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RECORD OF THE PLEISTOCENE AT KARST SITES OF THE ŚWIĘTOKRZYSKIE (HOLY CROSS) MOUNTAINS REGION – A REVIEW

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Abstract:
The objective of this paper is a review of data on reconstruction of the Pleistocene palaeogeography (environment) and stratigraphy based on studies of karst sites in the Świętokrzyskie (Holy Cross) Mountains. Although the number of known Pleistocene karst sites in this region is small, the investigations of them have played a crucial role in a research of the Pleistocene. The study of the Kozi Grzbiet site provided the first evidences for new climatostratigraphy and classification of glaciations in Poland. The explanation of genesis of cryogenic calcite crystals discovered in Chelosiowa Jama-Jaskinia Jaworznicka cave system started a new direction of palaeoenvironmental reconstructions of the last glacial period. Kadzielnia palaeontological site was one of the first Early Pleistocene fossil assemblages in karst studied in Poland, whereas Raj cave provided abundant palaeontological and archaeological material from the Last Glacial. Other sites are of less scientific importance, however some of them can be used in education and popularisation of geosciences. Small number of already studied sites does not exclude discoveries of next sites of high scientific importance.

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Key words: karst sites, caves, U-series dating, Pleistocene, Świętokrzyskie (Holy Cross) Mountains

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INTRODUCTION

Karst sites – caves or palaeokarst forms – are usually objects of scientific studies aiming palaeogeographical and palaeoecological reconstructions or enabling descriptions of fossil fauna communities and evolution of particular animal taxa. In areas where denudation predominates, i.e. in elevated terrains of uplands and mountains, the sequences of cave formations, both clayey-clastic sediments and speleothems, provide scientific evidences similar to lithostratigraphic sequences in superficial depositional basins that are usually used for reconstructions of geological history. In cases of late Quaternary sequences an occurrence of man and his environmental impacts become also important items of the studies (Głazek, 1973, 1989; Madeyska and Cyrek, 2002; Urban, 2004, 2006). Reducing the examples to the territory of Poland and to the last 20 years, there are numerous publications with results of such studies performed among others in the Cracow-Częstochowa (Cracow-Wieluń) Upland, Sudetes and Tatra Mountains, which included single sites or their groups and were dedicated to specific problems of lithostratigraphy, palaeogeography, palaeoecology, morphogenesis, palaeontology, archaeology and tectonics (e.g. Madeyska and Cyrek, 2002; Valde-Nowak *et al*., 2003; Dobrowolski, 2006; Lorenc, 2006, 2007; Urban *et al*., 2007, 2015; Gradziński *et al*., 2009, 2011; Nadachowski *et al*., 2009; Stefaniak *et al.,* 2009c; Cyrek *et al*., 2010; Gąsiorowski *et al*., 2014; Krajcarz and Krajcarz, 2014; Krajcarz *et al*., 2014, 2016; Dobrowolski and Mroczek, 2015; Stefaniak, 2015; Szczygieł, 2015; Żarski *et al*., 2017; Błaszczyk *et al*., 2018). Reconstruction of morphological evolution and environmental conditions in the Late Pleistocene and Holocene in the Outer Flysch Carpathians were based on studies of non-karst caves (Margielewski and Urban, 2017).

During the history of scientific studies of karst in the Świętokrzyskie (Holy Cross) Mountains, which have lasted since 1904 (Urban and Kasza, 2006), important publications comprising palaeographical, palaecological reconstructions and stratigraphical, paleontological and archaeological interpretations were issued. However, the geological-morphological investigations of karst landforms, conducted up to the middle of 20th century, principally provided descriptive data that served rather to documentation of features than enabled their interpretation (Gradziński and Wójcik, 1966; Urban and Kasza, 2006). The discovery of Pleistocene fossils at the Kadzielnia karst site (Kowalski, 1958) was the first significant event in this region which was used for scientific reconstruction of the Quaternary fauna communities and environment. This study was complemented by general description of karst in the Kadzielnia hill and quarry (Kozłowski *et al.*, 1965). The "milestone" in these studies were scientific: geological, palaeontological and archaeological investigations conducted along with geotechnical works preparing the touristic trail in the Raj cave in 1967–1972 (Rubinowski and Wróblewski, 1972; Rubinowski, 1974) as well as the discovery of the Kozi Grzbiet palaeokarst site in June 1970 (Wódkowski, 1971) and its subsequent detailed research (Głazek *et al.*, 1976, 1977a, b; Głazek, 1989; Lindner and Marciniak, 2008).

The studies of Chelosiowa Jama-Jaskinia Jaworznicka cave system (Urban, 1994) and scientific inventory of all accessible palaeokarst forms and caves in the Palaeozoic carbonate rocks (Urban, 2002), performed in the last decade of 20th century, can be recognised as the next stage of karst research in the Świętokrzyskie Mountains region (Urban and Kasza, 2006). The research conducted at the end of the 20th century made possible the systematic classification of genetic types and generations of karst of the Palaeozoic core of the Świętokrzyskie Mountains region (Urban, 2002, 2007, 2013). However, apart from the site of Chelosiowa Jama-Jaskinia Jaworznicka cave system, this research has not brought about discovering spectacular palaeontological sites of Cenozoic karst.

More or less at the same time the sequences of two palaeokarst dolines in Upper Jurassic limestones of the northern section of marginal zone of the Świętokrzyskie Mountains (Mirówek and Maziarze sites) have been cored and analysed (Barcicki *et al.*, 1991, 1996). Furthermore, several years ago the fills of two palaeokarst dolines in Devonian carbonates in the eastern part of the region (Winna and Komorniki sites within the Kielce-Łagów Basin) were subjected to mineralogical-petrographical analyses (Ludwikowska-Kędzia, 2013).

Petrographical and palaeontological description and U-series datings of karst fills of caves prepared to the arrangement of the Underground Touristic Trails at the Kadzielnia Hill, performed in 2005–2011, were the most recent significant scientific studies of karst in the Świętokrzyskie Mountains (Urban *et al.*, 2011a, b).

Results of the studies of the Permian–Triassic palaeokarst, as well as the Neogene palaeokarst and relict karst (caves) in the Świętokrzyskie Mountains region were published in several papers (Urban, 2002, 2007, 2013; Urban and Rzonca, 2009). Therefore, the objective of this paper is gathering and completion of basic data that concern the stratigraphical interpretation as well as palaeogeographical reconstructions of the Pleistocene environment based on studies of karst forms and fills in the Świętokrzyskie Mountains region.

MATERIALS AND METHODS

A part of the material presented in this paper is the review of published data. Therefore, the authors' work consisted in studying, summarising and interpretation of publications. In most of them the study material and methods are respectively described, therefore, they are not reported here. However, part of the scientific material presented here is a direct result of authors' research, often not published or partly published. Consequently, the methods of field investigations and laboratory analyses are shortly reported hereafter.

The study of Chelosiowa Jama-Jaskinia Jaworznicka cave system in 1986–1993 was the first such scientific project (Urban, 1994). This study included mapping and description of the most interesting Cenozoic secondary carbonate forms in this cave system: all accumulations of cryogenic calcite aggregates (Durakiewicz *et al.*, 1995; Žák *et al.*, 2004) and the most interesting typical speleothems – stalagmites, stalactites and flowstones. Several U-series datings of calcite aggregates and speleothems were performed, while in the case of aggregates also analysis of stable O and C isotopes were conducted (these last were described in Žák *et al.*, 2004).

The next project realised by one of the authors was a scientific inventory and sampling of all accessible (outcropped) palaeokarst and relict karst forms in the Palaeozoic, mainly Devonian, carbonate rocks in the region performed in 1998–2000 (Urban, 2002; Urban and Kasza, 2006). Totally ca. 220 sites (dolines, karst fissures and channels filled with sediments) in 26 superficial outcrops, mainly quarries, as well as several tens of karst sites in caves, were described. Apart from field investigations, borehole archival data were collected and interpreted (Urban and Rzonca, 2009; Urban, 2013). Samples taken from the sites were used for various laboratory analyses: (a) U-series datings of ca 20 Cenozoic speleothems; (b) optical microscopic observations, palaeomagnetic analysis and stable isotope (C and O) measurements of lithified pre-Quaternary (Permian, Triassic) rocks and several Cenozoic speleothems; (c) structural-petrographical analysis of 87 samples of unconsolidated, Cenozoic karst fills, (d) X-ray analysis and analysis of heavy mineral composition of ca 20 samples of unconsolidated formations (results of these analyses for the pre-Quaternary karst fills – see Urban, 2007, 2013).

The third project realised by the authors was connected with the geotechnical works preparing the Underground Touristic Trail at the Kadzielnia Hill in 2005–2011. The geotechnical works comprised excavation and removal mainly of Quaternary unconsolidated sediments, partly filling a karst system in order to merge three formerly known caves. Along with these technical works scientific documentation and sampling of successively exposed cross-sections (profiles) of sediments were being done (Urban *et al.*, 2011a,

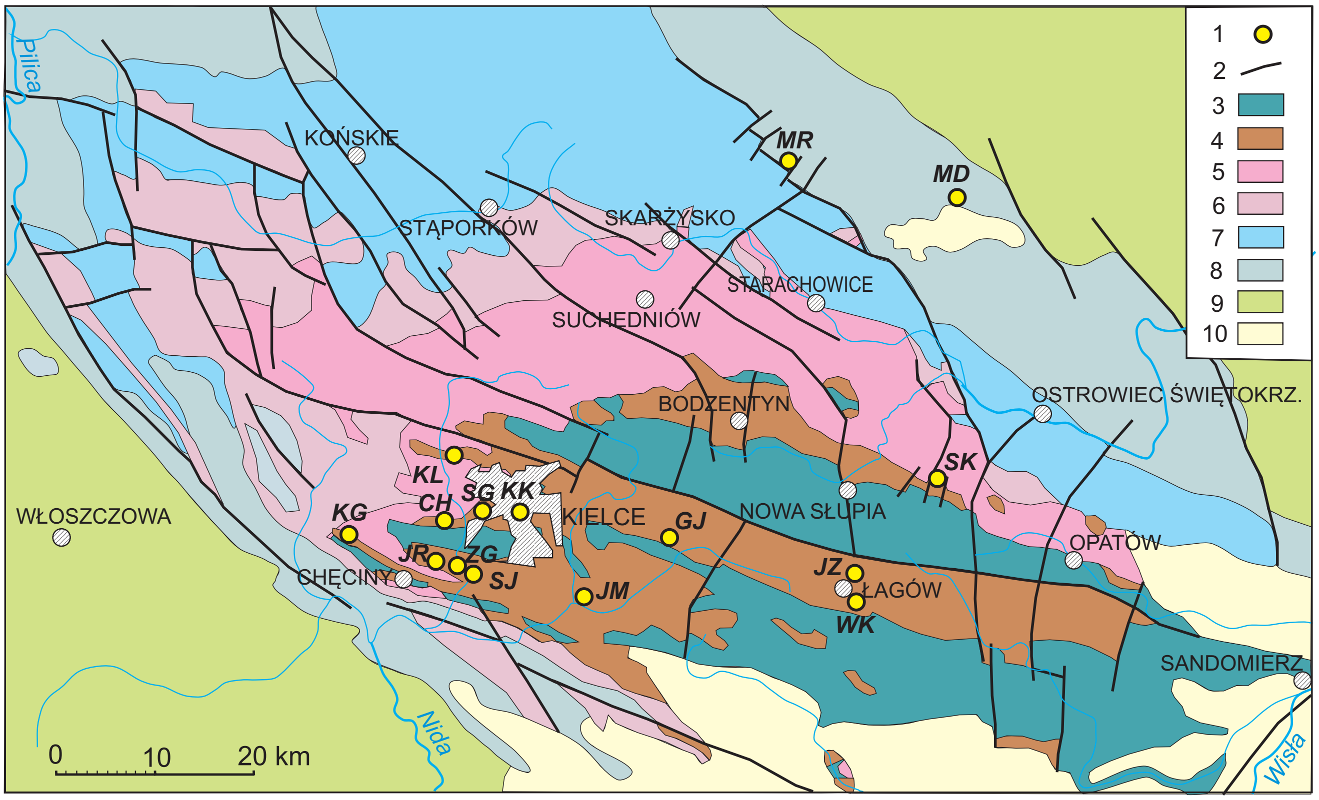

Fig. 1. Location of the karst sites described in the text against a background of a geological map of the Świętokrzyskie Mountains region (without the Quaternary cover). Explanations of symbols: 1 – sites described in the text: CH – Chelosiowa Jama-Jaworznicka cave, GJ – Górno, Józefka quarry, JM – Jaskinia w Marzyszu (Cave in Marzysz), JR – Raj (Paradise) cave, JZ – Jaskinia Zbójecka w Łagowie (Robber Cave in Łagów), KG – Kozi Grzbiet abandoned quarry, KK – Kadzielnia sites 1 and 2, KL – Kostomłoty, Laskowa quarry, MD – Maziarze, MR – Mirówek, SG – Szczukowskie Górki quarry, SJ – Sitkówka-Jaźwica abandoned quarry, SK – Skała quarry, WK – Winna and Komorniki quarries, ZG – Zgórsko abandoned quarry; 2 – fault, 3 – Cambrian, Ordovician and Silurian (sandstones, shales, claystones), 4 – Devonian and Lower Carboniferous (limestones, dolomites, marls, sandstones, shales), 5 – Upper Permian and Lower Triassic (sandstones, conglomerates, siltstones, claystones, marls), 6 – Middle and Upper Triassic (limestones, marls, sandstones, siltstones, claystones), 7 – Lower and Middle Jurassic (sandstones, siltstones, claystones, marls, limestones), 8 – Upper Jurassic (limestones, marls), 9 – Upper Cretaceous (marls, limestones), 10 – Neogene (limestones, gypsum, marls, clays, conglomerates).

