

Hydroclimatic events in the Carpathian karst during MIS 3–2: Evidence from sedimentary records in two Romanian caves

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ABSTRACT

Cave sediments are well-preserved terrestrial archives of Quaternary hydroclimatic variability, often recording changes at high temporal resolution. Urșilor and Muierilor caves in the Romanian Carpathians contain extensive paleoflood deposits that provide insight into past hydrological dynamics. Here, we integrate new and previously published data to reconstruct palaeohydrological activity during Marine Isotope Stages (MIS) 3–2, a period marked by rapid climate fluctuations. Our approach combines detailed stratigraphic logging, granulometric and clast-shape analyses, and chronological constraints derived from radiocarbon dating of fossil remains and U–Th dating of speleothems. The results indicate that both cave systems record recurrent high-magnitude flash floods, particularly during MIS 3 and the post–Last Glacial Maximum (LGM) phase of MIS 2, suggesting episodic intensification of hydrological extremes in the Carpathian region. Cave sediments are subdivided into allostratigraphic units, with paleoflood sequences represented by diamicton and thalweg facies, locally exhibiting channelized structures, and underlain by either backswamp (Muierilor) or slackwater deposits (Urșilor). Microstratigraphic variability within stalagmite PM163 further documents rapid environmental changes affecting the local hydrology at Muierilor. Three coeval hydrological events are identified in both caves, with deposition occurring after: ~46 ka, ~34.5 ka, and ~29 ka. These results demonstrate that integrating sedimentological, microstratigraphic, and chronological data provides a robust framework for paleoenvironmental reconstruction. The sedimentary record indicates that flooding was modulated by large-scale hydroclimatic variability, although the relative contributions of precipitation and glacial meltwater remain unresolved. Overall, the studied cave deposits represent valuable archives of high-energy paleofloods during MIS 3–2 in the Romanian Carpathians, offering new constraints on the timing of hydrological extremes and suggesting regional synchronicity across karst systems with contrasting geomorphological settings.

1. Introduction

Caves are excellent natural repositories for either detrital, biological,

and/or chemical deposits, recording the impact of multiple hydroclimatic events that shaped the underground networks (e.g., Zupan Hajna et al., 2010; Constantin et al., 2014; Winkler et al., 2016; Blatnik

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et al., 2020; Mirea et al., 2021). Scientific interest in clastic cave sediments has increased over the last decades, owing to their high reliability for paleodrainage reconstructions and landscape evolution (e.g., Farand, 2001; Bosch and White, 2007; Sasowsky and Mylroie, 2007; Farant and Smart, 2011; Häuselmann et al., 2015, 2020; Zupan Hajna et al., 2010, 2021; Ballesteros et al., 2023). Sediments deposited in caves form a so-called ‘lost stratigraphy’ (e.g., Sasowsky, 2007; White, 2007) because they preserve stratigraphic and fossil records that were removed by erosion at the surface. Cave sediments are not only indicative of past hydrologic regimes, but they also include fossil remains, pollen, or interbedded speleothem layers that are relevant to paleoenvironmental reconstructions. Dating such sediments is very challenging (e.g., due to reworking processes) and often relies on indirect methods such as dating of speleothems or fossil remains from stratigraphically-relevant positions or paleomagnetic measurements (Häuselmann et al., 2015). Sometimes, sediments may be dated using radiometric methods such as AMS ^{14}C , U—Th, and OSL (Constantin et al., 2014; Bartolomé et al., 2021a; Schmidt et al., 2025), or $^{10}\text{Be}/^{26}\text{Al}$ (e.g., Granger et al., 2001; Häuselmann et al., 2020; Mathes et al., 2026). Integrated analysis of fluvial and cave sediments provides a powerful framework for reconstructing Quaternary landscape evolution in karst regions, particularly by constraining rates of fluvial valley incision and cave level development (e.g., Calvet et al., 2024; Genuite et al., 2025). Limitations arise mostly due to the lack of suitable dating material, and the occurrence of reworking processes, which often disturb chronologies and sometimes may yield apparent stratigraphical reversals (e.g., Mirea et al., 2021).

Marine Isotope Stages (MIS) 3–2 (~57–11.7 ka; Lisiecki and Raymo, 2005) were marked by the rapid succession of millennial-scale climate oscillations known as the Dansgaard–Oeschger (DO) events (Dansgaard et al., 1993). These events involved abrupt temperature increases of up to 10 °C within a few decades, followed by gradual cooling over ~1000 years (Labeyrie, 2000) and a return to glacial conditions (Rousseau et al., 2022). In contrast, abrupt and short-term cooling events labeled as Heinrich (H) events preceded some of the DO warming phases during the last glacial period (e.g., Heinrich, 1988; Hemming, 2004). Notable insights into MIS 3–2 hydroclimatic variability in Europe have been derived from cave sediment records. Sedimentation phases reflect long-term regional environmental and tectonic forcing, as well as episodes of enhanced hydrological activity, including flooding (Zupan Hajna et al., 2010; Häuselmann et al., 2015; Blatnik et al., 2020). In particular, cave deposits from the Moravian Karst (eastern Czech Republic) preserve signals of MIS 3 climate variability relevant to the Carpathian region (Nejman et al., 2018; Lisá et al., 2025).

Cave clastic deposits in the Romanian Carpathians have been widely used to reconstruct Quaternary paleoenvironments, including paleoclimate, paleoecology, and landscape evolution in Eastern Europe (e.g., Häuselmann et al., 2010; Constantin et al., 2014; Moldovan et al., 2016; Mirea et al., 2021; Schmidt et al., 2025). The investigated caves serve as natural repositories preserving a wide range of proxy records within their deposits. However, the timing and dynamics of abrupt hydrological events during MIS 3–2 remain poorly constrained, particularly during the last deglaciation (~19–14.6 ka; Urdea et al., 2023). Speleothem records provide limited constraints on such events, as carbonate precipitation is often interrupted by hydrological disturbances (Frisia, 2015), including flooding and prolonged dry periods. This limitation is especially relevant for MIS 2, generally characterized in the Carpathians by cold and dry conditions that reduced vegetation cover and carbonate deposition (e.g., Constantin et al., 2007). On the other hand, speleothems are known as well-established recorders of cave flooding, typically marked by darker, detrital layers within or between growth laminae, as demonstrated in numerous studies (e.g., Gázquez et al., 2014; Denniston and Luetscher, 2017; Wilhelm et al., 2018; Bartolomé et al., 2021b, 2025; Piascik et al., 2025). While speleothems record hydrological disturbances at high resolution, cave sediments provide a complementary archive of these processes. Although they cannot directly constrain the timing of events, they yield important information

on (i) cave hydrology and morphology, (ii) links to surface processes such as erosion, sediment transport and hydrological connections, and (iii) depositional time spans when datable materials are present (e.g., interbedded or capping speleothems, fossil remains, charcoal).

In this study, we investigate the effects/impact of MIS 3–2 abrupt hydroclimatic events on cave processes and sedimentation patterns by integrating stratigraphic analysis, available climate proxies, and paleontological material of two key excavation sites in Muierilor and Urșilor caves (Romanian Carpathians). These caves, hosting a rich and diverse depositional heritage (i.e., detrital sediments, speleothems, fossil remains of Late Pleistocene vertebrate mammals) redeposited during recurrent flash flood events, were subjected to numerous studies (e.g., Dobos et al., 2009; Constantin et al., 2014; Robu, 2015, 2016; Moldovan et al., 2016; Robu et al., 2018; Mirea et al., 2021). Sediments and fossil bones have been dated to the MIS 3 and the post-Late Glacial Maximum (LGM) period. A general evaluation based on field observations distinguished between different hydraulic regimes ranging from low- to high-energy gradients and occasional severe floods (Mirea et al., 2021). Nonetheless, a systematic study is required to elucidate the hydrological mechanisms of the cave environment and their relation to the paleoclimate shifts.

We hypothesize that fluvial deposits, characterized by high hydraulic gradient facies, are most likely associated with abrupt climate oscillations during MIS 3–2. We focused our research on such sections, and the aim is to: (i) analyze the internal architecture of the sedimentary sequences within the caves based on allostratigraphic concepts; (ii) report new stratigraphically-relevant radiocarbon and U—Th dating results; and (iii) identify the flood processes in the facies suite of cave sediments. Therefore, we revisited in detail the stratigraphy of the PMP1 excavation in Muierilor Cave and compared it with a newly studied section from the upper level of Urșilor Cave (PUGO1), interpreting new and previously published data. We analyzed radiometric results from Muierilor and Urșilor caves to constrain the timing of hydrological events and to establish minimum ages for bone assemblage deposition. In addition, at Muierilor, we examined the microstratigraphy of a 62-cm-high stalagmite to investigate the record of environmental changes in Bears Passage during MIS 3–2, with potential complementary information on hydroclimatic mechanisms.

2. The cave sites

2.1. Geographic setting and geomorphology

Muierilor (=Women's) Cave (45°11'31.78" N, 23°45'14.07" E) is an ~8-km-long tiered karst system, carved in Upper Jurassic–Aptian reef limestones (Savu et al., 1985), which outcrop in the Parâng Mountains, central Southern Carpathians (Fig. 1A–B). During the Pleistocene cold periods, the local alpine catchment areas were occupied by small glaciers. Snow, firn, and ice accumulated between the narrow ridges in the alpine zone, at 1800–2136 m a.s.l. The cave functioned as a succession of underground meanders of the Galbenul River, and the passages evolved in parallel with the downstream incision of the gorge and terrace formation (Mirea et al., 2021). Two entrances are used to access Level 2 (the show cave), located at ~645 m a.s.l. Two levels (3 and 4; at ~663 and ~685 m a.s.l., respectively) are situated at the upper part of the karst system. A lower Level 1 (at ~625 m a.s.l.; the Scientific Reserve: Urșilor and Hades passages) contains most of the fossil remains as a jumble of bones embedded within or lying on top of sediments. A so-called Level 0 is located only a couple of meters above the Galbenul River level and includes temporary submerged passages that are only partially explored (Fig. 2). Currently, all levels are hydrologically inactive except for Level 0, which is totally flooded during the high-water stands of the Galbenul River.

Urșilor (=Bears') Cave (46°55'37" N, 22°56'92" E) is a 1.5-km long cave situated in the Bihor Mountains, northwestern Romania. The cave developed into Upper Jurassic (Oxfordian–Tithonian) reef limestones

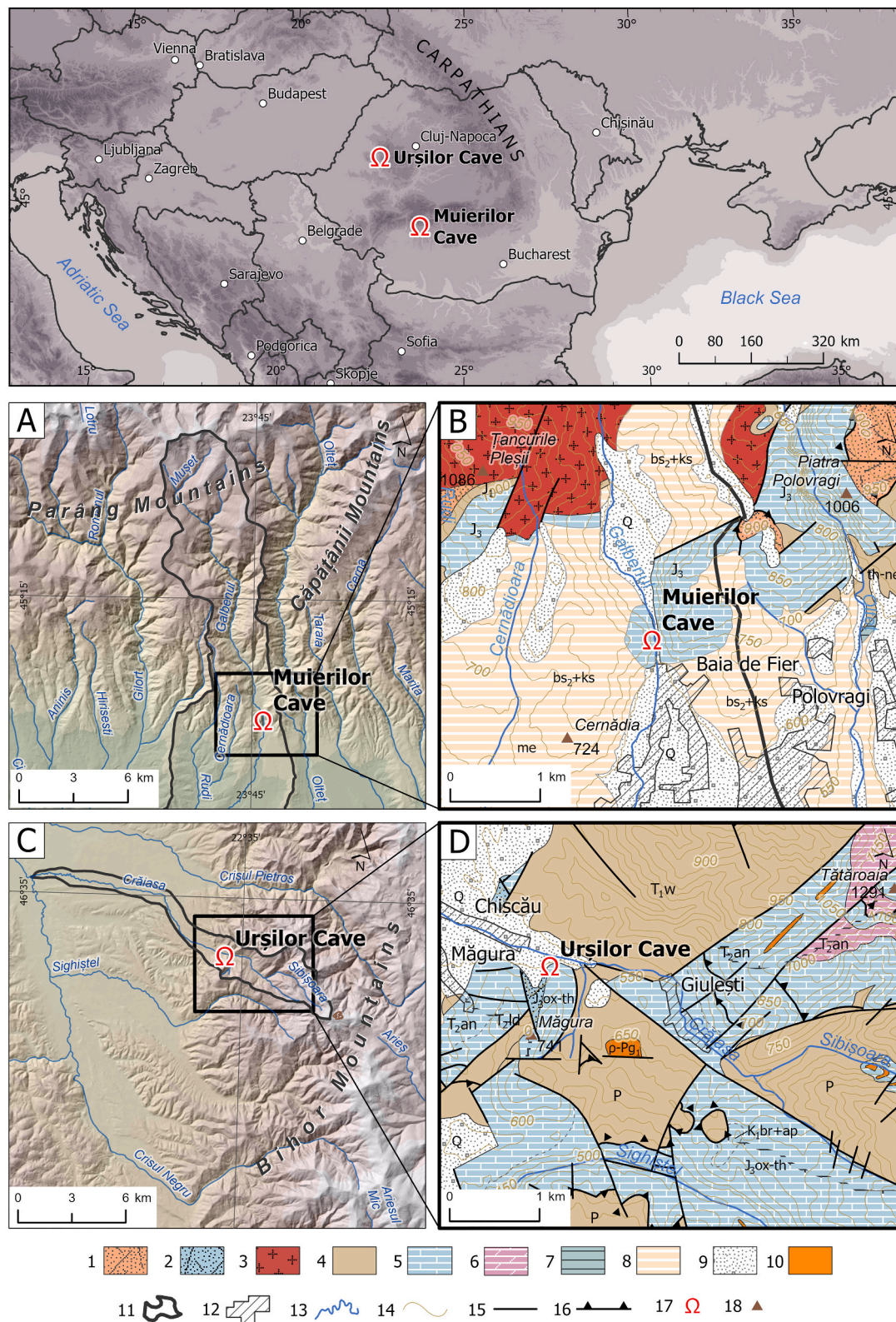


Fig. 1. Geographic and geologic setting of Muierilor (A–B) and Urşilor (C–D) caves, respectively: 1 – Gneisses, quartzites and micascists; 2 – Marbles and hornfels; 3 – Granitoids; 4 – Siliciclastites (sandstones, arkoses, siltstones, clays); 5 – Limestones; 6 – Dolomites; 7 – Carbonate mylonites; 8 – Sedimentary rocks; 9 – Fluvial deposits; 10 – Volcanic rocks (rhyolites, basalts); 11 – Crăiasa catchment area; 12 – Locality; 13 – River; 14 – Contour (50-m equidistance); 15 – Fault; 16 – Thrust; 17 – Cave entrance; 18 – Peak. The black squares indicate geological sketches simplified and redrawn from Bleahu et al. (1985), Savu et al. (1985) and Hann et al. (1986). Geological abbreviations: P = Permian; T_{2an} = Anisian; T_{2ld} = Ladinian; J_{3ox+th} = Oxfordian and Tithonian; K_{1br+ap} = Barremian and Aptian; p-Pg₁ = Paleocene; bs₂ + ks = Bessarabian + Kersonian; me = Maeotian; Q = Quaternary.

