermeable Drusberg marls, 40–50 m thick, which normally form the bottom of the karstic system. Above this is the 150–200 m thick Schrattenkalk, in which most of the caves are located. It is the main karstic aquifer. The Kieselkalk to Schrattenkalk sequence was deposited during the Lower Cretaceous. The overlying Hohgant series is of Eocene (Tertiary) age. It consists of a complicated sequence of alternating quartzitic and calcareous sandstones. Its thickness ranges up to 200 m.

The general structural setting is simple: a monoclinal slope, dipping to the southeast at about 15–30°, which is interrupted by a large longitudinal normal fault, extending from Lake Thun to the Northeast (Hohgant-Sundlauenen fault HSV). Vertical displacement along the fault is around 200 m in the Hohgant region, increasing to about 1000 m in Sundlauenen. The HSV divides the catchment area of the two caves Bärenschacht and St. Beatus Cave. This means that the two caves developed independently from each other, and the only thing they have in common is their spring area in the Aare valley. Any speleogenetic phase visible in both caves therefore has to have its origin in the Aare valley. This serves as further proof that the speleogenetic phases are not due to tectonic or local blockage of the water, but to the elevation of the spring.

3. Methods

3.1. A general model of cave genesis

This section briefly presents a model of cave genesis. Details are beyond the scope of this paper, a comprehensive review is given in Klimchouk et al. (2000). Water flowing onto limestone corrodes and erodes the rock. Driven by gravity and guided by geological structure, it flows down the steepest available fractures, until it reaches either the karst water table or impermeable strata (Ford and Williams, 2007). 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 its gallery. Therefore, with time, a meandering canyon is created. Water flowing within the saturated (phreatic) zone can corrode a passage over its entire cross-section, so that a tubular conduit forms. The morphologies that are preserved once the water courses have been abandoned give information about the prevailing position of the top of the phreatic zone during the genesis of the galleries. The transition of vadose canyons into phreatic tubes gives an absolute indication of the karst floodwater level which usually is inclined at 1–2° (Häuselmann et al., 2003). This level is usually in perfect accordance with the top of the undulating phreatic tube (Fig. 2) and indicates a lengthy phase of cave formation at rather stable base level (Palmer, 1987). The phase is related to its respective spring (Audra, 1994), which—as a general rule—is at or close to the valley bottom. A sequence of phases indicates a deepening of the spring elevation and therefore a downcutting of the valley. Morphological studies indicate that many caves are formed in discrete phases that reflect valley lowering in time (Klimchouk et al., 2000).

In this context it is important to note that "valley bottom" means the level of the stream. If a valley is overdeepened by glaciers, forming a lake, the level of the lake (and not the rock floor below) controls the corresponding speleogenetic phase.

Caves are a product of limestone dissolution. To dissolve limestone, there has to be enough water and acidic
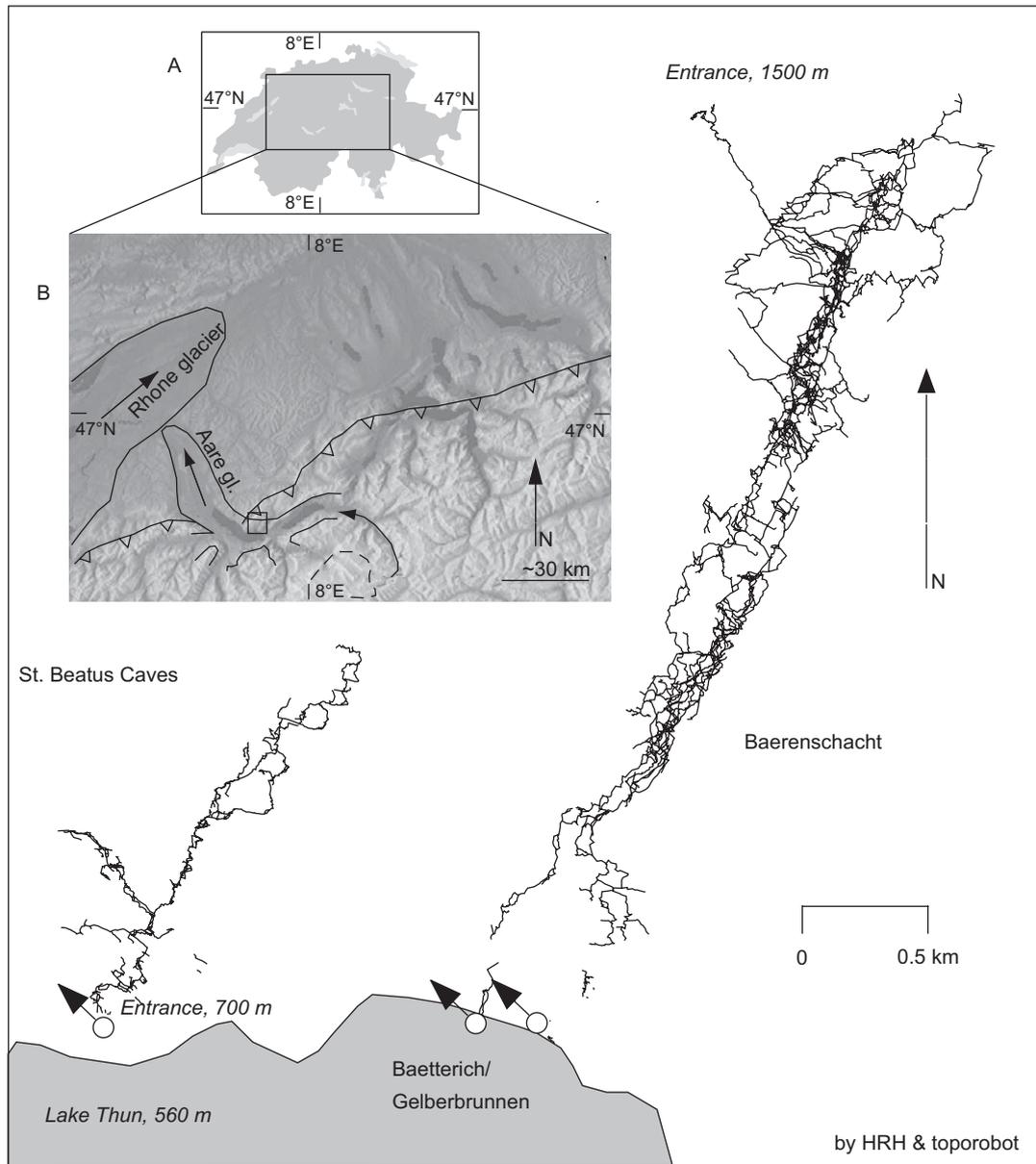
Fig. 1. Overview of the cave area north of Lake Thun. Inset A shows Switzerland. Inset B shows a DEM of west-central Switzerland. The cave area is indicated by the small rectangle. Last Glacial Maximum glacier extents are shown, with arrows indicating glacier flow direction. Dashed line shows area of today's glaciers. Bold line with tooth-marks: Alpine thrust front. © Atlas of Switzerland 2004 (modified), by permission.

substances, usually CO_2 (e.g. Dreybrodt and Gabrovsek, 2000). CO_2 is more soluble in cold water (Bögli, 1978), and therefore one might expect higher CO_2 concentrations in cold climate and an enhanced speleogenesis. However, a more important source of CO_2 is soil present at the surface (Bögli, 1978). Soil and the plants growing on it are the most important source for CO_2 and thus for enhanced solubility of carbonate rocks (Ford and Williams, 2007). Especially respiring green plants, but also (to a lesser extent) soil bacteria, fungi, etc. thrive much better in a moderate to warm climate. A warm climate is therefore producing more CO_2, thus enhancing speleogenesis much more than a cold climate (Audra et al., 2006).

