Original scientific article
Received: 2007-12-03

UDC 551.435.84:550.384(497.4Kozina)

PALAEOMAGNETIC RESEARCH INTO UNROOFED CAVES OPENED UP DURING THE HIGHWAY CONSTRUCTION AT KOZINA, SW SLOVENIA

Pavel BOSÁK
Institute of Geology, v.v.i, Academy of Sciences of the Czech Republic, CZ-165 00 Praha, Rozvojová 269, Czech Republic
E-mail: bosak@gli.cas.cz

Martin KNEZ
Karst Research Institute ZRC SAZU, SI-6230 Postojna, Titov trg 2, Slovenia

Petr PRUNER
Institute of Geology, v.v.i, Academy of Sciences of the Czech Republic, CZ-165 00 Praha, Rozvojová 269, Czech Republic

Ira D. SASOWSKY
University of Akron, Department of Geology, Akron, Ohio 44325-4101, USA

Tadej SLABE & Stanka ŠEBELA
Karst Research Institute ZRC SAZU, SI-6230 Postojna, Titov trg 2, Slovenia

ABSTRACT

*The construction of highway from Divača to Klanec (SW Slovenia, Classical Karst) uncovered a number of fossil caves and unroofed caves. Two of them were situated near Kozina. One (sites A and B) represented unroofed fossil channel rests of collapsed roof. It formed mild depression in the field. The sedimentary profile in cave was about 5 m high. The second (*site *C) was oblong shallow depression with nearly 8 m thick sequence. The profile at* site *A contains inverse and normal polarity magnetozones. The age of the profile at Kozina is older than Bruhnes/Matuyama boundary (0.78 Ma). According to the arrangement of individual magnetozone, it could be stated that sediments are older than the top of Olduvai chron (1.77 Ma), profile at* site *C is interpreted as younger than 0.78 Ma. We suppose that the fossil caves at Kozina are the result of post-Eocene speleogenetic epoch and its fossilization was connected with tectonic uplift of the area, probably after Messinian. If this hypothesis is close to the reality, the fossilization process could start at about 5.3 Ma as already expected.*

Key words: paleomagnetic analyses, cave sediments, roofless caves, Kozina, Slovenia

RICERCA PALEOMAGNETICA IN GROTTE SENZA TETTO, APERTE DURANTE LA COSTRUZIONE DELL'AUTOSTRADA NEI PRESSI DI COSINA, SLOVENIA SUD-OCCIDENTALE

SINTESI

La costruzione dell'autostrada da Divaccia a S. Pietro di Madrasso (Slovenia sud-occidentale, Carso classico) ha portato alla scoperta di numerose grotte fossili e grotte senza tetto. Due di queste sono situate nei pressi di Cosina. Nella prima (siti A e B) ci sono i resti del tetto crollato di un canale fossile, che formava una leggera depressione nel terreno. Il profilo sedimentario della grotta era alto circa 5 m. La seconda (sito C) era una depressione oblunga e poco profonda, con una sequenza spessa circa 8 m. Il profilo nel sito A contiene magnetozone con polarità inversa e normale. L'età del profilo di Cosina è superiore a quella del limite Bruhnes/Matuyama (0,78 milioni di anni). Conformemente alla disposizione delle singole magnetozone, gli autori suppongono che i sedimenti siano antecedenti la fine dell'evento Olduvai (1,77 milioni di anni), mentre il profilo del sito C sarebbe più giovane di 0,78 milioni di anni. Gli autori ipotizzano che le grotte fossili di Cosina siano il risultato di un'epoca speleogenetica post-Eocenica e che la loro fossilizzazione sia correlata al sollevamento tettonico dell'area, avvenuto probabilmente dopo il Messiniano. Se tale ipotesi corrisponde a realtà, il processo di fossilizzazione potrebbe essere iniziato circa 5,3 milioni di anni fa.

Parole chiave: analisi paleomagnetica, sedimenti di grotta, grotte senza tetto, Cosina, Slovenia

INTRODUCTION

The Classical Karst is the low NW-SE trending longitudinal plateau along the Gulf of Trieste in the NE Adriatic Sea extending from the Vipava Valley in the NE to Friuli-Venezia Giulia lowlands and the Soča River in the NW. Its length is about 40 km, whereas its width reaches 13 km. It covers a total of about 440 km^2. Its central part is situated at 200 to 500 m a.s.l.

The Kras plateau belongs to the Adriatic-Dinaric Carbonate Platform of the External Dinarides. It is composed of relatively shallow marine Cretaceous and Palaeogene limestones rich in fauna and flora. Eocene flysch sediments encircle carbonate plateau. Due to the strong pressures in the NE→SW direction, a complicated geological structure was formed with an alternation of flysch and limestone zones (slices) elongated in the NW-SE direction. Thrust planes are dipping towards the northeast *(cf.* Placer, 1981).

The area around Kozina is geologically dominated by an anticline that runs south from Kozina to the northern slopes of Slavnik Mountains in the Dinaric direction. The caves developed in the Upper Cretaceous limestones close to the tectonical contact with alveolinid and nummulitic limestones of Eocene age (Thanetian). Tectonic contact with Eocene siliciclastics (flysch) was located near the construction site.

The karstification of the region is characterized by the presence of old caves partly crossed by younger shafts. Shafts are connected with the drop of underground water level, which is presently situated about 200 m below the surface. Shafts are both empty and filled with young (Pleistocene) sediments *(e.g.,* Brodar, 1958; Rakovec, 1958).

Large valley systems on the surface of the Karst were believed to represent primary river valleys as they contain remnants of fluvial sediments. Nevertheless, after the start of identification of unroofed caves *(sensu* Mihevc, 1996), we know that fluvial sediments represent rather fill of fossil caves than remnants of surface fluvial systems *(cf.* Mihevc, 1998, 1999a, 1999b, 1999c, 2001). The palaeofill of caves appeared at surface due to erosion and chemical denudation of limestone surface, which is estimated at 20–50 m in 1 million years (Gams, 1981; Cucchi *et al.*, 1994).

The unroofed caves have been preserved as fluvial deposits and spelothems on the present surface, sometimes with traceable course of original passages. Such caves were originally described during the construction of highway network over the Classical Karst *(e.g.,* Knez & Šebela, 1994; Šebela & Mihevc, 1995; Slabe, 1996, 1997, 1998; Mihevc, 1996; Mihevc & Zupan Hajna, 1996; Kogovšek *et al.*, 1997; Mihevc *et al.*, 1998; Šebela 1999; Šebela *et al.*, 1999; Knez & Slabe, 1999a, 1999b, 2002, 2004a, 2004b, 2005, 2006). Altogether, 350 caves have been discovered along some 70 km long and 25 m wide construction strip of the highway. Among them, 50 were unroofed. Some of them represented parts of the same cave palaeosystem(s). Later on it was established that such caves are common over the whole Classical Karst *(e.g.,* Mihevc, 1998; Šusteršič, 1998; Geršl *et al.*, 1999; Stepišnik & Šušteršič, 1999).