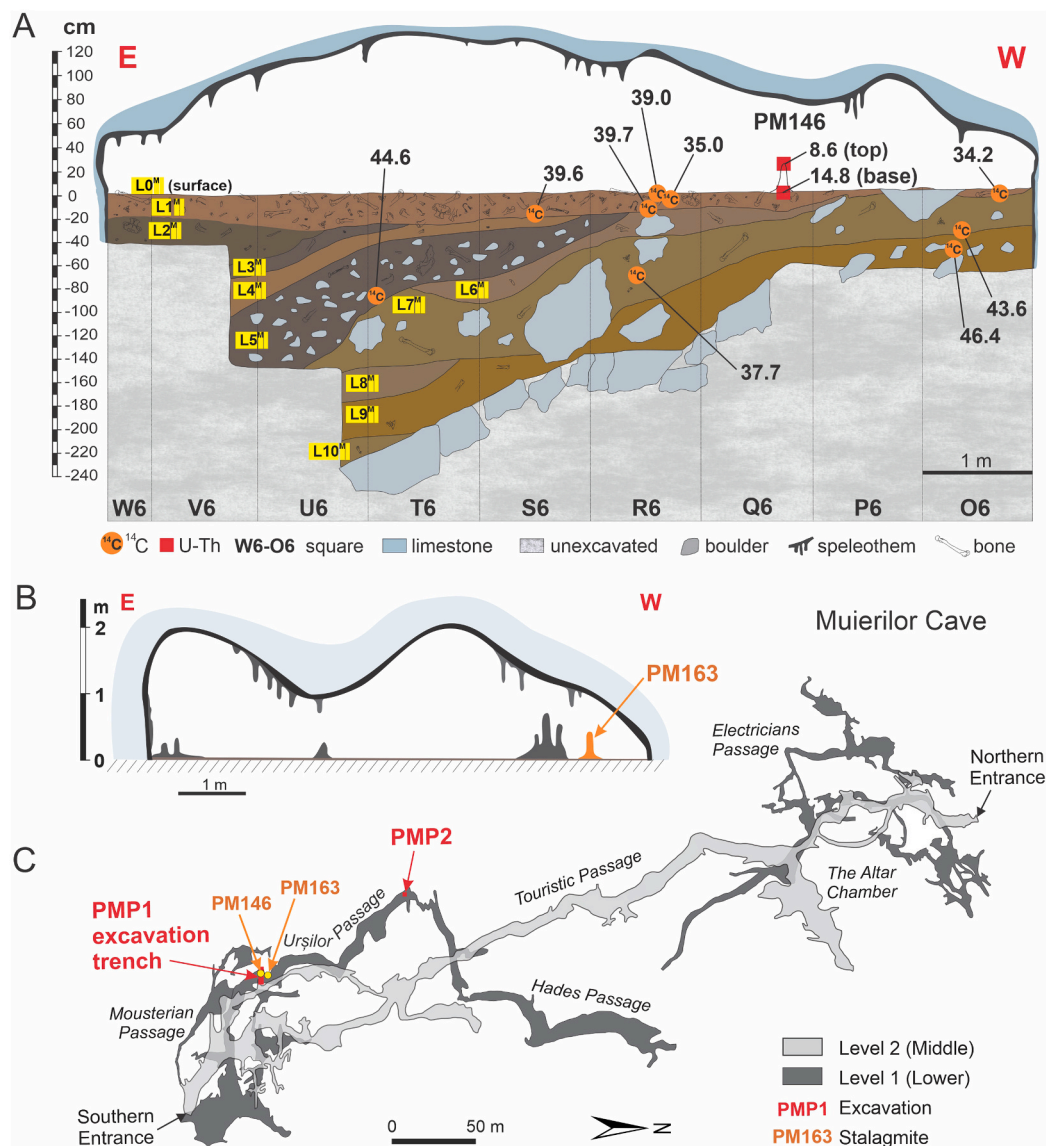


Fig. 2. Muierilor Cave: A) Stratigraphy and chronology of the PMP1 section; B) Muierilor Cave map (modified from Mirea et al., 2021, with permission from Elsevier). The numbers represent calibrated ages in ka (median ages BP). The red squares indicate the U-Th corrected ages (ka) of the PM146 stalagmite. The location of the PMP2 excavation pit, analyzed by Mirea et al. (2021), is shown only for informal purposes.

(Bleahu et al., 1985). The artificial entrance is located at 491 m a.s.l., in a former limestone quarry on the left side of Crăiasa Valley (Fig. 1C–D; Rusu and Racoviță, 1981). The Apuseni Mountains border the Pannonian Basin to the east, acting as an orographic barrier to humid Atlantic air masses. This region has the highest average precipitation in Romania (1631.5 mm/yr), recorded between 1961 and 2000 at the Stâna de Vale weather station (National Meteorological Administration, 2008). At the highest altitude of the Apuseni Mountains (~1850 m a.s.l.) several perched corries were also reported (Mac et al., 1990), as well as numerous nivation hollows at elevations between 1500 and 1650 m a.s.l. The cave was developed along two distinct levels, separated by an 18-m deep shaft following a local fault, and consists of ~1500 m of large, mostly horizontal passages (Vălenaş, 1979). The upper cave level (~1000 m in length), now hydrologically inactive, consists of four main passages (Oaselor, Candlesticks, Shafts, and “Emil Racoviță”), and a large chamber (Fig. 3). The lower level (The Scientific Reserve, ~500 m in length) also includes a horizontal passage, with small side passages and one chamber developed at the base of the shaft (Excavation Chamber), infilled with sediment. Both cave levels host important cave bear bone assemblages (both surface and sedimentary; scattered and

fully articulated specimens) and cave bear ichnofabrics (nests, scratch marks, footprints, and fur imprints) (Constantin et al., 2014; Robu, 2016; Robu et al., 2018).

2.2. Stratigraphic and paleontological context

Previous research in the two caves documented the initial stratigraphic context of the paleontological assemblages (Terzea, 1978; Constantin et al., 2014; Mirea et al., 2021; Faur, 2022). Muierilor Cave preserves complex Late Pleistocene sedimentary archives across two distinct levels. In the Scientific Reserve (lower level), a 260-cm sequence (PMP1) comprises ten layers (denoted as L1^M to L10^M; Figs. 2 and 4A–C)² of red clay, silt, and allochthonous gravel. High-energy hydraulic events periodically reworked this matrix, creating successive sediment-infilled channels characterized by a high density of weathered

² To avoid confusion, throughout this work, the superscripts “M” and “U” are used to differentiate between layers from Muierilor and Urşilor caves, respectively.

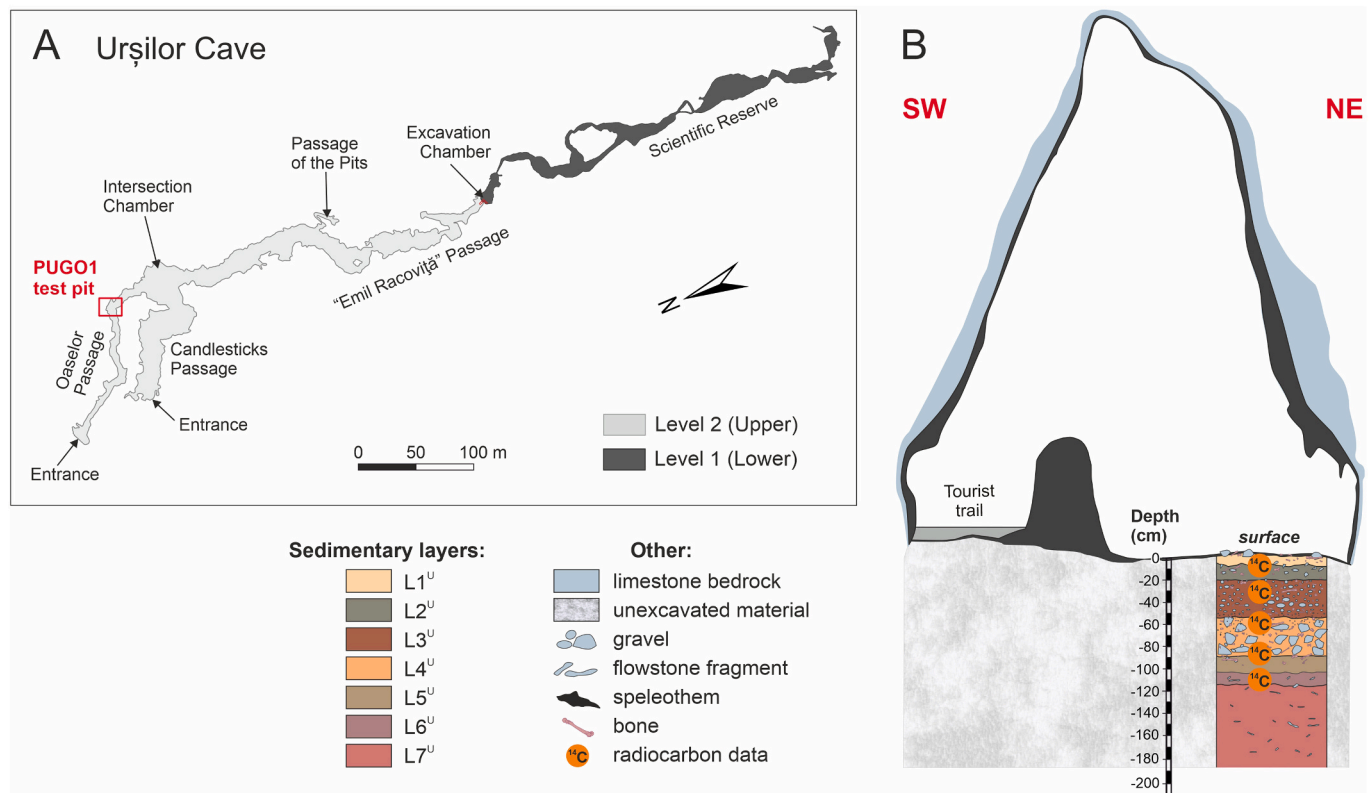


Fig. 3. Urşilor Cave: A) Cave map with the location of the PUGO1 section (modified from Constantin et al., 2014); B) stratigraphy of PUGO1 shown in the original (Terzea, 1978; to the left side of the section) and revisited description (this study; indicated to the right side).

fossil remains, primarily *Ursus spelaeus*, *Canis lupus*, and various micro-mammals (Mirea et al., 2021). The sequence culminates in a low-energy surficial red clay (L0^M) containing scattered speleothems and large mammal skulls. In the upper dry level of Urşilor Cave (Oaselor Passage; PUGO1 section), the depositional architecture reflects a distinct evolutionary trajectory with separate drainage mechanisms during MIS 3–2 (Constantin et al., 2014). Terzea (1978) first documented the 190-cm-thick PUGO1 section (Figs. 3 and 4E–G), describing a transition from a compact, sterile basal clay (190–110 cm) to an overlying 90-cm-thick dynamic alluvial succession (110–20 cm). The latter shifts from temperate ocher clays to cold-climate coarse grains and terminal open-forest brown-grey clays, all capped by a 20-cm layer of brownish-red clay containing angular clasts and flowstone fragments. Excepting the basal unit, all layers yield diverse Late Pleistocene taxa, including *U. spelaeus*, *U. arctos*, *P. spelaea*, *Crocota crocuta spelaea*, and *Canis lupus*. The high frequency of recrystallized clasts and rounded gravel throughout underscores a highly dynamic depositional environment characterized by significant hydraulic reworking (Fig. 4F–G; for more details see the Supplementary information (SI) – S2. Stratigraphic and paleontological context).

2.3. Geochronology

The formerly reported radiocarbon ages of the fossil fauna from the PMP1 excavation in Muierilor Cave fall between >50 and 22.5 ka (Mirea et al., 2021; Fig. 2). The basal U–Th age of the PM146 stalagmite that „sealed” the L1^M layer is 14.78 ± 0.38 ka (Mirea et al., 2021; Fig. 2A). For Urşilor Cave, the radiometric dating results suggested that, at least during the last 210 ka, the upper and lower levels may have functioned occasionally as hydrologically separated karst systems (Constantin et al., 2014). The embedded MIS 3 fossils from the Scientific Reserve have ages ranging between ~45.2 and 27.1 ka (Constantin et al., 2014; Robu, 2015; Duñó-Iglesias et al., 2024).

3. Methodology

3.1. Stratigraphic framework and analytical approach

Previous studies provided only limited stratigraphic descriptions of the PUGO1 test pit in Urşilor Cave (Terzea, 1978) and focused on the fine fraction (<5 mm) of sediments in the PMP1 trench for grain-size analysis (Mirea et al., 2021; Faur, 2022), primarily to establish the context of paleontological accumulations. Here, we re-examine both sequences using an allostratigraphic approach and a comprehensive sedimentological analysis, integrating grain-size, sorting, and clast shape. Grain-size distribution and sorting are used to distinguish sedimentary facies (Bosch and White, 2007), whereas clast shape (sphericity and roundness) provides additional constraints on transport processes and depositional dynamics (Benn and Ballantyne, 1993).

The analytical workflow applied at both sites includes:

- identification and description of stratigraphic layers (L);
- systematic sediment sampling at 10-cm intervals for grain-size analysis, using dry sieving (>0.063 mm) and the hydrometer method (<0.063 mm);
- selection of gravel clasts for morphometric analysis, as coarse particles are most sensitive to flow velocity and thus indicative of high-energy flood conditions;
- integration of available radiometric data (U–Th and AMS ¹⁴C) from speleothems and fossil remains to constrain depositional timing (Constantin et al., 2014; Robu, 2015; Mirea et al., 2021), complemented by new analysis of stalagmite PM163;
- identification of major discontinuities and definition of allostratigraphic units (U), followed by facies description, and interpretation of the depositional context.

To support the interpretation of the stratigraphic and



Fig. 4. Cave deposits in the Scientific Reserve of Muierilor Cave (A–D) and in the Oaselor Passage of Urșilor Cave (E–G): A) PMP1 excavation area, level 0 (=the surface; $L0^M$); B) the surface of W6 square in PMP1, before being excavated; C) the test-pit excavated by Nicolăescu-Plopșor (1957), with the corresponding layers from PMP1 trench; D) location of the PM163 stalagmite within the Urșilor Passage, at ~3-m distance from PMP1 section; E) location of the PUGO1 paleontological test-pit studied by Terzea (1978); F) the sedimentary layers of PUGO1 ($L1^U$ – $L7^U$); G) the surface of Oaselor Passage. Note that some surface bones in Oaselor Passage may have originated from other sectors of the Touristic Passage and were likely relocated by workers during construction of the concrete trail.

sedimentological data, we further outline the allostratigraphic framework and facies classification applied in this study. Additional methodological details are provided in the Supplementary material.

3.1.1. Allostratigraphic units

According to the North American Commission on Stratigraphic Nomenclature (1983), an allostratigraphic unit is a body of sedimentary material defined by bounding discontinuities (e.g., unconformities). This approach is particularly suited to Quaternary sedimentary successions (e.g., alluvial, lacustrine, glacial, or fluvial deposits), where such discontinuities provide key criteria for differentiating depositional units (Hughes, 2013). More recent studies have extended its application to cave environments (e.g., Martini et al., 2018; Ballesteros et al., 2023), highlighting the importance of internal stratigraphic architecture for interpreting depositional processes and linking cave records to regional hydroclimatic conditions. In cave systems, where lateral continuity is often limited, bounding discontinuities are typically the most diagnostic features of sedimentary sequences. Consequently, an allostratigraphic framework is especially effective for identifying depositional phases and

reconstructing shifts in sedimentation regimes associated with hydrological variability.

3.1.2. Facies of cave sediments

Cave sediment facies represent subsurface analogues of fluvial environments, adapted to conduit-confined conditions where sediment transport is controlled by flow velocity and passage morphology. Based on transport mechanisms, Bosch and White (2007) distinguished several facies types:

- (i) **channel facies**—sorted to partially sorted sediments ranging from silt to gravel, forming bedded deposits in active conduits and reflecting sediment transport and reworking;
- (ii) **thalweg facies**—well-sorted coarse material (pebbles to cobbles) forming armored beds mobilized only during high-energy flood events;
- (iii) **slackwater facies**—fine-grained silt and clay deposited from suspension during flood-stage ponding (Gázquez et al., 2014; Kurečić et al., 2021);

- (iv) **backswamp facies**—clay-rich, low-energy deposits formed in stagnant or poorly drained zones, occasionally recording flooding (Constantin et al., 2014; Mirea et al., 2021);
- (v) **diamicton facies**—unsorted, unstratified deposits (clay to boulders) transported as a single mass during high-energy flood events, providing clear evidence of flood pulses (Gillieson, 1986; Riddell et al., 2023).