3.2. A general model of sediment deposition in caves

When CO_2-saturated water reaches an air-filled cave, calcite is precipitated and speleothems grow (Maire, 1990). 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, so that the formerly air-filled caves are drowned and the older galleries reactivated (Bini et al., 1998). In cold climate, much of the precipitation falls as snow, so 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 ("rock flour"), then the corrosion
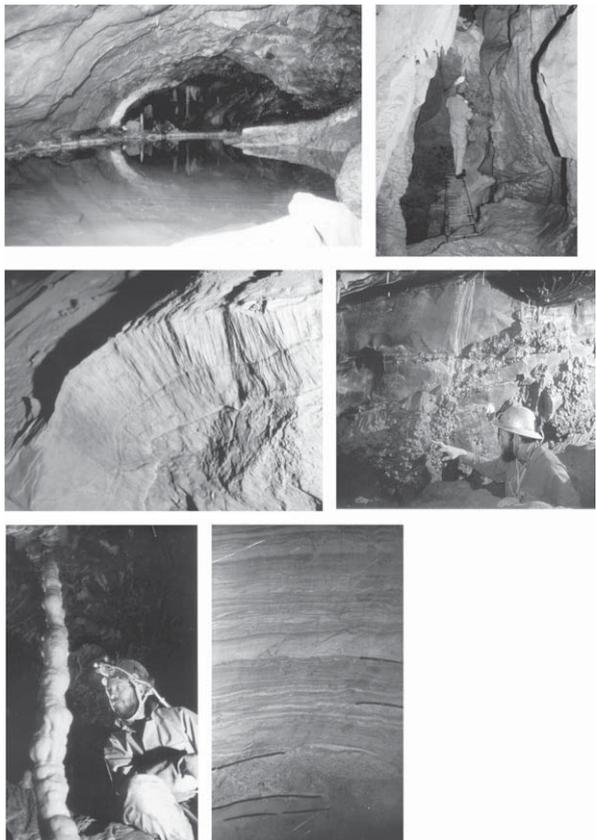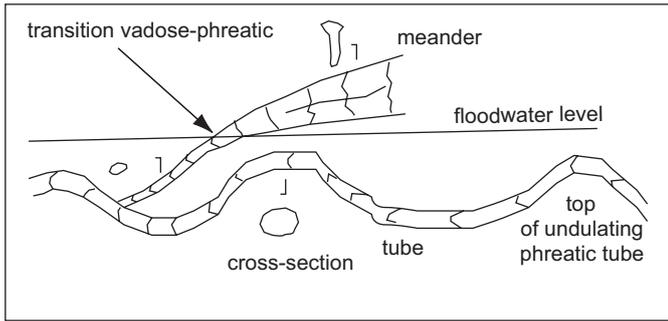
Fig. 2. Above: Recognition of vadose vs. phreatic speleogenesis, showing a longitudinal section and cross sections. Tubes with rounded cross sections indicate an origin under former saturated or epiphreatic conditions, whereas meandering canyons indicate a vadose origin. Transitions (arrow) indicate absolute height of the floodwater level at the time of phase formation. Pictures below: Rounded tube, formed below the water table (upper left); canyon from free-flowing water (upper right); flowstone deposit (middle left, shown in cross section in broken face); fluviatile pebbles cemented to the wall (middle right); stalagmite (lower left); laminated silts (lower right).

of cave walls is not possible, since the waters are already saturated. So, a glaciation is most likely to stop cave growth and to deposit calcareous, laminated silt (Fig. 2) throughout the water-filled part of the cave (Schroeder and Ford, 1983). Glaciers also incise the adjacent valley and thus prepare the initiation of another speleogenetic phase (see above).

As a general rule, it can be postulated that moderate to warm climate is responsible for speleogenesis and pre-cipitation of speleothems. Glaciations stop cave growth and deposit silt that can be very extensive.

Detrital sediments can be deposited in phreatic conditions. In contrast, most speleothems can only grow in the vadose parts of a cave, because CO_2 has to escape into the cave air. Underwater pool deposits are rare and easily recognizable by their morphology. This is of great importance for the correlation of sediment depositions in cave phases, since the first appearance of vadose speleothems must indicate that the passage was empty of water during their formation (Audra, 2001).

Flowstones, which may sometimes be followed over more than 1 km, are more useful for sediment correlations than stalagmites, which grow in discrete locations. However, flowstones commonly contain higher amounts of clay, and are therefore more difficult to date than stalagmites. Another sediment that can be used universally are carbonate silts derived from glacier erosion of the limestone surface. It is a good marker because the flooding by a glacier affects all of the passages in the cave that were present at that time.

Stock et al. (2005) present a model of sediment deposition in caves, implying that the coarsest sediment would be deposited during speleogenesis and immediately after. This stage is followed by flood deposits of clay and silt, and finally by a stage of speleothem deposition. While this scenario is quite logical for unglaciated landscapes, in glaciated areas the water flow and the abundance of sediment that can be washed into caves varies greatly with climate. In a full glaciation, the spring of the cave in the valley is blocked by ice, so laminated silts are deposited. After retreat, in a periglacial climate, the scarcity of plants, the frost shattering, and the remains of glacial action produce much debris. This can be washed into caves by glacial meltwaters and be deposited as pebbles. We therefore postulate that the presence of *laminated silts* is most probably linked to glacial damming, *pebbles* to periglacial climate, and *vadose speleothems* to warm phases.

3.3. Relation between cave morphology and sediment deposition

In the present study, sediments of several basically independent sedimentary profiles can be linked together and to the morphological succession of the cave passages. Thus, the sedimentary profiles are revealed to be no longer independent of each other, and a relative chronology of erosional and depositional events over the whole cave can be made. The detailed method is described elsewhere (Häuselmann 2007); only the main points are reviewed here.

An example from the St. Beatus Caves is presented in Fig. 3. Shown at the right side is a typical keyhole passage which indicates that a phreatic initiation of the ellipse on top was followed by a canyon incision. In the middle part of the figure, the canyon gradually disappears and is replaced by a passage with elliptic cross section that
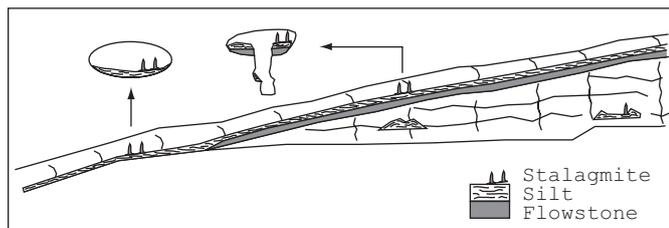
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Fig. 3. Schematic view of the link between morphology and sediment deposition. For explanation see text. Its chronology is presented below:

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Phreatic genesis of upper tube
------------------                            Water level lowering
Deposition of flowstone
Erosion of flowstone
Erosion of canyon
------------------                            Water level lowering
Silt deposition
Stalagmite growth
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descends toward the left side of the figure. We see therefore a transition from a vadose feature to a phreatic one, and thus the former position of a relatively stable water table. In the profile to the right, we observe flowstone deposited in the initial tubular passage, truncated by stream incision in the canyon. Therefore, the flowstone predates the canyon but postdates the genesis of the tubular passage. The canyon changes into an elliptical tube, and thus the two forms are contemporaneous. As expected, the older flowstone disappears in the area of this transition. Within all the passages, silts were deposited. They are younger than the canyon incision, and younger than the passage to the left, and indicate a glacially initiated inundation of the whole cave. Stalagmites grow on the silts and some are still active.

Dating of the stalagmites above the silts then gives a minimum age of the inundation, while dating of the flowstone gives the minimum age since the upper passage was abandoned by its water. They also give a maximum age for the glacial inundation.

Coupling of these morphological features with the sediment profiles thus gives a relative chronology of events that can be dated and correlated with changes in the environment outside of the cave. This relationship is summarized in a correlative chronological table (see legend of Fig. 3).

