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SEDIMENT LOAD WITH METALLURGICAL SLAG ADMIXTURE UNDER DIVERSE MORPHOLOGICAL CONDITIONS ALONG SUBMERGING KARST STREAM

OBREMENITEV S SEDIMENTI S PRIMESJO METALURŠKE ŽLINDRE V RAZLIČNIH MORFOLOŠKIH RAZMERAH OB PONIKALNICI

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Jan Lenart & Filip Chalupka: Sediment load with metallurgical slag admixture under diverse morphological conditions along submerging karst stream

This study investigates the clastic fluvial sediments of the Jedovnický submerging stream in the section between the Jedovnice village and Křtinský stream (Moravian Karst, Czechia). A total of 28 samples were collected to analyze clast composition, slag content, grain size, and roundness. The sediment primarily consists of allochthonous Lower Carboniferous material (greywackes, clayey shales) with varying amounts of metallurgical slag, occasionally mixed with autochthonous deposits such as rockfall accumulations and tailings from the excavation of connecting adits. The slag content fluctuates, peaking downstream of the erosive section of the Rudické propadání cave, near the Stará řeka passage connection. Grain size distribution is influenced by both surface and cave morphology, as well as hydraulic conditions. The alternation between erosive and depositional zones, along with the unique karstic and speleorelief features, plays a crucial role in clast mobilization. These features include ponors, erosive and paragenetic corridors, sumps, and rockfalls. Fine particle accumulations are particularly noticeable in front of sumps or dams. Throughout the studied section, the proportion of coarse particles (>10 mm and 5–10 mm) gradually decreases, while finer particle content increases toward the resurgence. The roundness of Carboniferous sediments remains relatively constant, although it is significantly influenced by the presence of well-rounded, weak and ductile slag clasts. Overall, both the slag content and the proportion of well-rounded and rounded clasts in the coarser fractions (>10 mm and 5–10 mm) show a decreasing trend toward the resurgence.

Keywords: allochthonous sediments, channel morphology, Moravian Karst, particle size, roundness.

Izvleček UDK 556.53:551.3.051:662.613.12(437.32)***Jan Lenart & Filip Chalupka: Obremenitev s sedimenti s primesjo metalurške žlindre v različnih morfoloških razmerah ob ponikalnici***

V tej študiji se proučujejo klastični rečni sedimenti ponikovalnega potoka Jedovnický na odseku med vasjo Jedovnice in potokom Křtinský (Moravski kras, Češka). Skupno je bilo odvzetih 28 vzorcev za analizo sestave grušča, vsebnosti žlindre, : velikosti in zaobljenosti delcev. Sediment je sestavljen predvsem iz alohtonega spodnjekarbonskega materiala (peščenjak, glinasti skrilavci) z različnimi količinami metalurške žlindre, ki se občasno meša z avtohtonimi usedlinami, kot so akumulacije skalnega podora in jalovina iz izkopa povezovalnih rovov. Vsebnost žlindre niha, največja pa je dolvodno od erozijskega dela jame Rudické propadání, v bližini povezave s prehodom Stará řeka. Na porazdelitev delcev glede na velikost vplivajo morfologija površja in jame ter hidravlične razmere. Ključno vlogo pri kopičenju grušča imajo menjavanje erozijskih in sedimentacijskih območij ter edinstvene značilnosti krasa in jamskega reliefa. Te značilnosti vključujejo požiralnike, erozijske in paragenetske jarke, sifone in skalne podore. Kopičenje drobnih delcev je še posebej opazno pred sifoni in jezovi. Na celotnem proučevanem odseku se delež grobih delcev (> 10 mm in velikih 5–10 mm) postopno zmanjšuje, vsebnost drobnih delcev pa se proti ustju povečuje. Zaobljenost karbonskih sedimentov ostaja razmeroma konstantna, čeprav nanjo pomembno vpliva prisotnost dobro zaobljenih, šibkih in duktilnih klastov žlindre. Bolj ko se bližamo ustju, sta na splošno čedalje manjša vsebnost žlindre in delež zelo zaobljenih in delno zaobljenih klastov v bolj grobih frakcijah (> 10 mm in velikosti 5–10 mm).

Ključne besede: alohtoni sedimenti, morfologija jarkov, Moravski kras, velikost delcev, zaobljenost.

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1. INTRODUCTION AND STUDY AREA

The submerging, relatively high gradient streams, flowing through the geological border from non-karst landscape into the well developed karst are among the most diverse geomorphic systems worldwide, evolved under the variety of influencing factors (Bonacci et al., 2013). The Jedovnický stream is one of the most hydromorphologically diverse watercourses in the Czechia. Due to the variable geology and the subsequent geomorphological conditions of the area, its hydromorphological character varies along with its longitudinal profile. We investigated, reviewed and discussed how stream load containing metallurgical slag admixture behaves depending on the channel morphological and hydraulic conditions along the stream longitudinal profile.

