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 (Sterne 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 glacial episodes extending as far back as the Pliocene (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; 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 glacial episodes extending as far back as the Pliocene (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;
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).

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 Chochołówka, 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 230Th/234U 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...
We obtained two dates for the L2 level: U-series ages are between 232 ±14 and 233 ±15 ka. Speleothems from the L1 Kalacka and Goryczkowa caves ples from the L1 Kalacka and Goryczkowa caves and uncorrected ages that is within uncertainty. We emphasize that growth could have started at the onset of speleothem growth; however, as 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 243 ±16 ka, L1 was a phreatic or epiphreatic conduit for the karst system. The L0 caves of the Chocholowska and Kościelska Valleys do not contain speleothems or the inferred sub-water table passages are inaccessible. The oldest ages of the L1 caves in these valleys, 232 ±15 ka (Szczelina Chocholowska cave) and 233 ±15 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 232 ±15 ka, the L1 caves were paleophreatic, and that the underlying L0 phreatic conduits were already established. A dye tracing test in Szczelina Chocholowska confirms the connection to the current drainage via soutirages (juvenile 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 Nizna 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 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 are younger than those from the L0 Kasprowa Nizna and Bystra caves; however, this does not imply that they were drained later, only that the onset of speleothem growth began later.

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 Nizna; 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.

[Diagram of cave systems with ages and locations]
### TABLE 1. U-Th DATING RESULTS OF THE BASAL LAYERS FROM STUDIED SPELEOTHEMS, TATRA MOUNTAINS (WESTERN CARPATHIANS)

| Sample | Cave | Cave level | U content (ppm) | $^{238}\text{U}/^{235}\text{U}$ AR* | $^{234}\text{Th}/^{238}\text{U}$ AR* | Age uncorrected (ka) | Age corrected (ka) | Initial corrected $^{238}\text{U}/^{235}\text{U}$ 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                    | 1.66 ± 0.08                  | 68                          |
| SC-5-1 | Szczelina Chocholowska | L1   | 1.284 ± 0.006   | 1.149 ± 0.005   | 0.986 ± 0.006   | 279 ± 2           | 323 ± 3            | N.A.                        | -46                         |
| SC-3   | Szczelina Chocholowska | L1   | 0.834 ± 0.003   | 1.165 ± 0.002   | 0.989 ± 0.005   | 1716 ± 9          | 318 ± 8            | N.A.                        | -46                         |
| DDI/3  | Dzudnia Dziura | L1      | 0.0573 ± 0.0004 | 3.055 ± 0.02    | 1.05 ± 0.02     | 39.0 ± 0.4        | 243 ± 7            | 238 ± 12                    | 4.9 ± 0.3                    | -35                         |
| W19.3B-1 | Wysoka | L0      | 1.1264 ± 0.0007  | 1.061 ± 0.01    | 0.95 ± 0.03     | 155 ± 4           | 300 ± 22           | N.A.                        | -10                         |
| W25-1  | Wysoka | L1      | 0.1747 ± 0.0009  | 1.353 ± 0.004   | 1.036 ± 0.006   | 6.88 ± 0.03       | 334 ± 1            | 323 ± 13                    | 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 ± 1            | 423 ± 13                     | 1.15 ± 0.04                  | -45                         |
| Bystra 1/1 | Bystra | L0      | 1.1655 ± 0.0006  | 1.538 ± 0.006   | 1.31 ± 0.02     | 14.9 ± 0.2        | 333 ± 12           | 325 ± 13                     | 2.3 ± 0.2                    | -30                         |
| Bystra B2 | Bystra | L0      | 0.1292 ± 0.0007  | 1.700 ± 0.007   | 0.98 ± 0.04     | >10,000           | 232 ± 2            | 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        | 30 ± 10            | 300 ± 13                    | 4.7 ± 0.2                    | 73                          |
| TK522  | 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.-Stf.2 | Kalacka | L1      | 0.0688 ± 0.0001  | 1.365 ± 0.005   | 1.020 ± 0.009   | 5.01 ± 0.04       | 307 ± 12           | 292 ± 13                     | 1.83 ± 0.08                  | 80                          |
| Goralleries | Goryczkowa | L1  | 0.0691 ± 0.0004  | 1.36 ± 0.01     | 0.91 ± 0.02     | 6.6 ± 0.1         | 210 ± 10           | 200 ± 10                     | 1.63 ± 0.10                  | 52                          |
| JKN 2A/1 | Kasprowa Nizna | L0 | 0.0464 ± 0.0003  | 1.354 ± 0.007   | 0.999 ± 0.009   | 15.1 ± 0.2        | 284 ± 13           | 279 ± 13                    | 1.8 ± 0.1                    | 10                          |
| TK9  | Kasprowa Nizna | L0 | 0.1055 ± 0.0005  | 2.26 ± 0.01     | 1.01 ± 0.02     | 214 ± 3           | 228 ± 9            | N.A.                        | 3.3 ± 0.1                    | 12                          |
| TK16/3 | Kasprowa Nizna | L0 | 0.1962 ± 0.0003  | 1.958 ± 0.007   | 0.966 ± 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 Szczypień et al. (2019).
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 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 nonglaciated Alps, constant fluvial erosion results in 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. Thermochemistry data suggest mean rock uplift rates of ~300 m/Ma during the past 9 Ma (Anzczykiewicz et al., 2015); however, no incision over the past 325 ka implies that tec-tonic 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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