3.4. Methods of sediment analysis

The collected samples were analyzed with the following methods:

- Calcimetry (coulometric procedure) to obtain the carbonate content of the silty deposits (expressed in % $CaCO_3$).
- Clay mineralogy (separation of the fraction $<2\,\mu m$ in Atterberg cylinders, and X-raying of dried, glycolated

and ignited (550 °C) samples) to obtain data about the contemporary climate. However, Deer et al. (1962) as well as Bolt (1982) indicate that the stability of clay minerals varies greatly with geochemical properties of the surrounding sediment and water. Therefore, the clay mineral analysis was not taken further.
- Pollen analysis to gain insight into the vegetation above the cave at the time the sediment was deposited, therefore giving information about the prevailing climate.
- U/Th dating has been done at the University of Bergen (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 were followed by an age calculation using the program 4U2U of S.E. Lauritzen.

Sampling for U/Th dating was mostly done on flowstones, since most of them are extensive and allow correlation with other deposits. To obtain ages for the speleogenetic phases, old and eroded flowstones were also sampled. This creates a potential problem, because U is soluble in water, and eroded/flooded flowstones may experience substantial U losses (e.g. Geyh, 1990; Wildberger et al., 1991), yielding ages older than the real ones. Therefore, we used a core driller for sampling, and sampled as far as possible beyond the erosional rims, thus minimizing the danger of diffusive U losses. Another control on reliability of the ages is that the dates have to be in a consistent stratigraphic order, for example, the tops of stalagmites have to be younger than their bases.

Before any dating attempt, each sample was carefully inspected for recrystallization, hiatuses, and dirt layers, to eliminate samples that appeared to be altered.

4. Morphological evidence of speleogenetic phases in St. Beatus Cave and Bärenschacht

Here the two caves are treated together, since the former water levels responsible for their development affected both caves simultaneously. Fig. 4 shows a projected section of the caves that indicates the investigated sedimentary profiles and sites.

The lowermost phase at 560 m a.s.l. is the presently active one, with the spring level at Lake Thun. The next higher (older) phase (660 m) is not clearly represented within Bärenschacht, but its existence is implied by a relatively large number of entrances at this level, as well as morphological indications in nearby Faustloch (Häuselmann, 2002). Owing to possible uplift processes, this and all the other given altitudes may not reflect the true altitude at the time of formation.

The 700 m phase is defined by two canyon-to-ellipse transitions within Bärenschacht, one being above FSPII, and the other above Empire (Fig. 4). Both transitions are morphologically very distinct.
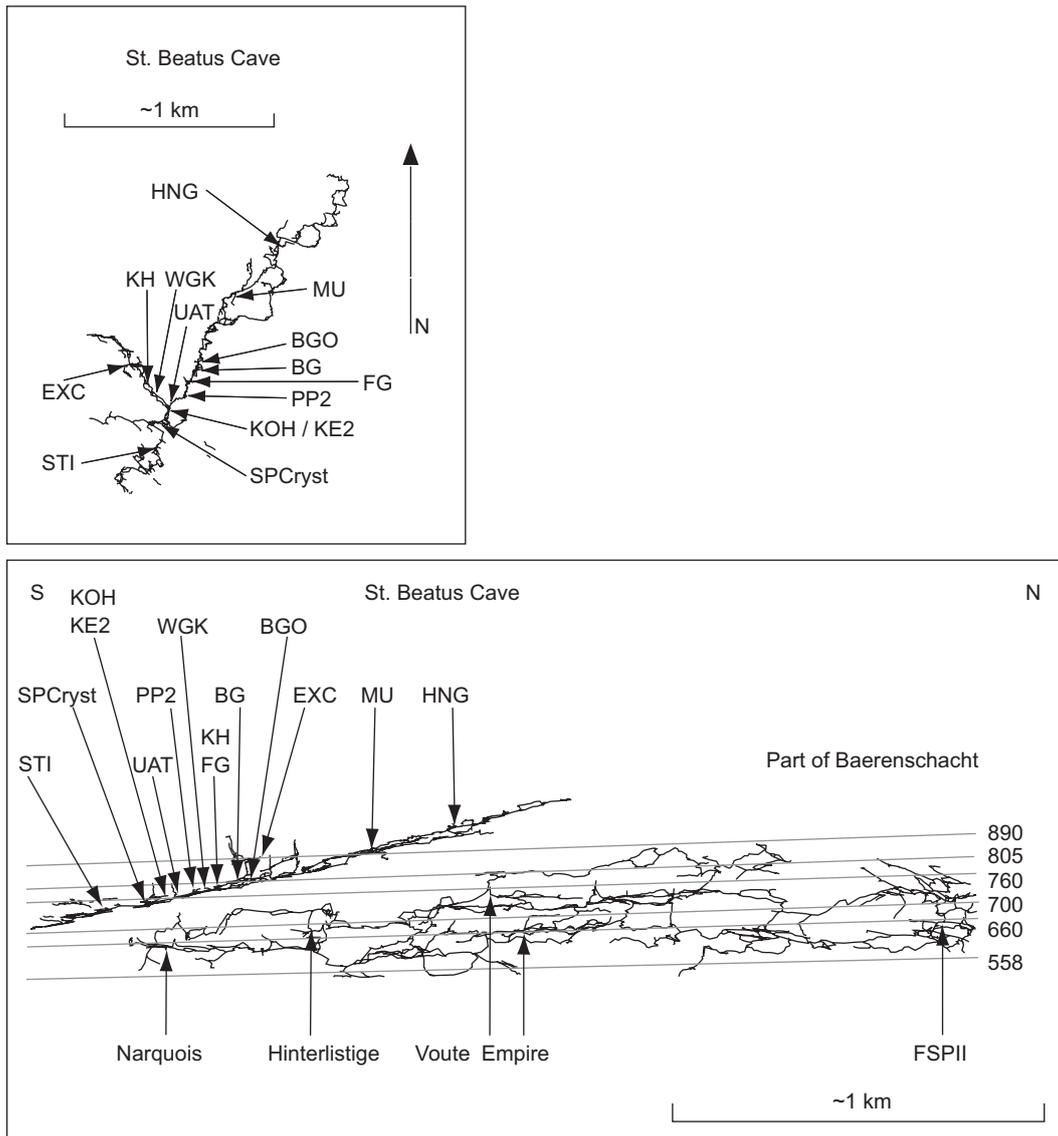
Fig. 4. Plan of St. Beatus Cave and N-S projection of St. Beatus Cave and the southern part of Bärenschacht. The sample sites are indicated, as well as the speleogenetic phases.

Despite the uninterrupted descending character of St. Beatus Cave, clear indications for speleogenetic phases are also apparent there. At the end of the tourist part (UAT), the phreatic tube changes into a keyhole passage (illustrated in Fig. 3). The disappearance of a very small vadose canyon is also visible at Bärenschacht at the same altitude (Voûte), giving an indication that there was a regional karst water table at the altitude of 760 m a.s.l., inclined at 1–2°.

The fourth phase (805 m) is found near BG (Fig. 4). A canyon changes downstream into phreatic tubes. Because the phreatic tubes are small, we hypothesize that the phase lasted for only a short time. In Bärenschacht, no corresponding evidence has been found.

The highest (oldest) phase at 890 m in St. Beatus Cave is visible near MU, where a large phreatic tube leaves the keyhole-shaped main passage towards an unknown spring. There are no known corresponding transitions in Bärenschacht, since the entire cave is lower than this phase. However, the existence of phreatic passages extending up to the expected altitude of phase 890 m gives a minimum height of this phase.

5. Description and morphological interpretation of the sediment profiles

Here we chose to present two representative sites out of 10 that can serve as example. For their locations see Fig. 4. A detailed description of all sites is given in Häuselmann (2002).

5.1. Excenter (EXC, Fig. 5)

One of the most significant sediment successions is found in the Upper Excenter, where a gallery is almost completely filled with laminated silts and stalagmites.

After the initial phreatic genesis of the cave, at phase 890, a first generation of stalagmitic deposit formed (EXC1 and 2), after that the water level dropped at least to phase 805. A later flooding of the gallery deposited silt, after which the gallery drained and another generation of stalagmite (EXC5) was deposited. This cycle was repeated three times. The position of the Excenter profile (along a horizontal passage that represents the top of a phreatic loop) indicates that flooding by ceiling collapse or sediment deposition in other parts of the gallery is very improbable. Therefore, it is assumed that the flooding of the galleries, responsible for deposition of the silts, was caused by glacial blockage of the entrance.

