Speleogenesis of the Hermannshöhle cave system (Austria): Constraints from $^{230}\text{Th}/\text{U}$ -dating and palaeomagnetic analysis

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Abstract: Hermannshöhle is a show cave located near Kirchberg/Wechsel in Lower Austria. Together with three nearby and genetically connected caves, it forms the Hermannshöhlen cave system (HHS). With a length of 5 km, the HHS is the longest cave in the Lower Austroalpine unit. It is arranged as an extreme three-dimensional maze on a ground area of 200 x 200 x 82 m. Speleothems are abundant in this cave and represent the focus of this study. Low carbon isotope values indicate the presence of a soil-covered catchment above the HHS during times of speleothem deposition. 28 samples were dated by the $^{230}\text{Th}/\text{U}$ -method and, in combination with palaeomagnetic data from a 5 m-high sediment profile, indicate multiple phases of sediment infill and erosion in the HHS. Although parts of the cave system are nowadays located at or below the level of the nearby Rams brook, they fell dry already at least 125 ka ago. The presence of 540 ka-old speleothems in the middle level demonstrate that this level of the HHS is at least about half a million years old, and the upper level is probably considerably older. A direct correlation between the cave and the modern surface morphology is therefore not possible. The observation that the palaeo-drainage direction in the HHS is perpendicular to the modern surface runoff also demonstrates the occurrence of a major reorganisation of the hydrological regime since the formation of the HHS. The new chronological data allow to constrain the evolution of the HHS as well as its catchment. An average valley incision rate of roughly 100 m/Ma was obtained, which is consistent with studies of other regions in the Alps unaffected by the Pleistocene glaciations. The spatial and temporal distribution of the dated speleothems as well as the lack of corroded flowstone indicate a single major speleogenetic period under phreatic conditions and support a continuous lowering of the groundwater table.

Keywords: speleogenesis, $^{230}\text{Th}/\text{U}$ -dating, palaeomagnetism, paragenesis, valley incision

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INTRODUCTION

Hermannshöhle is a speleothem-rich cave near Kirchberg/Wechsel in the South of Lower Austria, parts of which are developed as a show cave. Shaped like an extreme three-dimensional maze, Hermannshöhle is the longest cave in the Lower Austroalpine unit (Pfarr et al., 2014). Three neighbouring caves (Antonshöhle, Mäanderhöhle and Rauchspalten) appear to be genetically linked to Hermannshöhle (Hartmann et al., 1997; Schober et al., 2014). Together these caves form the Hermannshöhlen cave system (HHS), with a total corridor length of almost 5 km and a spatial extent

of only 200 x 200 x 82 m. The HHS is an example of a well-developed contact karst system. Besides some drip-water sites and a few pools, the cave system is vadose, although it reaches below the level of the nearby Rams brook at some points.

Several authors studied the speleogenetic evolution (Kempe & Mrkos, 1991; Mrkos, 1997) and the clastic sediments (Seemann, 1997) of the HHS. Seemann et al. (1997) reported results of eight speleothem samples from three different locations in the HHS, seven of which were analysed by ^{14}C and six samples also dated by the $^{230}\text{Th}/\text{U}$ -method (alpha-spectrometry). The radiocarbon values were inconclusive, and

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the $^{230}\text{Th}/\text{U}$ -ages ranged from about 42 to about 289 ka with very large uncertainties. A recent study (Schober et al., 2014), using modern approaches of speleogenesis (e.g., Klimchouk et al., 2000; Palmer, 2007), emphasises the role of paragenesis in the HHS cave formation.

This study focuses on the chronology of the HHS using state-of-the-art MC-ICP-MS $^{230}\text{Th}/\text{U}$ -dating of speleothems. In addition, a fine-grained sediment profile was investigated palaeomagnetically. Furthermore, the carbon and oxygen isotopic composition of speleothem samples was analysed. These data allow to constrain the evolution of the HHS in relation to the surrounding valleys and the long-term surface incision rate.

TOPOGRAPHIC AND GEOLOGIC SETTING

The HHS is located in the Eulenberg hill near Kirchberg am Wechsel in southern Lower Austria, an isolated block of weakly metamorphic (greenschist facies), banded calcite marble (Faupl, 1970; Seemann,

1997). These Middle Triassic carbonates (Tollmann, 1959; Herrmann et al., 1992) are mainly white to grey or greyish-blue, fine-crystalline and belong to the Lower Austroalpine Semmering-Wechsel-Unit (Schmid et al., 2008). For further details on the structural setting, see Schober et al. (2014).

