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No valley deepening of the Tatra Mountains (Western Carpathians) during the past 300 ka

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ABSTRACT

Wet-based mountain glaciers are efficient agents of erosion, which leads to the assumption that each glacial episode results in successive valley deepening. The tendency of subsequent glaciations to obscure evidence of previous events makes it difficult to study the work done by past glacial episodes. Epiphreatic and paleophreatic caves that developed at or under the water table and dried out in response to valley deepening can serve as recorders of the valley incision history. U-series data from speleothems in the cave networks at the base of the present-day valleys in the Tatra Mountains (Western Carpathians) consistently yield the oldest ages of ca. 325 ka. While speleothem ages are typically phreatic-vadose transition minimum ages, they nonetheless unequivocally demonstrate that neither glacial valley deepening nor fluvial incision occurred over the past 300 ka, unlike the successive valley deepening over the same period in the adjacent Alps.

INTRODUCTION

Wet-based mountain glaciers are documented to be efficient agents of erosion (Stern et al., 2005) that commonly create dramatic, high-relief landscapes. Indeed, mountain glaciers have been invoked as both limiting and amplifying relief creation (e.g., Brozović et al. [1997] versus Molnar and England [1990]) as well as exhumation (Stern et al., 2005; Thomson et al., 2010; Meyer et al., 2011). Yet the cyclic variation between hothouse and icehouse conditions during the Quaternary makes deciphering the magnitude of erosion attributable to any single glacial episode difficult to quantify. The general assumption is that each glacial episode deepens and widens the valleys occupied by glaciers (Harbor, 1992). In the case of mountain glaciers, the evidence supporting the idea of successive valley deepening are typically relative chronologies on terrace or moraine sequences with little, if any, absolute age control (Ehlers et al., 2011). Early work in glacial landscapes posited that the initial glacial episode was responsible for the majority of landscape modification and that work by subsequent glaciers was minimal (Tarr, 1893). This hypothesis, however, remains difficult to prove, especially given a glacier's tendency to rework deposits and reshape landforms developed in previous glacial episodes. Geochronology studies provide evidence for abrupt valley incision during the early and Middle Pleistocene (e.g., Shuster et al., 2005; Häuselmann et al., 2007). Given the extensive modification of the surficial environment with successive glacial episodes, glacial valleys developed in carbonates that favor the development of cave systems have the potential to reveal the chronology and magnitude of valley deepening with U-series dating.

The Tatra Mountains (Slovakia and Poland; also referred to as simply "the Tatra"), the northernmost portion of the central Western Carpathian Mountains (Fig. 1), rise on average 1.4 km above the surrounding Central Carpathian Paleogene Basin, and the northern side of the range contains deep and extensive cave networks. The Tatra are thought to have experienced eight glaciations, which we refer to using Marine Isotope Stages (MIS): MIS 2, 6, 8, 10, and 12, and three poorly constrained glaciations correlated with the Alpine Günz, Donau, and Biber glaciations (Lindner et al., 2003). The glaciations associated with MIS 2 (Last Glacial Maximum, LGM) and MIS 12 are thought to be the most extensive. During MIS 6, the climate conditions were milder, Tatra glaciers had a smaller range than during the LGM (Lindner et al., 2003), and conditions were conducive to speleothem growth (Hercman, 2000; Kicińska et al., 2017). There is no direct evidence of pre–MIS 12 glaciation within the Tatra, however perched glaciofluvial deposits are interpreted to represent MIS 16–22 and older glacial episodes (Lindner et al., 2003). In this study, we examine the history of glacial valley deepening using nine localities across three adjacent valleys by determining the ages of speleothems from the modern, active cave system at the base of the valley and from paleophreatic caves perched above the valley.

STUDY AREA

The Tatra are a fold-and-thrust belt composed of Paleozoic crystalline basement covered by Mesozoic sedimentary rocks (Jurewicz, 2005). The Tatra constitute a horst exhumed from a depth of at least 5 km since the Miocene. Exhumation rates are on the order of 100–500 m/Ma, with the highest rates in the southeastern corner of the range (Anczkiewicz et al., 2015; Śmigielski et al., 2016).

