Paleohydrology of a high-elevation, glacier-influenced karst system in the Central Alps (Austria)

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Abstract

Marble beds in the Tux Valley, Tyrol, host a series of cave systems, currently hydrologically largely inactive, the largest of which (Spannagel Cave) has ca. 11 km of explored passages. Despite their high elevation and low interior air temperatures (only barely above 0°C) calcitic speleothems are not uncommon in these caves and have been the focus of a long-term paleoclimate research project. In this study we take advantage of this comprehensive data set of stalagmite and flowstone samples, whose chronology is precisely established by U-Th dating. We utilize these samples to provide temporal and spatial constraints on speleogenetic processes including the formation of prominent canyons and the occurrence of floods.

The data show that in spite of its proximity to a modern glacier, Spannagel Cave's prominent erosion features date back at least three glacial cycles. Unconsolidated sand and gravel are wide-spread in this cave and represent till and glaciofluvial sediment washed into the cave between 48 and 13 kyr.

The strikingly small hydrological impact of the last few glaciations (and deglaciations) is consistent with (a) the antiquity of these high-elevation caves whose origin seems to be unrelated to today's adjacent glacier, and (b) underscores the unique preservation potential of cave systems and their sedimentary inventory. This is in stark contrast to the high rates of glacial erosion on the surface above the cave.

Im Talschlusss des Tuxer Tales, Zillertaler Alpen (Tirol), befinden sich eine Reihe von im wesentlichen hydrologisch inaktiven Höhlensystemen, von denen das größte, die Spannagelhöhle, eine erforschte Ganglänge von circa 11 km aufweist. Trotz der großen Seehöhe und der niederen Temperaturen (knapp über 0 °C) sind kalzitische Speläotheme in diesen Höhlen nicht selten und sind Gegenstand eines langfristigen Paläoklima-Forschungsprojektes. Die vorliegende Studie baut auf diesem umfassenden Datenmaterial von Stalagmiten, Wand- und Bodensinter auf, deren Chronologie mittels U-Th Datierung präzise bestimmt wurde. Wir benützen diese Proben um speläogenetische Prozesse, wie zum Beispiel die Bildung von Canyons und das Auftreten von Überflutungen, zeitlich und räumlich einzugrenzen.

Die Daten zeigen, dass trotz der Nähe zu einem stark vergletscherten Gebiet (Hintertuxer Gletscher) die prominenten Erosionsformen in der Spannagelhöhle älter sein müssen als die letzten drei Glazialzyklen. Unkonsolidierter Sand und Kies sind in dieser Höhle weit verbreitet und stellen Moränenmaterial bzw. glaziofluviatiles Sediment dar, welches zwischen 48 und 13 kyr durch Schmelzwasserbäche in diese unterirdischen Hohlräume geschwemmt wurde.

Der auffallend geringe hydrologische Einfluss der letzten Glaziale (und Enteisungsphasen) ist konsistent mit (a) dem hohen Alter dieser hochalpinen Höhlensysteme, deren Ursprung nicht in Zusammenhang mit dem heutigen, nahe gelegenen Gletscher gesehen werden sollte, und (b) unterstreicht das einzigartige Erhaltungspotenzial von Höhlensystemen und deren Sedimenten. Dies kontrastiert zu den hohen Geschwindigkeiten der glazialen Erosion an der Oberfläche in diesem Gebiet.

1. Introduction

Karst aquifers are characterized by high permeabilities and high incidence of large-magnitude springs. This high transmissivity reflects the solubility of the aquifer rocks - commonly limestone or dolomite - which is orders of magnitudes higher than that of silicate rocks and gives rise to self-organized channel networks formed by the positive feedback between dissolution and flow (e.g., Worthington and Ford, 2009). Because of the high discharge of karst springs, which provide drinking water for an estimated 20 percent of the world's population and their inherently high vulnerability for pollution groundwater resources in karst areas is a major issue in many regions of the world (White, 1988; Ford and Williams, 2007; Kresic and Stevanovic, 2010). In contrast to porous and fractured aquifers, karst terrains offer the unique opportunity to study parts of their aquifer directly as larger conduits are accessible to man. Such speleological studies laid the foundation for the first (empirical) models of karst aquifer evolution (e.g., Ford and Ewers, 1978; see Klimchouk et al., 2000 for a comprehensive review). Although many presently phreatic caves have been explored, most of our knowledge of aquifer geometries and evolution stems from caves which are accessible without scuba diving equipment, i.e. those currently located above the groundwater table, at least seasonally. In many large cave systems galleries, chambers, and shafts extend down to the (epi)phreatic zone, where conduit enlargement is actively taking place. Alpine examples include the Hölloch in the Muota

Valley, Europe's largest cave system with 196 km of surveyed passages (Möckli, 2000), and Lamprechtsofen in the Province of Salzburg, Austria, the deepest cave in the Alps (1.6 km deep, 38 km long).

Various external processes control the long-term evolution of karst aquifers, most notably climate (e.g., by glacial lowering of the fluvial base-level – e.g., Haeuselmann et al., 2007) and tectonics (either by rock deformation initiating new fractures, and/or by vertical rock uplift and exhumation – e.g., Farrant et al., 1995). The only direct source of paleoflow information apart from dissolution features on cave walls (e.g. scallops - Curl, 1974; Lauritzen et al., 1983) are sediments. Clastic sediments have received some attention in this respect as they can provide constraints on the hydrodynamic regime of turbulent flow in conduits (e.g., Bull, 1981). Establishing a reliable chronology of clastic cave sediments, however, is a daunting task, because thick successions are rare, are commonly riddled by hiati, and only very few dating methods can be applied to decipher their history (e.g., Sasowsky and Mylroie, 2004). Burial-age dating using cosmogenic nuclides, which requires coarse-grained quartz-bearing sediments, has recently opened a time window between a few hundred thousand and a few million years before present (Granger et al., 2001; Stock et al., 2005; Haeuselmann et al., 2007). Although these dates are associated with considerable analytical uncertainties and more detailed work is needed, these initial studies have already provided valuable insights into the long-term history of karst aquifers (see Wagner et al., 2010 for the first study of this kind in Austria).

