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RECONSTRUCTION OF PALAEOFLOW AND DEPOSITIONAL DYNAMICS FROM THE MERJASEC UNROOFED CAVE, LAZE PLAIN (CENTRAL SLOVENIA)

Primož Miklavc, Matej Lipar, France Šušteršič, Andrej Šmuc

Merjasec unroofed cave deposits.

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Reconstruction of palaeoflow and depositional dynamics from the Merjasec unroofed cave, Laze Plain (central Slovenia)

ABSTRACT: Sparsely preserved unroofed cave deposits are ancient remains of cave systems. The Merjasec unroofed cave is a perfect example of poorly preserved cave deposits where conventional sedimentological study revealed a greater potential for the reconstruction of local to regional palaeoenvironmental conditions. Cave deposits are characterised by polymictic conglomerates, pebbly sandstones and flowstone belonging to five distinct sedimentary facies. Sedimentary features indicate deposition of channel-related bedforms in a narrow cave-connecting conduit, activated only during extreme pulsating floods under epiphreatic conditions. In this sense, it mimics the current hydrology of the regional system and shows that the hydrological history of the cave system is strongly dependent on climatic conditions. Moreover, this study demonstrates a methodological approach that can be successfully applied to similary exposed cave deposits elsewhere, showing that even fragmentary or eroded remnants, when analysed in detail, can significantly contribute to understanding of karst palaeohydrology.

KEYWORDS: karst, denuded cave, clastic cave deposits, facies, fluvial, depositional dynamics, palaeoenvironment

Rekonstrukcija paleotoka in dinamike zapolnjevanja brezstrope jame Merjasec, Laški ravnik (osrednja Slovenija)

POVZETEK: Redkeje ohranjeni sediment brezstropih jam so ostanki starejših jamskih sistemov. Brezstropa jama Merjasec je odličen primer slabo ohranjenih jamskih sedimentov, kjer so konvencionalne sedimentološke študije pokazale velik potencial za rekonstrukcijo lokalnih do regionalnih paleookoljskih razmer. Jamske sedimente predstavljajo polimiktični konglomerati, prodnati peščenjaki ter sige in so organizirani v pet različnih sedimentnih faciesov. Sedimentne značilnosti kažejo na odlaganje v ozkem, povezujočem kanalu aktiviranem le med ekstremnimi pulzirajočimi poplavami pod epifreatičnimi pogoji. V tem smislu posnema sedanjo hidrologijo regionalnega sistema in kaže, da je hidrološka zgodovina jamskega sistema močno odvisna od podnebnih razmer. Poleg tega ta študija prikazuje metodološki pristop, ki ga je mogoče uspešno uporabiti za podobno razgaljene jamske sedimente drugje, in kaže, da lahko celo fragmentirani ali erodirani ostanki, če jih podrobno analiziramo, pomembno prispevajo k razumevanju kraške paleohidrologije.

KLJUČNE BESEDE: kras, brezstropa jama, klastični jamski sedimenti, faciesi, fluvialno, dinamika odlaganja, paleookolje

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1 Introduction

Caves are natural archives which contain a wide spectrum of clastic, chemical, and organic deposits that preserve valuable information about surface and subsurface palaeoenvironmental conditions (White 2007; Laureano et al. 2016; Caldeira et al. 2021; De Waele and Gutiérrez 2022). Volumetrically most abundant cave deposits are clastic autochthonous and allochthonous sediments; the former originate locally in the cave due to mechanical and chemical weathering of the host rock, whilst the latter were transported into the cave from outside (White 2007; Herman et al. 2012). The composition of clastic cave sediments depends mainly on their provenance, while their textures and structures relate on transportation and depositional processes (De Waele and Gutiérrez 2022). Cave sedimentary environments closely resemble surface fluvial systems, however, subterranean waterflows are strongly influenced by the resistant nature of the bedrock morphology and prone to dramatic changes in flow velocities, resulting in rapid local variations in transport and deposition processes (Trappe 2010; Bella et al. 2020; De Waele and Gutiérrez 2022). In this context, understanding the sedimentological processes, their depositional dynamics, and the facies concepts of clastic cave sediments (Bosch and White 2007; Trappe 2010; Campaña et al. 2017; Campaña et al. 2023) is crucial for reconstructing the hydrological history of cave systems, which is the starting point for advanced studies of palaeoclimate and land evolution in karst areas. Clastic cave sediments are found in recent cave systems and also unroofed caves exposed by denudation or human activity. These are of special importance for the reconstruction of temporal and spatial geomorphologic evolution of the area spanning over millions of years.

Unroofed caves, are ancient cave conduits that underwent a transition from phreatic or epiphreatic to vadose conditions until they were surface-exposed due to denudation (Mihevc 1996; Mihevc and Zupan Hajna 1996; Šušteršič 1998; Šebela 1999; Bosák et al. 2000; Šebela and Sasowsky 2000; Zupan Hajna et al. 2020). They can be identified by elongated, shallow depressions such as trenches or dolines, and by the sediment characteristics for caves (Mihevc 1999). They resemble the oldest still identifiable fragments of cave systems, which emphasises their value as they store the only preserved information on regional underground palaeohydrology. The preservation of unroofed cave deposits is often very sparse, so their interpretation can be very challenging as their sedimentary characteristics may be blurred or even unrecognisable. In this case, the study of such deposits requires a very comprehensive sedimentary analytical approach and diverse knowledge of various surface and underground processes (Caldeira et al. 2021), allowing the identification of sedimentary facies and their vertical and lateral distribution, which provide information about processes and the environment of the deposition (Reading 2001).

In this paper we reconstruct the cave palaeoenvironment and its palaeohydrological regime from the sparsely preserved Merjasec unroofed cave deposits from Laze Plain (slv. *Laški ravnik*), also known as Logatec-Begunje Plain (slv. *Logaško-Begunjski ravnik*), in central Slovenia using a conventional sedimentological methodology. This study demonstrates that even fragmentary remnants of unroofed cave deposits can yield valuable insights into karst palaeohydrology, highlighting the importance of applying similarly detailed methodologies to palaeocave deposits in other regions.

