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ARTESIAN ORIGIN OF A CAVE DEVELOPED IN AN ISOLATED HORST: A CASE OF SMOCZA JAMA (KRAKÓW UPLAND, POLAND)

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Abstract: The cave of Smocza Jama located in the centre of Kraków is developed in the Wawel Horst built of Upper Jurassic limestone and surrounded by grabens with Miocene clays. The cave is composed of two series: the old one has been known for ages and the new one was discovered when an artificial shaft was mined in 1974. The new series comprises small chambers separated by intervening thin walls while the old series consists of three connected together spatial chambers. The cave abounds in extensively developed solution cavities – cupolas and ceiling pockets. The internal fine-grained deposits, predominantly representing clay fraction are built of illite, mixed layer illite-smectite, kaolinite and iron oxides. They are probably the residuum after dissolution of Jurassic limestone. The cave originated in phreatic condition due to water input from below. The new series represents juvenile stage of cave evolution. The water rose through fissure-rifts located in chamber bottoms, circulated convectionally within particular chambers, finally led to bleaching of intervening walls, and hence to connection of the neighbouring chambers. The evolution of the old series is far more advanced. The rounded solution cavities imply that the cave was formed by water of elevated temperature. The lack of coarse-grained fluvial deposits, Pleistocene mammal remains and Palaeolithic artefacts prove that the cave was isolated since its inception till Holocene time. The cave originated due to artesian circulation, when the Wawel Horst was covered by impermeable Miocene clays. A foreland basin with carbonate basement, filled with fine-grained molasse-type deposits seems to be particularly favourable for the development of artesian caves.

Key words: speleogenesis, palaeohydrology, Carpathian Foreland Basin.

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INTRODUCTION

The caves originated due to basal input of water are known from different settings. Recently, Ford and Williams (2007) have clearly distinguished between caves formed by meteoric water developed in confined circulation and hypogenic caves. The latter category is limited to caves genetically connected with deep circulation of water usually of higher temperature and enriched in dissolved gases which govern its aggressiveness. Palmer (2007) hold a similar view and claimed that caves of this type represent around 10–15% of known caves. Conversely, Klimchouk (2009) stressed the hydrogeological condition in which caves are formed. Therefore, he used the term hypogenic caves to all the caves created by fluids migrating from the depth, disregarding the chemistry and temperature of the fluids.

Basal input of water is usually connected with artesian conditions and demands special geological/hydrological setting. Hence, such caves are called in the present paper as artesian caves. The unusual chemistry – content of substantial amount of CO_2 or H_2S and elevated temperature of upward migrating water – decide upon its corrosive properties and determine the cave pattern and morphology of cave passages. The mixing of deep and shallow waters also can influence formation of such caves (Palmer, 2007, p. 215).

Recognition of artesian caves overcomes some difficulties since majority of caves are inactive now, and moreover some of them are presently located in different hydrological condition than during their creation. Unravelling the temperature under which a particular cave was formed and

Fig. 1. Location of Smocza Jama cave, geology after Gradziński (1993)

Fig. 2. Aerial photograph of Wawel Hill, location of Smocza Jama is arrowed; photo by Michał Gradziński

chemistry of fluids which create the cave is even more complicated. Hence, the reconstruction of particular cave origin should be based on a set of criteria, that is on: spatial arrangement of cave passages, corrosion forms, relationship between a cave and present topography and hydrology, as well as internal sediments (cf. Dublyanski, 2000; Ford & Williams, 2007; Palmer, 2007; Klimchouk 2009). The artesian caves are commonly invaded by descending vadose water during subsequent stages of their evolution. It caused the strong reshaping and obliteration of their primary features (Audra *et al*., 2006).

Artesian caves were recognized in Hungary, in the Transdanubian Range, where their origin is connected with thermal solutions migrated upward beneath impermeable Neogene sediments filling the Pannonian basin (Müller, 1989; Dublyanski, 1995 and references quoted herein). The most spectacular examples are known from the Buda Hills and Pilisz Mountains. Since the 1970s such caves have been identified in several karst regions all over the world. It is worth mentioning that many extensive caves have an artesian origin, commonly connected with thermal water rich in deep CO_2 and H_2S. Wind Cave and Jewel Cave – the Black Hills, South Dakota (Palmer & Palmer, 2000), Carlsbad Caverns and Lechuguilla Cave – the Guadelupe Mountains, New Mexico (Hill, 2000), as well as huge caves developed in Miocene gypsum in Podolia (Klimchouk, 2000) may serve as examples.

