Supplementary information to “No valley deepening of the Tatra Mountains during the last 300 ka”

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METHODS

Speleothem samples were analyzed using standard $^{230}\text{Th}/^{234}\text{U}$ disequilibrium techniques (e.g., Ivanovich et al., 1992). All chemical preparations were performed in clean laboratory conditions. Calcite samples were collected along speleothem growth layers, using a dental drill, from sites with no visible detrital admixtures or porosity. The thickness of the sampled layers was approximately 2 mm; the calcite mass was 100–300 mg. The sample powders were mechanically cleaned several times in an ultrasonic bath prior to chemical treatment.

Chemical separation of U and Th from the carbonate matrix was performed at the U-Series Laboratory of the Institute of Geological Sciences, Polish Academy of Sciences (Warsaw, Poland), using the standard procedure described by Hellstrom (2003). Following thermal decomposition of organic matter (6 hours at 800°C), a mixture of ^{233}U – ^{236}U – ^{229}Th (calibrated via the analysis of uraninite in secular equilibrium) was added to the samples before further chemical treatment. Calcite was dissolved in nitric acid, and any subsequent residuum was removed after centrifuging. U and Th were separated from the carbonate matrix via chromatography using TRU Resin. The isotopic composition of U and Th was measured at the Institute of Geology of the Czech Academy of Sciences (Prague, Czech Republic). Measurements were performed with a double-focusing sector-field ICP mass analyzer (Element 2, Thermo Finnigan MAT) operated at a low mass resolution ($m/\Delta m \geq 300$). A double-pass spray chamber with a Teflon nebulizer was used as the sample introduction system. A detailed description of the measurement techniques appears in Shen et al. (2002). Measurements were corrected for background count and a chemical blank. The internal standard and blank samples were prepared simultaneously for all series of studied samples

and were used for necessary corrections and quality control.

U-series ages were iteratively calculated from the $^{230}\text{Th}/^{234}\text{U}$ and $^{234}\text{U}/^{238}\text{U}$ activity ratios using the decay constants of Jaffey et al. (1971) (^{238}U), Cheng et al. (2013) (^{234}U and ^{230}Th), and Holden (1990) (^{232}Th). All uncertainties, except those associated with decay constants, were evaluated and taken into account when assessing age uncertainty using error propagation rules. The obtained ages of samples with $^{230}\text{Th}/^{232}\text{Th}$ activity ratios below 200 (Hellstrom, 2006) were adjusted for detrital contamination, indicated by the presence of ^{232}Th , using the typical silicate activity ratio $^{230}\text{Th}/^{232}\text{Th} = 0.83 \pm 0.42$, derived from the following activity ratios: $^{232}\text{Th}/^{238}\text{U} = 1.21 \pm 0.6$, $^{230}\text{Th}/^{238}\text{U} = 1.0 \pm 0.1$, and $^{234}\text{U}/^{238}\text{U} = 1.0 \pm 0.1$ (e.g., Cruz et al., 2005). The initial value of the $^{234}\text{U}/^{238}\text{U}$ activity ratio was calculated based on the corrected activity ratio and the corrected age of the obtained sample.

Age uncertainties are reported at the 2σ level. Generally, correction, in this case, meant subtraction of non-authigenic Th and U from the measurement results. As could be expected in the case of old samples, there were no significant differences between corrected and uncorrected ages, and these two values generally agreed in terms of the error range.

Speleothems in the Tatra Mts. - assessment of the U-series results

U-series geochronology on speleothems in the Tatra Mts. is subject to some complicating factors that can affect the analysis. The first issue is the low speleothem deposition rate in the Tatra Mts. For speleothems in general, minimum calculated deposition rates for stalagmites are as low as $1 \mu\text{m}/\text{yr}$ based on dating results and flowstone deposition rates are an order lower – as low as $0.1 \mu\text{m}/\text{yr}$ (Ford & Williams, 2007). In the Tatra Mts. there are few published speleothems dating results, but we can estimate minimal stalagmite growth rates as low as $0.6 \mu\text{m}/\text{yr}$ (Hercman, 2000; Kicińska et al., 2017). Hence, some ages presented below span a relatively wide range of time considering the absolute vertical separation within the speleothem profile. Yet, the calculated growth rates are within the range of general estimates published by Ford and Williams (2007) and other studies in the Tatra Mts. The extreme example of slow-growing stalagmite in the presented results is the DD1 sample. The ages of two dated samples, located ca. 10 mm one from other, differ by approximately 70 ka. It means that the mean growth rate for DD1 stalagmite was ca. $0.1 \mu\text{m}/\text{yr}$. In general, speleothems are extremely rare in the Tatra Mts. and they crystallized very slowly but for long periods. It suggests that conditions for most of the Quaternary were not very favorable for speleothem growth, but they were not bad enough to stop or prevent crystallization. Those conditions affect a number of samples that are possible to collect in the given context, but most