2 Geological and geomorphological setting of the research area

The low-relief elevated plain of Laze Plain structurally belongs to the NW part of the External Dinarides (Placer 2008) (Figure 1A) and was in the Mesozoic part of the Adriatic Carbonate platform (Vlahović et al. 2005). During the Cenozoic, a complex northwest - southeast trending thrusting, divided the area into several thrusts and nappes (Placer 2008; Korbar 2009). The area was later in Neogene cut by dextral strike-slip faults with the most significant structural element represented by the Idrija Fault zone (Figure 1A). The Idrija Fault zone is characterised by chaotically displaced blocks separated by minor faults (Šušteršič 1996; Čar 2010) and plays an important role in the development of surface and subsurface karst forms and in determining the regional hydrological network (Šušteršič 1996; Čar 2018; Gabrovšek et al. 2022). The karst of Laze Plain is mainly formed in Jurassic, well-bedded limestone (micritic and oolithic) and coarse-crystalline dolomite (Buser 1978; Borenović 1993), as well as in Cretaceous, bedded limestone (micritic, bioclastic) and crystalline dolomite (Jež and Otoničar 2018), and the Upper Triassic bedded dolomites. The latest have proven to be the least permeable and are therefore less susceptible to karstification (Figure 1B).

Geomorphologically, the Laze Plain is a corrosion plain (Figure 1B), defined as a dry polje (Stepišnik and Ferk 2023), which extends parallel to the Planina Polje (i.e., a karst polje) in the NW-SE (Dinaric) direction

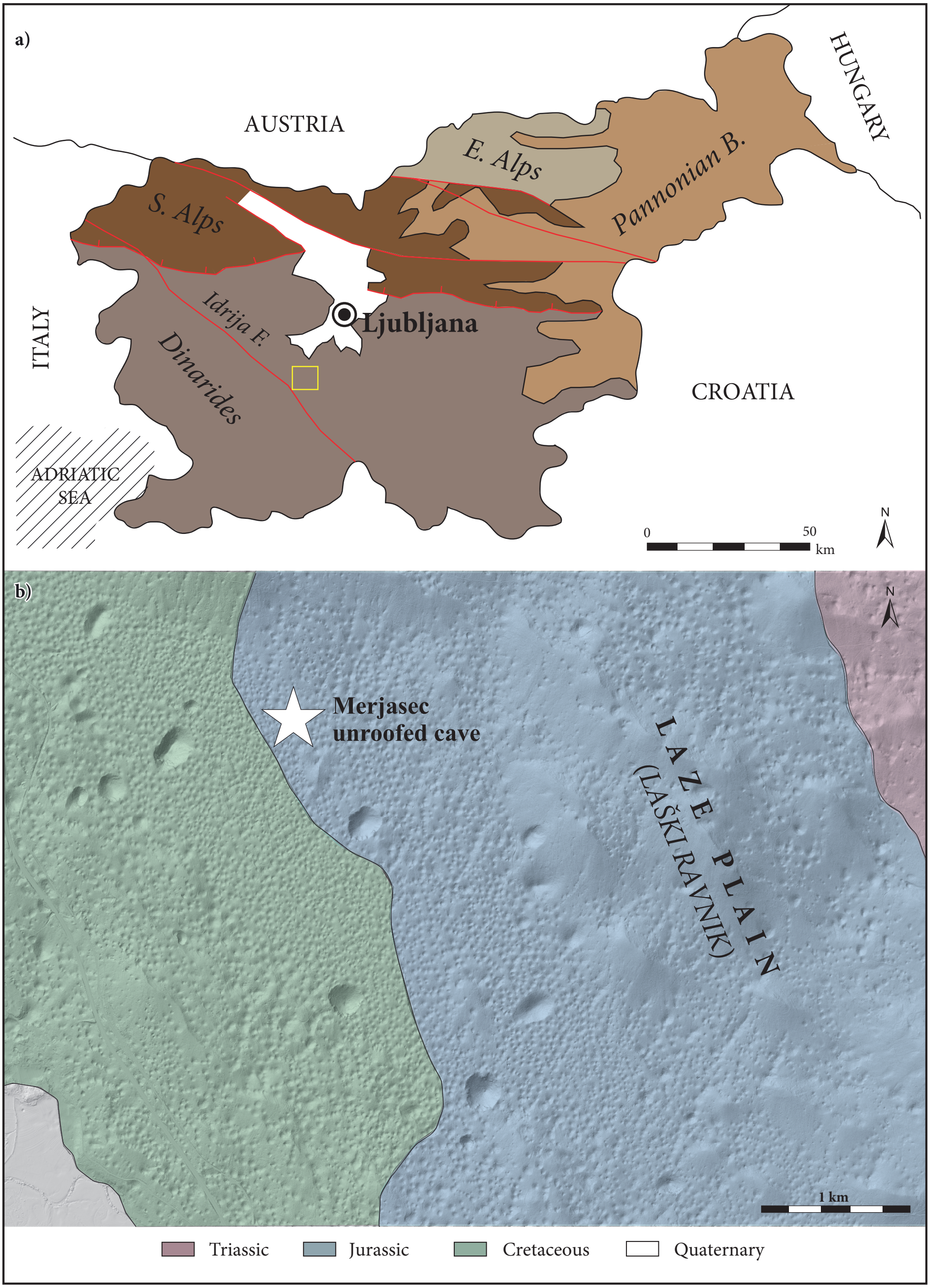


Figure 1: Location and geological characteristics of the investigated area. A) Structural map of Slovenia (Placer 2008). The yellow rectangle marks the investigated area. B) Geological map (Pleničar et al. 1970) of the investigated area with the exact location of the Merjasec unroofed cave (45º52'57.90" N; 14º17'23.34" E).

and is extremely rich in surface and subsurface karst forms (Figure 1B), especially solution dolines and caves (Šušteršič 1994; Šušteršič 2002). Laze Plain is a part of the Ljubljanica river recharge area and has a very complex structure of epiphreatic and vadose zones, where caves occupy multiple levels and are characterised by a very irregular geometry (Blatnik et al. 2019). The thickness of the vadose zone ranges from a few dozen to more than hundred metres, which allows a very dynamic epiphreatic zone in which water can rise up to 60 m during flood events (Gabrovšek and Turk 2010). A very complex organisation of the cave system is also detectable on the surface, where several cave conduits of phreatic or epiphreatic origin and outcrops of clastic cave sediments are exposed (Šušteršič 1998).

3 Methods

The unroofed cave sediment represents a unique archive of ancient cave system. Unfortunately, the exposed cave deposits are predominantly composed of fine-grained clays and silts that have been completely or partially transformed by pedogenetic processes. In this study we therefore focussed on coarse-grained cave sediments (conglomerates and pebbly sandstones) of Laze Plain, which are much rarer but can hold a rich archive of the past environmental events. Even though the exposed conglomerate outcrops are often highly eroded, understanding their sedimentary characteristics, facies types and architectural elements is crucial for reconstructing the depositional environment and interpreting the evolution of individual cave conduit, which, due to their inherent connectivity within the cave network, provide essential insights into the wider ancient cave system.