Mihevc *et al.* (1998), and Knez & Slabe (1999a, 1999b, 2002) tried to classify the typical forms of unroofed caves. They are transformed by surface processes and represent an important element of the epikarst zone (Knez & Slabe, 1999b). The shape and form of unroofed caves resulted from the morphology of present surface, original configuration of fossil caves, intensity of younger karstification (speleogenesis) and a degree of younger exhumation of the cave fill. In the field, they are expressed as shallow oblong depressions, doline-like forms and collapsed dolines. Unroofed caves are a typical example of denudated karst *(sensu* Bosák *et al.*, 1989) – partially incorporated into the present karst landscape and hydrological system.

The dating of sediments in some unroofed caves by palaeomagnetic method (Bosák *et al.*, 1998, 1999, 2000a, 2000b) indicated the substantial age of the cave fill, clearly older than 1.77 Ma, some even up to 3.2 Ma. Ages of interpreted magnetozones at two sites were calibrated by finds of small mammals at the time interval of about 2.0 Ma (Račiška pečina Cave, fossil cave in the Črnotiče Quarry) (Bosák *et al.*, 2004a, 2004b; Zupan Hajna *et al.*, 2007).

Paleomagnetic research into cave sediments in Slovenia initiated in 1999 by Bosák *et al.* (2000a) and Šebela & Sasowsky (2000) during the construction operations along the route of Divača-Klanec section of the highway. They studied two sedimentary profiles at one unroofed cave and one profile in somewhat distant palaeocave. Sampling sites were located in a cut carved during construction about 400 to 900 m NE from Kozina close to the former Ljubljana – Koper main road. The area is situated at about 520–540 m a.s.l. within typical karst landscape with dolines and collapse dolines.

MATERIAL AND METHODS

Site characteristics

Knez & Slabe (1999b) described in detail the character of unroofed caves in the vicinity of Kozina. The network of various karst forms (Fig. 1), resulting from unroofing of large and diversified cave system(s), spreads along the construction site. The largest cave system – 400 m long – was situated on the right side of construction near Kozina. The system appeared on the surface as more or less distinct oblong depressions forming the connection of doline-like depressions. Unroofed caves were morphologically more expressed near dolines, where erosion of cave fill down to dolines was more in-

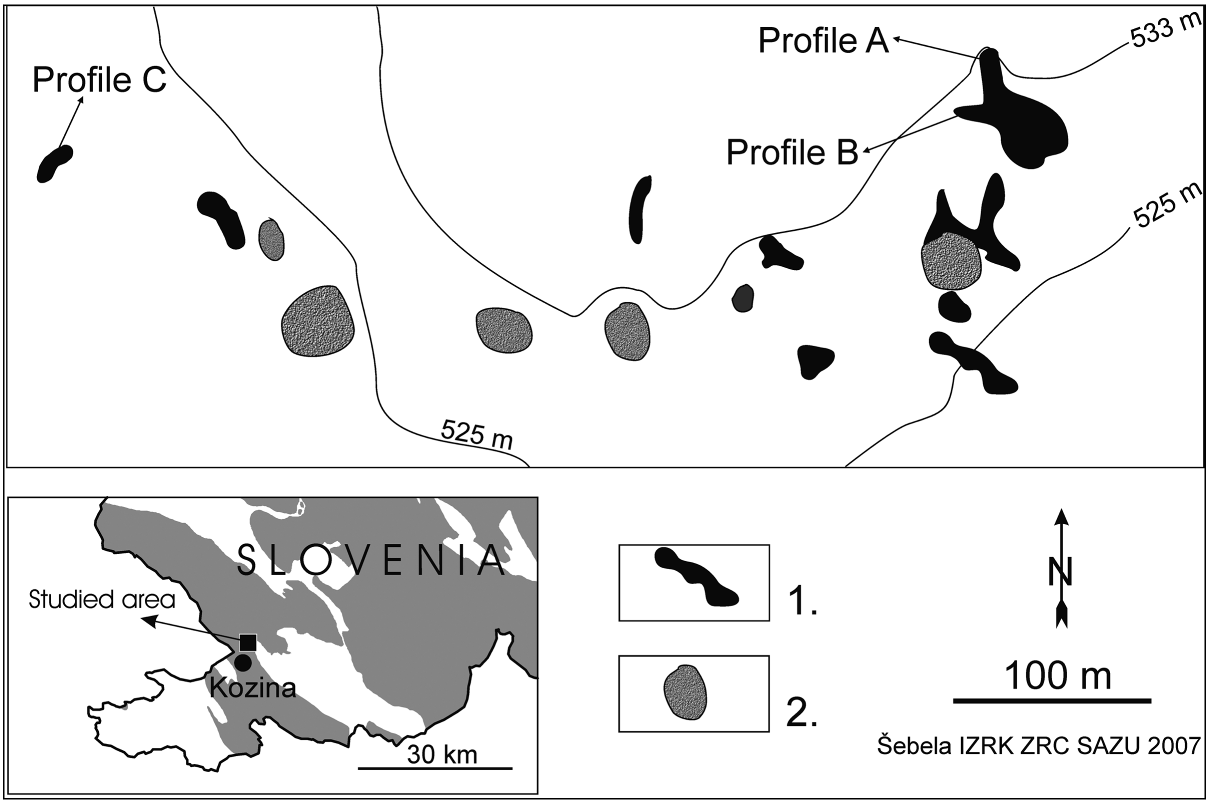

Fig. 1: Site location. Legend: 1 – unroofed cave; 2 – doline.
Sl. 1: Položaj profilov. Legenda: 1 – brezstropa jama; 2 – vrtača.

tensive. Depressions were mostly small and shallow. Their bottoms were filled by brown and red soils several metres thick. There were traces of water flow at the contact soil/limestone. At their bottoms, there were entrances to narrow and inaccessible shafts.

Cave passages were both free and choked, with very thin roofs, which have been partly removed. Caves were filled predominantly by fine-grained fluvial sediments, sometimes with gravel beds derived from flysch sediments. In the SW, piles of flowstones and stalagmites formed intercalations with fluvial cave fill. Some sedimentary sections were covered by angular blocks, boulders and debris derived from destructed roof limestones (Fig. 2). The debris is expected to be the result of weathering/disintegration in cold Pleistocene climate (Knez & Slabe, 1999b).