Rudnicki (1978) put forward an idea about artesian origin of Berkowa Cave (Jaskinia Berkowa) located near Podlesice in the Kraków-Wieluń Upland based on morphology of its ceiling cupolas. Similar origin has been later postulated to other caves of the Kraków-Wieluń Upland (Pulina *et al.*, 2005; Pura *et al.*, 2005; Tyc, 2009), as well as to some Tatra caves (Bac-Moszaszwili & Rudnicki, 1978; Gradziński *et al.*, 2007). In the opinion of the present authors Smocza Jama originated in a similar way. This paper is aimed to explain the origin of Smocza Jama and to reconstruct the palaeohydrological conditions enabling its formation.

GEOLOGICAL AND SPELEOLOGICAL SETTING

Smocza Jama (Dragon's Den) cave is located in the southernmost part of the Kraków-Wieluń Upland within the city of Kraków in Wawel Hill (Figs 1, 2; Szelerewicz & Górny, 1986). The Wawel Royal Castle perches on the top of this hill. Smocza Jama is famous owing to such a location, having been mentioned in literature since the Middle Ages (Firlet, 1996).

Wawel Hill is built of the Upper Jurassic massive microbial-spongy limestone, which is called 'wapień skalisty' in Polish regional terminology (cf. Dżułyński, 1952; Matyszkiewicz, 1989). The limestone builds a small tectonic horst which is surrounded by Miocene fine-grained clastic sediments, commonly called Miocene clays, occurring in the neighbouring grabens (Figs 1, 3; Gradziński, 1972, p. 234). The horst and graben system belongs to the foreland of the Carpathians being affected during the thrusting of this orogen and included into the Carpathian Foreland Basin. The horst is partly isolated, but its north-eastern part is attached to the other horst which is situated somehow lower. The historic city centre of Kraków is located on the latter horst. The horst constituting Wawel Hill was also covered with the Miocene clays; however, the post-Miocene erosion removed them thoroughly. The patches of Miocene

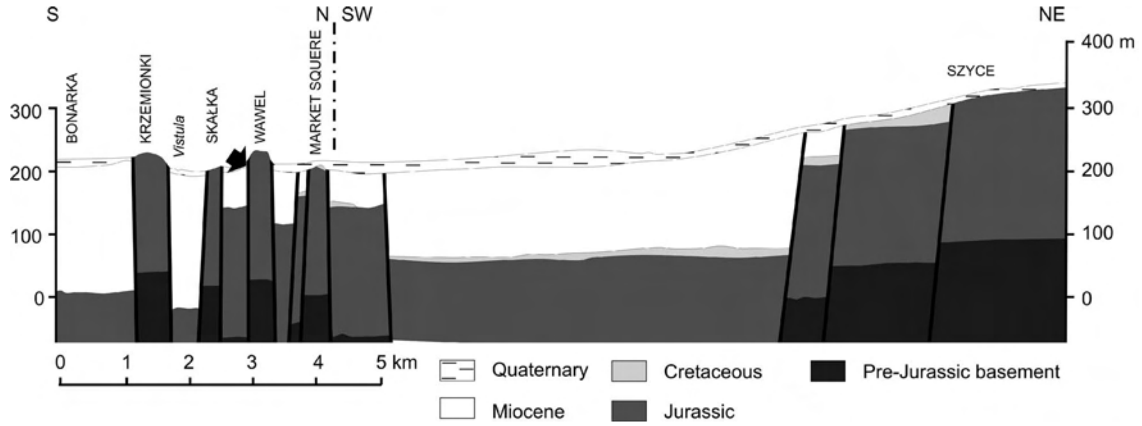

Fig. 3. Cross section compiled after Rutkowski (1986) and Kleczkowski (2003), location of Smocza Jama is arrowed

oyster limestone found in the cellars of the Wawel Castle mentioned by Friedberg (1933) indicate that the erosion stopped while reaching more resistant Jurassic limestone which builds the horst. Hence, the present surface of the hill reflects approximately the pre-Miocene surface. After the removing of Miocene clastics, the top of the hill was featured by karst processes forming small dolinas, which were recognized during archaeological excavations (Sawicki, 1955). The dolinas reach a depth of 1.5 m and are filled with weathered material, quartz sands derived from Cretaceous sandy limestone and probably loess-like sediment (Kowalski *et al.*, 1970).

Smocza Jama is 276 m long (Gradziński & Szelerewicz, 2004). It consists of two primarily separated parts linked by an artificial shaft mined in 1974 during the works aimed at stabilization of the hill (Figs 4, 5; Szelerewicz & Górny, 1986). In this paper they are called old and new series, respectively. The old series of the cave is spacious and accessible for tourists. In contrast, the new series comprises some small chambers linked by extremely narrow squeezes (Fig. 5). The pools occur in these chambers. The surface of the pools is located at the altitude about 199 m a.s.l., that is at the similar level as the Vistula (Wisła) River which flows in the proximity of about 50 m from the cave pools. The hydrochemical study by Motyka *et al.* (2005) shows that the water is a mixture of, at least, two components. One of them, being strongly degraded by human activity, represents the water of downward infiltration from the surface of Wawel Hill or lateral migration from the north-east. The water of this kind mixes with the other one coming due to ascension from below or seeping from the Vistula River owing to bank filtration mechanism. The cave almost lacks speleothems.