The HHS was probably fed by the precursor of the Rams brook, which borders the Eulenberg in the East and originates in the non-karstic Palaeozoic gneiss-and-schist-complex, which adjoins the marble in the North (Fig. 1). Thus, the HHS represents an example of a contact karst setting (Fig. 2). Small ponors were observed in the Rams brook during river regulation, indicating a modern, actively draining karst system, which, however, is not accessible (Mrkos, 1997). The local base level, the Otter brook, is located in the Kirchberg valley south of the HHS and flows eastwards. This area is covered by Quaternary sediments (580 m asl) overlying the Neogene infill of the Kirchberg pull-apart-basin (Ebner et al., 1991). The tectonic basin was formed during the lateral extrusion of the Eastern Alps, the last major phase of the Alpine orogeny.

Fig. 1. Detailed geological map of the investigated area, modified after Schober et al. (2014). The white polygon indicates the modern catchment of the Rams brook above the HHS. The yellow frame marks the map shown in Fig. 2. Modified after Herrmann et al. (1992) using laser scan data, courtesy of the federal government of Lower Austria (coordinate system: UTM 33N).

SPELEOGENESIS, CAVE MORPHOLOGY AND SEDIMENTS

The following represents a short overview of the major speleogenetic features of the HHS. For a detailed map, measurements and discussion see Schober et

al. (2014). The most striking morphologic feature of the HHS is its maze pattern, which is unique in the Eastern Alps. It ranges from 597 to 679 m asl and extends in all three spatial directions with corridor sizes of all scales from non-passable up to 10 m in diameter (Fürstenhalle) and 16 m height (Großer Dom).

Fig. 2. Topographic overview map of the Hermannshöhle cave system and its surroundings (based on an unpublished cave map by Eckart Herrmann, 1989). Note the border between karstic carbonate and non-karstic crystalline rocks. The blue arrows indicate the westwards palaeo-flow, perpendicular to the direction of the present-day Rams brook and opposite to the Otter brook. Samples and sample locations are labelled. Modified after Schober et al. (2014).

Although virtually all passages are canyon-shaped, the cave shows exclusively phreatic features, and – in contrast to what has been suggested in earlier studies (e.g., Kempe & Mrkos, 1991) – no indications of a vadose or epiphreatic speleogenesis. A hypogenic origin of the cave was also considered, but apart from a few cupolas (e.g., at the upper entrance) no supporting evidence was found. The primary morphological micro- and mesoscale features are paragenetic in origin, dominating almost the entire cave (for a review on paragenesis, see e.g., Pasini, 2009; Farrant & Smart, 2011; Plan, 2013). Nearly all corridors are paragenetic canyons (Fig. 3), and most of the overhanging parts show well-developed paragenetic ceiling channels as well as pendants. Paragenetic dissolution ramps and paragenetic bypass tubes are abundant.

Scallops are abundant especially in the lower parts of the cave, indicating flow velocities of up to 1.5 m/s. Cross-cutting relationships show that the scallops are older than the paragenetic features (Schober et al., 2014). Scallops are mostly absent above 645 m asl, which could be due to a longer exposure to condensation corrosion at higher altitudes. The scallops and rare imbrication of gravels indicate a general westward directed palaeo-flow. This is surprising as the modern surface water discharges perpendicularly (Rams

Fig. 3. Upper part of a typical paragenetic canyon with remnants of clastic sediments below the ceiling on the right.

brook) and in the opposite direction (Otter brook), respectively (Fig. 2). The resurgence of the modern karst water would be expected at the south-eastern edge of the marble near the confluence of the Otter and the Rams brook. However, no springs are present there (probably buried by Quaternary sediments).

In virtually all cave passages the floor is covered by thick layers of clastic sediment or flowstone, which also clog many passages. Hence, the apparent cave floors that resemble storeys within the cave system do not provide information about the host-rock base of the gallery, thus concealing the true extension of the cave.

