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Ascending speleogenesis of Sokola Hill: a step towards a speleogenetic model of the Polish Jura

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ABSTRACT:

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The paper deals with the origin of caves in Sokola Hill (Polish Jura). The caves abound in solution cavities in the walls and ceilings, many of them arranged hierarchically, some others arranged in rising sets. Blind chimneys and ceiling half-tubes are also present. These features collectively indicate that the caves originated under phreatic conditions by an ascending flow of water, probably of elevated temperature. Phreatic calcite spar, crystallized from water of elevated temperature, lines the cave walls. During the formation of the caves the Jurassic limestone aquifer was confined by impermeable cover. Three possible scenarios for the origin of the caves are suggested. The first scenario points to formation of the caves during the Palaeogene prior to the removal of the confining Cretaceous marls. The second connects the origin of the caves with regional palaeoflow driven by tectonic loading by Carpathian nappes to the south, while the third refers to local topographically driven palaeoflow. Both the second and third scenarios assume that the Polish Jura had a cover of Miocene impermeable clastics. All the scenarios account for the origin of the caves in Sokola Hill and explain the common occurrence of ascending caves throughout the Polish Jura.

In the subsequent stages of evolution the caves were partly filled with various deposits. Conglomerates composed of Jurassic limestone clasts, quartz sands and sandstones are preserved as erosional remnants, locally covered by or interfingered with calcite flowstones. The clastic deposits were laid down by surface streams that invaded the caves earlier than 1.2 Ma. The caves were not invaded by water from Pleistocene glaciers, which is proved by the assemblage of heavy minerals in the cave clastics.

Keywords: Hypogenic caves; Palaeohydrology; Carpathian foreland; Cenozoic; Poland.

INTRODUCTION

Karst features genetically connected with basal input of water have attracted increasing interest in recent years. The term hypogenic cave has been coined to describe a cave that originated by ascending circulation of water. Klimchouk (2007, 2009) stresses mainly the hydrogeological conditions, and uses this term to any cave formed by ascending circulation of water in a confined setting. Conversely, Ford and Williams (2007, p. 240–246) and Palmer (2007, p. 209–226) regard as hypogean or hypogenic caves only those created by water of unusual chemistry and elevated temperature, resulting in increased aggressiveness of water towards carbonate bedrock. They also point to the importance of mixing of deep and shallow waters for the formation of hypogenic caves. Hypogenic caves are always connected with upward migration of water and are hence referred to herein as ascending caves.

One of the first interpretations ascribing an ascending origin to inactive caves was that by Rudnicki (1978), concerning Berkowa Cave (Polish: Jaskinia Berkowa), a small cave in the Polish Jura. Caves formed by ascending warm water were recognized in the vicinity of Budapest, where artesian circulation of thermal water is still manifested in moderately warm springs (Müller 1989; Dublyansky 1995 and references quoted therein). The origin of great caves in the Guadelupe Mountains (New Mexico, USA), including Carlsbad Caverns and Lechuguilla Cave, is convincingly explained by upward migration of water charged with CO_2 and H_2S (Hill 2000). An ascending origin is also ascribed to the giant caves in the Black Hills (Dakota, USA; see discussion in Palmer and Palmer 2000). A recent review by Klimchouk (2007) provides examples of such caves from all continents except Antarctica.

Proper identification of inactive artesian caves encounters some difficulties since many caves are now located in hydrological settings different from those which prevailed during their formation. Moreover, no single criterion allows for unequivocal distinction of an ascending cave from other cave types. Klimchouk (2007, 2009) lists a set of morphological features which can indicate an ascending origin of a particular cave. Development of ascending caves is intimately connected with the presence of confined conditions. Thus, a proper recognition of inactive ascending caves sheds some light on the palaeohydrological conditions and may in some cases help to unravel the geological history of a given karst region.

After the seminal paper by Rudnicki (1978), some authors have suggested an ascending origin of selected caves in the Polish Jura (Głazek and Szynkiewicz 1980; Pulina *et al.* 2005; Pura *et al.* 2005; Gradziński *et al.* 2009; Tyc 2009a, b). Relics of former ascending caves have also been recognized in the surface relief of limestone crags (Tyc 2009a, b). However, no concise genetic model has been hitherto presented that would explain the formation of ascending caves in the Polish Jura in the context of a broad geological, palaeohydrological and tectonic setting. The case of Smocza Jama (Gradziński *et al.* 2009) is not typical because the cave is situated in a local isolated horst. A general model may be elaborated only when other regional examples are documented and interpreted.

In this paper we present evidence for an ascending origin of caves in Sokola Hill, where some of the most spacious caves of the Polish Jura are located, and we try to reconstruct the palaeohydrological conditions of their formation. We also present and discuss hypotheses on their origin in the wider context of the geological history of the Polish Jura during the Cenozoic.

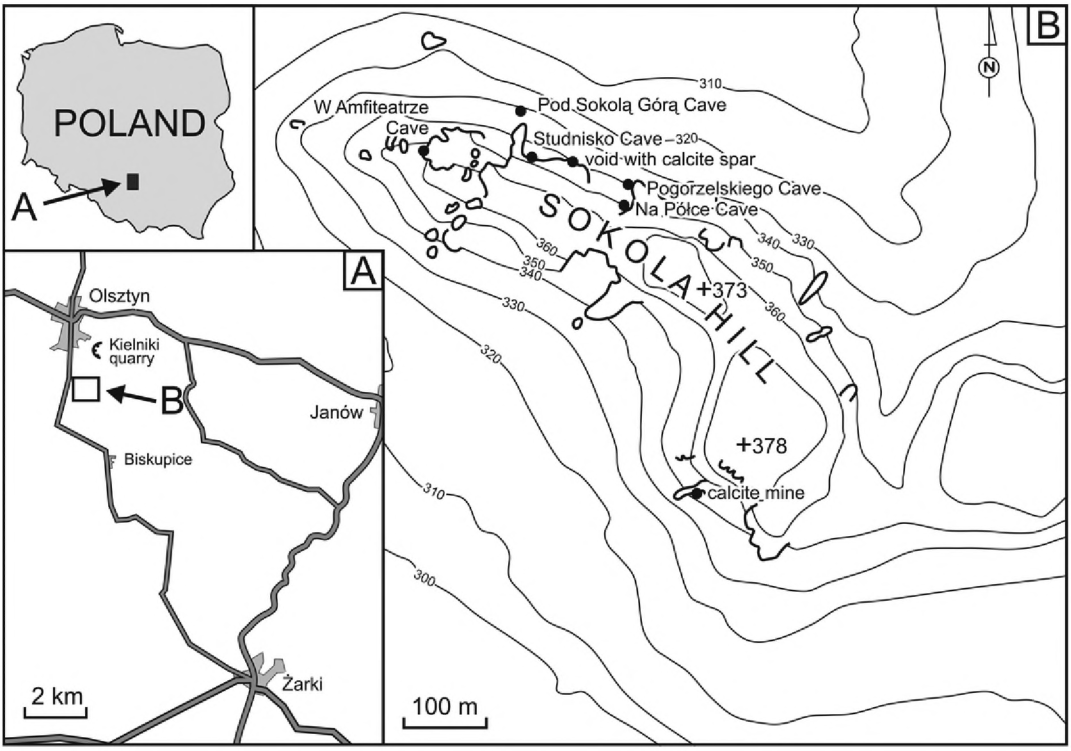
GEOLOGICAL AND SPELEOLOGICAL SETTING

Sokola Hill (Polish: Góra Sokola), with an altitude of 378 m, is located on the Kraków-Wieluń Upland, the region called the Polish Jura in some geological papers (Text-fig. 1). The hill belongs to a small hill chain called the Sokole Hills (Polish: Góry Sokole), stretching from west to east. They are composed of Upper Jurassic limestone, exposed in picturesque crags up to 20 m high on their tops and flanks. The hills stand up to 70 m over the surrounding plains covered with Pleistocene sands. Sokola Hill hosts sixteen caves, including Pod Sokolą Górą Cave and Studnisko Cave, both of which are famous for underground chambers that are exceptionally spacious for this region (Szelerewicz and Górny 1986; Urban and Gradziński 2004; Jerzy Zygmunt, personal information, 2005).

The picturesque hills in the Polish Jura, including Sokola Hill, are built of Upper Jurassic microbial-spongy limestone which also contains brachiopods, serpulids, bryozoans, peloids and carbonate mud. A sponge assemblage in the neighbouring Kielniki quarry, studied by Trammer (1989), is dominated by Hyalospongea. The limestone is massive, locally thick-bedded, and represents carbonate buildup deposits. The poorly exposed bedded facies, represents flank deposits of the buildups.