The properties of clastic sediments transported through karst conduits have traditionally been studied using vertical outcrops in sediment traps (e.g., Nehme et al., 2015), which limits the ability to capture the sediment dynamics along the longitudinal profile. Other studies have focused on clastic sediments to extract data on paleofloods (e.g., González-Lemos et al., 2015) or sediment mobility (Dogwiler and Wicks, 2004; Mueller et al., 2023). Van Gundy and White (2009) examined changes in sediment assemblages following a significant flooding event. Bettel et al. (2022) modeled sediment flux considering system hysteresis. Some authors, such as Herman et al. (2012), have approached the study of clastic sediments conceptually and systematically.

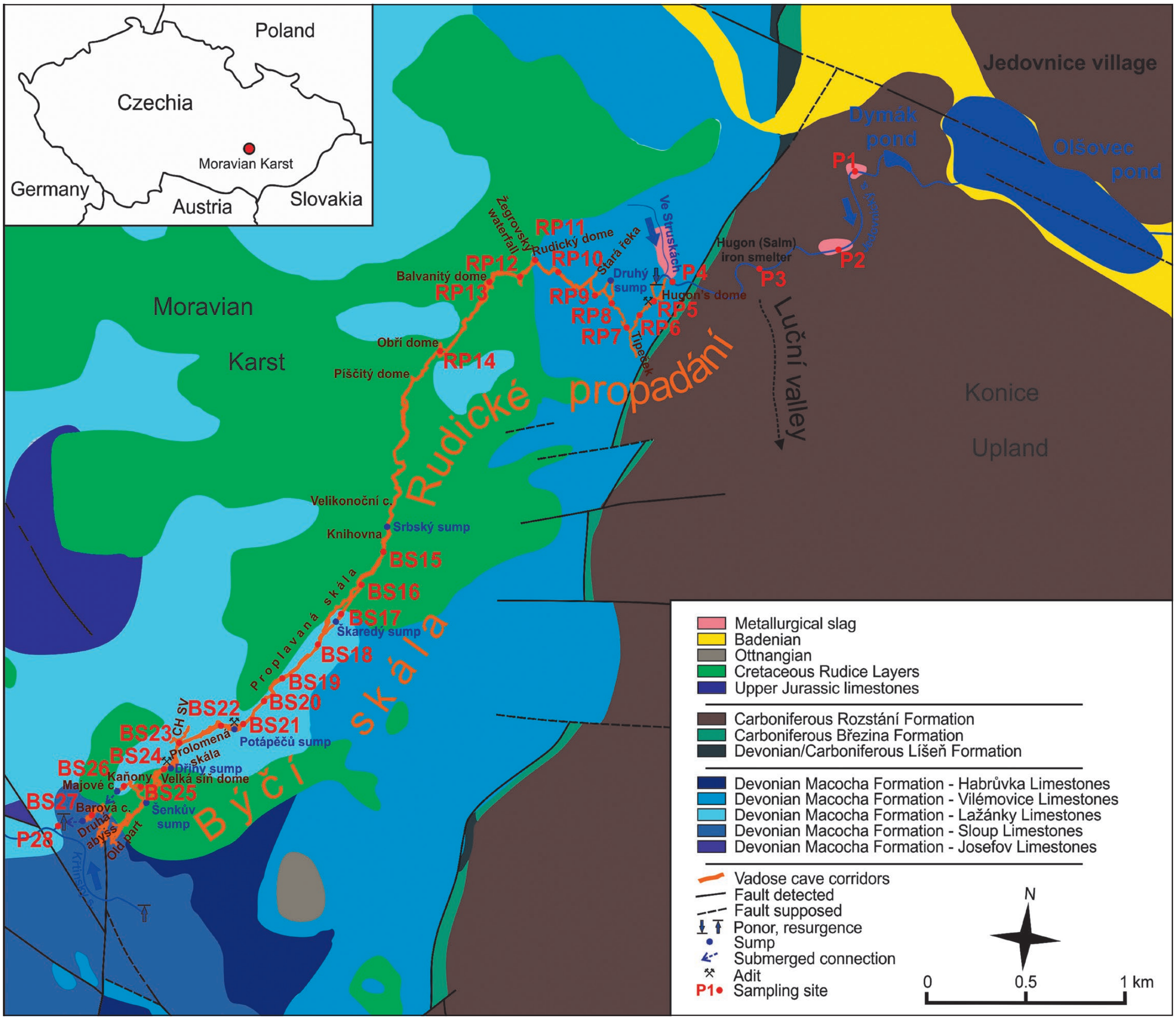

Figure 1: General overview of the surveyed stream section with important toponyms included, geology obtained from geological map 1 : 25 000 of the Czech Geological Survey.

