GEOCHRONOMETRIA 32 (2008), pp 1-12
DOI 10.2478/v10003-008-0023-8

Available online at
versita.metapress.com and www.geochronometria.pl

EVOLUTION OF BRESTOVSKÁ CAVE BASED ON U-SERIES DATING OF SPELEOTHEMS

HELENA HERCMAN[1], MICHAŁ GRADZIŃSKI[2] and PAVEL BELLA[3]
[1]Institute of Geological Sciences, Polish Academy of Sciences, Twarda 51/55, 00-818 Warsaw, Poland
[2]Institute of Geological Sciences, Jagiellonian University, Oleandry 2a, 30-063 Cracow, Poland
[3]Administration of Slovak Caves, Hodžova 11, 031 01 Liptovský Mikuláš, Slovakia

Received 23 July 2008 Accepted 5 November 2008

Abstract: The U-series dating indicates five episodes of flowstone growth in Brestovská Cave, namely: ca. 200 ka, ca. 128-88 ka, ca. 82-65 ka, ca. 64-50 ka, and during the Holocene. The age of flowstones and their spatial distribution within the cave prove that the upper storey of the cave was dewatered before 200 ka. At that time the lower storey also existed and was able to carry the whole water flowing through the cave. It suggests that 200 ka ago the water-table was at similar level as it is at present. Hence, one should accept that the valley bottom was then also at the present level. During at least a part of the MIS 6 the growth of speleothems was possible in the cave. It suggests that the cave was located outside the permafrost zone then. Between 50 ka and Holocene, Brestovská Cave was flooded by invasion waters originating from the melting of the Würm glacier; the water-table was additionally raised due to the blockage of a resurgence by glacifluvial sediments. The flooding event caused the destruction of older deposits, including speleothems, and deposition of fine-grained clastics on the cave walls.

Keywords: U-series dating, speleothems, cave evolution, Slovakia, Tatra Mts.

1. INTRODUCTION

The cave deposits are important archives of geological past of karst regions. Among them the calcite speleothems are of great importance as they can be dated quantitatively by isotopic methods. The speleothems provide reliable palaeoenvironmental record bearing information about geomorphic development of a given karst region as well as about ancient climatic conditions there.

Dripstones and flowstones grow above the karst water-table in a vadose zone, that is above the bottom of a draining valley. Hence, the dating of such speleothems yields a minimum age of cave dewatering and, subsequently of a valley bottom entrenchment to a particular level. Such analyses were successfully conducted for instance in the Canadian Rocky Mountains (Ford, 1973; Ford *et al*., 1981), Great Britain Uplands (Gascoyne *et al*., 1983; Rowe *et al*., 1989), Scotland (Hebdon *et al*., 1997) and Buchan Karst area in Australia (Webb *et al*., 1992) as well as in the Carpathian Mountains (Hercman, 1991; Hercman *et al*., 1997).

Several studies reveal that speleothem growth correlates well with the warm and humid climate stages of Pleistocene (e.g., Thompson *et al*., 1974; Harmon *et al*., 1975; Atkinson *et al*., 1978; Baker *et al*., 1993; Hercman, 2000). It is due to the fact that their growth is dependent on the supply of water charged with Ca and HCO_3 ions, which in turn depends on the supply of soil CO_2 into the system. Hence, dating of speleothems provides information about the past climatic conditions.

The main aim of this paper is to present the recent dating results of the speleothem from Brestovská Cave (in Slovak Brestovská jaskyňa) and to discuss the significance of these results for the development of the cave as well as late Pleistocene history of the Studený Stream Valley (in Slovak Dolina Studeného potoka). The obtained dates also add new dimension to the discussion on

Corresponding author: H. Hercman
e-mail: hhercman@twarda.pan.pl

ISSN 1897-1695 (online), 1733-8387 (print)

palaeoclimatic conditions in the Tatra Mountains during the last 200 ka.

2. GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

Brestovská Cave is situated in the Western Tatra Mountains, on the western side of the Studený Stream Valley near the village of Zuberec (**Fig. 1**; Droppa, 1972). The cave is located near the mouth of the valley. The total length of the cave reaches 1450 m (Bella *et al*., 2007). The majority of the cave passages are developed within Anissian-Ladinian dolomites of the Ramsau type. Some series are formed within Eocene carbonate conglomerates lying discordantly on the dolomites (Vlček and Psotka, 2008). The dolomites belong to the Choč nappe that constitutes a part of the northern sedimentary cover of the Western Tatra Mountains crystalline core, the latter being composed mainly of metamorphic rocks (Nemčok *et al*., 1994). In the Studený Stream Valley between the Choč nappe and the crystalline core the relatively thin Lower Triassic clastics occur representing autochthonous cover of the crystalline core. The Eocene conglomerates are in turn covered by thick package of Eocene siliciclastics of flysh type, which crops out northwestward and northward from the cave. The passages are guided by fissures of W-E, NE-SW, NW-SE and NNW-SSE orientation or by the contact between the Triassic carbonates and Eocene conglomerates (Vlček and Psotka, 2008).

The upper part of the Studený Stream Valley was glaciated at least three times during the Pleistocene. The cave, however, occurs in the downstream part of the valley which probably was not glaciated at all (Halicki, 1929-1930; Mazúr, 1955; Halouzka and Rączkowski, 1993). Certainly, the Würm glacier did not reach this part of the valley. The preserved till deposits and moraine ridges are located upstream of the cave. Mazúr (1955) found them ca. 1.7 km from the cave, however Nemčok *et al*. (1994) placed them ca. 450 m from the cave entrance. The valley bottom near the cave is filled with glacifluvial coarse-grained clastics attaining thickness of more than 10 m (Halicki, 1929-1930). They were laid down during the recession stage of a glacier. Dolines were formed in the glacifluvial terrace over the cave (Droppa, 1972).

The passages of Brestovská Cave form two storeys (terminology after Palmer, 2000). The vertical extent between them varies between 5 and 10 m (**Fig. 2**). The lower storey carries water of a recent underground stream. The water inflows in the ponor zone located in a riverbed of the Studený stream at the altitude of 886 m. Additional water flows from off-valleys Volariská and Múčnica where ponors are situated at an altitude of 925-910 m and 976 m respectively (**Fig. 1**). The water flowing from the cave issues to the surface in the resurgence located ca. 250 m from the cave entrance. Both the ponors and resurgence are divided from the accessible part of the cave by unexplored water-filled passages.

The upper storey has undulatory profile formed during phreatic condition (**Fig. 2**; Bella, 2008). The downward apices of phreatic loops are filled with clastic sediments reaching in places the thickness ca. 1.5 m. The vadose remodelling of this storey is inconspicuous.

The lower storey consists of wide horizontal passages with underground stream divided by sumps, the deepest of which reaches 17 m (Hochmuth, 1984). The horizontal passages are phreatic in origin but they were strongly remodelled in vadose or epiphreatic conditions (Bella, 2008). The bottom of the passages is filled with allogenic

