

CAVE SEDIMENTS FROM THE POSTOJNSKA–PLANINSKA CAVE SYSTEM (SLOVENIA): EVIDENCE OF MULTI-PHASE EVOLUTION IN EPIPHREATIC ZONE

JAMSKI SEDIMENTI IZ POSTOJNSKO–PLANINSKEGA JAMSKEGA SISTEMA (SLOVENIJA): PRIČA VEČFAZNEGA RAZVOJA V EPIFREATIČNI CONI

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Abstract

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Nadja Zupan Hajna & Petr Pruner & Andrej Mihevc & Petr Schnabl & Pavel Bosák: Cave sediments from Postojnska–Planinska cave system (Slovenija): Evidence of multi-phase evolution in epiphreatic zone

The Postojnska jama–Planinska jama cave system and number of smaller adjacent caves are developed in the Postojnski kras. These caves are located between two dextral strike-slip fault zones oriented in the Dinaric direction. The caves contain lithologically diversified cave fill, ranging from speleothems to allogenic fluvial sediments. The allogenic clastic material is derived from a single source, Eocene siliciclastics of the Pivka Basin. Small differences in mineral/petrologic composition between the sediments can be attributed to different degrees of weathering in the catchment area and homogenization of source sediments. Thick sequences of fine-grained laminated sediments, deposited from suspension are common. The depositional environment was mostly calm, but not completely stagnant. Such a sedimentary environment can be described as cave lacustrine, with deposition from pulsed flow. The homogeneity of the palaeomagnetic data suggests rapid deposition by a number of short-lived single-flood events over a few thousand years. This depositional style was favourable for recording of short-lived excursions in the palaeomagnetic field. The sediments were originally not expected to be older than Middle Quaternary in age (i.e. about 0.4 Ma). Later numerical dating (Th/U and ESR) indicated ages older than 0.53 ka. New palaeomagnetic data from selected sedimentary profiles within the cave system detected normal polarization in much of the profiles studied. Reverse polarized magnetozones, interpreted mostly as short-lived excursions of magnetic field, were detected in only a few places. Therefore, we interpreted most of the sediments as being younger than 0.78 Ma, belonging to different depositional phases within the Brunhes chron. Palaeomagnetic properties

Izvleček

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Nadja Zupan Hajna & Petr Pruner & Andrej Mihevc & Petr Schnabl & Pavel Bosák: Jamski sedimenti iz postojnsko–planinskega jamskega sistema (Slovenija): priča večfaznega razvoja v epifreatični coni

Postojnsko-planinski jamski splet in številne manjše jame med jamama so razvite v Postojnskem krasu, ki leži med dvema desnozmničnima prelomnima conama v Dinarski smeri. Jame večinoma vsebujejo obsežne in litološko raznovrstne jamske zapolnitve, od sige do aligenih fluvialnih jamskih sedimentov. Alogeni klastični sedimenti izvirajo iz enega vira (eocenski siliciklasti iz Pivške kotline). Majhne razlike v mineralni/petrološki sestavi med sedimenti, lahko pripisujemo različni stopnji preperavanja v povodju in homogenizaciji izvornega sedimenta. Najpogostejši so drobnozrnati sedimenti, pogosto v debelih sekvencah. Sedimentirani so bili iz suspenzije. Sedimentacijsko okolje je bilo večinoma mirno vendar ne popolnoma stoječe. Taka sedimentacijska okolja lahko opišemo kot jamsko jezersko ali kot usedanje iz pulznih tokov. Homogenost palaeomagnetnih podatkov lahko nakazuje hitro sedimentacijo (nekaj tisoč let) med kratkotrajnimi poplavnimi dogodki. Tak način sedimentacije je dobro odrazil kratkotrajne ekskurzije magnetnega polja. Zapolnitve jam naj bi bile po prvotnih pričakovanjih starejše od srednega kvartarja (okrog 400 tisoč let). Kasnejša numerična datiranja (Th/U in ESR) nakazujejo starosti na več kot 530 tisoč let. Novi palaeomagnetni rezultati, pridobljeni iz izbranih sedimentnih profilov v jamskem sistemu, so odkrili normalno polarizacijo v večini preiskoavnih profilov. Reverzno usmerjene magnetocene, interpretirane večinoma kot kratkotrajne ekskurzije magnetnega polja, so bile zaznane samo na nekaterih mestih. Zato smo večino študiranih sedimentov interpretirali za mlajše od 780 tisoč let. Pripadajo različnim sedimentacijski fazam v Brunhes razdobju. Palaeomagnetne lastnosti v dveh profilih, v jamah presekanih

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of two profiles in caves intersected by the artificial tunnel between Postojnska jama and Črna jama had reverse polarized magnetozones and of sediments in Zguba jama, may indicate an age much greater than 0.78 Ma. The cave system has evolved over a long period of time, governed by the functioning of Planinsko polje in the relation to the evolution of the resurgence area in Ljubljana Moor further to the east. General stabilization of the hydrological system with low hydraulic head led to the evolution of caves in epiphreatic and paragenetic conditions over a long time-span. Individual cave segments or passages were completely filled and exhumed several times during the evolution of the cave. Alternation of depositional and erosional phases may be connected with changing conditions within the cave system, the functioning of the resurgence area, collapse, climatic change, tectonic movement and the intrinsic mechanisms of contact karst.

Key words: dating, palaeomagnetism, magnetostratigraphy, karst geomorphology, Classical Karst.

z umetnim tunelom med Postojnsko in Črno jama, z reverzno usmerjeno magnetoco, in sedimenti v Zgubi jami, so lahko precej starejši od 780 tisoč let. Jamski sistem kaže na dolgo trajen razvoj pogojen z delovanjem Planinskega polja in odnosom do razvoja izvirov na Ljublanskem barju proti vzhodu. Splošna stabilizacija hidrološkega sistema z majhnim gradientom je v zelo dolgem časovnem obdobju vodila do razvoja jam v epifreatičnih in paragenetskih pogojih. Posamezni deli jam ter njihovih rovov, so bili za časa njihovega razvoja lahko večkrat popolnoma zapolnjeni ali izpraznjeni. Izmenjava sedimentacijskih in erozijskih faz je bila lahko povezana z menjavo pogojev v jamskem sistemu, delovanjem izvirov, s podori, klimatskimi spremembami, tektonskimi premiki in mehanizmi, povezanimi s kontaktnim krasom.

Ključne besede: datacije, palaeomagnetizem, magnetostratigrafija, kraška geomorfologija, klasični kras.

INTRODUCTION

The Postojnska jama (Postojna Cave) – Planinska jama (Planina Cave) cave system is the largest cave system in the Notranjski kras (Karst of Notranjska; Fig. 1), where several other large cave systems also occur. Waters from the Pivška kotlina (Pivka Basin) are drained to Planinsko polje (Planina Polje) through the Postojnski kras (Karst of Postojna). The Postojnska jama – Planinska jama cave system is the main drainage route, with a length of about 27 km. Only 2,200 m of unexplored water-filled passages separate the two caves.

The cave system is developed in the Upper Cenomanian and Turonian to Senonian limestone sequence, which is about 800 m thick (Buser, Grad & Pleničar 1967). The limestone sequence is deformed into a complicated thrust structure (nappes). These formed after the termination of Eocene flysch deposition, as a consequence of post-collision processes between African and European Plates. The area is situated between two dextral strike-slip fault zones, the Idrija and Predjama faults (Placer 1996), oriented in the Dinaric direction (NW–SE). These faults resulted from reactivation in the latest tectonic phase by counter clockwise rotation of the Adria Microplate, which started before ca 6 Ma (Vrabec & Fodor 2006). Some tectonic blocks along the Idrija fault were drowned and levelled by corrosion at the karst water table into karst poljes. This fault zone is well expressed in the karst relief. Čar & Gospodarič (1984) distinguished different generations of fault zones accompanied by crushed, brecciated and fissured zones.

The cave system developed in the Postojnski kras geomorphological unit. The geomorphology of the area

was described by Gams (1965), Gospodarič (1979), Habič (1982), and Mulec *et al.* (2005). The Postojnski kras is situated between the two high karst plateaus, Hrušica and Javorniki, with surfaces above 800 m a.s.l. and by two lower relief units, the Pivška kotlina (511–590 m a.s.l.) on the west and Planinsko polje (446–453 m a.s.l.) on the northeast.

Karst depressions have directly influenced the evolution of both the surface and the caves. The Postojnski kras surface, with dolines as the dominant relief forms, has an elevation of about 600 m with only some parts above 700 m a.s.l. (Fig. 9). Karst relief shows strong tectonic control, with structure guiding the general position of collapse dolines both on the surface and in the caves (Habič 1982).

The lower part of Pivška kotlina (511–590 m a.s.l.) is developed on Eocene flysch rocks, while the upper part is partly developed on limestone. Basinal waters concentrate on the flysch and sink in system of blind valleys at its boundary with the limestone. Rivers in the basin eroded the rocky substratum and transported sediments into the caves. This resulted in the erosion of more than 100 m of flysch during basin evolution. The morphology of the contact karst at the ponors shows that ponor altitudes and hydraulic head within the Postojnski karst controlled the evolution of Pivška kotlina (Mihevc 1990). The recent evolution of Pivška kotlina is also influenced by the relative subsidence of the Vipava valley on the west, but its influence on erosion of Pivška kotlina has been negligible.

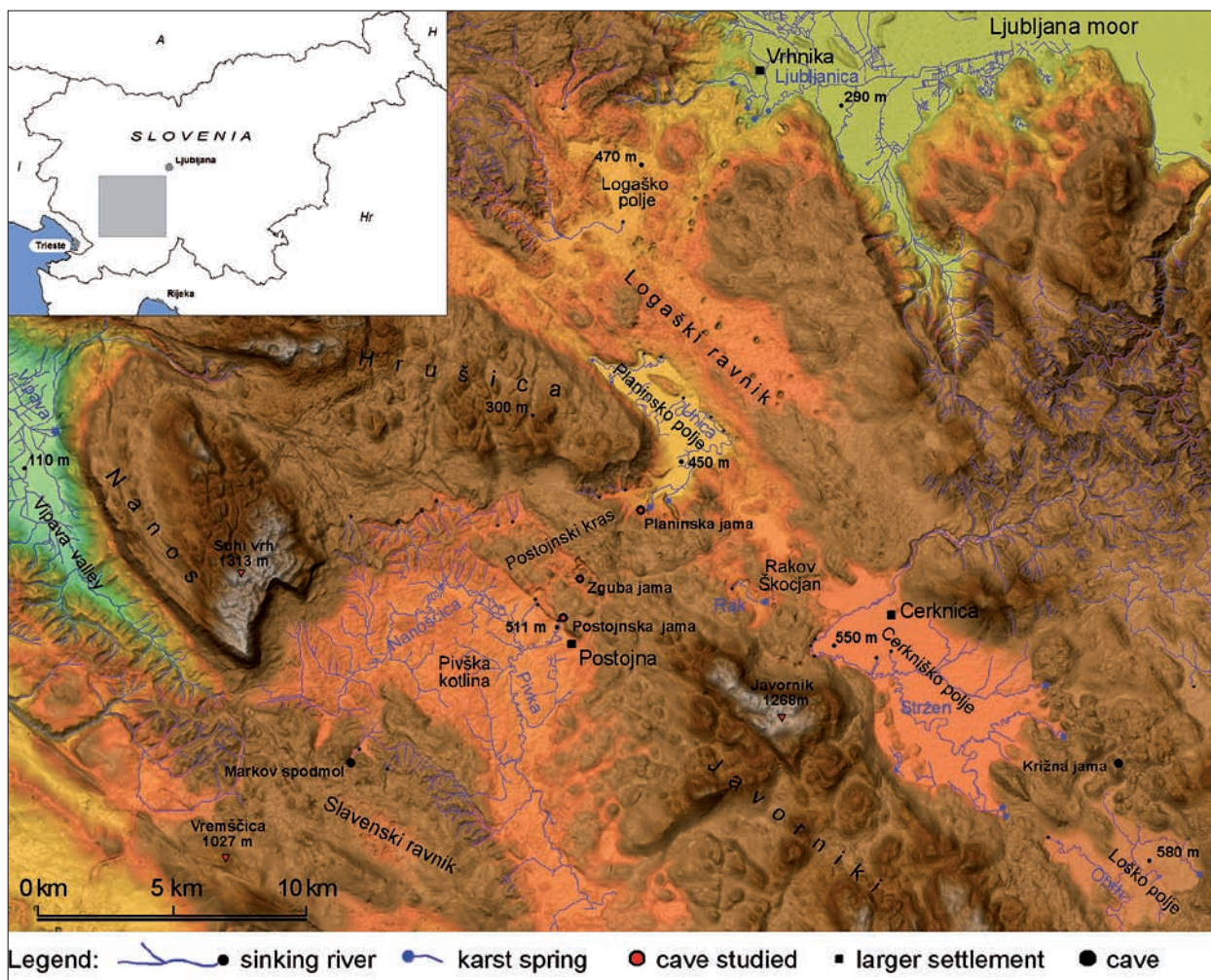


Fig. 1: Notranjski kras.