The Jedovnický stream (Figure 1) is formed by the confluence of several minor streams east of the village of Jedovnice (main spring N 49.363° E 16.811°; 560 m a.s.l.). Below the village (455 m a.s.l.), the stream forms 1.8 km long deeply incised blind valley (Burkhardt et al., 1975) terminated by the ponor below the 40 metres high rock wall (N 49.333° E 16.734°; 430 m a.s.l.). The remaining 6 km the stream flows through the cave system towards the resurgence (N 49.333° E 16.734°; 305 m a.s.l.). and the confluence with the Křtinský stream (N 49.333° E 16.734°; 305 m a.s.l.), a left-sided tributary of the Svitava river (Hromas, 2009). The catchment area of the stream (27 km^2 prior to the ponor, 36 km^2 prior the resurgence; Burkhardt, 1953) belongs to the Drahanská Upland geomorphic unit, the lower part of the catchment area belongs to the Moravian Karst sub-unit (Demek et al., 2006), where the entire subterranean part of the stream is located within the Rudická Plateau district. We investigated the eight kilometers long section of the stream with 150 metres elevation, of which 83 metres are accounted for ponor cascades.

The upper part of the basin is geologically younger, composed of clastic non-carbonate turbidites of the Lower Carboniferous conglomerates, greywackes, siltstones and slates. Moreover, Badenian deposits have been preserved at some locations. The flat saddles in the watershed areas are then covered with Quaternary loess and loess loam, while the valleys are filled with fluvial and colluvial material. This upper part of the basin is relatively flat with sharply incised valleys.

Down the Jedovnice village, the stream is dammed by system of five reservoirs, which represent a barrier to sediment transport. Beyond them, the stream forms a 1.8 km long deeply incised blind valley at the contact of non-carbonate Carboniferous rocks and Devonian limestones (Chlupáč et al., 2011; Gregor et al., 2014; Plichta et al., 2016). The stream enters the Moravian Karst geomorphological sub-unit. Fluvial terraces are preserved 10 to 26 m above the present water level on both sides of the valley (Burkhardt et al., 1975). In about two thirds of the length of this section, the higher situated Luční valley (Figure 1), through which the surface palaeodrainage of the Jedovnický stream flowed in the past, continues towards the south (Dvořák, 1994).

400 m beyond the contact between non-carbonate rocks and limestones beneath the terminating massive rock wall of the blind valley, the stream enters the Rudické propadání cave ponor (Štelcl, 1963). This is often jammed by large woody debris (Figure 2B). Such blockage typically causes formation of gravel bars and terraces prior the ponor (Figure 2A). During flood events, a lake up to 50 m long and 3 m deep forms in front of the jam (Burkhardt et al., 1975). In close proximity of the ponor, a short periodic Ve Struskách stream drifts metallurgical slag from the historical tailings of the former Hugon (Salm) iron smelter founded in 1746 and abandoned in the late 19th century (Baldik et al., 2018; Gregor at al., 2014). The slag subsequently participates in bedload transport through the cave system, where it mechanically abrades speleothems (Baldík et al., 2018).

The ponor composed of cascades of waterfalls with a total depth of 83 m (Burkhardt et al., 1973). After reaching the base level, the stream continues from the Hugon‘s (*syn.* Wankel-Mládek‘s) dome through actively flooded vadose corridors, which alternate with sumps and domes (the Rudický, Balvanitý, Obří and Písčitý domes; Balák et al., 1997). Some corridors are considered paragenetic (Gregor et al., 2014).

The subterranean portion of watercourse passes through several types of Devonian limestone. Moreover, their erosional surface is covered by younger Cretaceous clastic sediments of the Rudice Layers, penetrating into the cave system through karst chimneys (Gregor et al., 2014).

In the section Hugon‘s dome – Stará řeka passage, the distinct bedrock channel is formed along vertical fissures (Burkhardt et al., 1975) (Figure 2C). In the following section, wider tunnels alternating with large domes developed (Burkhardt et al., 1977). The Rudické propadání portion terminates with a 386 m long Velikonoční cave section with a corridor height of only 0.4–3 m above the thick bedload deposit, which is followed by the Srbský sump separating the Rudické propadání cave from the Býčí skála cave (Gregor et al., 2014). These sections are of paragenetic origin (Gregor et al., 2014).

In the Býčí skála cave, tunnel-like vadose sections (Figure 2D, E) again alternate with sumps (Piškula, 1986). Prior the Šenkův sump, the stream leaves the main tunnel of the Býčí skála cave, changes its direction towards the WNW through the Kaňony passage towards the Barová cave and through the four resurgences into the Křtiny valley (confluence with the Křtinský stream). In the past, the Jedovnický stream flowed through the Old part of the Býčí skála cave, which is recently flown only during floods (Gregor, 2015). The Jedovnický stream within the studied section lacks any importnat tributaries, apart from rather intermittently flowing ones (e.g., the Ve Struskách, Tipeček, Stará řeka passage, Žegrovský waterfall) (Šebela, 2011).