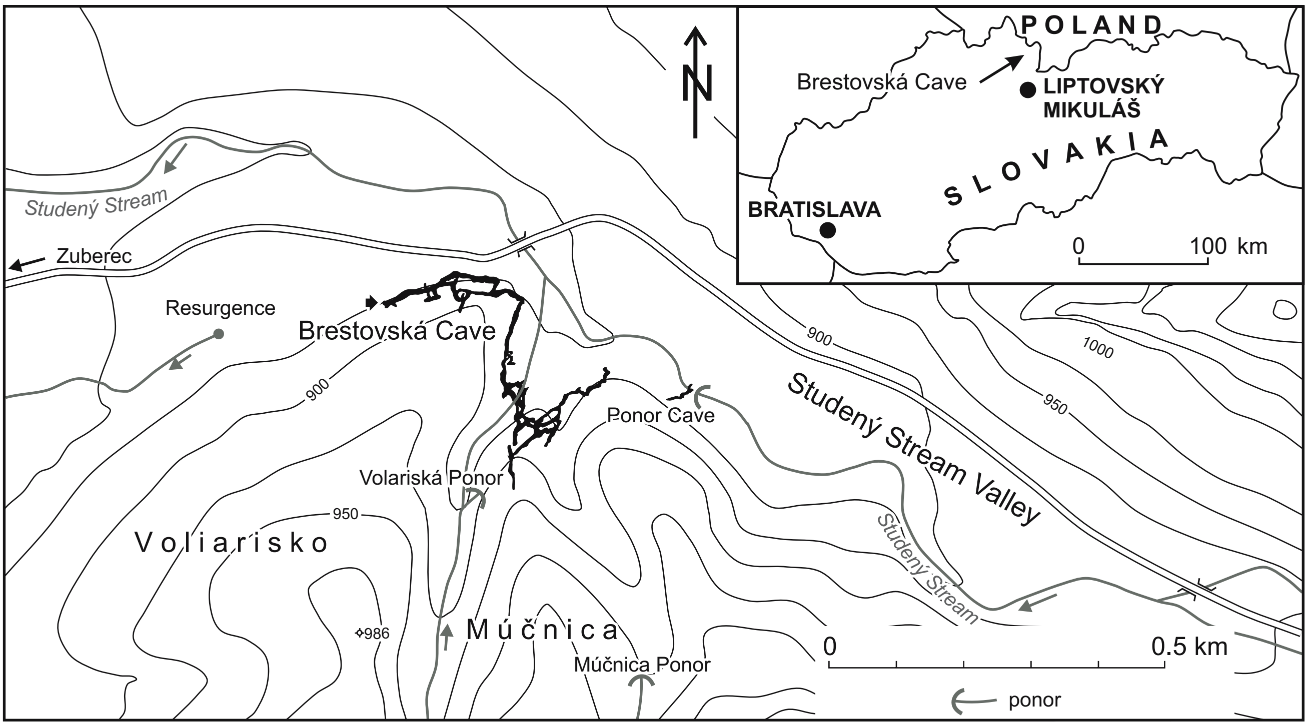

Fig. 1. *Location of Brestovská Cave.*

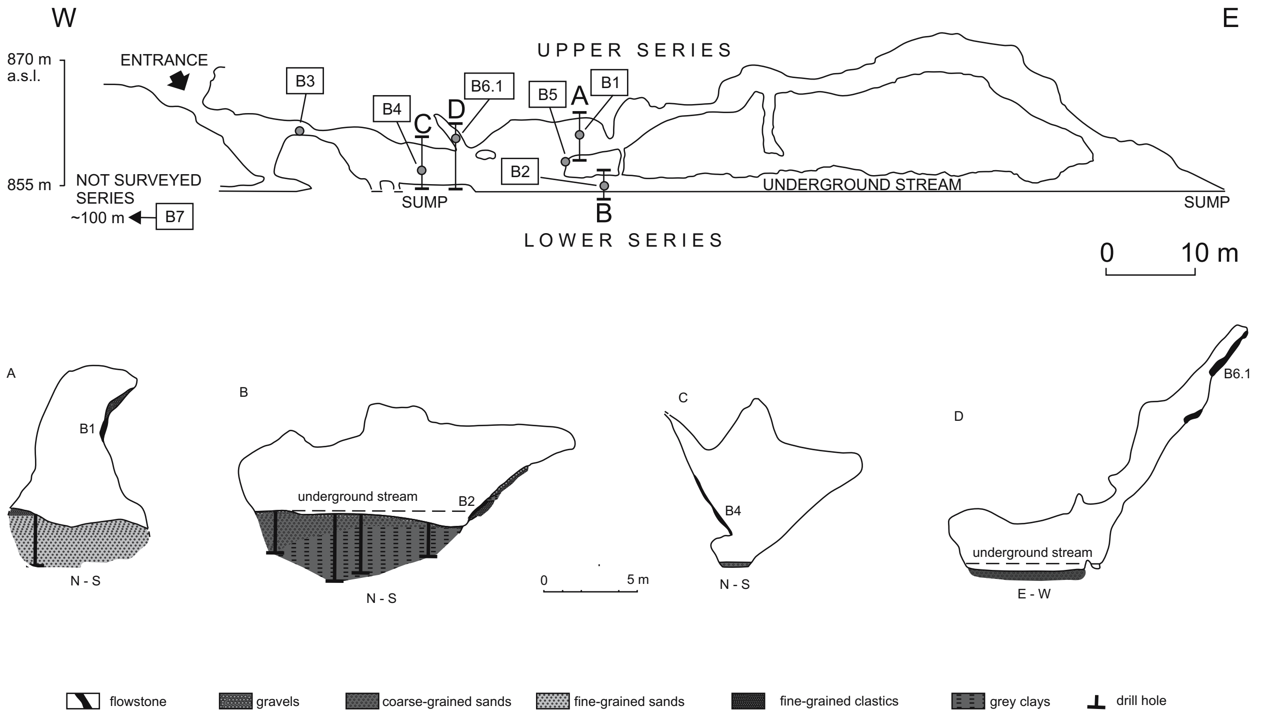

Fig. 2. *Schematic long-section of middle part of cave with location of sampled flowstone, cross-sections of chosen places depicts location of sampled flowstones and co-occurring clastic sediments.*

clastic deposits, whose thickness reaches 1.8 m. They consist of interbedded clay, sand and gravel. The gravel is up to 5 cm across, however the gravel between 1 and 3 cm dominates. It consists predominantly of clasts derived from various crystalline rocks which crop out in the upper part of the valley. In the lower section of the cave a fan built of cobbles occurs. The cobbles in question reaching more than 10 cm across are significantly of greater size than the clastics occurring in the riverbed. They were introduced from a doline occurring over the cave, and crept down to the cave.

Wójcik (1968) related the origin of the lower storey of Brestovská Cave to the main stadial of the Würm glacial stage. He also mentioned that the upper storey is slightly older and was significantly remodelled during this stage. Simultaneously, similar opinion was held by Droppa (1972), who also noted the possible rising up of water-table due to accumulation of glacifluvial sediments in the mouth of the valley.

3. MATERIAL

The cave is poor in speleothems, its walls are being predominantly bare. Only ten flowstones were selected for sampling. The majority of them were located in the upper storey (**Fig. 2**). Only one – labelled B2 – derived from the lower storey. This flowstone occurs in between grey clay approximately at the mean water level in the underground stream (see **Fig. 7**). Three flowstones B3.1, B3.2 and B3.3 occur on the bottom of the cave passage. They are fractured, rotated and displaced. Other flowstones survive in patches on the cave walls. **Table 1** presents basic characteristic of the flowstones (see also **Figs 3** and **4**).

4. METHODS

Collected flowstones were examined to find hiatuses and unconformities. The analysis was extended in some cases by the observation of thin section under the microscope.