In addition to clastic sediments, caves also commonly host a variety of chemical sediments (speleothems). Popularized in recent years because of their significance as high-resolution paleoclimate archives, speleothems locally also provide chronological anchor points for the hydrological history of cave systems (e.g., Gascoyne et al., 1983; Stock et al., 2005; Hercman et al., 2008; Häuselmann et al., 2008). The time window represented by speleothems is commonly the last 0.5 million years (i.e. the range of the U-Th method; for a notable exception see Polyak et al., 2008), i.e. dated speleothems complement burial-age dating of quartz pebbles. The purpose of this study is to use a comprehensive dataset of well-dated speleothems, established within the framework of a paleoclimate

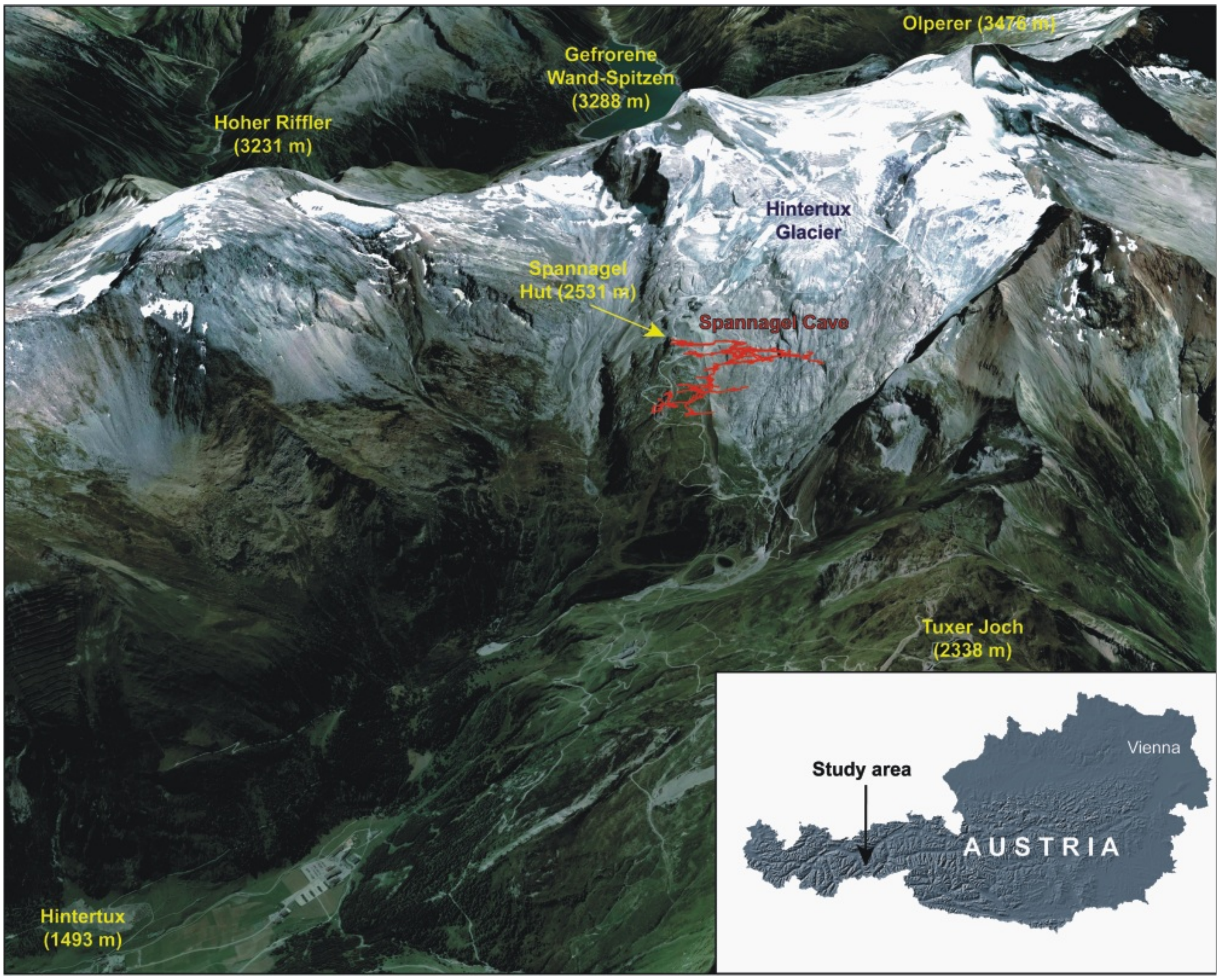


FIGURE 1: Head of the Tux Valley showing the location of Spannagel Cave adjacent to the glaciated main ridge of the Central Alps (oblique view toward SSE, satellite image downloaded from Google Earth Pro on 22 February 2010; image credit: Google Earth™ mapping service).

project, to draw conclusions about the history of a karst aquifer in the Eastern Alps (Spannagel Cave) during the last few hundred thousands of years.

2. Study site

Spannagel Cave (short hand for "Höhle beim Spannagelhaus", cave cadastre no. 2515/1) is the largest (ca. 11 km length) of a series of caves which are cut in a ca. 20 m-thick, inclined marble layer sandwiched between gneiss 30 km SSE of Innsbruck (Fig. 1). For details of the structural setting of the cave within the western part of the Tauern Window, a metamorphic core complex forming the backbone of the Eastern Alps, the reader is referred to Höck (1969), Lammerer et al. (2008), and Veselá et al. (2008). Conduits follow bedding planes and E-W as well as N-S trending fractures (Jacoby & Krejci, 1992). The most common passage types are canyons,