importantly, it affects the quality of the calcite in terms of U-series analysis. Porous or contaminated (detritus) layers are very common. The next important parameter is uranium content, which is usually low to extremely low. Its concentration depends on the lithology above the cave. Extremely low uranium content (< 0.1 ppm) is typical for caves developed in Jurassic-Cretaceous limestones (e.g., Kalacka Cave), while higher uranium content (> 1 ppm) is typical for caves developed in Middle Triassic or Cretaceous limestone. Even with several attempts, it is not always possible to obtain a subsample age despite well designed laboratory protocols and ICP-MS measuring procedures, so that even a single age obtained from a speleothem seems like important data.

S1. U-Th dating results for cave speleothems from Tatra Mts. (Poland).

Sample	Cave	Cave level	U cont. [ppm]	²³⁴ U/ ²³⁸ U AR*	²³⁰ Th/ ²³⁴ U AR*	²³⁰ Th/ ²³² Th AR*	Age uncorrected (ka)	Age corrected (ka)	Initial corrected ²³⁴ U/ ²³⁸ U AR*	Stratigraphy inside the speleothem
KM1/1	Kamienne Mleko	L0	0.486±0.002	1.255±0.004	1.028±0.007	7.44±0.05	355±15	344 ⁺¹⁷ ₋₁₆	1.66±0.08	Clast inside bottom layer of stalagmite
KM1/2	Kamienne Mleko	L0	0.345±0.001	1.296±0.005	0.996±0.006	65.6±0.7	292±12	291±15	1.67±0.09	Clast inside bottom layer of stalagmite
KM1/3	Kamienne Mleko	L0	0.3020±0.0007	1.268±0.004	0.928±0.006	89.9±0.7	231±5	230±5	1.51±0.04	Clast inside bottom layer of stalagmite
KM1/4	Kamienne Mleko	L0	0.375±0.002	1.277±0.004	0.883±0.006	51.3±0.3	200±4	199±5	1.43±0.04	Clast inside bottom layer of stalagmite
KM1/5	Kamienne Mleko	L0	0.430±0.002	1.268±0.004	0.927±0.004	100.5±0.6	230±5	229±5	1.51±0.03	Clast inside bottom layer of stalagmite
KM1/6	Kamienne Mleko	L0	0.2120±0.0006	1.258±0.006	0.81±0.01	110±2	164±5	163±5	1.41±0.04	Stalagmite – base above clasts
KM1/7	Kamienne Mleko	L0	1.220±0.004	1.375±0.003	0.744±0.004	1554±8	136±2	N.A. [†]	1.6±0.2	Stalagmite upper layer
KM1/8	Kamienne Mleko	L0	0.496±0.002	1.292±0.004	0.404±0.005	328±4	55.6±0.8	N.A. [†]	1.34±0.02	Stalagmite –top
SC-5-I - base	Szczelina Chocholowska	L1	1.284±0.006	1.149±0.005	0.988±0.006	279±2	323 ⁺⁹ ₋₈	N.A. [†]	1.37±0.04	Stalagmite base
SC-5-Ia - base	Szczelina Chocholowska	L1	0.838±0.005	1.181±0.005	0.99±0.01	44.2±0.5	325 ⁺¹⁸ ₋₁₆	312 ⁺²⁰ ₋₁₈	1.43±0.09	Stalagmite base (repeated analysis)
SC-5-I top	Szczelina Chocholowska	L1	1.008±0.005	1.178±0.003	0.857±0.009	724±9	193±4	N.A. [†]	1.31±0.03	Stalagmite top
SC-5-II base	Szczelina Chocholowska	L1	1.139±0.005	1.140±0.004	0.913±0.007	>10000	236±5	N.A. [†]	1.27±0.03	Stalagmite base
SC-5-II top	Szczelina Chocholowska	L1	1.452±0.007	1.215±0.003	0.824±0.007	>10000	173±4	N.A. [†]	1.35±0.03	Stalagmite top
SC-3 base	Szczelina Chocholowska	L1	0.834±0.003	1.165±0.002	0.989±0.005	1716±9	318±8	N.A. [†]	1.40±0.04	Stalagmite base
SC-3 top	Szczelina Chocholowska	L1	0.757±0.002	1.119±0.002	0.909±0.004	203±1	235±4	N.A. [†]	1.23±0.02	Stalagmite top
DD1/1	Dudzia Dziura	L1	0.0573±0.0004	3.05±0.02	1.05±0.02	39.0±0.4	243±7	238±12	4.9±0.3	Stalagmite lower layer