The extensive sediment infill presumably led to the formation of the extreme maze character (e.g., Farrant & Smart, 2011). Following pulses of clastic sediment input, the repeated clogging of preferred water paths favoured the enlargement of parallel corridors. Short flow paths within the cave system and high discharge along many alternate routes led to the equal widening of concurring corridors. Furthermore, the sheer presence of the sediment enhances the impression of a labyrinth: several ceiling canyons of individual conduits appear as independent features where the conduit is filled almost entirely by sediment. Remains of the extensive sediment fill are present throughout the cave system. Partly cemented relics of former sediment layers including sandstones and conglomerates can be observed all the way up to the

ceiling of many passages. The sediment contains mainly allochthonous components, i.e., schists and gneisses from the area north of the Eulenberg, as also shown by heavy-mineral analyses (Seemann, 1997). The grain size ranges from clay to cobbles with a diameter of up to 30 cm. Little autochthonous sediment is present, mainly consisting of local rock debris and only a few poorly rounded marble cobbles (Schober et al., 2014).

The HHS contains abundant active and inactive calcitic speleothems. These include flowstones, stalactites, stalagmites, draperies, coralloids, helictites, a shield, moonmilk, rimstone pools and calcite rafts.

METHODS

²³⁰Th/U-dating

30 speleothems from various locations within the Hermannshöhle and the Rauchspalten were sampled (Figs. 2 and 4). Three stalagmites as well as one flowstone were sampled using a hand-held cordless electric drill, extracting about 8 mm diameter cores. The remaining six stalagmites and 20 flowstones were broken from the wall (mainly at artificially enlarged parts of the tourist trail) using a hammer and chisel. Two samples were discarded during pre-sorting due to visible detrital contamination. The remaining 28 samples were cut with a diamond saw and processed for MC-ICPMS ²³⁰Th/U-dating. Sample preparation and

Fig. 4. Highly simplified longitudinal section of the Hermannshöhlen cave system (modified after Hartmann & Hartmann, 1997) showing the location of the dated speleothems. Locations of samples HH5, HH39, HH42, and HHX are projected onto the map. See Fig. 2 for a plan view of the cave system.

analysis were performed at the Max Planck Institute for Chemistry, Mainz, Germany, using a Nu Plasma MC-ICPMS. Briefly, the samples were weighted, dissolved in 7N HNO₃, and spiked with a mixed ²³³U-²³⁶U-²²⁹Th solution. Details on the calibration of the spike are given in Scholz et al. (2014) and Žák et al. (2012). The samples were then evaporated and treated with a mixture of concentrated HNO₃, HCl and H₂O₂ in order to destroy potential organic material. Then, the samples were dried down again, dissolved in 6N HCl, and U and Th were separated using classical ion exchange columns (see Yang et al. (2015) for details). A detailed description of the MC-ICPMS procedures is given by Žák et al. (2012). All activity ratios were

calculated using the decay constants of Cheng et al. (2000) and corrected for detrital Th assuming a bulk Earth ²³²Th/²³⁸U weight ratio of 3.8 for the detritus and ²³⁰Th, ²³⁴U and ²³⁸U in secular equilibrium.

Stable isotope analysis of speleothems

Samples for oxygen and carbon isotope analysis were hand-drilled from cut surfaces of speleothems as well as two marble samples. The analyses were performed at the University of Innsbruck using isotope ratio mass spectroscopy (ThermoFisher Delta^{plus}XL with Gasbench II). The results are reported in per mil on the VPDB (Vienna Pee Dee Belemnite) scale. See Spötl & Vennemann (2003) for further analytical details.

Palaeomagnetic analyses

A sediment profile at the end of Teichkluft (Fig. 2), a paragenetic canyon, was chosen for palaeomagnetic analysis. It is made up by a complex sequence of varicoloured clays (brown and purple colours prevail) and yellow micaceous clayey sands (Fig. 5). The profile is covered by a flowstone that was dated by the $^{230}\text{Th}/\text{U}$ -method (sample HH5). The cave wall is highly corroded, and the layered sediment sequence shows minor erosion features, such as small channels. In some parts, the sediment is coated by a Fe-Mn-crust. The profile has been disturbed by previous excavations, but several segments are still intact and suitable for high-resolution palaeomagnetic sampling (Bosák et al., 2003; Zupan Hajna et al., 2008). A total of 66 sediment samples and one speleothem sample were taken at intervals of 2 to 9 cm along a vertical range of 5 m. Unconsolidated sediments were sampled using 2 x 2 x 2 cm boxes (Fig. 5) made of nonmagnetic plastic (Natsuhara Giken Co., Ltd., Japan). The speleothem sample was cut to three 2 x 2 x 2 cm cubes in the laboratory. All specimens were sampled in oriented mode.

Fig. 5. Lower section of the sediment profile analysed for palaeomagnetism. The height of the scale is 80 cm.