The cave morphology corresponds to the geological structure. The whole cave system is predisposed by Variscan joint discontinuities in ENE–WSW to NE–SW directions (Burkhardt et al., 1975; Gregor et al, 2014; Skoupý & Kukla, 2014). Moreover, these are disrupted by younger SSE–SSW to ESE–WSW joint sets (Burkhardt et al., 1975; Skoupý et al., 2012). The opening section of the

Figure 2: Morphology and sediments: A – gravel bars near the P4 sampling site; B – The Rudické propadání cave ponor with recently eroded jam; C – bedrock channel ~150 m before the Druhý sump; D – tunnel in the Býčí skála cave ~200 m before the Škaredý sump (BS16); E – low tunnel filled by sediments, the Býčí skála cave before the Potápěčů sump (BS21); F – typical sampling site inside the cave. Photos: F. Chalupka.

cave system is developed within the Rudice subsided tectonic block (Burkhardt et al., 1975). The geological structures are further complicated by strata dipping, folds and thrusts (Burkhardt et al., 1975).

The petrographic composition of the stream channel bed sediments has been already described within the cave system (e.g., Hypr, 1975; Kadlec, 1997). The autochthonous sediments are clasts of limestone and sinter that have been transported into the watercourse by gravitational processes or abrasion (Káňa et al., 2013; Skoupý et al., 2012). However, allochthonous Carboniferous greywacke and slate clasts predominate (Burkhardt et al., 1975). Slates dominate over greywacke in the surface part of the stream in a ratio of 65 : 35. Down the stream, the destruction of less resistant slate decreases their amount in the gravel fraction, and greywackes already dominate over slate in a ratio of 53 : 47 in the Býčí skála cave (Burkhardt et al., 1957; Hypr, 1975). Metallurgical slag is substantially represented in the sediments, e.g. in the Velikonoční cave up to 13% (Hypr, 1975). Its subangular clasts have a glassy amorphous structure and also contain fragments of charcoal or blast furnace lining (Baldík et al., 2018; Gregor at al. 2014). Other sparse clasts are of hornfels and quartzites (up to 10% in the Býčí skála cave, Burkhardt et al., 1957), eroded materiál of the Rudice Layers, geodes, and even calcareous nodules from eroded loess that entered the cave by infiltration transport through karst chimneys (Burkhardt et al., 1975; Gregor et al., 2014; Káňa et al., 2013; Skoupý et al., 2012). Other anthropogenic material – angular limestone debris after the excavations of adits bypassing the sumps, rounded brick fragments and waste – is also sporadically represented (Gregor et al., 2014; Havlík & Mikeš, 2016).

2. METHODS

A total of 28 stream channel bed sediment samples (each ~0.0005 cubic meters) were collected for analysis. Four samples were taken from the section Dymák pond – ponor, 23 samples were taken within the cave system (Figure 1). One sample was collected down the resurgence. The sampling sites were selected within the distal portions of the recently active gravel bars with obviously fresh surface. For each sample, the surface layer of sediment was removed to a depth equal to the length of the b-axis of a typical sampled clast (Bunte & Abt, 2001) (Figure 2F).

Petrographic composition of the samples was determined for comparison with previous studies obtained by Burkhardt et al. (1975) or Gregor et al. (2014). We focused on the detection of metallurgical slag for fractions > 10 mm and 5–10 mm.

Volumetric sampling (sieving) with a Fritsch Analysette 3 PRO vibratory shaker was used to sort the samples into size fractions with interval boundaries of 20, 63, 200, 630, 2000, 5000 and 10000 μm. In individual samples for fractions > 10 mm and 5–10 mm, particle roundness was determined using the visual comparison chart (Powers, 1953) and the RA index was calculated, which is defined as the sum of very angular and angular clasts over the total number of clasts in a given sample, converted to a percentage (Benn & Ballantyne, 1994). Natural sediments, metallurgical slag and limestone debris after the excavation of adits were included in the analysis.

Locations of possible sources of sedimentary material, both on the surface (slag tailings) and within the cave system (tributary corridors, collapses, karst chimneys, tailings from mined adits and exploratory excavations), as well as locations with blocked sediment transport, i.e., ponds, sumps, wood jams and paragenetic corridors were identified.

3. RESULTS

3.1 CHANGES IN PARTICLE SIZE FRACTIONS ALONG THE STREAM

The gradual changes in the grain size composition of the sediments in the samples collected are shown in Figure 3. In the samples P1–P4, which were collected between the Dymák pond and ponor, the amount of fine fractions gradually decreases. Sample RP5 was collected in the Hugon's dome below the waterfalls of the ponor. There, the amount of the fine fraction is negligible, with >10 mm size predominating. In contrast, a local maximum in fine fraction content was observed with sample RP6, which represents a low gradient section of the stream.