DD1/2	Dudzia Dziura	L1	0.0525±0.0003	1.808±0.009	0.94±0.03	22.3±0.7	209 ⁺¹⁶ ₋₁₅	203 ⁺¹⁸ ₋₁₆	2.4±0.2	Stalagmite central layer
DD1/4	Dudzia Dziura	L1	0.0283±0.0002	2.47±0.02	0.78±0.02	22.6±0.5	136±6	132±7	3.1±0.2	Stalagmite upper layer
W19.3B-1	Wysoka	L0	0.1264±0.0007	1.06±0.01	0.95±0.03	155±4	300 ⁺⁴² ₋₃₁	296 ⁺⁶⁶ ₋₄₂	1.1±0.2	shelfstone inner (older) layer
W19.3B-3	Wysoka	L0	0.1290±0.0007	1.112±0.005	0.894±0.008	31.7±0.3	225±6	222±7	1.21±0.04	shelfstone outer (younger) layer
WZS1-1	Wysoka	L1	0.1747±0.0009	1.353±0.004	1.036±0.006	6.88±0.03	334 ⁺⁹ ₋₈	323 ⁺¹² ₋₁₀	1.87±0.06	Stalagmite base
M2A/1	Miętusza	L2	2.24±0.01	1.047±0.002	0.996±0.003	68.0±0.2	425 ⁺¹¹ ₋₁₀	423 ⁺¹⁹ ₋₁₆	1.15±0.04	Flowstone basal layer
M2A/2	Miętusza	L2	2.28±0.01	1.083±0.002	0.909±0.003	17.7±0.04	242±2	236±3	1.16±0.02	Flowstone top layer
Bystra 1/1	Bystra	L0	0.1665±0.0006	1.538±0.006	1.06±0.02	14.9±0.2	333 ⁺³³ ₋₂₆	325 ⁺³⁸ ₋₃₂	2.3±0.2	Stalagmite base
Bystra 1/1a	Bystra	L0	0.1795±0.0006	1.569±0.006	1.06±0.01	80.9±0.8	327 ⁺¹⁵ ₋₁₄	321 ⁺¹⁵ ₋₁₄	2.4±0.1	Stalagmite base (repeated analysis)
Bystra 1c	Bystra	L0	0.2047±0.0006	1.614±0.005	1.019±0.008	66.6±0.5	264±7	270 ⁺⁹ ₋₈	2.30±0.08	Stalagmite middle layer
Bystra 1/2	Bystra	L0	0.1635±0.0003	1.626±0.006	0.951±0.009	52.4±0.5	219 ⁺⁶ ₋₅	218 ⁺⁷ ₋₆	2.15±0.07	Stalagmite top
Bystra 1/2a	Bystra	L0	0.1816±0.0004	1.698±0.004	0.985±0.008	584±5	239 ⁺⁶ ₋₅	N.A. [†]	2.36±0.06	Stalagmite top (repeated analysis)
Bystra B2	Bystra	L0	0.1292±0.0007	1.700±0.007	0.98±0.04	>10000	232 ⁺²⁵ ₋₂₁	N.A. [†]	2.3±0.2	Small stalagmite base
JK2.1/1 (+)	Kalacka	L1	0.1043±0.0004	2.626±0.012	1.12±0.02	34.5±0.3	301 ⁺¹³ ₋₉	300 ⁺¹² ₋₁₀	4.7±0.2	Flowstone basal layer
JK2.1/2 (+)	Kalacka	L1	0.0774±0.0001	1.829±0.005	1.052±0.006	26.7±0.1	283±5	280±7	1.88±0.06	Flowstone central layer
JK2.1/3 (+)	Kalacka	L1	0.0817±0.0002	1.832±0.009	1.03±0.01	58.5±0.5	267±7	265±8	1.86±0.07	Flowstone upper layer
JK2.1/4 (+)	Kalacka	L1	0.1194±0.0009	1.841±0.008	0.36±0.02	2.8±0.1	47±2	35±4	2.05±0.16	Flowstone top layer
TKS22	Kalacka	L1	0.0907±0.0002	2.73±0.02	1.02±0.01	190±2	228±6	227±6	4.3±0.1	Thin flowstone cowering limestone wall
Kal.-Syf.2	Kalacka	L1	0.0688±0.0001	1.365±0.005	1.020±0.009	5.01±0.04	307 ⁺¹³ ₋₁₂	292 ⁺¹⁴ ₋₁₃	1.83±0.08	Stalactite covered with clastic deposits
Gor.listwa	Goryczkowa	L1	0.0691±0.0004	1.36±0.01	0.91±0.02	6.6±0.1	210 ⁺¹³ ₋₉	200 ⁺¹⁴ ₋₁₂	1.63±0.10	Thin flowstone covering deposits
JKN2A/1	Kasprowa Niżna	L0	0.0464±0.0003	1.354±0.007	0.999±0.009	15.1±0.2	284 ⁺¹⁶ ₋₁₄	279 ⁺¹⁶ ₋₁₄	1.8±0.1	Core bottom from stalagmite basal layer
JKN2A/2	Kasprowa Niżna	L0	0.0798±0.0004	1.150±0.006	0.92±0.04	2.19±0.08	240 ⁺³⁴ ₋₂₆	199 ⁺³⁸ ₋₃₄	1.3±0.2	Core top from stalagmite basal layer
TKS16/3	Kasprowa Niżna	L0	0.1362±0.0003	1.958±0.007	0.986±0.008	166±2	228±5	226±5	2.80±0.06	Flowstone lower layer
TKS16/4	Kasprowa Niżna	L0	0.0880±0.0002	1.904±0.015	0.86±0.02	57±1	168±6	166±8	2.4±0.1	Flowstone upper layer
TKS9	Kasprowa Niżna	L0	0.1055±0.0005	2.26±0.01	1.01±0.02	214±3	228±9	N.A. [†]	3.3±0.1	Flowstone covering limestone wall