The investigated Merjasec unroofed cave represents one of the best preserved outcrops of cave deposits of Laze Plain. These deposits were analysed using conventional methods for clastic sedimentary rocks (Boggs 2009). The sedimentary succession was logged on a scale of 1:10 using a standard sedimentological procedure. A total of 22 samples were collected to prepare polished slabs, which were used to determine and interpret the sedimentary structures and textures. The main criteria for determining the facies types and architectural elements was based on Miall (1977; 1996 in conjunction with existing facies classifications for clastic cave sediments (e.g., Bosch and White 2007; Ghinassi et al. 2009; Trappe 2010; Laureano et al. 2016; Campaña et al. 2017; Campaña et al. 2022). The identified facies types and sedimentary bodies (architectural elements) were used to reconstruct the depositional dynamics and evolution of the conduit.

4 Results

4.1 Unroofed cave

The Merjasec unroofed cave is characterised by its unique deposits, which are the only clear indicators of the cave´s existence. The surface around the cave is mostly flat and characterised by solution dolines. The cave was formed in Late Jurassic shallow-marine, well-bedded carbonates and is now surface-exposed on the southern slope of the doline. The cross-section of the cave conduit (Figure 2) is irregular and elliptical, at least 500 cm wide and 110 cm high. The cave conduit was most probably of phreatic origin and later modified by epiphreatic and alluviation processes. The outcrop is characterised by eight clearly detectable cave deposit remnants (Figure 2). The best preserved and most exposed is remnant 7 (Figure 2), where a detailed cross-section was recorded. Other remnants (Figure 2), on the other hand, are poorly preserved polymictic conglomerates, that are mostly covered by soil.

4.2 Merjasec section

The investigation of the Merjasec section (Figure 3A) in remnant 7 (Figure 2) of the unroofed cave outcrop revealed that it is a completely filled palaeocave conduit characterised by well-stratified polymictic conglomerates, pebbly sandstones and flowstone (Figure 3A; Table 1). The basal contact with the hostrock is covered. The cave deposits are organised into five sedimentary units (Figure 3C; Table 1) separated by major erosional contacts, representing five cut-and-fill sequences in which five distinct facies (Gh, Gp, Sp, Ss and Flowstone; see Table 1 for full names) and three architectural elements (CH, SB, GB; see Table 1 for full names) were identified (Figure 3A, B). Conglomerate (Gh, Gp) and sandstone (Sp, Ss) facies are

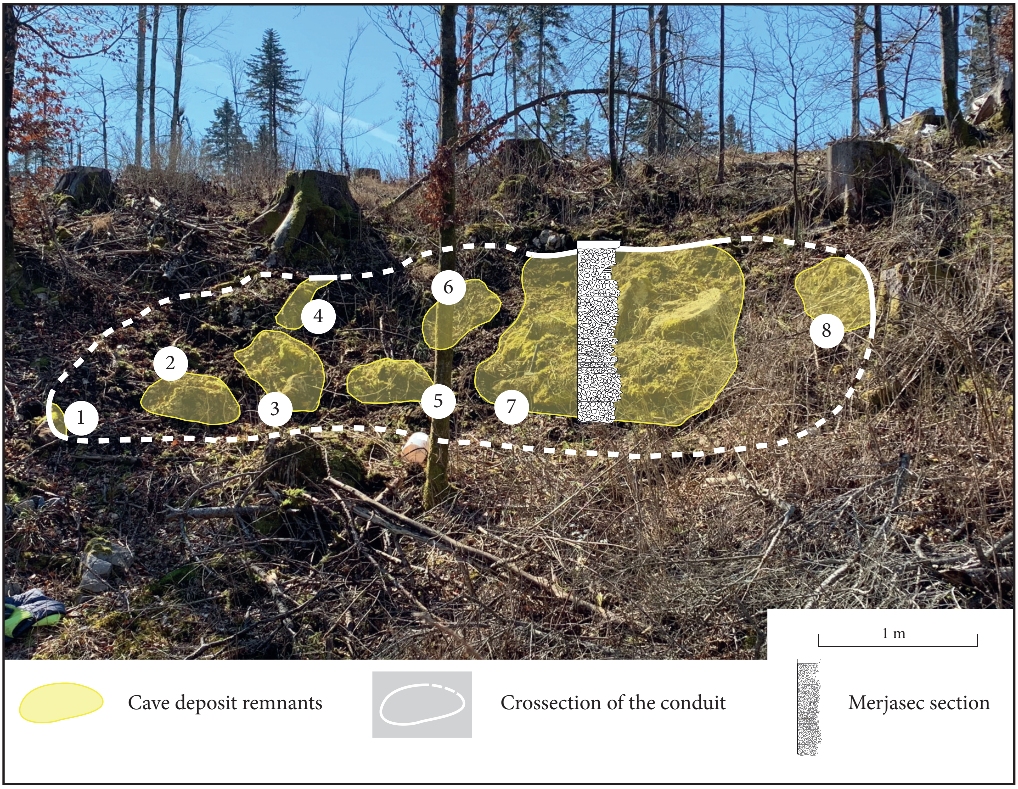
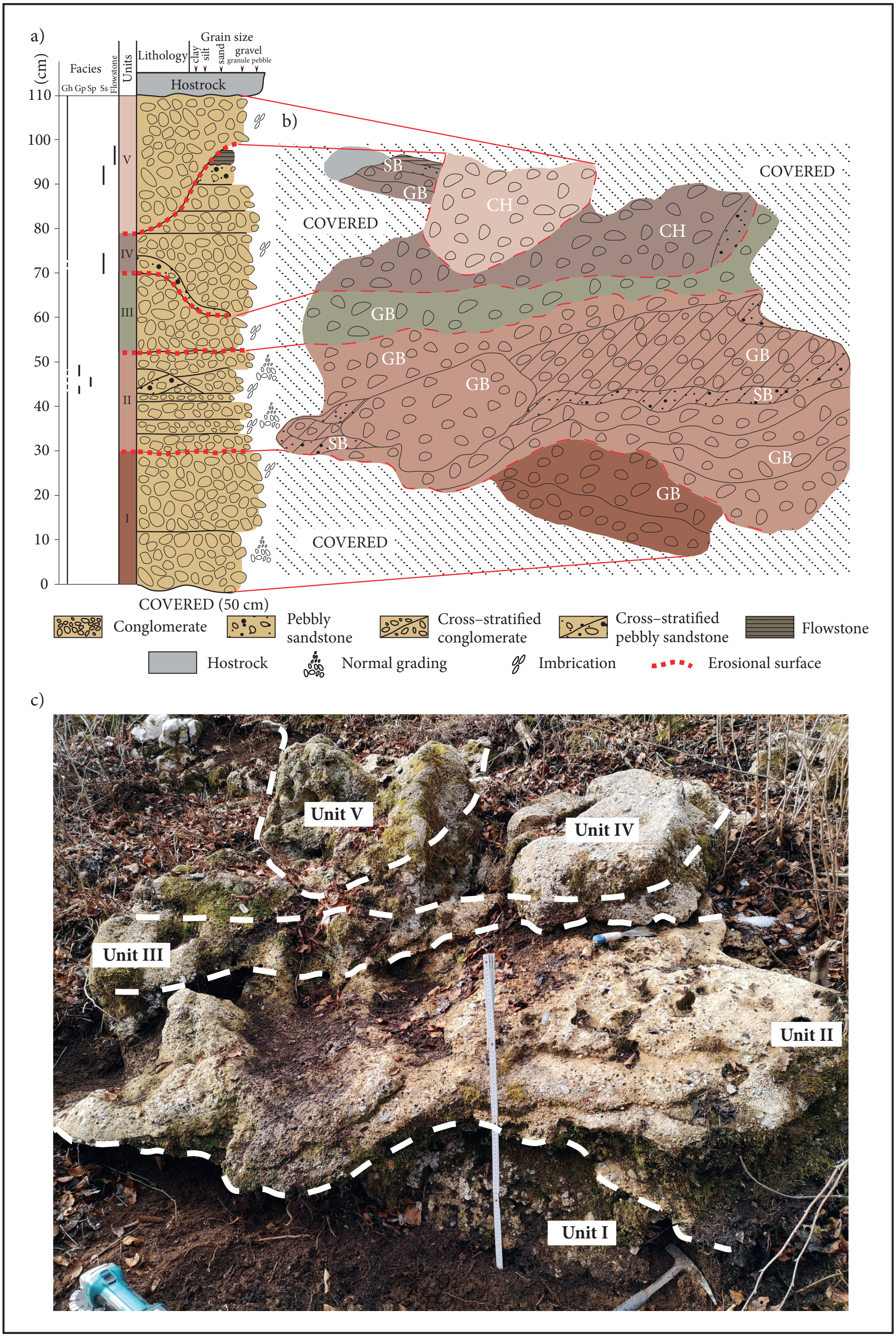