Fig. 4. Simplified map of Smocza Jama after Szelerewicz and Górny (1986)

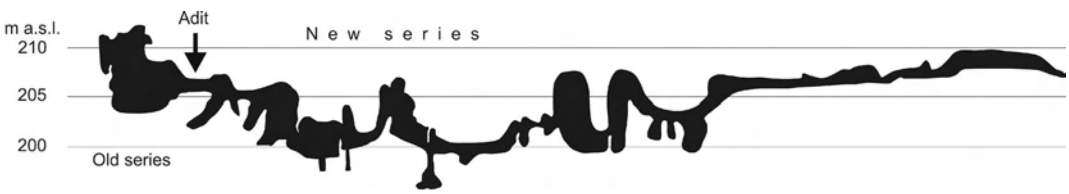

Fig. 5. Simplified cross-section of Smocza Jama after Szelerewicz and Górny (1986); old series perpendicular cross-section, new series longitudinal cross-section

MATERIAL AND METHODS

The observation of spatial pattern and rocky relief of the cave were carried out both in the old and new series of Smocza Jama. The authors used the published map of the cave (Szelerewicz & Górny, 1986). The cave wall and ceiling relief was documented in the field by carefully measuring a series of cross-sections with fibreglass type and a geological compass with clinometer.

The mineral and chemical composition of three samples of fine-grained cave deposits collected in the new series of the cave was analysed. Powder X-ray diffractometry (XRD) was performed on this material with a Philips diffractometer. Cu-Kα radiation (Ni-filtrated) was used. The bulk samples for IR absorption analysis were pressed with KBr. The analysis was done with a single beam spectrometer FTS 135 (BioRad) operated with Win-IR Foundation software. Si and S contents were determined by weight method, Al, Fe and Ca by complexometric titration, while K and Na by flume photometer. Contents of other elements were studied by atomic absorption analysis (AAS) with a Perkin-Elmer spectrometer. The particle size analysis was done in the same samples by a laser particle sizer Analysette 22 C Version (a Fritsch product).