2017). During these works 52 sites were documented and 74 samples of unconsolidated formations were used for structural-petrographical analysis. All samples bearing fossils, i.e. 27 ones, were examined for these fossils' identification. Several samples were also used for microscopic observation (lithified rocks – 6), X-ray analysis (clayey and ferruginous-manganese sediments – 6) and U-series datings (calcite speleothems – 10) (Urban *et al*., 2017).

In the mentioned above three projects structural-petrographical and palaeontological analyses of unconsolidated rocks as well as U-series datings of carbonate formations were principal methods used for identification and description of Quaternary fills of karst forms. As auxiliary methods also X-ray analysis and analysis of heavy minerals' composition were used. The structural-petrographical analysis included: grain size analysis, inspection of grain roundness and mineralogical-petrographical composition. Grain size analysis of sands and coarser fractions were conducted using a set of sieves, whereas percentage of finer fractions was determined on the basis of Buyucos-Casagrande areometric analysis modified by Prószyński (Lityński *et al*., 1976). Petrographical composition and grain roundness were identified with a use of a binocular.

Palaeontological analysis included identification of bat remains in sediments from the sites of Kadzielnia 2 and Jaskinia Zbójecka w Łagowie. The remains were cleaned (if necessary) using a dissecting needle and identified, if possible, to the species level. Identification was made based on the cranial skeleton only. Damaged, crashed postcranial bat skeleton parts could not be identified. Bones from the Kadzielnia 2 site, that were lithified by calcite-clayey material, were placed into the 5% aqueous solution of acetic acid to dissolve calcite. When the reaction was distinctly slowing down, bones were rinsed in clean water and reinserted into the acid solution. After a few cycles, the bones were washed last time and left to dry. Skulls and mandibles with teeth were protected with glue (Hermol dissolved with acetone) to avoid teeth loss and damage of fragile bat remains. Minimum number of individuals (MNI), which was used to calculate the percentage share of bat species in the sediments of localities, was calculated according to the method of Klein and Cruz-Uribe (1984).

Table 1. Results of U-series dating of speleothems and other secondary calcite formations from caves and palaeokarst sites in the Świętokrzyskie (Holy Cross) Mountains region.

Sample symbol	Concentration of U (ppm)	activity ratio $^{234}U/^{238}U$	activity ratio $^{230}Th/^{234}U$	activity ratio $^{230}Th/^{232}Th$	Age, corrected age (cor.) [ka]	Age limit** [Ma]	Location, type of formation
Underground Touristic Trail at the Kadzielnia Hill (Devonian limestone)							
38 BT 136	0.041±0,003	1.1±0.1	0.96±0.10	257	$320^{+\infty}_{-94}$		Komora Wiesława chamber, calcite incrustation above bone breccia
50 BT 138-3	0.047±0.003	1.2±0.1	0.81±0.08	79	170^{+40}_{-30}		Lewy Korytarz passage, horizontal (deposited on clayey-clastic sediments) flowstone
50 BT 138-2	0.065±0.004	1.2±0.1	0.87±0.07	132	200^{+40}_{-30}		
50 BT 138-1	0.162±0.007	1.14±0.06	0.95±0.05	30	270^{+50}_{-40}		
7 AN 60	0.076±0.004	1.266±0.290	2.778±0.442	15	OS		Partie Baby Jagi passage, calcite flowstone on a wall
	0.018±0.009	1.055±0.155	6.176±0.683	164	OS		
	0.076±0.005	1.030±0.080	1.054±0.081	124	>1.200		
23 AN 63	0.056±0.008	0.950±0.175	0.9318±0.177	65	>350	>1.2 (?)	Strzelisty Korytarz passage, calcite flowstone on a wall
	0.005±0.001	1.162±0.282	8.577±1.473	31	OS		
	0.048±0.004	0.920±0.080	1.068±0.098	78	>350	>1.2 (?)	
Chelosiowa Jama-Jaskinia Jaworznicka cave (Devonian limestone)							
Chel 6A*	0.140±0.030	1.190±0.030	0.950±0.030	41	265^{+40}_{-30}		Sala z Kominem chamber, thick flowstone of the older generation
Chel 6C*	0.110±0.040	1.260±0.040	0.880±0.030	43	200^{+20}_{-18}		
Chel 5*	2.120±0,030	1.480±0.020	0.290±0.010	>1000	36.0±1.2		Sala z Kominem chamber, CCC calcite aggregates
Chel 7*	2.490±0,040	1.920±0.030	0.320±0.020	807	40.0±1.3		
Chel 4*	0,390±0,010	2,450±0,040	0,020±0.001	29	2.5±0.3		Sala z Kominem chamber, stalactites of the youngest generation
Chel 3*	0,060±0,001	4,770±0,140	0,070±0.010	>1000	8.3±0.6		
Chel 1*	0,130±0,001	1,240±0,030	0,960±0,040	29	260^{+50}_{-40}		Górny Korytarz passage, large stalagmite of the older generation – lower (older) part
Chel 2*	0.130±0.001	1.260±0.040	0.800±0.040	83	160^{+16}_{-14}		Górny Korytarz passage, large stalagmite of the older generation – upper (younger) part
Jjaw 3*	5.620±0.110	2.000±0.030	0.310±0.001	376	38.8±1.4		Umaguma chamber, CCC large calcite aggregates
Jjaw 1*	8.350±0.140	1.810±0.010	0.450±0.010	>1000	61±1.8		
Jjaw 5*	8.180±0.130	1.930±0.013	0.399±0.009	336	53±1.5		
Jjaw 2*	0.130±0.001	1.060±0.030	0.940±0.030	38	278^{+57}_{-38}		NPWZ chamber. small stalactite
Kadzielnia. Jaskinia Jeleniowska cave (Devonian limestone)							
JELEN 1	0.058±0.004	1.303±0.124	0.866±0.149	16	190^{+101}_{-58} cor. 180^{+102}_{-60}		main (entrance) chamber of the cave: the oldest (2/2). older (2/1) and the younger (1) generation of flowstone
JELEN 2/1	0.034±0.004	1.117±0.157	0.094±0.145	3.4	>350 cor. >212	<1.2 (?)	
JELEN 2/2	0.076±0.006	1.088±0.123	1.088±0.126	10.5	>350 cor. >286	>1.2 (?)	
Łagów. Jaskinia Zbójecka w Łagowie cave (Devonian limestone)							
ZBOJ 1	0.142±0,004	1.078±0.033	1,036±0.024	25	>350	<1,2	Sala Naciekowa chamber, older generation of flowstones
ZBOJ 2	0.121±0.003	1.143±0.036	1.009±0.038	11	>350 cor. >283	<1.2	
Marzysz. Jaskinia w Marzyszu cave (Devonian limestone)							
MARZ 2.	9.110±0.004	1.024±0.050	1.113±0.035	112	>350	<1.2 (?)	flowstone on a ceiling
Kostomłoty. Laskowa quarry (Devonian dolostone)							
LAS 1/1	0.040±0.004	0.879±0.121	1.171±0.197	89	>350	<1.2	carbonate fissure fills: the older (1/1) and the younger (1/2) generation
LAS 1/2	0.066±0.004	1.062±0.096	0.949±0.060	41	290^{+70}_{-47}		

Szczukowskie Górki quarry (Devonian limestone)							
SZCZUK 11	0.075±0.003	1.158±0.058	1.040±0.060	131	>350	<1.2	karst channel filled with sediments, stalagmite
Górno. Józefka quarry (Devonian limestone)							
JOZ 6	0.198±0.011	1.143±0.036	1.009±0.038	175	>350	<1.2	flowstone filling a karst form

OS – dating impossible due to an open system and subsequent removal of uranium from the rock ($^{230}Th/^{234}U >> 1$); * samples analysed in 1993–1997; ** age limit estimated basing on equilibrium/disequilibrium of ^{238}U and ^{234}U ($^{234}U/^{238}U$ activity ratio ≠ 1 indicate age <1Ma).

U-series analysis in the case of all projects was performed in the Uranium Series Laboratory of the Institute of Geological Sciences, Polish Academy of Sciences in Warsaw. Uranium and thorium were separated using a standard chemical procedure for carbonate samples (Ivanovich and Harmon, 1992) by a chromatographic method using the DOWEX 1x8 ion exchanger. The chemical separation efficiency was controlled by the addition of a ^{228}Th-^{232}U spike (UDP10030 tracer solution by Isotrac, AEA Technology) before chemical treatment. The activity measurements were done on a DUO ANSEMBLE alpha spectrometer made by the EG&G ORTEC company, equipped in low-background detectors with 1200 mm^2 active area. Each spectrum was corrected for the background and delay time between the chemical separation and measurement. Due to the measurement method (α spectrometry), the range of dating was limited to 350 ka and results for relatively old samples were attributed by significant uncertainty. Moreover, low concentration of uranium in samples from several sites (Kadzielnia, Kostomłoty and Szczukowskie Górki) was a reason of inaccurate dating (Table 1). Furthermore, several samples (Jeleniowska and Zbójecka caves) were significantly contaminated with detrital thorium, which made possible to estimate age using correction algorithm only. These data were corrected assuming initial $^{230}Th/^{232}Th$ activity ratio in contaminant equal to 1.5±0.5. Nevertheless, the dating results enabled construction of general chronology in some cave systems presented hereafter.

GEOLOGICAL SETTING

In the geological terms the Świętokrzyskie (Holy Cross) Mountains unit comprises the south-eastern, most uplifted part of the Mid-Polish Anticlinorium. The unit of the Świętokrzyskie Mountains. consists of two general tectonic elements: Palaeozoic core and its Permian–Mesozoic marginal zone (Fig. 1). The Palaeozoic core was tectonically formed during the Caledonian and Variscan orogenesis, while the Permian–Mesozoic zone underwent the Alpine tectonic movements only (Karnkowski, 2008; Urban and Gągol, 2008). Both Caledonian–Variscan and Alpine geological sequences are formed almost exclusively of various sedimentary rocks. In morphological terms, the Świętokrzyskie Mountains region represents upland (with a single and small mountain range reaching 600 m a.s.l.) of clearly manifested structural relief and elevation differences between hill ranges and valleys (plains) ranging from several dozen metres to 300 m (Urban and Gągol, 2008).

In this region, a karst has developed in carbonate rocks of the Middle and Upper Devonian, mainly in the most commonly occurring stromatoporoid-coral limestone and dolostone of the Kowala Formation, up to 1 km thick, as well as in the Upper Jurassic limestone, several hundred metres thick. Karst landforms are less frequent in the Middle Triassic limestones and dolostones due to their relatively small thickness and marl-clay intercalations. Karst systems developed during two terrestrial periods of geological history of the region, namely after the Variscan tectonic movements (Carboniferous, Permian and Early Triassic) and after the Alpine, strictly Laramide tectonic movements (Palaeogene, Neogene and Quaternary). Palaeokarst features of these two periods are often overlapped and therefore, they were sometimes not correctly distinguished in the previous studies (e.g. Czarnocki, 1948, 1949; Kotański, 1959; Majchert, 1966). However, currently, lithological criteria, relationship to other geological structures (tectonic phenomena, hydrothermal mineralisation) as well as palaeomagnetic analyses make possible unequivocal distinction of fills of these karst generations (Urban, 1999, 2002, 2013).