The palaeomagnetic analyses were conducted in the Laboratory of Palaeomagnetism, IG CAS, v. v. i. in Praha-Průhonice. All samples were demagnetised by alternating field (AF), and one speleothem sample was demagnetised thermally (TD). The procedures were selected to allow the separation of the respective components of the remnant magnetisation (RM) and the determination of their geological origin. For a detailed description of the methodology of sampling

and data acquisition, processing and interpretation see Zupan Hajna et al. (2008).

RESULTS

$^{230}\text{Th}/\text{U}$ -dating

28 speleothem samples were dated by the $^{230}\text{Th}/\text{U}$ -method, three of which were measured twice (HH17, HH23 and HH24). The results are presented in Table 1. The samples show a broad age spectrum, ranging from approximately 1 ka (HH14) to >500 ka (HH7, HH23, HH24). These old ages (also including HH8 and HH39) approach the limit of the $^{230}\text{Th}/\text{U}$ -method (Scholz & Hoffmann, 2008), and should be considered as minimum ages. This is also reflected by their large analytical errors (Table 1). Some samples have a relatively large content of detrital ^{232}Th , which must be accounted for (Scholz & Hoffmann, 2008). This is reflected in a ($^{230}\text{Th}/^{232}\text{Th}$) activity ratio <5 and a relatively large difference between the corrected and uncorrected age (e.g., samples HH12 and HH13, Table 1). All ages of nearby samples that can be stratigraphically correlated are chronologically correct and are therefore considered trustworthy.

Although all known parts of the HHS are located above the regional water table, a few low lying sampling sites (Wasserschloss, Rauchspalten) are located at or even below the level of the Rams brook. We initially expected that these parts became vadose only recently, but the samples (HH32, HH33, HH35 and HHX) show remarkably old ages, indicating that those passages became vadose for the first time at least 125 ka ago already. In general, speleothem samples older than 125 ka are only present in higher cave parts.

At three locations (Ölberg, room with Wettertüre, Kyrlelabyrinth) it was possible to establish a stratigraphy of the flowstone layers that are separated by clastic sediments. The Ölberg section is developed in a paragenetic canyon and consists of a succession of four flowstone layers (false ceilings) showing relics of clastic sediments at their base. The uppermost (HH1/4) as well as the third layer from the top (HH1/2) were successfully dated, recording a time span of ca. 100 ka between these two samples (Figs. 6 and 7). After the sediment below the false ceilings had been eroded, small stalactites formed on the underside of the uppermost flowstone ceiling. One of these stalactites (HH1/5) yielded an age of 113.0 ± 1.8 ka, i.e., 87 ka younger than the corresponding flowstone it grew on. These data indicate that this part of the HHS had already become vadose ca. 300 ka ago and within a time span of ca. 190 ka the sediments were deposited and later eroded without significant corrosion of the false flowstone ceilings.

Stable Isotope Analysis

The stable isotope composition of HHS speleothems shows a large range, from -10.3 to +0.9 ‰ in $\delta^{13}\text{C}$ and from -10.7 to -4.8 ‰ in $\delta^{18}\text{O}$, but the majority of the data cluster between -9 and -3 ‰ in $\delta^{13}\text{C}$ and between -8.5 and -6.5 ‰ in $\delta^{18}\text{O}$ (Fig. 8). Values from modern speleothems (stalactites, thin flowstone deposited on

Table 1. Results of $^{230}\text{Th}/\text{U}$ -dating.