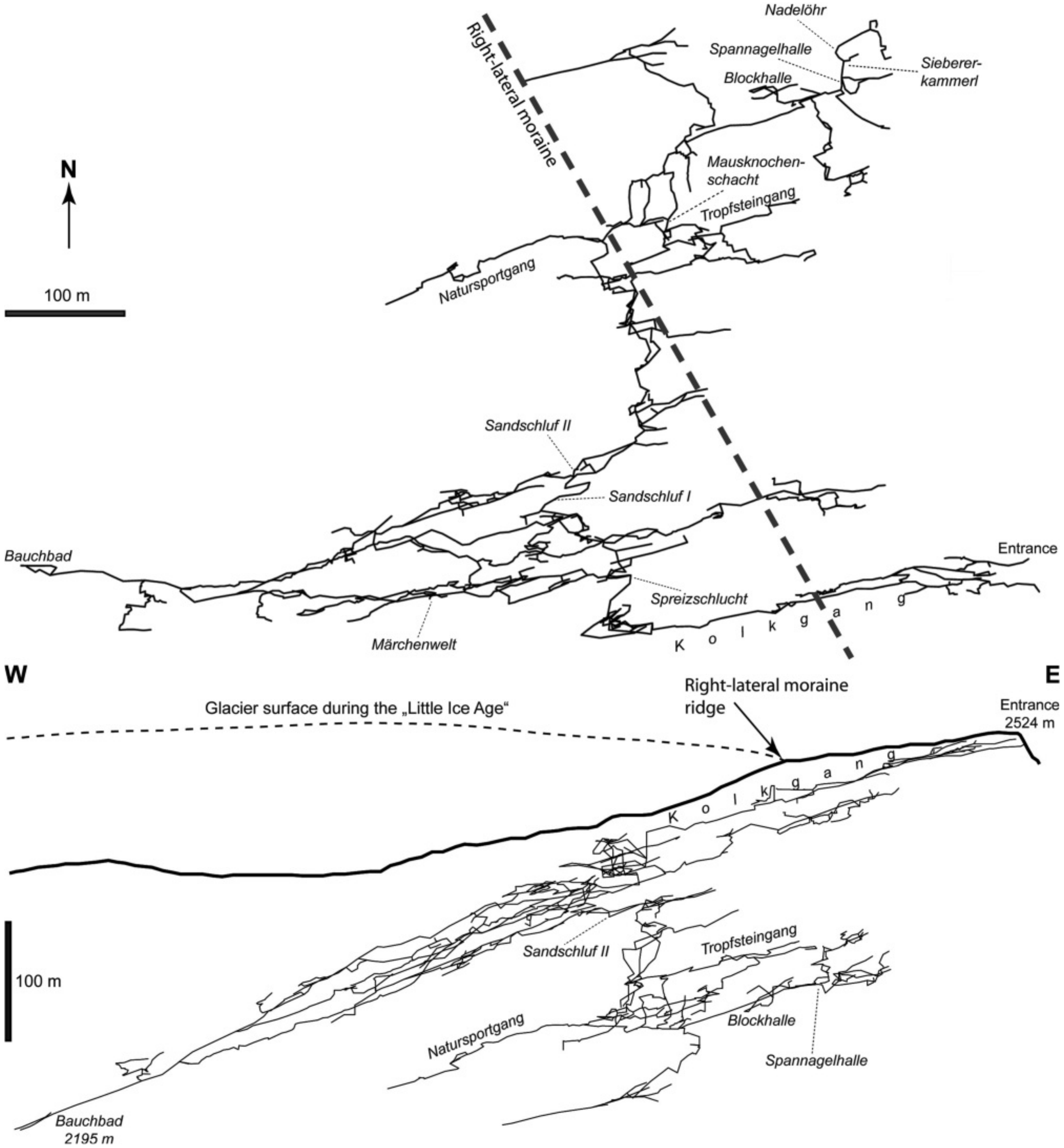


Figure 2: Upper panel: Plan view of Spannagel Cave and names of cave parts mentioned in the text. Note that the western segment of this cave was in a subglacial position during the "Little Ice Age" advances of the Hintertux Glacier, which currently (2010) terminates ca. 500 m south of the cave. Lower panel: Vertical perspective of the cave's dendritic network and the reconstructed surface of the glacier during its highstand in the middle of the 19th century. The near-linear, first-order arrangement of the cave passages follows the dip the marble. Both maps show the traverses only (excluding gallery boundaries).

typically no more than a 1-3 m wide, which extend down to the base of the marble (Spötl, 2002). The early history of this marble stripe karst (cf. Lauritzen, 2001) is unknown and speleothems older than ca. half a million years have not been found in these caves. Given the proximity to a temperate glacier (Gefrorene Wand Kees, nowadays also referred to as Hintertux Glacier, which terminates ca. 500 m south of the cave – Figure 1) this lack of ancient sediments does not come as a surprise. The entrance of Spannagel Cave is located at 2524 m a.s.l. and a significant part of the cave network extends beneath the former bed of Hintertux Glacier, which was occupied by a glacier tongue as recently as the early 20th century (Fig. 2).

Despite their position well above the timberline, Spannagel and adjacent caves contain calcitic speleothems (flowstone, stalagmites, stalactites, soda straws). The vast majority of these formations is Late Pleistocene in age (Spötl and Mangini, 2007), but Holocene speleothems are also common including actively forming stalagmites. These relatively abundant speleothems, formed close to the physical limit of calcite deposition (modern cave temperature 1-2°C), are not only valuable archives of past climate change (e.g., Holzkämper et al., 2005; Mangini et al., 2005, 2007; Spötl et al., 2007, 2008), but also provide the opportunity to constrain the hydrological history of this high-elevation alpine cave within the U-Th dating window.

Caves in the Spannagel area are characterized, apart from fissure-fed and seepage flow, by a few low-discharge streams only, which show a strong seasonal pattern with peak discharge (up to ca. 20 liters per second) during snowmelt (May-July) and base flow during winter. Two lines of observations suggest that these caves experienced – at least episodically – phreatic conditions in the past: (a) many passages show near-circular to elliptical cross sections diagnostic of phreatic tubes (Ford and Williams, 2007). Keyhole passages and in particular canyons are very common testifying a lowering of the water table and later vadose entrenchment (Fig. 4). (b) The walls, floors, and ceilings of well-preserved near-circular tubes show scallops confirming that these passages functioned as phreatic conduits (Fig. 5).

Another characteristic feature of Spannagel and neighboring caves is the presence of well-rounded orthogneiss cobbles in many cave galleries. These clasts originated in the subglacial drainage system of the Hintertux Glacier (this type of compact, light-colored granitic gneiss is absent within the hostrock of the cave) and demonstrate that large parts of the cave network were once occupied by streams capable of entraining cobbles typically ca. 5-20 cm in diameter.

3. Methods

In this study we use stalagmites and flowstone to constrain the last high-energetic hydrological event in different parts of Spannagel Cave both in space and time. The basic rationale is twofold:

- Stalagmite growth is restricted to vadose conditions and therefore postdates the last time a conduit was flooded or occupied by a high-discharge stream. Dating the base of an autochthonous (in-situ) stalagmite (or flowstone) therefore provides a minimum age ("terminus ante quem") of this