The Tatra landscape was sculpted by the Pleistocene glaciations and periglacial processes. All valleys in the Tatra were occupied by glaciers during the LGM and the total ice extent is well mapped, with the largest glaciers extending as much as 3 km from the mountain front (Zasadni and Kłapyta, 2014). Nearly all glacial geochronology in the Tatra is LGM or younger (Kłapyta and Zasadni, 2018). Cosmogenic nuclide ages on moraines and the valley walls above the trimlines yield LGM or younger ages (Makos et al., 2013, 2018; Engel et al., 2015). While eight glacial episodes extending as far back as the Pliocene Biber composite event are described in the literature (Lindner et al., 2003;

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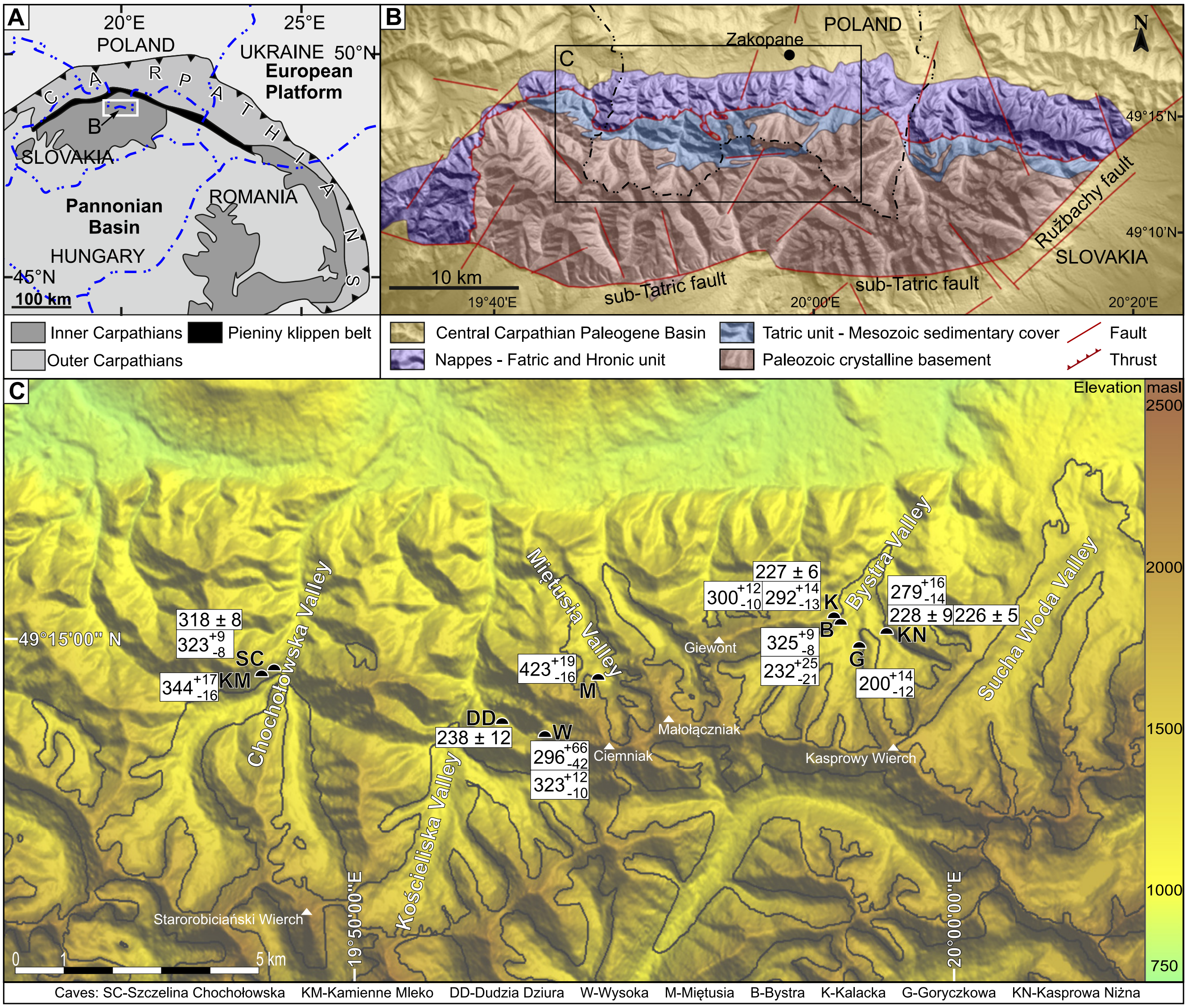

Figure 1. (A) Location of the Tatra Mountains in the Carpathian belt (white rectangle shows location of B). (B) Tectonic sketch of the Tatra (after Jurewicz, 2005) (black rectangle shows area of C). (C) Shuttle Radar Topography Mission 1 arc-second shaded relief with digital elevation model (masl—meters above sea level). Black labels show caves with U-series ages (in ka) of speleothem basal layers. Black line marks the extent of the Last Glacial Maximum, after Zasadni and Kłapyta (2014).