Currently accessible Cenozoic karst systems of the region formed before the Quaternary. This is proved by their hypsometric position which is significantly high above present-day water table, as well as incoherence with present-day and even Pleistocene river network. This is also indicated by lithology of karst fills which principally originated due to the weathering of local pre-Quaternary rocks, as suggested by their petrographical composition. The karst fills which contain the sediments characterised by features diagnostic for Pleistocene deposition, such as accurate roundness and mattness of quartz sand grains (caused by their aeolian abrasion), occurrence of semi-resistant and non-resistant heavy minerals and occurrence of magmatic or metamorphic rocks from the Scandinavia (sand grains, pebbles) (Urban and Kicińska, 2001; Urban, 2013) are rare. At the beginning of the Quaternary, or – more strictly – before the Pleistocene glaciations, the erosion basis and valley bottoms were located much lower than now (Łyczewska, 1971; Lindner, 1986; Lindner *et al.*, 2001), therefore most karst systems currently partly accessible (as caves or cross-sections of filled up by sediments channels and dolines visible in quarry faces) were set much above a water table and they were of relic character in that time. However, during the Pleistocene fragments of these karst systems were cleaned off of the sediments, and/or new allogenic sediments were deposited in them. Moreover, processes of accumulation of autogenic sediments, e.g. speleothems or other formations can be discerned in these systems. Consequently, karst sites that record information on stratigraphy, palaeogeography and palaeoecology of the Pleistocene were formed. Such sites are described hereafter.

MAIN PLEISTOCENE KARST SITES IN THE ŚWIĘTOKRZYSKIE MOUNTAINS

Kozi Grzbiet site

This site (Fig. 1) was a sub-vertical karst fissure filled with sediments which cropped out in the face of abandoned quarry of Devonian limestones cut into the small hill called Kozi Grzbiet. In the fissure fills numerous fossils were discovered in 1970 (Wódkowski, 1971). In the vertical sequence of these fills the following units were distinguished (numbering from the uppermost unit – Fig. 2) (Głazek *et al*., 1976, 1977a, b):

1: medium grained, yellow-pink sand with limestone clasts, bedded in lower part;

2: three-partite sandy loams with fragments of bones, gastropod shells, as well as limestone and calcite (speleothem) clasts; the highest sub-unit 2a was brown-yellow and contained numerous rock clasts; middle sub-unit 2b was dark brown and contained less amount of rock clasts, which were smaller and partly rounded; lower sub-unit 2c was light brown and contained large rock clasts;

3: cherry-red clay composed of small clasts of claystone;

4: cherry-red clayey sand (4a, 4c) intercalated by cherry red sandy clay (4b);

5: yellow-brown clay, composed mainly of kaolinite, with carbonate concretions;

6: cherry-red clayey sand with carbonate concretions;

7: dark yellow clay with carbonate concretions, clasts of corroded limestone and lenses of cherry-red sand.

Very abundant fossils in the unit 2 were represented by remains of gastropods, amphibians, reptiles, birds and mammals (Głazek *et al*., 1976, 1977a; Młynarski, 1977; Sych, 1980; Szyndlar, 1981; Bocheński, 1984, 1989; Sanchiz and Szyndlar, 1984; Nadachowski, 1985, 1989, 1990; Pradel 1988; Wołoszyn, 1988; Czyżewska, 1989; Młynarski and Szyndlar, 1989; Rzebik-Kowalska, 1989, 1994; Stworzewicz, 1989; Wolsan, 1989a, b). In the whole unit 2 fossils of animals specific for deciduous and humid forest environment predominated. They are represented e.g. by grass snake (*Natrix natrix*), crested newt (*Triturus* cf. *cristatus*), and, among mammals: shrews of the genus *Sorex*, bank vole (*Myodes glareolus*), Eurasian beaver (*Castor fiber*), wild boar (*Sus* cf. *scrofa*), elk (*Alces* sp.) (Głazek *et al*., 1976; Szyndlar, 1981; Czyżewska, 1989; Rzebik-Kowalska, 1994). Furthermore, remains of thermophilous taxa were also found in this unit (Szyndlar, 1981), such as: Aesculapian snake (*Zamenis longissimus*), green lizard (*Lacerta* cf. *viridis*) and viper (*Vipera* aff. *ammodytes*). However, within the unit no. 2, the sub-units nos. 2a and 2c differed from the sub-unit no. 2b in colour and composition of fossils. In both first mentioned sub-units, most remains of rodents represent remains of taxa living in relatively cold and arid, steppe climate, such as lemmings (Głazek *et al*., 1976).

The presence of remains of temperate climate and forest environment species in the unit 2 proves its deposition during a principal warming. The age of this unit can be estimated by finding of *Mimomys savini* teeth – a species typ-

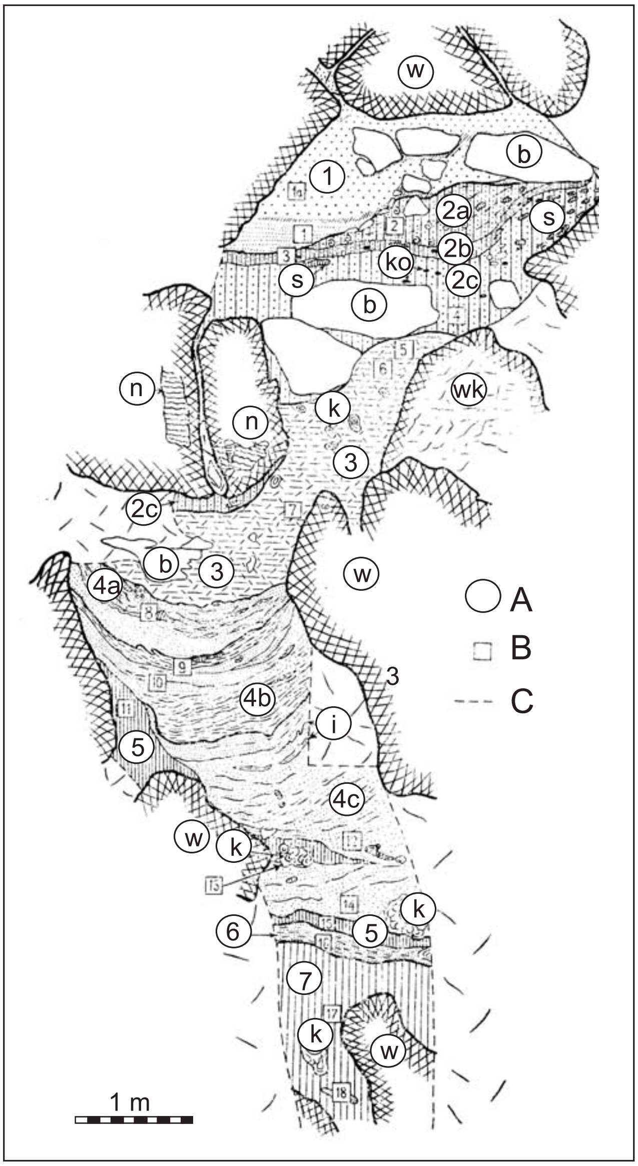

Fig. 2. Cross-section of fissure and its sediments at the Kozi Grzbiet site; copy from the paper: Głazek *et al.* (1977b) – numbers and letters of symbols were corrected. Explanations of symbols: A – symbols of units and other lithological elements, B – sample numbers, C – margins of the trench, 1–7 – unit numbers according to the description in the text, b – large limestone cobble or block, i – clay, k – carbonate concretion, ko – large bone, n – calcite flowstone, w – limestone, wk – corroded limestone surface.

ical for the Upper Biharian in Europe (Nadachowski, 1990). Dating of bones, performed with a use of fluorine-chlorine-apatite and collagen methods, point out the age of 700–550 ka BP. The palaeomagnetic data set the Brunhes-Matuyama reversal (MIS 19) within the lower section of the unit 2, whereas analysis of faunal communities and climate-stratigraphic considerations enabled identification of the period of unit 2 deposition with the Cromerian II (Głazek *et al*., 1977a, b; Lindner and Marciniak, 2008).

Lower part of the sequence (Fig. 2, units 3–7) were deposited during filling up of valleys just before and in the time of progressive glaciation. Lithology and composition of heavy minerals indicate that cherry-red sands and clays in the units 3, 4 and 6 are composed of re-deposited and weathered Lower Triassic (Buntsandstein) rocks, whereas clays of the units 5 and 7 are residual deposits of Devonian limestones. Nevertheless, in the upper part of the unit 3 grains of heavy minerals indicate admixture of Scandinavian material. Also sand of the uppermost unit 1 is of glaciofluvial origin (Głazek *et al*., 1976, 1977a, b; Lindner and Marciniak, 2008).

Such a sequence enabled – for the first time in Poland – identification of the depositional sequence (unit 2) with remains of forest fauna, which represents interglacial period within the former South-Polish Glaciation (Mindel) and consequently, its subdivision into two glaciations. The admixture of glacial material in the unit 3 indicates the older glaciation, while the unit 1 is the evidence of the younger one (Głazek *et al*., 1976, 1977a, b).

In the light of further comparative studies and analyses of other sites (Lindner, 1991a, b, 2004; Lindner and Wojtanowicz, 1997; Ber *et al*., 2007; Lindner and Marks, 2008; Lindner *et al*., 2013), the Kozi Grzbiet site became the most important site documenting the interglacial separating the Nida and San 1 (South-Polish) glaciations and was defined as stratotype for the Kozi Grzbiet formation of the Polish Pleistocene depositional succession (Lindner and Marciniak, 2008). This interglacial was named the Malopolanian Interglacial or the Kozi Grzbiet Interglacial (Gozhik *et al*., 2012; Lindner *et al*., 2013). According to the most recent conceptions the climate warming recorded by fossils of forest fauna in the unit 2 at the Kozi Grzbiet site can be identified with the second warming during the Podlasian Interglacial (MIS 19), which is documented by two floristic successions: older Augustovian succession (Szczerba and Kalejty sites) and younger Domuratovian one (Domuraty site). Chronostratigraphic position of the Kozi Grzbiet thermophilous forest in relation to these sequences (strictly Kalejty site) is recorded by the palaeomagnetic Brunhes-Matuyama reversal (Lindner *et al*., 2013; Marks *et al*., 2016).

Currently the Kozi Grzbiet site practically does not exist anymore. The bone bearing sequence was totally extracted (Lindner and Marciniak, 2008), whereas the karst fissure has got filled with loose material from the above and has overgrown. The quarry with small limestone outcrops still exists and has been protected as a nature monument since 1987 as a witness of a discovery of the palaeontological site (Wróblewski, 2000). The collection of fossils gathered there has been stored in the Institute of Systematics and Evolution of Animals of the Polish Academy of Sciences in Cracow (Poland).

Raj cave

According to Lindner and Braun (1974) the karst system with the Raj (Paradise) cave developed in the Neogene or early Quaternary, whereas its present-day sediments formed after the Last Interglacial (Fig. 1). The cave sediments were cut (by trenches) in 1967–1972 during the geotechnical works preparing the touristic trail. Along with these works comprehensive geological, palaeontological and archaeological investigations were performed in the following cave parts: Korytarz Wstępny (Entrance Passage), Komora Wstępna (Entrance Chamber), Sala Wysoka (High Chamber) and Sala Stalaktytowa (Stalactite Chamber) (Rubinowski and Wróblewski, 1972; Rubinowski 1974; Madeyska, 1972, 1974).

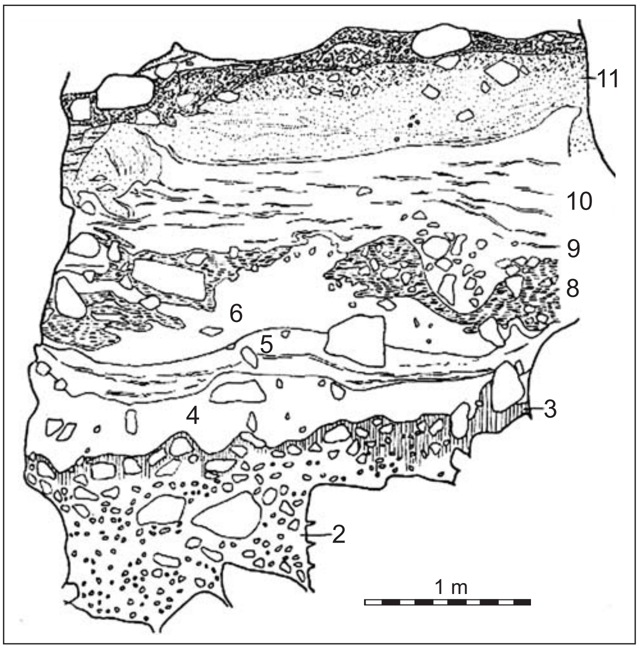

Fig. 3. Schematic transversal cross-section of sediments in the Korytarz Wstępny (Entrance Passage) of Raj cave (based on materials of J.K. Kozłowski, simplified); copy from the publication of Madeyska (1974) – numbers of lithological units were corrected (lack of units 7 and probably 12 in this cross-section).