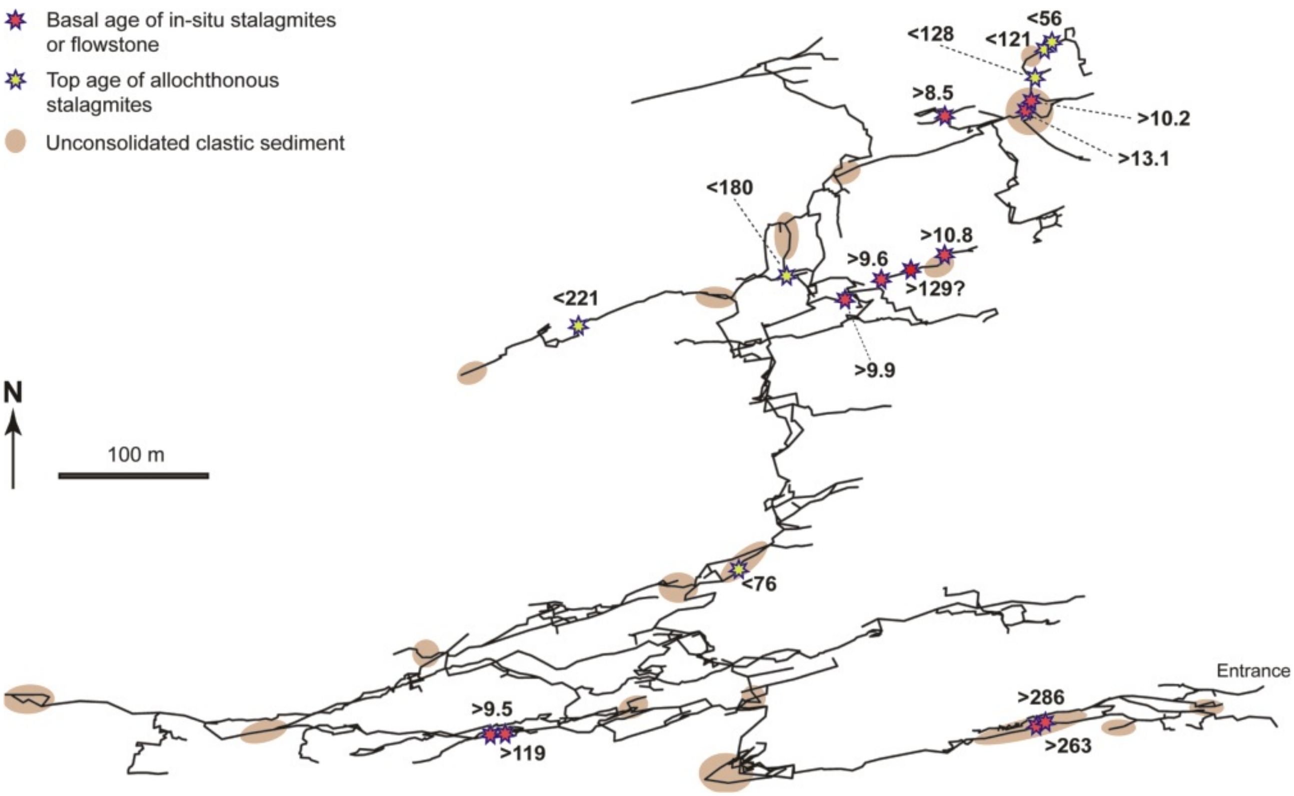


Figure 3: Location of the U-Th-dated speleothems discussed in this study. Ages are given in kyr. See text for further information.

Figure 4: Fossil phreatic gallery showing a circular cross section, later modified by vadose entrenchment (near Sandschluf II).

last flooding event. This approach is valid for samples which (a) lack any signs of surface corrosion (modern cave stream water is undersaturated with respect to calcite all year round (Spötl, unpublished data) and corrodes speleothems), (b) lack petrographic evidence of internal corrosion zones, and (c) show no evidence of layers of clay and silt (neither on the surface nor internally).

- Allochthonous (broken) speleothems are primarily associated with major hydrological events, whereby removal occurs either by the high energy of stream water and its associated coarse-grained bedload or by undercutting of stalagmites which grew on top of unconsolidated clastic sediment. Dating the top of such broken stalagmites therefore provides a maximum age estimate ("terminus post quem") of the last time a conduit was flooded or occupied by a high-discharge stream. Stalagmites, however, can also be broken by other mechanisms (ice, gravitational collapse, strong earthquakes, humans). We therefore excluded broken stalagmites samples unless they showed both erosional and/or corrosional features on their surfaces, and occurred together with coarse-grained sand or gravel, thus strongly pointing toward stream water as the cause of their breakage.

Figure 5: The lower end of this phreatic tube (Natursportgang) dipping beneath the former bed of the Hintertux Glacier is clogged by sand. Scallops covering the surface of this gallery testify its phreatic origin.

This study is based on a total of 13 stalagmites and four flowstones that were characterized by at least two (base and top of each speleothem), commonly, however, several subsamples dated by U-Th. Details of the chemical preparation and thermal ionization mass spectrometric analyses are given in Holzkämper et al. (2005). Ages are given in kyr before the year 2000 and analytical uncertainties are quoted at the 2-sigma level.

4. Results

Figure 3 provides an overview of the sample locations in Spannagel Cave. Some parts of the cave are densely sampled whereas others lack speleothems. A full list of the analytical results is given in Table 1, and for the sake of brevity individual U-Th dates are quoted in the text without their uncertainties.

Tropfsteingang. - This is one of the galleries with the highest density of dripstones and ascends from the main N-S trending cave axis in ENE direction (Fig. 2). The gallery's upper end is blocked by breakdown and survey data and the presence of humic soil material show that this part is located close to the ground surface. The passage was clogged by sand ca. 25 m before its end (now partly removed by cavers). Developed along the boundary of the marble to the overlying mylonitic gneiss the eastern (higher lying) part of the Tropfsteingang partly preserved the original near-circular cross section which passes downgradient into a canyon. Several in-situ stalagmites were sampled in the central and upper part of this gallery. The stalagmites rested on sand, angular rubble, or breakdown blocks. Basal ages of three stalagmites range from 10.8 to 9.6 kyr (Figs. 3 and 6). One sample, however, which grew on a breakdown-block, yielded a basal age of 129 kyr (and grew until 118 kyr – Fig. 7). In contrast to the Holocene samples, which are almost white, this stalagmite's outer surface is medium gray. Individual crystal terminations are clearly visible under the binocular and intercrystalline porosity is filled by fine-grained sediment. One flank of the stalagmite is covered by a thin veneer of gray calcite which was apparently subsequently removed from the other flanks. These observations suggest that at some point subsequent to 118 kyr a thin layer of additional calcite was deposited on this stalagmite, which was later partly corroded. The presence of silt and clay on this exposed surface could either be due to a rather short flooding event (which might also have accounted for the partial dissolution of the calcite coating) or due to particles entrained by strong cave winds. No air flow can be felt in this gallery today and the high degree of purity of the Holocene stalagmites strongly argues against significant dust transport and deposition since at least 10.8 kyr before present.

Spannagelhalle and adjacent parts. - This is the largest room in Spannagel Cave, 21 x 15 m and up to 10 m high. Its floor consists of breakdown blocks and sand and gravel of unknown thickness. Stalagmites growing on these substrates yielded basal ages of 10.2 and 13.1 kyr (plus several younger ones not reported here) providing a minimum age for the deposition of the sand (Fig. 8). A similar basal age (8.5 kyr) was obtained from an in-situ stalagmite (SPA 127) in the nearby Blockhalle, a large room filled by breakdown blocks but lacking sand (Fig. 2). A passage leads northward from Spannagelhalle into a small chamber (Siebererkammerl) followed by a tight squeeze (Nadelöhr; it was clogged by sand and later partly excavated by cavers) which opens into a larger gallery. Three speleothems were sampled along this route. A small stalagmite (SPA 139) was found in the Siebererkammerl embedded in loose sand. The surface of this sample is heavily corroded (Fig. 9) and a U-Th date near the top (128 kyr) provides a minimum age for the removal and corrosion of this specimen. Two stalagmites were collected behind the Nadelöhr squeeze (SPA 50 and 51 – Fig. 10). Both were allochthonous and their surfaces are pitted and show evidence of erosion by running water (incipient scallop-like surface features). Detailed U-Th dating along their extension axes (Holzkämper et al., 2004; Spötl et al., 2007) revealed that growth of SPA 50 ceased at 121 kyr. The main growth phase of SPA 51 also ended soon after (119 kyr), but a thin layer of calcite was deposited much later (56 kyr), providing a minimum age for the removal of this stalagmite from its base (Fig. 10).