Planinsko polje, formed along the Idria fault zone, is about 6 km long and 2 km wide. Several springs of the Unica River are situated on the southern edge of the polje. The river crosses the polje and sinks on its northern side. The levelled polje floor resulted from regular flooding accompanied by lateral corrosion.

The caves in the Postojnski kras are rather shallow because their depth is limited by the elevations of Pivška kotlina and Planinsko polje. During the evolution of the caves Pivška kotlina was levelled and adjusted to the altitude of the ponors, where large blind valleys developed. Postojnska jama has presumably served as the main out-

flow from the Pivška kotlina for a very long time but only about 20 m of entrenchment has occurred. Distinct traces of paragenetic development can be found in numerous parts of the accessible cave.

Clastic sediments have an important role in deciphering geological history and processes in the caves (Sasowsky 2007). Cave fill, in respect to its composition, position and fossil remains, can offer number of useful information on evolution of surface geology, morphology, and cave itself, character and environment of deposition or precipitation, age, palaeoclimatic and palaeogeographic conditions during their sedimentation.

PREVIOUS WORK

The large caves have attracted researchers for many years (see Shaw 1992). Some focused on the study of sedi-

ments and fossils. Cave sediments in this large system were studied at first by archaeologists and palaeontolo-

gists (Rakovec 1954; Brodar 1966, 1969). Older sediments were systematically studied by Gospodarič (1972, 1976, 1977a, b, 1981, 1988), who suspected that the oldest sediments from Postojnska jama and other caves in the region (Otoška, Risovec, Križna, Planinska a.o.) were not older than Middle Quaternary (i.e. about 400 ka). He compiled a stratigraphy of the cave sediments, from the oldest to the youngest, as follows: (1) gravel with coloured chert, (2) older laminated loam (Middle Quaternary), which is missing in Postojnska jama (Gospodarič 1976, p. 100), (3) rubble and gravel with white chert (Riss), (4) speleothems and red loam (Riss–Würm), (5) younger laminated loam (lower Würm) and flysch sand/flood loam (upper Würm), (6) speleothems (post-Glacial), (7) breakdown rocks, flood loam and sand, (8) speleothems (Holocene). Although the old laminated loam cannot be developed in Postojnska jama, some sediments from the Otoška jama and Male jame were misinterpreted as belonging to this lithostratigraphic unit (Šebela & Sasowsky 1999). He concluded that the oldest sediments from the cave system were no older than Middle Quaternary (i.e. about 400 ka) and that cave sediment and speleothem deposition was related to Quaternary climatic oscillations (e.g., glacial cycles; Gospodarič 1988). Some of his studies (Gospodarič 1977a, b, 1981) indicate that he started to doubt his chronostratigraphy, especially when much greater age for speleothems was obtained by numerical dating (Gospodarič 1981). Unfortunately all his attempts at palaeomagnetic dating produced by no results.

A number of samples has been analysed by ^{14}C , Th/U and ESR methods in Postojnska jama (Franke & Geyh 1971, 1976; Gospodarič 1972, 1977b, 1981; Ikeya *et al.* 1983; Zupan 1991; Zupan Hajna 1996; Mihevc 2002, 2004, 2008). Samples dated by the radiocarbon method range from about 7.5 to 42.9 ka, mostly clustering at about 7.5–14.2, around 20 and over 37 ka (Gospodarič 1972, 1977b).

ESR ages are 125, 280 and 530 ka (Gospodarič 1981, p. 93) and 190 ka (Ikeya *et al.* 1983). Samples analysed by Th/U method are dated from 4 to more than 350 ka (see Mihevc 2008).

Two samples from Podorna dvorana (Collapsed Dome) in Pisani rov were dated by the Th/U method (Zupan 1991): two samples were older than 350 ka, and also dates of $269.4 \pm 130.3/-80$ and $76 \pm 24.9/-21.9$ ka were obtained from one sample. The base of a stalactite under a collapse block yielded an age of about 75 ka and the base of a stalagmite, which grew on the block, was established to be $19.9 \pm 25.2/-24.7$ ka old.

Radiocarbon data (Franke & Geyh, 1971; Gospodarič 1977, 1981) indicated the same ages for young stalagmite growth (13.5–7.6 ka). Some collapsed stalagmites are

overgrown by new speleothem 8.4–8.8 ka old, similarly to other sites in the system.

Mihevc (2002, 2004, 2008) recorded two periods of flowstone growth at Velika gora (Great Mount) and Čarobni vrt (Enchanting Garden). The oldest flowstone was dated at the foot of the collapse at the railway station, where flowstone was deposited (152 ± 40 ka) above collapse boulders. A flowstone dome at the top of Velika gora was dated to 70 ± 26 ka. The stalagmites were growing on clays (41 ± 3 ka, 43 ± 10 ka), on rubble (47 ± 7 ka) and on collapse boulders (37 ± 7 ka). The youngest phase of flowstone deposition is recorded in samples of grey crystalline flowstone and stalagmite (12 ± 5 ka and 6 ± 4 ka) covering all collapse blocks.

Franke & Geyh (1971) recorded stalagmite growth between ca 12.1 and 14.4 ka from Kongresna dvorana (Congress Hall). Radiocarbon dated collapse of big stalagmite in Čarobni vrt to about 10–11 ka. It is overgrown by stalagmites dated to about 7.5 ka (Franke & Geyh, 1971, 1976). Overgrowth on fallen older stalagmites dated to about 7.4–10.5 ka was recorded also from other sites (Gospodarič 1977b).

More recent research on sediments and speleothems (Zupan 1991 a.o.), and the evolution of karst morphology (Mihevc 1996, 2001, 2002, 2004, 2007) suggested, that the sediments are older than previously thought.

Zupan Hajna *et al.* (2008a) described in detail 36 sedimentary profiles in caves, unroofed caves and surface sediments studied in Slovenia since 1997. Sedimentary profiles in Postojnska, Zguba and Planinska jama were sampled and analyzed between 2003 and 2007 (Tab. 1; Figs. 2, 4 and 8).

The names of caves and geographic features in the text are given in the original Slovene form: *jama* means *cave*, *dolina* means *doline*, *kotlina* means *basin*, *kras* means *karst* and *spodmol* means *overhang*. English transcription of geographic names is used in accordance with the recommendations of the Slovene Commission on Geographic Names.

The following abbreviations are used in the text: AF = alternating field (demagnetization); CRM = chemical remnant magnetism/magnetization; D = declination; HFC = high-field component; I = inclination; IG AS CR = Institute of Geology of the Academy of Science of the Czech Republic, v.v.i.; IZRK = Karst Research Institute; JZS = Speleological Association of Slovenia; LFC = low-field component; MAVACS = Magnetic Vacuum Control System; MS = magnetic susceptibility; N = normal polarization/polarity; NRM = natural remnant magnetization; R = reverse polarization/polarity; RM = remnant magnetization; TD = thermal demagnetization; ZRC SAZU = Scientific Research Centre of the Slovenian Academy of Sciences and Arts.

METHODS

Due to the limitations of different numerical dating methods (see Bosák 2002), the palaeomagnetic method was used on carefully selected profiles of cave sediments. The mineralogy of the sediments was investigated using x-ray diffraction; while speleothem was dated using the Th/U disequilibrium method.

Palaeomagnetic analyses were completed in the Laboratory of Palaeomagnetism, IG AS CR in Praha-Průhonice. All specimens were oriented *in situ* prior to removal. Unconsolidated sediments were sampled in boxes (non-magnetic plastic, size = 20 x 20 x 20 mm, approximate volume 6.7 cm³; Natsuhara Giken Co., Ltd., Japan). Samples from consolidated rocks and speleothems were collected from the profile in large pieces, which were cut in the laboratory into cubes 20 x 20 x 20 mm. Samples were demagnetized by AF (all samples) and or/TD (consolidated samples). Palaeomagnetic procedures were selected to allow the separation of the respective components of the RM and the determination of their origin. Schonstedt GSD-1 or LDA-3 apparatus was employed for the AF demagnetization and MAVACS (Přihoda *et al.* 1989) for the TD demagnetization. The RM was measured on JR-5 or JR-6A spinner magnetometers (Jelínek 1966). AF demagnetization was carried out up to a field of 100 mT in 12–16 steps. The NRM of specimens is identified by the symbol J_n , the corresponding RM moment by the symbol M. The MS values were measured on KLY-2 (or KLY-3) kappa-bridges and a KLF-4A Automatic Magnetic Susceptibility Meter (Jelínek 1966, 1973).

The multi-component analysis technique of Kirschvink (1980) was applied to separate the respective RM components. Fisher statistics (1953) were employed for the calculation of mean directions of the CRM components derived by the multi-component analysis.

Results of palaeomagnetic analyses, including values and mean values of the MS, NRM, I, D, discussion of primary data, palaeomagnetic profiles were summarized by Zupan Hajna *et al.* (2008a, b). Data in this article represent summary comments, only.

X-ray powder diffraction analyses were performed (1) in the Laboratory of Physical Methods, IG AS CR in Praha (analysts Dr. Karel Melka, Dr. Roman Skála, Mr. Jiří Dobrovolný), and (2) at the Geological Institute of Faculty of Natural Sciences and Engineering in Ljubljana (analyst Dr. Meta Dobnikar). In the Czech laboratory all powder patterns were collected with a Philips X'Pert APD diffractometer (Cu and Co radiation, graphite monochromator, 40 kV, 32 or 40 mA). For each specimen four individual sets of patterns were acquired for: randomly-oriented material, oriented specimens, glycolated specimens, and samples heated to 400 °C under ambient atmosphere. The qualitative mineral composition of samples in Ljubljana was determined by X-ray powder diffraction with a Philips diffractometer (anode CuK_α, 40 kV, 30 mA and Ni filter). The concentrations of minerals were determined from the height of the main reflection of each particular mineral in the X-ray record.

Th/U (U-Series) analyses were performed (1) in Geochronology Laboratory, Institute of Geological Sciences, Polish Academy of Sciences in Warsaw (analysts Prof. Dr. Helena Hercman, Dr. Tomasz Nowicki), and (2) in the Uranium Series Laboratory, Department of Geology, University of Bergen (Head Prof. Dr. Stein Erik Lauritzen; analysts Dr. Andrej Mihevc). Standard chemical procedures for uranium and thorium separation from carbonate samples were used (Ivanovich & Harmon 1992). In Warsaw activity was measured by α -spectrometry, using an ORTEC OCTETE PC. Spectral analyses and age calculations were made with URANOTHOR 2.5 software, which is the standard software in the Geochronology Laboratory in Warsaw (Gorka & Hercman 2002). The quoted errors are one standard deviation. Measurements in Bergen also used α -spectrometry, but the data were processed using the Age4U2U program (Lauritzen 1993).