Sample	^{238}U [$\mu\text{g/g}$]	$\pm$	^{232}Th [ng/g]	$\pm$	$(^{230}\text{Th}/^{232}\text{Th})$	$\pm$	$(^{234}\text{U}/^{238}\text{U})$	$\pm$	$(^{230}\text{Th}/^{238}\text{U})$	$\pm$	Age un-corrected [ka]	$\pm$	Age corrected [ka]	$\pm$
HH01_2	0.1427	0.0009	65.8	0.7	7.210	0.084	1.1298	0.0092	1.100	0.012	317.3	+14.2/-12.1	306.3	+25.5/-20.1
HH1/4	0.442	0.003	42.7	0.4	36.36	0.34	1.3013	0.0046	1.1520	0.0061	201.5	2.8	199.7	3.4
HH1/5	0.362	0.002	56.4	0.6	17.98	0.19	1.3628	0.0081	0.9131	0.0062	116.1	1.3	113.0	1.8
HH5	0.766	0.005	67.6	1.0	32.13	0.51	1.1622	0.0033	0.9257	0.0098	164.8	3.9	162.8	3.9
HH6	0.158	0.001	0.161	0.002	2310.7	29.2	1.2271	0.0059	0.7682	0.0063	103.1	1.6	103.0	1.6
HH7 ^b	0.1392	0.0009	0.540	0.006	817.5	7.9	1.0341	0.0021	1.0381	0.0052	512.1	+89.6/-48.5	512.0	+83.4/-48.1
HH8 ^b	0.1275	0.0009	0.492	0.005	820.3	8.1	1.0339	0.0035	1.0359	0.0063	493.0	+105.7/-53.6	492.9	+103.5/-53.4
HH9 ^a	0.1111	0.0008	10.4	0.1	2.940	0.080	1.2191	0.0051	0.067	0.012	8.41	0.23	6.2	1.1
HH10	0.149	0.001	57.4	0.6	8.544	0.098	1.1085	0.0083	1.089	0.011	340.4	+24.4/-19.5	331.1	+31.0/-23.9
HH11	0.195	0.001	96.0	1.0	6.133	0.059	1.199	0.016	0.9845	0.0073	183.6	3.7	172.0	+7.2/-6.4
HH12 ^a	0.202	0.001	213.3	2.5	2.770	0.031	1.0287	0.0078	0.937	0.015	289.7	+13.4/-11.3	256.1	+21.9/-17.6
HH13 ^a	0.181	0.001	126.0	1.5	3.189	0.039	1.243	0.028	0.663	0.038	98.0	1.5	80.8	+7.7/-7.0
HH14 ^a	0.151	0.001	3.84	0.04	2.21	0.13	1.1774	0.0061	0.0118	0.0035	1.72	0.10	1.10	0.33
HH15	0.202	0.002	40.7	0.5	11.69	0.13	1.1634	0.0075	0.7593	0.0089	116.3	1.8	111.5	2.6
HH16	0.298	0.002	24.4	0.3	28.76	0.35	1.1057	0.0020	0.7666	0.0063	127.5	1.8	125.4	1.9
HH17	0.127	0.001	54.7	0.6	7.574	0.085	1.0806	0.0080	1.072	0.011	381.8	+38.2/-28.6	371.1	+46.4/-33.6
HH20	0.148	0.001	25.9	0.3	14.20	0.15	1.1785	0.0071	0.8018	0.0079	123.5	2.0	119.4	2.5
HH21	0.175	0.002	5.11	0.06	107.4	1.1	1.1605	0.0079	1.0235	0.0087	210.1	6.9	209.4	+7.4/-6.8
HH22	0.170	0.002	8.38	0.09	68.74	0.67	1.145	0.010	1.110	0.011	296.1	+23.1/-19.6	295.1	+23.2/-19.1
HH23 ^b	0.1587	0.0009	73.0	0.8	7.333	0.075	1.0908	0.0065	1.118	0.010	532.9	+85.2/-49.8	522.7	+235.3/-85.6
HH24 ^b	0.136	0.001	80.1	0.9	5.694	0.058	1.0837	0.0081	1.110	0.012	554.2	+135.3/-62.3	540.8	+286.1/-110.2
HH32	0.484	0.003	214.9	2.4	5.842	0.064	1.185	0.012	0.828	0.013	135.8	1.8	125.0	4.5
HH33	0.185	0.001	24.4	0.3	19.39	0.24	1.2198	0.0051	0.8296	0.0081	121.4	1.9	118.4	2.2
HH35 ^a	0.1270	0.0008	37.5	0.4	2.404	0.044	0.9751	0.0029	0.168	0.035	29.70	0.56	20.6	4.8
HH38	0.856	0.005	2.85	0.03	1331.9	11.8	1.4030	0.0018	1.4520	0.0052	319.3	5.7	319.3	5.8
HH39 ^b	0.288	0.002	1.84	0.02	538.2	5.5	1.0974	0.0022	1.1240	0.0063	495.6	+68.2/-41.5	495.5	+67.4/-41.7
HH42	0.923	0.006	44.8	0.5	65.77	0.68	1.0655	0.0023	1.0439	0.0059	351.4	+16.3/-14.2	350.2	+16.1/-13.8
HHX	2.00	0.02	36.78	0.4	129.38	1.17	1.1054	0.0057	0.7773	0.0053	129.2	2.1	128.7	2.1

^a very large detrital correction; ^b close to limit of the method.

artificial substrate) overlap with those from inactive speleothems. High $\delta^{13}\text{C}$ values approaching 0‰ suggest strong kinetic isotope fractionation and partly even overlap with the composition of the (marine-derived) host rock marble (Fig. 8).