In the sedimentary sequence of the Korytarz Wstępny passage Madeyska (1972, 1974) distinguished the following units (numbering from the lowest unit – Fig. 3):

12: calcite flowstone;

11: stratified light-brown to reddish-brown, fine- and medium-grained sand with aggregates of charcoal (thickness: 20–50 cm);

10: stratified grey-brown and greenish-grey loess-like silt with sand lenses (40–60 cm);

9: brown or greenish-brown loess-like silt with angular, rarely partly rounded limestone cobbles up to 40 cm in diameter (up to 50 cm);

8: red-brown sandy loam with angular unweathered cobbles and sand lenses (up to 30 cm);

7: dark brown and red sand forming lenses and discontinuous patches;

6: dark brown sandy loam with sand lenses and small admixture of partly weathered limestone and calcite rubble (up to 50 cm); upper cultural horizon with archaeological artefacts;

5: grey-buff sandy silt forming patches and lenses (up to 20 cm);

4: brown and grey-brown sandy loam with small amount of limestone rubble and cobbles (up to 20 cm); lower cultural horizon with archaeological artefacts;

3: discontinuous lenses of brown sand with limestone rubble and admixture of humus (up to 15 cm);

2: grey-brown clayey loam with great amount of limestone rubble relatively well rounded as well as small calcite crystals and aggregates, some of them resembling cave pearls (50–80 cm);

1: dark brown loam with great admixture of organic matter; the sediment fills fractures in the rocky, limestone cave bottom.

The outcrops of sediments situated in the deeper parts of the cave presented less apparent (more difficult to describe) sequences, but generally similar to the sequence from the entrance part of the cave provided above (Madeyska, 1972, 1974).

Vertebrate bones were found in all units, except for the units 7 and 12. They represent mammals, reptiles, amphibians and rarely fish. In the uppermost unit 12 (calcite flowstone) gastropod shells were identified (Bocheński, 1974; Kowalski, 1972, 1974a; Nadachowski, 1982; Czyżewska, 1989; Młynarski and Szyndlar, 1989; Rzebik-Kowalska, 1989, 1994; Wolsan, 1989a, b). Among these fossils the most numerous animals are insectivores, bats, rodents, carnivorans, proboscideans (*Mammuthus primigenius*), perissodactyls (mainly *Equus caballus*) and artiodactyls (mainly *Bison priscus*). Due to fluvial redeposition bones within some units were mixed (Kowalski, 1972, 1974a).

In the units 4 and 6 (Fig. 3) numerous prehistoric tools made of flint and other rocks (e.g. erratics) and raw materials were found. Tool and raw material processing refers these artefacts to the Middle Palaeolithic Mousterian cultural complex, Charentian group (Kaczanowska, 1974; Kozłowski, 1972, 1974).

According to the authors of the geological and palaeontological description (Kowalski *et al.,* 1972, Kowalski, 1974a, Madeyska, 1974), petrography of the depositional sequence, content of organic, ferruginous and phosphate material as well as assemblage of fossils indicate that all lithological units of cave sediments, except for the uppermost calcite one (or – as Kowalski, 1974a, suggested – two uppermost units 11 and 12), were deposited during the Vistulian. Madeyska (1981) stated that units 1–6 formed in the Early Vistulian (MIS 5) and units 8–10 – in the Lower Plenivistulian (MIS 4). In the publications by Lorenc (2007), dedicated to the palaeo-temperature reconstruction of the Vistulian, based on fossil bird communities, only the units 2–3 are assigned to the Early Vistulian, while the units 4–10 – to the Plenivistulian. Rodent bones (*Microtus agrestis*, *Microtus glareolus*, *Castor fiber*), shrews (*Sorex araneus*, *Sorex minutus*) and brown bear (*Ursus arctos*) occurring in the units 1–3 indicate temperate climate and humid meadow-forest environment. The climate cooling occurred during the deposition of the unit 4 which is also a cultural horizon. Some vertebrate fossils in this unit represent taxons typical for cold climate and unforested environment such as two species of ptarmigans *Lagopus lagopus* and *Lagopus mutus* as well as ground squirrel *Spermophilus citelloides* – former *Citellus citelloides* (Kowalski, 1974a). Silt of the unit 5 marks periodic overflow of the cave passage, followed by remains of human dwelling in the cave. Upper units 7–10 developed owing to supply (mainly by flowing water) of clay (according to Madeyska, 1974 – of *terra rossa* type) and loess-like silts during the maximum cooling in the Plenivistulian and directly after it. Occurrence of loess-like silts upon sands and silt-rubble sediments resembles depositional sequences described in caves of the Cracow-Częstochowa Upland (see Madeyska-Niklewska, 1969; Krajcarz *et al*., 2016). In sediments of the unit 6, as well as the units 8 and 9 number of fossils of animals typical for arctic climate and tundra environment – firstly humid and later arid – gradually increases. Among them are lemmings *Lemmus lemmus* and *Dicrostonyx torquatus*, narrow-headed vole *Microtus gregalis*, ground squirrels *Spermophilus superciliosus* (*Citellus superciliosus*), *Spermophilus citelloides* and ptarmigans. However, the fauna remains in the unit 10 indicate gradual change in the environment and shrubs expansion (Kowalski, 1972, 1974a, b). The unit 11 developed due to water inflow into the cave and is correlated with the formation of the Vistulian terrace of the Bobrzyczka Stream in the valley next to the cave entrance (Lindner and Braun, 1974). In this unit both bones of mammals typical of tundra (lemmings and narrow-headed vole) and forest species, such as bank vole (*Myodes glareolus*), squirrel, mouse, fat dormouse (*Glis glis)*, Bechstein's bat (*Myotis bechsteinii*) and wildcat (*Felis silvestris*) were found (Kowalski *et al.,* 1972; Kowalski, 1974a, b; Madeyska, 1974).

In the time of research, Raj cave was one of the rare cave sites in Poland being studied in details and the Middle Palaeolithic cave site located farthest to the north in Europe (Kaczanowska, 1974). However, subsequently, Neanderthal cave sites situated farther to the north in Belgium, North Wales and Finland have been discovered (Schulz, 2010). Since 1968 the cave and its surroundings have been protected as a nature reserve (Kozłowski, 1974; Wróblewski, 2000). In June 1972 the Raj cave was opened to a public as a show cave and since this moment its sediments have not been a subject of study. The palaeontological collection gathered in 1969–1972 has been stored in the Institute of Systematics and Evolution of Animals of the Polish Academy of Sciences in Cracow (Poland).

Kadzielnia, site 1

The first information on a discovery of fossil bones at the Kadzielnia site derives from 1904 when, due to the quarrying of the Upper Devonian (mainly Frasnian) limestone, the main chamber of Jaskinia Jeleniowska (Deer Cave) in the Skałka Geologów (Geologists' Rock, a remained part of the Kadzielnia Hill) was opened. Within sediments of this chamber bones of deer and rhinoceros were found. Jaskinia Jeleniowska is much older than these fossils, pre-Quaternary which is proved by its hypsometric position in the upper part of the hill and the age of speleothems (Table 1, Figs. 4 and 5) (Urban *et al*., 2011a, b, 2018a).

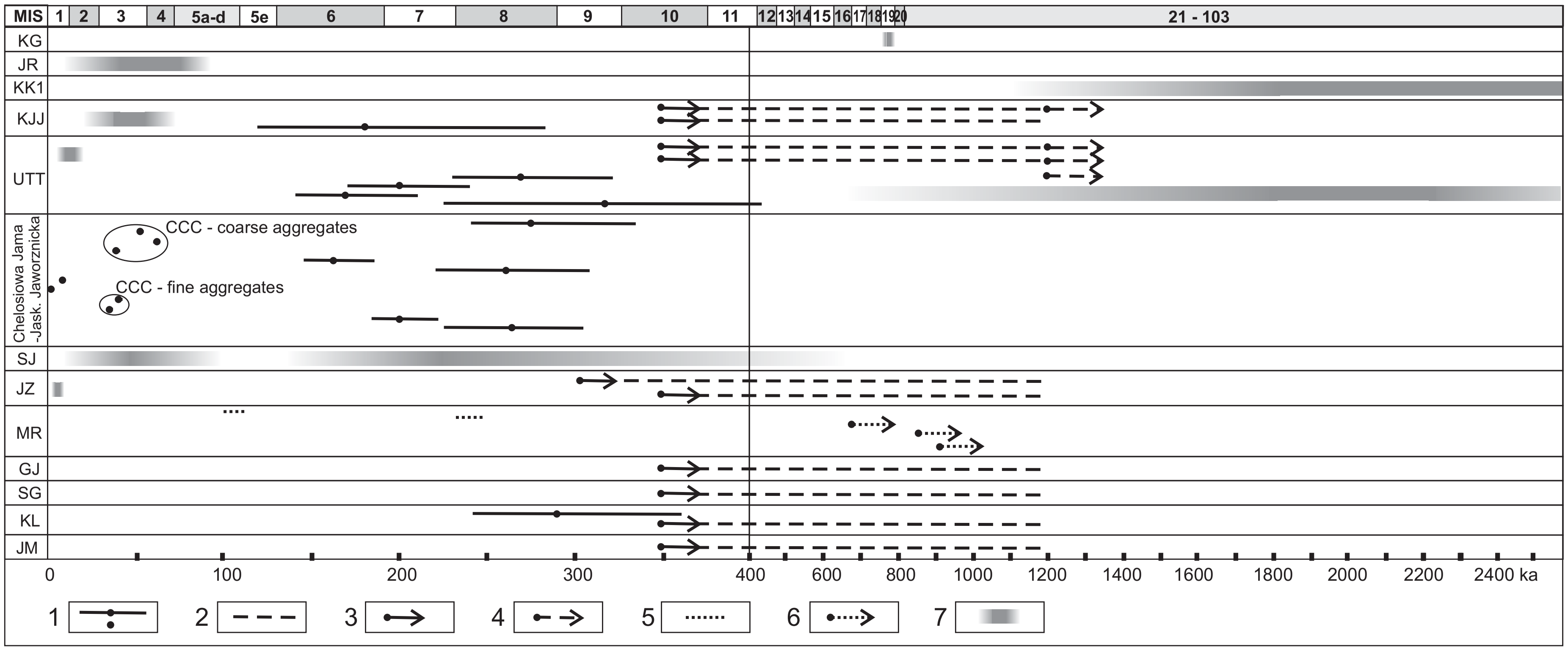

Fig. 4. Results of U-series datings (authors' data see Table 1), TL datings (after Barcicki *et al.*, 1991) and ages suggested by Quaternary paleontological data (after publications quoted in the text) of karst sites in the Świętokrzyskie Mountains region. Abbreviations: GJ – Górno, Józefka quarry, JM – Jaskinia w Marzyszu, JR – Raj cave, JZ – Jaskinia Zbójecka w Łagowie, KG – Kozi Grzbiet, KJJ – Kadzielnia, Jaskinia Jeleniowska and bones collected by J. Czarnocki in this cave and its surrounding, KK1 – Kadzielnia, site 1, KL – Kostomłoty, Laskowa quarry, MR – Mirówek, SG – Szczukowskie Górki quarry, SJ – Sitkówka-Jaźwica abandoned quarry, UTT – Underground Touristic Trail at the Kadzielnia Hill (Kadzielnia site 2). Symbols: 1 – U-series dating, 2 – U-series dating, possible age, 3 – U-series dating, older than, 4 – U-series dating, probably older than, 5 – TL (thermoluminescence) dating or datings, 6 – TL (thermoluminescence) dating, older than, 7 – estimated age of fossils.