Kłapyta and Zasadni, 2018), the oldest reported age on a glaciofluvial terrace in the Tatra is a thermoluminescence age of 443 ± 36 ka (MIS 12; Lindner et al., 1993).

The karstic caves of the Tatra are developed in levels *sensu* Palmer (1987) and serve as water-table indicators. Thus, as valley incision progresses, the cave network lowers in response to the falling water table, resulting in the transition of karst conduits from phreatic to vadose. This transition is reflected in a shift from clastic fluvial deposition to speleothem precipitation. This study targets caves in the (epi)phreatic zone that developed under the water table and subsequently dried out in response to valley deepening (Ford et al., 1981). In the Tatra, we distinguished five vertically stacked cave levels, L0 to L4 (Fig. 2). There are no direct constraints on the depth to bedrock in the valley floors; thus, we explored the potential for valley overdeepening and subsequent aggradation by estimating the maximum possible thickness of Quaternary deposits based on valley profile morphology and bedrock outcrops in the valley floor (Figs. S5, S12, and S13 in the Supplemental Material[1]). Prior to this study, the oldest reported age for L1 was 300 ± 12 ka by U-series on a flowstone deposit (Szczygieł et al., 2019).

U-SERIES DATING

We explored a total of 30 paleophreatic or epiphreatic caves spread across the Chochołowska, Kościeliska, and Bystra Valleys on the northern side of the Tatra (Fig. 1) and collected 16 speleothems for U-series dating from nine caves (Table 1). Ideal samples are speleothems deposited immediately after the transition between phreatic and vadose conditions. We focused on: L0, the active (epi)phreatic level; and the L1 and L2 paleophreatic levels (Fig. 2). Samples were analyzed by standard $^{230}Th/^{234}U$ disequilibrium techniques (Ivanovich and Harmon, 1992), allowing precise age determinations of up to 0.55 Ma. Details regarding sample locations, geomorphological context, and U-series geochronology, including correction for detrital Th, are given in Table S1 in the Supplemental Material.

Our samples are typical of other speleothems from the Tatra, with low U concentrations and admixtures of detrital contamination (Kicińska et al., 2017). Detrital contamination correction

[1]Supplemental Material. Methods, sample location, and their geomorphological context. Please visit https://doi.org/10.1130/GEOL.S.12456302 to access the supplemental material, and contact editing@geosociety.org with any questions.