Together, these facies provide a framework for interpreting sediment transport processes and reconstructing hydrological regimes within karst systems. Facies classification was further based on the combined evaluation of grain-size distributions and particle-shape parameters. Channel facies were identified by moderately to poorly-sorted sediments ($\sigma < \sim 2\phi$), with unimodal to weakly bimodal grain-size distributions and a dominance of sand to fine gravel fractions. In contrast, diamicton facies were defined by very poorly to extremely poorly sorted sediments ($\sigma > \sim 3\text{--}4\phi$), polymodal distributions, and the coexistence of clay to coarse gravel or boulder-sized clasts. Thalweg facies were distinguished by coarse, well-winnowed fractions with limited fine material and high roundness values. These criteria were evaluated using GRADISTAT outputs and supported by particle-shape indices (MPS, c/a ratios), allowing reproducible differentiation between depositional facies.

3.2. Sampling strategy

In Muierilor (PMP1 excavation trench), sediment was sampled from S6 and T6 squares, which intercept the thickest section of each stratigraphic level (i.e., the palaeo-thalweg of the underground river) and lack lateral variations that could lead to misinterpretation of the hydrologic events. Due to the consistent thickness of some layers (0.5–1 m), for a more accurate assessment of the stratigraphy, 22 bulk sediment samples were collected at 10-cm intervals to a depth of 2.20 m and stored in plastic sample bags. The samples weighed between 0.3 and 2 kg, depending on clast size. The same sampling protocol was followed in Urşilor, where 15 sediment samples were collected from the PUGO1 test-pit to a depth of 1.50 m. We separately sampled 30 individual clasts larger than 5 ϕ ; 32 mm (classified as coarse pebbles and cobbles sensu Pettijohn, 1975; Friedman and Sanders, 1978; Blott and Pye, 2001) from each targeted layer for size and shape analysis and measured them individually. The targeted layers were L3^U, L4^U and L5^M, because these levels are rich in gravel-size clasts larger than 32 mm compared to the other layers in the sequences. The pebble size was selected in accordance with recognized papers in the field that report experimental results and can serve as a comparable basis (e.g., Sneed and Folk, 1958). Coarse to very coarse pebbles (~32–64 mm and larger) reflect high-energy sensitivity, as they are mobilized only during high stream-power events (e.g., Buffington and Montgomery, 1997; Church, 2006) and therefore have the greatest potential to provide quantitative information on sediment transport processes during subterranean flash floods.

3.3. Grain-size and shape analysis

This procedure followed the Udden-Wentworth scale, as extended by Blair and McPherson (1999). Clasts smaller than 8 mm were processed via dry sieving, while the fine fraction (<63 μ m) was analyzed using the hydrometer method; then, all data were processed with GRADISTAT v9 (Blott and Pye, 2001). Mass percentages were calculated per Gee and Bauder (2018), and sediment facies were distinguished according to the classification framework by Bosch and White (2018). Particle shape was analyzed using ImageJ2 (Rueden et al., 2017) to determine circularity and roundness indices (i.e., R_i , SAI). Hydraulic transport dynamics was further assessed through the Maximum Projection Sphericity (MPS) index (Sneed and Folk, 1958; Benn and Ballantyne, 1993). Morphometric data were plotted on ternary diagrams using Tri-Plot (Graham and Midgley, 2000) to classify clasts as compact, platy, or elongated. Final characterization utilized Powers' (1953) roundness classes and

pebble counts to emphasize shape and size characteristics over potential manual sampling biases.

3.4. Speleothem examination and U-Th dating

The PM163 stalagmite from Muierilor Cave (Figs. 2, 4D and 9) was recovered from a calcite flowstone ~2 m upstream of the PMP1 trench (near square R6), which caps a faunal assemblage deposited prior to 31.22 ka (Mirea et al., 2021). Following longitudinal sectioning and petrographic examination of thin sections (Fig. 9C–F) at the LYTHOS Research Centre to classify crystal fabrics and identify flooding hiatuses (Frisia, 2015), the specimen underwent high-resolution U–Th dating. Twenty-two subsamples were analyzed using a Neptune Plus MC-ICP-MS at the Neptune Isotope Laboratory (USA), following the separation protocols described by Pourmand et al. (2014). Of these, eight ages from stratigraphically critical positions (Fig. 9A–B) are reported here to refine the preliminary baseline established by Mirea et al. (2021). No interbedded speleothems were identified within the sedimentary sequences at either Muierilor or Urşilor caves.

3.5. Radiocarbon dating

The AMS 14C dating of MIS 3 fauna, primarily cave bear, lion, and wolf remains, was conducted at the Poznan Radiocarbon Laboratory (Poland) and the Oxford Radiocarbon Accelerator Unit (ORAU, UK), following established extraction and ultrafiltration protocols (Longin, 1971; Piotrowska and Goslar, 2002; Brock et al., 2010). To mitigate systematic errors and 'young' biases associated with modern carbon contamination near the 50-ka limit, samples were deemed suitable only if they met a collagen yield threshold of $\geq 0.8\%$ (e.g., van Klinken, 1999; Wood et al., 2010; Higham et al., 2017). Sampling spanned the full vertical extent of the PMP1 and PUGO1 sections, prioritizing high-density dental remains and cortical long bone tissue to ensure superior preservation (Higham, 2011; Wood et al., 2016). Seven samples previously identified with low collagen yields (Robu, 2015; Mirea et al., 2021) were replicated at ORAU using rigorous purification standards (Higham et al., 2006; Bronk Ramsey et al., 2010). All results were calibrated using OxCal v4.4 (Bronk Ramsey, 2009, 2020) against the IntCal20 curve (Reimer et al., 2020). These radiocarbon ages represent minimum (*terminus post quem*) constraints, suggesting that deposition or reworking took place after the cessation of carbon exchange in the dated sample (e.g., Grün, 2006; Taylor and Bar-Yosef, 2014).

4. Results

4.1. Revisited stratigraphy and facies architecture

4.1.1. Muierilor Cave (PMP1 trench)

The re-examination of stratigraphy in the PMP1 excavation trench (Muierilor) did not require any major changes relative to the sequence described by Mirea et al. (2021). The most consistent sediment load across the trench section was observed within the layers L1^M–L3^M (~35 cm in thickness), L5^M (~50 cm), L7^M (~40 cm), L9^M (~30 cm), and L10^M (60 cm), also shown in Fig. 2. This sedimentary sequence is the most completely intercepted within the T6 quadrant, which is why it represents the focus of our revision in the PMP1 section (Figs. 5–8). The allostratigraphic units correspond to distinct sedimentary facies defined by grain-size distribution, sorting, and clast-shape characteristics (Fig. 5A).

The sedimentary sequence begins with sand and silt deposits with convolute texture (L10^M), separated as the U5^M allostratigraphic unit. The lower units (U3^M–U4^M; L6^M–L9^M) are characterized by very poorly to extremely poorly sorted sediments ($\sigma > \sim 3\text{--}5\phi$), polymodal grain-size distributions, and the coexistence of fine matrix with large angular to subangular clasts. This architecture indicates transport and accumulation of breakdown deposits (angular clasts of various size), mixed with

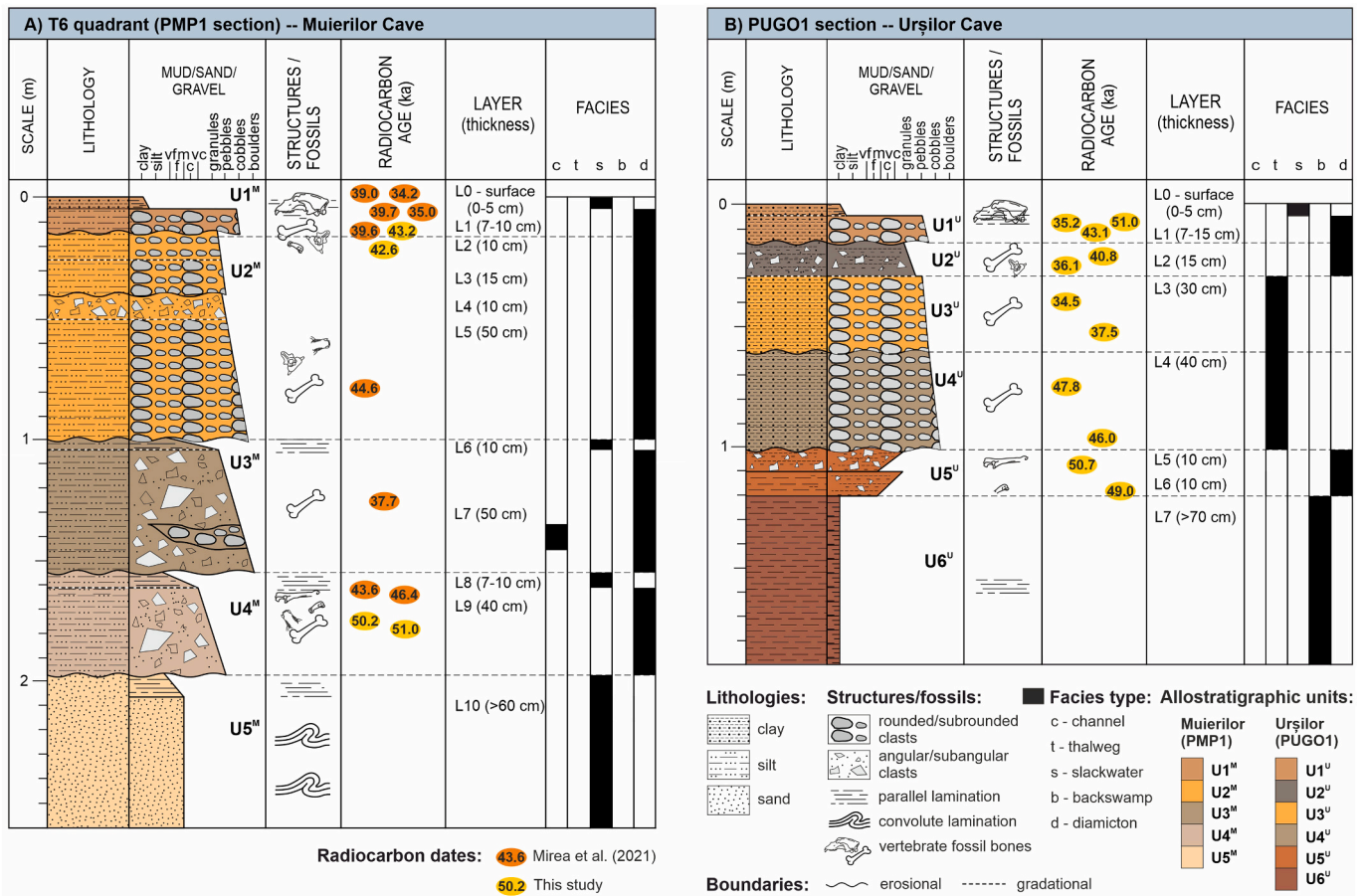


Fig. 5. Stratigraphic logs of the T6 section/PMP1 excavation in Muierilor (A) and PUGO1 test pit in Urșilor (B), illustrating the depositional processes in the two caves during MIS 3–2, based on allostratigraphic interpretation and radiocarbon geochronology. The logs were generated with the SedLog v3.1 software (Zervas et al., 2009) and underwent subsequent graphical refinements. Facies types are represented following the classification of Bosch and White (2007, 2018).

very poorly sorted or unsorted sediment and fossil bones. These features also define a diamicton facies, interpreted as the product of high-energy, short-duration flood events capable of transporting heterogeneous sediment loads. Locally, the improved sorting of coarse gravel ($\sigma < 2$) indicates episodic, organized flow characteristic of channel facies conditions (e.g., L7^M/U3^M at ~140-cm depth).

The intermediate unit U2^M (L2^M–L5^M) exhibits more heterogeneous grain-size distributions, including sand to gravel fractions with very poorly to extremely poorly sorting (typically $\sigma > \sim 3\text{--}5\phi$) and mixed roundness values. The penultimate major high-energy event, probably a single flood, resulted in the rapid and massive deposition of layers L5^M to L2^M (subrounded to rounded clasts), which ultimately infilled almost completely the meter-deep passage. This sequence is considered here as a single allostratigraphic unit (U2^M). The base of layer L5^M is strongly erosional, while the bases of the upper layers are relatively uniform and reflect the deposition of materials in order of their weight. L5^M contains heavy sedimentary compounds – the largest pebbles and the fewest bones. The abundance of bioclastic material, which is lighter than lithoclasts, increases toward the top, in level L2^M (containing the most bones – e.g., rib fragments, metapodials, teeth, molars, vertebrae, small bones). The very poor sorting of individual layers and the general architecture of the U2^M unit suggest mobilization as a single sediment flow, which is characteristic to a diamicton facies. This is also supported by the radiometric data, which show a weak correlation with depth (Fig. 5A).

The last flooding event led to deposition of the upper unit U1^M (L0^M–L1^M), dominated by coarse-grained sediments (gravel with subordinate silt and clay) displaying very poorly sorting and high

roundness. This is consistent with diamicton facies, indicative of high-energy depositional conditions, with larger and lighter bones (e.g., skulls, femurs, ulnae, etc.) being deposited last. Each of the U1^M, U3^M and U4^M units is capped by a thin clayey layer, indicative of slackwater facies.

4.1.2. Urșilor Cave (PUGO1 test pit)

In case of Urșilor, the sedimentary sequence of the PUGO1 test-pit showed different characteristics of sediment patterns, which allowed us to separate seven distinct layers (L1^U–L7^U), compared to five layers described by Terzea (1978). At the base of the sequence, a compact clay, without bones or clasts, forms the L7^U layer. It is followed by a matrix-supported clayey layer, 10-cm thick, with scarce subangular clasts (L6^U), then by a clast-supported layer of 15 cm, with scarce bones and angular clasts (L5^U). The sediment pattern changes abruptly within the following two layers (L4^U and L3^U, respectively), each about 35 cm thick, composed of sub-rounded to well-rounded limestone clasts embedded in a mostly silty-sandy matrix, with scarce fossil bones. The next layer (L2^U) varies in thickness and contains angular clasts with rare fragments of calcite flowstone. At the top of the sequence, we separated a very thin, but distinct clayey layer (L1^U) of ~10–15 cm, capping the entire sedimentary deposit. A rich deposit of cave bear bones and subrounded to well-rounded large clasts embedded in the clayey matrix of the L1^U layer forms the surface deposit throughout the Oaselor Passage (Fig. 4). Some of these features are sealed by stalagmites and stalagmitic flowstones that formed after the final depositional stage. All clasts consist of limestone, indicating a local source area.