Profile description

SITE A. The log of sampled profile is presented in figure 3. The whole profile consisted of more than 5 m thick sediments. Its bottom was uncovered. The fill was composed of two principal sequences. The lower one was composed of ochreous sandy to clayey sediments, which are about 3 m thick. Sediments of lower sequence were sampled for palaeomagnetism. The lower sequence was overlain with sharp erosional surface by collapse breccia with limestone blocks to boulders (cm to m in size) and matrix of brown loams with carbonate efforescences on cracks (pseudomycelia). In the upper part of collapse breccia, the matrix was rather ochreous with smaller rock fragments. The upper sequence was not sampled for palaeomagnetic analysis owing to the collapse character with possibility of postdepositional movement, slumping and sediment rotation.

Near the contact of sediments and limestone, narrow inclined cavity developed in sediments of the lower sequence. The cavity walls were covered by speleothems, which cemented surrounding sediment. The cavity represents younger waterway draining the fossil cave and shallow depression of the present surface.

Lower sequence was about 3 m thick. Palaeomagnetic samples are signed in cm from the base of the profile (sample No. 2–295). Following lithological units, the following was distinguished: **1.** Sand, yellow, black-violet schlieren, very fine-grained, silty, indistinct lamination with higher clayey admixture, angular rock fragments. **2.** Clay, silty, variegated (ochreous, light brown with dark grey and violet schlieren and lamination), slightly finely sandy, more at the base, laminated (dynamic lamination), erosional base with secondary ferruginisation (2–28). **3.** Clay, silty, ochreous to light brown,

Fig. 2: The complete profile A in road cut near Kozina.
Sl. 2: Celoten profil A v cestnem useku blizu Kozine.

yellow and whitish yellow laminated, with laminae of fine-grained sand and fine sandy silt, thin ferruginized laminae, erosional base (29–93). **4.** Clay, light brown, violet brown at the top, with thin white sand bend, erosional base (98–109). **5.** Clay, silty, ochreous to light brown, yellow and whitish yellow laminated, with laminae of fine-grained sand and fine sandy silt, clasts of brown clays in the upper part, in places calcitized, erosional base, disconformably on layer No. 4 (some 10° lower inclination) (116–212). **6.** Clay, silty, light brown, erosional base (219–231). **7.** Clay, silty, light brown, slightly finely sandy in indistinct laminae, with coarse flakes of micas, with irregular clasts, erosional base. **8.** Breccia with light ochreous clayey matrix, erosional base. **9.** Clay, silty, brown, with Mn schlieren, erosional base (290). **10.** Sand, yellow, fine-grained, with cross-bedding, erosional base (295).

Five samples were taken from the profile for palynological analyses, *i.e.* at 30, 30–45, 70–80, 130–150 and 180–200 cm from the profile base. Sample from 70–80 cm yielded two highly corroded pollen grains belonging to herb vegetation *(Dipsacaceae and Apiceae family)* typical of dry, steppe-like region with any stratigraphic value. Sample from 130–150 cm yielded one spore (fern).

SITE B. The site was situated several metres to the south from the site A (Figs. 1, 4). The profile was 164 cm thick. The lower part of this profile was at an elevation of 527 m a.s.l. On the top of the cave sediments, which were mostly laminated clays, a cave roof to the thickness of 0.5 m was still preserved. The colour of the sampled sediments was determined by comparison to Munsell Soil Chart: SLO033-SLO034 (7.5YR 6/8-redish yellow) and SLO035-SLO036 (7.5YR 5/8-strong brown). We took 4 samples (SLO033-SLO036).

SITE C. The site was situated about 500 m to the west of the site B (Figs. 1, 5). The thickness of cave sediments was 7.84 m. The column was probably thicker, but it was not possible to dig the material out and reach the original bottom of the cave. The upper part of the profile is a 7.4 m thick massive sandy layer with weathered flysch gravels of 5 cm average diameter.

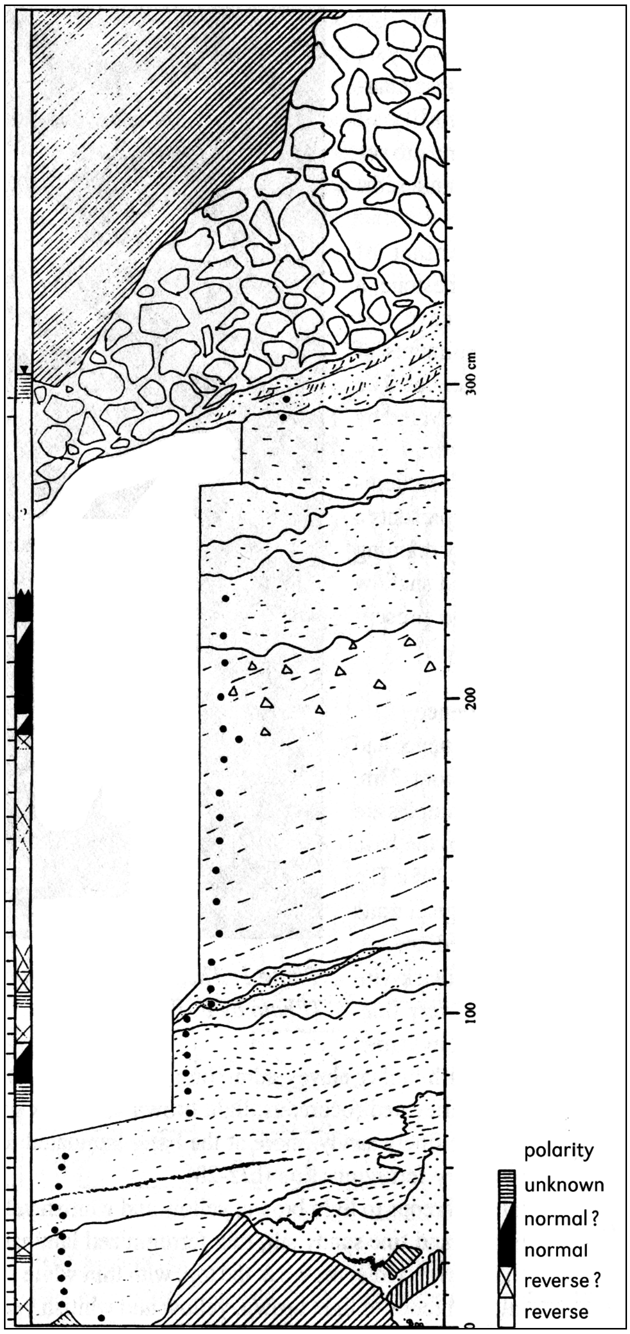

Fig. 3: Lithological log of the profile Kozina Site A with magnetic polarisation (Bosák* et al.*, 2000b), with black dots indicating sampling points.
Sl. 3: Litološka skica profila Kozina, vzorčno mesto A z magnetno polarizacijo (Bosák* et al.*, 2000b). Črne pike so točke vzorčenja.