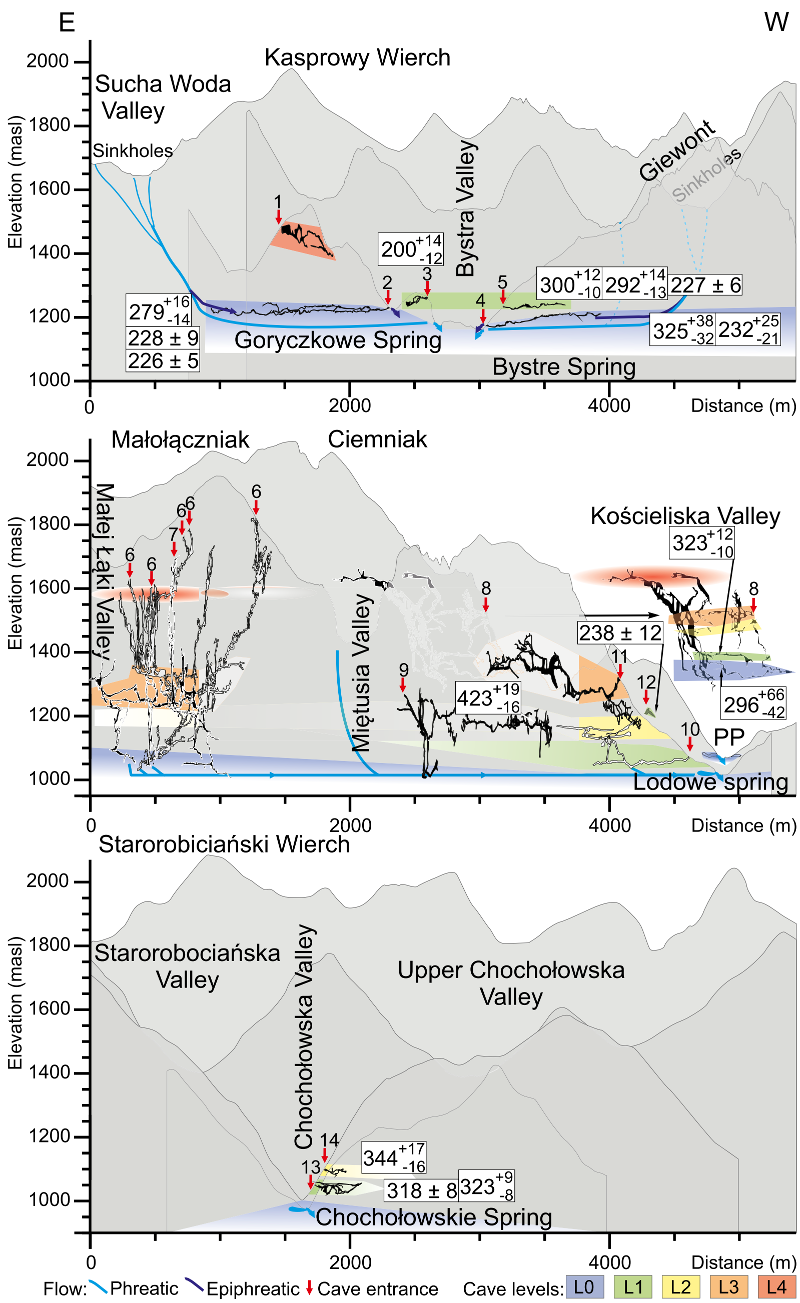

Figure 2. Cave systems projected into superimposed topographic profiles across the Tatra valleys (Western Carpathians). Cave levels are color-coded, and basal-layer U-series ages (in ka) of sampled speleothems are summarized in white boxes. Caves: 1—Magurska; 2—Kasprowa Niżna; 3—Goryczkowa; 4—Bystra; 5—Kalacka; 6—Wielka Śnieżna; 7—Śnieżna Studnia; 8—Wysoka; 9—Miętusia; 10—Zimna; 11—Czarna; 12—Dudzia Dziura; 13—Szczelina Chochołowska; 14—Kamienne Mleko; PP—Pod Pisaną outflow.

for low $^{230}Th/^{232}Th$ activity ratio (<200) typically results in a difference between corrected and uncorrected ages that is within uncertainty. We dated speleothem bases and tops (or other younger layers) in order to confirm a stratigraphic sequence and verify that U has not been leached due to flooding. Replicate analyses were performed on a subset of basal layers to ensure age reproducibility. Corrected basal speleothem U-series ages are between 200^{+14}_{-12} and 423^{+19}_{-16} ka. We obtained two dates for the L2 level: 423^{+19}_{-16} and 344^{+17}_{-16} ka. Speleothems from the L1 level yield nine ages ranging from 200^{+14}_{-12} to 323^{+9}_{-8} ka, while the active L0 level ranges from 226 ± 5 to 325^{+38}_{-32} ka in age (Table 1).

We interpret the oldest ages from each level as the onset of speleothem growth; however, we emphasize that growth could have started at any time after passage drying, thus speleothem ages must always be treated as minimum constraints on the phreatic-vadose transition. Samples from the L1 Kalacka and Goryczkowa caves are younger than those from the L0 Kasprowa Niżnia and Bystra caves; however, this does not imply that they were drained later, only that the onset of speleothem growth began later.