POSTOJNSKA JAMA

Postojnska jama (Reg. No. 747; 45°46'57.79"N; 14°12'13.18"E; 511 m a.s.l.; Fig. 2) is developed in the Postojnski kras (Fig. 1). Its entrance is situated near the contact of Eocene flysch with Upper Cretaceous limestone (Buser, Grad & Pleničar 1967). The limestones are folded into the NW-SE trending Postojna Anticline

(Gospodarič 1976). Cave passages have a general N-S trend, oblique to the anticlinal axis.

The Pivka River formed the cave. Its modern ponor has an elevation of 511 m a.s.l., while the terminal sump in Pivka jama has an elevation of 477 m a.s.l. Currently explored passages occur at two main levels with a total

length of 20.5 km. The upper cave level ranges in altitude between 529 m a.s.l. at the main entrance and 520 m a.s.l. in Črna jama. This level, mostly formed by epiphreatic speleogenesis, is composed of large passages, generally up to 10 m high and wide with rounded profiles and traces of paragensis. All studied sediment profiles were situated in this level between 533 and 520 m a.s.l. (Tab. 1). The lower level, where the modern underground Pivka river flows, is about 18 m below the upper one. The riverbed has a low gradient. The active river passages are smaller than the higher ones. The water level can rise substantially, by more than 10 m during floods.

The cave contains remnants of several kinds of alluvial deposits characteristic of internal cave facies cov-

ered by and/or intercalated with speleothems. Entrance facies deposits consisting of slope-derived debris mixed with the fluvial deposits are found in Biospeleološka postaja (Biospeleological station). Samples from a total of eight profiles (Fig. 2; Tab. 1) were collected in Postojnska jama.

SPODNJI TARTARUS

Spodnji Tartarus (Lower Tartarus) passage connects the upper cave level to the lower active level. The floor of the passage is covered with grey fluvial lutites and occasionally floods. There is a small higher-level side passage, Rov koalicije (Coalition Passage), in the southern part of Spodnji

Tartarus. It is a canyon-like passage about 50 m long, 2 m wide and up to 17 m high. Inclined and undulating notches on the walls show that it evolved in phreatic and paragenetic conditions. This passage is almost filled with sediments, leaving only a 2 m high space below the flat paragenetic ceiling (Pl. I/A, B). The sediments were later partly washed out, leaving a 13 m long pile of sediments in the central part of the passage, terminated on the northern and southern ends by two vertical profiles (Fig. 3): the Spodnji Tartarus North profile (at the entrance to Rov koalicije; Pl. I/A) and Spodnji Tartarus South profile (Pl. I/B).

LITHOLOGY

Both profiles in Spodnji Tartarus are composed of two units differing in colour. The lower unit is rather red while the upper unit is rather yellow. A sharp erosional boundary with a distinct colour change occurs in the

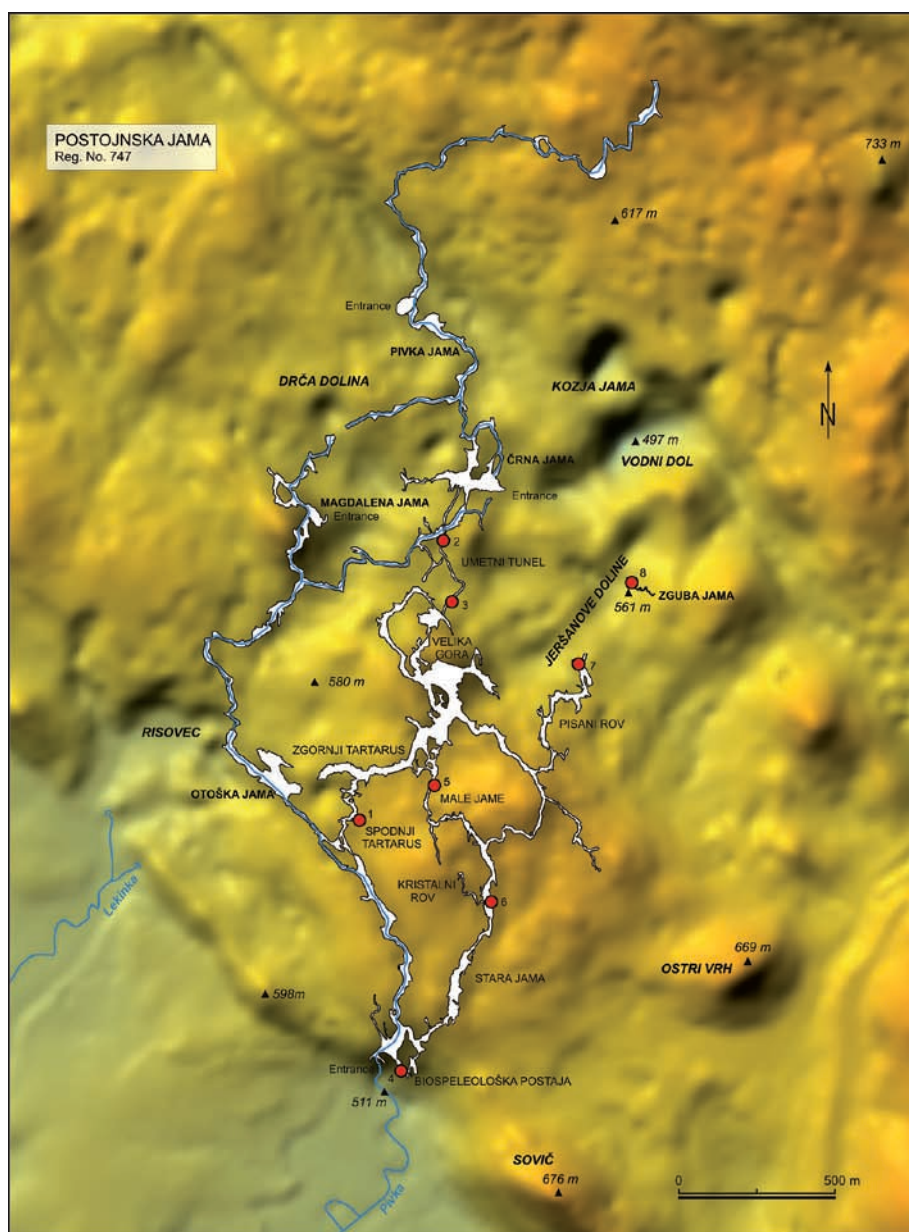


Fig. 2: Location of the profiles in Postojnska jama and Zguba jama (after Cave Register of IZRK ZRC SAZU and JZS).

Tab. 1: Coordinates of the bases and altitudes of the bases and tops of studied profiles.

Profile	Co-ordinates		Altitude [m a.s.l.]	
	N	E	base	top
Spodnji Tartarus North	45°47'23.16"	14°12'09.72"	526	533
Spodnji Tartarus South	45°47'22.58"	14°12'10.19"	522	533
Umetni tunel I	45°47'51.20"	14°12'21.22"	520	521
Umetni tunel II	45°47'47.82"	14°12'24.79"	521	522
Biospeleološka postaja	45°46'56.97"	14°12'16.80"	530	531
Male jame	45°47'28.49"	14°12'20.89"	520	521
Stara jama	45°47'15.26"	14°12'28.81"	528	530
Pisani rov	45°47'39.90"	14°12'41.66"	529	531
Zguba jama	45°47'47.10"	14°12'52.26"	563	564
Rudolfov rov (PL)*	45°48'50.49"	14°14'42.27"	468	470

* PL = Planinska jama, all other profiles are located within the Postojnska jama.

northern profile while the colour change in the southern profile is not distinct. The lower part (Fig. 3; Pl. I/A, B) consists of red to reddish brown clays overlying collapsed limestone blocks with weathered surfaces. The clays are silty, commonly laminated, and with sandy admixture. Small erosional features at layer boundaries are common and locally associated with slight ferruginization. Small clasts of corroded limestone occur close to the top of the northern profile. The upper part of the profile (Pl. I/A, B) is composed of yellow, yellowish brown and light brown

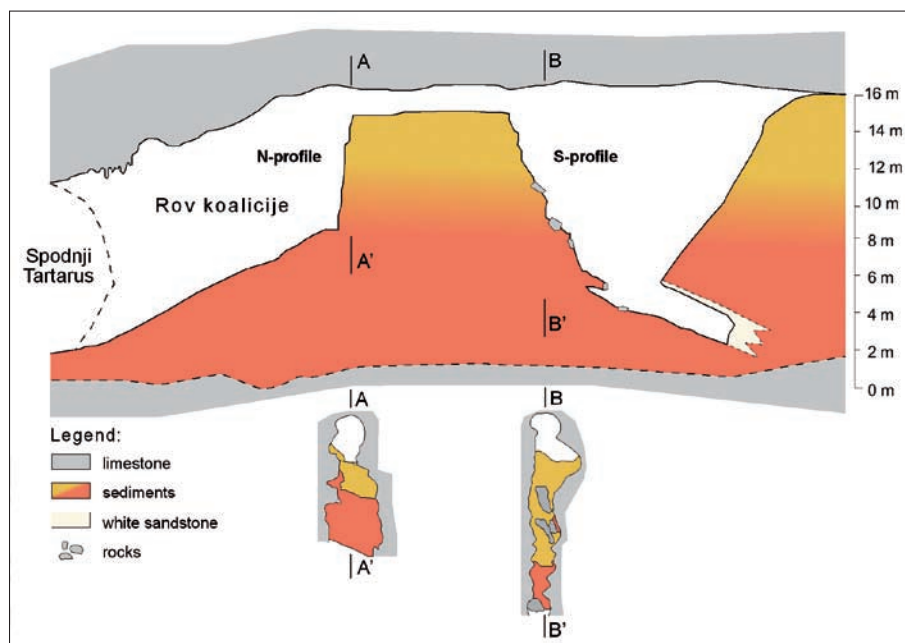


Fig. 3: Cross-section of the Rov koalicije passage showing the location of the Spodnji Tartarus North (A-A'), Spodnji Tartarus South (B-B') profiles and white sandstone (modified from Zupan Hajna et al. 2008a).

laminated and banded clays. Some laminae and bands are reddish brown. Mineral composition is summarized in Table 2. Thin calcite crusts, sometimes with candlestick stalagmites, cover the southern profile. Numerous scratch marks made by the cave bear (*Ursus spelaeus*), were discovered at the top of the sediments and on the passage walls.

NUMERICAL DATING

A small stalagmite on an inclined surface below the profile (sample No. 3) was taken radiometric dating from the Spodnji Tartarus North profile (Tab. 3). Four samples of speleothems were taken from the southern profile: No. 1, a stalagmite about 25 cm high with thin calcite crust at the base (with base at about 344 cm above the base of profile); No. 2, a small stalagmite on a rotated, collapsed limestone block (Pl. I/C), Nos. 4 and 5, thin calcite crusts covering the profile. Unfortunately, except for two analyses, the samples contained too high a proportion of detrital contamination

The new Th/U data placed the erosion of the profile in Spodnji Tartarus before 169 ka and the collapse took place after the erosion, during the Eemian (around 108 ka). Most probably, collapse occurred after the part of sedimentary profile was eroded away. Distinct and perfectly preserved scratches of *Ursus spelaeus* on the profile (top and incline) indicates that there have been no substantial changes to the morphology of the profile since the cave bear was climbing it.

PALAEOMAGNETIC ANALYSIS

The upper part (3.85 to 4.84 m) of the red profile has no defined polarity because it

Tab. 2: Mineralogical composition of selected cave sediments (mostly after Zupan Hajna 1998).

Mineral/site	Spodnji Tartarus			Umetni tunel I	Umetni tunel II	Rudolfov rov
	Red clay	Yellow clay	Brown clay			
Quartz	D	D	+	D	D	D
Chlorite	+	+	+	+	Tr	+
Kaolinite	+	+	Tr		Tr	
Muscovite	+	+	+	+	+	+
Montmorillonite		+	Tr			
Feldspars	+	+	+		+	
Microcline				+		+
Plagioclase				+		+
Calcite		+			+	+
Goethite					Tr	+

Note: D = dominant; Tr = traces.