5.2. Lower part of Biwakgänge (BG, Fig. 5)

The Biwakgänge consists of a keyhole passage, whose lower part is mostly filled with sediment that was exposed in profile by a trench dug by P. Pfister in 1973. A stalagmite grows on the floor (BG23). Younger red sand (BG1) is overlain by complexly interbedded sands, silts, and pebbly sands (BG1–BG9). The sequence is overlain by fine sand (BG11–BG13), which in turn is succeeded by laminated silt (BG15 and 17) partially interbedded with coarse sand (BG14) and a flowstone (BG20). The sequence is rimmed by other flowstone deposits (BG25). On the shoulder of the keyhole cross section, a flowstone (BG27) is overlain by layered silt (BG28).

The interpretation of this profile is as follows: An initial phreatic genesis of a tubular passage during phase 805 m was soon followed by deposition of gravel (BG31), which is not visible within the profile. The gravel was presumably deposited under vadose conditions. The following flowstone deposit preceded an important erosional event that excavated the lower part of the passage. This erosion must have taken place during phase 760 m. Because other meandering canyons postdate this incision, but are contemporaneous with phase 760, it is possible that BG23 was deposited during the development of phase 760. Then followed deposition of the gravel–sand layers (BG1–6, BG24, BG7–13) that reflect vadose conditions and a free-flowing small stream. A quite distinct change was the flooding of the gallery, which caused the silt deposition BG15-17, which was contemporaneous with the sands BG14, which subsided by gravity from the keyhole shoulder in phreatic conditions. The position of this gallery shows that this flooding was probably caused by a glacial blocking of the spring. During a break in silt deposition, flowstones BG20, BG25, and BG27 were deposited before a last (small) erosion occurred.

6. Correlation of events

The speleogenetic phases presented in Section 4, and the sediment succession presented in Section 5, are summarized in Table 1. The vertical axis shows the relative age, and the
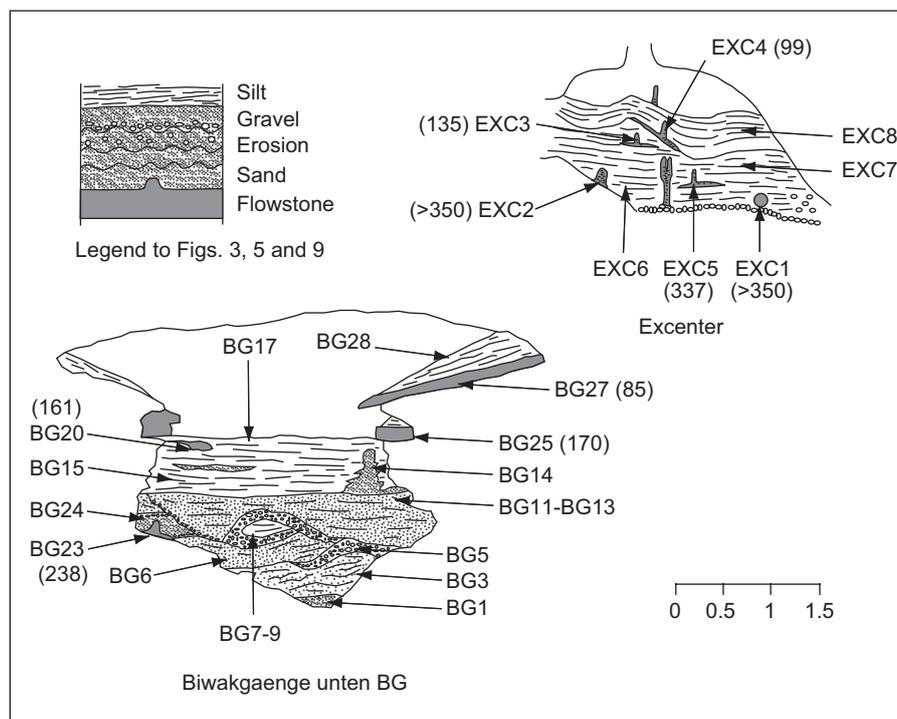

Fig. 5. Sediment profiles of Excenter and Biwakgänge unten. The numbers in brackets indicate measured ages. The profile legend is inserted.

Table 1

Excerpt of the relative chronological table of St. Beatus Cave *prior to the age* determinations presented in this paper

EXC	BGunten
890 ∅	
805 ∅	
Speleothem	
Silt6	
	760 ∅
	Pebble
Speleothem	Speleothem
Silt7	Pebble
Speleothem	Speleothem
Silt8	
Erosion	**Erosion**
	Sand
Speleothem	Speleothem (Stal.)
	Sand
	Silt22
	Sand
	Sand
	Silt
	Erosion
	Speleothem
	Erosion
	Silt
	Speleothem
	Silt

Morphological events are given in bold font. ∅ indicates a phreatic event. The table in that stage is correlated only tentatively by linking the silts and speleothems together and by assuming that a first silt occurrence marks the glaciation deepening to the next lower valley floor.

various sediment profiles are displayed horizontally. This relative chronology is based on the following principles:

- Each period of sediment deposition is assumed to be younger than the origin of the conduit in which the sediments were deposited.
- General flooding events linked to glaciers are assumed to affect all conduits simultaneously.

Table 1 summarizes the relative chronology. Absolute dating of representative flowstones then verifies the chronology. The stratigraphic (and morphologic) succession controls the precision of the dating results. Dating plus stratigraphy together validate the chronological table, and they allow the events to be placed in their correct timeframe. The completed table gives information about the timing of the glaciations and valley deepenings that happened outside the cave.

7. Results and interpretation of the sediment investigations

7.1. U/Th dating

Table 2 reflects the sample age, dates and errors, which are given to ± 1 sigma. The precision of the dates was greatly enhanced by a high U content in most samples. However, especially in young samples, the content of detrital Th can reach high levels. This is mainly because flowstone (where clay from the river is deposited as well) was sampled instead of stalagmites.

Some of the more difficult sample analyses (Fig. 4) are discussed here:

The two samples BG25 and BG27 have a position (Fig. 5) that was first thought to be older than (or at least contemporaneous with) the meandering canyon incision. However, the dates indicate that they are considerably younger. This does not contradict the stratigraphy because of their lateral position with respect to the main sediment. In addition, the ages lie within a range where many other ages were obtained. Therefore we think those dates are correct.

FG1, UAT, and KOH are all thought to be parts of the same flowstone that was sampled by coring. It is very dirty. The only age obtained (UAT, $276 + 98/-55$ ka) has a large analytical error, FG and KOH give a non-finite age. Therefore we expect that the deposition of this flowstone took place before 350 ka, which is also within the error of the date obtained.

HG-Mäanderboden, WGBoden1 and 5, KE2, represent young samples cored within the tourist part of St. Beatus Cave or at the bottom of the present meandering canyon (WGBoden, Mäanderboden). The latter are supposed to have formed after the last glaciation. The measured ages are in accordance with this hypothesis, but since they are also very dirty, the error is high, and no precise age can be given. The same holds true for the Rätsel and KE2 flowstones. The age of flowstone SPCryst is acceptable, whereas STI is unusable due to detrital contamination.

In the series from Westgang (WGU to WGK3), WGU is relatively dirty, and leaching of U is a possibility: the sample was not cored. All the other samples seem reliable, with the exception of KH3, which contains a lot of detrital Th and is therefore of only limited use.

Of the Bärenschacht samples, only the Empire has high detrital Th. In addition, the sample is quite porous. Thus the calculated age is only approximative.

Analysis of the data (Fig. 6) shows several distinct growth periods. Of course, the oldest growth period at more than 300 ka is very indistinct. Most of the dates are compatible with each other, taking into account the errors as well as absolute values. This is a good indication that (with exception of the samples mentioned above) the dates are reliable.