The precise age of the Upper Jurassic limestone in Sokola Hill is not known. According to Matyja and Wierzbowski (1992) the hills near Olsztyn, located nearby, are built of limestone belonging to the Bifurcatus and Bimammatum Zones. This age is also postulated for limestone in the neighbouring Kielniki quarry (Trammer 1989). Borehole data suggest that the base of the Upper Jurassic limestone in Sokola Hill area is located below 250 m a.s.l. (Heliasz *et al.* 1982).

The Jurassic limestone of Sokola Hill is underlain by various Lower Oxfordian and Middle Jurassic deposits. The Lower Oxfordian is represented by marlstone, marl and microbial-spongy limestone, whereas



Text-fig. 1. Location of the caves studied

the Middle Jurassic is composed of sandstone, limestone with various admixtures of siliciclastic material, sandy clay and clay (Heliasz *et al.* 1987). The total thickness of the Oxfordian deposits reaches 300 m. They dip northeast at an average angle of 2–4°.

Patches of siliciclastic and mixed siliciclastic-carbonate Cretaceous deposits, Albian to Turonian in age, are preserved above the Jurassic limestone, ca 10 km northeast of Sokola Hill (see Marcinowski 1970). Cretaceous deposits formerly covered the whole area of the Polish Jura, with the upper Upper Cretaceous ('Senonian') marly deposits being several hundred metres thick. The Cretaceous deposits were subsequently eroded during the long-lasting Palaeogene planation of the Polish Jura (Klimaszewski 1958), which took place after the Laramide tilting. The weathered Cretaceous deposits were the source of material for the so-called moulding sands which are locally preserved in karst depressions (Gradziński 1977). A more complete sequence of Cretaceous deposits still overlying the Upper Jurassic limestones is preserved, among other areas, in the neighbouring Nida Basin (Niecka Nidziańska), east of the Polish Jura (Walaszczyk 1992).

Sokola Hill is bordered by two SSW–NNE-trending faults, the precise age of which is not known. Gradziński (1977) assumed that they were post-Palaeogene and postdated deposition of the 'moulding sands', whereas Heliasz *et al.* (1987) considered that they were of Miocene age.

The limestone elevation of Sokola Hill is surrounded by non-cemented Pleistocene clastics, mostly of glaciofluvial origin. They were probably laid down during the Odra (Saalian I) glaciation, when the ice-sheet reached nearly as far as the town of Olsztyn, and stopped north of Sokola Hill (Klimek 1966; Heliasz *et al.* 1982; Lewandowski 1994, 2009). However, some of these deposits may also be related to an older glaciation, namely Sanian-2 (Elsterian-2), when ice-sheet lobes engulfed the Polish Jura, but did not cover it (cf. Różycki 1960).

There are sixteen caves in Sokola Hill (Urban and Gradziński 2004; Jerzy Zygmunt, personal information, 2006; Pura 2007). The majority of them are short and do not exceed 10 m in length. Basic morphometric data and major characteristics of the selected caves are listed in Table 1. Two caves are definitely outstanding: Pod Sokolą Górą and Studnisko caves with lengths of 70 m and 337 m respectively. Both caves consist of chambers which are among the most spacious in the Polish Jura. All the caves in Sokola Hill lie now in the vadose zone; they lack any underground watercourses. Only the lowermost parts of the Studnisko Cave, situated 77 m below the cave entrance, are located within the epiphreatic zone. They are periodically filled with stagnant water, probably due to fluctuations of the wa-

Cave	Entrance location	Entrance altitude	Length	Vertical extent	Forms of cave relief	Clastic deposits	Carbonate deposits
W Amfiteatrze	N50°43.728' E19°16.154'	355 m	12 m	6 m	solution cavities, ceiling half-tube		calcite spar, flowstones
Pod Sokolą Górą	N50°43.739' E19°16.244'	330 m	70 m	26 m	solution cavities, blind chimneys	loose sands, limestone debris	flowstones
Studnisko	N50°43.735' E19°16.257'	346 m	337 m	-80 m	solution cavities, blind chimneys	loose sands, sandstones, sand concretions, conglomerates, limestone debris	calcite spar, flowstones, stalagmites, stalactites
void filled with calcite spar	N50°43.729 E 19°16.291	339 m					calcite spar
Pogorzelskiego	N50°43.704' E19°16.415'	340 m	8 m	0 m	solution cavities, wall notch	loose sands, sandstones	calcite spar, flowstones
Na Półce	N50°43.696' E19°16.417'	350 m	33 m	10 m			calcite spar, flowstones
calcite mine	N50°43.502' E19°16.441'	350 m	6 m	5 m			calcite spar

Table 1. Major characteristics of the studied caves, the presence of modern soil in the entrance zones is omitted, the morphometric data of caves after unpublished data of Jerzy Zygmunt

ter table. The caves are thus completely disconnected from the modern karst drainage system and represent a subterranean relict karst (*sensu* Bosák *et al.* 1989).

Skalski and Wójcik (1968) have noted that the caves in the Sokole Hills form two distinct levels developed before the Pleistocene glaciations, but probably still in Pleistocene time. In their opinion, the caves were later invaded by glacial meltwater, which remodelled the caves and laid down internal clastic deposits. Conversely, Głazek and Szynkiewicz (1980) suggested that the spacious caves in the Sokole Hills were formed as resurgence caves in Eocene–Early Oligocene times.

METHODS AND MATERIALS

The studies of the spatial pattern of the caves and their rocky relief were conducted in six selected caves. The authors used published maps of the caves (Szelerewicz and Górny 1986) and unpublished documentation by Jerzy Zygmunt. Relief of cave walls and ceilings was documented in the field by careful measurements of a series of cross-sections with fibreglass tape and a geological compass with a clinometer. Internal deposits in the caves were sampled. Sampling was limited to a minimum due to cave protection.

For measurements of the carbon and oxygen stable isotope ratios of the carbonates, samples of ca 10 mg weight were taken with a Dremel drilling machine. The measurements of carbonate $\delta^{13}C$ and $\delta^{18}O$ were conducted with a mass spectrometer SUMY at the Institute of Geological Sciences, Academy of Sciences of Belarus in Minsk. The isotope ratios were measured in carbon dioxide obtained by reaction of the analysed samples with 100% orthophosphoric acid. Carbon dioxide was subsequently trapped in liquid nitrogen and purified in vacuum. The analytical error for single measurements is ± 0.2 ‰.

All U-series analyses were performed at the Quaternary Geochronology Laboratory at the Institute of Geological Sciences, Polish Academy of Sciences. Samples containing 10–25 g of clean, compact calcite with no visible traces of detrital admixtures were analyzed by the standard chemical procedure for the separation of uranium and thorium from carbonate samples (Ivanovich and Harmon 1992). A ^{228}Th-^{232}U mixture (UDP10030 tracer solution by Isotrac, AEA Technology) was used to check the efficiency of the chemical procedure. Uranium and Th were separated by ion exchange using DOWEX 1×8 resin. After final purification, U and Th were electro-deposited on steel disks. Energetic spectra of alpha particles were collected using an OCTETE PC spectrometer made by EG&G ORTEC. Spectra analyses and age calculations were conducted using "URANOTHOR 2.6" software, which is a standard software developed in the Quaternary Geochronology Laboratory at the Institute of Geological Sciences, Polish Academy of Sciences (Gorka and Hercman 2002). Each spectrum was corrected for background and delay since chemical separation. Uranium content in all samples was high enough for precise measurement. Three samples were clean enough with a $^{230}Th/^{232}Th$ activity ratio above 20 (cf. Schwarcz and Latham 1989).

The composition of heavy minerals in the clastic deposits was determined in samples collected in Studnisko Cave, Pod Sokolą Górą Cave and Pogorzelskiego Cave (for locations see Text-fig. 1). One sample of glaciofluvial sands was also taken. The samples were rinsed with water. Before separation of heavy minerals, the samples of carbonate-cemented deposits were dissolved in hot acetate buffer (CH_3COONa). Half a sample consisting of loose glaciofluvial sands was also treated with acetate buffer to check for possible changes in heavy mineral assemblage caused by such a treatment. Heavy minerals were separated from the 0.125 to 0.25 mm fraction by standard methods, using sodium polytungstate ($Na_6(H_2W_{12}O_{40})H_2O$) of density 2.85 g.cm^{-3}. Burkhard's (1978) classification of heavy minerals was applied.

RESULTS AND INTERPRETATION

Cave pattern

Studnisko Cave consists of two interconnected spacious chambers: the Entrance Chamber (Polish: Sala Wejściowa) and the Breakdown Chamber (Polish: Sala Zawaliskowa). The side narrow passage slopes down to the cave bottom (Text-fig. 2).

The Entrance Chamber, developed in massive Upper Jurassic limestone, measures 36 × 17 m in maximum lateral dimensions (Text-figs 2, 3). It reaches a maximum height of 27 m. The volume of the chamber is around 7,500 m^3. The entrance to the cave in the topmost part of this chamber was artificially opened during exploitation of calcite in the 19th century. The ceiling and walls of the chamber delineate a spacious dome-shaped space. They are well preserved without traces of major breakdowns and collapses. The chamber lacks a significant amount of clastic deposits at the bottom, hence its original shape is clearly visible.