The allostratigraphic framework similarly corresponds to a transition

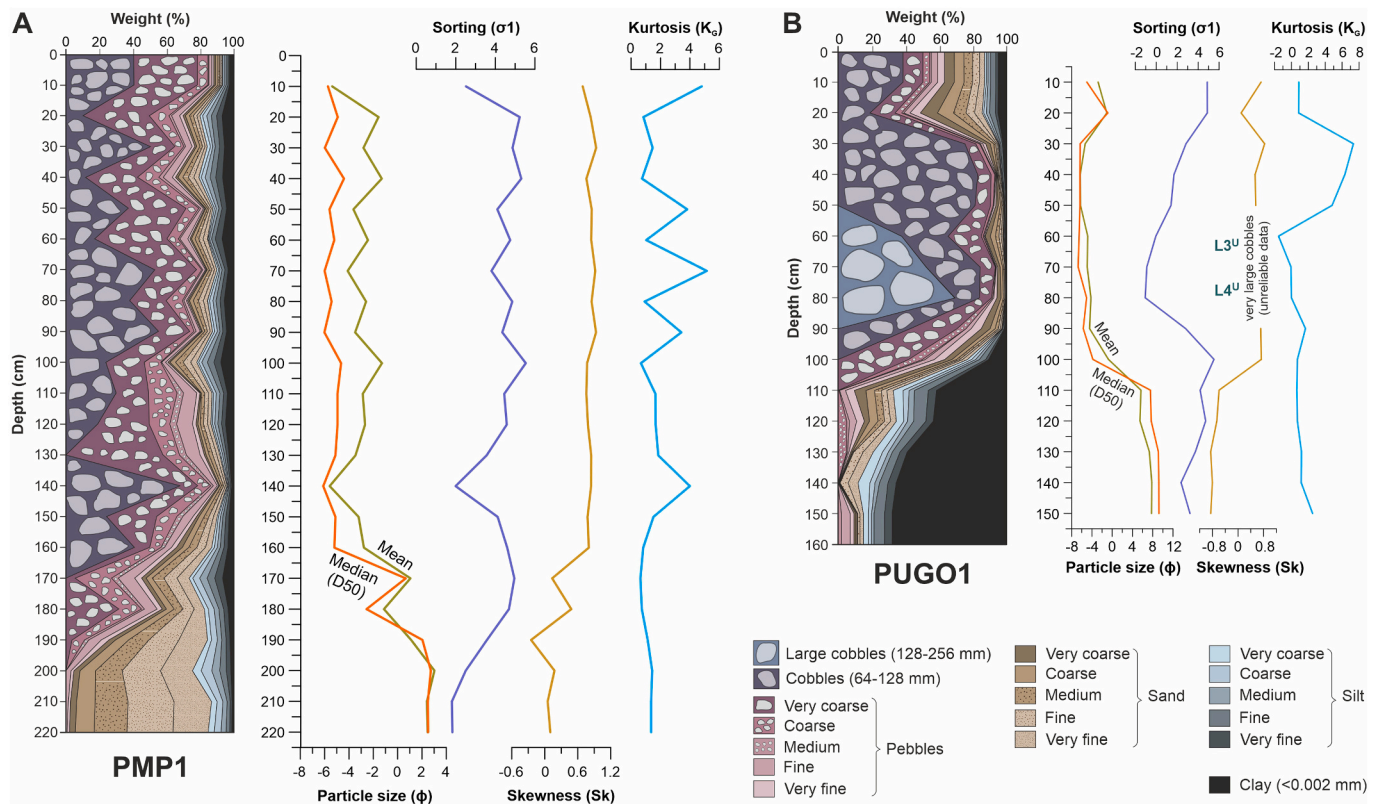


Fig. 6. Grain-size distribution and statistical parameters for the PMP1 (A) and PUGO1 (B) profiles. Stacked plots show the vertical variation in weight percentage of grain-size classes, together with mean grain size, median (d_{50}), sorting (σ_1), skewness (Sk), and kurtosis (K_s). Grain size is expressed in ϕ units. The PMP1 profile is dominated by poorly sorted coarse fractions with limited variability, whereas PUGO1 exhibits stronger vertical trends, including intervals with very large clasts (uncertain upper size limits) and marked shifts in sorting and skewness. Grain-size classes follow the Udden–Wentworth scale (Wentworth, 1922).

between distinct facies controlled by hydrological variability. The facies sequence differs in the first 110 cm when compared with that in the Scientific Reserve, where, except for a few short transitions to channel facies, backswamp facies is prevalent. Here, the facies suite ranges from slackwater ($U6^U$) to diamicton ($U5^U$ and $U2^U$), thalweg ($U4^U$ and $U3^U$), channel and again slackwater ($U1^U$) (Fig. 5B). The sediment layering and granulometric analysis results from the PUGO1 section indicate better sorting than in PMP1.

The lowermost unit $U6^U$ (–190 to –120 cm) comprises compact, fine-grained sediments with very limited coarse fraction and no mammal/vertebrate fossil content, consistent with a slackwater facies, reflecting deposition from suspension in low-energy, ponded conditions. The overlying succession ($U5^U$ – $U2^U$; –120 to –20 cm) reflects transitions from diamicton to thalweg and again diamicton facies. Vertical variability in grain-size and clast roundness suggests fluctuations in discharge and sediment supply, consistent with alternating flow regimes. The sediment matrix is dominated by clay with subordinate silt and sand. The fine fraction (silt and clay) is almost completely absent from layers $L4^U$ and $L3^U$ (<5%). In contrast, the very coarse fraction (well-rounded to subrounded clasts, medium and large cobbles with tangential contacts) comprises >90% of each sample, resembling the characteristics of texturally mature armored gravel beds. Here, the well-winnowed material is indicative of thalweg facies, associated with peak flow conditions. The uppermost unit $U1^U$ (0 to –20 cm) consists of clay-rich sediments with angular clasts and flowstone fragments, showing extremely poor sorting ($\sigma \approx 4.5$ –5 ϕ) and evidence of high-energy transport. This is consistent with a diamicton facies, heavily reworked during the last flooding event occurred in this passage, very similar to PMP1 in Muierilor. The sedimentary sequence ends with a capping thin clayey deposit (slackwater facies).

4.2. Grain-size and shape analysis of cave sediments

4.2.1. Grain-size analysis

In the PMP1 section, sediments are dominated by gravel, with an average proportion of 62.05%, followed by sand (23.01%), silt (10.78%), and clay (4.16%). Sequentially, sediments down to a depth of –150 cm (layers $L1^M$ – $L7^M$) are dominated by gravel, with an average proportion of 77.33%, followed by silt and clay (13.63%) and sand (9.03%). From –150 to –190 cm (layers $L8^M$ – $L9^M$) the gravel fraction decreases to 48.07%, followed by sand (32.72%) and mud (20.06%). At depths below –190 cm ($L10^M$), sand is dominant (78.87%), followed by silt and clay (17.91%). In contrast, gravel is only 3.22% (Table 1, Fig. 6A). Down to a depth of –160 cm, the mean values are strongly positively correlated with the percentage of silt and clay cumulated fraction (% mud/Mz; $r = 0.86$; $P < 0.0001$). The % mud/Mz values of the sandy silt samples (depth –200 to –220 cm; $N = 3$) are also strongly correlated ($r = 0.99$). The median particle size parameter (d_{50}) constrains better the sediment distribution with profile depth compared to the mean, showing more clearly the dominance of coarse particles, smaller than -4ϕ , and highlights better the facies changes. Standard deviation (1σ) values ranging from 1.98 to 5.23 show that sediments are very poorly and extremely poorly sorted (Fig. 6A).

All PMP1 sediment samples down to a depth of –160 cm exhibit positively skewed distributions, with a long tail toward the highest ϕ values (i.e., fine particles) between 0.69 and 0.93, averaging 0.82. The lower section (from –170 cm to –220 cm) has slight positively and normally skewed distributions, with a single negative value (at –190 cm). The mud fraction is present across the entire profile depth in a relatively low and constant proportion (5–20%), with five samples exceeding 20% of mud. The textural class of the PMP1 fine matrix is sandy silt ($N = 18$), followed by silt ($N = 4$). Relative to the total

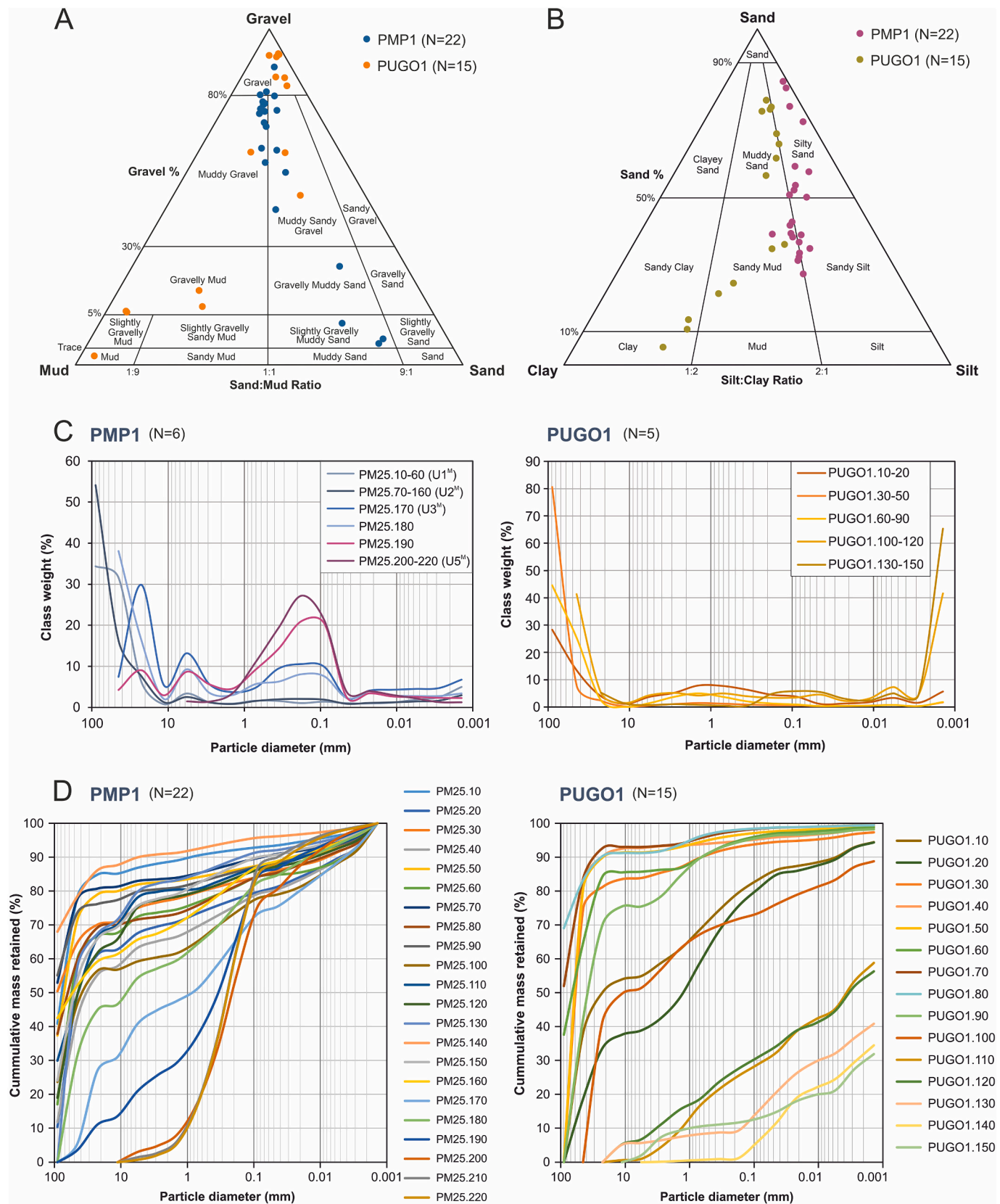


Fig. 7. Textural classification and grain-size distributions for the PMP1 and PUGO1 profiles: A) Ternary diagram showing gravel–sand–mud proportions, indicating that most samples plot within gravel-dominated fields, with PMP1 clustering in muddy gravel and PUGO1 displaying a wider spread toward sandy gravel and gravelly mud; B) sand–silt–clay ternary diagram highlighting the fine fraction, according to [Shepard's \(1954\)](#) classification scheme, where PMP1 samples are enriched in sand, whereas PUGO1 samples extend toward mud- and clay-rich compositions; C) representative grain-size distribution curves for selected samples from each profile, illustrating contrasting modal structures and variability; D) cumulative grain-size curves for all samples, emphasizing differences in sorting and the relative contribution of coarse and fine fractions between the two sites.

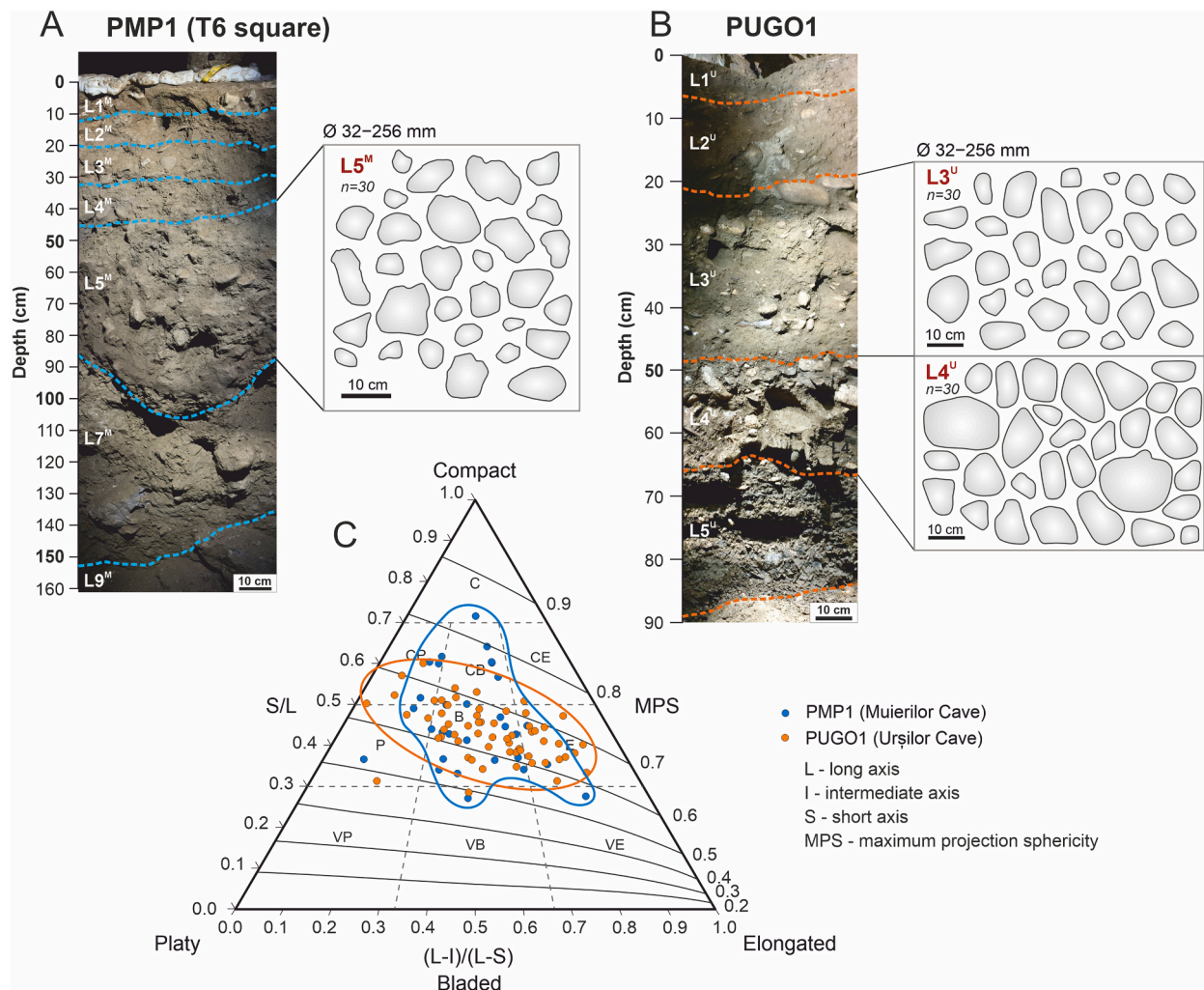


Fig. 8. Size and shape analysis of the coarse fraction (32–256 mm) from selected layers: A) The L5^M layer from T6 quadrant (PMP1 section); B) the L3^U and L4^U layers from PUGO1 section (Urşilor Cave); C) computed ratios of particle axes and MPS plotted on the sphericity-form ternary diagram (as in Fig. 2 of Sneed and Folk, 1958), indicating predominantly compact to bladed forms with overlapping distributions for both sites. PMP1 shows a slightly broader spread toward compact morphologies, whereas PUGO1 trends toward more elongated forms.