Erosional sections (RP7) alternate with accumulation ones (RP8) in the following part of the cave. Sample RP8 is located just upstream of the Druhý sump. Sample RP9 is composed of approximately 60% slag. In samples RP10–RP13, a gradual decrease of finer fractions is again observed. Sample RP10 is located below the Stará řeka passage, which is completely filled with sediments. Sample RP11 was collected in the Rudický dome. Sample RP12 was collected in front of the sump. Sample RP13 was collected in the Balvanitý dome with rockfall accumulations. Sample RP14 was collected in the Obří dome, which is developed on prominent tectonic fractures.

In samples BS15–BS18, i.e. already beyond the Srbský sump in the Býčí skála cave, the amount of finer clasts is relatively higher, with the highest volume of the finest fraction in sample BS15, but very slightly decreasing. Gradually, however, the content of the finer fraction slowly decreases between samples BS15–BS20, dropping very rapidly from 25% to 10% between samples BS18–BS20. In sample BS21, an increase in the fine fraction content before the Potápěčů sump is again observed. In contrast, in sample BS22, beyond the sump and the exca-

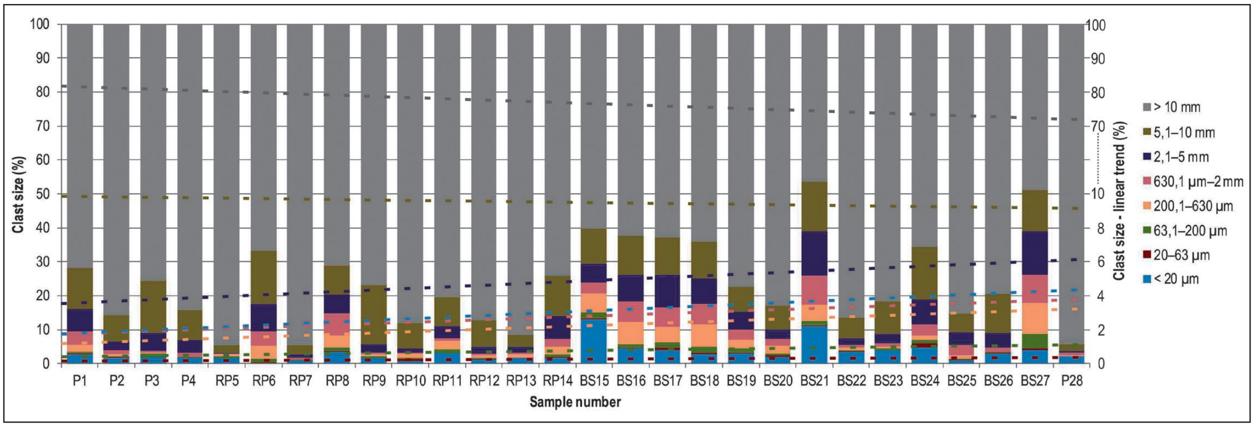

Figure 3: Grain size of clastic sediments and fractions trends.

vated adit, there is a sudden decrease in the finest particle content and an increase in the coarse fraction > 10 mm. In sample BS23 at the connection with the CH SV passage there is a slight increase in fine fraction.

Sample BS24 was collected beyond the Dřiny sump in the Velká síň dome, near which there is a tailings after the excavation of the adit that crosses the sump. For the next sample BS25, the finer particle level reaches a local minimum. In sample BS26, which was collected approximately 20 m upstream of the Májové caves sump, a gradual increase in fine fractions is again observed.

In sample BS27, fine fractions are found in large quantities. The sampling location is at the bottom of the Druhá abyss in the Barová cave. The last sample P28 was collected downstream of the terminating resurgence where a very minimal amount of fine fraction was identified.

As figure 3 shows, the relative content of the two coarsest fractions in the samples decreases slightly over the course of the investigated section, while the relative content of the six finer fractions increases gradually.

3.2 SLAG CONTENT AND CLASTS ROUNDNESS

The content of metallurgical slag within the two coarsest fractions is shown in Figure 4. In the first sample P1 collected below the Dymák pond, only several slag fragments were found. An increased amount of slag (up to 30%) is evident in sample P2. The content then decreases slightly towards the ponor. Another increase was detected starting with the RP7 and RP9 samples. The latter one located behind the sump contained the highest amount of slag of all samples collected (up to 60%). Further towards the resurgence, the slag content continuously decreases to a minimum, but local maxima can be observed.