RELIEF AGE

When a particular cave transitions from an epiphreatic to a paleophreatic passage, it implies that the water table has dropped and a new epiphreatic system developed. In this context, we track the progression of U-series ages that serve as minimums for the development of cave levels L2 to L0. A sample of the oldest layer of flowstone, sample M2A, was collected in Miętusia cave. The base of the M2A flowstone is in direct contact with vadose erosional forms and is located in a pit that intersects paleophreatic level L2 and enters L1. This vertical pattern indicates that the pit drained to L1 and, therefore, prior to 423^{+19}_{-16} ka, L1 was a phreatic or epiphreatic conduit for the karst system. The L0 caves of the Chochołowska and Kościeliska Valleys do not contain speleothems or the inferred sub–water table passages are inaccessible. The oldest ages of the L1 caves in these valleys, 323^{+9}_{-8} ka (Szczelina Chochołowska cave) and 323^{+12}_{-10} ka (Wysoka cave), overlap with younger L0 speleothem ages in the Bystra Valley. The passages where the speleothems were collected are the lowest and hence youngest paleophreatic passages. From this, we can infer that, at or prior to 323^{+9}_{-8} ka, the L1 caves were paleophreatic, and that the underlying L0 phreatic conduits were already established. A dye tracing test in Szczelina Chochołowska confirms the connection to the current drainage via soutirages (juvenlie pathways connecting the main conduit to the spring) (Barczyk, 2004). Samples from Bystra cave, although collected ~30 m above estimated local base level, belong to the active epiphreatic L0 level. Samples from the L0 Kasprowa Niżna Cave were collected from a low looping conduit that dips below the modern valley floor within 0–10 m of the bedrock valley floor. Sample W19.3B from Wysoka Cave, also L0, yields similar ages (Figs. 1 and 2; Table 1). The age and location of these samples indicate that ca. 325 ka, the L0 cave level was already established.

Our results constrain the minimum age of the valley floor on the northern slopes of the Tatra. The oldest speleothems collected in epiphreatic passages of the L0 caves from each valley are consistently between 284 and 325 ka (MIS 8–9). This shows that the modern karst drainage system of the Tatra was established prior to the late Middle Pleistocene, and the cave conduits changed to epiphreatic or vadose conditions between 280 and 330 ka. Because the L0 caves are at or below the modern valley floor, we can conclude that no valley incision occurred after ca. 330 ka, which includes both the penultimate and last glaciation periods. In fact, clastic sediments

TABLE 1. U-Th DATING RESULTS OF THE BASAL LAYERS FROM STUDIED SPELEOTHEMS, TATRA MOUNTAINS (WESTERN CARPATHIANS)

Sample	Cave	Cave level	U content (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*	Position above base level (m)
KM1/1	Kamienne Mleko	L2	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	68
SC-5-I	Szczelina Chochołowska	L1	1.284 ± 0.006	1.149 ± 0.005	0.988 ± 0.006	279 ± 2	323^{+9}_{-8}	N.A.†	1.37 ± 0.04	~46
SC-3	Szczelina Chochołowska	L1	0.834 ± 0.003	1.165 ± 0.002	0.989 ± 0.005	1716 ± 9	318 ± 8	N.A.†	1.40 ± 0.04	~46
DD1/3	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	~35
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	-10
WZS 1-1	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	26
M2A/1	Miętusia	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	~45
Bystra 1/1	Bystra	L0	0.1665 ± 0.0006	1.538 ± 0.006	1.31 ± 0.02	14.9 ± 0.2	333^{+33}_{-26}	325^{+38}_{-32}	2.3 ± 0.2	~30
Bystra B2	Bystra	L0	0.1292 ± 0.0007	1.700 ± 0.007	0.98 ± 0.04	>10,000	232^{+25}_{-21}	N.A.†	2.4 ± 0.1	~30
JK2.1/1**	Kalacka	L1	0.1043 ± 0.0004	2.626 ± 0.012	1.12 ± 0.02	34.5 ± 0.3	301^{+10}_{-9}	300^{+12}_{-10}	4.7 ± 0.2	73
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	72
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	80
Gor.listwa	Goryczkowa	L1	0.0691 ± 0.0004	1.36 ± 0.01	0.91 ± 0.02	6.6 ± 0.1	210^{+10}_{-9}	200^{+14}_{-12}	1.63 ± 0.10	52
JKN 2A/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	10
TKS 9	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	12
TKS 16/3	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	12

Note: Reported age errors are 2σ. See the Supplemental Material (see text footnote 1) for cave descriptions and locations.
*AR—activity ratio.
†N.A.—not applicable.
**Data from Szczygieł et al. (2019).

partially bury some of the oldest speleothems in several passages (e.g., Kalacka, Kasprowa Niżnia, Bystra caves), implying episodic aggradation and the stability of the water table at the L0 level.