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Note: Reported age errors are 2σ .

*AR – activities ratio.

† = not applicable.

(+) – U-Th results from Szczygiet et al. (2019)

Samples with names in *italics* indicate replicate U-Th analysis for the same sample.

SAMPLE LOCATION AND GEOMORPHOLOGICAL CONTEXT

Bystra Valley

Speleothems from four caves in the Bystra Valley were studied. The modern karst drainage system of this valley operates through two main karst springs: Bystrej (draining the SW part of the valley) and Goryczkowe (S2), whose catchment of which covers the neighboring Sucha Woda Valley. The Bystra Cave acts as a “safety valve” for the Bystrej spring. The entrance functions as an outflow during flood conditions, which means the Bystra Cave represents an active epiphreatic cave belonging to the L0 cave level. In Bystra Cave, two stalagmites (Bystra 1 and Bystra B2) grown on residual clay deposits and covered by collapse blocks, were collected. Scallops were carved on the surfaces of the stalagmite. The samples originate from a causeway separating siphons with periodic water flow. This location is the best possible indicator of the phreatic conduit transition to the epiphreatic zone.

Kalacka Cave is an older counterpart of Bystra Cave (λ : 19°58'01,54", ϕ : 49°15'18,03"; 1192 masl), with paleophreatic conduits belonging to the L1 cave level, located ~75 m above the valley bottom. The detailed investigations of the clastic deposits and speleothems within the Kalacka cave were made by Hercman (1991) and Kicińska et al., (2017). In Kalacka Cave (λ : 19°58'00,65", ϕ : 49°15'22,67"; 1230 masl), three samples were analyzed: (1) JK2.1, the flowstone sample covering the cave walls from the main passage (Szczygieł et al., 2019); (2) TKS22, flowstone covering the clastic sediments; and (3) a small stalactite enveloped by younger clastic deposits in the siphon (Kal.-Syf.2) (S4). The sampling strategy was to date the oldest possible speleothem indicating the drying phase. However, the ages of the speleothems Kalacka cave are younger than those of the lower, and thus younger, Bystra Cave and show the potential for a complex history, including possible washing-out of the oldest speleothem generation. Kalacka Cave has been reactivated as a drainage conduit in its current position, as supported by the presence of asymmetric scallops (Kicińska et al., 2017) and speleothems buried in allochthonous fluvial sand in the cave e.g., Kal.-Syf.2.