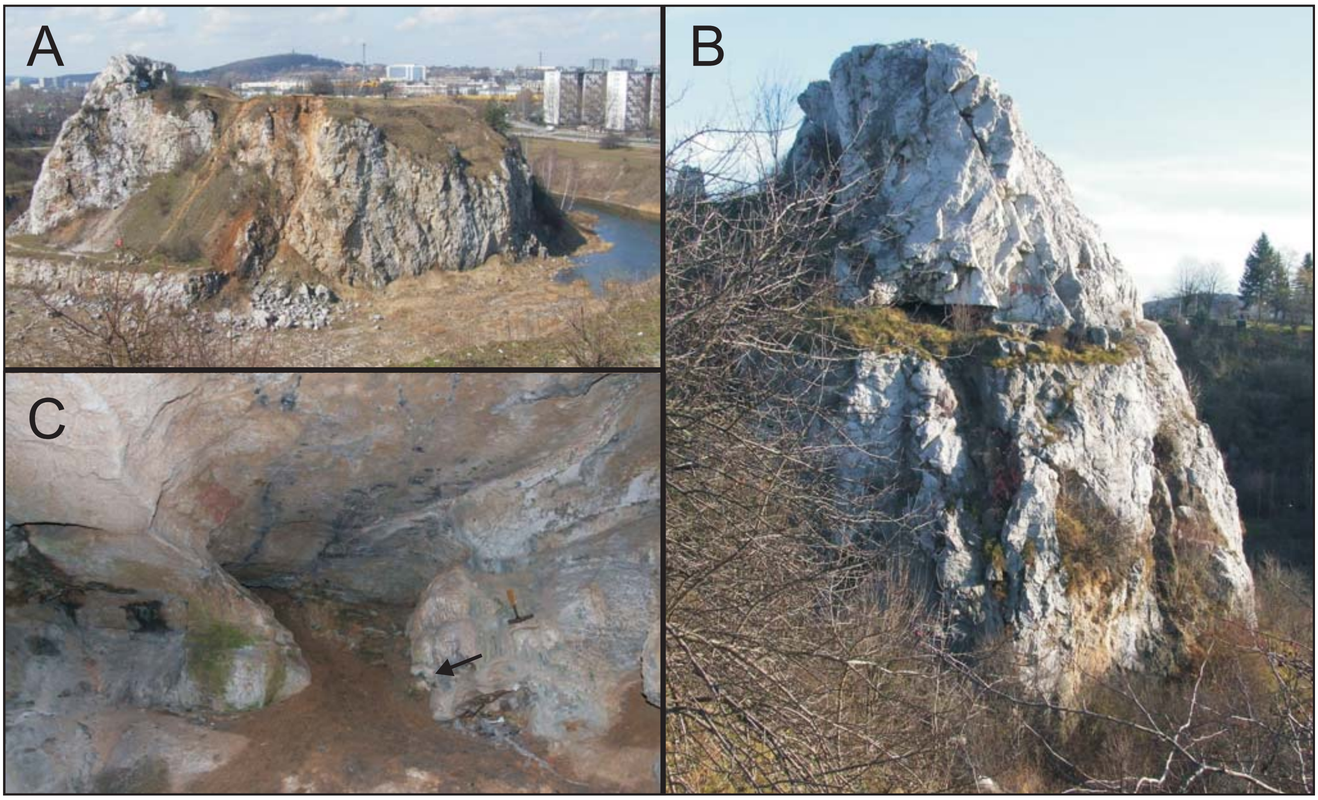

Fig. 5. Kadzielnia, site 1: A – Skałka Geologów (Rock of Geologists) from the north-east, B – Skałka Geologów from the west; the entrance to the main chamber of Jaskinia Jeleniowska (Deer Cave) is visible; C – main chamber of Jaskinia Jeleniowska with remains of large flowstones, the arrow points flowstone dated by U-series method (photo J. Urban).

In a note published in 1930s Czarnocki (1932) mentioned occurrence in "karst pockets" of the Skałka Geologów numerous remains of "arctic fauna", among which were bones of lemmings, reindeer and rhinoceros. The subsequent note of Czarnocki (1948), which mentioned large cave "with silty, loess-like sediments with abundant fossils of rodents and bones of rhinoceros and cave bear" indicates again the Jaskinia Jeleniowska (Fig. 5B, C) as a site with discovery of fossils. From more than 150 bones collected by Czarnocki at the Kadzielnia site and stored in the Geological Museum of the Polish Geological Institute – National Research Institute, 52 specimens have been recently studied. Among them mainly cave bear remains and single bones of bison, wild boar, rhinoceros, hare and mustelids were identified. This collection most probably represents a fauna from the middle Vistulian (Woroncowa-Marcinowska *et al.*, 2017).

The name "Kadzielnia site 1" is used here for the site with fossils studied in the middle of the 20th century and described in detail by Kowalski (1958) as the collection of bones of small mammals which occurred in fills of karst fissures within the upper part of the Skałka Geologów rock (Fig. 5A, B), however, the strict location of these fissures is unknown at present. They cannot be linked with "karst pockets" mentioned by Czarnocki (1932), because the age of fauna described by Kowalski (1958) is assigned to the end of the Neogene and the beginning of the Pleistocene (Nadachowski, 1990). In the assemblage of fossils collected by Kowalski typical Pliocene rodent species were identified, such as *Mimomys pliocaenicus*, *Mimomys reidi*, as well as taxons characteristic for the Early Pleistocene: *Microtus* (*Allophaiomys*) *pliocaenicus* and *Pliomys lenki* (Kowalski, 1958; Nadachowski, 1990). Remains of thermophilous mammals and reptiles were also described among these fossils, e.g. extinct lizard *Ophisaurus* cf. *pannonicus*, Aesculapian snake (*Zamenis longissimus*), greater horseshoe bat (*Rhinolophus* cf. *ferrumequinum*) and fossil bat species *Rhinolophus* cf. *macrorhinus* (Kowalski, 1958; Wołoszyn, 1988; Młynarski and Szyndlar, 1989). In this collection mammals characteristic for forest environment are also present, e.g. dormouse *Glis sackdillingensis* and *Muscardinus* cf. *avellanarius*, red-backed voles (*Myodes* sp.), four species of shrews of genus *Sorex* as well as wood mouse *Apodemus* sp. (Kowalski, 1958, 1963; Rzebik-Kowalska, 1994). Such a composition of fauna community indicates occurrence of forest in the vicinity of the Kadzielnia Hill, which, however, do not predominated, because remains of rodents connected with open areas, namely three species of hamsters (*Allocricetulus bursae*, *Allocricetulus ehiki*, *Cricetulus runtonensis*), ground squirrel (*Spermophilus polonicus*) and lemmings were identified in the collection (Fahlbusch, 1969; Black and Kowalski, 1974; Nadachowski, 1990).

The inventory of palaeokarst forms conducted at the end of 20th century as well as investigations of fossils in karst fills of the cavities (caves) in the Skałka Geologów performed in 2011–2012 in order to the identification of source sites of Czarnocki collection (stored in the Geological Museum, as mentioned above) have not provided new finds of fossils. These studies indicated that the fills of the currently accessible karst forms, also caves, represent mainly Neogene or Early Pleistocene sediments as well as loess-like silt of the last Pleistocene glacial period (Woroncowa-Marcinowska *et al*., 2017; Urban *et al*., 2018a).

Skałka Geologów in the Kadzielnia Hill has been protected as an inanimate nature reserve since 1962 (Wróblewski, 2000), while the collection of Kowalski has been stored in the Institute of Systematics and Evolution of Animals of the Polish Academy of Sciences in Cracow (Poland).

Kadzielnia, site 2

The Kadzielnia site 2 comprises the sediments in 3 caves: Jaskinia Odkrywców (Explorers' Cave), Prochownia (Gunpowder Magazine) and Szczelina na Kadzielni (Crevice in the Kadzielnia) which are fragments of a karst system developed along the vertical fault in the Devonian limestone of the eastern face of the Kadzielnia abandoned quarry. These caves were connected in order to preparation and arrangement of the Underground Touristic Trail at the Kadzielnia Hill – a show cave available to public since 2011 (Fig. 6A, E). Along with the geotechnical works in 2004–2011 that included partial removing of sediments, scientific studies of these sediments were performed. They consisted in sampling, field description of outcrops and subsequent petrographical and palaeontological analyses of rocks as well as U-series dating of calcite speleothems and sediments (Urban *et al*., 2011a, b, 2017, 2018a).

Although currently the Underground Touristic Trail is easily accessible, sediments in this range of karst passages represent relatively deep underground deposition, because the karst system became accessible owing to deep incision by the quarry of the limestone massif of the Kadzielnia Hill. The following types of Cenozoic sediments were distinguished in the studied passage range (Urban *et al*., 2011a, b):

A. Calcite flowstone covering cave walls and in some places, a cave floor formed of clayey-clastic sediments, as well as occurring as clasts in these sediments. The U-series datings indicate the age of wall flowstones older than 350 ka BP, possible older than 1,200 ka BP (where the radiogenic equilibrium state between ^{234}U and ^{238}U is less than measurement errors), the age of calcite aggregates formed on a bottom of a palaeolake, older than 226 ka and the age of flowstone covering the palaeofloor of cave passage (partly hung up to 2 m above the present-day floor) – between 150 ka and 300 ka (Table 1, Figs. 4 and 6A, C).

B. Lithified calcite-clayey fills which are not speleothems: marl and breccia composed of Devonian rubble cemented by marly material. A marl filling a karst fissure in the Lewy Korytarz (Left Passage) in the vicinity of remained lacustrine calcite aggregates older than 226 ka, bears bat bones (Table 1, Figs. 4 and 6A, B). Among these fossils there are: a fragment of jaw of Bechstein's bat (*Myotis* cf. *bechsteinii*) and teeth similar to extinct species of long-eared bats (*Plecotus* sp.) and pond bat (*Myotis dasycneme*), but more delicate and differing with some details of structure. It is not possible to determine the exact age of these fossils, but the Early Pleistocene age can be suggested.

C. Red-brown clay, silty clay and sandy-silty clay (loam) with admixture of limestone and/or calcite rubble in some places (Fig. 6D). This sediment is composed both of residuum of Devonian limestone weathering in a warm climate of the Neogene (i.e. *terra rossa*) and material of weathered Lower Triassic claystone of overburden of Devonian limestones (Urban *et al*., 2011a). Bat bones occurring in this sediment suggest that transport of this material from a ground surface to the karst system (where it is now) occurred not before the Late Pleistocene.

D. Beige and reddish-beige silt and clayey silt somewhere with an admixture of fine grained sand (Fig. 6C). This is a loess-like sediment (definition: see Krajcarz *et al*., 2016) transported from a ground surface to the karst system by water in the Late Pleistocene or at the beginning of the Holocene, as it is suggested by bat remains.

E. Loam-limestone rubble sediment developed due to the gravitational breakdowns of material of thin-bedded clayey-marl-limestone Famennian (Upper Devonian) series that occurs directly above the thick-bedded limestone within which the karst system formed. This sediment overlay clay (C) and silt (D), which indicates its younger age. The breakdowns could have occurred at the end of the Pleistocene and in humid periods of the Holocene. Such a succession of sediments is different than in the depositional sequences in caves of the Cracow-Częstochowa Upland, where rubble units occur under the loess-like units (Krajcarz e*t al*., 2014, 2016). This is caused by different factors controlling sedimentation – strictly climatic factor in the Cracow-Częstochowa Upland and lithological-climatic reasons of rock breakdowns at the Kadzielnia site, where the upward development of karst fissures had to precede a climatic impact on weathering and collapsing processes.