The results of clast roundness of the two coarsest grain size categories are expressed in Figure 4. Because the amount of slag in the sample correlates with the RA index value, the RA index value can be significantly influenced by the slag amount in the sample. This influence is observed in sample RP9, where the amount of slag is up to 60 % and where the clasts have the highest roundness. The calculated correlation coefficient

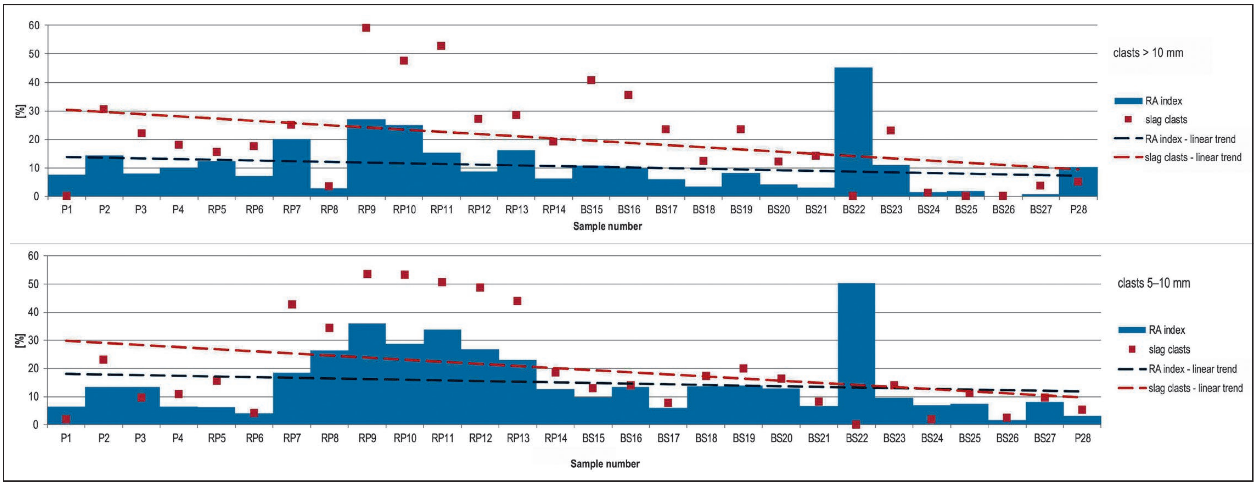

Figure 4: RA index, slag content and trends of progression of both parameters for two biggest grain-size fractions.

between the percentage of slag and the RA index value converted into percentages is 0.81 in the > 10 mm fraction and 0.95 in the 5–10 mm fraction. Sample BS22, whose slag content, but especially the RA index value, is anomalous, was not included in the calculation of the correlation coefficient because its material is composed mainly of angular limestone clasts – tailings from the excavations.

4. DISCUSSION

4.1 SUBSTANTIAL INFLUENCES ON BEDLOAD

Fluvial sediments in subterranean river may help to reveal the past or recent character of the environment of the respective basin as well as the erosional-depositional history (Hercman et al., 2023). The character of the channel bedload – composition, grain size and roundness – is strongly affected by the varied material sources and varied channel morphological and hydraulic conditions (Kadlec, 1996), which poses problems in the detailed interpretation of the results. Nevertheless, we discuss key points and variety of processes along the Jedovnický stream which are important for changes in sediments parameters and their environmental functions along the stream:

1. The ponds near Jedovnice village: It currently captures most of the allochthonous sediments from the upper part of the catchment, especially the coarse fraction. Below the ponds, a hungry water effect (Kondolf, 1997) forms bedrock channel in certain places. The sediments are being eroded, which is reflected in the lower contents of the fine fraction prior to the ponor;
2. Sources of metallurgical slag prior to the ponor: Below the ponds near Jedovnice village, the stream erode the slag deposit covered by colluvial and anthropogenic sediments. The main source of slag, however, is the Hugon (Salm) iron smelter spoil heap with distinct steep slopes in the northern vicinity of the ponor. Its estimated volume is up to several thousand cubic meters of material, which is periodically eroded by a short tributary stream Ve Struskách (Figure 1). The slag material is transported easily into the cave system (Baldík et al., 2018);
3. Erosive high gradient rock channel in a cave: especially finer material is continuously evacuated from it and moved to sections with stagnant water. These sections are typical with the reduction in the fine fraction content within the samples (samples RP5 and RP7). In places, there are potholes developed, representing traps with selective accumulation effects on transported material (Burkhardt et al., 1975);
4. Accumulation sections in the cave with slow or stagnant flow: especially in the Velikonoční Cave and Proplavaná skála section of the Býčí skála cave, the paragenetic character of corridors (Farrant & Smart, 2011) supports accumulation of both coarse and finer fractions in wide but vertically narrowed cross-profile, as documented previously by Burkhardt et al. (1975) and Hypr (1975). Hypr (1975) found that clasts are imbricated in that vadose tunnels with open channel. There, the stream acts as superficial one to a certain extent (compare with Kadlec, 1996).
5. Sumps: they represent obstructions in the longitudinal channel profile, areas of hydraulic overpressure. These are the only sections where the stream is capable to transport sediments "uphill" - the Srbský sump by almost 2 m in height with an channel bed inclination of about 20° (Havlík & Mikeš, 2016) or the Škaredý sump by about 3 m (Měkota & Měkotová, 1993). At the same time, there is pressure flow through them, sometimes even long distance: 195 m long sump between the Májové and Barová caves, 175 m long sump between the Barová Cave and the resurgence (Měkota & Měkotová, 1993). In front of the sumps, especially during higher water levels, deposition of even finer clasts is typical (RP8, BS21, BS27) (Burkhardt et al., 1975, 1977), whereas beyond the sumps there are erosional sections from where the finer fractions are evacuated (RP9, BS22/BS23, P28).
6. Damming the stream: Burkhardt (1953) notes the collapse in the Velká síň dome in the Býčí skála cave, which partially dammed the stream and formed the Dřiny sump. Burkhardt et al. (1975) describe a dam formed by rockfall in Balvanitý dome and its effect in the form of increased slag accumulation upstream of this barrier – up to 5 m above the present channel elevation. The same authors describe the prevailing accumulation in front of the dam formed by the remains of wooden ladders, while the erosion beyond this dam.
7. Blocking sediment transport by cementation: Burkhardt (1959) describes a phenomenon from the Hugon‘s dome, where chemical transformations in the stream water (iron changes from the soluble phase into the (oxy)hydroxides) cement the recent sediments, preventing them from transport. Burkhardt