7.2. Pollen analysis

Among the five samples analyzed (MU4, BG15, EXC6, KH58, KH42), MU4 and EXC6 contained no observed pollen. BG15 contained 8 Pinus, 1 Alnus, 1 Juniperus, 3 Poaceae, 6 Artemisia, 3 Asteraceae, 1 Chenopodiaceae, and 4 trilete spores. KH58 had 1 Picea, 1 Pinus, 1 Pocaceae,

Table 2
Results of the datings

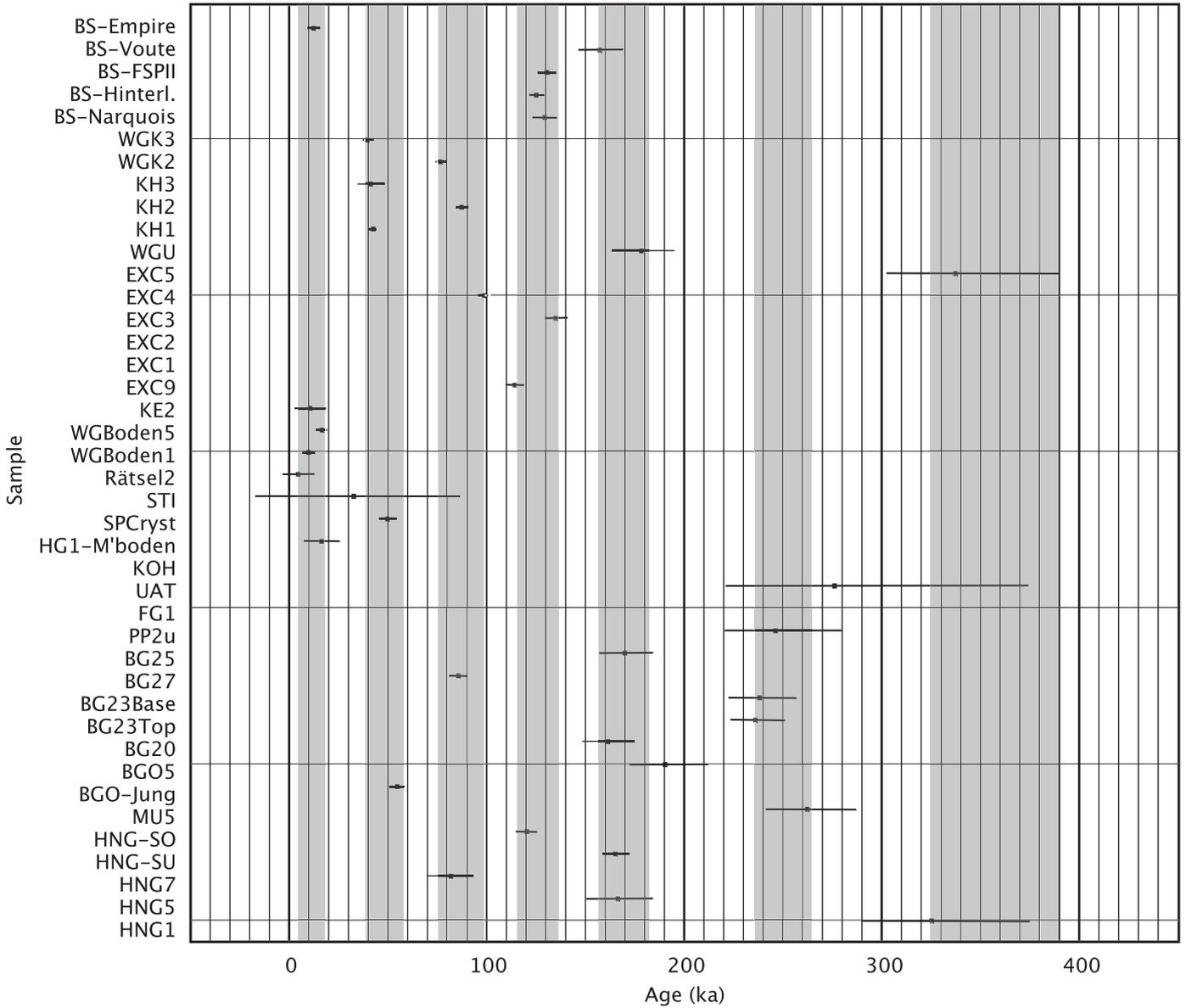| UIB no.	Name	Yield U (%)	Yield Th (%)	Conc U (ppm)	$^{234/238}$U ratio	$^{234/238}$U initial	$^{230/234}$Th/U ratio	$^{230/232}$Th ratio	Age (ka)	Age corr. for det. Th (ka)
Results of the U/Th datings										
2354	HNG1	65.5	37.6	0.40	1.19 ± 0.02	1.47 ± 0.05	0.999 ± 0.023	10,000.0	325 (+50/−35)	
2449	HNG5	73.1	44.0	0.11	1.27 ± 0.05	1.43 ± 0.08	0.825 ± 0.036	35.0	170 (+18/−16)	166 (+18/−16)
2355	HNG7	57.8	45.3	0.13	1.28 ± 0.05	1.39 ± 0.07	0.713 ± 0.029	2.9	126 (+10/−9)	81 (+12/−12)
2356	HNG-SU	70.6	36.3	0.68	1.44 ± 0.02	1.70 ± 0.03	0.829 ± 0.016	235.9	165 (+7/−7)	
2357	HNG-SO	67.1	37.4	0.32	1.32 ± 0.02	1.44 ± 0.03	0.693 ± 0.019	195.8	120 (+6/−5)	
2364	MU5	61.8	36.8	0.44	1.51 ± 0.03	2.06 ± 0.07	0.998 ± 0.026	397.0	262 (+25/−21)	
2409	BGO-JUNG	67.1	38.4	0.24	1.31 ± 0.04	1.37 ± 0.05	0.414 ± 0.022	24.4	57 (+4/−4)	54 (+4/−4)
2466	BGO5	66.1	42.0	0.24	1.23 ± 0.04	1.39 ± 0.07	0.869 ± 0.034	26.0	195 (+21/−18)	190 (+22/−18)
2392	BG20	51.2	21.6	0.47	1.23 ± 0.02	1.37 ± 0.04	0.845 ± 0.024	6.5	182 (+13/−12)	161 (+14/−13)
2394	BG23 Top	79.2	31.4	1.23	1.24 ± 0.01	1.47 ± 0.03	0.932 ± 0.018	180.1	236 (+15/−13)	
2395	BG23 Base	61.4	18.3	1.25	1.25 ± 0.01	1.48 ± 0.03	0.935 ± 0.021	10,000.0	238 (+19/−16)	
2407	BG27	69.1	37.2	0.44	1.27 ± 0.03	1.34 ± 0.04	0.581 ± 0.020	15.5	91 (+5/−5)	85 (+5/−5)
2408	BG25	72.3	38.8	0.24	1.37 ± 0.04	1.59 ± 0.07	0.835 ± 0.030	10,000.0	170 (+14/−13)	
2448	PP2u	30.5	54.7	0.57	1.11 ± 0.04	1.23 ± 0.08	0.928 ± 0.029	22.7	252 (+33/−26)	246 (+34/−26)
2396	FG1	50.4	41.4	0.19	1.16 ± 0.06	(1.42)	1.140 ± 0.061	6.1		(376)
2412	UAT	64.5	40.6	0.19	1.22 ± 0.05	1.51 ± 0.12	0.989 ± 0.048	6.4	298 (+95/−52)	276 (+98/−55)
2413	KOH	55.7	36.3	0.22	1.19 ± 0.04	(1.57)	1.067 ± 0.039	6.8		(388)
2411	HG1-M'bodn	62.0	19.9	0.18	1.53 ± 0.06	1.63 ± 0.07	0.428 ± 0.030	1.9	58 (+5/−5)	16 (+9/−9)
2431	SPCryst	77.2	37.5	0.22	1.24 ± 0.04	1.27 ± 0.05	0.391 ± 0.024	16.8	53 (+4/−4)	49 (+5/−4)
2432	STI	52.3	9.5	0.16	1.08 ± 0.06	1.12 ± 0.08	0.718 ± 0.083	1.7	134 (+35/−27)	32 (+54/−50)
2433	Ratsel2	25.3	31.0	0.16	1.43 ± 0.09	1.48 ± 0.10	0.331 ± 0.025	1.6	43 (+4/−4)	4 (+8/−8)
2428	WGBoden1	56.8	32.3	0.17	2.01 ± 0.06	2.11 ± 0.07	0.277 ± 0.014	1.9	34 (+2/−2)	9 (+3/−3)
2429	WGBoden5	61.6	40.3	0.18	1.44 ± 0.05	1.47 ± 0.06	0.205 ± 0.014	4.0	25 (+2/−2)	16 (+3/−3)
2430	KE2	59.1	27.7	0.22	1.53 ± 0.06	1.60 ± 0.07	0.366 ± 0.026	1.8	48 (+4/−4)	10 (+8/−8)
2358	EXC9	60.8	33.1	0.71	1.11 ± 0.04	1.15 ± 0.02	0.658 ± 0.016	255.3	114 (+5/−5)	
2359	EXC1	57.1	22.6	1.92	0.94 ± 0.01		1.114 ± 0.029	1640.3		
2360	EXC2	55.0	27.6	2.57	0.91 ± 0.01		1.060 ± 0.029	1069.0		
2361	EXC3	60.2	26.9	1.05	1.09 ± 0.01	1.13 ± 0.02	0.721 ± 0.017	10,000.0	135 (+6/−6)	
2362	EXC4	73.2	33.9	0.71	1.15 ± 0.01	1.19 ± 0.02	0.606 ± 0.012	412.3	99 (+3/−3)	
2363	EXC5	71.0	32.8	1.50	0.99 ± 0.01	0.99 ± 0.02	0.955 ± 0.017	10,000.0	338 (+52/−35)	
2365	WGU	37.6	34.7	0.34	1.33 ± 0.04	1.56 ± 0.07	0.878 ± 0.028	8.5	193 (+16/−14)	178 (+17/−15)
2397	KH1	68.7	37.3	0.45	1.53 ± 0.04	1.59 ± 0.04	0.336 ± 0.012	36.8	43 (+2/−2)	42 (+2/−2)
2378	KH2	66.0	33.5	1.93	1.29 ± 0.01	1.37 ± 0.02	0.565 ± 0.011	248.7	87 (+3/−3)	
2406	KH3	71.6	43.7	0.19	1.26 ± 0.04	1.32 ± 0.05	0.529 ± 0.023	2.6	79 (+5/−5)	41 (+7/−7)
2367	WGK2	64.2	38.5	0.57	1.28 ± 0.02	1.35 ± 0.03	0.515 ± 0.014	757.7	76 (+3/−3)	
2368	WGK3	50.3	28.9	0.38	1.26 ± 0.04	1.29 ± 0.05	0.331 ± 0.017	14.6	43 (+3/−3)	39 (+3/−3)
2379	BS-Narquois	64.3	36.9	1.11	1.05 ± 0.02	1.07 ± 0.02	0.719 ± 0.017	16.9	136 (+6/−6)	129 (+7/−6)
2380	BS-Hinterl.	81.3	33.0	3.58	0.90 ± 0.01	0.86 ± 0.01	0.672 ± 0.011	2329.8	125 (+4/−4)	
2381	BS-FSPII	80.0	30.4	5.05	0.91 ± 0.01	0.87 ± 0.01	0.687 ± 0.013	464.2	130 (+5/−5)	
2390	BS-Voute	75.8	40.3	0.34	1.52 ± 0.04	1.83 ± 0.06	0.835 ± 0.026	14.7	165 (+11/−10)	157 (+12/−11)
2391	BS-Empire	60.5	31.7	0.20	1.48 ± 0.04	1.52 ± 0.05	0.231 ± 0.014	2.4	28 (+2/−2)	12 (+3/−3)