The Breakdown Chamber is more complex in shape (Text-fig. 2). It comprises several smaller, interconnected chambers. Its lateral dimensions are 38 × 22 m with a mean height of 4 m. The volume of the chamber is estimated at around 1,500 m^3. The shape of the chamber is clearly modified by breakdowns which followed bedding of the Jurassic limestone hosting this chamber. The ceiling is locally flat and inclined along a bedding plane. Slabs of single beds and irregular limestone debris litter the floor of the chamber.

Pod Sokolą Górą Cave consists of a SE–NW-trending chamber and a short, steeply dipping passage connecting the chamber with the cave entrance (Text-fig. 4). The chamber is 40 m long and 18 m wide with a mean height of 4 m; its volume totals around 1,900 m^3. The ceiling in the northwest part of the chamber is shaped by collapse. The cave entrance is located in a small collapse doline with rocky walls displaying remnants of solutional relief such as partly collapsed solution cavities.

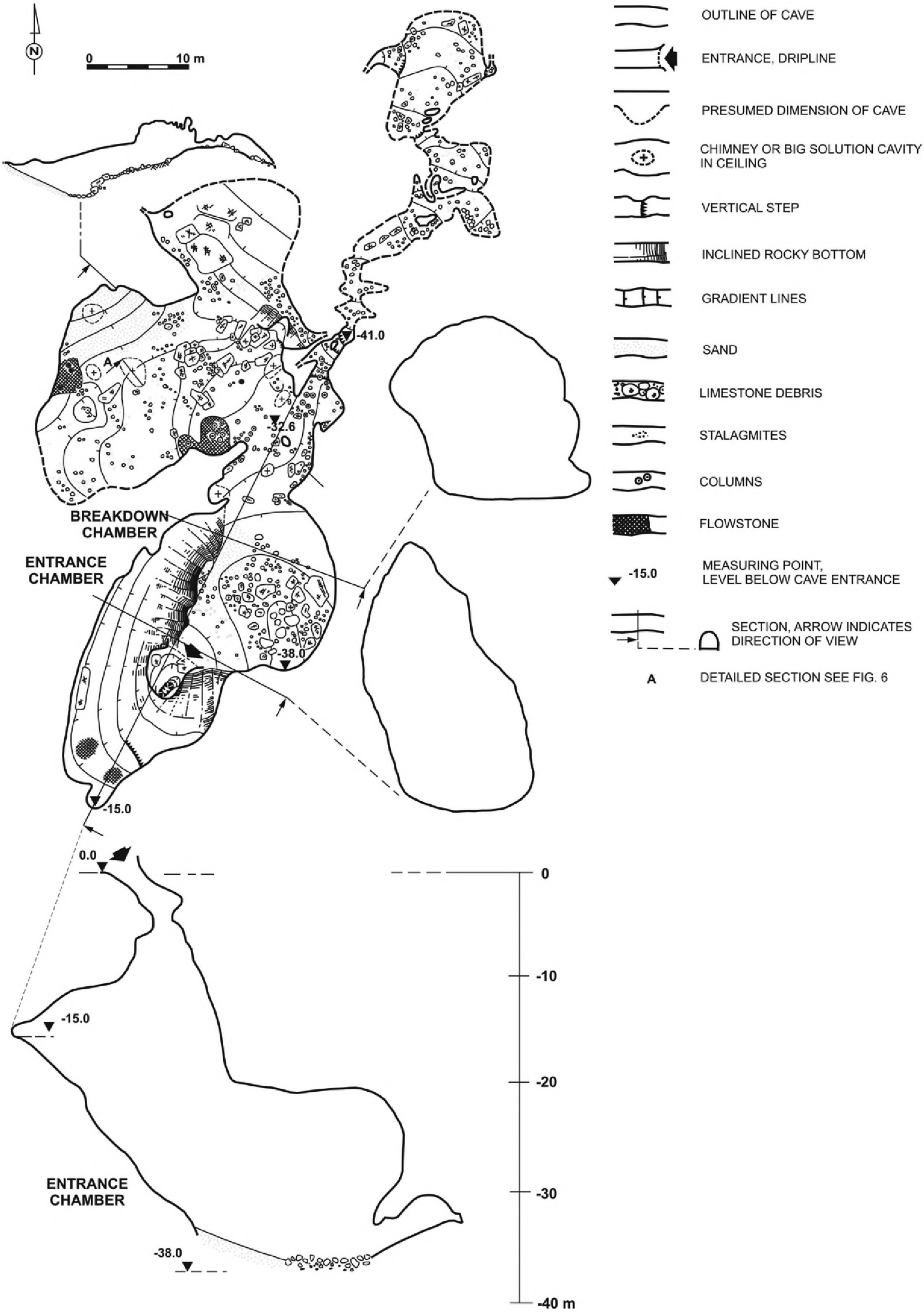
The specific volume of the spacious Entrance Chamber in Studnisko Cave, that is the ratio between the volume and the longest horizontal dimension, equals around 200 m^3.m^{-1}. According to Dublyansky (2000b) this parameter of individual chambers exceeds 100 m^3.m^{-1} in hydrothermal caves. Other authors also ascribe the origin of giant chambers to ascending circulation. Palmer (1991, 2007, p. 145, 215) points to the hypogenic origin of large chambers. Frumkin and Fischhendler (2005), based on examples from Israel, indicate that the origin of spacious circular chambers is connected with mixing of deeply circulating water and shallow water. Such chambers, called 'cathedrals', are also common in other caves of ascending origin (Osborne 2004, 2007).

The specific volumes of two other spacious chambers, the Breakdown Chamber in Studnisko Cave and the chamber in the Pod Sokolą Góra Cave, are 38 m^3.m^{-1} and 48 m^3.m^{-1}, respectively. Such values, according to data in Dublyansky (1980), are slightly too high for typical non-hydrothermal caves, which are characterised by specific volumes less than 20 m^3.m^{-1}, and usually ranging between 2 and 5 m^3.m^{-1}. In contrast to the Entrance Chamber in Studnisko Cave, the bottom of the chambers under discussion is littered with various clastic deposits and their primary height was greater than the present one. Hence, the calculated specific volume of these chambers is lower than their actual specific volume.

The other caves in Sokola Hill are small fragments of bigger caves dissected and fragmented by surface erosion (Urban and Gradziński 2004). Their dimensions are definitely smaller than those of the two caves characterized above and the primary shapes and dimensions of their ancestor caves cannot be credibly inferred.

Cave relief

Dome-shaped solution cavities are abundant in several caves in Sokola Hill (Table 1; Text-figs 5A, 6). Their diameters range from 0.2 m to more than 3 m. The biggest of them fall within the cupola category, since their diameter exceeds 1.5 m, the lower limit of this cat-



Text-fig. 2. Simplified map of Studnisko Cave, after Szelerewicz and Górny (1986), modified egory (see Osborne 2004). Smaller forms may be referred to the solution pockets of Palmer (2007, p. 150–151). However, the forms studied represent one population with a wide range of dimensions, hence they are collectively called solution cavities in this paper.

The solution cavities occur in the walls and ceilings of the caves. The majority of them are semicircular in cross section and open to the cave interior. Some of them form large wall pockets that are round, circular in plan view and regular in shape. Only a minority of the solution cavities, mostly those of elongated shape, are guided by joints. These joint-guided solution cavities now host stalactites and draperies. Examples are present in the Breakdown Chamber in Studnisko Cave.

Some of the solution cavities coalesce by breaching of the limestone walls between them. This is testified by remnant rock bridges within some solution cavities or remnants of walls preserved as curved rock blades with biconcave shape, still intervening between two neighbouring cavities (Text-fig. 5A, 6; see Osborne 2007, 2009).

Some of the larger solution cavities in Pod Sokolą Górą Cave, as well as in the Breakdown Chamber in Studnisko Cave, host smaller forms. They collectively display a hierarchical arrangement. Solution cavities displaying such a relief are called multicuspate by Ford and Williams (2007, p. 252). Similar forms are described by Rudnicki (1978) from the Berkowa Cave and from Hungarian caves, and by Gradziński *et al.* (2009) from the Smocza Jama Cave.