On the east side of the Bystra Valley, a similar pattern was recognized, i.e., Kasprowa Niżna Cave (λ : 19°58'42,84", ϕ : 49°15'14,31"; 1228 masl) acts as a “safety valve” for the Goryczkowe spring, and the entrance functions as an outflow during flood conditions (Barczyk, 2003). Kasprowa Niżna Cave, apart from being fed with water overflowing from the Goryczkowe spring system, is recharged from ponors in the Kasprowa Valley (the upper eastern cirque of the Bystra Valley). Kasprowa Niżna Cave is an active L0 level epiphreatic cave. The detailed investigations of the

clastic deposits and speleothems within the Kasprowa Niżna cave were made by Hercman (1986, 1991) and Kicińska et al., (2017).

S2. Geologic map of the central part of Bystra Valley draped over a LIDAR shaded relief image. Geology after <https://cbdportal.pgi.gov.pl/smg/>; red dashed line represents the LGM trimline (after Zasadni and Kłapyta, 2014); yellow dashed lines represent profile positions shown in figure S5.

S3. a) Map of the Bystra Cave (source: <http://jaskiniepolski.pgi.gov.pl/>) with sample locations; grid: 50 m; b) and c) samples Bystra 1 and Bystra B2, respectively, with dated layers marked (see S1 for details).

In the Kasprowa Niżna Cave, core JKN2 was collected from the basal layer of a large (0.7 m high, 0.3 m wide) stalagmite. The stalagmite was broken (*ex-situ*), but its size and weight indicated that it had not been transported and that, at most, it fell from the adjacent walls. The absence of transport is also supported by the lack of bed material larger than sand-sized, indicating high flow conditions within the cave were insufficient to transport larger caliber material. The stalagmite surface shows signs of fluvial abrasion, such as scallops and diagonal rills. The stalagmite was found in a passage 12 m below the entrance, i.e., the valley bottom, and indicates a drop in the water table. The large

stalagmite is not only broken at the base, but also a quarter of the stalagmite is detached from the side, which allows us to observe its internal structure and reach its axis even with shallow drilling. The JKN2A core was drilled in the oldest part of the stalagmite, just above the limestone base. The shallow core is divided by a very thin brownish layer, which considering the long interval between samples JKN2A/1 and JKN2A/2, is interpreted as hiatus (S6).

TKS9 is a flowstone that covers the limestone cave wall. It was collected in the first sump, 12 m below the entrance. The TKS16 is a flowstone as well, located about 10 m below the entrance.

S4. a) Map of the Kalacka Cave (sourced: <http://jaskiniepolski.pgi.gov.pl/>) with samples location; grid: 50 m; b) and e) shows sampling sites before sample collection; c) and d) samples TKS22 and JK2 respectively, with marked dated layers (see S1 for details).

DR5. Morphological profiles across Bystra Valley (profiles lines on DR2) with Quaternary deposits thickness estimation: red area represents minimum thickness, and the yellow area represents maximum thickness. Schematic position of caves and sampling sites (blue stars) shows its relation to the local base-level

S6. a) Map of the Kasprowa Niżna Cave (sourced: <http://jaskiniepolski.pgi.gov.pl/>) with samples location; grid: 50 m; b), f), g) show samples with marked, dated layers (see S1 for details); d) and e) excavated stalagmite JKN2 with pointed borehole and zoom-in (c) for the basal part of the JKN2 stalagmite.

The youngest paleophreatic cave level, i.e., L1a within the Gorczykowie spring system, is represented by the Gorczykowa Cave (λ : 19°58'21,20", ϕ : 49°15'08,10"; 1263 masl), suspended ca. 50 m above the valley bottom (Hercman, 1991; Szczygieł et al., 2015a; Kicińska et al., 2017). Here, flowstone-covered clastic sediments were collected (sample: Gor.listwa). As in the case of Kalacka Cave, our sampling strategy targeted the oldest speleothems; however, with the flowstone ages of 200 ka, the cave's history must be more complicated.