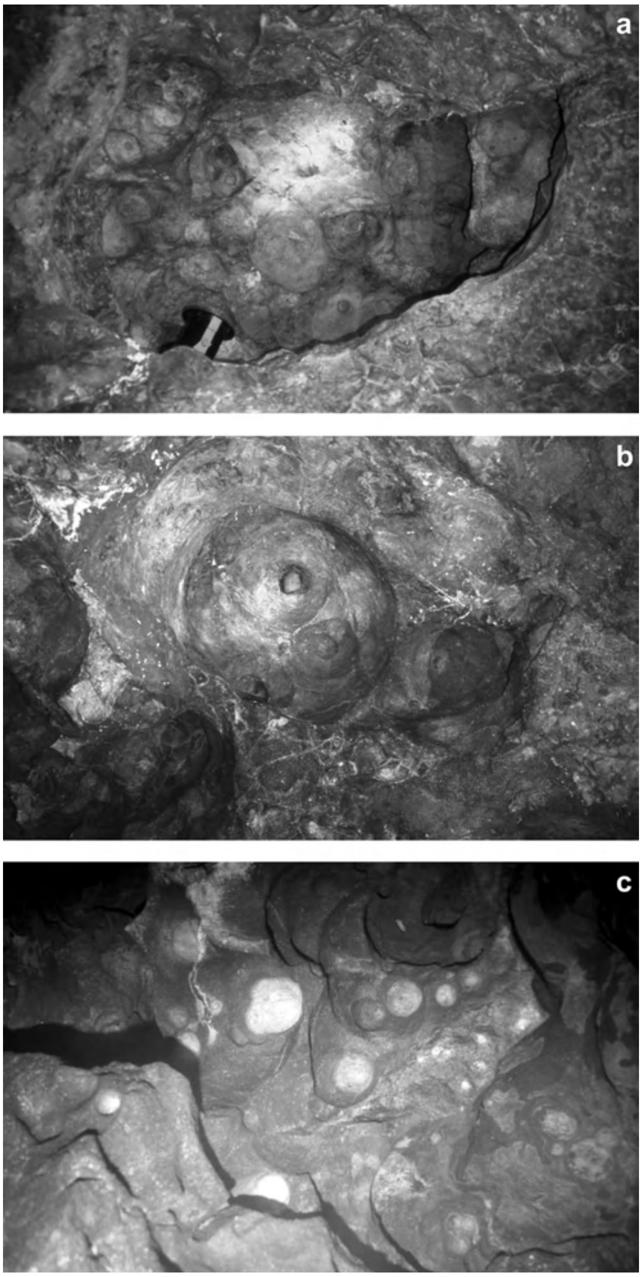

Fig. 6. Ceiling solution cavities; **a** – cupola with solution pockets developed inside, photo width ~1.5 m, Alth's chamber; **b** – solution pockets in Alth's chamber, photo width ~0.7 m, **c** – partly dissected solution pockets in new series, photo width ~1.8 m; photos a and b taken by Michał Gradziński, photo c by Mariusz Szelerewicz

RESULTS AND INTERPRETATION

Cave pattern

The new series of Smocza Jama comprises small chambers separated by intervening thin walls (Fig. 5). Locally, the wall thickness is less than 10 cm. The neighbouring chambers are interconnected by randomly distributed openings. Only some of them allow traversing from chamber to chamber, others are of to small dimensions. The chambers are from <1 m to 3.5 m in lateral extent and up to 8 m in height. The elongation of the chambers also reflects the orientation of vertical or steeply dipping joints. There are narrow rift-fissures filled with water in chamber bottoms. The water depth reaches 4.5 m (Szelerewicz & Górny, 1986). The majority of the rifts are guided by 40°–50° trending joints, which is one of the dominant joint sets in Jurassic limestone building the Wawel Hill (Heflik & Matl, 1991).

The old series of the cave comprises three rounded spatial chambers which form NNW–SSE trending passage (Fig. 4). Particular chambers reach 8 m in width while their length is between 10 and 25 m. Hence, their length/width ratio equals between 2 and 3.1. They maximal height is more than 10 m, however, the original height is bigger because the rocky bottom is covered with clastic deposits around 1.5 m in thickness (Kleczkowski, 1976). The chambers originated along joints and bedding planes, which is especially visible in the northernmost chamber, named Alth's chamber. Its ceiling, from which the solution cavities raised up, is almost flat and reflects the position of a bedding plane. It is possible that the ceiling was partly modified by collapses along this bedding plane. A big solution cavity in the ceiling of Grabowski's chamber led to the surface and acted as a cave entrance in the 19th century. At present, it is blocked with a brick cupola.

Solution cavities

The chamber ceiling in the old series is tremendously rugged (Figs 6a, b, 7a–c). The dome-shaped rounded solution cavities rise up from the ceiling. They are hierarchically arranged, that is within one big form several smaller forms occur. Owing to their dimension the bigger forms fulfil the definition of cupola *sensu* Osborne (2004) and Palmer (2007, p. 150–151). The former author assumed 1.5 m as a

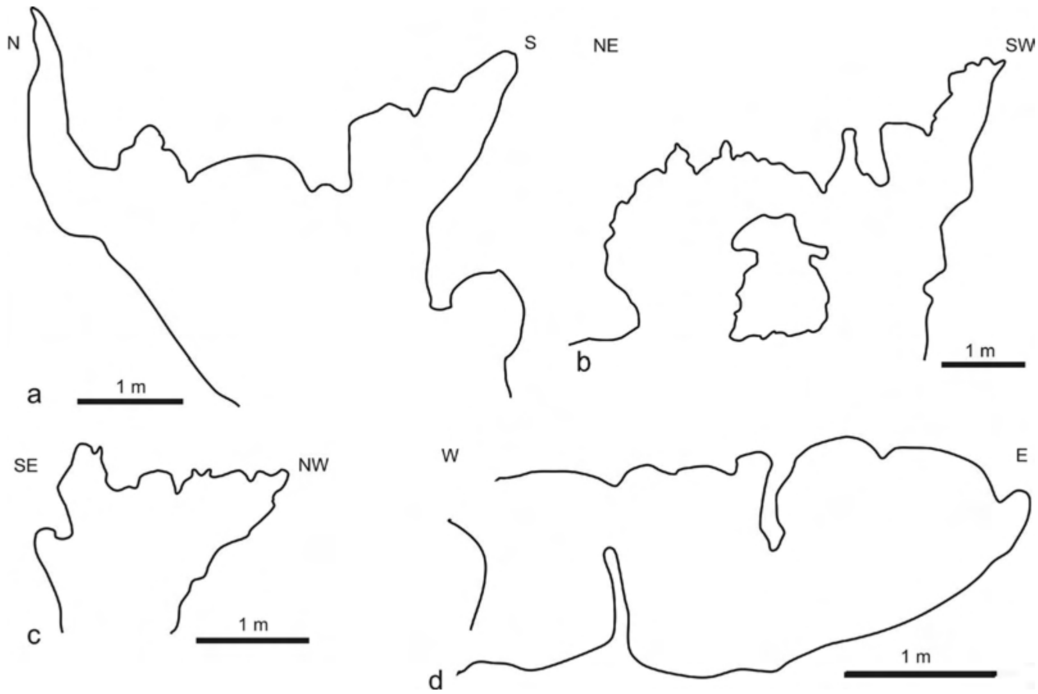

Fig. 7. Detailed cross-sections through solution cavities, **a**–**c** – cupolas with solution pockets developed inside, old series, **d** – small chamber in new series with solution pockets in its ceiling