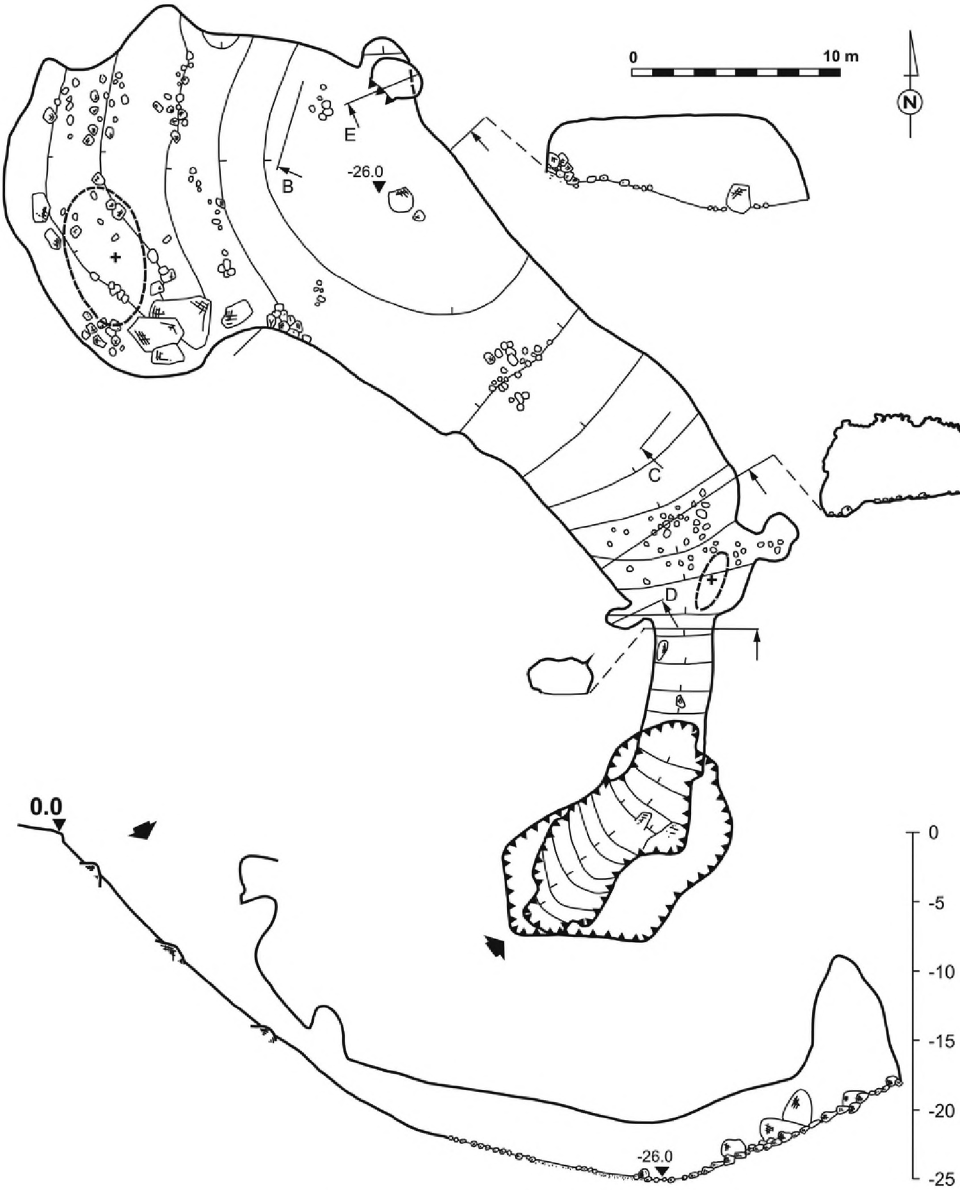
In the entrance part of Pod Sokolą Górą Cave, large solution cavities, exceeding 4 m in diameter, are arranged over one another (see cross section in Text-fig. 4). They form a so-called rising set of cupolas (see Klimchouk 2007, p. 37). Similarly arranged solution cavities, but smaller in diameter, have been identified in the ceiling of W Amfiteatrze Cave, where they form a ceiling half tube.

Blind chimneys are another solution form present in the ceiling of the caves, of which Pod Sokolą Górą Cave provides the most spectacular examples. A blind chimney in the western part of the cave is elliptical in plan view, and more than 10 m high. A similar form is present in the Entrance Chamber in Studnisko Cave. The artificial entrance to this cave was opened in the topmost part of this chimney.

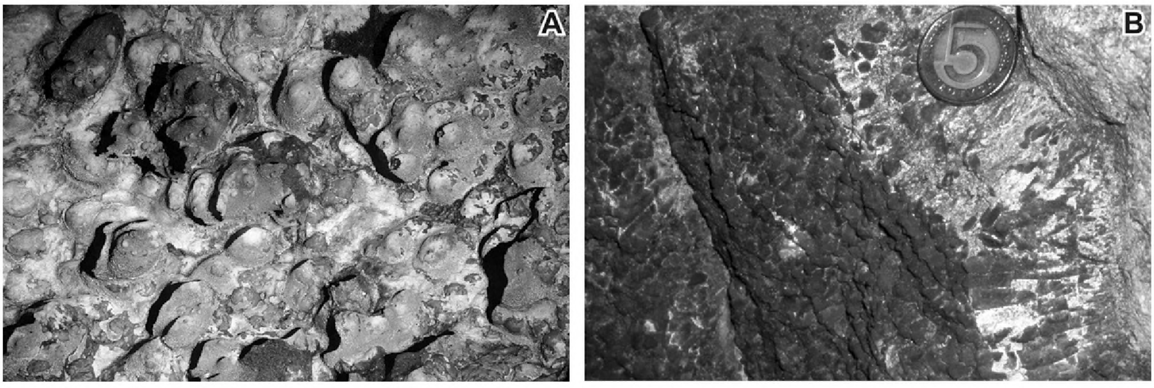
The origin of solution cavities has been extensively discussed (e.g., Osborne 2004; Palmer 2007; Ford and Williams 2007; Klimchouk 2007, 2009 and literature quoted therein). They may form in various ways. Audra *et al.* (2007), following the opinion by Szunyogh (1989), postulate their origin just above bodies of aggressive hot water. However, the lack of any traces of a stagnant palaeowater table strongly suggests a different origin for the types of solution cavities under discussion. The mechanism of mixing corrosion can also be ruled out because of the lack of guiding fractures in most solution cavities. Hence, the solution cavities were formed below the water table, in the phreatic zone, by buoyancy-driven slow movement of water. The hierarchical arrangement of solution cavities suggests that thermal convection was presumably the main factor responsible for their origin. This mechanism was put forward to explain similar forms in a small cave in Berkowa Hill (Polish Jura) in the classic paper by Rudnicki (1978). Similar hierarchically arranged ceiling cavities are also known from the Budapest caves created by ascending circulation of thermal water (Müller and Sárváry 1977; Rudnicki 1978; M. Gradziński, unpublished data). The larger solution cavities were formed by the enlargement and coalescing of neighbouring smaller ones (Osborne 2007). The presence in these caves of rising chains of solution cavities, blind chimneys and ceiling tubes is also noteworthy.

All of the above discussed forms of cave relief prove that the caves were predominantly formed under phreatic conditions. Although none of the forms itself is an unequivocal criterion of specific speleogenetic conditions, their widespread occurrence in the caves definitely is. Klimchouk (2007, 2009) includes the forms in question in 'the morphologic suite of rising

Text-fig. 3. Entrance Chamber in Studnisko Cave; photo taken upward at about 45° angle, note person (black figure) standing at the cave entrance; photo by Aleksander Dobrzański



Text-fig. 4. Simplified map and extended cross-section of Pod Sokolą Górą Cave, after Szelerewicz and Górny (1986), modified; see Text-fig. 3 for symbols