Tab. 3: Th/U dating results using α -spectrometry, Spodnji Tartarus.

Sample	Lab. No.	U content [ppm]	$^{234}\text{U}/^{238}\text{U}$	$^{230}\text{Th}/^{234}\text{U}$	$^{230}\text{Th}/^{232}\text{Th}$	Age [ka]
Tartarus 3/2	W 1624	0.0638±0.0040	1.0419±0.0886	0.1611±0.0259	2.8±0.8	-
Tartarus 3/1	W 1637	0.0862±0.0044	1.0339±0.0691	0.0943±0.0157	12±8	-
Tartarus 5	W 1639	0.0249±0.0020	0.9732±0.1045	0.4016±0.0587	1±0.2	-
Tartarus 4	W 1638	0.0489±0.0032	1.0552±0.0934	0.7397±0.0701	>1,000	+26 +143 -22
Tartarus 2/2	W 1623	0.2988±0.0094	1.2166±0.0461	0.9452±0.0345	2,9±0.2	-
Tartarus 2/1	W 1636	0.0486±0.0031	0.9054±0.0825	0.6219±0.0664	25±12	+19 108 -17
Tartarus 1/2	W 1625	0.0523±0.0030	0.8276±0.0670	0.4304±0.0472	3.4±0.7	-
Tartarus 1/1	W 1635	0.0367±0.0028	0.7570±0.0838	0.5312±0.0764	4.5±1.2	-

contains coarse magnetic grains. The petromagnetic results from the upper part (4.5 to 7.8 m) of the yellow profile (Spodnji Tartarus North), show changed RM and MS values when compared with both values of lower part of the profile. Detailed comparison based on palaeomagnetic inclination and the NRM and MS shows the possibility of correlating the following segments: (a) North red 2.55–4.83 m with South 2.45–4.73 m and (b) North yellow 3.05–4.80 m with South 7.66–9.40 m. The correlated segments have identical depositional rates. The basal parts of the North and South profiles cannot be correlated at all.

Palaeomagnetic results from the Spodnji Tartarus North – yellow profile show two short R polarized excursions in the middle of the section. Palaeomagnetic results from the rest of the red profile show only N polarization. Palaeomagnetic results from the Spodnji Tartarus South

profile show a short R polarized excursion in the middle part of the section. It cannot be excluded, that the R excursion in profile North yellow (4.85–4.95 m) probably correlates with the R excursion in the South profile (9.45–9.55 m). Thus we may assume that deposition of the entire northern profile occurred within the Brunhes chron (<0.78 Ma), but we cannot be certain without comparative data (e.g. with fossils).

Principal palaeomagnetic parameters and their characteristics for all profiles are presented in Table 4.

UMETNI TUNEL I

The Umetni Tunel I profile samples a passage filled with fluvial sediments, intersected by the artificial tunnel (Umetni tunel) between Postojnska Jama and Črna jama.

Tab. 4: Review and characteristics of principal magnetic values.

Profile/parameter	Interval [m]*	J_n [mA.m ⁻¹]	$k_n \times 10^{-6}$ [SI]	Character of J_n and k_n magnetic values	Scatter J_n and k_n	n*
Spodnji Tartarus North, red	4.835–0.03	7–398	228–3,180	Low – high	Great	101
Spodnji Tartarus North, yellow	7.445–3.05	1–63	89–551	Low – high	Great	88
Spodnji Tartarus South	9.41–0.02	0.6–211	80–2,610	Very low – high	Extreme	176
Umetni tunel I	0.02–0.42	0.6–15	123–734	Very low – intermediate	Great	59
Umetni tunel II	0.54–0.04	0.2–1	50–112	Very low	Minor	14
Biospeleološka postaja	0.31–1.04	97–158	1,960–2,720	Intermediate – high	Minor	15
Male jame	0.95–0.03	0.8–14	96–309	Very low – intermediate	Great	33
Stara jama	1.35–0.01	2.7–10.6	225–561	Low – intermediate	Minor	26
Pisani rov	1.92–1.19	6.8–45	27–785	Low – intermediate	Moderate	66
Zguba jama, profile I	1.04–0.01	2–35	114–1,119	Low – intermediate	Moderate	37
Zguba jama, profile II	0.21–0.03	1–54	114–269	Low – intermediate	Great	8
Rudolfov rov	0.02–2.23	0.68–4.94	82–233	Low – very low	Moderate	85

Note: All listed samples are demagnetized

It is located approximately half way along the tunnel (Fig. 2; Tab. 1; Pl. I/D). The filled passage is cut by the NE–SW-trending cross-Dinaric fault. Both Gospodarič (1964) and Sasowsky *et al.* (2003) concluded that the fault was active after the sediments were deposited.

Lithology

The Umetni tunel I profile is 130 cm high, terminated by the limestone ceiling and the excavated floor of the tunnel. The lower half of the profile is composed of alternating medium to coarse-grained, slightly arcose and cross-bedded sands. The upper half (Pl. I/D) consists of alternating laminated brown to grey clays and medium-grained, slightly arcose sands. A thin ferruginized horizon (ferricrete) is developed here, accompanied by weathering of the clay surface. Mineral composition is summarized in Table 2. The sediments are disturbed by slickensides and the middle clay layer is anticlinally banded.

Palaeomagnetic analysis

Šebela & Sasowsky (1999) and Sasowsky *et al.* (2003) studied this profile previously, but their sampling was widely spaced and their results showed distinct scatter. They interpreted the age of profile as being between 0.99 and 0.78 Ma (top of the Matuyama chron) and also calculated palaeo-rotations, but the distribution of directions from so few samples cannot be used for Fisher statistics (Fisher, 1953).

Our high-resolution magnetostratigraphy of the fine-grained deposits indicated a N polarized zone within the R polarized. Neither Šebela & Sasowsky (1999)

nor Sasowsky *et al.* (2003) detected this N polarized magnetozone, due to their smaller number of samples. The presence of the N polarized magnetozone may shift the age of sediments in this profile beyond the expected limit of 0.99 Ma. The N polarized zone could represent the Jaramillo subchron (0.99–1.07 Ma) as well as other N polarized subchrons within the Matuyama (e.g., Olduvai: 1.77–1.95 Ma, Reunion: 2.14–2.15 Ma) or older chrons (Pruner *et al.* 2004). The sediments in the Umetni Tunel I profile are the oldest so far discovered in the Postojnska jama-Planinska jama system.

UMETNI TUNEL II

This profile is located near the entrance to the tunnel from Postojnska jama (Fig. 2; Tab. 1).

Lithology

The section is composed of yellowish brown clays, laminated to banded with sandy admixture, with yellowish brown fine- to medium-grained sands at the base. Cross bedding can be observed in the middle part of the section. The upper part consists of homogeneous light yellowish brown coloured silty clays, laminated at the top and with an indistinct erosional base. Mineral composition is summarized in Table 2.

Palaeomagnetic analysis

Only two components were isolated after AF demagnetization. The characteristic component is not stable and cannot be isolated in AF. The samples are not suitable for palaeomagnetic investigation.

BIOSPELEOLOŠKA POSTAJA

The profile in the Biospeleološka postaja (Fig. 2; Pl. I/E) is situated at the entrance to Rov novih podpisov (Passage of New Signatures). This passage is one of the former entrances to the cave.

Lithology

Two sediment profiles each approximately 7 m thick occur in the Biospeleološka postaja section of the cave. One is exposed in the (artificial) railway tunnel and the other is exposed along the tourist path.

The profile along the tourist path was investigated. It contains four types of sediment. The top layer consists of reddish loam covered with flowstone (Pl. I/E). The upper part of this layer is composed of limestone clasts. Brodar (1969) found Palaeolithic tools (Mousterian, about 40 ka old) here. Below them the profile consists of gravels composed of angular clasts of flowstone and limestone. The base of the exposed profile is composed of silts, sands and gravels with clastic components derived from flysch source rocks.

Palaeomagnetic analysis

We were aware that the sediments in this profile are very young but wanted to test the method in this kind of deposit. The profile showed only N polarized magnetization. We assume that deposition occurred within the Brunhes chron (<0.78 Ma), which is in accordance with archaeological finds.

MALE JAME

Male jame (Lesser Cave) is a smaller epiphreatic passage. It connects Stara jama passage to Zgornji Tartarus (Upper Tartarus) passage. The profile is located in the northern part of the passage (Fig. 2; Pl. II/A). Šebela & Sasowsky (1999) sampled this profile previously.

Lithology

The top 60 cm of the profile consists of greenish grey, clayey-silty-sandy gravels with fine-grained laminae and bands. They are underlain by 120 cm of quite well lithified, brownish grey to reddish brown and red, fine to medium-grained, highly-micaceous sands with a clayey-silty matrix. These sands contain well-rounded pebbles of flysch sandstone, small clasts of decomposed white cherts and angular clasts coated by ferruginous crusts, with schlieren enriched in Mn compounds. The sandstone pebbles are strongly decomposed *in situ* and covered with Mn-enriched coatings. The lower part of the profile (90 cm) is composed of soft yellowish brown clays, with brown bands and

laminae in its upper part, while the lower part is homogeneous (Pl. II/A, B).

Palaeomagnetic analysis

All samples from this profile have N polarization suggesting, as far as can be determined, deposition within the Brunhes chron (<0.78 Ma). Šebela & Sasowsky (1999) reached the same conclusion. Nevertheless, the *in situ* weathering of the flysch-derived sandstone pebbles and strong lithification could indicate a substantial age for these deposits.

According to the stratigraphy of Gospodarič (1976, p. 100), the soft and slightly lithified clays should be the youngest sediment in the passage (<0.78 Ma) overlying, deposited on or in a cavity within the already eroded sandy-gravelly unit with white cherts (see Osborne 1984). The sandy-gravelly unit could easily be much older (even >0.78 Ma).

STARA JAMA

Stara jama (Old Cave) is the main passage in the upper level of the cave. The passage slopes gently to the north. There are traces of paragenesis on the passage ceiling. Relicts of sedimentary fill are preserved in some parts of the passage where they have been protected by flowstone or collapse (Pl. II/C). The Stara jama profile is located at Križ (Old Cave at Cross) opposite to the entrance to Kristalni rov (Crystal Passage; Fig. 2).

Lithology

This profile is approximately 220 cm high. The lower half of the profile consists of grey clayey-sandy gravels with flat clasts to pebbles and some bands of fine-grained sand constitute. Laminated greyish light brown silty-sandy clays overlie the gravels. Fragments of bones (probably *Ursus spelaeus*; det. I. Horáček, 2007) were found in the right part of the outcrop. The clays are succeeded by greyish light brown, clayey, fine-grained sands with dark-coloured schlieren/laminae and clay clasts in the upper part. These are overlain by yellowish to light brown and silty clays, micaceous, indistinctly laminated, with sandy admixture increasing to the top, at the top up to unsorted sands with single flat pebbles. The top of the profile consists of light brown silty clays with flaky disintegration and small clasts of limestone near the top. The flowstone at the top is about 20 cm thick (Pl. II/C, D).

Palaeomagnetic analysis

Since only N polarization was detected, the palaeomagnetic results indicate the sediments are younger than 0.78 Ma. Pleistocene bear bones occurring on the top of the profile support this interpretation.

PISANI ROV

Pisani rov (Coloured Passage) deviates to the north from the main passage of Stara jama. It terminates below the slopes of the collapse doline of Velika Jeršanova where the bottom is filled by sediments. The profile is situated at the end of the Pisani rov (Fig. 2; Pl. II/E).

Lithology

This profile is roughly 145 cm thick and is composed of yellowish brown silts to clays with dark stains and schlieren, with an olive-green horizon in the lower third, finely laminated in the lower part. Cubic to columnar disintegration with Fe stains on the fractures occur at the top of the silts and clays. The profile is covered by two layers of flowstone with broken stalagmites (Pl. II/E, F).