9

Fig. 6. Age determinations, with error bars (1 standard deviation). A non-uniform distribution of ages is shown; the periods of speleothem growth are shaded.

and 4 Asteraceae. KH42 contained 4 trilete spores and 5 Asteraceae.

Only this sample (BG15) had a satisfactory pollen count, and it indicated a relatively cool climate. This poor result reflects the findings of Groner, who observed only few broken pollen in Hölloch cave (Groner, 1990) and in Jochloch on Jungfraujoch (Groner, 2004).

It seems that the interpreted (peri)glacial conditions during the deposition of the sediments already impeded a dense vegetation, and that according to Groner (1990) the remaining pollen are mostly destroyed during their underground stay. We might therefore conclude that palynologic analyses in soft sediments in alpine caves usually do not provide useful results.

It seems that only the analysis of pollen trapped within speleothems (Bastin, 1990) can lead to interpretable results.

7.3. Calcimetry

With the exception of the samples PP2-5 and KH57, which contain quite low carbonate contents (about 5%) and are thus thought to be deposited in a moderate climate, all the other samples contain appreciable amounts of carbonate (15–33%) and thus confirm the idea that they were deposited in a glacial environment (see Section 3.2. for explanation).

8. Interpreted chronology of valley deepening, climatic changes, and glaciations

Absolute datings set milestones to the relative timeframe presented in Section 6. The end result is an absolute chronological table (Table 3) that indicates phase transitions, valley deepenings, sedimentation and erosion events, and the obtained ages. The last column indicates the timing of the valley deepening. While uplift certainly plays a role in the rejuvenation of the mountain chain, it is probably a slow and steady process which would not result in discrete speleogenetic phases. Therefore we conclude that, in our inner-alpine context, valley deepening should reflect erosion by glaciations. In Table 3, all observed sedimentary successions and dates are shown in correct order. However, it may be difficult to time correctly a silt deposited between two dated speleothems. To partially solve this problem, we correlated those silts with better-constrained silt deposits from other profiles, inferring that a given flooding affected the whole cave. Fig. 7 shows the succession graphically; the numbers at the left side correspond to the numbers in brackets below and indicate the sequence of events.

Hoher Nordgang and Hoher Ostgang were created during a phase above 890 m a.s.l. There are no sediments that can be attributed with certainty to this phase. The same holds true for phase 890, which was active at more than 350 ka (1). A valley deepening to 805 m, probably due to a glaciation, followed (2).

During phase 805, gravel was deposited by a fast-flowing river in Murgelegang (3). After this fast-flowing river (that may indicate deglaciation environment and a washing-in of the unconsolidated gravel remaining at the surface) waned, speleothem deposition began, building stalagmites EXC1 and 2 in the Excenter (4). These stalagmites are all older than 350 ka.

As the next glaciation progressed and filled the Aare valley, the water level rose and deposited a layer of laminated silt (Silt6) in Excenter (5). This glacier was also responsible for the deepening of the valley to 760 m a.s.l.

During phase 760, gravel was deposited in the conduits belonging to phase 805, both in Kunsthalle/Kegelbahn and in Biwakgänge (6). After a change towards warmer climate, a thick flowstone (FG, KOH) was deposited in the downstream tube of Biwakgänge (7). Both samples are older than 350 ka. Speleothems EXC5 and HNG 1 also grew within this timespan, indicating a long warm period active until 325 ka.

The climate then became wetter, probably slightly more so than today. It induced a huge flow rate and re-erosion of both speleothems and bedrock to a depth of about 2 m (8). A next, drier phase was responsible for the deposition of flowstone MU5, PP2u, and the stalagmite BG23 (262–235 ka, 9).

A next deterioration of climate led to the deposition of a sand–gravel succession, which is truncated at least two times by other minor erosions (10). This succession (responsible for the filling up of the tourist part of St. Beatus Cave with gravel) was then capped by another laminated silt deposit that indicates the onset of the next glaciation, which was responsible for the deepening of the valley to 700 m (11). At the end of this glacial cycle, evidence for an erosional event is seen in the Biwakgänge (12).