S7. a) Sample Gor.listwa with a marked dated layer (see S1 for details); b) Map of the Goryczkowa Cave (sourced: <http://jaskiniepolski.pgi.gov.pl/>) with samples location; grid: 50 m.

The relationship between the surface of the Quaternary deposits and the bedrock valley floor) is the most complicated in the Bystra valley. Here, caves entrances belonging to the L0 cave level were covered by glacial ice during the Last Glaciation (and likely previous glaciations). Also, here the Quaternary deposits are the thickest among the three studied valleys. Quaternary deposits cover the valley bottom and reach a thickness of 40 m above the valley bottom (S2). Morphological profiles have been determined through outcrops, or near them, to estimate the plausible minimum and maximum thickness of the Quaternary deposits. Our estimate is based on the delineation of U-shaped valley bottom between bedrock slopes and exposures of bedrock within the Quaternary deposits. The estimation is interpretative; nonetheless, bedrock cropping out in the broader part of the valley suggests rather small thickness of glacial deposits present below the modern valley floor (S2 and S5, profile AA'A"). Also, bedrock exposures located in sinkholes (as point A' in S2), which are not positive morphological forms, seem to support the above arguments.

Samples in the Kasprowa Niżna cave were collected from 10-12 m below the entrance (1218-1216 m a.s.l.), while the lowest possible position of bedrock in the valley floor is 1206 m a.s.l. (S5).

Samples in Bystra Cave were collected 13 m above the entrance, i.e., 1195 m a.s.l. The position of the local base-level was estimated in the range of 1152 to 1159, considering the maximum and

minimum valley fill scenarios. The speleothems analyzed were then located ca. 30 m above the local base level. However, it should be taken into account that speleothems in the Bystra cave are documented also ca. 10 m below the entrances. Although, we could not analyze them because diving is required to enter that portion of the cave. The studied samples are archival, collected in 1987 during a rescue mission for missing diver, afterwards access to the cave was denied. Since the cave is one cave level and drains in one direction, passages below experience the same episodes of drying and flooding.

Kościeliska Valley

The most extensive karstic system in the Tatra Mts., the Lodowe spring system, east of the Kościeliska Valley, also drained Miętusia and Mała Łąka Valleys (Szczygieł et al., 2015a). Unfortunately, caves of the L0 level are characterized by an absence of speleothems, while speleothems from the L1 cave level from Zimna Cave (see Fig. 2 in the main text; S8a) contain admixtures of detrital contamination too large to permit dating. Flowstone covering erosional forms was collected from the L2 level in Miętusia Cave (λ : 19°53'56,37", ϕ : 49°14'46,80"; 1273 masl) (S9). These erosional forms are genetically connected with the development of vertical shafts and the (L1) cave network. The oldest layer of flowstone (sample M2A) was dated at over 420 ka, indicating that at a point at least 420 ka before the present, L2 was already dry, and the underlying L1 had to capture water from L2. Hence 420 ka ago L1 drained the karstic system as phreatic or epiphreatic conduits.

To the south of the Lodowe spring (S8) system, and on the east side of Kościeliska Valley, is a little-studied cave system in karstic Kraków Gorge. The largest cave in the upper part of Kraków Gorge is the Wysoka-Za Siedmiu Prokami cave system (λ : 19°53'06,58", ϕ : 49°14'01,54"; 1499 masl), the only such system in the Tatras where all five cave levels are present at once (Szczygieł, 2010). Here, we studied speleothems from the two lowest levels. Sample W19.3 is shelfstone from the edge of a flowstone-covered floor, collected from the looping passage that connects L0 and L1 (S10). The sampling site is located 190 m below the entrance. There was no speleothems in the lowermost, periodically flooded conduit. Sample WZS1 is a stalagmite grown on clastic sediments in the L1 passage (S10), 26 m above the local base level. Both samples indicate the minimum age of the L0 cave level in Kraków Gorge. Importantly, W19.3 is located 10 m below the bottom of the gorge, and WZS1 is located 26 m above it.