lower limit of cupola diameter. The smaller solution cavities may be called solution pockets. Some neighbouring cupolas integrate owing to breaching of intervening limestone walls (cf. Osborne, 2009). Most of the pockets are rounded in shape, and their height equals or exceeds their diameter (Fig. 6b). Only the minority of the cupolas and pockets, which are elongated in plan, are guided by joints. The elongation reflects the 140°–320° trending joints. Vermiculation structures are visible on walls in some places of the old series. They are located up to 1.5 m above the present cave bottom.

The ceiling solution cavities of small cupola or ceiling pockets size also commonly occur in chambers of the Smocza Jama new series. They are also circular in plan view and rarely guided by joints. Some of them joined and the intervening walls are preserved as curved rock blades (Fig. 6c, 7d).

Cave deposits

Fine-grained clastic deposits are widespread in the new series of Smocza Jama. They coat cave walls and ceilings, however, upper parts of some solution cavities are devoid of them. Their thickness varies from a few centimetres on the walls to more than 40 cm on the cave bottom, where the deposits fill the rugged rocky relief. They are intensively red or reddish-brown while their uppermost part displays greyish-black colour. In spite of different colours, their mineral composition, as well as textural properties are almost uniform. They consist predominantly of clay-sized particles, which constitute more than ~98% of the analysed samples (Fig. 8). The samples comprise illite (main peak 10 Å), a kaolinite-group mineral (main peak 7.2 Å), and mixed layer illite-smectite minerals (~12 Å peak). The presence of kaolinite-group mineral is additionally confirmed by infrared spectroscopy (absorption bands 3620 and 3693 cm^{-1}). Si, Al, Fe and in one sample Ca are the dominant elements (Table 1).

The majority of cave deposits in the old series most probably have been destroyed during long lasting use of the cave since the Middle Ages (see Firlet, 1996). Moreover, they are inaccessible because of adaptation of this part for tourists. However, the preserved vermiculation in some places on cave walls suggest that fine-grained clastics also occurred there (cf. Bini *et al.*, 1978). Alth (1877), who carried out excavation in the cave, characterized these deposits as 'red, greasy clay' with limestone debris. He also noted

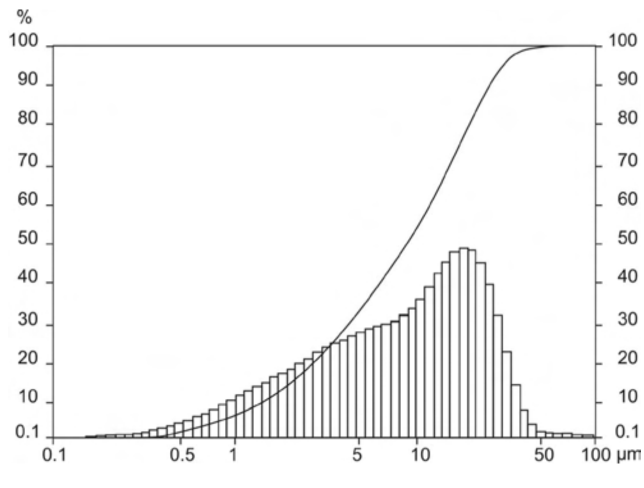

Fig. 8. Histogram and cumulative frequency curve of grain size distribution in fine-grained deposits from new series, sample SJ2

Table 1

Chemical composition of fine-grained deposits from new series of Smocza Jama

Sample number	Colour	Si[a] %	Al[b] %	Fe[b] %	Ti[c] %	Ca[b] %	Mg[c] %	K[d] %	Na[d] %	S[e] %	Mn[c] ppm
SJ 1	greyish-black	16.53	7.46	11.32	0.21	7.46	0.72	2.5	0.22	0.1	1800
SJ 2	red	12.84	5.87	24.6	0.09	3.28	0.78	1.95	0.21	0.2	1810
SJ 3	reddish-brown	17.9	8.73	17.0	0.33	0.9	0.96	4.0	0.17	0.1	1300

analytical error: [a] ±0.2%, [b] ±0.05%, [c] ±0.1 ppm, [d] ±0.02%, [e] ±0.01%

the presence of some animal bones belonging only to the species presently inhabiting the vicinity of Kraków and stressed the lack of any Pleistocene mammal bones. Heflik and Matl (1991) mentioned thin gypsum crusts on the walls in the middle part of the old series.