Figure 2: The cross-section of the Merjasec unroofed cave. White line marks the clearly detectable cross-section, white dashed line marks the possible cross-section of the conduit with no clear contact between the hostrock and cave deposits.

Table 1: List of facies, depositional environments, characteristics of depositional units, architectural elements and interpretation.

Facies	Facies characteristics	Depositional environment	Depositional unit	Architectural elements	Interpretation
Gh – clast-supported conglomerate	Bedded, graded, imbricated	Fluvial	I, II, III, IV, V	GB - gravel bars and bedforms, CH – channel	Channel lags or low relief longitudinal bars
Gp – cross-stratified clast-supported conglomerate	High-angle, cross-stratified	Fluvial	II	GB - gravel bars and bedforms	Migration of longitudinal and transverse bars
Sp – cross-stratified pebbly sandstone	High-angle, cross--stratified, imbricated	Fluvial	II	SB - sand bars and bedforms	Migration of longitudinal and transverse bars
Ss – pebbly sandstone	Non-stratified, imbricated	Fluvial	IV	CH - channel, SB - sand bars and bedforms	Rapid channel-fill of coarse bedload or final deposit during flood's waning stage
Fl – flowstone	Laminated	Precipitation	IV	/	Weak supersaturated sheet flows under sub-aerial conditions

Figure 3: Merjasec unroofed cave. A) Merjasec section with distribution of sedimentary units and facies. B) Architectural elements and their bounding surfaces. C) Outcrop of the Merjasec section and the sedimentary unit distribution (white dashed lines mark the erosional contacts; the length of the measuring rod is 80 cm). ➤ p. 35


a)
(cm)
Facies
Gh Gp Sp Ss
Flowstone
Units
Lithology
Grain size
clay
silt
sand
gravel
granule pebble
Hostrock
110
100
90
80
70
60
50
40
30
20
10
0
V
IV
III
II
I
COVERED (50 cm)
b)
COVERED
SB
GB
CH
COVERED
CH
GB
GB
GB
GB
SB
SB
GB
GB
COVERED
Conglomerate
Pebbly sandstone
Cross–stratified conglomerate
Cross–stratified pebbly sandstone
Flowstone
Hostrock
Normal grading
Imbrication
Erosional surface
c)
Unit V
Unit IV
Unit III
Unit II
Unit I

characteristic for fluvial environment, while flowstone facies (Fl) represents autochthonous sediment accumulation. Clast composition is very similar throughout the entire section. Most abundant are coarse-grained dolomite clasts and various types of limestone clasts, while quartz, chert, iron oxide/hydroxide and speleothem clasts are less common.

4.3 Description of sedimentary facies

Facies Gh (clast-supported conglomerate) is the most abundant and is present in every unit of the section (Figure 4A, B). This facies forms 2–31 cm thick beds, which are graded and imbricated (Figure 5A, B) or may locally express plane-parallel stratification (Figure 4B). The contact between beds is usually irregular or erosional. The conglomerate is characterised by a clast-supported texture and consists of moderately to well-sorted, mostly subangular to rounded granule- to pebble- sized clasts and a fine-grained carbonate matrix.

Facies Gp (cross-stratified clast-supported conglomerate) is represented in unit II of the section (Figure 4C). This facies forms up to 3 cm thick lenticular beds, which underlie and overlie sandstones of Facies Sp. The high-angle cross-stratified conglomerate is moderately sorted, clast-supported and consists of angular to subrounded granules and rarely pebbles. Matrix is fine grained carbonate.