Table 1
Grain-size statistical parameters calculated for the analyzed sediment samples.

Excavation site	Clay (%)	Silt (%)	Sand (%)	Pebbles (%)	Cobbles (%)	Median D ₅₀ (φ)	Mean (Mz-φ)	Sorting (σ ₁)	Skewness (S _k)	Kurtosis (K _G)
Muierilor Cave PMP 1	1.03–7.88	2.92–22.73	4.83–84.01	2.11–82.21	0.00–68.03	–6.11–2.73	–5.59–3.03	1.81–5.54	–0.25–0.92	0.64–5.15
Urşilor Cave PUGO1	0.48–65.75	0.69–27.19	2.43–36.26	0.39–62.93	0.00–83.75	–6.72–9.23	–6.31–7.83	–1.06–5.52	–0.86–0.83	–1.53–7.34

sedimentary content, the main textural classes are silty gravel and silty sand (Fig. 6A). In the PUGO1 section, the gravel fraction increases abruptly from 50 to 63% in the upper layers to over 85–93% in the middle layers (L3^U and L4^U). Layers L1^U–L4^U also show a higher sand content compared to silt and clay, a situation reversed at the bottom layers (L5^U–L7^U), where the mud content increases from 66% to 90–98% (Table 1, Fig. 6B). The clay content is positively correlated with silt ($r = 0.81$; $P < 0.0001$) and shows no correlation with sand. The median particle size (d_{50}) highlights a sudden facies shift at –100 cm and the strong coarse fraction ($< -7\phi$; large cobbles) within layers L3^U – L5^U. Samples from the upper PUGO1 section (–10 to –50 cm; $N = 5$) show normal to positive skewness, indicating a dominance of coarse fractions. Samples at –60 to –80 cm

($N = 3$) exhibit extremely positive skewness, followed by continued positive skewness at –90 and –100 cm. Below –110 cm, distributions are consistently negatively skewed, typical of fine sediments. The apparently normal distribution of sample PUGO1–140 is actually negatively skewed, influenced by thin calcite flowstone fragments. Most layers exhibit platykurtic to very platykurtic distributions (kurtosis < 0.67), except for L3^U, which is extremely leptokurtic. Although layers L3^U and L4^U share similar sedimentation patterns, L3^U is very poorly sorted with more outliers, whereas L4^U is more heterogeneous but very well sorted. The main textural classes are, from the bottom to the top of the sequence: gravelly mud (L7^U–L6^U; $N = 5$), muddy gravel (L5^U; $N = 1$), very coarse gravel (L4^U–L3^U; $N = 7$), and muddy sandy gravel (L1^U–L2^U; $N = 2$).

In the gravel–sand–mud ternary diagram (Fig. 7A), the distributions confirm the predominance of coarse fractions at both sites, with PMP1 samples forming a relatively tight cluster, whereas PUGO1 samples show a wider dispersion toward mud-enriched fields. The sand–silt–clay diagram (Fig. 7B) further illustrates this contrast, with PMP1 samples grouped mainly within silty sand and sandy silt, while PUGO1 samples extend toward clay-rich compositions, highlighting their greater compositional variability. Particle size frequency distributions (Fig. 7C) emphasize the polymodal character of most samples, supporting the wide grain-size ranges identified in the statistical analysis. Only the sandy samples from the basal PMP1 levels show a more simplified distribution. Cumulative curves (Fig. 7D) show similar shapes among PMP1 samples, reflecting internal consistency within the sequence, whereas PUGO1 samples display more variable curve patterns. These graphical results are consistent with the statistical parameters (Tables S4–S5), which indicate very poor to extremely poor sorting at both sites, with greater heterogeneity at PUGO1. Overall, Fig. 7 provides a graphical synthesis of the grain-size characteristics, confirming the multimodal distributions and high variability already identified in the statistical analysis, and highlighting the stronger textural heterogeneity of PUGO1 compared to PMP1.

4.2.2. Shape analysis of the gravel fraction

The analyzed gravel samples from levels L5^M (Muierilor), L3^U, and L4^U (Urșilor) consist of cobbles (–6φ to –8φ; 64–256 mm) and medium- to very coarse pebbles (–3φ to –6φ; 8–64 mm). The clasts are generally rounded (0.49–0.70) and sub-rounded, well-rounded (0.70–1.00) across all three levels in both caves, with few subrounded pieces (0.35–0.49). Statistical results for each level are given in Table 2. The size and shape of the coarse fraction (<–3φ; >8 mm) reflect the ImageJ2 data summarized in Table 2 [data for each count (*N* = 90) are provided in Table S1 in the SI].

The clastic sediment in level L5^M is unsorted, with clasts generally smaller than in Urșilor (Fig. 8). Pebbles and cobbles range in size between –5.50φ and –7.04φ (44–130 mm), are moderately elongated (*C_i* = 0.62–0.87) and well rounded (*R_i* > 0.7 for 63% of the total clast sample). Except for several minor lenticular deposits (L2^M–L4^M), the layer is only overlain by a compact fossil bone layer (L1^M), which forms the floor paleosurface. The L3^U and L4^U layers contain abundant cobbles and scarce pebbles. The L3^U clasts range in size from –5.45φ to –7.36φ (44–164 mm), are slightly elongated (*C_i* = 0.66–0.88), and are sub-rounded to very well rounded (*R_i* = 0.43–0.98). Layer L4^U contains larger clasts, between 5.80φ and –7.74φ (56–214 mm), that are rather spherical (*C_i* = 0.72–0.89) and subrounded to very well rounded (*R_i* = 0.48–0.93). The maximum projection sphericity index (*MPS*) ranges from 0.48 to 0.84, with average values of 0.66 and 0.65, respectively (Table S2, Fig. 8C).

4.3. Speleothem microstratigraphy

Stalagmite PM163 is a 62-cm high calcite formation of candlestick

shape from Muierilor Cave, grown at the top of a floor crust in a recess of the Bears Passage (Fig. 9A). A clear difference is macroscopically visible between the lower section (the first 13 cm from the base) and the upper section (the next 50 cm to the top). The stalagmite started to form at ~4 cm above the flowstone covering the cave floor. Extremely thin, micron-scale laminae of light to medium yellowish to reddish-brown coloration are interspersed with white, opaque to translucent layers (*N* = 5) across the lower section. The latter consist of columnar, elongated crystals with interlocking edges, abruptly terminated by sharp erosional or dissolutional hiatuses, numbered h₁–h₅ (Fig. 9B).

At the base, several minor hiatuses occur at 1–5 mm intervals, ending with a major erosional hiatus with detrital drape (h₁) above the first translucent columnar calcite (TCC1) layer (mm 12). The crystal lattice was disrupted, and renewed nucleation produced microsparite fabrics (Ms) that formed the foundation of a new columnar elongated calcite layer with lateral crystallite overgrowths (Ce₁₀, Fig. 9C). At mm 21, light brown microsparite layers are capped by a minor hiatus (h₂). The next 12-mm high columnar elongated calcite layer (Ce, TCC2) is interrupted by prominent dissolutional hiatuses (h₃ to h₅). Dendritic fabric (D) occurs above h₃, followed by another layer of columnar calcite (Fig. 9D). This layer shows syntaxial crystal growth above h₄ and h₅, meaning it continues the existing lattice without being significantly disturbed by the detrital content. Sparse sand-sized mineral grains (e.g., quartz) are observed entrapped within dissolutional fringes incised into the calcite layer (Fig. 9E), which is locally almost completely eroded. From mm 50 to 70, multiple dense, dark-colored lamina sets (1–1.5 mm thick) exhibit alternating microsparite and opaque, micrite laminae (M), forming microbands at intervals of 30–40 μm (Fig. 9F).

4.4. U–Th dating results

The results of U–Th measurements for the lower section of stalagmite PM163 (the first 15 cm from the base, including the underlying flowstone) are presented in Table 3. The ages range between 31.23 ± 0.20 ka and 11.12 ± 0.05 ka. The oldest ages except for the lowermost, previously published value (subsample PM163.1; Mirea et al., 2021), yielded by subsamples 1b (28.49 ± 0.21 ka) and 1c (27.38 ± 0.13 ka), date the calcite flowstone layers comprised between hiatuses numbered h₁ and h₂, and h₂ and h₃, respectively (Fig. 9B). The dense set of erosional hiatuses h₃–h₅ is followed by a pristine, bright white columnar calcite layer that yielded an age of 14.24 ± 0.09 ka. This age is stratigraphically significant because it marks the beginning of stalagmite formation above the cave-floor flowstone. The youngest U–Th ages (subsamples 3, 3b and 4) successively date the calcite layers at intervals of 4–6 cm, yielding the following ages: 13.37 ± 0.07 ka, 11.95 ± 0.07 ka, and 11.12 ± 0.05 ka, respectively. These layers are separated only by minor hiatuses, suggesting different depositional (climate- and hydrology-driven) conditions compared to the lower layers.

Table 2

Gravel-size classes according to Wentworth (1922) and average values for particle size distribution and shape indices provided by ImageJ2 analysis.

Level	Count	Cobbles (%)	Pebbles (%)	Major axis <i>A_m</i> (φ)	Minor axis <i>A_m</i> (φ)	Mean (φ)	Sorting (1σ)	Skewness	Kurtosis	Circularity (<i>C_i</i>)	Roundness (<i>R_i</i>)	<i>MPS</i>
Muierilor Cave (PMP1)												
L5	30	60	40	–5.50 to –7.04	–4.69 to –6.66	–6.22	0.48	+0.09	–1.29	0.79	0.73	0.66
Urșilor Cave (PUGO1)												
L3	30	84.3	16.7	–5.45 to –7.36	–5.09 to –6.81	–6.59	0.47	–0.73	0.23	0.80	0.70	0.64
L4	30	96.7	3.3	–5.80 to –7.74	–5.57 to –7.31	–6.82	0.41	+0.02	0.60	0.80	0.67	0.65

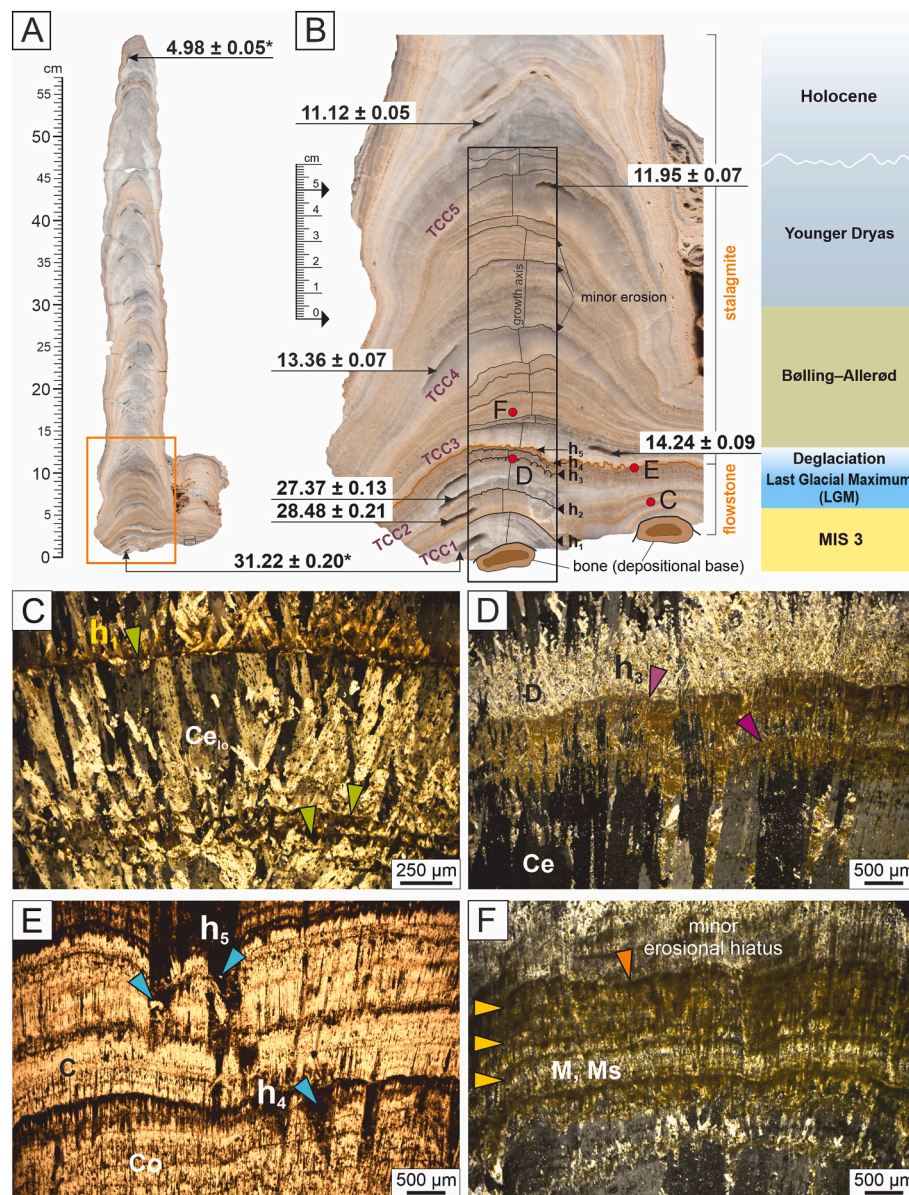


Fig. 9. Environmental changes during the MIS 3–2 as recorded in the PM163 stalagmite from Muierilor (Scientific Reserve, near the PMP1 trench): A) Longitudinal section showing the base and top U-Th ages and growth intervals; B) stratigraphic description of the basal section (the first 13 cm, shown within the orange frame in A) with the observed major and minor hiatuses, photomicrograph positions and rough assignment to the main climatic periods based on the presented U-Th ages, reported as ka (* Mirea et al., 2021); C) photomicrograph showing multiple dark-colored, possibly either humic or detrital layers (yellow arrows), CPL image; D) renewed crystal nucleation above a hiatus (h_3) underlined by calcite layers incorporating fine detritus (purple arrows), CPL; E) dissolutional hiatuses (h_4 and h_5) with detrital grains (light blue arrows), PPL; F) calcite crystal arrays rising above two minor and one major hiatus (h_1), showing interruption of crystal growth and detritus deposition (green arrows), CPL. See text for detailed explanations. Abbreviations for crystal fabrics (according to Frisia, 2015): C – columnar calcite; Ce_{10} – columnar elongated with lateral overgrowth; D – dendritic; M – micrite; Ms. – microsparite; other abbreviations: TCC – translucent columnar calcite; h – hiatus.

4.5. Radiocarbon dating results

The radiocarbon dating results are presented in Table 4. We discarded four results ($N = 3$ from Urşilor; $N = 1$ from Muierilor), from a total of 18 analyzed samples, with collagen yields below 0.8%. The calibration of the new radiocarbon dataset indicates that Urşilor bone assemblage (~51.0–34.5 ka; median ages) had a longer time span than Muierilor (~51–42.5 ka; Fig. 10, Table 4). However, when adding all the reliable radiocarbon data (with $\geq 0.8\%$ collagen yield, $N = 29$; Fig. 10; Table S3), it results that the PMP1 in Muierilor had a longer time span for bone deposition (~51–29 ka; $N = 18$) than PUGO1 in Urşilor (~51–34.5 ka; $N = 11$). The distribution of the median calibrated radiocarbon ages shows, for PMP1 ($N = 18$), that a large part of the

obtained results falls within the 50–30 ka interval (72.2%), while other intervals are poorly represented (60–50 ka: 22.2%; 30–20 ka: 5.6%). In Urşilor Cave, the radiocarbon results from PUGO1 test pit and cave surface ($N = 11$) indicate that 81.8% of the samples fall within the 50–30 ka interval, whereas 18.2% are > 50 ka.