The bat remains that occur in clay (C) and silt (D), and exclusively (in the secondary deposit) in loam-rubble sediment (E), are represented most often by long bones that are not suitable for detailed taxonomic identification, and less frequently by teeth. Identified fossils comprise taxons currently living in the Polish territory. Among them teeth of Bechstein's bat (*Myotis bechsteinii*) and brown long-eared bat (*Plecotus auritus*) predominate. Moreover, Natterer's bat (*Myotis nattererii*), whiskered bat (*Myotis mystacinus*), Brandt's bat (*Myotis brandtii*), pond bat (*Myotis dasycneme*) and Daubenton's bat (*Myotis daubentonii*) were identified. Such a taxonomic composition and fauna structure is typical for sediments of the Late Pleistocene and Early Holocene in Poland. This opinion is confirmed by occurrence of species, which emerged in the Polish territory at the end of the Pleistocene (*M. daubentonii*) or became common in tanatocenoses in the Holocene (*M. brandtii*, *M. mystacinus*). Furthermore, white or light yellow colour of

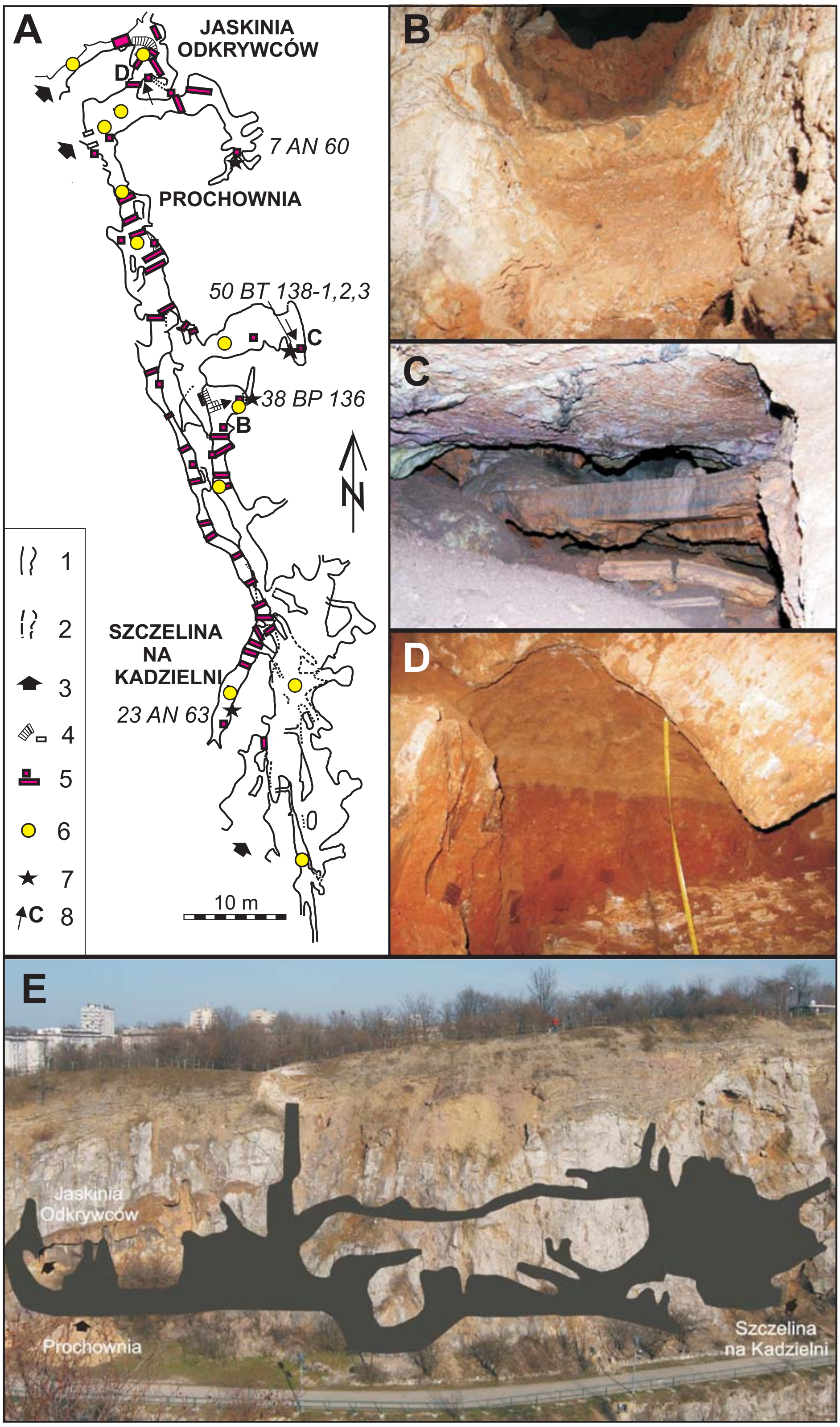

Fig. 6. Kadzielnia, site 2 – Underground Touristic Trail at the Kadzielnia Hill: A – simplified map of cave system explored and studied during the geotechnical works preparing the touristic trail (after Urban *et al*., 2011a) with outcrops and other sites documented and sampled (sampling sites mentioned below are described by symbols); B – outcrop of marl bearing bat bone breccia, the calcite incrustation occurring just above it was dated (sample 38 BT 136, Table 1, Fig. 4) (photo J. Urban); C – dated calcite flowstone that covered clayey-clastic sediments in the past (samples 50 BT 138-1, 50 BT 138-2, 50 BT 138-3, Table 1, Fig. 4) (photo J. Urban); D – cross-section of sediments: clay in the lower part of the sequence, loess-like silt in its upper part (photo A. Kasza); E – longitudinal cross-section of cave system explored and studied during the geotechnical works preparing the touristic trail against the quarry face (after Urban *et al*., 2011a). Explanations of symbols: 1 – cave contours, 2 – cave contours in places of overlapping cave passages situated on different levels, 3 – cave entrance, 4 – anthropogenic elements (stairs, artificial walls), 5 – documented and sampled outcrops and other sites, 6 – educational point of the touristic trail, 7 – site of sampling for U-series datings (with sample symbol – Table 1), 8 – site of photograph: B, C and D.

most bones suggest their Late Pleistocene–Holocene age. Nevertheless, in some samples (fossil assemblages) older, brown and dark brown bones are present. Among these bones teeth of fossil species and sub-species, i.e. *Myotis* cf. *bechsteinii robustus* and *Plecotus* cf. *abeli*, were identified. They could have come from the Early Pleistocene sediments (Urban *et al*., 2011a, b).

In the Late Pleistocene–Early Holocene bat community identified at the Kadzielnia site 2, species connected with forest environment predominate (25% of fossils of Bechstein's bat). However, a contribution of taxons connected with water environment as e.g. pond bat and Daubenton's bat indicates occurrence of slow flowing and stagnant water (stream and lakes) in the proximity of the site. Also the occurrence of numerous bones of whiskered bat and Brandt's bat, suggests cooling and higher humidity (Urban *et al*., 2011a, b).

Collected samples were stored in the Geopark Kielce, an office of the Kielce Municipal Council, which managed the Underground Touristic Trail at the Kadzielnia Hill. Selected depositional sequences of sediments outcropped during preparatory works and then studied, among them the marl bearing bat bones, are a subject of presentation in this trail (Urban *et al*., 2011b, 2017).

Chelosiowa Jama-Jaskinia Jaworznicka cave system

Chelosiowa Jama-Jaskinia Jaworznicka comprises the longest cave system in the Świętokrzyskie Mountains region and one of the longest in Poland, ranging a length of 3670 m and a vertical extent (to the water table in the bottom lake) of 61 m (Urban, 1996; Urban *et al*., 1997). The cave system is of maze shape and is principally horizontal, developed on two storey not very distinctly separated (with vertical distance of some 10 m), which are connected with sloping and vertical channels (Fig. 7A, B). Such a shape of this cave system is a result of its development within a zone of mixing waters derived from different rock environs and,

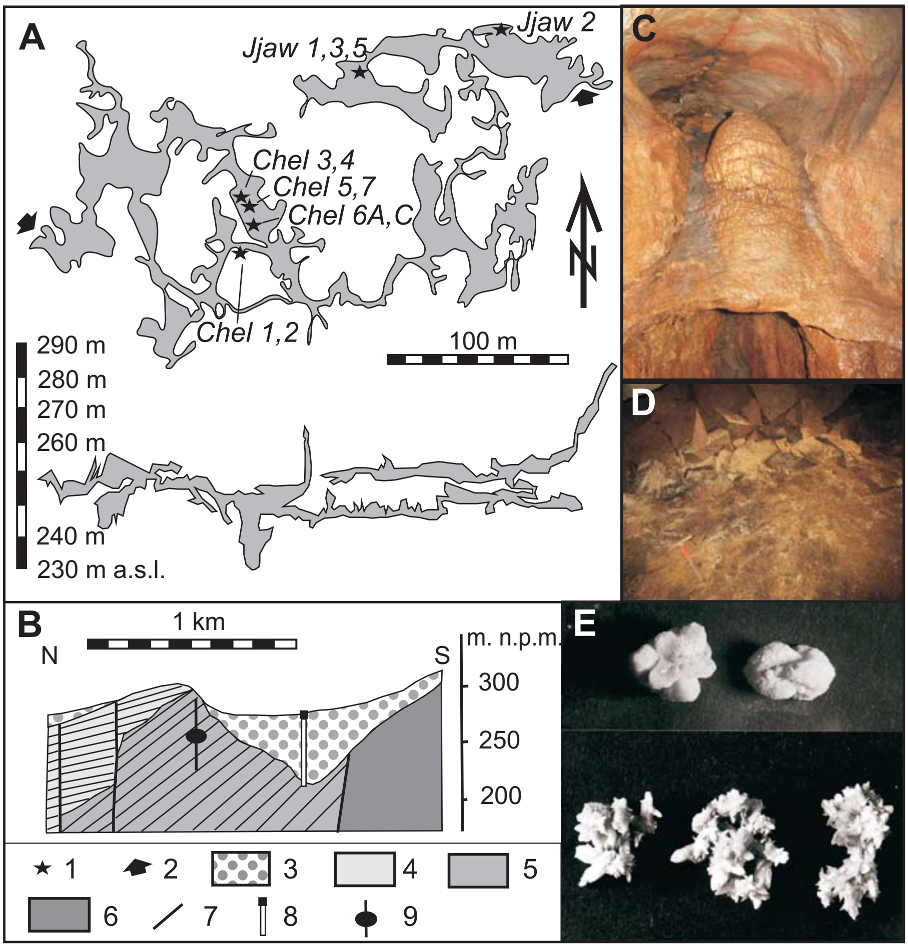

Fig. 7. Chelosiowa Jama-Jaskinia Jaworznicka cave system: A – simplified map and longitudinal cross-section of the cave; in the map sampling places for the U-series datings are situated (map after J. Gubała and A. Kasza in Urban, 1996); B – situation of the cave against the geological and morphological cross-section (after Urban and Rzonca, 2009); C – stalagmite hung on walls dated by the U-series method (samples Chel 1, 2), the sediments supported the stalagmite and flowstone at its basement must have been washed out (photo J. Urban); D – accumulation of aggregates of CCC (cryogenic calcite crystals) in Sala Kokosowa chamber (photo A. Kasza); E – aggregates of CCC of an estimated size up to 10 mm (photo P. Suchanek). Explanations of symbols: 1 – place of sampling presented in Table 1 and Fig. 4; 2 – cave entrance (artificial, in quarry face); 3 – Quaternary fills of pre-glacial valley, 4 – Permian-Triassic conglomerates, sandstones and heterolites (sandstone-siltstone-claystone series), 5 – Devonian limestone, 6 – Lower Palaeozoic and Lower Devonian siliciclastic-clayey rocks; 7 – fault, 8 – borehole recording the pre-glacial palaeo-valley, 9 – vertical extent of Chelosiowa Jama-Jaworznicka cave in which the levels of horizontal development of most passages is marked by a circle.

consequently, of different mineralisation. Hypsometric situation of the system and its horizontal formation with 2 levels proves its connection with an erosional basis when it was located much higher than at the beginning of the Quaternary, and consequently, formation of the system before the Quaternary, most probably in the Neogene. Nevertheless, in the Pleistocene, particularly during the ice-sheet advances and after a glaciofluvial filling of the valleys, the system was overflowed and washed out by waters (Urban and Rzonca, 2009; Urban, 2013).

In a framework of the documentation and research of this cave system in the last decade of the 20th century the U-series datings, stable isotope analysis and petrographic observations of speleothems and other calcite secondary forms were performed. The older generations of speleothems, somewhere partly corroded, are represented by thick flowstones covering walls and large stalagmites which are currently hung on the walls (Fig. 7C) or broken and collapsed (after a removal of supporting clayey-clastic sediments by water). Their age is principally estimated (using the U-series method) at 150–350 ka. Typical speleothems of the youngest generation, comprising white or glassy-white small stalactites and helictites, have developed in the Holocene and often keep growing (Table 1, Fig. 4).

The most interesting group of secondary formations discovered and described in Chelosiowa Jama-Jaskinia Jaworznicka is represented by calcite aggregates of a size from <1 mm to several centimetres, which occur on cave floor or gently sloping walls forming smaller or larger accumulations (up to a few centimetres thick lenses of loose aggregates) (Fig. 7D, E). Such aggregates were discovered and for the first time (in the world) described just in this cave system (Durakiewicz *et al*., 1995). After the findings of very similar formations in 2 other caves of central Europe, their genetic interpretation was given: composition of C and O stable isotopes of calcite aggregates proved that they developed due to precipitation of calcite during repeated freezing and melting of water that partly or totally filled karst channels. The U-series datings indicated that aggregates formed during the Lower Plenivistulian and Interplenivistulian (not in the climatic pessimum, Table 1, Fig. 4), therefore they could be related with oscillation of permafrost margins (Žák *et al*., 2004). Since that moment such aggregates, named commonly the cryogenic calcite crystals (CCC), have been found in many other caves and their isotopic composition, structures and ages provide prominent evidence of permafrost occurrence in karstified rock massifs during the last Pleistocene glaciation (e.g. Lacelle *et al*., 2006; Richter *et al*. 2010; Žák *et al*., 2012, 2017).