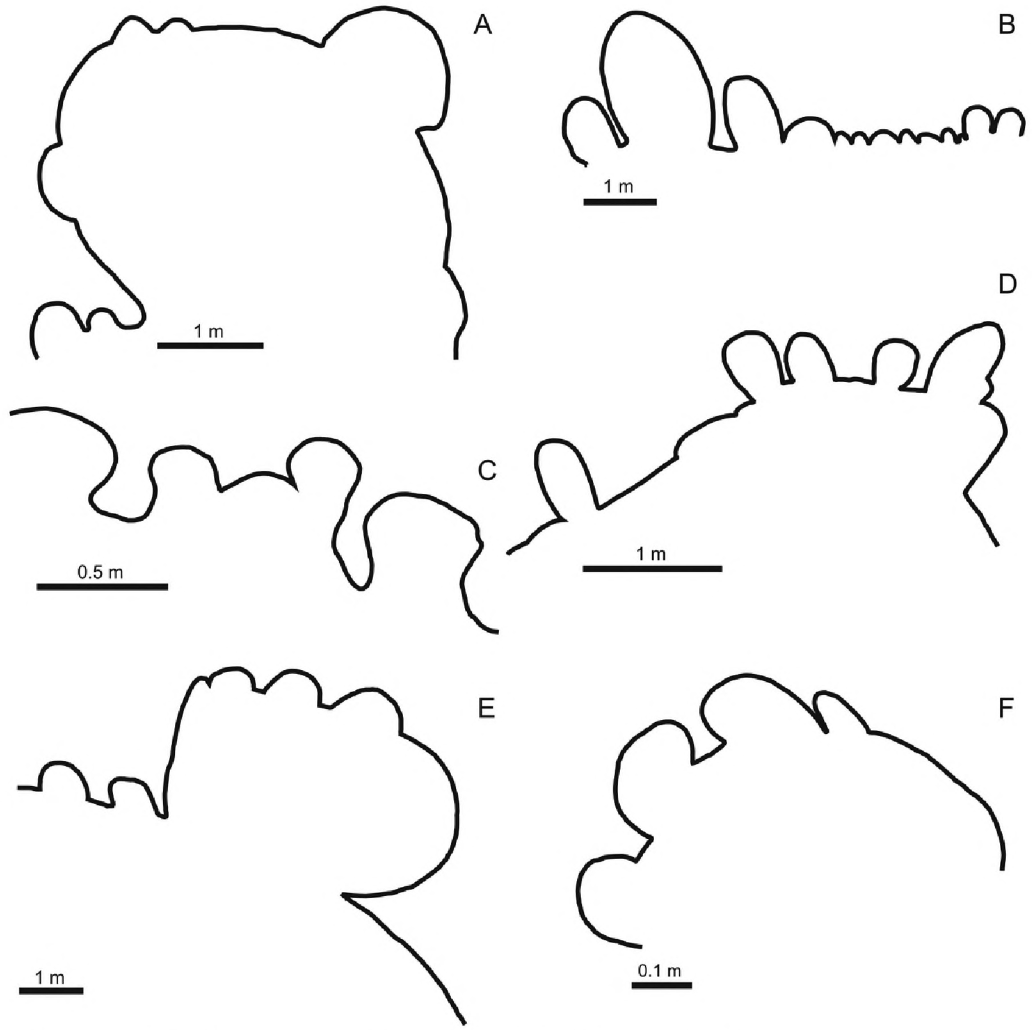
Text-fig. 5. A – Solution cavities in ceiling of Pod Sokolą Górą Cave; photo taken vertically upward; width of photo ca 4 m; B. – Calcite spar with rhombohedron terminations covering the cave wall visible on right side of photo; coin is 23 mm across flow', typical of hypogenic caves. Osborne (2007) also regards such forms of cave relief as diagnostic for *per ascendum* speleogenesis. The pattern of the caves, together with their rocky relief, thus both indicate their ascending origin, presumably by the action of thermal water. Some parts of the caves under study may have subsequently been included into normal karst drainage systems and modified.

Vadose remodelling seems to have been subordinate since forms of vadose relief are scarce. The only example of a wall notch in the caves was identified in the entrance of the Pogorzelskiego Cave. The notch is 1 m long, and its vertical aperture is c. 20 cm. The notch is horizontally incised up to 30 cm into the bedrock.

Calcite spar

Calcite spar occurs in the majority of the caves (Table 1). It was mined in many of them in the 19th and the first half of the 20th century (Maślankiewicz 1937; Wójcik 2004). Some subterranean voids were completely filled with the calcite spar. An abandoned subterranean mine of calcite spar is a good example of such voids. This cave was completely filled with calcite spar which was later partly mined. Another example is a small karst form filled with calcite spar, subsequently cut by surface erosion and now exposed in a rock cliff (Text-fig. 1; Table 1).

The calcite spar lines the walls of the caves (Text-figs 5B, 7). It consists of calcite rhombohedrons, more or less perpendicularly oriented to the cave wall. The crystals are either white with a milky appearance or are yellowish to pinkish and translucent. The length of particular crystals exceeds 10 cm. The crystals show well defined acute terminations. Examination of thin sections proves that crystals do not contain significant admixtures of non-carbonate impurities.



Text-fig. 6. Detailed cross-section through selected ceiling solution cavities, for location of A–E see text-figs 2, 4, F – W Amfiteatrze Cave

Sample	Lab. No.	U cont. [ppm]	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$	Age [ka]	Comment
Pogorzelskiego Cave, calcite spar	W 1789	0.017 ± 0.002	1.02 ± 0.13	1.07 ± 0.14	90	> 350	sample older than 1.2 Ma
Studnisko cave flowstone	W 1788	0.040 ± 0.003	1.04 ± 0.12	0.99 ± 0.11	34	> 350	sample older than 1.2 Ma
Studnisko cave calcite spar	W 1787	0.041 ± 0.003	0.96 ± 0.11	0.99 ± 0.11	117	> 350	sample older than 1.2 Ma
Studnisko cave flowstone	W 2177	0.35 ± 0.01	1.55 ± 0.06	0.090 ± 0.008	4		detrital contamination

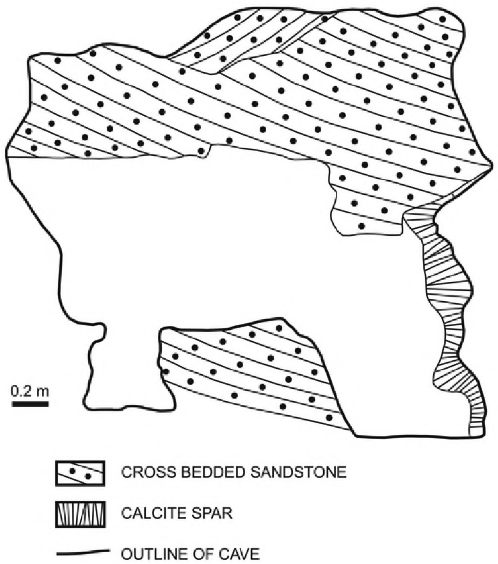
Table 2. Results of U-series dating of calcite samples

$^{230}Th/^{234}U$ activity ratios of calcite spar samples (Lab. No. W 1787, 1789) indicate radioactive equilibrium and an age of >350 ka (Table 2). Radioactive equilibrium of the uranium isotopes ($^{234}U/^{238}U$ activity ratios within the error limit equalling 1) indicates an age of >1.2 Ma. The $\delta^{13}C$ and $\delta^{18}O$ values of the calcite spar fall within a range from −11.5 ‰ to −9.0 ‰ and from −11.1 ‰ to −5.4 ‰ respectively (Table 3).

The calcite spar represents the oldest generation of cave fills in Sokola Hill since it nucleated directly on the rocky substrate, and in some places was covered by clastic deposits. The euhedral habit of the calcite crystals, their acicular terminations, and the continuous crystal lining around the cave perimeter, all testify that the calcite spar grew under phreatic conditions. Such phreatic calcite spar, also termed simply 'phreatic calcite', is known from several caves, chiefly those of ascending origin (e.g., Bakalowicz *et al.* 1987; Dublyansky 1995; Hill and Forti 1997, p. 101; Bottrell *et al.* 2001; Immenhauser *et al.* 2007; Spötl *et al.* 2009). It grows slowly under stable conditions below the water table. This process is commonly stimulated by changes

Sample number	Sample location	Sample type	$\delta^{13}C$ [‰ VPDB]	$\delta^{18}O$ [‰ VPDB]
1	Pogorzelskiego Cave	flowstone	-10.7	-10.1
2	Pogorzelskiego Cave	flowstone	-11.8	-8.6
3	Pogorzelskiego Cave	flowstone	-9.7	-8
4	Pogorzelskiego Cave	flowstone	-10.4	-10.6
5	Calcite mine	calcite spar	-10.8	-8.8
6	Calcite mine	calcite spar	-10.1	-11
7	Calcite mine	calcite spar	-11.5	-10.2
8	Calcite mine	calcite spar	-10.4	-10.9
9	Calcite mine	calcite spar	-9.0	-9.3
10	Studnisko	flowstone	-9.6	-7.7
11	Studnisko	flowstone	-9.3	-5.7
12	Studnisko	flowstone	-9.9	-7.1
13	W Amfiteatrze Cave	flowstone	-9.8	-0.2
14	Pod Sokolą Górą Cave	flowstone	-8.3	-5.2
15	Pod Sokolą Górą Cave	flowstone	-8.3	-7.1
16	void filled with calcite spar	calcite spar	-10.6	-11.1
17	Pogorzelskiego Cave	calcite spar	-9.9	-7.5
18	Na Półce Cave	calcite spar	-10.2	-5.4
19	Calcite mine	calcite spar	-9.8	-6.3

Table 3. Stable isotope composition of calcite speleothems



Text-fig. 7. The Pogorzelskiego Cave, cross-section showing the position of calcite spar and cross-bedded sandstones

in CO_2 pressure, which controls the calcite solubility and leads to supersaturation of water with respect to calcium carbonate over the given depth (Ford *et al.* 1993). According to Dublyansky (2000a, fig. 4.1.5.1), this takes place at a depth less than 0.5 km below the water table. The thorough study by Ford *et al.* (1993) suggests that precipitation of calcite in the Wind Cave in the Black Hills of Dakota, USA, took place down to ~70 m below the water table. The lack of impurities in the calcite spar reflects its growth in water, well isolated from the surface environment (Ford 1989; Dublyansky 2000b). The $\delta^{13}C$ values of the calcite spar suggest that the water was charged with isotopically light CO_2 of soil origin.