Märchenwelt. - The western branch of the cave follows the dip of the marble beneath the recently deglaciated fore field of the Hintertux Glacier (Fig. 2). These passages vary from near-circular cross sections of well-preserved phreatic tubes with very large scallops (up to almost 1 m in diameter testifying a very slow flow regime on the order of 1 cm/s) to rectangular cross sections caused by breakdown. Samples were obtained from one part of the passage which contains dozens of small stalagmites, abundant stalactites, and flowstone forming on rubble (Märchenwelt – Fig. 2). A small in-situ stalagmite yielded a basal age of 9.5 kyr (others show slightly younger ages, not reported here). Another stalagmite (SPA 143), which formed on a breakdown block, grew between 119 and 113 kyr (Fig. 11). Given the fact that this (inactive) stalagmite was found in growth position demonstrates that the breakdown occurred prior to 119 kyr. The surface of this specimen is white and lacks signs of corrosion or erosion strongly suggesting that this part of the cave was never flooded since the late Eemian.

Natursportgang. - This is another passage descending beneath the former glacier bed of Hintertux Glacier and whose end is clogged by well-sorted, coarse-grained sand for ca. 10 m

Cave area/ sample	Ref.	Lab #	$\delta^{234}U$		Conc. ^{238}U		Conc. ^{232}Th		Conc. ^{230}Th		Age	
			(‰)	± (‰)	(µg/g)	± (µg/g)	(ng/g)	± (ng/g)	(pg/g)	± (pg/g)	(kyr)	± (kyr)
Tropfsteingang												
SPA 133 (base)*		4611	-1.8	1.5	55.821	0.056	<0.1		85.68	0.57	10.77	0.08
SPA 129 (base)*		3273	12.4	2.4	5.307	0.005	4.3190	0.0281	60.955	0.555	128.5	2.4
SPA 130 (base)*		3267	-20.1	1.4	22.163	0.022	0.8766	0.0025	29.98	0.13	9.63	0.05
SPA 70 (base)*	1	2121	-4.1	2.6	45.7667	0.0915	19.282	0.058	64.69	0.25	9.89	0.05
Spannagelhalle												
SPA 140 (base)*		4496	-0.2	1.4	9.6742	0.0097	6.918	0.033	14.08	0.13	10.15	0.10
SPA 115 (base)*		2733	-10.6	2.0	26.959	0.038	5.9735	0.0239	49.21	0.29	13.06	0.09
Blockhalle												
SPA 127 (base)*		3188	-7.2	1.4	34.374	0.034	0.3912	0.0029	41.579	0.457	8.45	0.10
Siebererkammerl												
SPA 139 (top)+		4515	16.9	1.8	3.6385	0.0036	3.0026	0.0081	41.97	0.22	128.3	1.4
Nadelöhr												
SPA 50 (top)+	2	2605	16.3	1.3	3.481	0.002	1.415	0.003	38.84	0.09	120.8	0.9
SPA 51 (top)+	3	2478	-23.9	1.8	109.14	0.13	<0.05		701.531	3.087	56.35	0.37
Märchenwelt												
SPA 143 (base)*		4530	55.2	1.7	7.3118	0.0073	0.2374	0.0014	84.55	0.66	119.2	1.7
SPA 145 (base)*		4532	-4.1	1.6	11.826	0.012	3.407	0.012	16.07	0.13	9.50	0.08
Sandschluf II												
SPA 121 (top)+	4	4364	-157.4	1.3	4.0580	0.0041	0.1543	0.0010	27.59	0.18	76.25	0.77
Natursportgang												
SPA 119 (top)+	5	2931	118.5	3.6	7.088	0.010	20.0176	0.0440	115.57	0.44	220.5	3.7
Mausknochen-schacht												
SPA 146 (top)+		4882	29.6	1.9	174.317	0.174	2.4372	0.0056	2385.4	5.5	179.7	1.5
Kolkgang												
SPA 43*		3941	-19.6	1.4	132.92	0.13	2.421	0.011	1928.8	6.8	262.5	4.5
SPA 134*		3848	-5.7	1.4	16.931	0.017	21.082	0.048	254.91	0.76	285.5	5.1

Table 1: U/Th ages. Errors are quoted as 2-sigma standard deviations. Legend: *in-situ stalagmites, +broken stalagmites. References (including additional U/Th dates of individual stalagmites): 1..Vollweiler et al. (2006), 2..Holzkämper et al. (2004, 2005), 3..Spötl et al. (2007), 4..Spötl et al. (2008), 5..Spötl & Mangini (2007).

(Figs. 2 and 5; attempts to excavate this passage have so far been unsuccessful). A broken stalagmite was collected in a pile of sand in this gallery (SPA 119). Dated by several U-Th subsamples (Spötl and Mangini, 2007) the top yielded an age of 221 kyr, which represents a maximum age for the time when this stalagmite was removed from its substrate, likely by a cave stream.

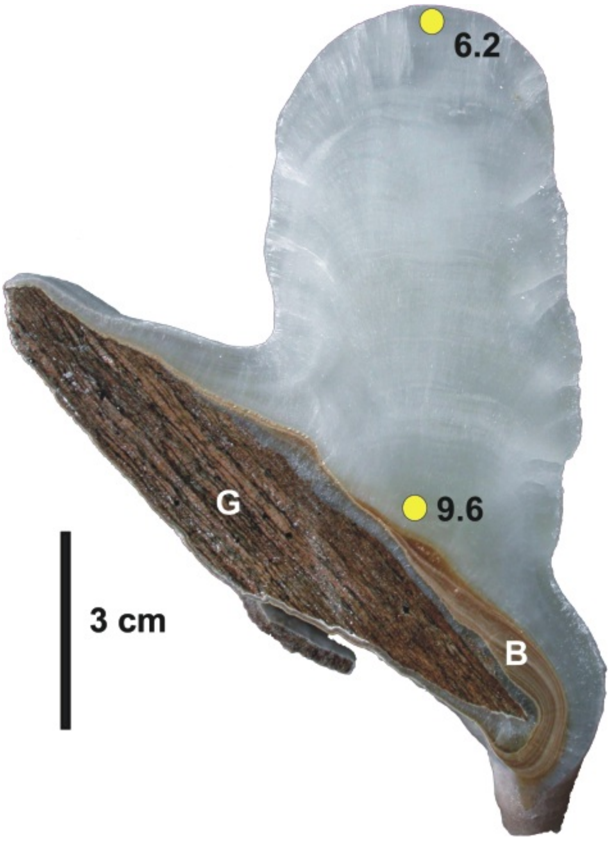


Figure 6: Example of an in-situ Holocene stalagmite from Tropfsteingang cut open and polished to highlight the clean calcitic fabric (sample SPA 130). Bottom and top U-Th dates are given in kyr. The initial brown calcite flowstone (B) overlying the mylonitic gneiss (G) is probably MIS 3 in age.