et al. (1975) describe the overlying of clastic Carboniferous sediments by sinter crusts in the Stará Řeka passage and Hypr (1975) describes a similar phenomenon documented in a chimney 1.5 m above a recent stream. Cementation results in less sediment mobility and greater resistance to erosion.

8. Secondary sources of material within the cave system: the fluvial system of the stream inside the cave is semi-closed. Most of the transported material is of allochthonous origin, yet there are secondary sources of material in the cave that then participate in channel load. There are tributaries of the main stream (Tipeček, Stará řeka passage, Žegrovský waterfall), which may bring pieces of limestone, sand or sewage waste, i.e. partly also allochthonous material (Burkhardt et al., 1975, 1977; Káňa et al., 2013; Skoupý et al., 2012; Šebela, 2011). Kadlec (1996) described the contribution of less rounded pebbles from the short tributaries into the main subterranean stream. Furthermore, infiltration sediments, which penetrate into the cave through abysses and chimneys, enrich the sediment composition with sand from the Rudice Layers, hornfels, quartzites or calcareous nodules (Burkhardt, 1959; Gregor et al., 2014; Káňa et al., 2013; Skoupý et al., 2012).

   Among the most rapid but even long-lasting changes in sediment supply are rockfalls, especially in larger domes or sections strongly disrupted by rock discontinuities. The Balvanitý dome is the source of the coarse fraction following the 1959 collapse of several hundred tons of rock from the ceiling (Nejezchleb, 1959). Havlík and Mikes (2016) documented 7 collapsed rock blocks, the largest of which has a longest axis of about 7 m, in the Srbský sump. Similarly to rockfalls, sandy sediments may be transported into the cave via gravitational slides through abysses (BS27). Káňa et al. (2013) describe slides of sediments in 2008 and 2011 in the Druhá Abyss in the Barová Cave. Another prominent source of mainly angular clasts of autochthonous limestone is the tailings from adits excavated in the past to cross the sumps (Piškula, 1986).

4.2 SUBTERRANEAN FLOOD AS KEY MORPHODYNAMIC FACTOR

During the subterranean flood, the fossilised sediment temporalily deposited in higher cave levels may be mobilised again. Sobol (1949) described gravels from the Barová cave in a passage 20 m above the recent channel level. Burkhardt et al. (1973) describe the same sediments up to 22 m high. Recently, sediments reach the elevated parts of the caves during floods, or are deposited in the form of thick layers near the recent stream channel in blind cavities. Havlík and Mikeš (2016) describe up to 2.6 m thick accumulations in the cavity within the Srbský sump (part called Knihovna), but also fragments of brick and Carboniferous slates (up to 25 cm in long axis; Burkhardt et al., 1975) in chimneys up to 8.5 m above the stream level in the same location. Hypr (1975) describes a flood line 6 m above the recent channel in the S komíny dome in the Velikonoční cave. Gregor et al. (2014) infer the flood level in the chimneys from lines on the walls of the Velikonoční cave 4–9 m above the normal water level. Brick fragments and waste also reach that elevation. Thus, at times of increased discharge, clasts are transported through the cave system in a rather "aggressive" way, which affects especially its roundness. In the turbulent flow, clasts grind not only against each other but also against the cave floor, walls and ceiling (Kadlec, 1997).