Calcite spar crystallized slowly under stable conditions and presumably in oxygen isotopic equilibrium with the parent water (Bakalowicz *et al.* 1987; Immenhauser *et al.* 2007). Under this assumption, it is possible to calculate the temperature of crystallization using the equation formulated by O'Neil *et al.* (1969) and modified by Friedman and O'Neil (1977):

$$10^3 \ln\alpha_{c\text{-}w} = 2.78\ (10^6 T^{-2}) - 2.89, \qquad (1)$$

where T is the temperature of crystallization (in absolute scale), and $\alpha_{c\text{-}w}$ is the oxygen equilibrium fractionation factor between calcite and water, which can be expressed by the following equation:

$$\alpha_{c\text{-}w} = \frac{1000+\delta^{18}O_C}{1000+\delta^{18}O_W} \qquad (2).$$

Values of $\delta^{18}O_c$ and $\delta^{18}O_W$ denote isotopic composition of calcite and parent water respectively, both reported in per mill deviations from the VSMOW standard. The $\delta^{18}O_W$ of the palaeowater is not known and must be assumed. Close to the Kraków area, the oxygen isotope composition of groundwaters recharged during Holocene is ~−10 ‰ vs. VSMOW (Duliński *et al.* 2001; Zuber *et al.* 2004). For groundwaters recharged in colder climatic episodes (glacial waters), the values of $\delta^{18}O_W$ are between −13 and −11 ‰ vs. VSMOW (Zuber *et al.* 2004). Pluta and Zuber (1995) claim that the Palaeogene waters had $\delta^{18}O_W$ values around −4 ‰ vs. VSMOW, whereas in Neogene (post-Tortonian) waters the $\delta^{18}O_W$ values varied between −6 and −8 ‰ vs. VSMOW. Since the age of the calcite spar is not known, all of the above cited values are used in calculations whose results are listed in Table 4. The calculated crystallization temperatures (t_c) fall in a range between −6.4 and 52.7 °C. The lowest and highest values have been obtained assuming the glacial and Palaeogene parent water isotopic composition respectively. Temperatures below 0°C must be ruled out. The negative temperature values result from the assumption of $\delta^{18}O_W$ values typical of the isotopic composition of Holocene and

Sample number	$\delta^{18}O_c$ [‰ SMOW]	t_c calculated for $\delta^{18}O_w$ = -4‰ [° C]	t_c calculated for $\delta^{18}O_w$ = -6‰ [° C]	t_c calculated for $\delta^{18}O_w$ = -8‰ [° C]	t_c calculated for $\delta^{18}O_w$ = -10‰ [° C]	t_c calculated for $\delta^{18}O_w$ = -11‰ [° C]
5	21.84	39.2	28.7	19.2	10.5	6.5
6	19.57	52.1	40.3	29.4	20.1	15.6
7	20.50	46.6	35.4	25.3	16.1	11.8
8	20.19	48.4	37.0	26.7	17.4	13.0
9	21.63	40.3	29.7	20.1	11.4	7.3
16	19.47	52.7	40.9	30.2	20.6	16.1
17	23.18	32.2	22.4	13.5	5.3	1.5
18	25.46	21.4	12.6	4.5	-2.9	-6.4
19	24.52	25.7	16.5	8.1	0.4	-3.3

Table 4. Calculated values of calcite spar crystallization temperature

glacial parent waters. It thus seems that the precipitation of the calcite spar occurred with the participation of waters of Neogene or Palaeogene age, which is in line with the results of calcite spar dating.

If the above assumption is correct, the calcite spar crystallized at a temperature not higher than 52.7 °C. Similar temperature values have been postulated for the crystallization of phreatic calcite spar in the Budapest caves (Dublyansky 1995), and in the Jabal Madar diapir in Oman (Immenhauser *et al.* 2007).

The temperatures calculated for any given isotopic composition of parent water differ significantly from sample to sample. This implies that the sampled calcite crystals grew under various thermal conditions and that they are probably of various ages. This, in turn, implies that the hydrological system evolved during the crystallization of calcite (cf. Dublyansky 2000b; Palmer 2007, p. 213). Nonetheless, it cannot be ruled out that at least some of the calcite spar crystals grew under conditions of isotopic disequilibrium and that, in such a case, the above calculations have been based on a false assumption.

Allochthonous cave deposits

Two types of allochthonous clastic deposits have been identified in the caves: (i) conglomerates, containing Upper Jurassic limestone clasts, and (ii) quartz sandstones and sands.

Conglomerates

The conglomerates have been found exclusively in the Entrance Chamber in Studnisko Cave. They form lenses and patches attached to the inclined walls of the chamber and locally to the ceiling. Where the basement of the conglomerates is visible, they directly overlie Upper Jurassic bedrock. Some patches of conglomerates are covered with flowstones which are also dissected by erosion. The patches reach 1 m in thickness and are located 27 to 32 m below the cave entrance.

The conglomerates are composed of sub-angular to sub-rounded clasts of Upper Jurassic limestones (Text-fig. 8A, B). Sub-rounded blackened pebbles occur subordinately. The clasts are between a few centimetres and a few millimetres across and reach a maximum of 20 cm. A subtle tendency to upward decrease in grain size can be observed in the conglomerate section. The matrix is red-stained and consists of quartz grains of sand-size and, sporadically, gravel-size. It additionally contains rounded speleothem clasts, vertebrate – probably bat – bones, fine-grained reddish material and calcite cements (Text-fig. 8C). The conglomerates are grain-supported in the lowermost patches, whereas in the uppermost ones they are mud-supported. In the latter, the conglomerates are interbedded with horizontally lying flowstones (Text-fig. 8D).

Sands and sandstones

Quartz sand and sandstones are the most common clastic deposits identified in the caves. They are moderately sorted, medium- to coarse-grained, with an admixture of granules and pebbles. The sandstones are cemented with calcite.

Loose accumulations of sand are preserved locally on cave bottoms. In the Breakdown Chamber in Studnisko Cave a sandy fan descends from the northwestern wall towards the chamber centre. Horizontally layered sand also builds a loose accumulation in the northern part of the chamber. Sandy concretions attached to the ceiling and walls are present in the same chamber (Text-fig. 8E, F; Skalski and Wójcik 1968). They are spherical in shape and reach 25 cm in diameter. Neighbouring concretions are cemented together and arranged into clusters.

The sandstones attached to the cave ceiling and walls fill a substantial part of Pogorzelskiego Cave (Text-fig. 7). They display large-scale cross-bedding. The rocky floor of the cave is littered with loose sand, probably originated from weathering of the sandstone.