Fig. 6. Sediment profile at the Ölberg paragenetic canyon. Within a time span of ca. 190 ka, episodic floodwater deposited and later eroded sediments as recorded by false sediment ceilings and stalactites formed beneath.

Fig. 7. Detailed view of the outcrop section as shown in Fig. 6. The ruler is 20 cm long.

Palaeomagnetism and magnetostratigraphy

A total of 69 oriented laboratory samples were studied for their palaeomagnetic properties (Table 2). Studied sediments are characterised by a natural remanent magnetisation (NRM) intensity between 0.31 and 44.79 mAm^{-1} and volume magnetic susceptibility (MS) values between 58.65 and 1392.93 $\times 10^{-6}$ SI units. The mean NRM and MS moduli values are listed in Table 2.

Fig. 8. The stable isotope composition of HHS speleothems scatters widely: green and yellow symbols represent fossil and active speleothems, respectively. Note strong kinetic isotope fractionation in some samples (high carbon isotope values). Data of host rock marble (orange squares) are shown for comparison.

The multi-component analysis of the remanence shows that the samples have a two-component RM. The A-component is undoubtedly of viscous (weathering) origin and can be demagnetised in the AF (0–5 up to 10 mT). The C-component is the most stable component against demagnetisation in the AF (15–40 up to 100 mT). For five samples, the C-component could not be determined. The mean palaeomagnetic directions of the C-components for the normal polarity are $D = 2^\circ$ and $I = 56^\circ$, and for the reverse polarity $D = 171^\circ$ and $I = -28^\circ$, respectively (Table 3).

The data allowed the construction of a detailed, high-resolution magnetostratigraphic profile (Fig. 9). A semi-continuous record of the magnetic and palaeomagnetic parameters was obtained for intervals of polarity change. Overall, the studied profile shows normal (N) polarized magnetisation and two very short polarity intervals (excursions) with reverse (R) polarity (at 0.41 m and 2.19–2.26 m above the base). Measurements of rock magnetic properties and anisotropy of the low-field magnetic susceptibility indicate mostly the presence of an oblate, low coercivity magnetic fraction, presumably magnetite. However, the R polarity interval at 2.19–2.26 m revealed also another, higher coercivity fraction. Its identity is unknown (probably higher haematite/goethite contents). Thus, this interval requires confirmation.

DISCUSSION

The results show that parts of the HHS must have become vadose already more than 500 ka ago. As these old speleothems were found at middle altitudes

Table 2. Mean value and standard deviation of the NRM and volume MS.

Hermannshöhle	NRM [mA.m ⁻¹]	MS x10 ⁻⁶ [SI]	Interval [m]*
Mean value	13.024	507.1	0.02 - 4.95
Standard deviation	11.074	364.4	
Number of samples	69	69	

* from base to top

Table 3. Mean palaeomagnetic directions obtained in the studied profile at the end of Teichkluff.

Sample No.	Polarity	Mean palaeomagnetic directions		α_{95}	k	n
		D	I			
HH002-495	N	1.98°	55.69°	4.96°	13.04	61
HH041; 219-226	R	171.45°	-27.95°	9.49°	54.24	4

N – normal polarity, R – reverse polarity; D, I – declination and inclination of the remanent magnetisation after dip correction; α_{95} – semi-vertical angle of the cone of confidence calculated according to Fischer (1953) at the 95 % probability level; k – precision parameter; n – number of analysed samples

Fig. 9. Palaeomagnetic properties of the studied sediment profile. NRM – natural remanent magnetisation; MS – volume magnetic susceptibility; D – palaeomagnetic declination; I – palaeomagnetic inclination; discriminant function of polarity zones (calculated after Man, 2008). Polarity: white – reverse polarity, black – normal polarity; hatched – not sampled.

within the cave system, it is likely that the upper parts, which are up to 40 m higher, are even older. Overall, it is evident that older samples are exclusively present in the higher parts of the cave, while younger ages are more common in lower cave sections (Fig. 10). Even low-lying cave passages, such as Wasserschloss, already became vadose at least during the Last Interglacial (ca. 125 ka), although they are located at or even below the level of the nearby present-day Rams brook.