Numerical dating

Gospodarič (1981, p. 93) dated a stalactite from Pisani rov using ESR. Red flowstone in the nucleus was older than 530 ka; the next two rings, separated by lamina of flood loam, were dated to about 280 ka and to about 125 ka, respectively. Another stalactite core was dated to 190 ka (Ikeya *et al.* 1983).

Palaeomagnetic analysis

The profile showed only N polarized magnetization. This suggests that deposition occurred within the Brunhes chron. Numerical dates from speleothems limit the time span of deposition to between >0.53 and <0.78 Ma.

ZGUBA JAMA

Zguba jama (Reg. No. 6290; 45°47'47.50"N; 14°12'49.57"E; 561 m a.s.l.; Fig. 2) is a small blind cave formed in Upper Cretaceous limestones (Buser, Grad & Pleničar 1967). The cave located at an elevation above Postojnska jama. Pisani rov, the closest part of Postojnska jama, ends 265 m horizontally and 34 m below Zguba jama (Fig. 2). The cave entrance opens in the eastern slope of Mala Jeršanova dolina.

Zguba jama is 122 m long and consists of a simple SW-NE-trending channel, no more than 2 m wide, 2 m high and 4 m deep. It was once completely filled with allogenic fluvial sediments (Pl. II/G). Šebela (1994) interpreted the cave as probably being a high level fossil phreatic channel.

Lithology

The Zguba jama profile is located inside the cave close to its end, where a small excavation on the NE side of the channel was sampled to a depth of about 121 cm. The upper part (Pl. II/G) consists of reddish brown silt to clay, bioturbated at the top (worms). The lower part

is very fine-grained sand, with flakes of muscovite and small irregular concretions. The boundary with the underlying layer is marked by a carbonate-cemented horizon about 3 cm thick. The lower 70 cm is multicoloured banded silty-clayey fine-grained sand with flakes of muscovite and some clay laminae near the base. The basal part (about 20 cm) contains desiccation cracks, filled in places by red silt to clay.

Palaeomagnetic analysis

Nearly all samples in the profile showed N polarity, except for some very short R or transient excursions (N-R) in upper profile (I). The upper and lower parts of the profile differ in principal palaeomagnetic parameters (Tab. 4). Although data could support quite young ages, D and I parameters indicate that the N polarization could belong to an older chron/subchron than Brunhes and that the sediments could be substantially older than 0.78 Ma. This is supported by the alteration due to a depositional hiatus in the lower part of the profile.

PLANINSKA JAMA

Planinska jama (Reg. No. 748; 45°49'11.62"N; 14°14'44.39"E; 453 m a.s.l.; Fig. 2) is situated on the southern edge of Planinsko polje, with its entrance at the end of a large pocket valley. The cave is developed in Up-

per Cretaceous limestones and dolomites (Buser, Grad & Pleničar 1967).

Planinska jama is a 6,656 m long outflow cave (Fig. 4) and is the main spring of the Unica River (Fig. 1). Passages in Planinska jama are large, about 15 m wide and

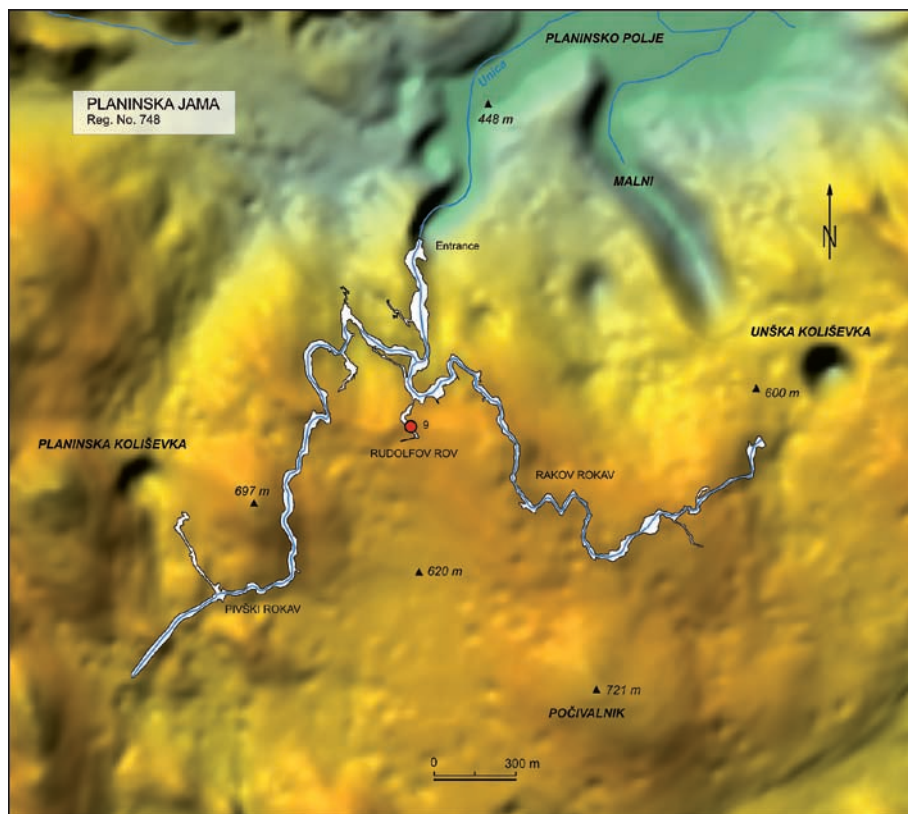


Fig. 4: Location of the Rudolfov rov profile; Planinska jama (after Cave Register of IZRK ZRC SAZU and JZS).

high. There are some collapse chambers. The confluence of the Pivka River, from Postojnska jama and the Rak River from Rakov Škocjan occurs in the cave. The two main passages of the cave were named after their tributaries: Pivški rokav (Pivka Branch) and Rakov rokav (Rak Branch). There are a few inactive small side passages at higher elevations, such as Rudolfov rov (Passage of Rudolf).

Rudolfov rov, a south-side passage of Rakov rokav, is approximately 200 m long and is located at an elevation of 460–475 m a.s.l., about 16 m higher than the main passage floor. A small stream flows out of Rudolfov rov. The water in this stream comes from the Javorniki Mountains and Cerkniško polje (Cerknica Polje) and fluvial sediments once completely filled the passage. The Planinska jama profile sampled the same sediments, old laminated loam, as Gospodarič (1976) and Šebela & Sasowsky (1999), but in a different location, at an elevation of about 460 m a.s.l. (Fig. 4; Pl. II/H).

Lithology

Gospodarič (1976) compiled a stratigraphic succession for sediments from Planinska jama. He considered that erosion of the sediments was contemporaneous with

the last phase of flowstone formation (post-glacial). He reported that Rudolfov rov was filled with the older laminated (varved) loam, resting on the erosional bed of the channel. Like all the oldest sediments in other caves of the region (Postojnska, Otoška, Risovec & Križna caves), Gospodarič dated the older laminated loam to about 350–400 ka (Gospodarič 1976, 1981, 1988). Flowstone on old laminated loam was dated by the Th/U method to 77.8 ka by Gospodarič (1977b). The mineral composition of these sediments indicates that their provenance is from the Eocene flysch of Pivška kotlina (Gospodarič 1976; Zupan Hajna 1992, 1998).

The profile is approximately 2.2 m thick and is a sequence of yellowish brown and yellow silty clays interlaminated by yellowish

brown to whitish grey silts and fine-sandy silts to sands. Cross bedding with ferruginous laminae are locally developed in the lower part of the profile (Pl. II/H). Mineralogical composition is summarized in Table 2.

Numerical dating

Gospodarič (1976) dated speleothems from a number of localities in Planinska jama using ^{14}C and Th/U methods. The range of dates is from 3.6 to 44.2 ka by the first method. Seven samples were older than 30.7 to 49.9 ka. One sample, with age >45.6 ka was dated by Th/U method to 79.7 ± 1.6 ka. Flowstone above the older laminated loams was dated to 77.8 ± 8.4 ka (Gospodarič 1976). Comparison of Th/U and radiocarbon ages shows that ^{14}C dates older than about 30–32 ka are not reliable due to the state of the radiometric method at the time Gospodarič was working.

Palaeomagnetic analysis

Šebela & Sasowsky (1999) published results from a profile consisting of approximately 4 m of yellowish brown laminated loams. Palaeomagnetic properties were studied on 12 samples (6 duplicates). Normal polarization of all samples was interpreted as indicating an age

younger than 0.73 Ma. They suggested that the palaeomagnetic results are in good accordance with Mindel age (0.35–0.59 Ma) proposed by Gospodarič (1981). Our results confirmed only the N polarization. It appears that

the profile can be placed within the Brunhes chron, i.e. the sediments are most probably younger than 0.78 Ma but older than ca 80 ka.

DISCUSSION

SEDIMENTOLOGY AND MINERALOGY

The most common clastic sediments in the profiles are fine-grained laminated sediments (laminites), often occurring in quite thick sequences. Grain size often fines upwards within the laminae, creating a colour change. Lamination and fining upwards are normal and indicate deposition from suspension of waning floodwaters or other pulsed flow or from ponding as consequence of outflow routes becoming blocked by collapse, tectonic movements etc. (*cf.* Ford & Williams 2007). The abundance of lutitic clastic components indicates that the coarse-grained load was previously deposited or sieved (e.g., in sumps and semi-sumps) as suggested by Gospodarič (1976) and Zupan Hajna (1992).

The depositional environment was mostly calm but not completely stagnant. Such an environment can be described as cave lacustrine with deposition from pulsed flow. Homogeneity of the palaeomagnetic data indicates fast continuous deposition during short-lasting single flood events.

The mineral composition of the fluvial sediments indicates that the catchment area for allogenic streams was situated for a very long time on weathered flysch rocks in the Pivška kotlina (Gospodarič 1976; Zupan Hajna 1992, 1998). The uniformity of mineral composition results from homogenization of the source material. According to Zupan Hajna *et al.* (2008a), the principal reasons for homogenization are firstly that the influent streams flow perpendicular to strata of varying composition in the catchment area, secondly weathering and pedogenesis on the surface affected by the alternation of climates in post-Oligocene times, thirdly multiple reworking and re-deposition within the catchment area and subsequently in the subsurface, and fourthly unroofing of caves.

The lithological character of the upper parts of the profiles in Male jame and Zguba jama, profile II, indicates *in situ* weathering of previously deposited sediments. *In situ* weathering inside caves requires a long residence time in the cave and may indicate a different external climate than currently exists (Zupan Hajna *et al.* 2008a).

NUMERICAL DATING

A number of samples from Postojnska jama were analysed by radiometric dating (^{14}C , Th/U and ESR) and palaeontology. Numerical dates identified speleothem older than 350 ka (Gospodarič, 1981; Zupan, 1991) with some older phases dated to about 270–280 ka, 190 ka, 150–125 ka and around 70–75 ka (Ikeya *et al.* 1983, Zupan 1991; Mihevc 2002). Such dates indicate a substantial age for the clastic sediments underlying the speleothem. Layers of flood loam inside the stalagmites dated flood events during Riss, Riss/Würm and Würm (Ikeya *et al.* 1983; Zupan 1991). Younger Th/U dates yielded ages from 47 ± 7 ka to 12 ± 5 ka and 6 ± 4 ka (Mihevc 2002). Th/U and radiocarbon dates younger than about 20 ka are in very good agreement and show a phase of stalagmite collapse at about 10–11 ka (Franke & Geyh 1971, 1976). The sediments at several sites in Postojnska jama and the dating of flowstone, even if the errors are large, indicate that some clear phases of collapse alternating with phases of flowstone deposition occurred after the upper cave level was drained.