All isotopic analyses have been performed at the Quaternary Geochronology Laboratory at the Institute of Geological Sciences, Polish Academy of Sciences. Samples have been cut for sub-samples for U-series analyses. Each of them contains 10-25 g of clean, compact calcite with no visible traces of detrital admixtures. Standard chemical procedure for uranium and thorium separation from carbonate samples has been used (Ivanovich and Harmon, 1992). ^{228}Th-^{232}U mixture (UDP10030 tracer solution by Isotrac, AEA Technology) has been used as a controller of the chemical procedure efficiency. U and Th have been separated by ion exchange using DOWEX 1x8 resin. After final purification, U and Th have been electro-deposited on steel disks. Energetic spectra of alpha particles have been collected using OCTETE PC spectrometer made by EG&G ORTEC. Spectra analyses and age calculations were conducted using "URANOTHOR 2.6" software, which is standard software developed in Uranium-Series Laboratory in Warsaw (Gorka and Hercman, 2002). Each spectrum was corrected for background, chemical and counting efficiency and delay since chemical separation. Uranium content in all samples collected in Brestovská Cave has been high enough for precise measurement (0.07-1.3 ppm). A few of the analyzed samples had significant non-radiogenic Th contamination but most of them were clean enough with ^{230}Th/^{232}Th activity ratio above 20 (cf. Schwarcz and Latham, 1989). Based on the dating results, the speleo-

Table 1. *Basic characteristics of flowstones from Brestovská Cave.*

Flowstone number	Maximal thickness (cm)	Lithology	Comments	Location
B1	>11	White, translucent subtle laminated, up to 2 cm thick intercalation of fine-grained clastics	Upper part strongly corroded; covered by few cm thick layer of uncemented fine-grained clastics	Upper storey, 7 m above riverbed
B2	2.9	Laminated calcite, predominantly brownish in colour, few laminae built by clear calcite	Under and overlain by fine-grained clastics	Lower storey, at the level of mean water-table
B3.1	8.5	Yellow laminated calcite	Bedrock clasts incorporated in lower part, flowstone corroded	Upper storey, loose block, 7 m above water-level
B3.2	11	Yellow laminated calcite with lens of coarse crystalline porous calcite	Bedrock clasts incorporated in lower part, flowstone corroded	Upper storey, loose block, 7 m above water-level
B3.3	15	Yellow laminated calcite	Bedrock clasts incorporated in lower part, flowstone corroded	Upper storey, loose block, 7 m above water-level
B4	3	Yellow laminated calcite	Upper part of flowstone strongly corroded with scallops, rocky wall below flowstone is covered with thin film of sand-sized clastics	Upper storey, 2 m above water-level
B5.1	2.5	Flowstone composed of three layers, translucent, white laminated and yellow laminated		Upper storey, 4 m above water level
B5.2	1	White, laminated flowstone		Upper storey, 4 m above water level
B6.1	16	Yellow to tan laminated flowstone	Flowstone strongly corroded	Upper storey, 4 m above water level
B7	1	White translucent calcite	Actively growing (?)	Lower storey, flowstone covering crystalline cobbles, 0.5 m above water level

them growth frequency curve has been constructed using the method elaborated by Hercman (2000).

5. RESULTS

Analytical results are presented in **Table 2** (see also **Figs 3** and **4**). Based on these results, five generations of speleothems formed in individual periods have been distinguished. The first generation was deposited at approximately 200 ka, the second between ca. 128 and 88 ka, the third between ca. 82 and 65 ka, the fourth between 64 and 50 ka, and the fifth during Holocene.

First generation

The first generation is represented only by the lower part of flowstone labelled as B3.3, whose age is about 200 ka (**Table 2**, **Fig. 3F**). It is a horizontally laminated flowstone which was found as a loose block in the present passage bottom. The sub-angular clasts of Mesozoic carbonates up to 4 cm across incorporated within the basement part of the flowstone indicate that the flowstone did not grow on a cave rocky wall but most probably on the bottom of the cave passage (**Fig. 3F**). The upper part of this flowstone constitutes the second generation. The generations are divided by neither a detritus layer visible by naked eye nor by corrosion surface distinguishable under a microscope. Only a small hiatus which marked the cessation in the growth of the flowstone is visible under a microscope (**Fig. 5**).

Second generation

The second generation is represented by samples B3.1, B3.2, B6.1 and upper part of B3.3 (**Table 2**). All of them are massive, laminated flowstones (**Fig. 3D, E, F, 4B**). They grew between 128 ka and 88 ka, however no particular speleothem comprising the whole time span was detected. It may have been caused by local factors preventing growth of particular speleothems and postdepositional corrosion which affected them.

Only the age of the lower part of the flowstone labelled as B6.1 could be dated. It falls within the range of 128 and 117 ka. It is impossible to obtain a U-Th age of the upper part of this flowstone because of later U mobilization. This is suggested by the low U content and enormous $^{230}Th/^{234}U$ activity ratio. Thus, the moment of cessation of this flowstone growth is not known. However, it is very probable that the flowstone in question grew after 117 ka. Thus, it coincides with other speleothems representing the second generation. The above view is based on the fact that the horizon dated at 117 ka is covered by 14.5 cm of flowstone without macroscopically visible hiatuses. The age of this part of the flowstone is unknown. Moreover, one should bear in mind that the upper surface of the flowstone is strongly corroded, which testifies that an unknown part of the flowstone has been dissolved (**Fig. 4B**).

Flowstones B3.1, B3.2 and B3.3 were collected in a scree littering the cave floor. Although the spatial relationship between them are not obvious, the obtained ages fall into the same time period taking into account 1σ error (**Table 2**, **Fig. 3D, E, F**).

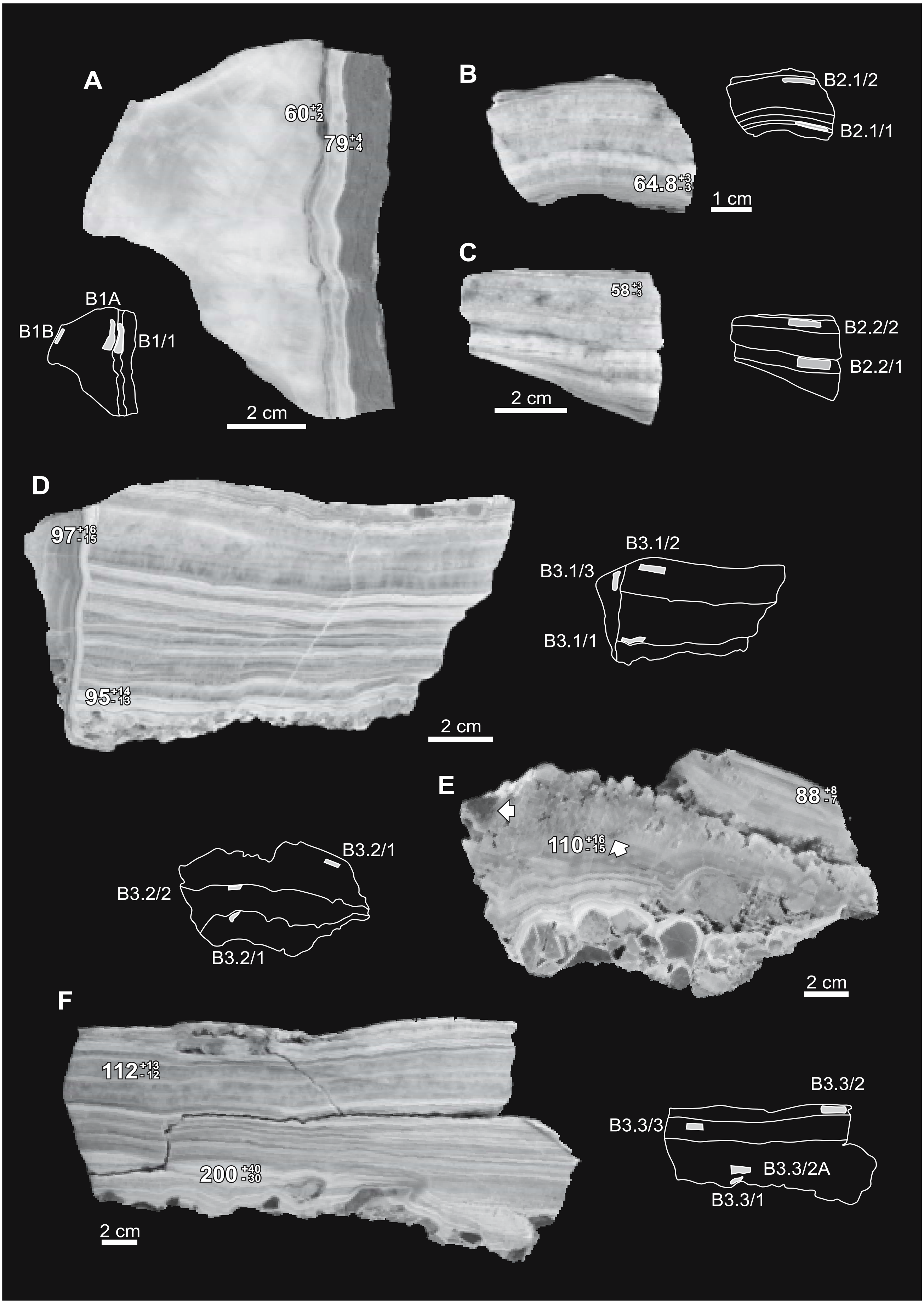

Fig. 3. *Analyzed flowstones: A – B1, B – B2.1, C – B2.2, D – B3.1, E – B3.2, F – B3.3 with location of sub-samples taken for dating; angular clasts of Triassic carbonates incorporated within flowstone are arrowed in E.*