S8. a) Panoramic view on the of the central-eastern Kościeliska Valley with discussed caves position identified; b) Geologic map of the Kościeliska Valley draped over a LIDAR derived shaded relief image <https://cbdportal.pgi.gov.pl/smg/> (map explanation same as in S2); the red dash lines represent the LGM trimline

after Zasadni and Kłapyta (2014); yellow dashed lines represent profile positions shown in S12; white dashed lines represent a schematic range of the S8b.

S9. Map (a) and profile (b) of the Miętusia Cave (sourced: <http://jaskiniepolski.pgi.gov.pl/>) with the sample location; grid: 100 m; c) show samples M2A with marked, dated layers, and hiatuses highlighted by thin layers of detritic material (see S1 for details).

S10. Map (a) and profile (b) of the Wysoka Cave (sourced: <http://jaskiniepolski.pgi.gov.pl/>) with sample locations; grid: 100 m on the map view and 50 m in profile; d) and f) shows sampling sites before sample collection; c) and e) samples W19.3 and WZS1 respectively, with marked, dated layers (see S1 for details); black arrows on (c) indicate the direction of shelfstone growth.

In the lower part of Kraków Gorge, a small paleophreatic cave (S11; L1), Dudzia Dziura (λ : 19°52'20,97", ϕ : 49°14'08,75"; 1201 masl), is perched ca. 35 m above the gorge bottom (S8). The stalagmite collected from the cave wall is not as old as those from Wysoka Cave; given its position, it suggests delayed speleothem precipitation after drying rather than a younger cave age.

S11. a) Map of the Dudzia Dziura (sourced: <http://jaskiniepolski.pgi.gov.pl/>) with sample location; grid: 5 m; b) phreatic morphology of the passage where the DD1 sample was collected; c) Sample DD1 with marked, dated layers (see S1 for details); d) sampling site DD1 before speleothem collection.

Although we have no direct dating of the L0 level in the Lodowe spring system, the age of the oldest speleothems (collected below the valley bottom) from the neighboring Kraków Gorge indicates the same age for the Lodowe spring system.

In the Kościeliska Valley, glaciers covered the upper part, built of crystalline rocks (S8). Within the sedimentary rocks, where karst drainage occurs, the valley has a V-shaped morphology with canyon-like parts cutting through the more resistant limestone. There is no bedrock cropping out in the trunk stream riverbed, but, for example, in the Kraków Gorge, an exposed bedrock channel is common. In the main valley, Quaternary deposits are limited to thin, alluvial gravels (up to 3 m), intercalated with fan deposits, where tributary gullies connect. In the Kościeliska Valley, there is one strat terrace, ca. 15 m above the modern valley bottom, however, it has not been dated. In summary, the floor of the Kościeliska valley can be considered as the local base-level, which is not the case of the Bystra Valley.

The exception is Miętusia Valley, a tributary to the Kościeliska Valley. Here, glacial cirque and three hanging valleys are curved in sedimentary rocks. The karstic drainage system of the Lodowe spring was fed by the sub-glacial water, which makes the system directly connected to the glaciers. Glacial deposits fill a major part of the Miętusia Valley floor. Unfortunately, we did not succeed with sampling any cave belonging to L0 or L1 cave level in Miętusia Valley, providing data from the L2 Miętusia Cave (S1). Since we do not discuss the Miętusia Valley incision, estimation of the Quaternary deposits thickness seems to be unjustified.

S12. Valley profiles (profile lines at S8) across upper Kraków Gorge with Quaternary deposits thickness estimations: red area represents minimum thickness, and the yellow area represents maximum thickness. Schematic position of the Wysoka Cave and sampling sites (blue stars) shows its relation to the local base-level.

Chochółowska Valley

Chochółowska Valley is the westernmost of the studied valleys. Modern karst drainage is accomplished through the Chochółowskie karst spring (L0). Speleothems from two caves were studied: (1) Szczelina Chochółowska (λ : 19°48'43,14", ϕ : 49°14'45,40"; 1051 masl), whose entrance is located 26 m above the valley bottom, and (2) Kamienne Mleko (λ : 19°48'39,78", ϕ : 49°14'43,08"; 1096 masl), located 66 m above the valley bottom. The direct connection between Szczelina Chochółowska (L1) and the Rybia Cave (L0; S13) was determined by dye tracing experiments (Barczyk, 2004) and, in our opinion, the connection pattern is a textbook example of *soutirages sensu* Häuselmann et al. (2003). Kamienne Mleko is a paleophreatic cave, older than Szczelina Chochółowska, and hence should be regarded as an L2 cave.