In this way the next karst site in the Świętokrzyskie Mountains region – apart from the Kozi Grzbiet site – has become a basic site for the new field of paleoenvironmental and paleoclimatic research. However, currently the Chelosiowa Jama-Jaskinia Jaworznicka cave system is not a subject of research. Since 1997 it has been protected in the inanimate nature reserve "Chelosiowa Jama", together with its surface surroundings (Wróblewski, 2000).

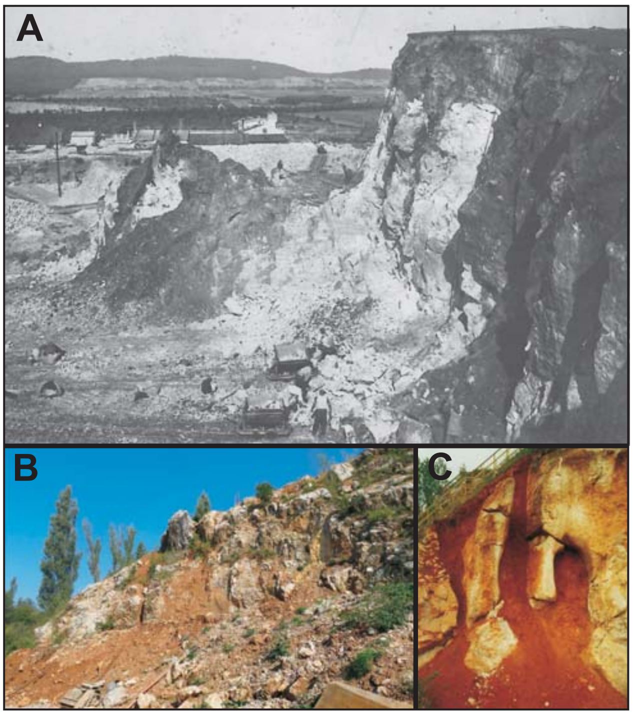

Fig. 8. Sitkówka-Jaźwica site: A – quarry in which the palaeokarst doline described by Czarnocki (1935) was found (after Woroncowa-Marcinowska *et al*., 2017, photo. J. Czarnocki in 1948, from the collection of the Geological Museum, Polish Geological Institute – National Research Institute); B – northern face of the southern quarry in the cluster of quarries in which the palaeokarst doline was found, Devonian limestone densely dissected by karst fissures filled with loams (photo J. Urban); C – northern face of the same quarry, typical Neogene palaeokarst forms filled with clay (photo J. Urban in 1999).

Sitkówka-Jaźwica site

In 1935 or shortly before 1935 in the southern part of a cluster of quarries of Devonian limestone at Sitkówka village (currently the system of jointed quarries is used by Trzuskawica SA, CRH Company, as a slime settler), in the northern face of the quarry (Figs. 1 and 8A) a karst doline cropped out. It was filled with boulders of local limestone and erratics lying upon loam. The inter-boulder space was filled with sand and clayey-silty sand, in which fossils of vertebrates as well as flints and fragments of charcoal were found at a depth of 8–10 m. According to Czarnocki (1935), among bones there were remains of cave bear, deer, carnivores, rodents and birds, while flint fragments look like processed and used by a man. Czarnocki suggested that the material originated owing to the washing out of a till of the Odranian Glaciation and was transported to the karst doline during an interglacial period. Consequently, the bones which displayed a traces of rounding, were also re-deposited. His collection of bones was stored in the Geological Museum of the Polish Geological Institute – National Research Institute in Warsaw. From among 90 specimens of this collection 44 ones have been recently analysed in detail and the following taxons were identified: horse, rhinoceros, elk, rein-deer, bear, cave hyena and badger. The occurrence

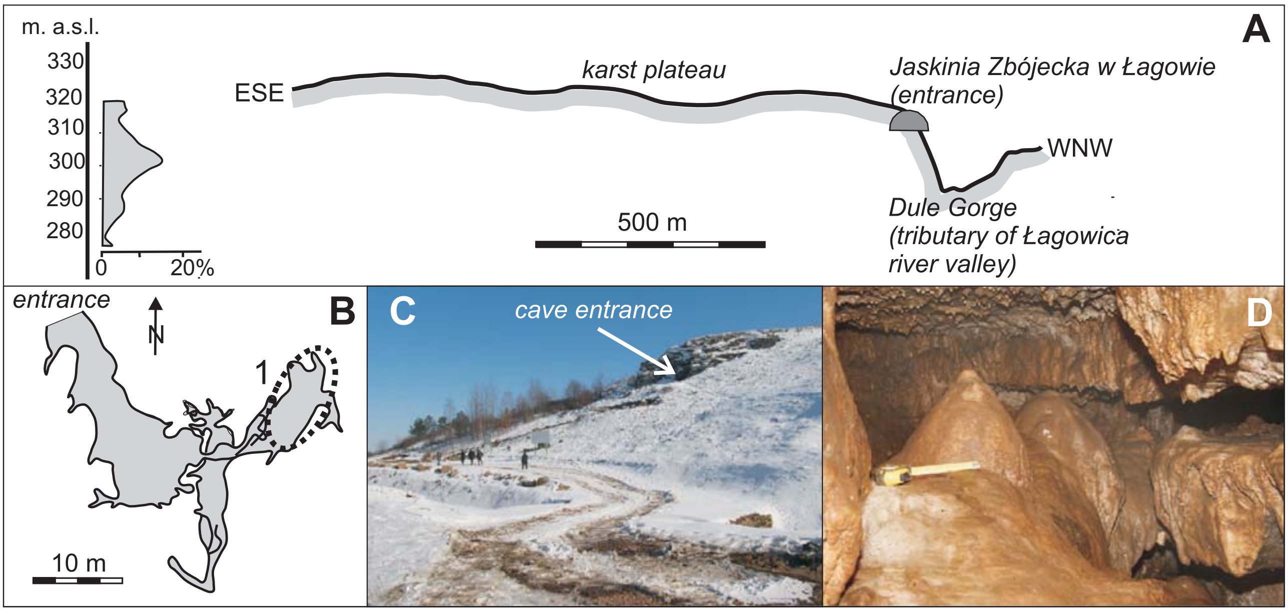

Fig. 9. Jaskinia Zbójecka w Łagowie (Robber Cave at Łagów): A – the cave location against the morphological profile and (in the left side) a graph of relative karst rate versus hypsometry calculated on the basis on borehole data (after Urban and Rzonca, 2009, modified); B – map of the cave (after Z. Grzela, J. Gubała and A. Kasza in Urban, 1996, significantly simplified); description of number: 1 – Sala Naciekowa (Speleothem Chamber), palaeontological and archaeological locality, also the place of occurrence of the speleothems sampled for U-series datings; C – Dule Gorge with the entrance of the cave (photo J. Urban); D – old speleothems in the Sala Naciekowa (photo P. Suchanek).

of *Cervalces latifrons* suggests that at least part of this bone assemblage represents the Middle Pleistocene, whereas a part could have been of the Vistulian age (Stefaniak *et al*., 2014; Woroncowa-Marcinowska *et al*., 2017; Urban *et al*., 2018b).

The site (palaeokarst doline) described by Czarnocki (1935) was destroyed before the middle of the 20th century, when the cluster of quarries was abandoned (Kotański, 1959). At the end of the 20th century and at the beginning of the 21st century, palaeokarst forms filled with Neogene clay, loam, sand and gravel (without fossils) were described in a southern quarry of the quarry cluster, however, this quarry was probably developed directly after the Second World War and located farther to the south of the site (Fig. 8B, C) (P. Król oral information; Urban, 2013; Woroncowa-Marcinowska *et al*. 2017; Urban *et al*., 2018b).

Jaskinia Zbójecka w Łagowie

Jaskinia Zbójecka w Łagowie (Robber Cave at Łagów) (Fig. 1) is 160 m long cave horizontally developed on two levels: ca. 295 m a.s.l. and ca. 310 m a.s.l., i.e. high above a valley floor. Such hypsometric setting proves its genetic connection with one of the oldest Neogene karst horizon recorded in the region, based of analysis of borehole data (Fig. 9) (Urban and Rzonca, 2009; Urban, 2013). U-series datings of the older generation of calcite flowstones from the Sala Naciekowa (Speleothem Chamber) in this cave (Fig. 9B, D) suggested their age from 350 ka to 1,200 ka BP (Table 1, Fig. 4).

In the same chamber (Fig. 9B), under a thin young calcite flowstone covering a floor, in 1961 (or 1962) Wołoszyn found fragments of Medieval pottery and Holocene mammal bones, among which were large bones of a pig or a wild boar (*Sus* sp.) (Wołoszyn and Wójcik, 1965). Fine bones collected by Wołoszyn, which belong to bats, were studied by Ochman (2003), who identified 11 species. In this assemblage Bechstein's bat (*Myotis bechsteinii* – 21.3%), Natterer's bat (*M. nattererii* – 16.0%), Daubenton's bat (*M. daubentonii* – 13.3%) and Geoffroy's bat (*Myotis emarginatus* – 8.0%) predominate. This fossil assemblage differs from the present-day bat community of Jaskinia Zbójecka w Łagowie. High frequency of *M. bechsteinii* suggests the Holocene, Subboreal age of this fossil fauna (Ochman, 2003). Palaeontological material from the cave is deposited in the collection of the Institute of Systematics and Evolution of Animals of the Polish Academy of Science in Cracow.

Fragments of Medieval pottery collected in this cave in 1960s and/or 1970s are considered to originate at the end of the 13th century or in the first part of the 14th century (Hadamik *et al*., 2004; Hadamik, 2008).

Mirówek site

This site comprises a karst doline recognised using boreholes in the Upper Jurassic limestone of the northern marginal zone of the Świętokrzyskie Mountains (Fig. 1). The doline is at least 68 m deep and filled with a sequence of Neogene and Quaternary sediments, which were examined using standard structural-petrographical methods (grain size, mineralogy and roundness, heavy minerals) (Barcicki *et al.*, 1991). A lower section of the geological sequence (up to 31.0 m) represents Neogene formations: flint gravel (unit I) and silty sand (unit II), likely deposited in the marginal zone of a marine basin. The upper units: III (31.0–18.6 m) and IV (18.6–16.2 m) are considered to be of the Early Pleistocene age, which is suggested by the heavy minerals' composition (several percent of unstable minerals: pyroxenes, garnets and amphiboles), as well as higher (than in I and II units) percentage of sub-rounded and rounded grains. The unit III comprises sandy silt with admixture of organic detritus, which is supposed to be deposited in limnic environments with a contribution of aeolian transport. The unit IV is formed of loam of probably deluvial provenience. Unit V (16.2–6.2 m) is built of sandy silt that contain significant content of rounded and matt sand grains. Among grains of heavy minerals epidote and garnets are very frequent, whereas pyroxenes and amphiboles are rare. Thermoluminescence (TL) dating suggest the ages older than 830 ka BP for the lower section of the unit V (15.1–15.2 m depth) and older than 670 ka BP for its upper section (8.0 m), thus it was deposited during glaciations of the South Polish Complex. The uppermost unit VI (6.2–0.6 m) is formed of tills, TL-dated at 247–105 ka BP, i.e. deposited during glaciations of the Middle Polish Complex (Barcicki *et al.*, 1991). Such depositional succession and present-day morphology of the site (slight depression) indicate that there have been several periods of the karst doline development (deepening) since the Neogene up to now or this process was almost continuous with periods of faster and slower rate.

Other sites

Among ca 220 palaeo-karst features (dolines, channels fissures filled with sediments) outcropped in quarry faces and several dozen such features in cave walls, documented during their inventory in the last decade of the 20th century, in the case of about 20 ones only the evident Quaternary sediments were identified. General criteria of such identification were: lithology of sediments (e.g. loess-like silts), character of quartz sand grains (rounded and matt) and composition of heavy minerals. No fossils have been found during these investigations (Urban, 2002).

Apart from the above described sites, among the interesting karst forms filled, at least partially, with Pleistocene sediments are: palaeo-doline (palaeo-valley) in the active quarry of Devonian dolomites Skała near Waśniów, and palaeo-doline (palaeo-valley) in the northern face of the abandoned Zgórsko quarry near Sitkówka-Nowiny (Fig. 1) (Urban, 2002, 2013). This first one is the elongated doline or a karst blind valley, filled with sands and loams (with pebbles), with discernible vertical changes in a mineral-petrographic composition of sand grains (mainly heavy minerals) and pebbles, as well as grain roundness. Lower part of the sequence is formed of sand composed of angular and sub-rounded quartz grains, however grain roundness increases upwards, suggesting growing role of aeolian abrasion and transport (probably at the beginning of the Pleistocene). This unit is overlain by loamy sand composed of well rounded quartz grains and containing semi-stable heavy minerals (garnets and epidote – Urban, 2013). The upper loam unit bears pebbles of local origin and erratic (magmatic) rocks, evidently indicating a Pleistocene glaciation.