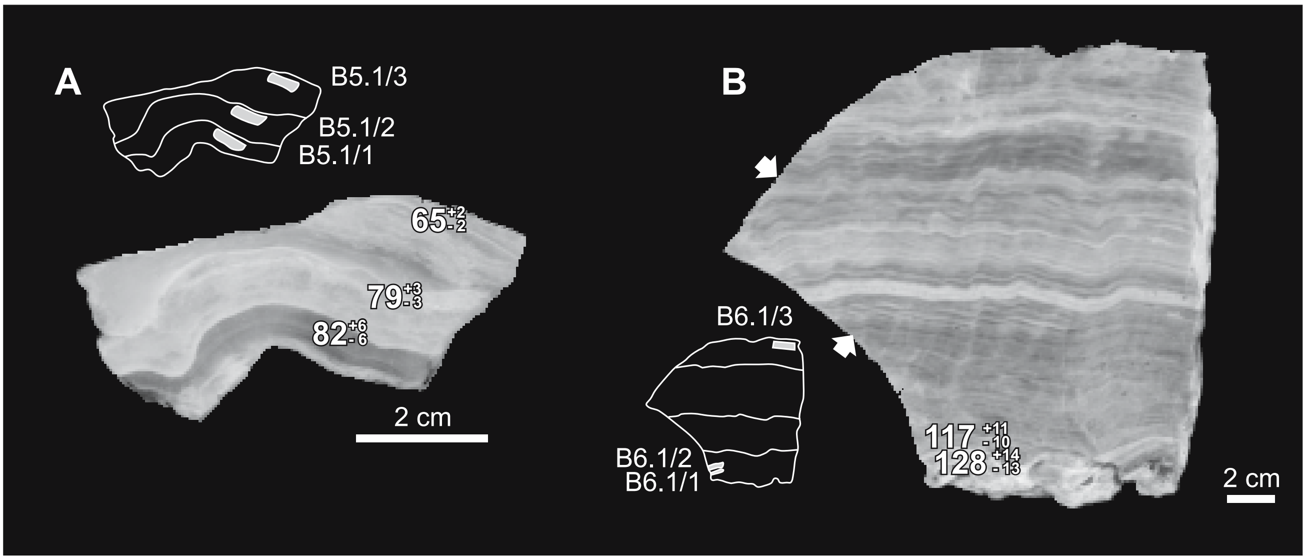

Fig. 4. *Analyzed flowstones A – B5.1, B – B6.1 with location of sub-samples taken for dating; post-depositional corrosion surface is arrowed in B.*

Bearing in mind the petrography of the flowstones, some changes of depositional condition must have occurred during their growth. The visible lens of upright growing sparry crystals in sample B3.2 deposited most probably in a small pond (cf. González *et al.*, 1992) may serve as an example (**Fig. 3E**). The flowstones in question underwent fracturing which is recorded in sample B3.1 (**Fig. 3D**). The fissure cutting the flowstone was immediately sealed with subsequent portions of crystallized calcite. The apparent reversal ages of the host flowstone and fissure filling is not significant because they overlap at 1σ error.

Table 2. *U-Th isotopic data used for dating of Brestovská Cave speleothems; DC – detrital contamination.*

Sample	Lab. No.	U cont. (ppm)	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$	Age (ka)	Comment
B1 A	W 1922	0.76±0.02	1.38±0.04	0.44±0.01	387	60±2	Lower layer
B1 B	W 1920	0.42±0.01	1.35±0.05	0.36±0.02	16		DC*; Upper layer
B1 / 1	W 1998	0.89±0.06	1.19±0.04	0.52±0.02	>1000	79±4	Below hiatus
B2.1 / 1	W 1919	0.79±0.03	1.52±0.05	0.46±0.02	20	64.8±3	Lower layer
B2.1 / 2	W 1921	0.80±0.03	1.54±0.05	0.46±0.02	13		DC
B2.2 / 1	W 1948	0.61±0.02	1.50±0.05	0.48±0.02	14		DC
B2.2 / 2	W 1947	0.82±0.03	1.54±0.05	0.43±0.02	20	58±3	Upper layer
B3.1 /1	W 2098	0.11±0.01	1.16±0.10	0.59±0.06	30	95^{+14}_{-13}	
B3.1 / 3	W 2100	0.09±0.01	1.14±0.11	0.60±0.07	53	97^{+16}_{-15}	
B3.2 / 1	W 2108	0.08±0.01	1.10±0.10	0.79±0.07	4.7		DC
B3.2 / 2	W 2109	0.07±0.01	1.21±0.11	0.64±0.06	48	110^{+16}_{-15}	
B3.2 / 3	W 2110	0.21±0.01	1.18±0.06	0.57±0.03	255	88^{+8}_{-7}	
B3.3 / 1	W 2102	0.050±0.004	1.10±0.11	0.70±0.07	13		DC
B3.3 / 2A	W 2104	0.075±0.006	1.18±0.11	0.87±0.08	291	200^{+40}_{-30}	
B3.3 / 3	W 2101	0.19±0.01	1.10±0.08	0.65±0.05	58	112^{+13}_{-12}	
B3.3 /2	W 2103	0.08±0.01	1.11±0.10	0.76±0.07	4.3		DC
B4.1	W 2111	0.22±0.01	1.14±0.06	0.38±0.03	208	50±4	
B5.1 /1	W 1982	0.89±0.06	1.24±0.06	0.54±0.03	85	82±6	
B5.1 / 2	W 2002	1.26±0.06	1.26±0.03	0.53±0.01	>1000	79±3	
B5.1 / 3	W 1983	0.92±0.03	1.31±0.03	0.46±0.01	>1000	65±2	
B5.2	W 1984	0.38±0.01	1.22±0.04	0.030±0.005	>1000	3.3±0.6	
B6.1 / 1	W 2105	0.12±0.01	1.15±0.07	0.71±0.05	24	128^{+14}_{-13}	
B6.1 / 2	W 2106	0.16±0.01	1.08±0.06	0.67±0.04	26	117^{+11}_{-10}	
B6.1 / 3	W 2107	0.023±0.002	1.22±0.17	2.57±0.3	40		Open system – U mobilization (?)
B7	W 2112	0.073±0.005	1.12±0.11	0.07±0.02	2.4	Holocene	DC

Third generation

This generation is represented by flowstone B5.1 and the lowermost part of flowstone B1 (**Table 2**, **Figs 3A, 4A**). Both flowstones started to grow directly on a cave wall approximately 82 and 79 ka respectively. The upper surfaces of flowstone B5.1 is corrosional while in sample B1 the lamina built of fine grained clastics divides flowstone into two parts and marks the upper boundary of the third generation.

Fourth generation

Flowstones B2.1 and B2.2 as well as B4 and the upper part of flowstone B1 constitute the fourth generation (**Fig. 3A, B, C**). The age of these flowstones falls between 64 and 50 ka (**Table 2**). However, it is very probable that these speleothems grew also later than 50 ka since the upper surfaces of flowstones B1 and B4 were strongly corroded. The corrosional surface testifies an advanced period of destruction, and dissolution of the flowstone youngest layers of an unknown thickness and age. It is recorded as scallops developed on the surface of flowstone B4 (**Fig. 6**). Flowstone B2 was most probably covered by clastic sediments immediately after its formation, which prevented it from corrosion by flowing water (**Fig. 7**).