MAGNETOSTRATIGRAPHY

Šebela & Sasowsky (1999) did the first palaeomagnetic research on fluvial sediments from Postojnska jama (Male jame, Otoška jama & Partizanski rov = Umetni tunel). Unfortunately the number and sample density of their sampling was not sufficient for detailed palaeomagnetic analysis, so their and magnetostratigraphic framework was very rough. All samples showed N orientation. They concluded that all the sediments are younger than 0.73 Ma.

Their palaeomagnetic measurements from the natural cavity in Umetni tunel showed R polarity and they proposed these sediments were at least 0.73–0.90 Ma in age. They deduced that reddish-brown sandy loams in Umetni tunel are older than both the coloured chert gravel and older laminated loam (*sensu* Gospodarič 1976). The Umetni tunel sediments were disturbed by a recent movement on a cross-Dinaric fault situated in this part of the cave (Gospodarič 1964; Sasowsky *et al.* 2003). Šebela (2008) interpreted this movement as being younger than

0.78 Ma, which conflicts with our magnetostratigraphic results from profile Umetni tunel I, previously presented by (Pruner *et al.* 2004).

The multi-component analysis technique of Kirschvink (1980) shows that all our samples, except those from profile Umetni tunel II, display three-component RM. The A component in all samples is undoubtedly of viscous origin. It can be demagnetized in AF and at a temperature range of 0–2 to 5 (up to 10) mT. The B component (mostly LFC) is also of secondary origin, but shows harder magnetic properties. The B components represent the transition between the A and C components and occur in many samples in the AF range of 2–10 to 15 mT. They are characterized by a great scatter of directions (see

Tab. 5). For example, the B component is clearly visible in Figures 5 and 6. The C component (mostly HFC) is the most stable and can be demagnetized in the AF or at temperature range of ca (10) 15–80 to 100 mT or 320 to 520 (560) °C. Magnetomineralogical analyses and unblocking temperatures (520 to 560 °C) determined indicate that magnetite is the carrier of the RM for all samples analysed, which is in accordance with published data (for summary see Bosák, Pruner & Kadlec 2003).

Our data partly confirmed the findings of Šebela & Sasowsky (1999), produced some new dates, but indicated a different age interpretation than was offered by Sasowsky *et al.* (2003) and Šebela (2008). Samples from most profiles were N polarized. Three short R magne-

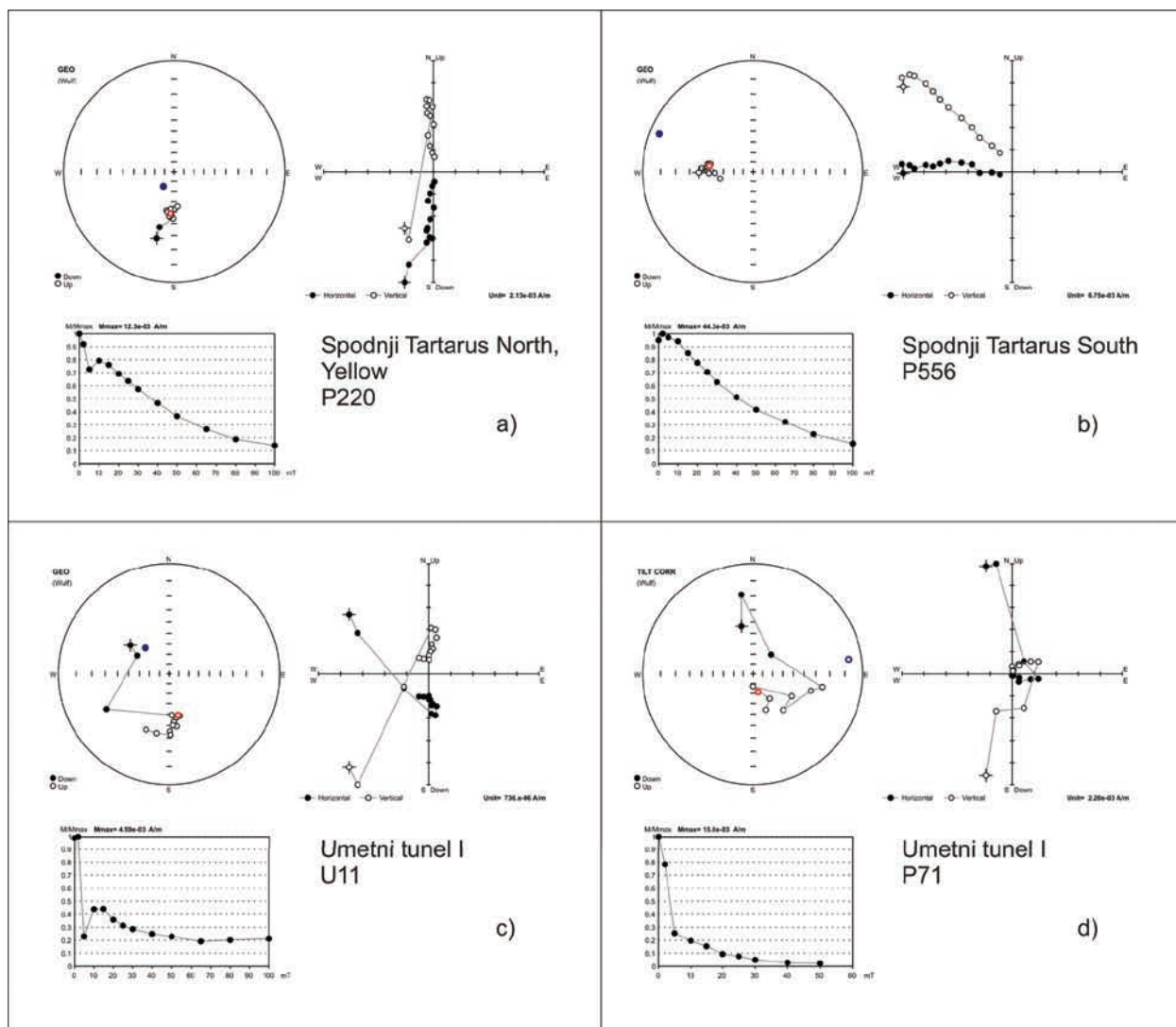


Fig. 5: Results of AF demagnetization with R palaeomagnetic polarity (a–d). Top left: stereographic projections of the remnant magnetization of a sample in the natural state (crossed circle) and after AF demagnetization. Top right: Zijderveld diagram – solid circles represent projection on the horizontal plane (X, Y), open circles represent projections on the north–south vertical plane (X, Z). Bottom left: a graph of normalized values of the remnant magnetic moments versus AF demagnetizing fields.

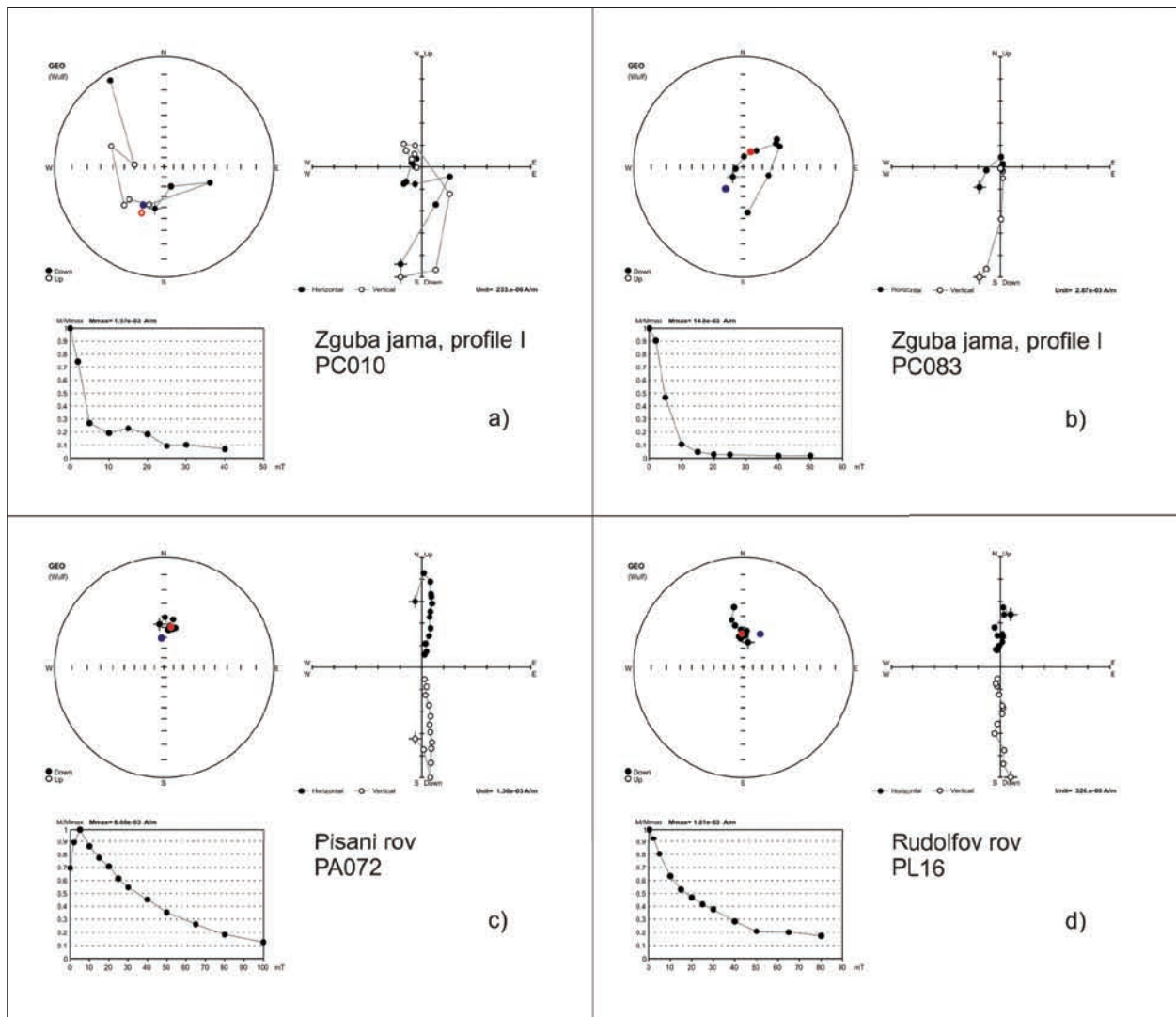


Fig. 6: Results of AF demagnetization with R (a) and N (b–d) palaeomagnetic polarity. For explanations see Figure 5.

tozones (excursions) were detected in only a few places (Spodnji Tartarus).

The present magnetic directions for study sites are: $D = 2.46$ (2.46 – 2.47) [$^{\circ}$] and $I = 62.18$ (62.17 – 62.20) [$^{\circ}$]. Palaeomagnetic directions for the profiles are summarized in Table 6 and Figure 7. These data indicate that the Spodnji Tartarus North, Pisani rov and Biospeleološka postaja profiles show D and I directions close to the present, within the limits of statistical error. The Rudolfov rov, Spodnji Tartarus South, Umetni tunel I, Male jama and Zguba jama profiles show slight to distinct counter-clockwise rotation. Palaeomagnetic directions of the Stara jama profile indicate clockwise rotation since the profile was deposited. The inclination in N polarized samples from Spodnji Tartarus South and Umetni tunel I profiles is anomalously low.

We have interpreted most of the sediments as being younger than 0.78 Ma, belonging to different depositional phases within the Brunhes chron. Nevertheless, the N polarization in some profiles may be linked with other N polarized subchrons much older than 0.78 Ma (e.g., the Umetni tunel 1 site and Zguba jama; Fig. 8). The lithological situation in Male jama is questionable.

The dominant N polarization of the sediments and the lack of more common R polarized excursions also indicate that deposition of most profiles was relatively rapid, occurring in short time-spans. Some profiles may therefore represent single flood events or deposition lasting at most a few thousand years. Homogeneity of palaeomagnetic data and lithological character, especially in the laminated sequences, may indicate continuous deposition, which is generally favourable for recording

Tab. 5: Directions of B and C components in selected samples.