Facies Sp (cross-stratified pebbly sandstone) is present in Unit II of the section (Figure 4B, C). This facies forms a high-angle cross-stratified, up to 2 cm thick lenticular bodies with weakly developed imbri-

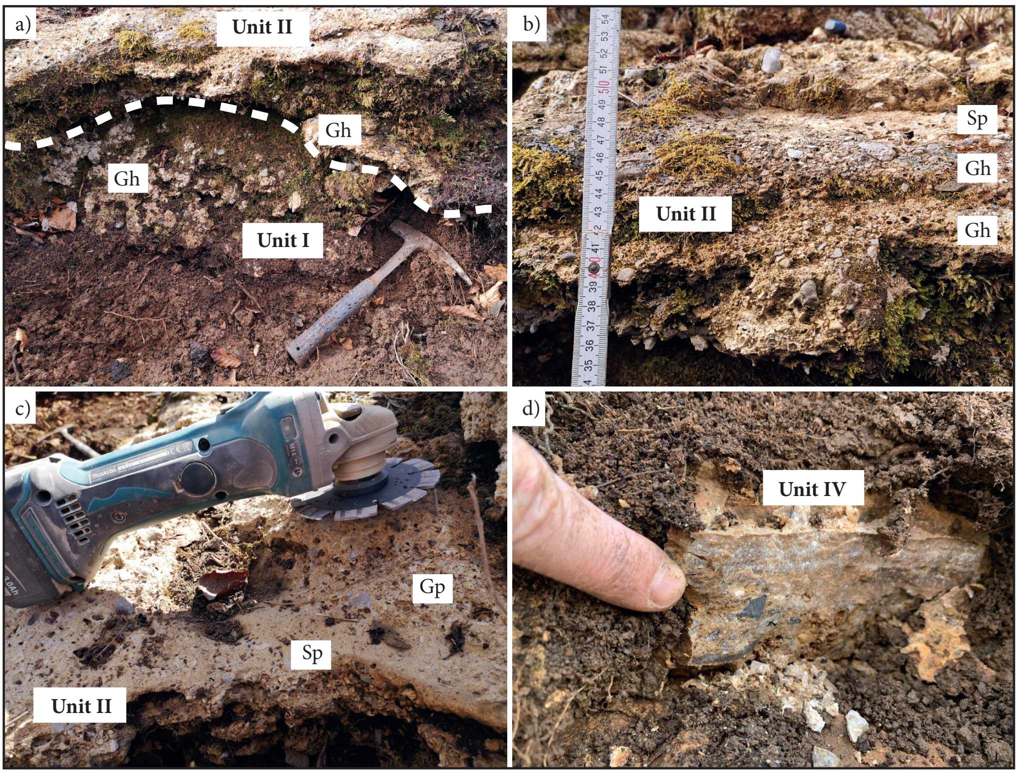


Figure 4: Details from the Merjasec unroofed cave deposits. A) Basal part of the section. Erosional contact (white dashed line) between conglomerate (facies Gh) of Unit I and conglomerate (facies Gh) of Unit II. B) Pebbly-sandstone (facies Sp) overlaying plane-parallel bedded conglomerate (facies Gh) of Unit II. C) Pebbly-sandstone (facies Sp) and conglomerate (facies Gp) from Unit II. D) Flowstone layer covering the irregular surface pebbly-sandstone of Unit IV.

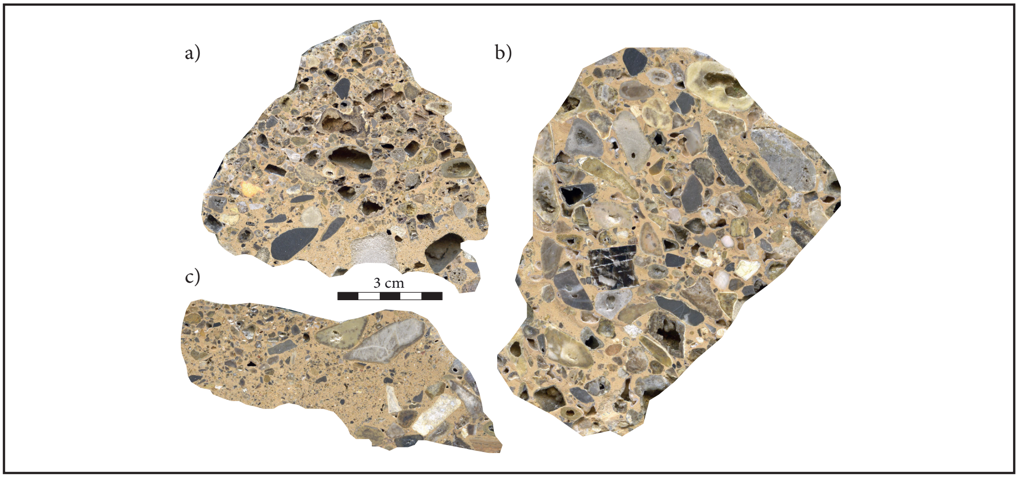


Figure 5: Polished slabs of Merjasec unroofed cave deposits. A) Graded and imbricated conglomerate (facies Gh) of Unit II. B) Imbricated conglomerate (facies Gh) of Unit IV. C) Cross-stratified pebbly-sandstone (facies Sp) of Unit II.

cation (Figure 5C), that are present as insets in conglomerates of facies Gp. The cross-stratified pebbly sandstone is characterised by a clast-supported texture and is poorly to moderately sorted. It consists of angular and rounded medium to coarse sand sized clasts and rare granules and pebbles. Matrix is mostly composed of fine-grained carbonate.

Facies Ss (pebbly sandstone) is present in Unit IV of the Merjasec section. This facies forms lenticular shaped or sheet-like beds up to 5 cm thick, which are overlying erosional bounding surfaces or gravel lags of facies Gh. The pebbly sandstone is clast-supported and moderately to poorly sorted. It consists of mostly subrounded to subangular medium to coarse sand clasts and rare granules and pebbles that exhibit moderate imbrication. The matrix is mostly fine-grained carbonate.

Facies Fl (flowstone) is present in Unit IV of the section (Figure 4D). The facies forms a 3 cm thick bed precipitated over an irregular bed surface of pebbly sandstone (facies Ss). The flowstone is characterised by the alternation of thin microcrystalline laminae and thicker laminae of sparry calcite crystals covered by columnar calcite.

4.4 Description of sedimentary architectural elements

Gravel bars and bedforms (GB) are represented by coarse-grained facies Gh and Gp (Figure 3B). GB deposits characterised by sheet-like bed geometry or rarely lenticular geometry. Irregular, low-relief scoured bases are common. These gravels mostly occur as conduit-wide conglomerate deposits.