The speleothems represent a minimum age constraint on the phreatic formation of the respective cave passage, and the data suggest a gradual lowering of the karst water table. (Fig. 10). Furthermore, HHS speleothems lack evidence of corrosion or other

damage suggesting that they were not affected by significant corrosion during subsequent flooding. The many residual false ceilings made of flowstone capping clastic sediments indicate extended quiet, vadose intervals between periods characterised by intense sediment transport, deposition and erosion. Therefore, clastic sedimentation and erosion appear to have been short events. No evidence of a long-term rise of the karst water table that had a significant influence on the passage morphology was observed. The only confirmed water table marks (by tube water level, see Schober et al., 2014) are located in the deepest parts of the HHS (Sandtunnel, Traumland). They seem to correspond to each other and can be explained by a local pool.

Fig. 10. $^{230}\text{Th}/\text{U}$ -ages of speleothem samples and their corresponding elevation in the HHS. Ages are shown with their 2-sigma analytical uncertainties (Table 1). The green lines indicate the derived valley incision rates.

Both the cave morphological study (Schober et al., 2014) and the radiometric data presented here suggest a single continuous phase of phreatic speleogenesis (Fig. 11). The $^{230}\text{Th}/\text{U}$ -dates of speleothems and detailed field work are inconsistent with a model of multi-phase speleogenesis (that lacks specific criteria

for its differentiation) as proposed by Kempe & Mrkos (1991). In our opinion, it is not possible to distinguish different phases of speleogenesis or cave levels. Epiphreatic and/or vadose speleogenesis cannot be ruled out, however, but clear-cut evidence has not been observed.

Fig. 11. Overview of the results of $^{230}\text{Th}/\text{U}$ -dating of speleothems and palaeomagnetism in relation to the evolution of cave formation, sediment deposition and erosion at each sampling site. Explanation: a: time in Ma before present; b: stratigraphic age; c: palaeomagnetic record; d: deep-sea oxygen isotope record (Cohen & Gibbard, 2011). The horizontal grey bars represent warm periods.

Speleothems from the HHS show low carbon isotope values (except some samples, which experienced kinetic fractionation probably due to very slow drip rates), which indicate that the seepage waters were derived from a soil-covered catchment. The oxygen isotope values also show significant scatter, part of which probably represents climate-driven variability. Most inactive samples show similar $\delta^{18}\text{O}$ values as the modern samples, but a few speleothems yielded significantly lower values, which suggest precipitation during cold climate periods. A thorough assessment of the climate significance of the HHS speleothems is planned for a separate article.

The profile at Teichkluft studied by palaeomagnetism revealed an overall normal polarisation with two short intervals of reverse polarity. The lower R polarity interval at 0.41 m represents a clear geomagnetic excursion. The palaeomagnetic directions (D, I) are very close to the present-day magnetic field. Therefore, the deposition of the studied sediments likely occurred within the N-polarised Brunhes chron (<780 ka) and the excursions of magnetic polarity might be correlated with the excursions of Jamaica-Pringle Falls (205–215 ka) and/or Calabrian Ridge 1 (315–325 ka; Langereis et al., 1997).

The investigated clastic sediment profile is capped by a flowstone (HH5) dated to 163 ± 4 ka, which supports the interpretation of the palaeomagnetic profile. Another $^{230}\text{Th}/\text{U}$ -age was obtained from a stalagmite at the tourist trail at the opposite end of Teichkluft (HH39; $495 \pm 67/-41$ ka), 31 m northwest and 8 m below the top of the Teichkluft profile. As this stalagmite probably grew directly on the bedrock and was partly covered by similar fine-grained sediments it can be interpreted as a maximum age for the clastic sedimentation of Teichkluft, which also supports the interpretation of the palaeomagnetic data. As it is close to the limit of the $^{230}\text{Th}/\text{U}$ -method the age could be even older. However, as Teichkluft lacks traces of corroded speleothems and the clastic sediments show only minimal erosion features, it is unlikely that the sediments of the investigated profile were responsible for the formation of the paragenetic evolution of Teichkluft. The profile seems to have already been filled and excavated at least once before the deposition of the dated clastic and chemical sediments.