In PMP1, the reliable radiocarbon ages obtained for the fossil record from the studied layers are as follows, from the bottom to the top: $L9^M > 54.8$ –46.4 ka; $L7^M \sim 43.6$ –37.7 ka; $L5^M \sim 46.5$ –42.3 ka; $L2^M$ – $L1^M \sim 43.2$ –34.9 ka; $L0^M$ (surface) ~ 50.2 –29 ka. In PUGO1, the $L7^U$ layer has no fossil record. Therefore, the radiocarbon data start, chronologically, from $L6^U$ upwards: $L6^U \sim 49.0$ ka; $L5^U \sim 50.1$ ka; $L4^U \sim 47.8$ –46.2 ka; $L3^U \sim 37.5$ –34.5 ka; $L2^U$ – $L1^U \sim 51.0$ –41.0 ka (Tables 4 and S3).

Apparently, a poor correlation is observed between the depth of all

Table 3

Summary of the U-Th data achieved for stalagmite PM163 subsamples. All ratios are activity ratios. Uncertainty levels are represented at a 95% confidence interval.

Sample code	Distance from base (mm)	Sample mass (g)	^{238}U (ppb)	$^{230}\text{Th}/^{238}\text{U}$	$^{230}\text{Th}/^{232}\text{Th}$	Age (yr)	$^{234}\text{U}/^{238}\text{U}$ initial (corrected)	Corrected age (yr)
PM163.1 ^a	1	0.162	637.515 ± 0.562	0.302 ± 0.001	49.950 ± 0.274	31,666.376 ± 169.014	1.208 ± 0.004	31,228 ± 198
PM163.1b	9	0.107	704.036 ± 0.739	0.284 ± 0.001	29.167 ± 0.188	29,187.532 ± 122.157	1.219 ± 0.004	28,488 ± 208
PM163.1c	15	0.111	702.538 ± 0.422	0.271 ± 0.001	69.216 ± 0.797	27,655.489 ± 111.786	1.221 ± 0.003	27,375 ± 132
PM163.2	25	0.087	732.132 ± 0.617	0.156 ± 0.001	53.631 ± 0.425	14,443.613 ± 72.579	1.261 ± 0.004	14,242 ± 88
PM163.3	55	0.113	759.007 ± 1.255	0.145 ± 0.001	96.665 ± 0.846	13,469.863 ± 62.780	1.256 ± 0.005	13,365 ± 68
PM163.3b	96	0.154	918.930 ± 0.547	0.132 ± 0.001	51.728 ± 0.866	12,128.882 ± 48.666	1.264 ± 0.003	11,952 ± 65
PM163.4	118	0.085	686.258 ± 0.707	0.122 ± 0.001	117.929 ± 2.195	11,195.132 ± 50.302	1.252 ± 0.004	11,123 ± 54
PM163.14	593	0.151	486.206 ± 0.263	0.052 ± 0.000	46.808 ± 4.540	5070.984 ± 43.842	1.147 ± 0.003	4986 ± 49

^a Sample PM163.1 was published in Mirea et al. (2021).

Table 4

Results of radiocarbon AMS dating of fossil remains from Muierilor and Urșilor caves. The radiocarbon dates were calibrated using the IntCal20 calibration dataset (Reimer et al., 2020). I1 – first upper incisor; C – canine; m1 – first lower molar. Lab acronyms: OxA – Oxford Radiocarbon Accelerator Unit; POZ – Poznan Radiocarbon Laboratory. Notes: All depths are in cm below the surface. Collagen yields are given in percent of extracted collagen with respect to the initial weight of the sample. Samples highlighted in grey were discarded due to the low collagen yield (<0.8%).

Field no.	Lab no.	Specimen	Location	Depth (cm)	Coll. Yield (%)	% Ccoll	%N coll	C:N	^{14}C age (uncalibrated)	Calibrated age (ka; median)	Age range (ka; 2σ)
Muierilor Cave - Bears' Passage											
PM/S6-I-II-1	Poz-161930	<i>U. spelaeus</i> mandible	PMP1	-15	1.4	57.0	20.6	2.8	39,500 ± 1100	43,223	44,852–42,071
PM/U6-II-III-C	Poz-161929	<i>U. spelaeus</i> mandible	PMP1	-25	2.3	51.1	18.4	2.8	38,500 ± 1000	42,575	44,205–41,476
PM/P6-IV-V	OxA-43460	<i>U. spelaeus</i> radius.	PMP1	-45	1.5	39.6	12.2	3.2	> 48,100	50,957	54,493–49,784
PM/P6-IV-V	OxA-43461	<i>U. spelaeus</i> radius.	PMP1	-45	1.3	40.7	12.5	3.3	> 47,600	50,176	51,686–48,945
PM/T6-XIII-XIV	OxA-X-3233-7	<i>U. spelaeus</i> M ₂	PMP1	-135	0.3	33.3	10.2	3.3	> 42,400	44,952	45,281–44,662
PM/T6-XVII-XVIII	OxA-43459	<i>U. spelaeus</i> M ₁	PMP1	-175	1.8	42.3	12.9	3.3	> 54,800	54,800	54,801–54,800
Urșilor Cave - Oaselor Passage											
PU/GO-0-004	OxA-X-3231-9	<i>U. spelaeus</i> M ₂	Oaselor Passage	Surface	0.6	42.5	13.1	3.2	28,530 ± 380	32,759	33,869–31,754
PU/GO-0-005	OxA-43458	<i>U. spelaeus</i> P ⁴	Oaselor Passage	Surface	1.6	36.4	11.34	3.2	> 48,100	50,957	54,493–49,784
PU/GO-0-006	OxA-X-3231-11	<i>U. spelaeus</i> Mtt 4	Oaselor Passage	Surface	0.8	42.1	12.9	3.3	39,200 ± 1200	43,082	45,010–41,805
PU/GO-10	Poz-156049	<i>P. spelaea</i> phalanx	PUGO1	-7	1.8	50.1	18.2	3.2	35,700 ± 700	40,771	41,951–39,603
PU/GO-11	Poz-156050	<i>U. spelaeus</i> M ₂	PUGO1	-15	0.6	50.9	18.5	3.2	35,700 ± 700	40,771	41,951–39,603
PU/GO-18	Poz-156058	<i>C. lupus</i> mandible	PUGO1	-35	1.2	50.4	18.2	3.2	30,000 ± 400	34,497	35,321–33,759
PU/GO-12	Poz-156051	<i>U. spelaeus</i> Mtt 2	PUGO1	-45	6.5	47.0	17.1	3.2	32,800 ± 500	37,516	39,054–36,273
PU/GO-14	Poz-156052	<i>U. spelaeus</i> I ³	PUGO1	-83	6.5	53.3	19.3	3.2	44,000 ± 2000	47,764	52,606–43,925
PU/GO-15	Poz-156053	<i>U. spelaeus</i> M ₁	PUGO1	-90	1	50.0	18.2	3.2	42,000 ± 2000	46,022	51,485–42,427
PU/GO-003	OxA-43143	<i>U. spelaeus</i> peroneus	PUGO1	-110	4.5	41.4	12.9	3.2	> 47,900	50,689	52,151–49,470
PU/GO-16	Poz-156054	<i>U. spelaeus</i> mandible	PUGO1	-120	0.5	45.2	16.4	3.2	37,000 ± 800	41,677	42,568–40,653
PU/GO-17	Poz-156055	<i>U. spelaeus</i> humerus	PUGO1	-120	2.6	49.5	17.9	3.2	45,000 ± 3000	49,025	53,020–44,613

analyzed bone samples and their calibrated radiocarbon age (median) for the PMP1 and PUGO1 profiles for both Muierilor ($r = 0.3195$) and Urșilor ($r = 0.3066$; Fig. 10). However, in Urșilor, the chronology is confusing especially because of the fossil ages from the uppermost layer (L1^U), representing the last flooding event, clearly bearing reworked fossil material. Therefore, if the radiocarbon ages from the L1^U layer are discarded, a very strong correlation coefficient ($r = 0.916$) is obtained for the PUGO1 test pit (Fig. 10B–orange).

5. Discussion

5.1. Sedimentary evidence: cave morphology and facies architecture

5.1.1. Control of cave morphology over the flooding regime

The configuration and the diameter of underground conduits strongly influence groundwater hydraulics in open-channel stream conduits. High water velocities are needed to entrain and transport large

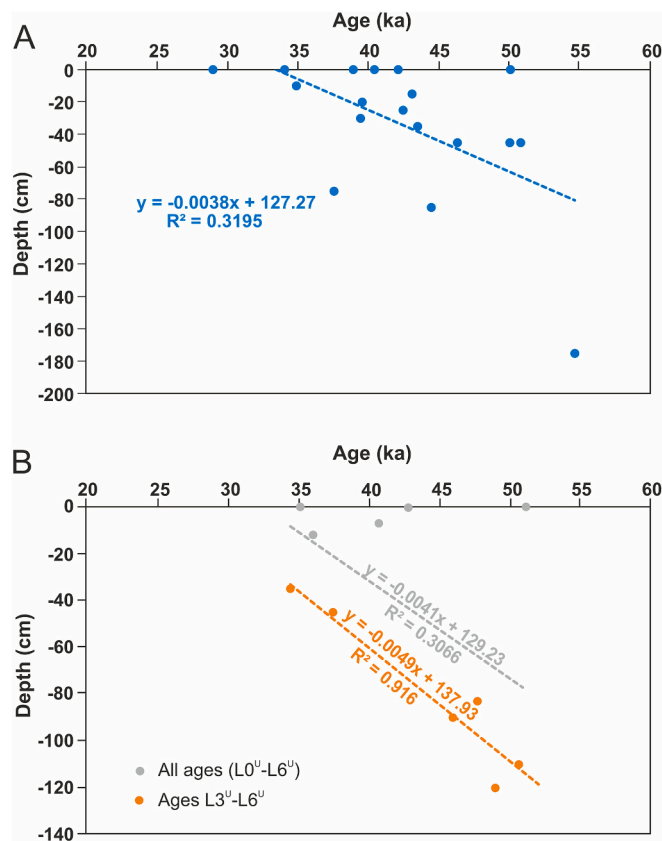


Fig. 10. Correlation of radiometric ages (median ka) from Muierilor PMP1 (A) and Urșilor PUGO1 sections (B) vs. depth; Compared plots and correlation coefficients between the L1^U-L6^U (grey) and L3^U-L6^U (orange) radiometric ages indicate a surprisingly good correlation (0.9) if the reworking layer L1^U is ignored (L2^U and L7^U are not considered, since they lack fossil bone dates).

sediment grains, as well as finer sediments such as silt and clay (Springer, 2019). In simple, morphologically uniform passages, the flow velocity usually increases with discharge, but not in direct proportion (Palmer, 2007). Local irregularities, such as vertical tectonic breaks or narrow passages, can obstruct conduits or chambers, impede the transport of coarse sediments, and impose distinct sedimentation regimes.

The investigated stratigraphic sections are hosted by open-channel stream passages tens of meters long and several meters in diameter, partially filled with sediment (Figs. 2 and 3). During floods, high-velocity water flows may have transited such passage sections, capable of transporting a wide range of clasts (Church, 2006), from large fragments to silt and clays. Depending on the available sediment type and load, side passages, pockets, or other niches are infilled mostly with fine particles that the flowing water cannot readily reach. In contrast, both coarse and fine fractions tend to accumulate along the main stream (e.g., Gázquez et al., 2014). For example, the PMP2 section, located approximately 120 m upstream of the PMP1 trench (Fig. 2), consists almost exclusively of fine-grained sediments (Mirea et al., 2021). This section has been thoroughly studied and is included here solely to highlight its connection to the sedimentological context of PMP1.

5.1.2. Facies architecture and depositional processes

Grain-size distribution is a well-established proxy for depositional hydraulics in a wide range of sedimentary environments. Increasing flow strength enables the entrainment and transport of progressively coarser and heavier clasts, as described by classical hydraulic models such as the Hjulström curve and Shields criterion, and supported by experimental and field-based studies (e.g., Buffington and Montgomery, 1997; Church, 2006; Nichols, 2009). In gravel-bed systems, coarse

surface sediments exhibit higher thresholds of resistance to erosion and are typically mobilized only during high-magnitude flow events (Wohl, 2007). Furthermore, bed grain size has been shown to scale with reach-average high-flow hydraulics (Snyder et al., 2013).

Building on this framework, grain-size distributions, sorting, and clast-shape characteristics observed in the studied sections provide a robust basis for interpreting depositional processes in cave environments, where flow velocity and shear stress control sediment entrainment, transport, and deposition. The facies assignments presented in Section 4.1 allow a process-based reconstruction of sediment dynamics within the two cave systems.

The vertical organization of facies in the PMP1 sequence reflects similar depositional regimes associated with variable flow conditions. The lowermost part of the sequence is characterized by poorly sorted fine sands, here interpreted as sediments derived by base-level back-flushing, indicative of slackwater facies. The overlying very poorly sorted, polymodal sediments indicate rapid deposition from sediment-laden flows in which hydraulic sorting was limited. Such deposits are consistent with high-energy events capable of transporting heterogeneous sediment loads and emplacing them over short time intervals (Pettijohn, 1975; Gillieson, 1986; Bosch and White, 2007). Up-section, the occurrence of mixed clast roundness together with partially stratified and locally channelized structures, apparently suggesting channel-facies characteristics, indicates more organized flow conditions. These features reflect selective transport and partial reworking within active conduits, where hydraulic conditions fluctuated but remained sufficiently energetic to maintain sediment mobility. Quantitative analysis of grain size and sorting, however, indicates a threshold favoring classification as diamicton rather than channel facies. Channel facies are typically characterized by sorted to moderately sorted sediments, whereas the very poor to extremely poor sorting observed here is consistent with diamicton deposition. Although the sedimentary architecture locally suggests channelized flow, this reflects flow organization rather than sustained transport conditions, as the poor sorting indicates deposition during short-lived, high-energy flood pulses.

The entire sequence is capped by a thin clayey layer, indicating an abandonment suite, which is diagnostic for the final, low-energy stage of the hydraulic event (Springer, 2019). The predominance of suspension-derived deposits mixed with abundant, large fossil bones indicates low-energy conditions, likely associated with back-flooding within the cave system, during which flow velocities were reduced and fine particles settled from suspension (Mirea et al., 2021). Overall, the PMP1 succession records a highly variable hydrological regime, in which short-lived, high-energy depositional events alternate with phases of either organized flow, or reduced flow energy and suspension settling. This variability is also consistent with repeated sediment reworking, as suggested by the heterogeneity of clast characteristics and the lack of systematic vertical trends in sediment properties.

The PUGO1 sequence exhibits a more clearly differentiated facies architecture, reflecting more stable and organized flow conditions compared to Muierilor. Coarse, clast-supported deposits in the intermediate units U3^U-U4^U, composed predominantly of well-rounded gravels and cobbles, with negligible fine fractions, indicate strong hydraulic sorting and effective removal of finer particles (Bosch and White, 2007; Church, 2006). These deposits require sustained high shear stress capable of mobilizing coarse material while winnowing out fines, reflecting peak-flow conditions within confined cave conduits (Buffington and Montgomery, 1997; Church, 2006). The well-winnowed material is indicative of thalweg facies, which can only form during exceptional floods, capable of providing the boundary shear necessary to move cobbles (Bosch and White, 2007). In contrast, both the lower and upper units display features indicative of rapid deposition from sediment-laden flows, including poorer sorting, the presence of a fine matrix, and mixed clast populations. These characteristics are consistent with diamicton facies, reflecting deposition during recurrent flash floods with limited hydraulic sorting and significant sediment reworking. The

fine-grained, massive deposits observed at the base and top of the sequence are interpreted as slackwater facies, formed during the waning stages of flood events or under temporary ponding conditions following high-discharge pulses, rather than representing background low-energy sedimentation.