Minor channel deposits (CH) (Figure 3B) are represented by deposits of facies Gh and Ss and are characterised by sharp, high-relief erosional base. The channel infills consist of massive conglomerates or conglomerates and lenticular bodies of pebbly sandstones. The channel deposits are covered by sheet-like, bedded conglomerates of the element previously described.

Sand bar and bedform (SB) (Figure 3B) are represented by deposits of facies Sp and Ss and are characterised by a lenticular geometry. They occur as interbeds in gravel bedforms (facies Sp) or minor channel fills (facies Ss).

5 Discussion

The sparsely preserved Merjasec unroofed cave deposits were deposited in a very dynamic, high-energy underground environment, mainly characterised by channel-related bedforms with a multistorey architecture controlled by fluvial forces and the resistant nature of the hostrock. The coarse-grained clastic cave material mostly consists of carbonates, which means that it is a product of underground erosion of the conduit walls – the corrosion of caves is much more intense during flood waters than during low waters (Palmer 2007) or is related to collapse of the tectonically weakened zones (Zupan Hajna et al. 2024) or a combination of both processes. The presence of channel-related bedforms, erosional surfaces and the complete absence of fine-grained overbank flood sheets, crevasses and levées indicates that deposition took place in a narrow cave-connecting conduit, where the open channel flow may become a pipe-full flow during floods (Ghinassi et al. 2009; Trappe 2010; Herman et al. 2012; Laureano et al. 2016; Bella et al. 2020). During these flood events, a conduit-wide stream channel was formed, in which the mobilisation of the riverbed generated bedforms similar to those in surface rivers (Trappe 2010; Bella et al. 2020).

5.1 Facies interpretation

Conglomerate facies Gh is present in every unit and is characterised by sheet-like bedded or minor channel-fill, clast-supported conglomerates. The abundant clast-supported framework, graded bedding, clast imbrication, and scoured erosive surfaces indicate deposition in a bedload-dominated fluvial system in which the flow conditions change rapidly from high-energy to waning-energy flows. Therefore, the facies is interpreted as a channel lag deposit or low relief longitudinal bars developed by ephemeral high-energy dynamic events (seasonal floods) (Miall 1977; Miall 1996. In this scenario, gravels are moving and accumulating along the riverbed, while fine-grained sediments are washed downstream, forming openwork conglomerates in which pores were filled by filtration of suspended load during the waning phase of the flood event (Ramos and Sopeña 1983; Zhang et al. 2020).

Conglomerate facies Gp occurs in Unit II in lenticular beds of high-angle, cross-stratified and clast-supported conglomerate. Facies is in direct contact with cross-stratified sandstones, which indicates channel deposition and migration of longitudinal and transverse bar forms (Miall 1981; Miall 1996).

In general, the Merjasec cave conglomerate facies exhibit similar characteristics to other cave environments. Ghinassi et al. (2009) described the clast-supported gravels of the channel-lag deposits (facies Gh in the present study) as a result of the erosive and rising phases of the stream floods and cross-bedded gravels (facies Gp in the present study) as alternate or side bars. Campaña et al. (2017) and Laureano et al. (2016) interpreted clast-supported gravels (facies Gh in the present study) as deposits of water flow in fluvial channels, while according to the classification of Bosch and White (2007), investigated deposits are mainly characteristic for the thalweg facies, although they could also be determined as »gravelly« channel facies deposits due to the presence of fabrics (imbrication, normal grading) and sedimentary structures (horizontal bedding, cross-stratification).

Sandstone facies Sp occurs in Unit II as lenticular bodies of high-angle, cross-stratified coarse-grained sandstone with a weakly imbricated pebbly admixture. Facies is imbedded in channel lag/bar conglomerates and was deposited from traction by a unidirectional current, which indicates a downstream migration of longitudinal and transverse bar forms (Miall 1977; Miall 1981; Miall 1996; Opluštil et al. 2005).

Sandstone facies Ss occurs in unit IV as a lenticular or sheet-like bodies of non-stratified mainly coarse-grained sandstone with abundant granule- to pebble-sized clasts that exhibit moderate imbrication. Facies directly overlies scoured basal surface of channel lag conglomerates, indicating rapid channel-fill deposition of coarse bedload (Miall 1996), or it covers conglomerate lags as a final deposit during the flood's waning stage.

Compared to other investigated caves (Ghinassi et al. 2009; Laureano et al. 2016), similar sandstone facies were mostly described as channel bedforms (bars, side-bars, dunes) formed as a result of localised sediment deposition related to channel floor irregularity, channel widening, channel migration or as channel-fill deposits accumulated by vertical accretion.

Flowstone facies Fl occurs in Unit IV as laminated bed precipitated over conglomerate. Facies indicates a cessation of fluvial sedimentation and beginning of flowstone formation under sporadic or weak supersaturated sheet flows under sub-aerial conditions with typically slow accretion (Fairchild et al. 2007; Ford and Williams 2007; De Waele and Gutiérrez 2022). Flowstone indicates a hiatus in the stratigraphic sections, which means that during its precipitation, other sediments should not be deposited (Gillieson 1986).

Flowstones, which are very common authigenic deposits in caves are described as a very useful indicator for palaeoenvironmental conditions (Fairchild and Baker 2012; Nehme et al. 2015) and geochronology (Bosák 2002; Fairchild et al. 2006; Laureano et al. 2016; Ferk et al. 2019; Sierpień et al. 2021; Zupan Hajna et al. 2021).

5.2 Architectural interpretation

The Merjasec cave conduit represents a complex, channel-fill sequence consisting of various types of intra-channel bars and minor channel deposits, mostly separated by erosional bounding surfaces (Figure 3). Investigated cave deposits have been recognised as three distinct architectural elements defined by their geometries, bounding surfaces and sediment fills. The most common are deposits of gravel bars and bedforms (GB) interbedded with rare deposits of minor channels (CH) and sand bars and bedforms (SB).

Gravel bars and bedforms (GB) form multistory sheets, rarely lenses composed of facies Gh, and Gp, and represent an intra-channel (conduit-wide) bar (longitudinal, transverse) deposited during pulsating high-water discharge (Miall 1996).

Minor channels (CH) were incised into underlying conglomerate sheets of element GB during the erosional stage of the flood and were filled rapidly after the formation of the channel. Two types of channels were recognised. First is a single channel with a complex fill of pebbly sands (facies Ss) and gravels (facies Gh) and the second is a single channel with a simple fill of gravels (facies Gh) (Ramos and Sopeña 1983; Miall 2014).