ORIGIN OF SMOCZA JAMA

The rounded solution cavities are the most characteristic features of Smocza Jama. The great body of literature exists discussing the origin of such forms (e.g., Osborne, 2004; Palmer, 2007; Ford & Williams, 2007). The prevailing opinions have inclined towards phreatic conditions of their formation. The condensation corrosion above the aggressive water bodies is also postulated (Audra *et al.*, 2007 and references quoted herein). However, it is not a case of Smocza Jama, since any traces of former water level – as for example corrosion notches – are seen in this cave. Thus, the discussed solution cavities originated due to corrosion below the water table, while the whole cave persisted within a phreatic zone. Bögli (1980, p. 160) pointed to mixing corrosion as an agent responsible for creation a ceiling cupolas. However, from the mass balance point of view this mechanism seems to be improbable (Ford & Williams, 2007, p. 252). Moreover, the ceiling solution cavities in Smocza Jama are hardly ever guided by joint fractures. It proves that no water effectively seeped down from the epikarst zone to the cave and mixed with phreatic water, to produce aggressive solution. Hence, one may rule out the mechanism of mixing solution as a factor responsible for formation of ceiling solution cavities in Smocza Jama. The slow convection in phreatic conditions is put forward as an agent influencing the creation of ceiling solution cavities. The convection can be triggered off by chemical gradient within the solution (Curl, 1966) or thermal gradient between the warmer solution and colder rock (Rudnicki, 1978). It is impossible to ascertain which of the two above processes predominated in Smocza Jama. Most probably they coexisted and their effects overlapped each other.

In the new series, there is no evidence of unidirectional water flow. The only one acceptable explanation for its formation is basal input of water rising from below through the fissure-rifts located in the bottoms of chambers. The water circulated convectionally within particular chambers. Thus, every chamber acted as one convection cell (Fig. 9a). The water circulation caused creation of ceiling solution cavities and thinning of rocky walls intervening neighbouring chambers. Finally the walls were bleached, which connected the chambers (Fig. 9b, see Osborne, 2009). The proceeding corrosion also dissected rock separated adjacent solution cavities. The formation of the new series of the cave was stopped at this stage. Hence, this series represents juvenile stage of evolution of artesian cave. Slightly more advanced stage was described by Audra *et al.* (2009). In their example walls, which still separate many neighbouring chambers in Smocza Jama, are preserved only as blades rising from the bottom, ceiling pendants or biconcave pillars.

Definitely, the old series of Smocza Jama represents a more advanced stage of cave evolution. The ceiling cupolas have larger dimensions; some of them intersected each other (Fig. 7b). The chambers are more spacious. It may suggest that the water circulation in this part of the cave was more effective or more prolonged. Moreover, the connection of adjacent chambers may be facilitated by the presence of bedding planes which are visible in the old series. Their lack in the new series probably mirrors the lateral disappearance of bedding planes, which is known from the outcrops in the Kraków region (Matyszkiewicz, 1989).

The presence of only fine-grained deposits dominated by clay fraction supports the above view, that water flow in the cave was extremely slow. Any coarse-grained material constitutes autochthonous debris falling from the ceiling (Alth, 1877). The lack of quartz sands, being the common deposit of the Vistula River, indicates that the river never invaded the cave, although it flows in a very close vicinity. Only small water insects migrate through water filled fissures from the Vistula River (Dumnicka, 2000).

The red coloured clay in Smocza Jama is similar to 'red phreatic clay' described by Bretz (1942) in his seminal paper. The material constituting the deposits may have derived from the residua after the dissolution of Oxfordian limestone. Their mineral composition bears a resemblance to insoluble residua of Oxfordian limestone from the neighbouring Zakrzówek Horst described by Krajewski and Bajda (2002). Both red clays and residua contain illite, mixed layer illite/smectite and kaolinite. The clay in Smocza Jama is strongly enriched in Fe_2O_3 compared to the insoluble residua of Oxfordian limestone. It suggests that the amorphous looking iron oxides precipitated from solution within the cave, most probably at the redox boundary, and they mixed with small particles of clay minerals carried by water.