5.2. Hydrologic processes inferred from flow hydraulics and regional setting

The sedimentological characteristics described above indicate deposition under predominantly high-energy flow conditions within underground gravel-bed systems. The occurrence of coarse-grained deposits and transport of cobbles and large pebbles imply steep hydraulic gradients and efficient sediment transfer in both caves. Quantitative grain-size parameters further constrain these conditions: maximum clast size reflects peak flow velocity (Folk and Ward, 1957), whereas sand–silt–clay ratios indicate the degree of hydraulic sorting and sediment reworking (Shepard, 1954; Poppe et al., 2005). Poor sorting (standard deviation: 2.0–4.3), together with kurtosis and skewness values (−0.68 to 0.44), is consistent with high-energy depositional environments and suggests a largely common sediment source (López, 2017).

Polymodal grain size distributions and weak correlations between radiometric ages and depth indicate multiple phases of sedimentation, reworking, and redeposition (Constantin et al., 2014; Mirea et al., 2021). These features support a flood-dominated regime in both caves, where episodic high-energy events transported and reworked pre-existing sediment and fossil material.

Differences between the two systems primarily reflect local controls on sediment supply and hydraulic expression. In the PMP1 section (Muierilor), sediment accumulation occurred through repeated depositional and reworking stages, as indicated by mixed fossil ages and variable clast roundness. The predominance of poorly sorted, matrix-supported deposits is consistent with diamicton facies formed by rapid emplacement from sediment-laden flows during high-magnitude flood events. In mid- to high-latitude cave environments, such deposits are typically linked to intense precipitation or meltwater pulses rather than glacial processes (Valen et al., 1997; Bosch and White, 2007; Kurečić et al., 2021).

Clastic cave sediments are commonly remobilized within karst systems and may undergo multiple reworking phases prior to final deposition (Ford and Williams, 2007; White, 2007), complicating the identification of sediment sources and depositional timing. Nevertheless, clast size and roundness remain reliable proxies for transport conditions: rounded clasts indicate sustained reworking, whereas angular clasts reflect short-distance transport or breakdown-derived inputs, occasionally mobilized during debris-flow-like events (Krumbein, 1941; Benn and Ballantyne, 1993). The ~80-cm-thick L5^M–L2^M succession in Muierilor is consistent with recurrent high-energy flooding, likely occurring before or after the Last Glacial Maximum, but no later than the Bølling–Allerød interstadial (Mirea et al., 2021).

In Urșilor Cave, sedimentological characteristics likewise indicate high-energy deposition, but with clearer hydraulic differentiation. The unimodal gravel lithology suggests a predominantly local limestone source, while high source-area index (SAI) and roundness index (Ri) values indicate repeated reworking of relatively soft clasts. Compared to Muierilor, sediment supply is more likely derived from in situ weathering residuum.

Consistent with the facies framework outlined in Section 5.1.2, both caves record flood-dominated deposition, but differ in the degree of hydraulic organization. Muierilor is dominated by diamicton facies with limited sorting, reflecting repeated high-magnitude flood pulses. Urșilor, while also shaped by recurrent flooding, preserves intervals (U3^U–U4^U) of well-developed thalweg facies formed during peak-flow conditions capable of efficient winnowing. The lower and upper units, however, retain diamicton and slackwater characteristics, indicating

deposition during waning or less organized flood stages. Thus, the key difference lies not in sustained versus episodic flow, but in the extent to which peak discharges were able to organize and sort the sediment load.

Both cave systems function as highly responsive karst drainage networks, characterized by rapid hydrological responses to intense recharge events. Differences in sediment texture and composition are best explained by local controls, including sediment source, passage morphology, and connectivity with external drainage systems. Muierilor appears to reflect a greater contribution of externally sourced sediment, whereas Urșilor is dominated by internally derived material, resulting in distinct sedimentary signatures under broadly similar hydrological forcing.

5.3. Climatic attribution and proxy limitations

The chronology of the five identified flooding events in Muierilor Cave suggests that sedimentation occurred throughout the late part of MIS 3 and into MIS 2, broadly coinciding with a period of pronounced climatic variability. These events are constrained by minimum ages of ~46.4 ka, ~37.7 ka, and ~34.9 ka, as well as a final episode occurring after ~29 ka but no later than ~14.8 ka (Fig. 11), within an interval characterized by frequent DO events. While this temporal correspondence may indicate a climatic influence on flooding frequency, direct correlation between individual depositional events and specific DO events remains uncertain due to dating limitations and sediment reworking. The final flooding episode is better constrained: the proximity of the Parâng ice cap to the Muierilor catchment, together with the youngest fossil ages (~29 ka; onset of MIS 2), suggests that this event likely occurred during the Last Termination, driven by increased meltwater input and regional climate warming.

The geographic setting of Urșilor Cave in the NW Apuseni Mountains accounts for the higher frequency of flash-flooding events relative to Muierilor in the Southern Carpathians. During MIS 3 and subsequent deglaciation, rapid warming transitions (DO events), particularly driven by the Atlantic Meridional Overturning Circulation (AMOC), led to increased precipitation over Europe (Van Meerbeeck et al., 2011). The Apuseni Mountains present ideal conditions for the occurrence and persistence of orographic rainfall. However, such abundant precipitation is documented to have fed several cirque glaciers and firn fields that clustered only around the highest peaks during the Pleistocene cold intervals (Urdea and Reuther, 2009; Urdea et al., 2022). Ice, firn, and snow melt, coupled with heavy orographic rainfall, might have triggered rapid flooding along the surrounding valleys during the rapid temperature fluctuations that characterized the MIS 3–2 period. These also involved extreme storms (Aumann et al., 2018), which are expected to have further boosted the flood intensities. In the case of Oase Cave, located at equally low elevations in the SW Carpathians, a study that has combined data from speleothem dating, sedimentology, and taphonomy concluded that the accumulation of Level 2 has been the result of a torrential episode produced around ~47 ka, an age which was correlated with the H5 event (Constantin et al., 2012). The presence of *Microtus nivalis* (a species found today at elevations >1600 m) in the faunal record was essential for indicating a cold climate. Comparatively, in the PUGO1 section (and the upper level of Urșilor Cave), sediment analysis indicates deposition during successive flash floods, likely linked to DO events. The presence of *M. oeconomus* in layer L4^U (unit U4^U) may further suggest cold conditions with relatively high precipitation.

It is worth mentioning that no fossil remains with reliable radio-carbon ages younger than ~29.0–27.1 ka were found either in Muierilor or Urșilor, which may be indicative of the harsh climatic conditions starting with the MIS 2. On the other hand, no flash-flooding deposition has occurred later than ~14.8 ka in either cave (as indicated by the ages of speleothems capping the clastic sediments). This suggests that even underground settings across different geographical regions exhibit similar responses to the first-order hydroclimatic cycles.

Despite these observations, the climatic forcing of sedimentation

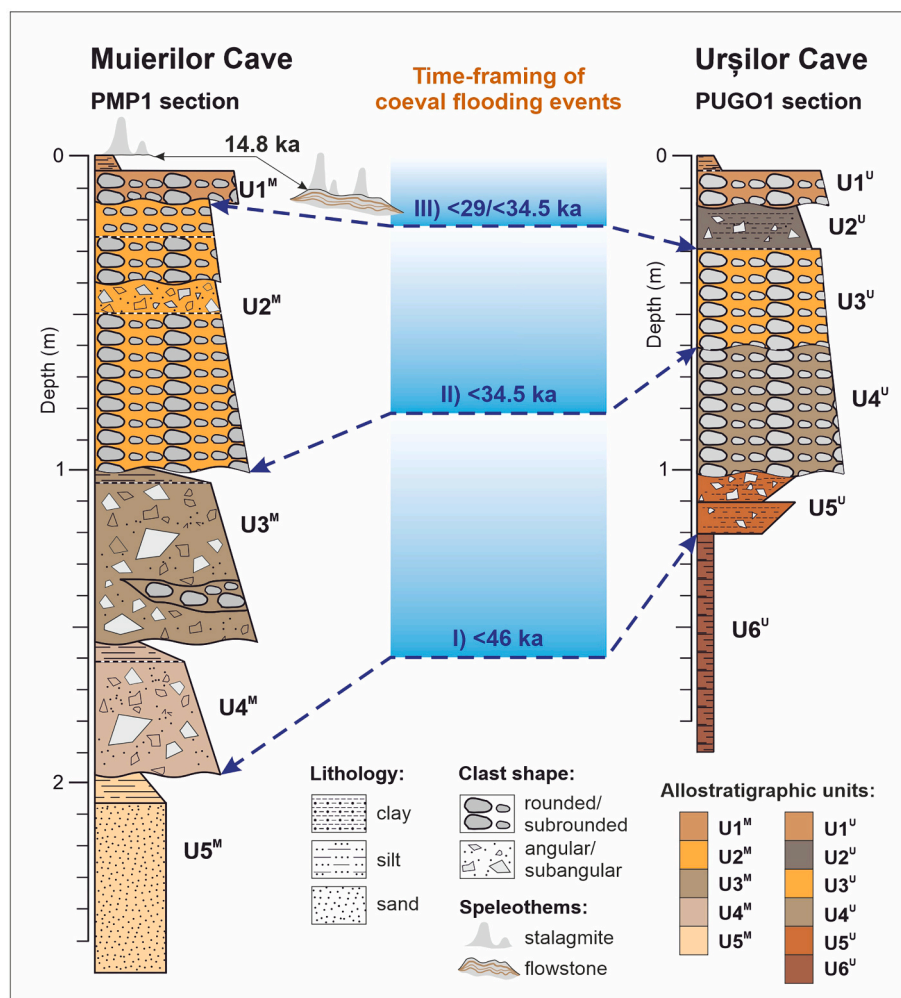


Fig. 11. Possibly coeval flooding events of MIS 3–2 detected in the two sedimentary sequences of Muierilor and Urșilor caves, supported by AMS ^{14}C dates of fossil bones.

remains difficult to constrain. Deposition occurred during the late part of the Middle Pleniglacial, a period marked by frequent DO oscillations with an average periodicity of ~ 1470 years (e.g., Grootes and Stuiver, 1997; Schulz, 2002), yet linking individual sedimentation events to specific cycles is challenging. The short duration of these oscillations, together with the inherent uncertainties of radiocarbon dating and repeated sediment reworking, limits temporal resolution and hinders event-scale correlations. As a result, the sedimentary record primarily reflects hydrologic responses to high-discharge events, while the relative contributions of precipitation and glacial meltwater cannot be unambiguously resolved with the available proxies. Further constraints on the paleoclimatic context may be obtained through future analyses, such as stable isotope studies of well-dated MIS 3 speleothems.

5.4. Environmental shifts recorded in speleothems

Independent of the PMP1 sedimentary sequence, stalagmite PM163 and its basal flowstone record strongly fluctuating growth conditions between 31.22 and 11.95 ka (MIS 3–2), reflecting unstable local hydroclimatic regimes in the Bears Passage of Muierilor Cave. The sharp contrast between the lower and upper sections shows a fundamental shift in growth conditions, likely driven by changes in drip-water availability, cave hydrology, and external environmental forcing. The deposition of the thin clay layer (LO^{M}) that is capping the sediment pile of the Bears Passage occurred sometime between ~ 11.69 and 8.66 ka (Mirea et al., 2021), long after the formation of the floor crust on which

the stalagmite growth had begun. Therefore, the lowermost section, or flowstone, is of particular interest, as it documents the period from the MIS 3–2 transition through the final phase of MIS 2 (31.22–14.24 ka).

The repeated alternation between columnar calcite growth, dissolutional hiatuses, and detrital input in the lower section indicates frequent shifts between supersaturated and undersaturated drip-water conditions (Frisia and Borsato, 2010). Columnar calcite fabrics form during periods of relatively stable recharge and low impurity flux (Frisia, 2015). In contrast, sharp erosional and dissolutional surfaces (h_1 – h_5) record episodes of enhanced water aggressiveness, likely driven by increased infiltration, reduced epikarst, and/or changes in soil CO_2 production under colder or more variable climatic conditions. Major hiatuses are associated with detrital drapes and lattice disruption transporting clastic material into the cave while simultaneously promoting calcite dissolution. The development of dendritic and microsparite fabrics above these surfaces reflects rapid nucleation following growth interruptions, consistent with abrupt hydrological reactivation after periods of reduced drip supply or corrosive water input (Martín-Chivelet et al., 2017). Crystallite overgrowths on columnar calcite record renewed calcite precipitation under disturbed but short-lived departures from steady-state growth, during which nucleation occurred preferentially on pre-existing crystal surfaces rather than through complete lattice reorganization (Self and Hill, 2003).

Calcite precipitation over the cave floor ceased sometime after 27.37 ka, with the onset of the Last Glacial Maximum (LGM). The initiation of stalagmite growth above the cave-floor flowstone suggests the

establishment of a focused drip point following a period of surface stabilization, sometime before 14.24 ka. Optimal climatic and depositional conditions were met again only at the peak of the Bølling oscillation, following a long, multi-millennial interval (~13.35 ka, including uncertainties) during which no calcite precipitation occurred. This age is highly consistent with other speleothem records documented for the Romanian Carpathians (e.g., Onac et al., 2002; Constantin et al., 2007, 2012; Mirea et al., 2021).

Most studies associate the hiatuses with detrital material deposited during cold periods, during which speleothem growth was absent. For instance, Klose et al. (2024) present the case of a German speleothem that grew episodically during the warm phases of MIS 3, with calcite precipitation alternating with the deposition of fine detrital particles. The base of the PM163 stalagmite may have formed similarly. However, we do not exclude the possibility that incorporation of sand-sized quartz grains within dissolutional fringes may indicate episodic high-energy recharge linked to intensified precipitation, snowmelt, and associated flooding episodes. The internal texture of the composite speleothem (flowstone and stalagmite) reflects the result of multiple processes and, although it may not directly record individual paleoflood events, it provides valuable context for the turbulent environmental conditions during sediment deposition. Collectively, these features indicate that PM163 archived evidence of pronounced hydroclimatic instability, with alternating phases of intense recharge, dissolution, and rapid calcite precipitation, consistent with highly variable environmental conditions during the end of MIS 3 through the beginning of the Holocene.

5.5. Timing constraints on past (flash) flooding episodes

Dating hydrologic events is challenging because cave sediments are typically reworked during infrequent floodings (or succession of floodings). Hence, such events can only be constrained by using complementary karst archives (e.g., bone remains, speleothems, clastic sediments, guano) that are found in stratigraphically relevant positions relative to a given depositional or erosional event. To better constrain the timing of the flooding events, the youngest reliable radiocarbon ages from the analyzed sediment layers were used as minimum ages. Figs. 5 and 11 illustrate, for both sites, the correlations between sedimentary layers grouped into allostratigraphic units, based on the integration of radiocarbon data and facies-type interpretation, as discussed in more detail below.