Below this sandy layer lies a 20-cm thick layer of loam, and a sandier bedded clay layer below it. We took 6 samples (SLO037-SLO042). The colour of the sampled sediments was determined by comparison to Munsell Soil Charts: SLO037-SLO038 (7.5YR 5/8- strong brown), SLO039-SLO040 (7.5YR 6/8- reddish yellow) and SLO041-SLO042 (10YR 5/6- yellowish brown). Samples were taken at an altitude of about 522 m a.s.l. On the top of cave sediments, about 1–1.5 m thick layer of rubble has been preserved in some places. However, the original cave roof was no longer existent.

Palaeomagnetic analyses

Plastic sampling cubes with volume of about 8 cm^3 were inserted into a clean sediment face. Strike, dip direction, dip, and tilt of the cubes were recorded

Altogether, 38 oriented laboratory specimens of cave sediments were investigated as to their palaeomagnetic properties from the site A, 4 specimens from site B, and 6 specimens from site C.

Laboratory specimens were measured on the spinner magnetometers (JR-4 and JR-5; Jelínek, 1966). Laboratory specimens of solid sample in a natural state were subjected to progressive thermal demagnetization (TD) on the MAVACS (Magnetic Vacuum Control System) generating high-magnetic vacuum (Příhoda *et al.* 1989). All specimens were demagnetized by alternating field (AF; Schonstedt GSD-1), up to the field of 1,000 Oe in 14 steps. The susceptibility of specimens demagnetized by the TD procedure (k_t) and values of volume magnetic susceptibility of specimens in the natural state (k_n) values were measured on a kappa-bridge KLY-2 (Jelínek, 1973).

The directions of remanent magnetization (J_n) and those of the remanent magnetization (M) of demagnetized specimens by the TD or AF procedure in the course of progressive demagnetization procedures were done. The separation of the respective remanent magnetization components was carried out by multi-component Kirschvink analysis (Kirschvink, 1980). The statistics of Fisher (1953) were employed for calculation of mean directions of the pertinent remanence components derived by the multi-component analysis.

The samples were refrigerated and protected from strong magnetic fields after being collected. Magnetic properties were determined at the University of Pittsburgh Palaeomagnetic Laboratory. Magnetic strength and direction were measured on a superconducting rock magnetometer housed in a shielded room. Natural remnant magnetization (NRM) was measured first, followed by step-wise alternating field demagnetization and additional remnant magnetization measurements.

RESULTS

Palaeomagnetic results

SITE A. All collected samples (totally 38) were subjected to the AF demagnetization; one sample was demagnetized thermally. The values of the module of J_n of rocks in natural state show big scatter. Mean values of module of remanent magnetization J_n and of magnetic susceptibility k_n in their natural state from 38 samples are J_n = 7.005 ± 8.391 [nT], k_n = 267 ± 216 x 10^{-6}[SI]. Rocks show low or medium degree of magnetization.

The directions of remanent magnetization inferred by the above given procedures were tested by multi-component analysis. Generally, the samples showed three remanence components. *A-components* are mostly of viscose or chemoremanent (weathering) origin. They can be removed by alternating field with the intensity of 10 up to 30 Oe. Detected remanent magnetization in a natural state varies between 95 and 36,470 pT, with the values of volume magnetic susceptibility ranging from 55 to 998 x 10^{-6} SI. Some samples showed expressive viscose component (up to 90%); the primary component of magnetization and resulted polarity therefore cannot be stated.

Normal and reverse *C-component* directions of the samples form two defined sets of samples with the fisherian distribution. Mean directions of remanent magnetization of the Kozina profile are documented in Table 1.

The top and lower part of the profile shows reverse magnetozone. There are two normal zones in the middle part of the profile.

Tab. 1: Mean palaeomagnetic directions: Kozina, site A.
Tab. 1: Srednje paleomagnetne smeri: Kozina, vzorčno mesto A.

Locality	Polarity	Mean directions of the remanent magnetisation D[°]	I[°]	α_{95}	k	n
Kozina	N	338.2	62.3	20.7	8.1	8
	R	206.0	-67.6	20.1	3.1	25

SITES B AND C. The samples had a strong magnetic signal, with NRM values near 10^{-5} kA^{-1}. However, due to low-coercivity most of this signal was removed by application of a 20 mT alternating field.

Principle components analysis (Kirschvink, 1980) was used to fit a vector through the demagnetization data points for each sample. The resulting field directions were then plotted. The sample pairs in general

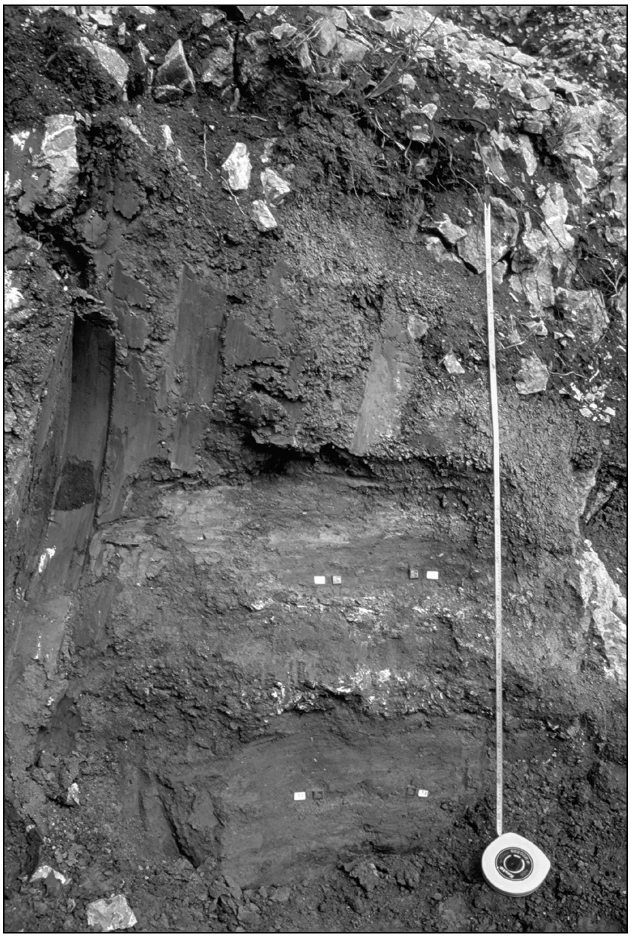

Fig. 4: Profile site B.
Sl. 4: Vzorčno mesto B.

Fig. 5: Profile site C.
Sl. 5: Vzorčno mesto C.

showed good correlation (indicated by light dashed lines in figure 6). Samples from the first location clustered slightly west of the present day field, with a somewhat greater inclination. This steepening of inclination is unusual in our experience. Samples SLO037 and SLO038 did not show a good match. The remainder of samples from the second location clustered tightly near the present day field.