Speleothem succession in the Szczelina Chochółowska cave was previously studied by Hercman et al. (1998). Two pieces of stalagmites, with broken basal and top parts, were collected in Nowy Passage ca. 20 m above the main entrance to Szczelina Chochółowska Cave (S14). Both stalagmites grew between 320 and 180 ka. The ages of the basal parts of the stalagmites suggest that more than 320 ka ago, the Chochółowskie spring existed, and the Chochółowska Szczelina passage was dry.

Similar to Kościeliska Valley, in the Chochółowska Valley, glaciers occupied the upper part of the valley (S13). The narrow, canyon-like part of the valley, where the caves we studied are located, is just below the junction of two glacial valleys (S13). Although local slopes are covered with thin debris, the floor of the V-shaped valley is covered with thin (≤ 2 m) alluvial (gravel) deposits of the latest Pleistocene to Holocene. Hence, in the Chochółowska Valley, the valley floor can be considered as the local base-level.

S13. a) Geologic map of the central portion of the Chochółowska Valley draped over a LIDAR derived shaded relief image; geology after <https://cbdportal.pgi.gov.pl/smg/> (map explanation same as in S2); the red dashed line represents the LGM trimline after Zasadni and Kłapyta (2014), yellow dashed lines represent profile positions for b) morphological profiles across Chochółowska Valley with an estimate of Quaternary deposits thickness: red area represents minimum thickness, and the red and yellow area represents maximum thickness. Schematic position of caves and sampling sites (blue stars) shows its relation to the local base-level.

S14. a) Map of Szczelina Chochołowska cave (sourced: <http://jaskiniepolski.pgi.gov.pl/>) with the location of samples SC-3 and SC-5; grid: 50 m; b) and c) samples SC-5 and SC-3, respectively, with marks showing dated layers (see S1 for details); d) Panoramic view on the central part of the Chochołowska Valley with the LGM advance and caves position marked.

In Kamienne Mleko Cave, we collected the stalagmite (KM1) with several clasts of older speleothems cemented in its basal part. The stalagmites grew on the clastic deposits (S15) in the passage 2 m above the entrance, i.e., 68 m above the valley bottom. Speleothem clasts range from 340 to 200 ka in age. The basal layer of the cementing stalagmite was around 160 ka and the top ~55 ka in age. The clasts were not transported as indicated from uneroded and unweathered outer layers. The most probable origin of the fragments as fallen ribs is indicated by their growth layers. The damage leading to rib collapse could have been caused by frost, slope processes, or earthquakes. Nonetheless, in the context of establishing a minimum moment of cave drying, the clasts are as valuable as stalagmites. The clasts we dated were previously a speleothem growing in vadose or epiphreatic conditions. The clasts are fragments of speleothems from the same growth phase as the stalagmites in Szczelina Chochłowska. The destruction of the speleothems in Kamienne Mleko is probably coincident with that of the top parts of the stalagmites in Szczelina Chochłowska. This suggests that after 320 ka, when modern karst circulation was developed, there was no valley incision. Still, processes, such as slope failures and earthquakes (?) occurred, destroying speleothems.

S15. a) Map of the Kamienne Mleko Cave (sourced: <http://jaskiniepolski.pgi.gov.pl/>) with the location of sample KM1; grid: 5 m; b) and c) sampling site and context of sample KM1 before collection; d) Sample KM1 with dated layers highlighted; dash line the lines mark the clasts in the basal layer of the stalagmite, two zoom-in images shows the internal structure of the clasts (see S1 for details).

Data availability statement

LiDAR DTM data in this study were used under an academic license no. DIO.DFT.DSI.7211.1619.2015_PL_N and DIO.DFT.7211.9874.2015_PL_N awarded to the Faculty of Earth Sciences and the Environmental Management University of Wrocław, according to Polish legal regulations of the administration of the Head Office of Land Surveying and Cartography. WMS source data for the Geological map of Tatra Mts. 1:10 000 (Szczegółowa Mapa Geologiczna Tatr w skali 1: 10 000) used after <https://cbdportal.pgi.gov.pl/smgt/>. Caves sketches used after <http://jaskiniepolski.pgi.gov.pl/>.

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