In Muierilor, the youngest reliable radiocarbon age (collagen yield $\geq 0.8\%$) was obtained from a *Canis lupus* lower molar (m1), found on the surface, close to the PMP1 excavation (~29 ka). Nonetheless, this youngest sample was found on the surface (layer L0^M), in a niche that also includes older bone samples, ranging from >54.8 to ~29 ka. The lack of correlation between stratigraphy and radiocarbon ages from PMP1 may indicate several rapid flash-flood events that reworked bones of different ages over, and the radiocarbon ages from PMP1 may indicate several rapid flash-flood short intervals. Our combined sedimentological and geochronological data indicate the occurrence of five major flooding events, with the following minimum age estimates (Fig. 5A):

- (1) **Post-46.4 ka**, corresponding to the L9^M sediment layer (~210–140 cm-deep); bone deposition between ~54.8 and ~46.4 ka, followed by reworking after ~46.4 ka during a short-lived, flash-flood event (as indicated by the angular clasts embedded in a sandy-silty matrix).
- (2) **Post-37.7 ka**, corresponding to the L7^M layer (from ~150 to ~20 cm), bone deposition between ~43.6 and ~37.7 ka; reworking after ~37.7 ka during a comparable flash-flood event.
- (3) and (4) **Post-34.9 ka**, corresponding to the L5^M (~85 to ~20 cm) and L2^M layers (~20 to ~5 cm).
- (5) **The last flood**, corresponding to the L1–L0^M layers, occurred sometime after 29 ka, but no later than DO 1 (i.e., ~14.8 ka; Mirea et al., 2021; S. Constantin, unpublished data).

At Urşilor Cave, by applying the $\geq 0.8\%$ collagen yield threshold, the youngest reliable radiocarbon age from the PUGO1 section is ~34.5 ka, providing a minimum age constraint for the upper part of the sequence. A general agreement between the depth of sampled bones and their radiometric ages is observed for the lowermost samples. Together with the paleontological association (Terzea, 1978), this suggests a succession of several well-defined stages of bone deposition and reworking, constrained by the following ages (Fig. 5B):

- (1) **~51 ka**, corresponding to the L5^U sediment layer at ~110 cm; bone deposition around ~55 ka, followed by massive transport as a single load (debris flow);
- (2) **Post-46 ka**, corresponding to L4^U at ~90 to ~80 cm; bone deposition during a cold climate with increasing precipitation in a highly dynamic hydroclimatic environment (based on a paleofaunal association with *Microtus oeconomus*, a tundra species);
- (3) **Post-34.5 ka**, corresponding to L3^U at ~45 to ~35 cm; bone deposition around ~37.5 ka, followed by reworking shortly after, as indicated by ages younger than ~34.5 ka. This layer is the most tightly constrained by radiocarbon data from both sections;
- (4) and (5) **Post-34.5 ka**, corresponding to L2^U and L1^U layers (~35 cm to the surface), which contain bones dated between ~51 and 35.2 ka. The two layers reflect different depositional conditions. L2^U contains quasi-angular clasts, indicating short-distance, high-energy transport, whereas L1^U comprises abundant fossil bones with large cobbles and boulders, comparable to deglaciation-related deposits in the upper PMP1 sequence of Muierilor Cave (Onac et al., 2002; Tămaş et al., 2005; S. Constantin, unpublished data).

The youngest reliable radiocarbon ages from both stratigraphic sections represent minimum age constraints for sediment deposition (e.g., Grün, 2006). Accordingly, the timing of these events may extend into more recent periods, but not beyond 14.8 ka. Achieving millennial-scale resolution is hindered by the effects of sediment reworking, as the incorporation of older materials into younger layers can obscure the boundaries between distinct climatic oscillations or depositional phases (e.g., Ager, 1993; Kidwell, 2013). The resulting lack of a clear age-depth correlation implies that a single reworked bone may shift the entire timing of an event by several thousand years. Moreover, the high-energy nature of flooding may mask whether a given layer represents a single depositional pulse or a palimpsest of multiple events occurring over centennial to millennial timescales. Finally, the gap between the youngest dated bones and the 14.8 ka speleothem cap suggests a potentially condensed or incomplete record of the Last Glacial Maximum, which must be considered when evaluating the temporal resolution of these sequences.

5.6. Regional correlations and coeval flooding events

The growing importance of cave sediments for reconstructing Quaternary paleoenvironments across Europe is reflected in the literature. Along a west–east transect of major karst regions, sedimentary facies and depositional models have been investigated in the Cantabrian Mountains and northern France (Ballesteros et al., 2020, 2023), the Central Pyrenees (Bartolomé et al., 2021a, 2021b, 2025), and the French Alps, where cave sediments were used to reconstruct Middle and Late Pleistocene glacial advances (Jaillet et al., 2023). In the Eastern Alps, Holzer et al. (2025) analyzed multiple cave systems to infer transport processes, sediment sources, and paleoclimatic conditions, while the sequence at Račiška Pečina (SW Slovenia) provides a long-term paleoenvironmental record extending beyond the Pliocene–Pleistocene boundary (Zupan Hajna et al., 2021).

In this broader regional context, the Muierilor and Urşilor cave records provide new constraints from the Carpathian region in south-eastern Europe, highlighting the role of high-energy flooding during MIS 3–2 in driving sediment reworking, shaping facies architecture, and

influencing the preservation and stratigraphic distribution of fossil assemblages. Based on the radiocarbon and sedimentological data, we identified three coeval flooding events in both caves (Fig. 11):

- I. The first event recorded in PMP1 (post-46.4 ka; $L9^M/U4^M$) may be correlated with the second event identified in PUGO1 (post-46 ka; $L5-L6^U/U5^U$).

- II. The strongest correspondence between the two stratigraphic sections (PMP1 and PUGO1) is observed for layers $L2-L5^M$ and $L3^U$ (third and fourth events, respectively). In both cases, reworking occurred shortly after ~ 34.9 ka and ~ 34.5 ka, respectively, and the deposits display comparable grain-size distributions and clast roundness. These similarities indicate broadly similar, most likely humid, hydroclimatic conditions.

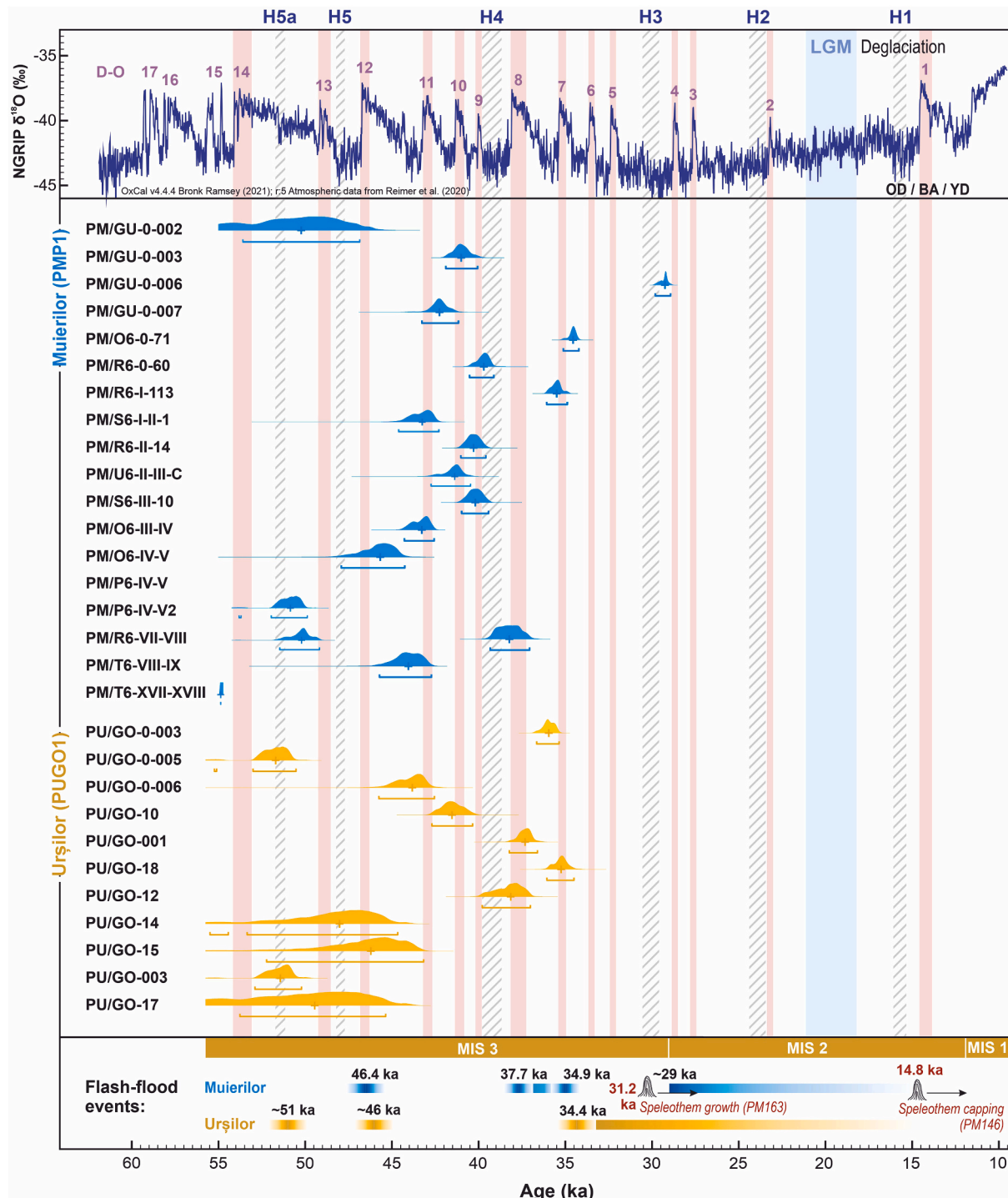


Fig. 12. Radiocarbon calibration of dated fossil remains from Muierilor (blue; $N = 18$) and Urşilor (yellow; $N = 11$) caves using the Intcal20 (Reimer et al., 2020) calibration curve and Oxcal v.4.4, function R_date (Bronk Ramsey, 2009, 2020). Upper panel: NGRIP data from Lisiecki and Raymo (2005). Lower panel: estimated timing of flood event occurrence in Muierilor and Urşilor caves, in conjunction with speleothem growth at Muierilor. The timing of Heinrich and DO events (synthesized from, e.g., Hemming, 2004) is displayed on the graph background.

III. A further similarity is observed in the upper parts of the sequences, $L1^M$ – $L0^M$ and $L2^U$ – $L1^U$, interpreted as products of the last major flooding phase. Both sets of layers are characterized by a high density of limestone cobbles embedded into a bone-rich matrix and capped by a reddish clay layer. In terms of radiocarbon chronology, layers $L1^M$ and $L0^M$ were deposited after ~29 ka, whereas layers $L2^U$ and $L1^U$ postdate the ~34.5-ka event recorded in $L3^U$.

All geochronological data (radiocarbon and U–Th) obtained in this study are synthesized in Fig. 12, plotted against the NGRIP $\delta^{18}O$ curve (Lisiecki and Raymo, 2005) and the MIS 3–2 glacial chronology (Heinrich and DO events).

Overall, our results show that in both cases the radiocarbon age distribution of fossil bones spans a time interval between >50 ka and ~29 ka, covering most of MIS 3 and preceding the onset of MIS 2. In the case of Muierilor, Mirea et al. (2021) argued that flooding events (or a succession of floodings) may be linked to post-LGM deglaciation pulses, as suggested by speleothem chronology coupled with cosmogenic isotope exposure dating of glacial retreat from nearby cirques. Further research oriented toward alternate, more refined proxies could contribute to a better understanding of sedimentary processes in response to abrupt, short-term climatic oscillations.

6. Conclusions

This study provides the first integrated evidence for the impact of abrupt climatic oscillations during MIS 3–2 on the occurrence of flash-flood events in the Carpathian karst. High-energy flooding repeatedly reworked cave sediments prior to their final deposition within facies assemblages. Based on integrated sedimentological, paleontological, and speleothem data, we infer that such flash-flood activity was closely linked to these climatic oscillations. A preliminary chronology of the identified events is presented here in the context of established cave facies models.

The sedimentary records of Muierilor and Urşilor caves document predominantly high-energy depositional environments governed by episodic flooding. In Muierilor, the succession is dominated by diamicton and subordinate slackwater and channel facies, reflecting repeated short-lived, high-magnitude flood pulses with limited hydraulic sorting and extensive sediment reworking. In contrast, Urşilor preserves a more differentiated facies architecture, including diamicton and slackwater facies in the lower and upper units, and well-developed thalweg facies in intermediate levels, indicating efficient winnowing during peak-flow conditions. Together, these facies associations point to a common flood-dominated hydrological regime in both systems, with differences arising from the degree to which peak discharges were able to organize and sort the sediment load within cave conduits.

Sometime before 55 ka, low-energy flow regimes left behind either slackwater (in Muierilor Cave) or backswamp deposits (in Urşilor Cave), identified at the base of the stratigraphic sequences. These were followed by high-energy flow regimes and extreme flooding episodes, as evidenced by the predominance of diamicton facies and subordinate thalweg deposits throughout the sedimentary successions. Episodic, sustained flow resulted in improved sorting, characteristic of channel facies conditions. At Muierilor, in the PMP1 section, the radiocarbon data indicate the occurrence of at least five palaeohydrological events with the following age estimates: (1) post-46.4 ka; (2) post-37.7 ka; and (3–4) post-34.9 ka. At Urşilor, in the PUG01 test-pit, several depositional stages were identified at: (1) ~51 ka; (2) post-46 ka; (3) pre-34.5 ka; and (4–5) post-34.5 ka. Three coeval events are documented at both sites: (a) post-46 ka; (b) post-35 ka; and (c) post-29 ka (with reworking no later than 14.8 ka).

Stalagmite PM163 and its underlying cave-floor flowstone records strongly fluctuating growth conditions between 31.22 and 11.95 ka (MIS 3–2) near the PMP1 section, providing independent evidence of

rapid changes in dripwater and internal hydrological conditions. These are reflected by repeated alternations between calcite precipitation, dissolution, and detrital input. The entrainment of sand-sized quartz grains within dissolutional fringes further supports short-lived, high-energy infiltration events, which, given the sedimentary context of stalagmite growth, are most likely related to flooding episodes. Stalagmite growth beginning at 14.24 ± 0.88 ka is consistent with that of PM146 (14.78 ± 0.38 ka; Mirea et al., 2021), also collected from the same passage in Muierilor Cave, as well as with other speleothem records from the Romanian Carpathians marking the onset of the Bølling oscillation. Overall, the microstratigraphy of PM163 documents pronounced environmental instability and non-steady-state speleothem growth during the MIS 3–2 interval.

The results demonstrate that caves located in different geomorphic settings, yet sharing similar sedimentary evolution (torrential fluvial systems) and paleontological content (MIS 3 faunal assemblages), can exhibit broadly comparable depositional histories. This integrated approach provides an effective framework for investigating cave systems and their sedimentary records, improving our understanding of how hydroclimatic events are recorded in underground environments under rapidly changing climatic conditions. The sedimentary record indicates that flooding events were modulated by large-scale hydroclimatic variability, although the relative contributions of precipitation and glacial meltwater likely varied through time and remain difficult to resolve with the available proxies. Future research should therefore focus on high-resolution approaches capable of better constraining MIS 3–2 events and their environmental impacts.

CRediT authorship contribution statement

Marius Robu: Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Maria-Laura Tîrlă:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ionuț-Cornel Mirea:** Writing – review & editing, Visualization, Investigation, Funding acquisition, Formal analysis, Data curation. **Luchiana-Maria Faur:** Visualization, Investigation, Formal analysis, Data curation. **Daniel Veres:** Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization. **Adrian Priceputu:** Writing – review & editing, Formal analysis, Data curation. **Constantin Ungureanu:** Writing – review & editing, Formal analysis, Data curation. **Marius Vlaicu:** Writing – review & editing, Investigation, Funding acquisition. **Marius Kenes:** Visualization, Formal analysis, Data curation. **Alexandru Petculescu:** Visualization, Investigation, Funding acquisition, Data curation. **Ali Pourmand:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Silviu Constantin:** Writing – review & editing, Writing – original draft, Validation, Project administration, Investigation, Funding acquisition, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.sedgeo.2026.107104>. These data include the Google maps of the most important areas described in this article

Data availability

Data will be made available on request.

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