Magnetic susceptibility was measured in 2 orientations using a Sapphire Instruments device. Values ranged from $1x10^{-5}$ to $7.5x10^{-5}$ (cgs units) with an average of $5x10^{-5}$. These are relatively high values for cave sediments. There was no anisotropy of susceptibility. Cave sediments from both sites showed only normal magnetic polarity.

Magnetostratigraphic results

SITE A. Palaeomagnetic and magnetostratigraphic investigations yielded data on basic magnetic properties and identification of palaeomagnetic directions: (i) magnetostratigraphic results defined normal and reverse polarity magnetozones, and (ii) magnetostratigraphic results of samples from Kozina and Divača profiles (Bosák *et al.*, 1998) show close similarities (Fig. 7): (a) two normal subzones in reverse magnetozone were interpreted within both profiles, and (b) good correlation of module values of remanent magnetization (J_n).

SITE B. It was located stratigraphically above site A, where the profile terminates by normal polarized section (Bosák *et al.*, 2000b). Results from both sites are compatible, as sediments of site B are higher and show normal polarity, indicating they are of the same age as upper part of the site A or younger.

DISCUSSION

SITE A. The lithology of profile clearly shows two-phase depositional history. The lower sequence, after its deposition, was partly eroded. The erosional channel was more deeply developed on the left side of the passage. The free space between sediment and the cave

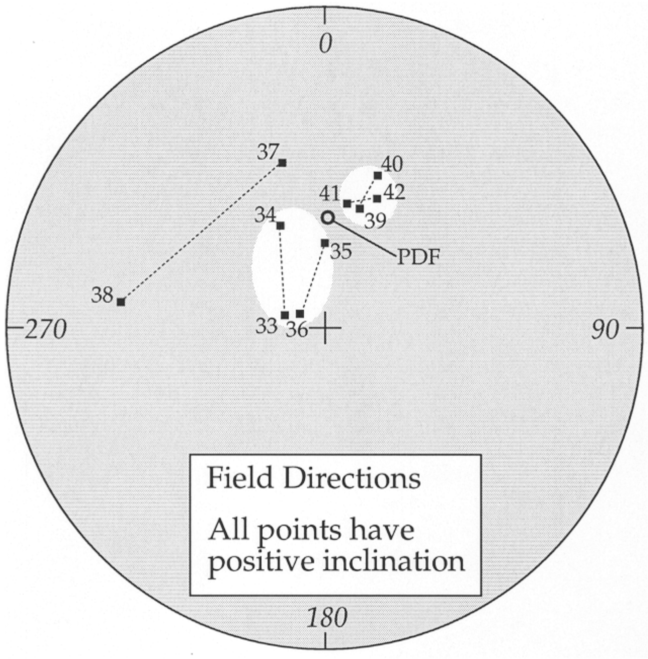

Fig. 6: Lambert equal area stereoplot of magnetic field directions for profiles B and C. Sample numbers (series SLO) are adjacent to sample squares. Present-day field is shown as bold circle. Light areas indicate possible clustering of field directions.
Sl. 6: Lambertov stereografski prikaz enakih področij smeri magnetnega polja za vzorčni mesti B in C. Številke vzorcev (oznaka SLO) ustrezajo kvadratkom. Današnje magnetno polje je označeno s sivim krogom. Svetlejša polja nakazujejo mogoče združbe smeri polj.

ceiling in the cave was later filled during collapse processes by block to boulder debris mixed with brown sediments. Ochreous intercalations in the upper part of the upper sequence can indicate the presence of eroded sediments comparable with the lower sequence. Thinning of cave roofs by erosion and karst denudation induced their collapses.

Lithological composition of the lower sequence is comparable with the Divača profile in a fossil cave near the village of Divača (Bosák *et al.*, 1998); with its sequences Nos. I and II. Layer No. 10 of the Kozina profile it could particularly be correlated with the base of sequence No. III of the Divača profile. It seems that sediments were derived from similar source rocks, most probably from weathered Eocene flysch.

Important erosional boundaries of the main lithological units within the lower sequence are located between samples Nos. 28/29, 93/98, 109/116, 212/219, 290/295. In contrast to other studied profiles (Bosák *et al.*, 2000a), erosional boundaries are not situated at boundaries of normal and reverse polarized zones, but within them. This fact can also indicate that breaks in deposition did not take a substantial time-span.

The magnetostratigraphic picture obtained in the Kozina profile is fully comparable with magnetozones detected in the Divača profile (Bosák *et al.*, 1998, 2000a), both in occurrence of the normal and reverse polarized magnetozones and in the character of the module of remanent magnetization (J_n). The dominant part of both profiles is represented by reversed magnetozones. There are two relatively narrow normal polarized zones. Unfortunately, there is a gap in sampling between the Kozina samples No. 213 and 290, owing to rock petrography unfavourable for sampling. Some difference in the arrangement of normal polarized magnetozones in both profiles can also result from different rates of deposition during fossilization of both channels.

The age of the profile at Kozina is older than Bruhnes/Matuyama boundary (0.78 Ma). According to the arrangement of individual magnetozones, it could be stated that sediments are older than the top of Olduvai chron (1.77 Ma), as the magnetostratigraphic profile at Kozina terminates by reverse polarized magnetozone and contains two normal polarized zones. Closely comparable character of module values of remanent magnetization (J_n) highly supports the age correlation of both profiles from fossil caves at Divača and Kozina.