DISCUSSION AND CONCLUSION

The onset of speleothem growth in the L2, L1, and L0 levels between 423 and 325 ka corresponds to MIS 11–9, a transition from an extraordinarily long and warm interglacial to the so-called Saalian supercycle (Kukla, 2005). It is worth noting that the MIS 12 glaciation is assumed to be the most extensive in the Tatra (Lindner et al., 2003; Kłapyta and Zasadni, 2018). The lack of MIS 10 terminal moraines implies a smaller extent of MIS 10 glaciers than of subsequent episodes. Hence, we interpret the water-table lowering that led to the establishment of the L0 cave network as the result of valley-bottom glacial erosion during the MIS 12 glaciation. Our data demonstrate that none of the subsequent glaciations or fluvial erosion resulted in significant valley deepening by bedrock erosion. There are documented cases of overdeepened, buried valleys in the Alps that were not affected by the last two glaciations within valleys characterized by thick ice flows (Preusser et al., 2010). In contrast, smaller, tributary alpine valleys usually show a record of younger valley deepening and widening associated with the MIS 8, 6, and 2 glaciations (e.g., Häuselmann et al., 2002, 2007).

Despite the lack of valley lowering during the last glacial period, there are well-developed moraines throughout the valleys of the Tatra. The granitic lithologies used for cosmogenic nuclide dating are largely sourced from cirques, above the LGM equilibrium line altitude (Makos et al., 2018). All reported ^{10}Be boulder ages are <20 ka, which implies efficient removal of at least 2 m of bedrock in the granitic lithologies of the cirques such that cosmogenic ages show no signs of prior exposure. We posit that while there was no deepening of the valley bottom, glacial erosion was most active in the cirques during the last glaciation. Alternatively, material could have come from the valley walls, but the relatively weak and quartz-poor Mesozoic sedimentary rocks are less ideal for ^{10}Be geochronology.

With MIS 12 as the last major glaciation responsible for valley deepening and the present position of the water table, we consider the origin of the four cave levels that overlie L0. The U-series dates on the L1 and L2 caves provide minimum constraints on their age of formation, given their overlap in age with the L0 caves. In addition to the L1 and L2 caves, there are two additional cave levels perched above the modern valley floor with a total relief on the cave system of ~500 m. The L0 to L3 caves are closely spaced (within 50–100 m vertically of one another), while L4 lies 150–200 m above the L3 caves (Fig. 2). If pre–MIS 12 glaciations (>400 ka) were responsible for formation of each cave level, it would have required significant glaciation of the Tatra during the 40 ka orbital forcing (Lisiecki and Raymo, 2007); however, it is unclear whether snow lines would have depressed to the height of the Tatra during that time. In fact, the last decades of cave sediment ages call into question the cave level–glaciation correlation (Audra et al., 2007). Studies show that glaciers can even hamper cave development via filling, and many multilevel cave systems in the Alps predate the Quaternary (Audra et al., 2007; Häuselmann et al., 2007, 2015; Wagner et al., 2010).

The greater vertical separation of the L4 level suggests that it could potentially be much older and developed under a nonglacial, pre-Quaternary climate. Now, and likely since their initial glaciation, the Tatra have maintained a glacial morphology, which results in cave development that is distinct from that of a purely fluvial mountain landscape. Differences in fluvial and glacial erosion rates may affect the vertical pattern of cave levels. For example, in the non-glaciated Alps, constant fluvial erosion results in fewer cave levels (Wagner et al., 2010), while in the glaciated Alps, the threshold behavior of glacial erosion has resulted in the development of more tightly spaced cave levels (Häuselmann et al., 2002, 2007).

Our data clearly demonstrate that glacial valley deepening did not occur in the Tatra during the penultimate and last glaciations, nor did fluvial bedrock incision occur in interglacial periods. This has several important implications for the evolution of glacial valleys, regional glacial chronologies, and Pleistocene rock uplift in the Tatra. Prior work demonstrated that some valley widening occurred during the last glaciation (Makos et al., 2013), perhaps at the cost of valley deepening (Harbor, 1992). Prior to this study, all regional glacial chronologies were built around those established in the Alps (Lindner et al., 2003); however, our work suggests that these chronologies may need to be revised. Thermochronology data suggest mean rock uplift rates of ~300 m/Ma during the past 9 Ma (Anczkiewicz et al., 2015); however, no incision over the past 325 ka implies that tectonic uplift of the Tatra has ceased. The cave levels above the modern valley floor are almost certainly of an antiquity outside the resolution of U-series dating, and their genesis likely represents a mixture of Pleistocene glacial incision and pre-Quaternary fluvial erosion.

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