Sand bars and bedforms (SB) record intra-channel deposits, which were probably generated by migrating dunes within the shallower part of the conduit (facies Sp) (Opluštil et al. 2005; Miall 1996) or by the flood's wanning stage (facies Ss) (Miall 1996).

5.3 Reconstruction of palaeodepositional dynamics

Stratigraphy and sedimentary characteristics of the exposed cave deposits reveal five cut-and-fill sequences (Figure 6), which describe the local palaeohydrological evolution of the investigated cave conduit and resemble the palaeohydrological conditions of the regional system. The architecture of the sediments indicates ephemeral, high-energy dynamic events terminated by a longer period of subaerial exposure under epiphreatic conditions.

The first **sequence S1** (Figure 6) indicates the deposition of conduit-wide sheet-like gravel lags during the high-energy pulse generated by the rising stage of the stream flood.

Second **sequence S2** (Figure 6) begins with an erosive phase during the rise of the flood, followed by a conduit-wide aggradation of sheet-like gravel beds during the high-energy flow, which were covered by the migration of longitudinal and transverse bars by the pulsating moderate- to low-energy flow during the waning of the flood.

The **sequence S3** (Figure 6) recorded a reactivation of flooding-induced erosion and a subsequent accumulation of gravel lag under high-energy flood flow conditions.

The **sequence S4** (Figure 6) records one of the two major erosional events, forming a channel incised into the underlying gravel pavement, which was filled with a complex-fill of gravels and gravelly sands immediately after the flood´s erosional phase. A conduit-wide aggradation covers the channel deposits under high-energy flow conditions and accumulates gravel lags that were covered by a sheet-like sand bed during the flood's waning stage. The accumulation of flowstone over slightly irregular surface records a break of the fluvial activity in the conduit.

After this quiet period, the **sequence S5** (Figure 6) records an upstream barrage breakthrough and a restoration of epiphreatic flood-induced fluvial activity with a second major, very intensive erosional event that cuts the stream channel through the flowstone into the deposits of the fourth sequence, which was filled with gravel immediately after the flood´s erosional phase and covered by a conduit-wide gravel lag during later phase of the flood that eventually completely filled the conduit. Sequence 5 thus documents the last known erosional and depositional activity in the conduit before it was abandoned.

5.4 Energy fluctations of palaeoflow

Merjasec cave palaeoflow was characterised by high-energy ephemeral flood-flows and intra-channel deposition, as evidenced by upper-flow regime features such as planar bedding, the predominance of coarse-grained material, erosional surfaces and the presence of speleothem debris, indicating also an upstream erosion of older cave deposits.

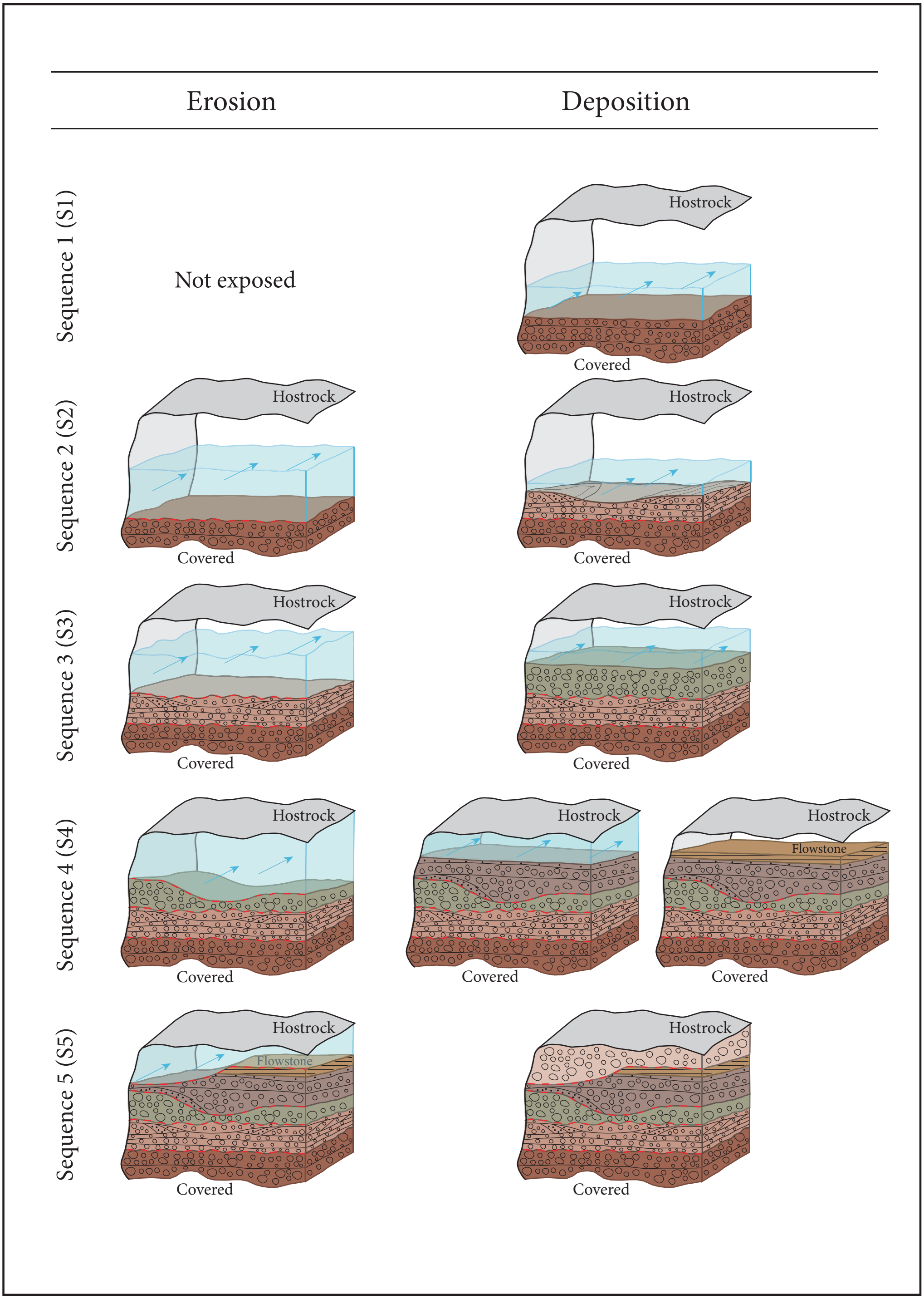


Figure 6: Schematic evolution of depositional dynamics in the Merjasec unroofed cave conduit. Illustration (not to scale) represents erosional and depositional phases in each of the five sequences. A description of each sequence is provided in section 5.3.