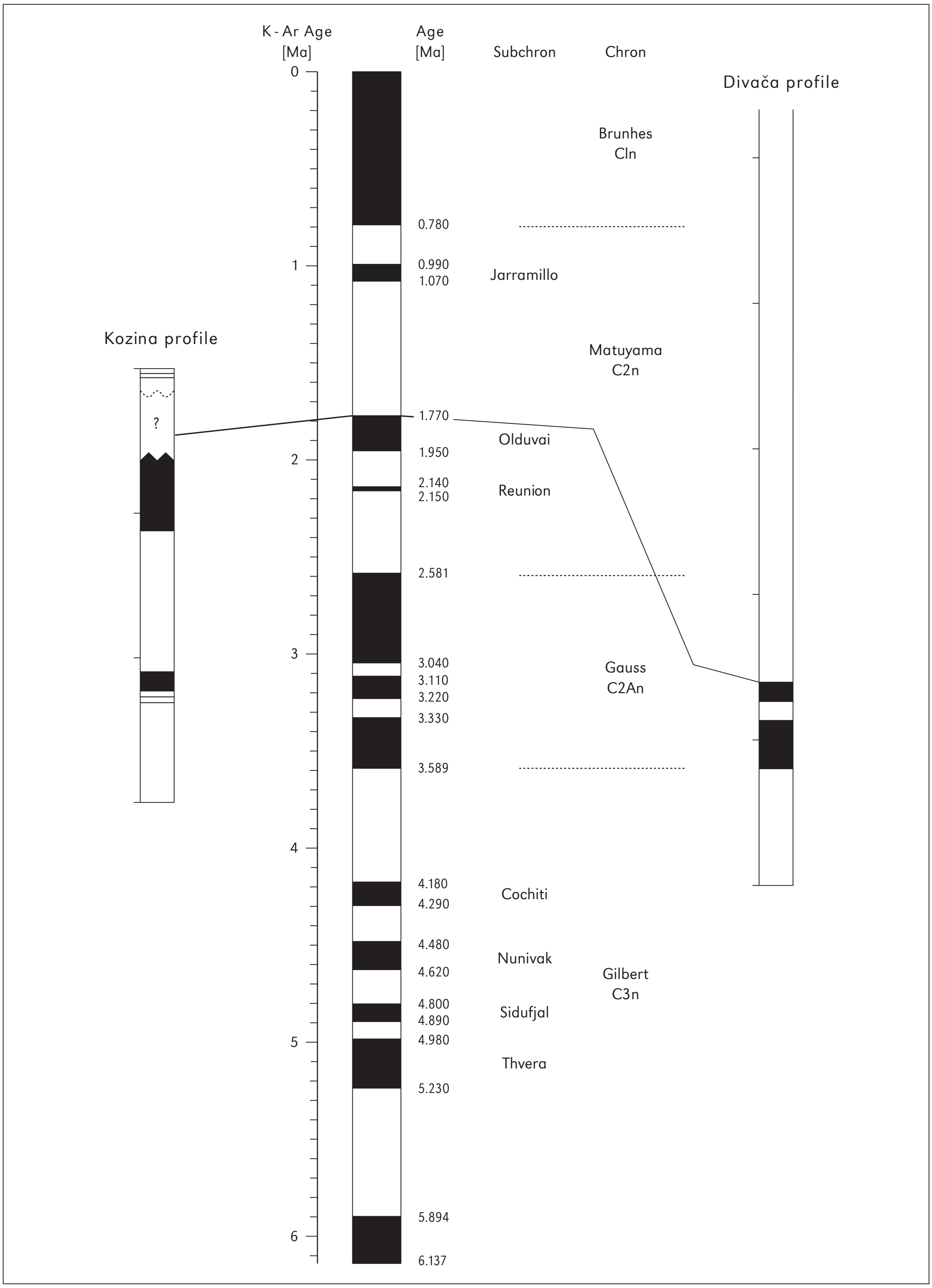

Fig. 7: Correlation of magnetostratigraphic results from Kozina site A (left; Bosák** et al.**, 2000a, 2000b) and Divača profile (right; Bosák** et al.**, 1998) with the standard palaeomagnetic scales (centre; after Cande & Kent, 1995).
Sl. 7: Korelacija pridobljenih magnetostratigrafskih rezultatov iz Kozine, vzorčno mesto A (levo; Bosák** et al.**, 2000a, 2000b) in Divače (desno; Bosák** et al.**, 1998) s standardnimi paleomagnetnimi lestvicami (sredina; po Cande & Kent, 1995).

SITES B AND C. Palaeomagnetic analysis of cave sediments from sites B and C showed that all of the 10 samples have normal polarity. Based on sample mineralogy, the source for all analyzed cave sediments was the Eocene flysch.

Cave sediments from site B (SLO033-SLO036) are almost certainly younger than 0.78 Ma. This is consistent with the studies by Bosák *et al.* (2000b). Regarding their results, which show that sediments are older than 0.78 Ma, our profile is younger than 0.78 Ma, because it was stratigraphically higher.

Site C has a thicker profile, and we collected sediments from its lower part. Regarding our results that show normal polarity, it is difficult to conclude that sediments are really younger than 0.78 Ma. If we consider the fact that sediments from roofless caves can be older than 0.78 Ma and that those samples were taken from the lower part of 7.5 m thick profile, we can suggest a possibility that they may have been deposited during an older normal polarity period. They could even be from the Gauss Normal chron (2.48–3.4 Ma), or according to Bosák *et al.* (1998) could correlate with some normal magnetozones (about 3.8–5.0 Ma) within the reverse Gilbert chron.

CONCLUSIONS

The construction of highway from Divača to Klanec (SW Slovenia, Classical Karst) uncovered a number of fossil caves and unroofed caves. Two of them were situated near Kozina. One (sites A and B) represented unroofed fossil channel. It formed mild depression in the field. The sedimentary profile in the cave was about 5 m high. It was composed mostly of sandy sediments of light brown colour with clayey and silty intercalations. Sediments contained dynamic structures and textures (lamination, cross-lamination, etc.). Erosional surfaces divided the profile into individual sequences. The second (site C) was oblong shallow depression with nearly 8 m thick sequence of brown to yellow-coloured sands with some silt to clay beds in the lower part. The profile was covered by limestone gravel.

The profile at site A contains inverse and normal polarity magnetozones. The age of the profile at Kozina is older than Bruhnes/Matuyama boundary (0.78 Ma). According to arrangement of individual magnetozone, it could be stated that sediments are older than the top of Olduvai chron (1.77 Ma), as the magnetostratigraphic profile at Kozina terminates by reverse polarized magnetozone and contains two normal polarized zones. Profiles at sites B and C showed only normal magnetic polarity. Profile at site C is interpreted as younger than 0.78 Ma, whereas profile B can be substantially older than this datum, similarly to profile at site A sediments. The found corroded pollen grains belonging to herb vegetation *(Dipsacaceae* and *Apiceae* family) typical of dry, steppe-like region were unfortunately of no stratigraphic value.

The profile at site A can be correlated with the Divača profile, not only from the palaeomagnetic point of view, but also from lithological aspect. We suppose, similarly as at Divača, that the fossil caves at Kozina are the result of post-Eocene speleogenetic epoch and its fossilization was connected with tectonic uplift of the area, probably after Messinian *(cf.* Willet *et al.*, 2006). If this hypothesis is close to the reality, the fossilization process could have started at about 5.3 Ma as already expected by Bosák *et al.* (1998, 2000a, 2000b).