Considering the hydrologic regime of the Eulenberg karst system, surface water could have infiltrated into the marble via ponors, sinks and joints. The logical emergence would have been located at its deepest point on the southeast face of the hill, at the confluence of the Otter and the Rams brook. However, the general palaeo-flow direction within the cave system – obtained from scallops and imbrications – was westward. This is perpendicular to the southward discharge of the modern Rams brook and opposite to the modern eastward flow direction of the Otter brook (Fig. 2). One model to account for this pattern is the presence of non-karstic bedrock (e.g., of the gneiss-and-schist-complex) or impermeable sediments (e.g., clay-rich Neogene infill) in the Southeast of the Eulenberg that have been eroded since then.

According to former studies (e.g., Waldner, 1942), it seems obvious that the evolution of the HHS is intrinsically tied to the development of the Rams brook as well as its breakthrough to the Kirchberg valley in the South (e.g., Waldner, 1942; Mrkos, 1997). Waldner (1942) postulated a former discharge of the Rams brook over the Eulenberg saddle towards the (South-)West. This assumption can neither be confirmed nor refuted. Since the Eulenberg saddle is considerably higher than the highest parts of the HHS, this evolution is not relevant for the known cave parts. It appears possible though, that Eulenberg and Kernstockwarte (Fig. 1) had been connected by a continuous marble ridge with a surface drainage into the karst system on the northwestern border of the marble. Despite the new data, it is not possible to determine since when the upper part of the Rams brook has been discharging mainly superficially.

The results of $^{230}\text{Th}/\text{U}$ -dating allow a first-order assessment of the average incision rate of the Otter brook. By assuming a linear correlation between the oldest ages of every sampled cave elevation, the lowering of the karst water table can be estimated. Sample HH17 is 350 ka older than sample HH35 and was obtained 29 m higher, resulting in an average linear incision rate of 83 m/Ma (Fig. 10). Five more samples within this time span plot close to this line, and three samples at ca. 640 m asl are on the extrapolated part of this line within their error bars. Alternatively, linear correlation between the altitudes of the modern Otter brook (575 m asl) and the oldest sample with a relatively small error (HH39, 642 m asl) results in a maximum average incision rate of 135 m/Ma (Fig. 10). Both rates are in agreement with data from the Mur valley (north of Graz, Styria, Austria), where Wagner et al. (2010) determined a valley incision rate of 100 m/Ma for the last 4 Ma using cosmogenic nuclide dating. In contrast, incision rates for the last ca. 0.8 Ma derived from caves in glaciated areas of central Switzerland are up to ten times higher (Häuselmann et al., 2007).

Extrapolating the rates obtained for the Otter brook also allows to estimate when the lowering of the karst water table affected the highest known parts of the HHS (Taubenloch, 679 m asl). Depending on the rate, the resulting minimum ages range from 0.76 to 0.92 Ma (Fig. 10).

CONCLUSIONS

The HHS, a nearly 5 km-long contact karst cave system, is outstanding due to its pronounced maze character and the dominance of paragenetic morphologies on various scales. It is developed in a low-grade metamorphic Middle Triassic marble and was formerly considered to have originated from an alternating succession of vadose and phreatic cave enlargement phases. We found no evidence to support this proposition, and all genetically relevant cave features can be attributed to epigene phreatic speleogenesis. Vadose speleothems are common in many parts of the cave system and include stalagmites, stalactites and flowstones. Their stable isotope

composition is consistent with calcite precipitation from seepage water derived from a soil-covered catchment. They do not show signs of corrosion nor erosion, thus indicating only a single major phase of phreatic cave development. Passages throughout the entire cave are filled with sediment to an unknown extent, thereby giving the false impression of various storeys.

²³⁰Th/U-ages of 28 speleothem samples range from 1 to about 500 ka and indicate that the HHS is at least half a million years old. Although parts of this cave system are nowadays located at or below the level of the nearby Rams brook, they have fallen dry at least 125 ka ago. Vadose speleothems formed in mid-altitude parts of the cave system since more than half a million years. As these and higher cave parts must be considerably older, a correlation with the modern surface topography is impossible. Moreover, the drainage pattern of the HHS indicates a westward palaeo-flow that is inconsistent with the modern topography and surface hydrology.

The speleothem ²³⁰Th/U-ages as well as the palaeomagnetic data from a sediment profile indicate multiple phases of sedimentation and erosion within the HHS. The spatial and temporal distribution of the dated speleothems as well as the lack of corroded samples suggest a single phreatic period of speleogenetic relevance and support a continuous lowering of the karst water table. The reconstructed valley incision rate of roughly 100 m/Ma is consistent with estimates from other non-glaciated catchments in the Alps.

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