Fifth generation

Flowstone B5.2 represents the youngest, fifth generation of Holocene age. Similarly, sample B7 seems to be Holocene in age, which is suggested by the low ratio of $^{230}Th/^{234}U$. Unfortunately, high concentration of detrital material caused more precise estimation of its age impossible. The thickness of Holocene speleothems is considerably smaller than that of the older speleothems.

6. CORRELATION OF FLOWSTONE GROWTH STAGES IN BRESTOVSKÁ CAVE WITH OTHER PALAEOCLIMATIC RECORDS

It is commonly accepted that speleothems grow especially vigorously during warm and humid climatic conditions. Hence, they are a sensitive palaeoclimatic tool. The constructed speleothem growth frequency curve based on 17 dates from Brestovská Cave generally fits with the curve built for the whole Carparthians (**Fig. 8**; Hercman, 2000). The successive speleothem generations correlate quite well with marine isotope stages (MIS, see Imbrie *et al.*, 1984; Martinson *et al.*, 1987). The first generation of speleothems in Brestovská Cave can be correlated with MIS 7. The second generation is related to MIS 5. More precisely, it coincides with substages MIS 5e-c. The third generation grew during the MIS 5a while the fourth one during the break of MIS 4 and 3 (**Fig. 8**). The fifth generation – the youngest one – is coeval with the MIS 1. However, some differences are observed, which are discussed below.

Almost uninterrupted, that is without traces of corrosion or higher supply of clastic material, the growth of flowstone 3.3 between MIS 7 and 5e, during the cold MIS 6, is difficult to explain. It implies that Brestovská Cave was located outside the permafrost zone during most of this time, which is less probable taking into account its location. Hercman (2000) distinguished the break of speleothem growth between 142 and 128 ka in Carpathian caves. The break was clearly marked with destruction of older speleothems and deposition of non carbonate silt. Similarly, Nowicki (2003) stated that there

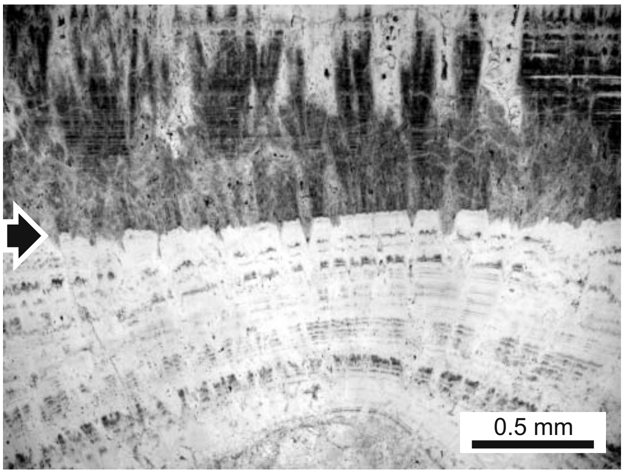

Fig. 5. *Hiatus (arrow) marking cessation of B3.3 flowstone growth, thin section, parallel nicols.*

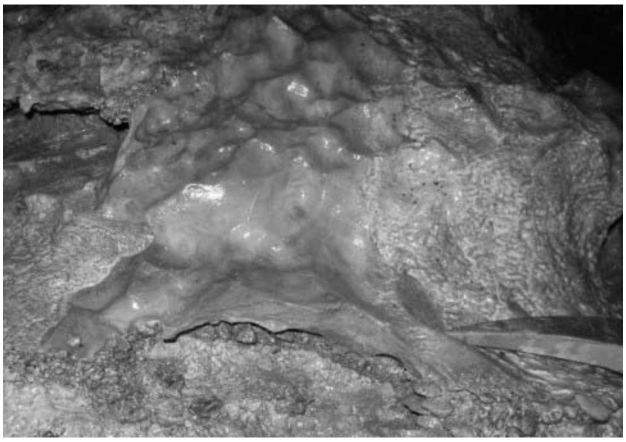

Fig. 6. *Flowstone B4 with scallops developed on its surface, hammer spike as a scale.*

Fig. 7. *Flowstone B2 sandwiched in-between fine-grained clastics.*

is a hiatus in speleothem growth in the Tatra Mountains between ca. 150 and 146 ka. On the other hand, he claimed that some speleothems could grow during that time. They include the stalagmite from Miętusia Cave which crystallized continuously between 170 and 130 ka. Analogously, in the Demänova Cave System, located in the neighbouring Low Tatra Mountains, speleothems representing MIS 6 have been found (Hercman *et al.*, 1997, 2006). A 12 cm thick flowstone from Demänova Ice Cave growing from 169 and 140 ka can serve as an example. Several speleothems growing also during MIS 6 are noted from the western European caves (Plagnes *et al.*, 2002 and references herein). Hence, the problem of determining whether speleothem growth during MIS 6 in Brestovská Cave is only local or regional phenomenon requires further work.

The second speleothem generation in Brestovská Cave originated during MIS 5e-c (**Fig. 8**). Conversely, earlier works pointed out a hiatus between MIS 5e and 5c in Tatra caves. Hercman (2000), basing on speleothem growth frequency curve, distinguished two phases of crystallization (III and IV) divided by a hiatuses (III/IV). It is possible that the hiatus recorded in other caves as a break in crystallization in Brestovská Cave was connected with changing of a hydrologic regime and intensification of water supply. It might have caused, for instance, a creation of a local rimstone pool where calcite crystals visible in flowstone B3.2 originated (**Fig. 3E**).

The short break in deposition, which was visible in flowstone B1 as a thin film of fine grained clastics and which caused the cessation of the growth of flowstone B5.1 correspond exactly to Hercman's (2000) hiatus V/VI lasting between 70 and 62 ka. She noted that a substantial amount of silt-sized clastics was introduced into speleothems in that time, which agrees with the record in Brestovská Cave.

There are strong differences in the textures of the speleothems constituting the fourth generation within Brestovská Cave. Flowstone B2 has a great admixture of fine-grained clastics while the isochronous upper part of flowstone B1 is built of clear calcite devoid of non carbonate fraction (**Fig. 3A, B, C**). On the one hand, it is concordant with the view expressed by Hercman (2000) and Nowicki (2003) that speleothems of this age grew in unstable conditions, and on the other hand, it confirms the general rule that the local site conditions can greatly influence the growth and texture of speleothems. The fourth generation of speleothems seems to be coeval with the break between MIS 4 and 3 (**Fig. 8**). Flowstones B1 and B4 are cut by corrosion surfaces, which suggests that their growth extended also to the whole of MIS 3. Brestovská Cave is not an exception in the Tatras. Speleothems of similar age were found in other Tatra caves. Głazek (1984) noted a flowstone from Miętusia Cave yielding an age of 60±5 ka, Hercman *et al.* (1998) described a stalagmite and flowstone displaying similar age from Szczelina Chochołowska and Nowicki (2003) from Naciekowa and Zimna caves. Speleothems yielding similar age are known for instance also from the Low Tatra Mountains (Hercman *et al.*, 2006) and Central Alps (Spötl and Mangini, 2002).