The studied red clay contains scarce silicified Jurassic microfossils, for instance foraminifers and sponge spicules (I. Felisiak, personal communication, 2009). The lack of

Cretaceous and Miocene microfossils as well as quartz and glaucony grains differentiates the discussed clays from other cave and palaeokarst fillings in the Kraków region (Gradziński, 1962; Felisiak, 1988, 1992). It also denotes the isolation of the cave from water seeping vertically down from the top of Wawell Hill, where quartz sand derived from weathered Cretaceous deposits fills some small dolinas (Sawicki, 1955; Kowalski *et al.*, 1970). The latter conclusion is additionally confirmed by the scarcity of speleothems in Smocza Jama. Moreover, the absence of any Pleistocene mammal bones and Palaeolithic artefacts, which are very common in neighbouring caves, is significant. All the above facts prove that the cave was isolated since its inception till Holocene time. The opening of the old series was caused most probably by collapse of cave wall or ceiling as well as surface erosion. The new series was completely isolated till the artificial shaft was dug.

PALAEOHYDROLOGICAL CONDITIONS CONTROLLING THE ORIGIN OF SMOCZA JAMA

The above presented interpretation shows that Smocza Jama originated due to the basal input of ascending water, which demanded special hydrological and morphological conditions. At present, in the city of Kraków, several natural artesian outflows from artificial wells exist (Kleczkowski *et al.*, 1994; Kleczkowski, 2003). The water migration paths and recharge area of this artesian circulation were recognized by means of multidisciplinary study involving a noble gas method (Zuber *et al.*, 2004). The circulation is recharged north of Kraków, where natural outcrops of Jurassic limestones occur. The cover of Miocene clays acts as a confining bed. Similar hydrological situation is in Budapest, where classic artesian hydrothermal caves were recognized (Müller, 1989). One may presume that in the Kraków area during the formation of Smocza Jama the general scheme of the water circulation was similar to the present one. Bearing in mind a general palaeotopographic scheme with recharge area situated higher than 100 m above the potential discharge zone one may conclude that the speleogenesis took place in artesian conditions. It means that the water had at least a potential capacity to flow out at the surface. The cave was formed before the erosion of confined Miocene clays from the top of the limestone horst, which is evinced by cave isolation from the surface environment and before downcutting of the Vistula River to its present level. The Vistula River flew at the level several metres above its present riverbed since the whole cave, presently located a few metres above the water table, was in the phreatic zone.

Concentration of flow, which enabled the formation of spacious cave, was possible due to (i) proximity of potential discharge zone which had been created due to Vistula downcutting, and (ii) possible hydrologic connection across the confining bed just over the cave. The faults bounded the limestone horst and cutting the overlying Miocene clays may have served as a migration path for ascending water (cf. Cook *et al.*, 2006). Bearing in mind a general palaeotopographic scheme with recharge areas situated higher than 200 m above the potential discharge zone one may conclude that the speleogenesis took place in artesian condition. It proceeded before the erosion of confined Miocene clays from the top of the limestone horst, which is evinced by cave isolation from the surface environment and before downcutting of the Vistula River to its present level.

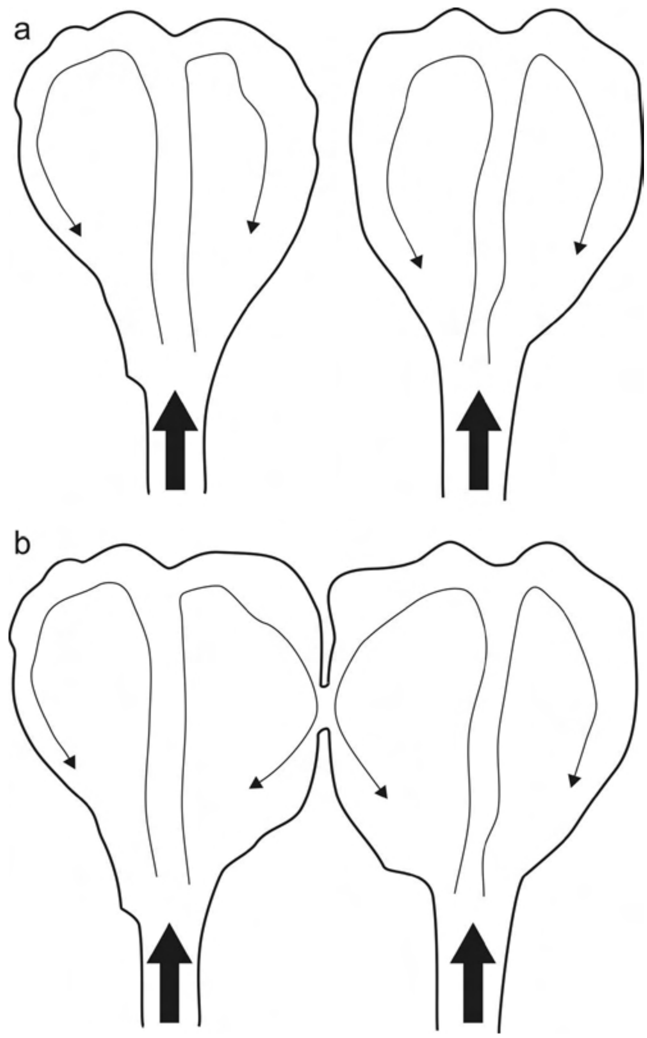

Fig. 9. Development of chambers in new series, **a** – convection circulation within particular chambers, **b** – connection of neighbouring chambers due to bleaching of intervening walls; big arrows indicate raising inflow of water through rift-fissures, small arrows convection circulation