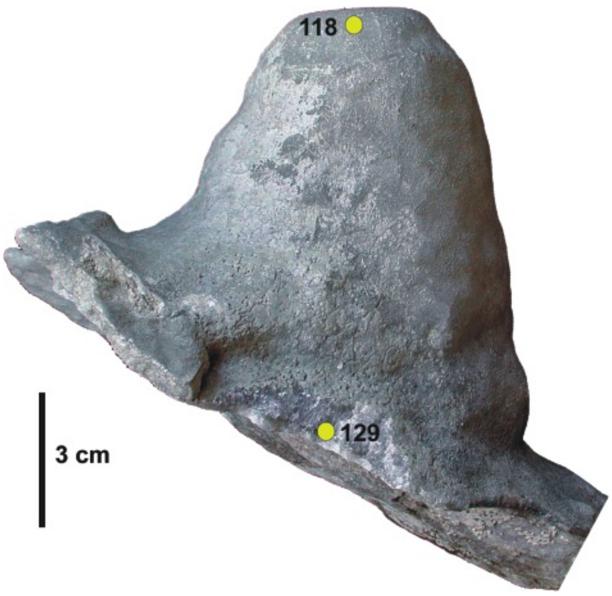


Figure 7: Stalagmite sample SPA 129, found in-situ in the Tropfsteingang, grew during the Last Interglacial (ages in kyr). The thin layer of gray clay on the left flank suggests either a short flooding event during the last glacial or deposition of dust.

Near Mausknochenschacht.- A stalagmite (SPA 146) was found in the sandy sediment and the top age of the sample indicates that this speleothem was removed from its base sometime after 180 kyr, i.e. subsequent to the end of the Penultimate Interglacial. Judging from the unaltered surface this specimen was not transported far from its substrate.

Sandschluf II. - An interesting stalagmite was found behind a ca. 10 m long, narrow crawl passage initially filled by sand almost to the ceiling. Sample SPA 121 was found detached from its substrate and its pitted surface attests some corrosion by aggressive water (Fig. 12). A detailed study of its internal stratigraphy (Spötl et al., 2008) revealed a long growth history which encompasses almost the entire Marine Isotope Stage (MIS) 7 (240-192 kyr), MIS 5.5 (129-118 kyr), as well as pulses of deposition until 76 kyr. The latter date provides a maximum age for the last strong hydrological event in this (main) gallery which apparently removed this stalagmite from its base.

Kolkgang. – This canyon leads westward down from the highest part of the cave (the entrance part, Fig. 2) and harbours a perennial cave stream whose discharge reaches several litres per second during peak snowmelt. The bottom of the Kolkgang and its upward (eastward) extension in the show cave part of Spannagel Cave cut up to a few meters into the impermeable basal gneiss and includes a series of potholes lined up in a string-of-pearl-like manner over a distance of almost 200 m. These potholes show diameters between 2 and 4 m and are filled up to their rims by fine-grained gravel and coarse-grained sand. Three potholes were excavated and yielded depths of 4-5 m (Fig. 13). The walls of some (unexcavated) potholes are covered by white, knob-like speleothems which also locally extend below the sand surface (Fig. 14). We dated two samples (SPA 43 and 134) from one pothole wall and obtained ages between 263 and 286 kyr. These high ages suggest that fluvial erosion subsequent to ca. 260 kyr was apparently insufficient to erode these deposits. This was a rather unexpected result given the fact that these speleothems grew inside the potholes, whose dimensions clearly testify erosion by a high-energy stream.

5. Discussion

We shall first assess the quality of the data and subsequently use these data to provide temporal and spatial constraints on the hydrological evolution of this high-alpine cave system.

5.1 Data quality

The quality of the data presented is regarded as fairly high given the fact that 17 individual speleothem samples were included (plus a few additional ones which were only mentioned briefly in the text because they replicate other samples at a given location in the cave). Although some galleries have not been sampled, this is a comprehensive data set, in particular considering the setting of this cave (many other high-alpine caves are largely devoid of speleothems).

The strength of the data set clearly lies in the exceptionally high U contents of Spannagel speleothems (several ppm to a few hundred ppm; sourced from the gneiss) coupled with negligible detrital Th giving rise to precise U-Th dates, even for very young material. In addition, there is no evidence of significant diagenesis even of allochthonous samples. We observed evidence of an alteration of the U-Th system in only one sample, where isotope values were shifted within a few millimeters of a prominent growth hiatus of a flowstone (Hoffmann et al., 2009). Stratigraphically correct U-Th-based age models of individual stalagmites (e.g., Spötl et al., 2008) also provide strong proof that the isotope system remained closed in all other samples.

5.2 Providing minimum age estimates of large-scale erosion features

Previous work by our group revealed that the majority of speleothem samples in Spannagel Cave are younger than ca. 350 kyr (Spötl and Mangini, 2007). Only very few samples yielded equilibrium values, i.e. ages in excess of 400 kyr. The validity of the U-Th dates was confirmed by U-Pb dating and one such sample yielded the currently oldest date in this cave system, 551 ± 10 kyr (Cliff et al., 2010; Fig. 15). These values provide constraints on the minimum age of these galleries, and it is interesting to note that this oldest (flowstone) sample was found in the highest part of the cave. Still, the main phase of phreatic conduit formation may be significantly older, and the lack of older speleothems may be attributed to the low preservation potential in such a glacial meltwater-influenced setting.

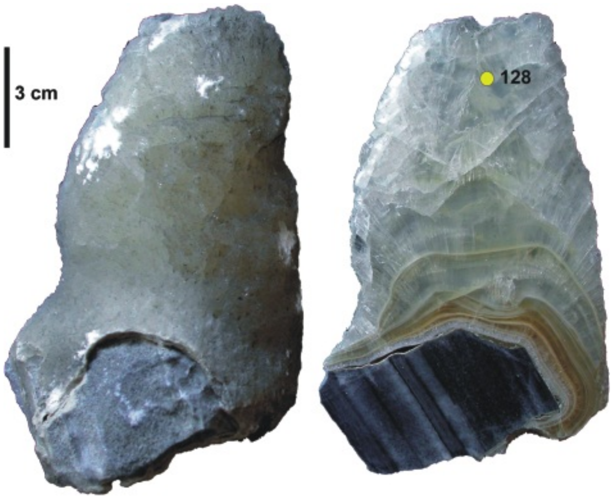
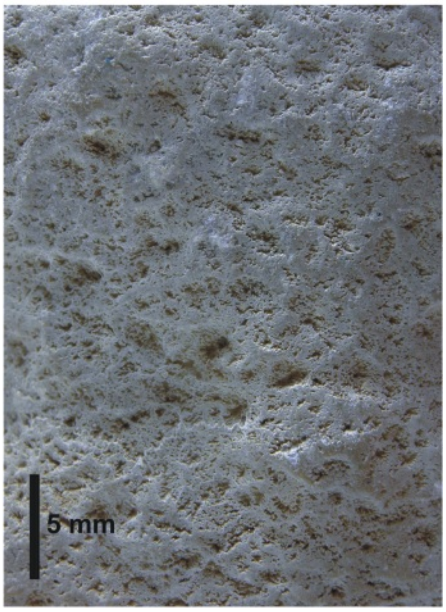


Figure 9: Stalagmite SPA 139 (outside left, polished slab right), found less than 30 m from SPA 51 (Fig. 10), was broken and exposed to aggressive water resulting in a dissolution-sculptured surface.