ACKNOWLEDGEMENT

We are grateful particularly to DARS (Motorway Company in the Republic of Slovenia) and DDC Consulting & Engineering who financed karstological control and gave permission to access the construction site. The company also covered the expenses of analytical procedures. We are also grateful to the Institute for the Protection of Natural and Cultural Heritage, Nova Gorica, by which the karstological control was organized. We acknowledge field assistance of Dr Nadja Zupan Hajna and technical staff of the Karst Research Institute, ZRC SAZU, Postojna, Slovenia, during sampling. We would like to thank William Harbert (Department of Earth and Planetary Sciences, University of Pittsburgh, Pennsylvania, USA, responsible for the Palaeomagnetism Laboratory) for his help during the analyses carried out on April 26–27th, 1999. Palynological analyses were kindly carried out by Dr. Metka Culiberg from the Institute of Biology, ZRC SAZU, in Ljubljana, Slovenia. Software for the evaluation of palaeomagnetic measurements in the Czech Republic was prepared by Dr. Ota Man, while measurements were performed and evaluated by Mrs. D. Otrubová and dr. D. Venhodová (all from the Institute of Geology AS CR, v.v.i., Praha). Travel costs of the Czech part were covered within the framework of the KONTAKT No. ME.251 program of the Czech Ministry of Education, Youth and Sports and Slovenian Ministry of Higher Education, Science and Technology. Expenses of analytical procedures were partly covered from sources of the Program of Advancements in Scientific Research in Key Directions of the Academy of Sciences of the Czech Republic No. K1-042-603. The study is a result of the Research Plan of the Institute of Geology AS CR No. CEZ:A09/98:Z3-013-912 and Grant Projects of the Grant Agency of the Academy of Sciences of the Czech Republic Nos. IAA300130701 Palaeomagnetic research of karst sediments: palaeotectonic and geomorphological implications (2007–2010) and IAA3013201 Magneto-mineralogical and magnetostratigraphic research into cave and fluvial sediments in the Central European region (2002–2005). The grant for S. Šebela was provided by the Research Fund of ZRC SAZU.

PALEOMAGNETNE RAZISKAVE BREZSTROPIH JAM, KI SO SE ODPRLE MED GRADNJO AVTOCESTE PRI KOZINI, JZ SLOVENIJA

Pavel BOSÁK
Institute of Geology, v.v.i, Academy of Sciences of the Czech Republic, CZ-165 00 Praha, Rozvojová 269, Czech Republic
E-mail: bosak@gli.cas.cz

Martin KNEZ
Inštitut za raziskovanje krasa ZRC SAZU, SI-6230 Postojna, Titov trg 2, Slovenija

Petr PRUNER
Institute of Geology, v.v.i, Academy of Sciences of the Czech Republic, CZ-165 00 Praha, Rozvojová 269, Czech Republic

Ira D. SASOWSKY
University of Akron, Department of Geology, Akron, Ohio 44325-4101, USA

Tadej SLABE & Stanka ŠEBELA
Inštitut za raziskovanje krasa ZRC SAZU, SI-6230 Postojna, Titov trg 2, Slovenija

POVZETEK

Graditev avtoceste med Divačo in Klancem je razkrila številne fosilne in brezstrope jame, zapolnjene z jamskimi sedimenti. Raziskali smo jih s paleomagnetno analizo, s kakršno raziskujemo jamske naplavine na Krasu že od leta 1997 v okviru znanstvenega sodelovanja med Inštitutom za geologijo Akademije znanosti Češke republike, Oddelkom za znanosti o Zemlji in planetih Univerze v Pittsburghu, ZDA, in Inštitutom za raziskovanje krasa ZRC SAZU.

Jamski sedimenti iz profilov pri Kozini so starejši od meje bruhnes/matuyama (0,78 milijona let). Iz razporeditve posameznih magnetocon bi bilo mogoče trditi, da je usedlina starejša od konca dogodka olduvai (1,77 milijona let), saj se magnetostratigrafski profil pri Kozini zaključi z magnetocono inverzne polaritete in vsebuje dve coni normalne polaritete. Zelo primerljiva značaja vrednosti modulov remanentne magnetizacije močno podpirata starostno korelacijo profilov iz fosilnih jam pri Divači in Kozini. Menimo, da je, tako kot v divaškem profilu, jama rezultat messinske speleogeneze, še posebno, če lahko magnetocone normalne polaritete koreliramo s tistimi iz inverzne gilbertove dobe.

Fosilizacija jamskih sistemov je bila povezana s hitrim dvigom ravni baze, potem ko se je pred okoli 5,3 milijona let odprl Gibraltarski preliv in se je Sredozemski bazen spet zapolnil. Nadaljnja fosilizacija je bila posledica sprememb na regionalni ravni baze in hidroloških razmer, ki so nastale s postopnim razvojem površja in neotektonike tega dela Krasa ter zaradi sprememb v višini gladine morja v Sredozemskem bazenu.

Ključne besede: paleomagnetne analize, jamski sedimenti, brezstrope jame, Kozina, Slovenija

REFERENCES

Bosák, P., D. C. Ford & J. Głazek (1989): Terminology. In: Bosák, P., D. C. Ford, J. Głazek & I. Horáček (eds.): Paleokarst. A Systematic and Regional Review. Elsevier-Academia, Amsterdam-Praha, pp. 25–32.

Bosák, P., P. Pruner & N. Zupan Hajna (1998): Paleomagnetic research of cave sediments in SW Slovenia. Acta Carsologica, 27(2), 151–179.

Bosák, P., A. Mihevc, P. Pruner, K. Melka, D. Venhodová & A. Langrová (1999): Cave fill in the Črnotiče Quarry, SW Slovenia: Palaeomagnetic, mineralogical and geochemical study. Acta Carsologica, 28(2), 15–39.

Bosák, P., M. Knez, D. Otrubová, P. Pruner, T. Slabe & D. Venhodová (2000a): Palaeomagnetic Research of Fossil Cave in the Highway Construction at Kozina, SW Slovenia. Acta Carsologica, 29(2), 15–33.

Bosák, P., P. Pruner, A. Mihevc & N. Zupan Hajna (2000b): Magnetostratigraphy and unconformities in cave sediments: case study from the Classical Karst, SW Slovenia. Geologos, 5, 13–30.

Bosák, P., A. Mihevc & P. Pruner (2004a): Geomorphological evolution of the Podgorski Karst, SW Slovenia: Contribution of magnetostratigraphic research of the Črnotiče II site with *Marifugia* sp. Acta Carsologica, 33(1), 175–204.

Bosák, P., P. Pruner, A. Mihevc, N. Zupan Hajna, J. Horáček, J. Kadlec, O. Man & P. Schnabl (2004b): Račiška pečina. 12th International Karstological School, Classical Karst. Dating of Cave Sediments. Guide booklet for the excursions and abstracts of presentations. Postojna, pp. 23–27.

Brodar, S. (1958): Črni kal, nova paleolitska postaja v Slovenskem Primorju. Razprave, IV, 269–364.

Cande, S. C. & D. V. Kent (1995): Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. J. Geophys. Res. B, 100, 6093–6095.

Cucchi, F., F. Forti & F. Ulcigrai (1994): Valori di abbassamento per dissoluzione di superfici carsiche. Acta Carsologica, 23, 56–62.

Fisher, R. (1953): Dispersion on a sphere. Proc. R. Soc. Lond., A, 217, 295–305.