Profile	Polarity of C comp.	B component		C component	
		D [°]	I [°]	D [°]	I [°]
Spodnji Tartarus N Yellow Sample P 220	R	216	71	185	-49
Spodnji Tartarus South Sample P 556	R	292	5	278	-46
Umetni tunel I Sample U 11	R	314	63	171	-56
Umetni tunel I Sample P 71	R	82	-7	165	-71
Zguba jama, profile I Sample PC 010	R	209	47	206	-40
Zguba jama, profile I Sample PC 083	N	219	61	27	72
Pisani rov Sample PA 072	N	355	60	10	49
Rudolfov rov (PL) Sample PL 16	N	27	52	358	56

ska jama–Planinska jama cave system. Our team has, however detected them in lutitic sediments in some other caves (Bella *et al.* 2007; Zupan Hajna *et al.* 2008a).

AGE

The interpretation of the age of the profiles in Table 7 is based on all available numerical and correlated-ages, but the primary source is the results of our magnetostratigraphy of the cave sediments. Maximum ages, except where substantiated by other methods, represent rough estimates only and could be far from reality. Furthermore, at most sites the sedimentary profile was not excavated completely to the rock cave floor, so the beginning of deposition may be substantially older, particularly where ages are designed as over 0.78 Ma.

Zupan Hajna *et al.* (2008a) recognised three periods of cave fill deposition in Slovenia, with the oldest sediment dated as Pliocene by Horáček *et al.* (2007). Deposition in the studied cave system can be placed in two periods (Tab. 7).

Sediments dated from about 0.78 Ma (palaeomagnetic age) up to more than 4.0 Ma (palaeomagnetic age; i.e. Pleistocene max. to Pliocene): this group includes a succession of detected ages across the whole Kras. The base of most of these profiles is probably not much older than 3.58 Ma, i.e. the datum adjusted by palaeontological finds at the Črnotiče II and Račiška pečina sites in the Classical Karst (Horáček *et al.* 2007). Some phases can be distinguished from the

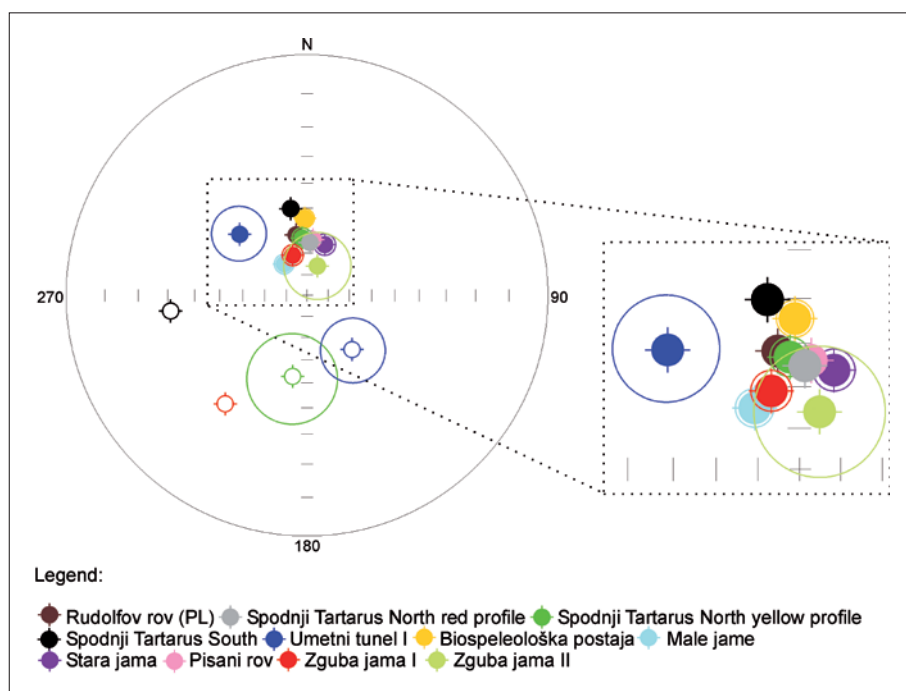


Fig. 7: Directions of C-components of remanence of samples with N and R polarities, Postojnska, Zguba and Planinska jama. Stereographic projection, open (full) small circles represent projection onto the lower (upper) hemisphere. The mean direction calculated according to Fisher (1953) is marked by a crossed circle; the confidence circle at the 95% probability level is circumscribed about the mean direction.

short-lived palaeomagnetic excursions. Despite these favourable conditions, excursions of the palaeomagnetic field were not detected in the profiles from the Postojn-

and Račiška pečina sites in the Classical Karst (Horáček *et al.* 2007). Some phases can be distinguished from the

Tab. 6: Mean palaeomagnetic directions, Planinska (PL), Postojnska and Zguba jama.

Profile	Polarity	Mean palaeomagnetic directions		α_{95} [°]	k	n*
		D [°]	I [°]			
Spodnji Tartarus N Red	N	3.11	65.17	3.52	20.55	77
Spodnji Tartarus N Yellow	N	355.18	63.05	4.35	16.41	63
	R	190.13	-52.25	14.23	24.19	4
Spodnji Tartarus South	N	349.34	49.72	3.2	11.49	167
	R	263.48	-30.63	-	-	2
Umetni tunel I	N	312.23	48.63	10.22	7.22	26
	R	140.33	-57.38	12.26	5.01	26
Biospeleološka postaja	N	358.34	54.47	3.86	87.52	15
Male jame	N	323.93	71.67	4.37	32.08	32
Stara jama	N	19.19	64.84	4.59	51.61	18
Pisani rov	N	6.19	63.79	3.31	27.16	66
Zguba jama, profile I	N	340.38	69.93	4.62	27.81	33
	R	217.04	-31.14	-	-	2
Zguba jama, profile II	N	19.27	75.25	12.99	19.37	6
Rudolfov rov (PL)	N	349.73	61.33	2.16	50.2	84

Note: only samples suitable for statistical evaluation are listed.

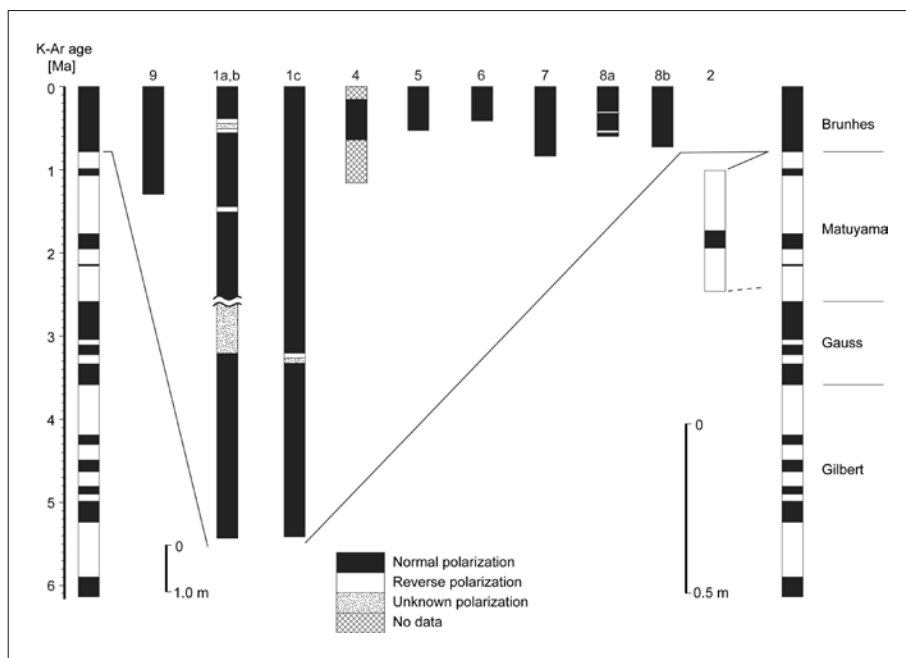


Fig. 8: Correlation of magnetostratigraphy profiles with the GPTS (on both sides; modified from Cande & Kent 1995). Position of individual study profiles does not reflect mutual correlations and/or altitude; top of profiles is located on the same line. Numbers of profiles from Postojnska jama refer to Figure 2. 1a – Spodnji Tartarus North, red; 1b – Spodnji Tartarus North, yellow; 1c – Spodnji Tartarus South; 2 – Umetni tunel I; 4 – Biospeleološka postaja; 5 – Male jame; 6 – Stara jama; 7 – Pisani rov; 8a – Zguba jama, profile I; 8b – Zguba jama, profile II; 9 – Rudolfov rov. Right scale bar is valid for profiles Nos. 2 and 8b, left scale bar is valid for the rest of profiles.

dates: (a) more than 0.78 up to about 4.2 Ma (palaeomagnetic ages e.g., Umetni tunel I & Zguba jama), and (b) less than 0.78 to about 2 Ma (palaeomagnetic ages), i.e. something between Brunhes/Matuyama boundary (and somewhat younger) and base of Jaramillo and/or Olduvai subchrons (and somewhat older). Dates from Male jame and Zguba jama do not allow for more detailed age correlation.

Sediments younger than 0.78 Ma (i.e. Pleistocene): caves containing sedimentary fill younger than the Brunhes/Matuyama boundary have one common feature – a part of the cave is still hydrologically active, with one or more streams flowing in the lower levels (e.g., Postojnska, Planinska).

EVOLUTION OF THE CAVE SYSTEM

Data obtained from sedimentological analyses, palaeontological and quantitative dating indicates that the Pivška kotlina – Postojnska jama – Planinska jama – Planinsko polje system evolved over a long period of time during relatively stable hydrological conditions. The development of the whole system has been governed by the level of Planinsko polje in relation to that of the resurgence area in Ljubljansko barje (Ljubljana Moor). Ljubljansko barje is a tectonic basin that has been slowly subsiding during the Quaternary. The evolution of Pivška kotlina has been governed by the elevation of the ponors of Pivka River that drain into Postojnska jama.

Tab. 7: Ages of cave sediments interpreted on studied sites (modified from Zupan Hajna et al., 2008a).

Name of site	Name of profile	Age [Ma]		Age of cave fill
		Min.	Max.	
Planinska jama	Rudolfov rov	>0.08	<0.78	Pleistocene (Mindel) to Holocene
Postojnska jama	Stara jama	?	<0.78	
Postojnska jama	Tartarus South	>0.122	<0.78	
Postojnska jama	Pisani rov	>0.53	<0.78	
Postojnska jama	Tartarus North	?	<0.78	
Zguba jama	I+II	<0.78	>0.78	Pliocene* to Pleistocene (Günz/Mindel)
Postojnska jama	Male jame	?	>0.78	
Postojnska jama	Umetni tunel 1	<0.99	>2.15	

Explanations: bold numbers = Th/U data; * Pliocene mentioned in the traditional sense (1.8–5 Ma).

Recent palaeomagnetic data from the lower part of a profile in Markov spodmol indicate that Pivška kotlina has been active for a long period of time. Declination and inclination parameters in this profile indicate that the N polarization could belong here to an older chron/subchron than the Brunhes. This suggests that the sediments may be substantially older than 0.78 Ma. Several segments in this profile are separated by distinct unconformities, and at least one of them is accompanied by *in*

situ underground weathering, indicative of a substantial time break (Zupan Hajna et al. 2008a).

Continued stability of the Pivka River hydrological system over a long period of time led to the formation of a long and complex cave system with three currently accessible cave levels (Zguba jama + upper and lower levels of Postojnska jama; Fig. 9). Vertical separation between the levels is not great (about 30 and 18 m, from top down). The Zguba jama level is a single phreatic channel abandoned without epiphreatic or vadose modification; the period of hydrological stability represented by this level was apparently relatively short.