Figure 8: Unconsolidated gravel and sand in Spannagelhalle overgrown by stalagmites (yellow arrow) whose growth commenced 13 kyr ago. Red arrow points to active stalactites feeding the stalagmites. Inset: close-up of sample SPA 140 from Spannagelhalle which formed during the first part of the Holocene (ages in kyr).

Figure 10: Stalagmite SPA 51 was one of two samples found detached from its substrate behind the Nadelöhr in the northeastern corner of Spannagel Cave. Growth occurred during the Last Interglacial and a thin layer deposited on top constrains the maximum age of removal to < 56 kyr. Note abundant corrosion features on the surface of this sample (right photo is a close-up). The fresh fracture surface at the base of the stalagmite was produced during sampling.



The transition from phreatic to vadose speleogenesis also appears to have occurred at least a few hundred thousand years ago already. The most instructive piece of evidence in this respect is the Kolkgang gallery (Fig. 2), whose bottom is formed by a series of several-meter-deep and typically 2-3 m wide potholes aligned one after the other in a staircase-like manner. Although potholes have been reported to form locally even under phreatic conditions (Palmer, 2007), the geometry of the Kolkgang potholes and the fact that they are exclusively carved into the underlying gneiss (Fig. 13) convincingly argues for a vadose origin. Flowstone deposited inside one of these large potholes yielded U-Th ages between 263 and 286 kyr, i.e. these large erosional features must have formed earlier. And, the preservation of these old speleo-thems demonstrates that hardly any erosion has occurred in these potholes since then. The ancient origin of the Kolkgang gallery is consistent with observations made in the Spreizschlucht, a canyon downstream of the Kolkgang (Fig. 2). The bottom of this canyon is also formed by gneiss showing a few large potholes, but the upper parts are abundantly decorated by flowstone and stalagmites. U-Th dates indicate ages between 336 and 185 kyr (Spötl and Mangini, unpublished data) hinting again toward an old age of this canyon. In addition, these speleothems are typically white and clean, i.e. it is unlikely that this canyon was severely flooded after ca. 336 kyr, except for its bottom part.

While the apparent old ages of the Kolkgang and the Spreizschlucht canyons are consistent with their high elevation within Spannagel Cave possibly implying a successive lowering of the base level with time, the fact that three glacials (and their associated deglaciations) hardly left any erosional trace in the potholes is an astonishing finding. A paleoglaciological reconstruction suggests that Spannagel Cave was covered by ice during the Last Glacial Maximum (van Husen, 1987). Our data show, however, that the Kolkgang and the Spreizschlucht canyons did not act as conduits of high-energetic meltwater streams during this (and two previous) glacial maxima. Instead, the fact that all potholes are filled by loose, fine-grained gravel and coarse-grained sand (the same sediment on which 13 kyr-old stalagmites formed in the Spannagelhalle) suggests that only low-discharge streams occupied this upper part of the cave and washed clastic surface sediments into the subsurface karst system probably during the last deglaciation. Importantly, we never found clastic sediment successions underneath spe-

Figure 11: This inactive stalagmite (SPA 143) was found in growth position on a breakdown block at Märchenwelt in the western branch of Spannagel Cave. The brown loam stems from cavers who touched the specimen. The right picture shows the stalagmite after cleaning. Note smooth, uncorroded surface, demonstrating that this gallery was never flooded since the Last Interglacial (dates in kyr).

leothems >13 kyr old, except for very small and localized occurrences of partly cemented, coarse-grained gravel. Although undated, the isolated position of these pockets above the bottom on the galleries suggests that they once formed more extensive sediment fillings later removed by powerful streams.

Figure 12: This broken stalagmite (SPA 121) recorded a long growth history which is based on a total of 33 U-Th dates; only bottom and top dates (in kyr) are shown here. Note corroded surface (close-up on right side). The fresh fracture surface on the left side of the specimen was produced during sampling.

5.3 Constraining the age of past hydrological events

Although rare in the uppermost parts of Spannagel Cave, speleothems are more common in the western and in particular in the northern part of this cave, both of which are located at lower elevation compared to the entrance part (Fig. 2). These speleothems provide useful anchor points with respect to the hydrodynamic history of the cave.

The western branch of Spannagel Cave is composed of a series of subparallel tubes and canyons dipping beneath the formerly glaciated terrain of the Hintertux Glacier (Fig. 2). A few of these canyons show modern low-discharge streams (which follow the marble-gneiss boundary) and the presence of unconsolidated clastic sediment suggests similar or somewhat larger streams, e.g. during deglaciations. Monitoring of cave streams shows that hardly any clastic sediment is introduced from the surface into the karst system today. While the bottoms of these western canyons were apparently occupied by vadose streams in the geological past, speleothem data from Märchenwelt (Fig. 3) demonstrate that the upper parts of these passages, which partly preserve their initial phreatic morphologies, have remained unflooded since at least 119 kyr. This again points toward an old age of these conduits consistent with upstream data (e.g. Spreizschlucht).

A similar situation exists in the Tropfsteingang, a tributary passage of the main S-N trending branch of Spannagel Cave (Fig. 2). At this location, speleothems demonstrate that the upper part of the canyon has not experienced backflooding since the beginning of the Holocene and possibly since 129 kyr (Fig. 3). The latter estimate hinges on a single in-situ stalagmite, whose surface features preclude an unequivocal interpretation with respect to whether flooding has occurred since its deposition. Cave streams may have episodically occupied the deeper parts of the canyon (not anymore today) but the lack of speleothems prevents us from constraining the timing of this hydrodynamic process. On the other hand, two stalagmites found in unmodified phreatic tubes west of Tropfsteingang provide maximum ages for the time of their removal, i.e. 180 and 221 kyr (Fig. 3). Both were found associated with unconsolidated coarse-grained sand and do not seem to have been transported far from their original growth position. While the 180 kyr-old sample constrains the presence of a strong, erosive cave stream in today's dry galleries to the MIS 6 or younger, sample SPA 121 found in the main S-N trending branch helps to further elucidate the hydrodynamic history of this part of the cave. This stalagmite also recorded vadose conditions during MIS 7 until

Figure 13: A ca. 4 m-deep pothole carved into the gneiss beneath the marble (near-vertical view). The pothole is ca. 2.5 wide in the upper part and its diameter narrows significantly in the lower part. The sediment fill (gravel and sand) was artificially removed.

Figure 14: Thick, white flowstone covers the inner wall of a large pothole filled by sand (foreground). These speleothems, which extend beneath the sand as shown by digging, provide a minimum age estimate of the formation of these erosion features. Width of photo ca. 1.5 m.