Gams, I. (1981): Comparative research of limestone solution by means of standard tablets. Proc. 8th Int. Congr. Speleol., Bowling Green, pp. 273–275.

Geršl, M., U. Stepišnik & F. Šušteršič (1999): The "unroofed cave" near the Bunker (Laški Ravnik). Acta Carsologica, 28(2), 77–90.

Jelínek, V. (1966): A high sensitivity spinner magnetometer. Stud. Geophys. Geodaet., 10, 58–78.

Jelínek, V. (1973): Precision A.C. bridge set for measuring magnetic susceptibility and its anisotropy. Stud. Geophys. Geodaet., 17, 36–48.

Kirschvink, J. L. (1980): The least-squares line and plane and the analysis of palaeomagnetic data. Geophys. J., 62, 699–718.

Knez, M. & S. Šebela (1994): Novo odkriti kaški pojavi na trasi avtomobilske ceste pri Divači. Naše jame, 36, str. 102.

Knez, M. & T. Slabe (1999a): Unroofed caves met during the motorway construction near Kozina and their recognition on karst surface. 7th International Karstological School, Classical Karst. Roofless Caves. Book of Abstracts. Postojna, pp. 30–31.

Knez, M. & T. Slabe (1999b): Unroofed caves and recognizing them in karst relief (Discovered during motorway construction at Kozina, South Slovenia). Acta Carsologica, 28(2), 103–112.

Knez, M. & T. Slabe (2002): Unroofed caves are an important feature of karst surfaces: examples from the Classical Karst. Z. Geomorphologie, 46(2), 181–192.

Knez, M. & T. Slabe (2004a): Karstology and the opening of caves during motorway construction in the karst region of Slovenia. Int. J. Speleol., 31(1/4), 159–168.

Knez, M. & T. Slabe (2004b): Highways on karst. In: Gunn, J. (ed.): Encyclopedia of caves and karst science. Fitzroy Dearborn, New York, London, pp. 419–420.

Knez, M. & T. Slabe (2005): Caves and sinkholes in motorway construction, Slovenia. In: Waltham, T., F. Bell & M. Culshaw (eds.): Sinkholes and Subsidence. Karst and Cavernous Rocks in Engineering and Construction. Springer, Chichester, pp. 283–288.

Knez, M. & T. Slabe (2006): Krasoslovne raziskave pri graditvi avtocest prek slovenskega krasa. Annales, Ser. Hist. Nat., 16(2), 259–266.

Kogovšek, J., T. Slabe & S. Šebela (1997): Motorways in Karst (Slovenia). Proceedings and Fieldtrip excursion guide, 48th Highway geology symposium, pp. 49–55.

Mihevc, A. (1996): Brezstropa jama pri Povirju. Naše jame, 38, 92–101.

Mihevc, A. (1998): Speleogeneza matičnega krasa. Doktorska disertacija. Univerza v Ljubljani, Filozofska fakulteta, Ljubljana, 150 str.

Mihevc, A. (1999a): The caves and the karst surface-case study from Kras, Slovenia. Etudes de géographie physique, suppl. XXVIII, Colloque européen-Karst 99, 141–144.

Mihevc, A. (1999b): Roofless caves. 7th International Karstological School, Classical Karst. Roofless Caves. Book of Abstracts. Postojna, pp. 2–25.

Mihevc, A. (1999c): Unroofed caves as geomorphic and speleologic features. 7th International Karstological School, Classical Karst. Roofless Caves. Book of Abstracts. Postojna, pp. 33–34.

Mihevc, A. (2001): Speleogeneza Divaškega Krasa. Zbirka ZRC, 27, 1–180.

Mihevc, A. & N. Zupan Hajna (1996): Clastic sediments from dolines and caves found during the construction of the motorway bear Divača, on the Classical Karst. Acta Carsologica, 25, 169–191.

Mihevc, A., T. Slabe & S. Šebela (1998): Denuded caves-an inherited element in the karst morphology; the case from Kras. Acta Carsologica, 27(1), 165–174.

Placer, L. (1981): Geološka zgradba jugozahodne Slovenije. Geologija, 24(1), 27–60.

Příhoda, K., M. Krs, B. Pešina & J. Bláha (1989): MAVACS – a new system of creating a non-magnetic environment for palaeomagnetic studies. Cuaderna Geológica Ibérica, 12, 223–250.

Rakovec, I. (1958): Pleistocenski sesalci iz jame pri Črnem kalu. Razprave, IV, 365–434.

Slabe, T. (1996): Karst features in the motorway section between Čebulovica and Dane. Acta Carsologica, 25, 221–240.

Slabe, T. (1997): The caves in the motorway Dane–Fernetiči. Acta Carsologica, 26(2), 361–372.

Slabe, T. (1998): Karst features discovered during motorway construction between Divača and Kozina. Acta Carsologica, 27(2), 105–113.

Stepišnik, U. & S. Šušteršič (1999): The "unroofed cave" near the Bunker (Laški Ravnik). 7th International Karstological School, Classical Karst. Roofless Caves. Book of Abstracts. Postojna, pp. 35–36.

Šebela, S. (1999): Morphological and geological characteristics of two denuded caves in SW Slovenia. 7th International Karstological School, Classical Karst. Roofless Caves. Book of Abstracts. Postojna, pp. 36–37.

Šebela, S. & A. Mihevc (1995): The problems of construction on karst-the examples from Slovenia. In: Beck, B. F. & F. M. Pearson (eds.): Karst geohazards – Engineering and environmental problems in karst terrane. Proceedings of the 5th Multidisciplinary Conference on Sinkholes and the Environmental Impacts of Karst. A.A. Balkema, Rotterdam, pp. 475–479.

Šebela, S. & I. D. Sasowsky (2000): Paleomagnetic dating of sediments in caves opened during highway construction near Kozina, Slovenia. Acta Carsologica, 29(2), 303–312.

Šebela, S., A. Mihevc & T. Slabe (1999): The vulnerability map of karst along highways in Slovenia. In: B. F. Beck, A. J. Pettit & J. G. Herring (Eds.): Hydrogeology and engineering geology of sinkholes and karst. Proceedings of the 7th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst. A. A. Balkema, Rotterdam, pp. 419–422.

Šušteršič, F. (1998): Interaction between cave systems and the lowering karst surface: case study: Laški Ravnik. Acta Carsologica, 27(2), 115–138.

Willet, S. D., F. Schlunegger & V. Picotti (2006): Messinian climate changes and erosional destruction of the central European Alps. Geology, 34, 613–616.

Zupan Hajna, N., A. Mihevc, P. Pruner & P. Bosák (2007): Time recorded in cave deposits – 10 years of paleomagnetic research in Slovenian caves. Acta Carsologica, 36(1), 242.