Gregor et al. (2014) found that in low gradient stream sections the flow velocities are as low as 0.01–0.05 m/s, while within riffles it is commonly 0.5 m/s. The discharge can be very low in dry years. Burkhardt (1953) measured only 0.014 m^3/s within the resurgence during the great drought of 1902. Thus, the main factor for the mobilisation of transported sediments seems to be rather the confinement of the channel and its pressurized flow during floods (Cao et al., 2021; González-Lemos et al., 2015). In the wide, but vertically narrowed channel profile of the paragenetic passages within the Velikonoční cave, Gregor et al. (2014) estimated discharge from the dimensions of the ceiling and wall facets up to 12 m^3/s, which is 2.8 times more than the long-term average discharge on the Svitava river at the station Bílovice nad Svitavou (ca. 13 km beyond the resurgence) and approximately 1/15 of the value of the N100 water level at the same station (Povodí Moravy, 2019).

During flood events, a series of temporary sumps with submerged tubes are formed in the caves, in front of which extensive inundations are formed, reaching up to 4.5 m above the normal level with a discharge up to 8 m^3/s (Grolich, 1975) or 10 m^3/s (Hypr, 1975). A lake 50 m long and 3 m deep is formed prior to ponor (Burkhardt et al., 1975). Burkhardt and Kocman (1950) observed 20 m high water level rise in the Hugon's dome during the 1927 flood. In the Býčí skála cave, the water level rose 6 m higher during the 1972 flood (Burkhardt et al., 1973). Burkhardt et al. (1975) suggested that 10 sumps form during floods in the Rudické propadání cave, where the longest of them within the Velikonoční cave reach 300 m. Because of this character, Hypr (1975) describes an abnormal amount of fluvial sediments from that part compared to other sections of the cave system. There are many more such sumps in the Býčí skála cave.

4.3 SLAG PENETRATES EASILY

As can be seen in Figure 4, the slag content is highest beyond the high gradient channel sections of the Rudické propadání cave. Already in sample RP9, i.e. before the tributary of the Stará řeka passage, the highest slag content was detected in the two coarsest fractions of all the samples taken (up to 60%). For > 10 mm fraction, the slag content then gradually decreases until the resurgence; for the 5–10 mm fraction, the high slag content is maintained until sample RP13 (45%), i.e. to the Balvanitý dome (1959 collapse; Nejezchleb, 1959), then decreases to about 10% and such content is than maintained until the resurgence. It is clear from the above that slag is relatively quickly and easily transported from the surface through the high gradient channel cave sections and then accumulates in the predominantly accumulation section Stará řeka passage – Balvanitý dome. With the exception of the Proplavaná skála section, the amount of slag is then nowhere noticeable.

The ease with which light slag can penetrate sumps was reported by Burkhardt et al. (1973), when they describe how its clasts, together with sand, quickly came out of the sump against divers. For example, the RP9 sample is about 60% slag, which is lighter than the other clasts and enters more easily through the Druhý sump, where it accumulates in the low gradient channel section.

The results of the correlation between slag content and RA index values show that the roundness of the Carboniferous clastic material is almost constant during the studied stream (compare Kadlec, 1996), and the decisive differentiating factor seems to be the presence of ductile slag, whose presence significantly increases the proportion of roundness clasts in the deposit.

Burkhardt (1949) notes that the former stream, which flew through the Luční valley, which remained preserved 20 m above the recent stream (Figure 1), by diverting waters into the cave system, changed into a stream in unbalanced condition. This means that hydromorphological aspect will continue to evolve rapidly in the future.

5. CONCLUSIONS

Clastic fluvial sediments of the Jedovnice stream were investigated in the section Jedovnice village – Křtinský stream. We collected 28 samples, which were examined for composition, metallurgical slag content, grain size and roundness. Allochthonous Carboniferous clastic sediments with metallurgical slag admixture are supplemented with autochthonous material (rockfall accumulations, tailings after adit mining), whereby the slag content fluctuates with a maximum following the erosional high gradient channel sections of the Rudické propadání cave at the connection with the Stará řeka passage tributary. The proportions of grain size fractions within individual samples are strongly influenced by stream channel morphology, expressed mainly by the alternation of erosion and accumulation channel sections. Moreover, the specific conditions of karst relief and speleorelief affect the ability of clasts to pass through the system of vadose and paragenetic sections, sumps or domes affected by rockfalls. Subterranean floods play a crucial role. In particular, the accumulation of finer fractions in front of sumps or jams is evident. The content of fractions > 10 mm and 5–10 mm in the samples slowly decrease, while the content of finer fractions slowly increase towards the resurgence. The roundness of the allochthonous Carboniferous clasts remains constant, but the content of well rounded and rounded clasts increases significantly due to the ductile metallurgical slag content within the channel infill. Along the investigated cave section, the amount of slag in the > 10 mm and 5–10 mm fractions gradually decreases towards the resurgence, as does the content of angular clasts in the same fractions.

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