Heavy mineral composition

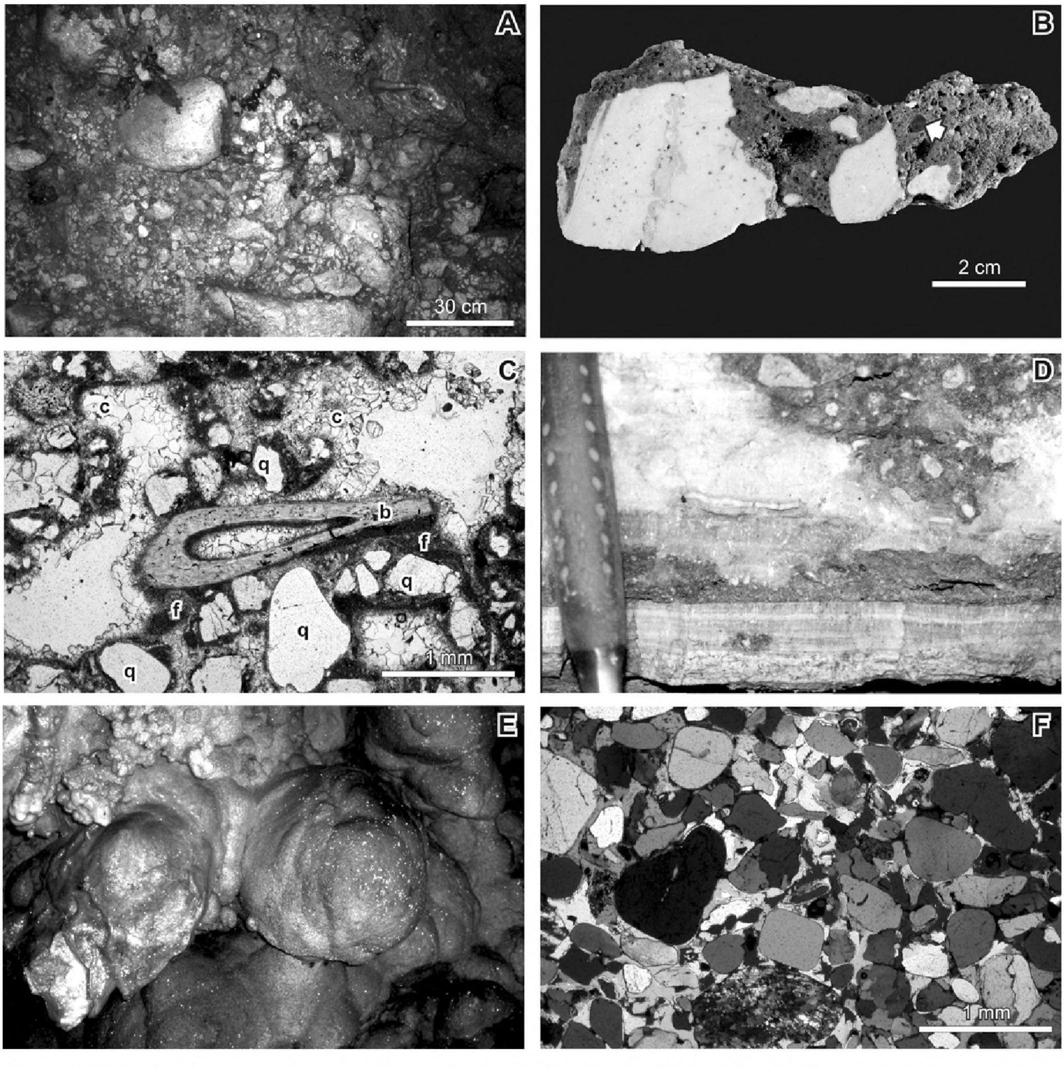
Heavy minerals make up between 0.08 wt. % and 0.3 wt. % of the allochthonous cave clastics (Table 5). Opaque minerals predominate in the analyzed samples, reaching up to 72.8 wt. % (Text-fig. 9). The translucent minerals are dominated by chemostable ones (Text-fig. 10), kyanite and tourmaline being the most common. Mechanostable and unstable minerals are less common. Conversely, a translucent mineral assemblage of glacifluvial deposits is dominated by mechanostable minerals, with garnet reaching 66.1 wt. %. These deposits have a lower content of opaque minerals than the cave clastics.

Origin of cave clastics

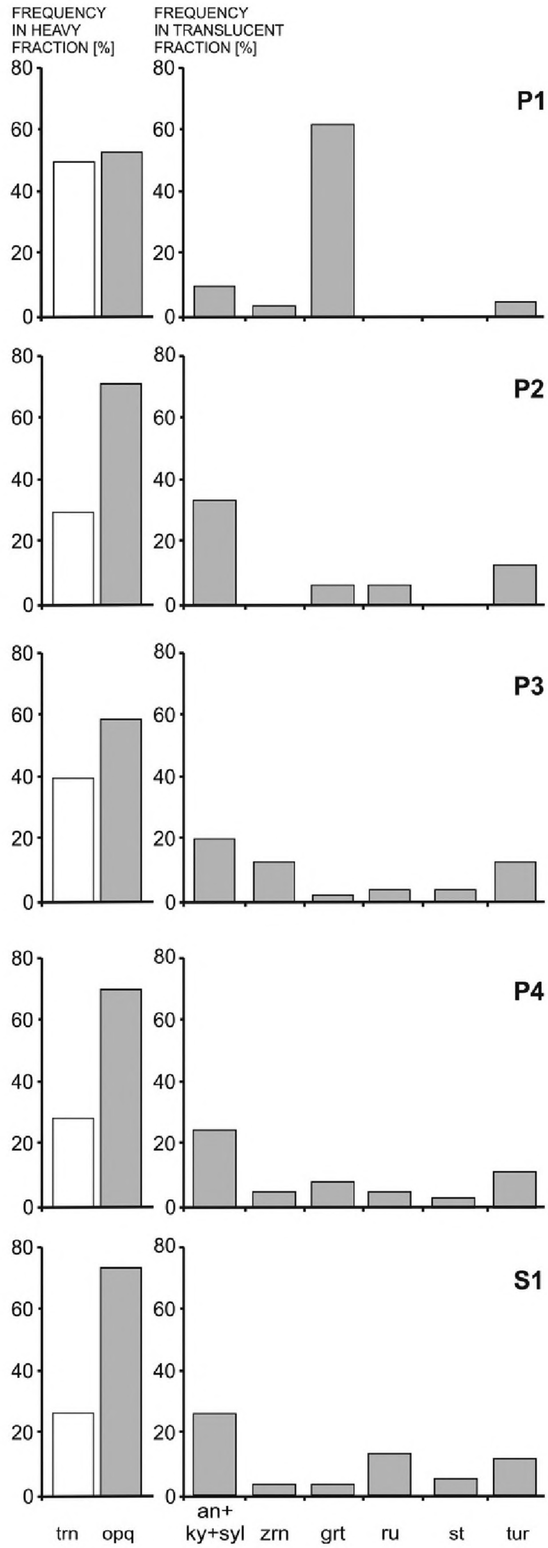
Allochthonous material brought into the caves is present as conglomerates, sands and sandstones. Its presence proves that the caves were connected with the surface and that streams washed clastic material into the caves. The occurrence of vertebrate bones in the conglomerates supports this interpretation. The age relationships between the conglomerates and the sands and sandstones are not known. The deposition of the clastics took place in several episodes interrupted by episodes of erosion and episodes during which streams dwindled or dried up. During the dry episodes, crystallization of vadose speleothems proceeded and the clastics were undergoing selective cementation. Both processes depended on the distribution of percolating supersaturated water. The cemented zones became more resistant to the subsequent erosion, and are preserved as irregular patches of conglomerates or sandstones and as sand concretions.

The heavy mineral assemblage dominated by chemostable minerals differs from that typical of Pleistocene clastics of glacial origin (Table 5, Text-figs 9, 10). The latter comprises mostly mechanostable minerals with substantial amount of garnets, as is shown by reference samples of glacifluvial sands (samples P1, P1A), and by the data from earlier studies (e.g., Krysowska-Iwaszkiewicz 1974; Rutkowski *et al.* 1998; Racinowski 2008).

The source of the material for the clastics is not known. The so called mouldic sands that fill extensive karst depressions in the vicinity of the Sokole Hills are characterized by a similar heavy mineral assemblage, with kyanite, tourmaline, zircone, rutile and staurolite (Bosák *et al.* 1978). The cave clastics may derive from the mouldic sands or may share a common source with them. Since the Albian and Cenomanian deposits are re-



Text-fig. 8. Cave clastics: A – Conglomerate cemented to ceiling in northern part of the Entrance Chamber in Studnisko Cave, photo taken vertically upward; B – Conglomerate composed of Upper Jurassic limestone pebbles and red fine-grained matrix, blackened pebble is arrowed, Entrance Chamber, Studnisko Cave, polished specimen; C – Conglomerate matrix with quartz grains (q), fine-grained clastics (f), calcite cements (c) and vertebrate bone (b), Entrance Chamber, Studnisko Cave; thin-section, parallel nicols; D – Conglomerates interfinger with flowestone covers, Entrance Chamber, Studnisko Cave; E – Sand concretions cemented to cave wall, Breakdown Chamber, Studnisko Cave, width of photo ca. 25 cm; F – Quartz grains cemented with calcite composing sand concretions, Zawaliskowa Chamber, Studnisko Cave; thin-section, crossed nicols



Text-fig. 9. Frequency diagram showing quantitative diversity of selected heavy minerals; trn – translucent, opq – opaque, an+ky+syl – andalusite+ kyanite+ syllimanite, zrn – zircon, grt – garnet, ru – rutile, st – staurolite, tur – tourmaline

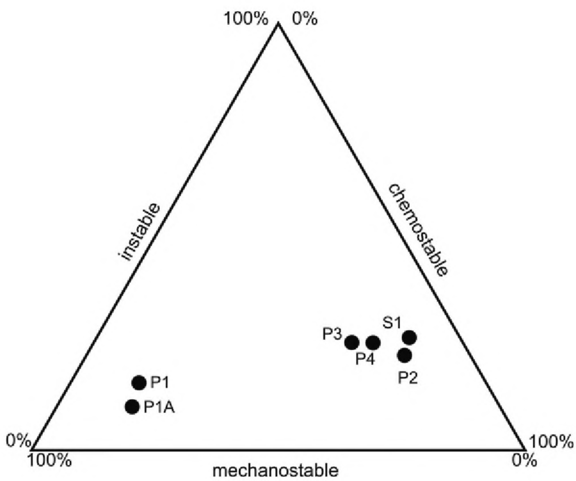
garded as the source for the mouldic sands (Gradziński 1977), these deposits may have also provided material for the cave clastics. However, any clastic deposits younger than Cretaceous and presently not preserved in the vicinity may also have acted as a source for the cave clastics.