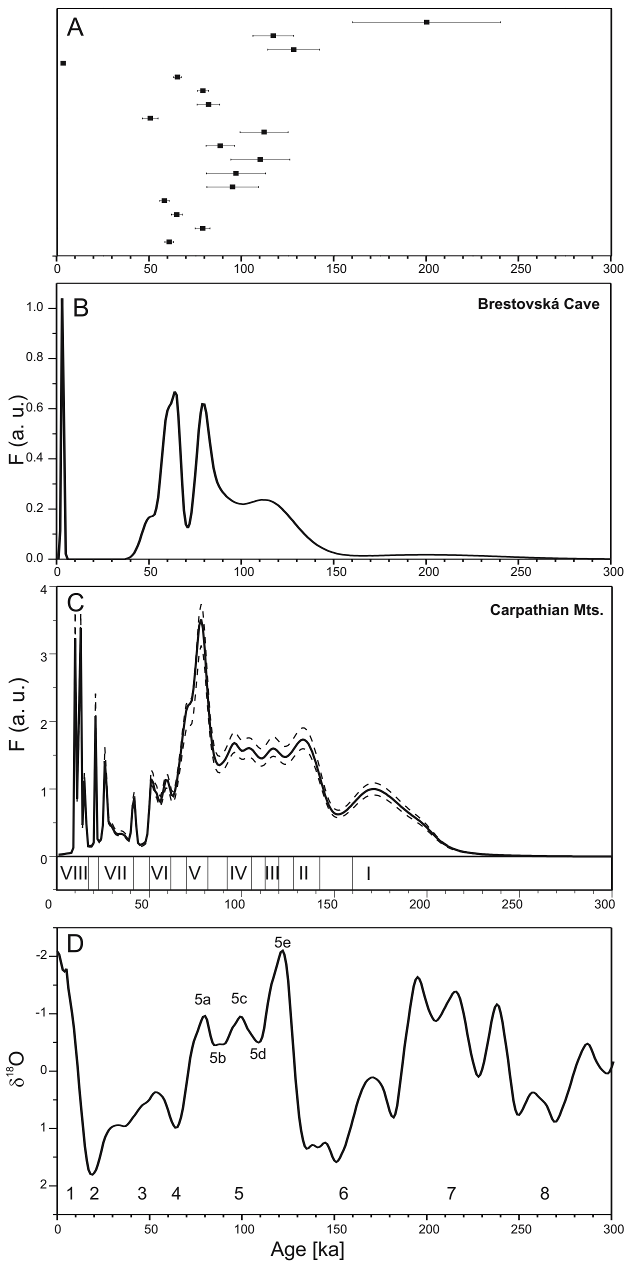

Fig. 8. *A – U-series dates from Brestovská cave, B – crystallization growth frequency of speleothems from Brestovská Cave, C – crystallization growth frequency of speleothems from Carpathian caves and phases of speleothem growth after Hercman (2000), D – stacked, smoothed oxygen-isotope record as function of age after Imbrie* et al. *(1984).*

The significant hiatus between 50 ka and Holocene is recorded not only as a cessation of speleothem growth but, above all, as a substantial corrosion of older speleothems. It affected flowstones B1 and B4 representing the fourth speleothem generation and probably other flowstones, for instance B3.1, 3.3, B6.1 constituting the second generation (**Figs 4B, 6**). The discussed hiatus mirrors the severe climate conditions of MIS 2. It seems to be of crucial significance for the present scattered pattern of flowstone distribution in Brestovská Cave. This aspect is discussed in detail in the further section.

7. EVOLUTION OF BRESTOVSKÁ CAVE

The ages of speleothems and their spatial arrangement within the cave shed new light on its. Both storeys of Brestovská Cave were created in phreatic zone below the water-table, however the lower storey was strongly remodelled and enlarged in epiphreatic and vadose conditions during subsequent stages of the cave (Bella, 2008). The upper storey shows the typical zig-zag profile and represents phreatic loops, partly dissected during the further stages of cave evolution (**Fig. 2**; cf. Ford and Ewers, 1978; Ford and Williams, 2007).

The upper storey of Brestovská Cave must have been dewatered earlier than 200 ka which is documented by the age of the oldest flowstone occurring there. The spatial arrangement of the cave passages suggests that the creation of the lower storey which captured the water drained the upper storey. Hence, the lower storey existed 200 ka ago and then it was able to carry all the water provided by ponors. It means that the lower storey passages were of substantial dimensions at that time.

It is not clear when a vadose zone reached the lower storey. The oldest flowstone found there is dated at 64 ka. The position of the flowstone implies that the lower storey has not been substantially enlarged since the flowstone crystallization. Taking into account the dimensions of the passages constituting the lower storey and the possibility of several episodes of deposition and subsequent sweeping away the majority of clastic sediments, it is very probable that the lower storey was of similar shape during the last interglacial. To sum up, the dating results clearly show that the cave was formed earlier than it was suggested by Wójcik (1968) and Droppa (1972) who ascribed the origin of the lower storey to the maximum of the last glacial and regarded the upper storey as "slightly older".

Age determinations of particular flowstones compared to their position within the cave make it possible to constrain the ages of individual stages of the cave development, especially between ca. 128 ka and the present times. The majority of the studied samples were derived from the upper storey hence the reconstruction concerns mainly this series of the cave.

During the MIS 5 e-c the conditions in the cave were favourable for the deposition of flowstones, which led to the crystallization of thick, massive flowstones B3.1, B3.2, B3.3 and B6.1. The lack of clastic layers and absence of distinct corrosion surfaces within these flowstones proves that at least the upper storey of the cave did not experience flooding during this time.

The flowstone growth was interrupted by the event of breakage and tilting or shifting of their dismembered fragments. These processes were recorded in flowstone B3.1 (**Fig. 3D**). They took place around 97-95 ka. The episode of speleothem destruction may be an effect of earthquakes (see Kagan *et al*., 2005 and references herein), instability of valley slopes after the deglaciation (see Wójcik and Zwoliński, 1959) or some local processes, as for example erosion of underlying clastic deposits. The angular clasts of Triassic dolomites incorporated into flowstone B3.2 during the same time period allows the exclusion of the last scenario (**Fig. 3E**). It seems significant that crushing of speleothems during a similar period was stated in the other Tatra caves. For instance, Hercman *et al*. (1998) described the fallen stalagmite with the postfallen regrowth from Chochołowska Szczelina cave. The stalagmite was destroyed between 117 ka and 95.8 ka. The above arguments imply that the episode of flowstone crushing recorded in Brestovská Cave might be connected not with a local phenomenon but with a regional one recorded also in the other Tatra caves.

The conditions for speleothem growth deteriorated between 88 ka and 65 ka. It is documented by the development of thinner flowstone covers, namely flowstone B5.1 and lower part of flowstone B1. The supply of clastic material increased in that time. It might have been transported by percolating water or by underground stream. The latter possibility demands a rise of water level in the cave of about a few metres, since the clastic horizons were found within the lower part of flowstone B1, and below flowstone B4, which are situated 7 m and 2 m above the present water-table respectively. The above scenario assumes that the position of the water-table was at that time similar to its present position.

The lower cave storey must have been partly dewatered around 64 ka, which is evidenced by the age of flowstone B2. The flowstone is located at least 2 m above the present rocky bottom of the passage presently covered by thick series of clays, sands and gravels (**Fig. 2**). The spatial relationship between the flowstone and the clastic sediments is unclear hence their temporal relationship remains an open question. One can, however, presume that the upper part of clastic sediments represented by sands and gravels is younger than flowstone B2.

After the deposition of the fourth generation of flowstones the cave underwent strong reshaping. The flowstones of the fourth generation, especially those situated in the upper cave storey were strongly corroded (**Figs 3A, 5**). The corrosion was recorded as scallops formed on flowstone B4 and irregular corrosion pits developed on flowstone B1. Older flowstones, especially the thick ones of the second generation are also strongly corroded probably during the same event (**Fig. 4B**). The episodes of their corrosion between 88 ka and 79 ka seem less probable, however they cannot be ruled out.

The corrosion of several flowstones after 50 ka strongly suggests the flooding of the cave which reached the upper storey. The water-table rose at least up to the heavily corroded flowstone B1. Thus, minimal flood amplitude equalled 7 m. It is documented by the vertical extent between the isochronous flowstones B1 and B2 (**Fig. 2**).