All recorded floods in Merjasec cave are characterised by an early erosional and subsequent depositional stage, developing a cut-and-fill sequence (Simms 1994; Adams et al. 2019). However, a detailed analysis of the facies and architecture reveals that the floods differ in their flow energy, resulting in different erosional bounding surfaces and different channel bedforms. The low-relief, conduit-wide erosions indicate a high-energy, laterally stable flow and occur in the early erosional flood stage in sequences 1, 2 and 3. These low-relief erosional surfaces were in the later depositional stage covered by conduit-wide gravel bars of the facies Gh. High-relief erosion with increased localised incisions represents the early flood stages in sequences 4 and 5, indicating thalweg migration within the conduit-wide stream channel, probably associated with oscillations in flow velocity (Collinson 1970). High-relief incisions were later covered by minor channel fills of facies Gh and Ss (also noticed by Miall 1996; Ghinassi et al. 2009; Scherer et al. 2015; Fambrini et al. 2017; Bella et al. 2020).

Low-energy bedforms are rare in Merjasec cave and were only found in the sequence 2. They are characterised by a lenticular geometry and cross-bedded structure composed of facies Gp and Sp. They represent a downstream migration of subaqueous dunes and bars in lower flow regime (Miall 1977; Miall 1996; Miall 1996; Fambrini et al. 2017). Direct stacking of high-energy conglomerates and low-energy sands clearly demonstrate relatively fast changes in the flow energy and consequently depositional dynamics (Ramos and Sopeña 1983). Sequence 2 is therefore the only one that records the flood´s waning stage, while in other sequences the deposits of this stage were probably washed away by the rising and erosive stage of the flood in other sequences (Zupan Hajna et al. 2024).

5.5 Regional implications

The regional underground palaeohydrology, mostly characterised by periodic, pulsating flooding, as evident from the Merjasec section, was probably controlled by climatic conditions (Ghinassi et al. 2009; Hercman et al. 2023; Zupan Hajna et al. 2024), which transferred larger amounts of rainwater into the cave system during storm periods or to processes related to allogenic recharge, leading to a sudden rise in the water table and thus to the reactivation of several levels in the epiphreatic zone of the cave system, including the investigated conduit. Similar conditions are also present in a current hydrological regime of the regional system with variable recharge conditions, characterised by increased discharge of influent rivers, causing pulsating flooding of the system (Prelovšek et al. 2008; Gabrovšek and Turk 2010; Gabrovšek et al. 2014; Blatnik et al. 2019).

The end of sequence 4 record a significant change in the depositional environment and thus in the depositional dynamics. The formation of the flowstone layer over the irregular morphology of the fluvial deposits indicates a break of fluvial activity (Bella et al. 2020; Hercman et al. 2023; Zupan Hajna et al. 2024). It is possible that the irregular contact between the flowstone and the underlying fluvial deposits record yet another flood event with only detectable erosional stage, as conduits can undergo several phases of deposition and removal without leaving clear indicators (Zupan Hajna et al. 2024), but this remains only a conjecture as this part of the section is very sparsely exposed. This sudden change in environmental conditions from repetitive flooding (epiphreatic) to calm, intermittent thin flows in sub-aerial exposed conduit and back again could be explained by the temporary drier conditions or underground flow bypass created by the upstream blockage of the conduit due to cave-roof collapses (Bella et al. 2020).

Sequence 5 records the last active phase in which the conduit was completely filled with clastics. After this phase, the conduit became completely abandoned, which can be related to (a) base level drop and regional uplift that moved the conduit to higher levels of the system, where it became out of reach even for large flood events (b) clogging of the conduit and therefore forcing flood waters through different pathways or (c) the deflection of flood waters by faults that can act as very effective underground flow barriers.

Regarding the morphological features and sedimentary characteristics, the investigated cave was most likely connected to the main regional drainage system and functioned as a bypass conduit that was fully activated only during extreme floods under epiphreatic conditions. Such conduits are usually draining flood waters from the main conduit, a characteristic of a cave systems with a complex, interconnected conduit network.

The detailed sedimentological investigation of the Merjasec section highlights the significant value of unroofed cave deposits in reconstructing past subsurface and surface environmental conditions, despite their typically sparse preservation, poor exposure, and frequent erosion. The present study demonstrates that, when examined in detail, such deposits can yield far more than just confirmation of ancient fluvial activity; they can provide insights into the provenance, energy, and dynamics of palaeoflow, offering an understanding of past hydrological conditions. The Merjasec case further underscores the potential of unroofed cave deposits to act as key pieces in deciphering the evolution and hydrodynamics of regional cave systems, particularly in areas like Laze Plain where few caves intersect the epiphreatic zone (Blatnik et al. 2019). Importantly, this work also demonstrates a methodological approach that can be successfully applied to similarly exposed deposits elsewhere, showing that even fragmentary or degraded remnants, when analysed with appropriate techniques, can significantly enrich our understanding of karst palaeohydrology.

6 Conclusion

The sedimentological characterisation of sparsely preserved Merjasec unroofed cave deposits from Laze Plain (central Slovenia) provided very valuable information about past regional hydrological conditions:

1) Stratigraphy and sedimentary characteristics of the exposed cave deposits reveal five cut-and-fill sequences formed during high-energy ephemeral flood-flows and intra-channel deposition, terminated by a longer period of subaerial exposure under epiphreatic conditions.
2) Most of the bedforms indicate high-energy flows generated by the rising stages of stream floods, while low-energy bedforms indicate the flood´s waning stages.
3) The direct stacking of high-energy bedforms and low-energy bedforms indicates fast changes in the flow energy and consequently depositional dynamics. The interpreted sediment characteristics indicate that the flood flows range from conduit-wide and laterally stable flows to oscillating flows with increased localised incisions formed by thalweg migration. Sedimentary data of the Merjasec cave suggests that the regional palaeohydrology was mostly affected by the storm periods and/or allogenic discharge, leading to a sudden rise in the water table and epiphreatic zone reactivation.
4) Similar conditions are also present in a current hydrological regime of the regional system with variable recharge conditions, characterised by increased discharge of influent rivers, causing pulsating flooding of the system.

This work demonstrates that even fragmentary or degraded remnants of unroofed cave deposits, when studied in detail, can provide most valuable information about karst palaeohydrology and therefore should not be overlooked. We suggest that a similar detailed methodological approach in studying comparable palaeocave deposits in other regions.

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