During phase 700, most of the St. Beatus Cave was already in vadose conditions, due to the geological perching of this cave. Therefore, this phase is mainly visible in Bärenschacht (see Häuselmann, 2002). There, the speleothem in Voûte céleste (157 ka) indicates the age of the 700 phase (13). However, several sedimentation/erosion events of St. Beatus Cave can also be attributed to this interval. After the deglaciation and some erosion, a warm period was responsible for the deposition of flowstone BG20 and BG25 in Biwakgänge (161–170 ka). It is probable that the cementation of the filled tourist part of St. Beatus Cave is of the same age. A next erosional event, followed by a deposition of laminated silt, marks the onset of another glaciation, which may have been responsible for the deepening of the valley to 660 m (14). The correlation of this glaciation to phase 660 m is based on a "best fit" idea, for which there is no direct field evidence. However, a comparison of morphology and absolute dates indicates that this deepening must have happened between 160 and 100 ka.

During phase 660, the glacier receded, and a significant erosional event within the cave emptied the tourist part of St. Beatus Cave, leaving residual gravel (15). The next stalagmite deposition in Excenter has an age of 135 ka (16). This warm period is also visible in Bärenschacht, where three speleothems between 125 and 135 ka were found. They may have been deposited during phase 660.

This period was followed by a next glacial advance (17). The following warmer period deposited stalagmite EXC4 (99 ka) as well as many flowstones in Kunsthalle, Kanonenrohr, and Hoher Nordgang (87–76 ka, 18). The next varved silt deposition is attributed to another glacial advance (19), which was succeeded by a warmer period with new flowstone deposition, mainly found in Kunsthalle and the tourist part (39–49 ka, 20). The next laminated silt deposition in Kunsthalle was huge, but truncated by several erosional events (21), and can possibly be correlated to the prior glacial event. Another erosion and gravel deposition marks the beginning of today's 560 phase (22). The exact timing of this deepening has not been determined; however, the age has to lie between 116 and 16 ka. A speleothem-erosion cycle is again followed by the last flowstone deposition (23), visible at the bottom of the Hauptgang meandering canyon and upstream from Kunsthalle, taking place between 16 and 4 ka. The flowstone is currently being eroded away by the present river. At the same time, the Aare valley has been filled by Kander and Zulg gravel, bringing up the level of Lake Thun to 560 m a.s.l. (24). The last stage in the evolution of St. Beatus Cave to be dated precisely is the building of the tourist part in 1903/1904 (25).

Table 3
Overview of the datings and events around St. Beatus Cave and Bärenschacht

Text no.	Westgang			Nordgang		Hauptgang				Tourist part (Knuchel 1968)			Bärensch.	Age	Valley deepening
	EXC	KH	WGK	HNG	MU	BGO	BGunten	FG	PP2	KOH	Dom	ATvorn			
1	>890∅			>890∅	>890∅										→890
2	890∅					890Ø									→805
3		805∅	805∅	805v	805∅v Pebble	805v	805∅	805∅	805∅	805∅					
4															
5	EXC1+2 Silt6													>350	→760
6		760v Pebble	760v Pebble		760v	760v	760v Pebble	760v Pebble	760v	760v∅	760∅	760∅			
7	EXC5			HNG1			Speleot.	FG		KOHUAT				>350	
8														325–337	
9						Erosion Pebble	Erosion BG1-6	Erosion	Erosion						
				Speleot.	Speleot.	Speleot.	BG23 BG24 BG22		PP2u Sand Silt	UAT				236–262	
10							BG7-9 BG11-13		Pebble	Pebble.	Pebble				
11	Silt7						BG15 Silt								→700
12						Erosion	Erosion								
13		WGU	Speleot.	HNG5		BGO5	BG20/25		Speleot.	Speleot.	Speleot.		Voute	157–190	
14						Sand									→660
15					Erosion!	Erosion	Erosion			Erosion Pebble	Erosion Pebble				
16	EXC3/9			SchO							Speleot.	Speleot.	Speleot.	114–135	
17	Silt8	Silt	Silt				BG17		Silt						

12

	Erosion												
18	*EXC4*	*KH2*	*WGK2*	*HNG7*			*BG27*						*76–99*
19		Silt	Silt										
		KH1				*Speleot.*			*SPCr/StI*				*42–54*
20		*KH3*	*WGK3*		Speleot.								*39–41*
		50–55			SiltSand								
		Erosion											
	Silt	44-42-12			Silt.			Moonm.					
		(Erosion)											
		25/13											
21		**Erosion**					**Erosion**						
		27-1											
		Erosion											
		41/18/15											
		22/19						Silt					
		30–57											
22		36-61-8	Silt			Fillup	BG28	Silt					→**558**
		Erosion!	**Erosion!**						**Erosion**	**Erosion!**	**Erosion!**		
		Pebble											
		Speleot.	Speleot.										
			.										
											Frost sh.		
		Erosion	**Erosion**										
23		Speleot.	*WGBoden5*						*HG-M'b,*	Speleot.	Speleot.		*16*
			KE2									*Empire*	*10–12*
			WGBoden1						*Rätsel*				*3–8*
			Stalagm.										
25									**Construction of the tourist part**				**1903 AD**

The first numbers refer to the sequence described in the text. Towards the right are several profiles of St. Beatus Cave, then one column represents events in Bärenschacht. To the left, the ages obtained and the phase interpretation are presented. A →700 means that at this time the phase 700 began and continued to the →660 sign.
Bold: a morphological event (valley deepening, erosion); *italic:* a dated speleothem. Speleothems not dated are in normal lettering.
A ∅ means that the gallery was in the phreatic zone after the valley deepening event, **v** means that the gallery was in the vadose zone.
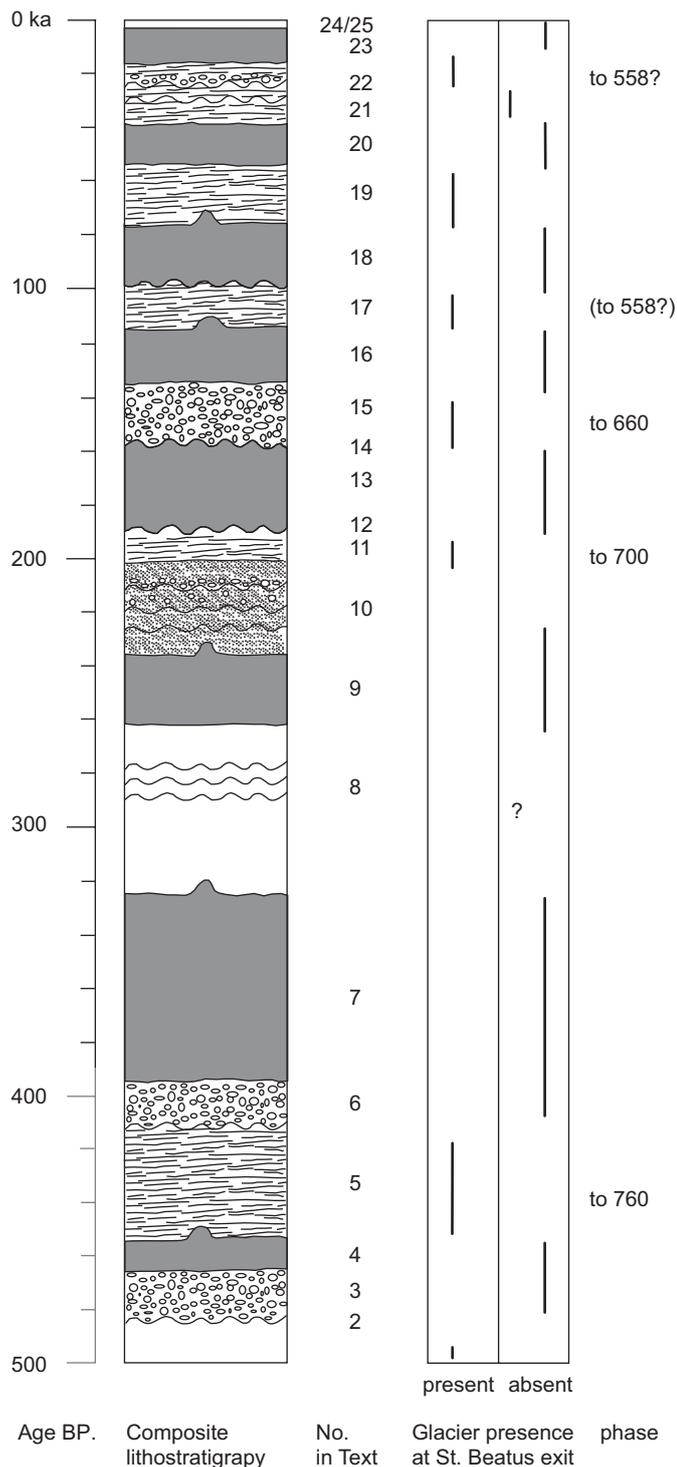
Fig. 7. Composite profile over the last 400+ ka, showing periods of glacier presence at the entrance, deduced from the presence or absence of layered sediments. The profile legend is inserted in Fig. 5. Ages between 350 and 390 ka are estimated using the $^{234/238}$U approach, ages above are speculative.