The second, Zgórsko site, is a depression in Devonian limestone filled with loess-like silt with inserts of fine-grained sand. It suggests correlation of this sediment with loess deposition periods during the Pleistocene glaciations, most probably during the last glaciation.

The U-series dating of calcite speleothems in Jaskinia w Marzyszu (Cave at Marzysz) as well as in palaeo-karst forms in the quarries in Szczukowskie Górki and Józefka-Górno (sites in Devonian carbonates, Fig. 1) did not determine their exact ages, suggesting it in between 350 ka and 1,200 ka BP (Table 1, Fig. 4). Only in the case of younger calcite (originally aragonite) generation of speleothem filling karst fissure in the Devonian dolostone of Laskowa quarry at Kostomłoty village (Fig. 1), the U-series dating pointed out to 240–360 ka BP (Table 1, Fig. 4).

Analysis of heavy minerals' composition in sand and sand-gravel fills of palaeo-karst dolines outcropped in active quarries of Devonian carbonates Winna and Komorniki near Łagów (Fig. 1) indicates distinct predomination of stable minerals (average 83.2%), but also relatively high content of amphiboles (15.6%). High amount of stable minerals differs from these fills in typical Quaternary sediments in the region that contain glacial material. Therefore, these fills were considered to be of the Miocene age (Ludwikowska-Kędzia, 2013, 2018). Nevertheless, occurrence of amphiboles – in the case of lack of any other unstable heavy minerals – makes mineral assemblages of both studied fills similar to the composition of heavy minerals of post-Miocene (Early Pleistocene?) sediments described by Mycielska-Dowgiałło (1978) in the south-eastern periphery of the Świętokrzyskie Mountains region (Tarnobrzeg area).

Quaternary sediments occur also in the uppermost part of sequence of fills of large palaeo-karst doline formed in the Upper Jurassic limestone of the northern marginal zone of the Świętokrzyskie Mountains at Maziarze village near Iłża (Fig. 1). They are represented by tills, 12.0 m thick (unit IV at 13.0–1.0 m depth) and possibly by deluvial sandy loams 2.0 m thick (15.0–13.0 m) of not clearly defined age (Barcicki *et al.*, 1996).

DISCUSSION

Karst forms and systems currently discerned in the Świętokrzyskie Mountains region developed in the Neogene, possibly also in the Paleogene, and principally were filled up at least partly by sediments before the Pleistocene glaciations and input of typical glacial material. This is proved by lithology of most these fills that were produced due to weathering of clayey-clastic Permian and Triassic rocks, which shortly before mantled Devonian carbonates or occurred close to the Devonian outcrops (Urban, 2002, 2013).

Consequently, a number of sites in which Pleistocene fills were found is small. The preglacial Early Pleistocene is documented only at the following sites: Kadzielnia sites 1 and 2, as well as probably in the palaeodolines at the Skały site and the Winna and Komorniki quarries. The Kadzielnia site 1 is a very important one owing to rich fossil assemblage, which accurately presents the environmental conditions. It should be compared, strictly presented against a background of much longer lithostratigraphic and palaeontological succession of the Jaskinia Żabia (Frog Cave) site in the Cracow-Częstochowa Upland (see e.g. Stefaniak *et al*., 2009a).

During the Pleistocene glaciations, as well as probably in periglacial conditions the underground, particularly deeper fragments of karst systems in the study region were filled with water and they could have been washed out, cleaned from sediments, which resulted in development of the present-day caves (parts of karst channel networks accessible for people). Speleothems dated to between MIS 6 and MIS 10 (Table 1, Fig. 4), i.e. the Middle Polish Glaciation Complex, are the evidences of this washing out process, because they are currently devoid of original (depositional) substratum (Figs 6C and 7C), partly broken and corroded. A growth of these speleothems (as presented in Fig. 4 and Table 1) usually corresponds to coolings (MIS 6 and MIS 8), recognised as glaciations by Marks *et al.* (2016). This could have been caused by adequate, increased humidity and not so acute climatic conditions, similarly to the earlier Middle Pleistocene climate cooling favourable to growth of flowstones in Jaskinia Głęboka (Deep Cave), Cracow-Częstochowa Upland (Błaszczyk *et al*., 2018).

Nevertheless, most of the Neogene karst forms filled with the pre-Pleistocene sediments have remained in this state up to now. Possibly, the process of filling of karst networks and adjacent valleys could have resulted in present-day difficult accessibility of them and low number of karst caves in the region (some 150).

Among very rare karst infills formed just during the Pleistocene glaciations, which were not leached by subsequent underground water flows, the Kozi Grzbiet site was a unique one – because of its evidently proved age and scientific importance for palaeoenvironmental reconstruction – which represents the Middle Pleistocene in the Świętokrzyskie Mountains region. And there has not been discovered (studied) karst site in Poland of similar age and fossil assemblage yet (Stefaniak *et al*., 2009b). Even in the Middle Pleistocene calcite flowstone in Jaskinia Głęboka (cave), Cracow-Częstochowa Upland, the second (middle) warming period of the Podlasian Interglacial (MIS 19), documented by the Kozi Grzbiet sequence, is lacking (Błaszczyk *et al*., 2018).

Raj cave is the most representative karst site of the Upper Pleistocene in the Świętokrzyskie Mountains region. This site can be compared with depositional sequences of similar ages described in caves of the Cracow-Częstochowa Upland. In the depositional sequences described in those caves, e.g. Biśnik cave (Krajcarz *et al*., 2014) or Jaskinia Nietoperzowa (Bat Cave) (Madeyska-Niklewska, 1969), and many other ones (Madeyska, 2009; Krajcarz *et al*., 2016) similar succession of lithological units is discerned: sandy units and fluvial facies are set below loess and loess-like units which are correlated by Krajcarz *et al*. (2016) with the younger upper loess (LMg *sensu* Maruszczak, 1986) deposited during the Upper Pleniglacial. Such a location of the loess-like units in the Raj cave – above sandy fluvial units and below younger fluvial units – suggests environmental conditions of their deposition similar to those in the Cracow-Częstochowa Upland and the same time-frame of their deposition. The fossil assemblages as well as archaeological artefacts collected in the Raj cave can be compared with many palaeontological and often also archaeological sites in caves and rock shelters studied in this upland, such as e.g. Biśnik cave, sites in the Skały Zegarowe (crags), sites at Mt. Birów, Jaskinia Deszczowa (Rain Cave), Jaskinia Nietoperzowa (Bat Cave), Jaskinia Komarowa (Mosquito Cave) (see e.g. Madeyska, 1981; Cyrek, 2009; Stefaniak *et al*., 2009b, c; Krajcarz *et al*., 2016).

Although loess-like sediments occur also in the Underground Touristic Trail at the Kadzielnia Hill (Kadzielnia site 2), the lithostratigraphic comparisons of the depositional sequence at this site with karst sites of the Cracow-Częstochowa Upland is more difficult, because sediments at this site were deposited in much deeper part of a karst system, weakly connected with ground surface (however, not quite closed, which is proved by occurrence of bat remains). Also formation of rubble sediments at the Kadzielnia site 2 cannot be directly connected with the climatic conditions, as it can be considered in the case of caves of the Cracow-Częstochowa Upland. A lithological specificity of the cave system surroundings must be taken into account for interpretation of the rubble development.

The environmental-climatic comparison based on interpretation of taxonomic composition and proportion of fossils of bat taxons at the Kadzielnia site 2 is much easier. The composition of fauna is similar to the assemblages studied at the sites of the Cracow-Częstochowa Upland, such as e.g. units A and A' in Jaskinia Komarowa (Nadachowski *et al*., 2009) and indicates mixed the Late Pleistocene–Holocene age of the fossils (Urban *et al*., 2011b). Furthermore, a fossil bat community described in Jaskinia Zbójecka w Łagowie displays similarities with the site in Jaskinia Komarowa (Ochman, 2003).

In contrast, there is a complete lack of the Upper Pleistocene cryogenic calcite CCC (that were found and studied in detail in the Chelosiowa Jama-Jaskinia Jaworznicka) at other sites in Poland. This can be caused by concentration of scientific investigations of caves in the Cracow-Częstochowa Upland and Sudetes in their entrance parts, where palaeontological and archaeological sites are usually located. These parts have been relatively changed by exogenic factors (temperature, wind, etc.) and human impact during the Late Pleistocene and the Holocene. The other reason could be hypsometric and consequently, hydrological setting of majority of caves in these regions, because caves are located above reconstructed groundwater aquifers, even during the Pleistocene glacial periods.

Moreover, formation of cryogenic calcite proving multiplied freezing during the Interplenivistulian (MIS 3), which is not the coldest part of the last glacial period, indicates pretty cold climate during the Vistulian pessimum, whereas development of speleothems during the Middle Pleistocene climate coolings considered as glaciations (Marks *et al.*, 2016) in caves of the Świętokrzyskie Mountains region (Table 1, Fig. 4) and earlier, in Jaskinia Głęboka, Cracow-Częstochowa Upland (Błaszczyk *et al.*, 2018), suggests humid but rather not very cold environments.

The inventory of karst sites documenting the Pleistocene in the Świętokrzyskie Mountains region is modest in comparison to a number of such sites in the Cracow-Częstochowa Upland and displays significant time gaps. The principal reason of this is the sealing of Neogene karst forms in the Świętokrzyskie Mountains region by sediments, produced due to weathering of clayey-clastic Permian and Triassic rocks overlying or occurring close to Devonian carbonates, while a vast area of Upper Jurassic limestone outcrop in the Cracow-Częstochowa Upland was deprived of such overburden or it was (partly) karstified and removed in solution (Cretaceous marls). The other reason can be subsequent different extent of glaciations in these two regions. According to Lewandowski (2009, 2011) the Cracow-Częstochowa Upland has never been covered by the Pleistocene ice-sheet, whereas carbonate areas of the Świętokrzyskie Mountains region were covered by the ice-sheet during one or two glaciations of the South Polish Complex (Lindner, 2004). This fact could have played significant role in different morphological evolution and, in particular, hydrological processes in these areas, and, in consequence distinct state of filling or washing out of karst systems and filling of adjacent valleys, which resulted in present-day disparate accessibility of karst systems. In the Świętokrzyskie Mountains only about 150 karst caves have been documented up until now, most of them are accessible through artificial entrances, opened due to quarrying or mining (see Urban *et al.*, 2011b), whereas in the Cracow-Częstochowa (Cracow-Wieluń) Upland some 2000 caves, mostly with natural entrances in valley and hill slopes have been identified (see Gradziński and Szelerewicz, 2004).

CONCLUSIONS

Despite a small number of the Pleistocene karst sites in the Świętokrzyskie Mountains region, the studies of these sites played crucial role in research of the Pleistocene in Poland. Studies of the Kozi Grzbiet site were the most important, because they provided the first evidences for new climatostratigraphy and new classification of glaciations in Poland. Similarly, explanation of genesis of cryogenic calcite crystals, firstly discovered in the Chelosiowa Jama-Jaskinia Jaworznicka cave system, started new direction of palaeo-environmental studies of the last glaciation, used for reconstruction of periglacial conditions. In turn, further detailed studies of its speleothems representing the younger Middle Pleistocene could provide interesting scientific data on this period. The Kadzielnia palaeontological site was among the first studied Early Pleistocene fossil assemblages in the Polish karst, whereas the Raj cave provided very abundant palaeontological and archaeological material from the last glaciation. Other (several) sites are of less scientific importance, however some of them, e.g. Early and Late Pleistocene–Holocene sediments and bat fossils in the Underground Touristic Trail at the Kadzielnia Hill can be efficiently used in geoscience education.

A number of karst sites recording the Pleistocene in the Świętokrzyskie Mountains region is much less than a number of such sites in the Cracow-Częstochowa (Cracow-Wieluń) Upland. This could have been caused by different geological structures and geological history of these regions, strictly the sealing of Neogene karst forms of the Świętokrzyskie Mountains region by weathered material from clayey-clastic rocks overlying the Devonian carbonates and then different extent of Pleistocene glaciations in these regions. Nevertheless, several mentioned above prominent sites in the Świętokrzyskie Mountains region suggest that a small number of sites does not exclude discoveries of the next ones of high scientific importance in this area.

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