The upper level of Postojnska jama shows traces of original phreatic channels developed along geological structures. They were substantially modified in the epiphreatic zone by paragensis, entrenchment and bypasses during a long period of stable hydrologic and speleogenetic conditions with a low hydraulic head. Processes in epiphreatic zone involved multiple periods of sediment filling and erosion causing the present cave shape to evolve by paragensis. A two-phase evolution is also expressed in the relief of Pivška kotlina (see Mulec et al. 2005). In Planinska jama, located on the lower (outflow) side of the system, sedimentation was less important and the dominant process in cave development was and is vadose entrenchment.

Šušteršič and his colleagues (a.o. Šušteršič, Šušteršič & Stepišnik 2003) in a number of nearly identical papers, proposed a very young evolutionary history for Planinsko and Cerkniško poljes and related cave systems, with cave development

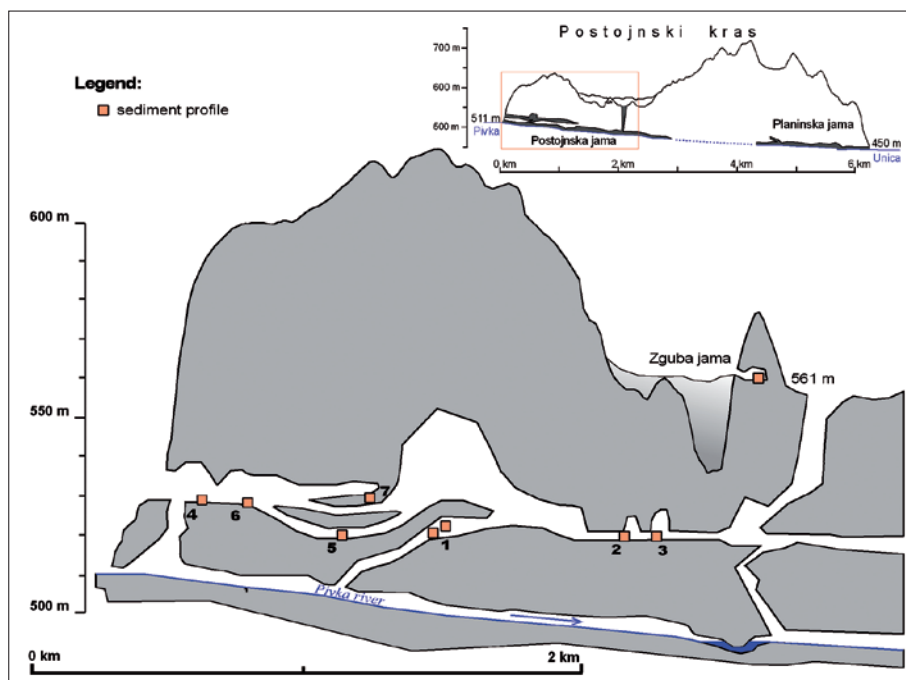


Fig. 9: Schematic cross-section of Postojna cave system showing the location of sediment profiles. Legend: 1 –Spodnji Tartarus profiles, 2 –Umetni tunel I profile, 3 – Umetni tunel 2 profile, 4 – Biospeleološka postaja profile, 5 – Male jame profile, 6 –Stara jama profile, 7 –Pisani rov profile and Zguba jama profile.

occurring within the last 30–100 ka. This hypothesis should now be abandoned, as it is not in accordance with the data summarized here. Their model was based on re-interpretation of the original stratigraphy of Gospodarič and his evolution phases (1976, 1977a, b). The succession of events Šušteršič and others propose may be correct, but their timeframe for the infilling and erosional phases is unrealistic and far too short.

The interpretation given here is based on (1) all available numerical and correlative ages (including archaeology) referred to or described in this paper: numerical dates up to 530 ka from speleothems and correlated-ages over 1.1 Ma (magnetostratigraphy); (2) the morphology of Planinsko and Cerknjsko poljes: the present geographical limits of the flat polje floors are far from the faults limiting the Idrija fault zone. If poljes along the Idrija fault zone really have developed as pull-apart basins (Vrabec 1994), then their enlargement by lateral corrosion to the present extent requires much more than 100 ka (Šušteršič, Šušteršič & Stepišnik 2003), with a stable karst water table, and (3) knowledge of the dynamics of depositional and erosional phases in the Postojnska and Planinska jama system (e.g., Gospodarič 1976; Pruner *et al.* 2004; Zupan Hajna *et al.* 2008a, b).

The dating presented above and field observations both indicate a long and complex history of alternating depositional and erosional phases in the Postojnska–Planinska cave system. Individual cave segments or passages were fully filled and exhumed several times during cave evolution, as indicated, for example, by paragenetic features and remains of cemented sediments on walls and ceilings in the main passage of Stara jama and in other places, and by different palaeomagnetic parameters (D, I).

As previously noted by Gospodarič (1976), deposition was not uniform throughout the entire cave at any one time. There was erosion in one part of the cave and deposition in another. Repeated reworking and re-deposition of the same sedimentary material is typical for long, voluminous and complicated cave systems like Postojnska–Planinska system. Some passages underwent repeated flooding and deposition (e.g., Pisani rov).

This complicated depositional history was caused by the prolonged evolution of the drainage system in epiphreatic conditions, particularly in the upper level of Postojnska jama. The alternation of depositional and erosional phases may be connected with (1) low hydraulic head in a stable hydrological situation and (2) oscillation of the karst water table through unblocked connection passages between the lower and upper cave levels as a result of changing conditions within the cave system (reflecting the function of the resurgence area, climatic changes, tectonic movements, collapse and the intrinsic mechanisms of contact karst).

Unfortunately, most of these processes have not yet been properly dated; but cave sediments can provide a useful tool and the first attempt of dating these processes is presented here. Nevertheless, sediments from different profiles from caves developed in different geomorphic units showing the same palaeomagnetic polarity do not necessarily represent the same depositional conditions/times in different segments of the cave system. Sediment dating does not give the time of speleogenesis itself, but only the age of the last preserved cave fill (see Bosák 2002).

CONCLUSIONS

The Postojnska jama – Planinska jama cave system and number of other smaller caves contain rich and lithologically diverse cave fill, ranging from autogenic speleothems to allogenic fluvial sediments. The most common clastic sediments are fine-grained (lutitic) laminated sediments (laminites). They were deposited from suspension from waning floodwaters or other pulsed flow or as a result of ponding due to the blockage of outflow routes. The prevalence of a lutitic clastic component indicates low head in the catchment area and/or fact that the coarse-grained load was already deposited. The deposition of fine-grained material was due to the regular flooding, characteristic for the sinking rivers. Homogeneity of palaeomagnetic data can indicate

fast and continuous deposition during short-lived (few thousand years) single-flood events. Depositional style was favourable for record of short-lived excursions of the palaeomagnetic field, which is rarely reported from cave deposits.

The mineral composition of the fluvial sediments indicates that the catchment area of allogenic streams was situated on weathered flysch rocks in the Pivška kotlina for a very long time. The uniformity of mineral and petrologic composition found in all profiles resulted from homogenization before the sediments were deposited in the caves and from multiple reworking and re-deposition in the subsurface. *In situ* weathering of grains inside the cave was also detected.

Numerical dating identified many phases of speleothem growth. Layers of loam inside stalagmites indicate repeating flood events in some parts of cave system. Some speleothem dates clearly indicate a substantial age for underlying cave sediments. The sediments, especially in several sites of the Postojnska jama, and dating of speleothems, even if the errors are large, show some clear phases of erosion and collapse in alternating with sediment and flowstone deposition.

Multi-component analysis shows that sediments mostly display a three-component remnant magnetization. Magnetomineralogical analyses and unblocking temperatures (520 to 560 °C) indicate that magnetite is the carrier of the remnant magnetization in the analysed samples.

Palaeomagnetic and magnetostratigraphy data reported here partly confirmed previous results, but also indicated different age interpretations. Samples from most profiles were N polarized. Three short R magnetozones (excursions) were detected only in a few places (Spodnji Tartarus). Within the limits of statistical error, the Spodnji Tartarus North, Pisani rov and Biospeleološka postaja profiles show declination and inclination directions close

to the present. The Rudolfov rov, Spodnji Tartarus South, Umetni tunel 1, Male jame and Zguba jama profiles must be older due to slight to distinct counter-clockwise rotation. Palaeomagnetic directions of the Stara jama profile indicate clockwise rotation since profile was deposited. The inclination in N polarized samples from Spodnji Tartarus South and Umetni tunel I profiles is anomalously low.

We therefore interpreted most of the sediments as being younger than 0.78 Ma, belonging to different depositional events within the Brunhes chron. Nevertheless, the N polarization in some profiles can be linked with N polarized subchrons older than 0.78 Ma, as in the Umetni tunel 1 site and Zguba jama. The lithological situation in Male jame is questionable. Sediments in Umetni tunel 1 are the oldest in the system (below the gravel with coloured chert) and were not included in older stratigraphic schemes. They may be correlated with Olduvai, Reunion or even older chrons (i.e. from 1.77 to over 2.15 Ma).

Data from the Kras as a whole, suggests that the cave fill in the region is unlikely to be much older than the Pliocene (in the traditional sense). Deposition in the Postojnska jama – Planinska jama cave system can be placed in two principal deposition periods: (1) from about 0.78

Ma (palaeomagnetic age) to more than 4.0 Ma (palaeomagnetic age) – Pliocene to Pleistocene (Günz/Mindel) – this group contains a succession of detected ages: (a) more than 0.78 up to about 3.58 Ma (palaeomagnetic ages), and (b) less than 0.78 to about 2 Ma (palaeomagnetic ages), and (2) from 0.78 Ma – Pleistocene (Mindel) to Holocene.

The dating suggests a prolonged evolution of the Pivška kotlina – Postojnska jama – Planinska jama – Planinsko polje system in relatively stable hydrological conditions related to the function of Planinsko polje. Hydraulic stability and a low hydraulic head for a long period of time led to the formation of a long and complex cave system with three currently accessible cave levels in the ponor area, the middle level being the most evolved, mostly in epiphreatic zone.



Photo plate I: Examples of fluvial sediments and speleothems sampled for dating; part 1 – Postojnska jama. A – Spodnji Tartarus North profile. The lower part consists of red clay with some yellow laminae; the upper part consists of yellow clay and some sandy layers; B – Spodnji Tartarus South profile; C – Small stalagmite on rotated collapse block was dated by Th/U method, Spodnji Tartarus South; D – Umetni tunel I profile; E – Red clay from the upper part of the Biospeleološka postaja profile.



Photo plate II: Examples of fluvial sediments and speleothems sampled for dating; part 2 – Postojnska and Planinska jama. A, B – Male jama profile; C, D – Stara jama profile; E, F – Profile at the end of Pisani rov; G – Zguba jama profile; H – Profile in Rudolfov rov, Planinska jama.

The proposed model of prolonged evolution of the cave system is based on (1) all numerical- and correlative-ages (dates over 530 ka from speleothems and up to 3.58 Ma from cave sediments); (2) the morphology of Planinsko and Cerkniško poljes, which present limits are far behind marginal faults of the Idrija fault zone; their

lateral enlargement and bottom planation by corrosion to the present extent needed prolonged stabilization of than karst water table than earlier proposed 30 to 100 ka, and (3) dynamics of filling and erosion phases in the system, where several depositional and erosion events/phases alternated especially in epiphreatic evolution phase. Individual cave segments or passages of the system were fully filled and exhumed several times during the cave evolution. The deposition was not uniform throughout the entire cave at the same time. There was erosion in one part of the cave and deposition in another. The alternation of depositional and erosion phases may be connected with changing conditions within the cave system, functions both of the catchment basin and the resurgence area, climatic changes, tectonic movements, collapses, and the intrinsic mechanisms of the contact karst.

The petrologic, palaeomagnetic and numerical data do not allow the construction of facies time-dependent models because (1) there are very few sequences of sediment suitable for palaeomagnetic analysis in the cave system and most have been examined here, (2) most of the system was in epiphreatic conditions with a low hydraulic head for a long period of time causing multiple re-deposition and reworking and (3) there is little difference in elevation between the profiles– making stratigraphic correlation extremely difficult without additional numerical or palaeontological dating.

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