Fig. 7 shows this succession graphically. Note that the ages given above, and the shaded areas in Fig. 6, do not overlap, except where the ages are highly unreliable. This makes sense, considering the deposition of other sediments between the dated speleothems. This provides a good indication that the ages are reliable.

9. Discussion

No comparable data are available from caves in Switzerland, and therefore we must rely on data presented by Quaternary geologists, cave data elsewhere in the world, and other paleoclimatic data.

Schlüchter and Röthlisberger (1995) indicate that the end of the last glaciation happened around 14 ka, which would correspond roughly with our youngest dates. Our dating of the preceding glaciation, corresponding to marine isotopic stage 2 (MIS 2), ranges between 16 and 39 ka. The finding of the skeleton of a brown bear in Melchsee-Frutt (Central Alps) at 1800 m a.s.l., dated to ~33 ka (Morel et al., 1997), indicates that around this time the extent of glaciers was restricted, and in places corresponding to their present state. This implies that St. Beatus Cave would have been deglaciated at 33 ka, which is in accordance with findings from Norway (Mangerud, 1991). Schlüchter and Röthlisberger (1995) states that the alpine foreland was free of ice from 60 to 28 ka. This corresponds with the speleothem generation found in the tourist part of the St. Beatus Cave (39–54 ka) and with MIS 3.

The preceding glacial advance is recognized in the Swiss plateau and corresponds to stage 4.

The next warmer period, as suggested by evidence from the cave, took place around 76–99 ka. It has almost no corresponding dates in the Swiss plateau (Schlüchter and Kelly, 2000). A single date at 86 ka could correspond to this interstadial (Wegmüller, 1992), while in Norway two warm phases fall into that timespan (Mangerud, 1991). Marine isotope stages 5a and 5c may correspond to this warmer period. MIS 5b, which is not seen in St. Beatus Cave, may not be visible because of its short duration.

The next ice advance, between 99 and 114 ka, is currently in debate. Recent dating in the Gossau profile (Swiss plateau, Preusser, 1999) strongly supports a significant glacial advance, which appears to be less pronounced, though present, in Norway. The marine equivalent to this would be MIS 5d.

The next warm period for which evidence has been found in the cave, around 114–135 ka, is also supported by field data from the Swiss plateau at Gondiswil (Wegmüller, 1992), where the average of the dates is 115 ka (94–144 ka). This date corresponds closely with the data from St. Beatus Cave and indicates the "Eemian" interglacial and MIS 5e. The well-dated marine isotopic stage 5e begins at around 135 ka and lasted for 21 ka. Both the beginning and the duration are in close accordance with data from Devils Hole, Vostok, and Austria (Spötl et al., 2002), but in disagreement with the Specmap data (see discussion in Winograd et al., 1997).

The next glaciation in the Swiss plateau has no clear timeframe (Schlüchter and Kelly, 2000); however, it would correspond to the first part of MIS 6. According to other

authors (e.g. van Husen, 2004) this would be the classical Riss glaciation.

The next warm period identified in St. Beatus Cave, from 155 to 180 ka, has no direct equivalent, either in the foreland, or in the marine stages. The only evidence for a warmer time is found in Thompson et al. (1976) by oxygen isotopes from a cave in West Virginia (USA). A close examination of the marine record (Martinson et al., 1987) and of the Devils Hole data, however, indicates a warm period within stage 6. For Devils Hole, the isotopic ratio is comparable to stages 5a and 5c. This evidence allows us to postulate that the Aare valley (and thus the Swiss foreland) was deglaciated during this first part of MIS 6.

The next glaciation for which there is evidence in St. Beatus Cave corresponds to the very beginning of MIS 6. The inferred age (235–180 ka) agrees with the Devils Hole data (~220 ka).

The next warm period (235–260 ka) would roughly correspond to the beginning of stage 7. In this range, the uncertainty of the dating methods is greater, and therefore an exact correlation is not possible. However, there is a nice match with the Devils Hole data, although the onset of the warm phase at 260 ka seems a little early.

The next period, interpreted from St. Beatus Cave as erosion, corresponds to MIS 8 and to a glaciation. However, there is as yet no proof available for a glaciation in the Siebenhengste area. The beginning of the next warm phase is dated to 325 ka, which corresponds well with Devils Hole stage 9.

There is almost no literature available on the timing of the valley deepening in Switzerland. Based on morphology only, Beck (1954) states that the deepening of the Aare Valley from Beatenberg (1100 m a.s.l.) to the present (560 m) took place during the four glaciations of Penck and Brückner (1909).

With the two well-dated valley deepenings to phases 700 and 660, we can reconstruct average valley deepening rates. They are 1.3 mm/a for the deepening to 700 m a.s.l., and 1.8 mm/a for the one to 660 m. These values do not take into account the timespans when the phases were at their respective elevations. The average valley deepening rate for the whole datable timespan (i.e. from the onset of deepening 235 ka ago) would be 0.9 mm/a. The values obtained are in good agreement with recent data of Riihimaki et al. (2005), Hallet et al. (1996), and Hebdon et al. (1997), all of which suggest average rates of glacial incision in the order of 1–2 mm/a. They correspond with recent data from cosmogenic isotopes, which indicate an incision rate of about 1 mm/a for the last million years (Häuselmann et al., 2007).

10. Conclusions

The prior literature shows that evidence of glacial advances and retreat is usually scattered among many widely spaced outcrops. St. Beatus Cave, on the contrary, provides at a single location evidence for six glacial advances. The location at the rim of the Alps, where glaciations are traditionally defined, is ideal for differentiating true glaciations from inner-alpine ice advances. Moreover, the timing of those advances is possible by dating flowstones that were deposited before and after the glacial cycles. We thus have dated several old glacial advances in a precise way. Glacial advances occurred at the following time windows: 16–30, 54–76, 99–114, 135–160, 180–235, and prior to 350 ka. St. Beatus Cave is thus an important site for dating the continental Quaternary.

We were also able to date the latest events of erosional deepening of the Aare valley. Deepening from 805 to 760 m a.s.l. took place at more than 350 ka, from 760 to 700 m a.s.l. between 235 and 180 ka, from 700 to 660 m a.s.l. between 160 and 135 ka, and from 660 to 560 m a.s.l. between 30 and 16 ka. These dates are new for this part of the Alpine Arc.

In the last few decades, caves have been shown to be valuable tools for the reconstruction of paleoclimate by the analysis of stable isotopes in speleothems. Other approaches were usually regarded as impossible because of discontinuities or insufficient resolution. The investigations presented here show that despite those ordinarily valid objections, caves have great potential for reconstructing both paleoclimate and paleogeography that is not possible at the Earth's surface.

However, the interpretation of paleoclimate or paleogeography from cave information is not straightforward. The genesis and sedimentology of a cave have to be investigated and understood in order to reconstruct its entire history and its relationship to the outside environment. This approach can therefore provide much more information than simple speleothem sampling and analysis. With this paper, we hope to demonstrate the benefits of such comprehensive studies.

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