The flooding of the cave's upper storey also caused the deposition of the thick layer of clastics which covered flowstone B1. Bearing in mind its fine-grained composition, one can presume that the clastics were transported in suspension. They probably densely wrapped also the walls in other places of the cave's upper storey. The majority of these deposits were removed from the walls during the lowering of water-table or later by percolation water. The common occurrence of vermiculation structures on the cave walls reaching the level of about 12 m above the present water-table is a remnant of the former mud cover (Bella, 2008, see also Bini *et al*., 1978). During the flood the transport of coarse grained clastics, if any, must have been a short-lasting event. The scallops display perfect three-dimensional morphology. Their crests were not abraded, which would not be a case if the water had transported a load of coarse-grained resistant clastic material, for instance quartz grains (Ford and Williams, 2007, p. 259). Hence, it seems unlikely that the sandy deposits covering in some places the bottom of the passages on the upper storey originated during the same flood event. Presumably, they were deposited earlier, that is before 200 ka.

The discussed flooding of the cave occurred between 50 ka and the Holocene times. It suggests that invasion of water was an effect of the decline of the last glacial stage. Huge flows induced by glacier thawing have already been described from numerous other caves of the Tatra Mountains (Głazek *et al*., 1977), the Demänova Cave System (Hercman *et al*., 1997), those of the Matlock area in Derbyshire (Ford and Worley, 1977), and Castelguard Cave in the Canadian Rocky Mountains (Schroeder and Ford, 1983). In the case of Brestovská Cave the abrupt release of a huge quantity of water in the upstream section of the valley overlapped with the rising of a local base level (cf. Palmer and Audra, 2003). The latter process was caused by sedimentation of huge glacifluvial deposits forming a fan in the downstream section of the valley. The deposits in question blocked the resurgence located ca. 250 m downstream from the cave entrance (**Fig. 1**). It is impossible to estimate how long the water level was raised. The lack of flowstones in the lower storey passages, excluding the B2, implies that this storey was filled with water definitely longer than the upper one, which enabled the total corrosion of speleothems. During the Holocene the cave's upper storey and the parts of its lower storey were again dewatered since flowstones B5.2 and B7 were formed in that time. It might have been caused by the decrease of water supply into the cave and exhumation of the resurgence from glacifluvial deposits, which caused the unblocking of cave outlet section.

8. IMPLICATIONS FOR THE DEVELOPMENT OF STUDENÝ STREAM VALLEY

As the stages of a cave development are closely connected with the development of the position of the resurgence draining that cave, which in turn depends on an incision of a valley, one can reconstruct the history of the valley basing on the evolution of the cave. Since the lower storey of Brestovská Cave, which is still active now, has existed and carried the entire underground stream for around 200 ka, one can conclude that the valley was incised at that time approximately to the same level as at present. It is in line with the previous opinion presented by Hercman (1991), which concerned other valleys in the Tatras. The opinion was formerly based on TL and ESR dating of cave sediments and it was later confirmed by the Th/U dating (H. Hercman, unpublished data). Similar conclusions concenring the rate of valley deepening were achieved in the Low Tatra Mountains also by means of speleothem dating (Hercman *et al*., 1997).

Halicki (1929-1930, 1932-1933) estimated the Pleistocene incision of the Studený Stream Valley at 60 m. Taking into account the conclusions presented above, one can presume that the valley was deepened during the Early and Middle Pleistocene, while the last two glaciations did not cause significant further downcutting.

During MIS 6 the lower part of the valley, where the cave is located, seems to have been out of the permafrost zone. This is suggested by only a small hiatus between the first and the second generations in flowstone B3.3. The presence of the fourth speleothem generation confirms the view by Głazek (1984) that the most prominent glaciation in the Tatra Mountains during the Würm stage took place during the MIS 2.

The melting out of the last glacier in the Studený Stream Valley, most probably during the end of MIS 2, released a large quantity of water. It caused the deposition of a spacious outwash fan in the mouth of the valley which blocked the resurgence existing there. It resulted in the rise of the water-table and flooding of the cave by melt water. The water-table continuously decreased following the exhumation of the resurgence and the valley incision into the glacifluvial sediments. After the falling down of the water-table dolines started to develop in the outwash fan and they introduced the cobbles from glacifluvial cover into underlying cave passages.

9. CONCLUSIONS

1) The upper storey of Brestovská Cave became dewatered before 200 ka. The cave's lower storey existed in that time and was the main active karst conduit carrying water from ponors to the resurgence.
2) The lower storey was partly dewatered earlier than 64 ka. It was in the vadose zone during the last interglacial.
3) The water-table in the Studený Stream Valley is presently at the similar level as 200 ka. The bottom of the valley is also in similar position.
4) Brestovská Cave bears a record of five episodes of speleothem growth, that is ca. 200 ka, ca. 128-88 ka, ca. 82-65 ka, ca. 64-50 ka, and during the Holocene.
5) Between 50 ka and the Holocene, Brestovská Cave was flooded by invasion waters originating from the melting of the Würm glacier; the water-table was additionally raised due to the blockage of the resurgence by glacifluvial sediments. The flooding event caused the destruction of older speleothems and the deposition of fine-grained clastics on the cave walls.

ACKNOWLEDGMENTS

The help in field offered by the Slovak cavers, mainly: Vlado Mikula, Palo Staník and Lukaš Vlček is kindly acknowledged. Renata Jach is thanked for preparing the figures and Marek Kucharski for correcting the English text.

REFERENCES

Atkinson TC, Harmon RS, Smart PL and Waltham AC, 1978. Paleoclimatic and geomorphic implications of $^{230}Th/^{234}U$ dates on speleothems from Britain. *Nature* 272(5648): 24-28, DOI 10.1038/272024a0.

Baker A, Smart P and Ford DC, 1993. Northwest European paleoclimate as indicated by growth frequency variations of secondary calcite deposits. *Paleogeography, Paleoclimatology, Paleoecology* 100(3): 291-301, DOI 10.1016/0031-0182(93)90059-R.

Bella P, 2008. Morphology and origin of Brestovská Cave. *Slovenský kras* 46: (in print) (in Slovak, English summary).

Bella P, Hlaváčova I and Holúbek P, 2007. *Zoznam jaskýň Slovenskej Republiky*. (Register of Slovak caves). Liptovský Mikuláš, Slovenské múzeum ochrany prírody a jaskyniarstva: 362pp (in Slovak).

Bini A, Cavalli M and Gori S, 1978. A critical review of hypotheses on the origin of vermiculations. *International Journal of Speleology* 10: 11-33.

Droppa A, 1972. Karst on Sivý vrch. *Československý kras* 23: 77-98 (in Slovak, English summary).

Ford DC, 1973. Development of the Canyons of the South Nahanni River, N.W.T. *Canadian Journal of Earth Sciences* 10(3): 366-378.

Ford DC and Ewers RO, 1978. The development of limestone cave systems in the dimensions of lenght and depth. *Canadian Journal of Earth Sciences* 15(11): 1783-1798.

Ford DC, Schwarcz HP, Drake JJ, Gascoyne M, Harmon RS and Latham AG, 1981. Estimates of the age of the existing relief within the Southern Rocky Mountains of Canada. *Arctic and Alpine Research* 13: 1-10.

Ford DC and Williams PW, 2007. *Karst Hydrogeology and Geomorphology*. Boston, Unwin Hyman: 562 pp.

Ford TD and Worley NE, 1977. Phreatic cave and sediments at Matlock, Derbyshire. In: Ford TD, ed., *Proceedings of the 7th International Speleological Congress, Sheffield 1977*. Bridgwater, British Cave Research Association: 194-196.

Gascoyne M, Ford DC and Schwarcz HP, 1983. Rates of cave and landform development in the Yorkshire Dales from speleothem aga data. *Earth Surface Processes and Landforms* 8(6): 557-568, DOI 10.1002/esp.3290080607.

Głazek J, 1984. First isotope datings of speleothms from Tatra caves and their bearing on Pleistocene stratigraphy of the Tatra Mts. *Przegląd Geologiczny* 32: 39-43 (in Polish, English summary).