The cave chambers were formed near the pre-Miocene top of Oxfordian limestone. It suggests that mixing of different waters facilitated the dissolution of limestone and influenced the cave formation (Palmer, 2007, p. 215). The chemical agent which could boost the aggressiveness was the presence of dissolved chlorides. The chlorides derived probably from halite concentration within the Miocene clays known from the close vicinity of Kraków. The mixing of chloride-rich deeply circulating water with chloride-poor descending meteoric water may substantially enhance the aggressiveness of water in an analogous manner as it occurs in a sea-coast karst zone. However, the concentration of chlorides is far more lower than in sea water. At present, it reaches 101.3 mg/L in the artesian water in Kraków (Kleczkowski *et al.*, 1994). On the other hand, the presence of gypsum crusts on the Smocza Jama walls (Heflik & Matl, 1991) may suggest the importance of H_2S oxidation processes. However, the H_2S concentration in the present artesian water in Kraków region does not exceed 4.5 mg/L (Kleczkowski *et al.*, 1994). Moreover, the gypsum may be connected with infiltrating of degraded water from the Wawel Castle area into the cave. The infiltration water in Smocza Jama contains at present up to 1,013.8 mg/L of SO_4 (Motyka *et al.*, 2005). Nonetheless, the concentration of iron oxides in the cave sediments also implies the existence of paleoredox boundary within the cave (cf. Palmer, 2007, p. 214, 294).

The extensively developed ceiling solution cavities, assuming the Rudnicki's (1978) theory of their origin, show elevated temperature of water during the formation of Smocza Jama. At present, the temperature of outflowing artesian water in Kraków ranges from 10.6 °C to 11.5 °C (Kleczkowski *et al.*, 1994), and is approximately 2–3 °C higher than the mean annual temperature in this area. The temperature of water ponded in Smocza Jama pools falls between 11.0 °C and 13.0 °C (Motyka *et al.*, 2005). It is doubtful that such small thermal gradient between water and rock can trigger off thermal convection effect. In comparison in Budapest, where many hypogenic caves with ceiling cupolas occur, the artesian water reaches the temperature between 20 °C and 60 °C (Müller, 1989). However, the present situation in Kraków may represent a senile stage of artesian circulation, while Smocza Jama may have been formed in its earlier stages.

The rate of cave formation process may be estimated to several hundred thousand years, since the experimental work by Andre and Rajaram (2005) shows that enlargement of initial fissures during thermal convection is a long lasting process. Their model implies that under ideal conditions a fissure is widened around 1 cm per 10 thousand years. Hence, the hydrological situation favouring the origin of Smocza Jama must have been stable throughout a prolonged period.

The location of Smocza Jama in an isolated horst situated within a foreland basin seems to be particularly favourable for the development of artesian caves. The basement of such basins is faulted into horst and graben systems, which are covered with molasses-type sediments (Einsele, 2000, p. 610–612). The former are commonly built by carbonate rocks whereas the latter have fine-grained composition and can act as confining beds. Thus, one can expect finding artesian caves or their remnants in other foreland basins.

CONCLUSIONS

1. Smocza Jama (Dragon's Den) developed in the phreatic conditions, which is proved by extensively developed ceiling solution cavities. They suggest that the water forming the cave was of elevated temperature. The water circulation was slow and long lasting.

2. Cave deposits represent red clay originated as residuum after dissolution of Jurassic limestone. The lack of quartz sand, Pleistocene mammal bones and Palaeolithic artefacts prove that the cave was isolated since its inception till Holocene time.

3. The cave originated due to the basal input of ascending water. The limestone horst was then confined by overlying Miocene clays. The artesian circulation within Oxfordian limestone was possible owing to a topographic gradient between recharge zone located northward of Kraków and potential discharge zone in the former Vistula River valley over the cave.

4. Smocza Jama was developed in the isolated limestone horst located within a foreland basin. Such foreland basins, where faulted carbonate basement is covered with fine-grained molasse-type deposits and being surrounded by elevated recharge zones, seem to be regions especially advantageous to formation of artesian caves.

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