192 kyr followed by a 60 kyr-long gap in deposition during which only a thin, white calcite layer was deposited, probably moonmilk (Spötl et al., 2008). There is no petrographic evidence suggesting dissolution of MIS 7 calcite; hence we conclude that this central part of the cave (near Sandschluf II – Fig. 2) was not occupied by a meltwater-fed cave stream during the Penultimate Glaciation. Growth continued at the same drip site during much of the Last Interglacial. Importantly, the top of the interglacial is marked by another hiatus with unequivocal corrosion features. This, and the presence of scattered angular, fine-sand size quartz grains at this hiatus strongly suggest invasion of turbulent stream water at this site probably during MIS 5.4 (Spötl et al., 2008). This episode was too short to damage the stalagmite, however, and calcite deposition continued in pulses until 76 kyr. This top age indicates that the cave stream, which removed this stalagmite from its substrate, entered this part of the cave during MIS 4 or later.

Data from the northernmost (and deepest) part of the northern branch of Spannagel Cave are consistent with these findings. There, two allochthonous stalagmites record the last phase of calcite deposition during MIS 5.5, while a third one, which also grew during this climatically benign period, recorded a much later episode of calcite at 56 kyr (Fig. 3). Consequently, this sample narrows the timing of meltwater invasion into the cave down to essentially MIS 3 or later. Stalagmite evidence from a nearby cave (Kleegruben Cave) located ca. 350 m below the entrance of Spannagel Cave demonstrates that vadose conditions persisted there during MIS 3 between 58 and 48 kyr (Spötl et al., 2006). Combining the maximum estimates from both caves with several Late-Glacial and Holocene basal ages of in-situ stalagmites from Spannagelhalle (Fig. 3) brackets this hydrodynamic event to between 48 and 13 kyr.

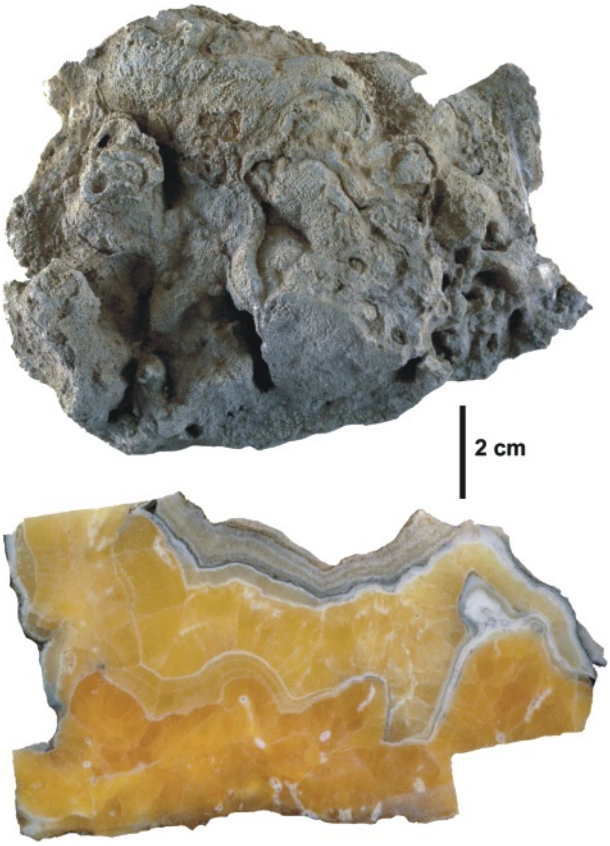


Figure 15: Outside (top) and inside (bottom) of a heavily corroded flowstone fragment (sample SPA 15) from the show cave part of Spannagel Cave which yielded the oldest radiometric age so far, based on U-Pb isotope data (see text).

6. Synthesis

The picture of the long-term hydrological evolution of Spannagel Cave emerging from the comprehensive data set of both autochthonous and allochthonous, well-dated speleothems can be summarized as follows:

- The origin of major canyons and erosional features therein dates back to well before ca. 0.5 million years before present. As a consequence, the initial phreatic morphologies, preserved in several places in this large cave system, must be significantly older. Using a long-term exhumation rate of 0.2 mm/yr for this part of the Tauern Window based on thermochronology data (Fügenschuh et al., 1997) the elevation of Spannagel Cave was ca. 500 m lower at the onset of the Quaternary 2.6 million years ago. Precision levelling data reveal a much higher modern uplift rate of this part of the Alps relative to the Bohemian Massif of ca. 1.4 mm/yr (Hofmann and Schönlaub, 2007). We therefore regard the 0.2 mm/yr rate as a conservatively low estimate for the last few million years and using even only slightly higher rates (also suggested by apatite fission-track data obtained from a water tunnel within 1 km of Spannagel Cave - Grundmann and Morteani, 1985) places the cave system well below the modern timberline in this region (which was likely higher before the onset of the Quaternary). We therefore suggest that the phreatic conduits of Spannagel Cave formed prior to the onset of Pleistocene glaciations and hence unrelated to glacier activity. We note in passing that conduit formation under phreatic conditions most likely takes place today in the same marble unit 3.5 km NNE of Spannagel Cave, where springs emerge in the village of Hintertux (Fig.1; Zötl and Goldbrunner, 1993). The elevated temperature of the water (12-22°C, mean annual air temperature 5°C) implies a deep-looping karst aquifer, likely controlled by the very steep dip of the marble at this location.

- Following exhumation, glacial erosion, and valley deepening, the water table was progressively lowered and the cave catchment became influenced by the growth and retreat of the mountain glacier. Conduits were re-activated by meltwater flows giving rise to vadose entrenchment and canyon development.
- Surprisingly little conduit modification by stream erosion and corrosion appears to have occurred within the U-Th dating "window", i.e. during the last ca. 400-500 kyr. This contrasts with the high rates of glacial erosion in surface environments (e.g., Hallet et al., 1996) and can be illustrated by a flowstone found in-situ at the entrance of a newly discovered cave near the left-lateral moraine ridge of Hintertux Glacier (the area became ice-free after ca. 1970). This flowstone formed 118 kyr ago, i.e. at the very end of the Last Interglacial (C. Spötl and A. Mangini, unpublished data). The cave chamber, in which it formed, has since been eroded by the glacier.
- An episode of (melt)water invasion in today's dry passages is constrained by broken stalagmites to subsequent to 48 kyr. None of these samples, however, shows evidence of strong fluvial erosion (e.g., scallopped surfaces) implying rather short-lived and/or only moderately energetic streams. Although we cannot rule out the possibility that ice flow may also have caused local damage of speleothems, clear-cut evidence for this process is lacking in Spannagel Cave. In addition, our previous work has shown that, despite its high-alpine setting, this cave has not been deeply frozen even during most glacial periods (Spötl & Mangini, 2007).
- Gravel and coarse-grained sand associated with these reworked stalagmite fragments are wide-spread in Spannagel Cave and represent till and fluvioglacial sediment which originated beneath the Hintertux Glacier. These coarse-grained cave sediments are overlain by 13 kyr-old stalagmites, i.e. this flooding occurred towards the end of the last glacial period and probably during the last deglaciation.
- Hydrological activity during the Holocene has been comparable to today, i.e. only a few low-discharge streams draining parts of the cave system.

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