Głazek J, Rudnicki J and Szynkiewicz A, 1977. Proglacial caves - aspecial genetic type of caves. In: Ford TD, ed., *Proceedings of the 7th International Speleological Congress, Sheffield 1977*. Bridgwater, British Cave Research Association: 215-217.

González LA, Carpenter S J and Lohmann KC, 1992. Inorganic calcite morphology: roles of fluid chemistry and fluid flow. *Journal of Sedimentary Petrology* 62: 382-399.

Gorka P and Hercman H, 2002. *URANOTHOR v. 2.6. Delphi Code of calculation program and user guide*, MS, Archive of Quaternary Geology Department, Institute of Geological Sciences, PAS, Warsaw.

Halicki B, 1929-1930. La glaciation quaternaire du versant nord de la Tatra. *Sprawozdania Polskiego Instytutu Geologicznego* 5: 377-534 (in Polish, French summary).

Halicki B, 1932-1933. Quelques remarques sur l'évolution des vallées tatriques. *Sprawozdania Polskiego Instytutu Geologicznego* 7: 301-318 (in Polish, French summary).

Halouzka R and Rączkowski W, 1993. Kvartér. (Quaternary). In: Nemčok J, ed, *Vysvetlivky ku geologickej mape Tatier 1:50 000*. Bratislava, Geologický ústav Dionýza Štúra: 67-98 (in Slovak).

Harmon RS, Thompson P, Schwarz HP and Ford DC, 1975. Uranium-series dating of speleothems. *National Speleological Society Bulletin* 37: 21-33.

Hebdon NJ, Atkinson TC, Lawson TJ and Young IR, 1997. Rate of glacial valley deepening during the late Quaternary in Assynt, Scotland. *Earth Surface Processes and Landforms* 22: 307-315.

Hercman H, 1991. Reconstruction of geological environment on the Western Tatra Mts. based on isotopic dating of speleothems. *Zeszyty Naukowe Politechniki Śląskiej, Matematyka-Fizyka*, 66, *Geochronometria*, 8: 1-139 (in Polish, English summary).

Hercman H, 2000. Reconstruction of palaeoclimatic changes in central Europe between 10 and 200 thousand years BP, based on analysis of growth frequency of speleothems. *Studia Quaternaria* 17: 35-70.

Hercman H, Bella P, Głazek J, Gradziński M, Lauritzen S-E and Løvlie R, 1997. Uranium-series of speleothems from Demänova Ice Cave: A step to age estimation of the Demänova Cave System. *Annales Societatis Geologorum Poloniae* 67: 439-450.

Hercman H, Bella P, Gradziński M, Głazek J, Nowicki T and Sujka G, 2006. Results of U-series dating of carbonate speleothems from Demänová Cave System. In: Bella P, ed., *Výskum, využívanie a ochrana jaskýň* 5: 21-36.

Hercman H, Nowicki T and Lauritzen S-E, 1998. Development of Szczelina Chochołowska Cave (Western Tatra Mts.), based on uranium-series dating of speleothems.. *Studia Geologica Polonica* 113: 85-103 (in Polish, English summary).

Hochmuth Z 1984. Výsledky speleopotápačského prieskumu Brestovskej jaskyne. (Results of diving in Brestovská jaskyňa). *Slovenský kras* 22: 151–156 (in Slovak).

Imbrie J, Hays JD, Martinson DG, McIntyre A, Mix AC, Morley JJ, Pisias NG, Prell WL and Shackleton NJ, 1984. The orbital theory of Pleistocene climate: support from a revised chronology of the marine $\delta^{18}O$ record. In: Berger A, Imbrie J, Hays J, Kukla G. and Saltzman B, eds., *Milankovitch and Climate, Understanding the Response to Astronomical Forcing. Part I.* Dordrecht, Reidel: 269-305.

Ivanovich M and Harmon RS, 1992. Uranium Series Disequilibrium. Applications to Environmental Problems. Oxford, Clarendon: 571pp.

Kagan EJ, Agnon A, Bar-Matthews M and Ayalon A, 2005. Dating large infrequent earthquakes by damaged cave deposits. *Geology* 33(4): 261-264, DOI 10.1130/G21193.1.

Martinson DG, Pisias NG, Hays JD, Imbrie J, Moore TC and Shackleton NJ, 1987. Age dating and the orbital theory of the Ice Ages: development of a High-Resolution 0 to 300,000 year chronostratigraphy. *Quaternary Research* 27(1): 1-29, DOI 10.1016/0033-5894(87)90046-9.

Mazúr E. 1955. Beitrag zur Morphologie des Wassergebietes des Studený-Baches in der Liptauer Tatra. *Geografický časopis*, 7(1-2): 15-45 (in Slovak, German summary).

Nemčok J, ed., 1994. *Geological map of the Tatra Mountains*. Geologický ústav Dionýza Štúra, Bratislava.

Nowicki T, 2003. Ewolucja jaskiń systemu Lodowego Źródła w świetle datowania nacieków jaskiniowych metodą uranowo-torową. (Evolution of caves of Lodowe Źródło system in the Ligot of speleothem dating by means of U-Th method). Unpublished PhD thesis, Institute of Geological Sciences, Polish Academy of Sciences, Warszawa: 152pp (in Polish).

Palmer AN, 2000. Hydrogeologic controls of cave patterns. In: Klimchouk AB, Ford DC, Palmer AN and Dreybrodt W, eds, *Speleogenesis. Evoultion of Karts Aquifers*. Huntsville, National Speleological Society: 77-90.

Palmer AN and Audra Ph, 2003. Patterns of caves. In: Gunn J, ed, *Encyclopedia of Caves and Karst Sciences*. New York, Fitzroy Dearbon: 573-575.

Plagnes V, Causse C, Genty D, Paterne M and Blamart D, 2002. A discontinuous climatic record from 187 to 74 ka from a speleothem of the Clamouse Cave (south of France). *Earth and Planetary Science Letters* 201(1): 87-103, DOI 10.1016/S0012-821X(02)00674-X.

Rowe P, Austin T and Atkinson T, 1989. The Quaternary evolution of the South Pennines. *Cave Science* 16: 117-121.

Schroeder J and Ford DC, 1983. Clastic sediments in Castelguard Cave, Columbia Icefields, Alberta, Canada. *Arctic and Alpine Research* 15(4): 451-461, DOI 10.2307/1551232.

Schwarcz HP and Latham AG, 1989. Dirty calcites I: Uranium series dating of contaminated calcite using leachates alone. *Isotope Geoscience* 80(1): 35-43, DOI 10.1016/0168-9622(89)90046-8.

Spötl Ch and Mangini A, 2002. Stalagmite from the Austrian Alps reveals Dansgaard-Oechger events during isotope stage 3: Implications for the absolute chronology of Greenland Ice cores. *Earth Planetary Science Letters* 203(1): 507-518, DOI 10.1016/S0012-821X(02)00837-3.

Thompson HP, Ford DC and Schwartz HP, 1974. Continental Pleistocene climatic variation from speleothem age and isotopic data. *Science* 184(4139): 893-895, DOI 10.1126/science.184.4139.893.

Vlček L and Psotka J, 2008. Geology of Brestovská Cave. *Slovenský kras* 46: (in print) (in Slovak, English summary).

Webb JA, Fabel D, Finlayson BL, Ellaway M, Li Shu and Spiertz, H-P, 1992. Denudation chronology from cave and river terrace levels:

the case of the Buchan Karst, southeastern Australia. *Geological Magazine* 129(3): 307-317.

Wójcik Z, 1968. Geomorphological development of the limestone areas of the Tatra Mts. And other karst massifs in the Western Carpathians. *Prace Muzeum Ziemi* 13: 3-169 (in Polish, English summary).

Wójcik Z and Zwoliński S, 1959. Young tectonic displacement in the Tatra caves. *Acta Geologica Polonica* 9: 319-342. (in Polish, English summary).