Limestone debris

Limestone debris occurs in the majority of the caves, especially in Studnisko Cave and Pod Sokolą Górą Cave. It contains angular or subangular blocks, centimetres to more than 1 m across. The debris is autochthonous and originated from local breakdown. Some blocks could have crept down the inclined cave floor for some distance, as they are found now just beneath solution cavities in the ceiling. At least some of the debris originated during the Pleistocene by ice wedging mechanisms (cf. Madeyska-Niklewska 1969; White and White 2000). Larger blocks were detached from the ceilings along bedding planes.

Vadose speleothems

Flowstones, stalagmites and stalactites are present in the caves. Some of them have overgrown bat bones of Holocene age (cf. Postawa 2004). Most of the vadose speleothems lie beyond the scope of this study. Detailed observations were carried out only on those which can throw some light on the development of the caves, especially on those interbedding or directly covering the cave clastics (Text-fig. 8E). Such spatial relationships between flowstones and clastic deposits have been identified in Studnisko and Pogorzelskiego caves.



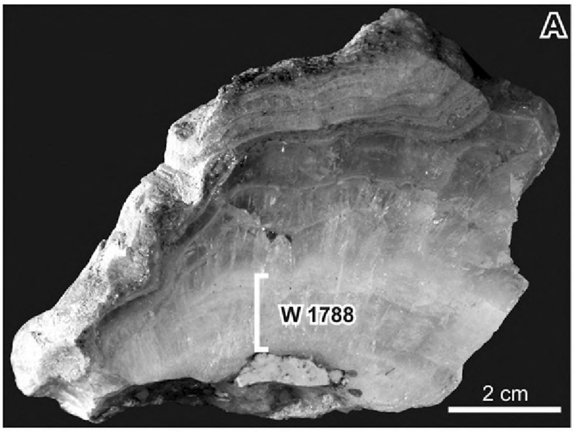
Text-fig. 10. Relationship between instable, chemostable and mechanostable heavy minerals in the studied samples, classification diagram after Burkhardt (1978)

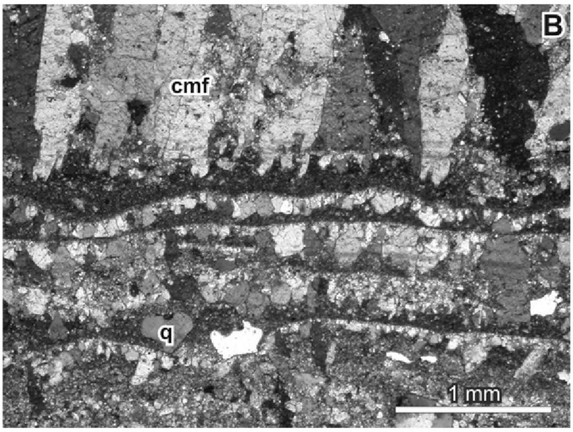
In Studnisko Cave, a 6 cm thick flowstone cover directly overlies a patch of conglomerates in the Entrance Chamber (Text-fig. 11A). The flowstone is translucent and white to very pale yellowish, and is composed of columnar microfacies (*sensu* Dziadzio *et al*. 1993; Gradziński *et al*. 1997). Pale to dark yellowish laminae built of clastic impurities, for instance quartz grains, are visible (Text-fig. 11B). The

	P1 glacifluvial sand	P1A* glacifluvial sand	P2 Pogorzelskiego Cave, sand	P3 Pod Sokolą Górą Cave, sand	P4* Pogorzelskiego Cave, sandstone	S1* Studnisko Cave, conglomerate
	[wt % of heavy minerals]	[wt % of heavy minerals]	[wt % of heavy minerals]	[wt % of heavy minerals]	[wt % of heavy minerals]	[wt % of heavy minerals]
opaque	51.5	53.8	71.6	59.5	71.8	72.8
translucent	48.5	46.2	28.4	40.5	28.2	27.2
	[wt % of translucent heavy minerals]	[wt % of translucent heavy minerals	[wt % of translucent heavy minerals	[wt % of translucent heavy minerals	[wt % of translucent heavy minerals	[wt % of translucent heavy minerals
amphibole	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
andalusite	0.8	2.7	8.3	9.2	4.3	12.9
apatite	3.9	2.7	8.3	5.6	9.8	8.1
biotite	n.d.	n.d.	4.2	11.0	3.0	3.2
chlorite	4.2	1.4	14.5	5.6	12.6	16.2
dolomite	n.d.	n.d.	n.d.	n.d.	1.6	n.d.
epidote	10.8	6.7	6.3	10.5	8.2	9.7
garnets	61.4	66.1	6.3	1.9	8.2	3.2
glauconite	n.d.	1.4	n.d.	n.d.	n.d.	n.d.
kyanite	6.9	5.4	22.7	11.0	19.7	12.9
muscovite	2.3	n.d.	4.2	12.6	6.3	1.6
pyroxene	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
rutile	1.2	n.d.	6.3	3.7	4.9	12.9
staurolite	n.d.	2.7	2.1	3.7	3.3	4.8
syllimanite	1.9	1.4	2.2	n.d.	1.6	n.d.
tourmaline	3.9	5.4	12.5	12.6	11.6	11.3
zircon	2.7	4.1	2.1	12.6	4.9	3.2

* - sample dissolved in acetete buffer, n.d. - not detected

Table 5. Contents of opaque and translucent heavy minerals in studied samples, composition of translucent heavy mineral assemblage





Text-fig. 11. Vadose speleothems: A – Flowstone covering conglomerates in Entrance Chamber, Studnisko Cave; location of sample for U-series dating is indicated, polished specimen, B – Calcite flowstone built predominantly of columnar microfacies (cmf), laminae rich in siliciclastic detritus with outstanding quartz grain (q) are visible at the base, Entrance Chamber, Studnisko Cave; thin section, crossed nicols base of this flowstone was dated with the U-series method (sample W 1788, see Text-fig. 11A for location). The thin flowstone locally covers the exposed eroded surface of the conglomerates and hence it postdates their erosion. This flowstone was also sampled for dating (sample W 2177).

The $^{230}Th/^{234}U$ activity ratio of sample W 1788 indicates radioactive equilibrium and the age of the sample is >350 ka (Table 2). Radioactive equilibrium of the uranium isotopes ($^{234}U/^{238}U$ activity ratios within the error limit equaling 1) suggests the age of these samples as >1.2 Ma. The only chance for a precise determination of the age of such old speleothems is the use of U-Pb methods. However, the very low U content in the flowstones (in the range 0.01–0.04 ppm) may pose a problem.

Sample W 2177 – flowstone covering the eroded surface of the conglomerates – has a significantly higher concentration of U than other samples studied. This may indicate a different source of U, probably owing to different paths of the parent water. The very low $^{230}Th/^{234}U$ activity ratio suggests a relatively young age – probably Holocene. The measured value of the activity ratio corresponds to an age of about 10 ka. However, the presence of ^{232}Th ($^{230}Th/^{232}Th$ activity ratio equaling 20) indicates a significant detrital contamination and prevents a reliable dating of the sample. The assumption that there is only thorium contamination enables age correction using the initial $^{230}Th/^{232}Th$ activity ratio at the contaminant (B0) as a contamination index. B0 values between 0.5 and 1.7 are commonly used (cf. Kaufman and Broecker 1965; Geyh 2001). Using the correction index B0 = 1.5 ± 0.5 (it covers the range most commonly used for age correction) the corrected age is 6 ± 4 ka.

Thin flowstones, up to 12 mm in thickness, interfinger with sandstones in the Pogorzelskiego Cave. They are composed of blocky and columnar microfacies and are rich in non-carbonate impurities, which make it impossible to date them by the U-series method. Thin flowstones also line some solution cavities in the ceiling of Pod Sokolą Górą Cave. Flowstone also builds a so-called false floor in the W Amfiteatrze Cave, a flowstone cover laid down on clastic deposits, which were later removed.

Some of the flowstones have incorporated bat bones, probably Holocene in age (Tomasz Postawa, personal communication, 2005). Vadose speleothems show $\delta^{13}C$ values between −11.8 ‰ and −8.3 ‰, whereas their $\delta^{18}O$ values range from −10.6 ‰ to −0.2 ‰ (Table 3). These values fall within the range typical of speleothems from a temperate zone.

SPELEOGENESIS OF SOKOLA HILL

Four main stages have been distinguished in the speleogenesis of Sokola Hill by considering the speleogenetic conditions, origin of the cave deposits and their spatial relationships: (i) formation of the caves, (ii) crystallization of calcite spar, (iii) invasion of vadose streams, and (iv) drying of the caves. Each of the stages may include several episodes whose net effect is registered as formation or modelling of the caves, as deposition of internal sediments within them or as erosion of these sediments (Text-fig. 12).

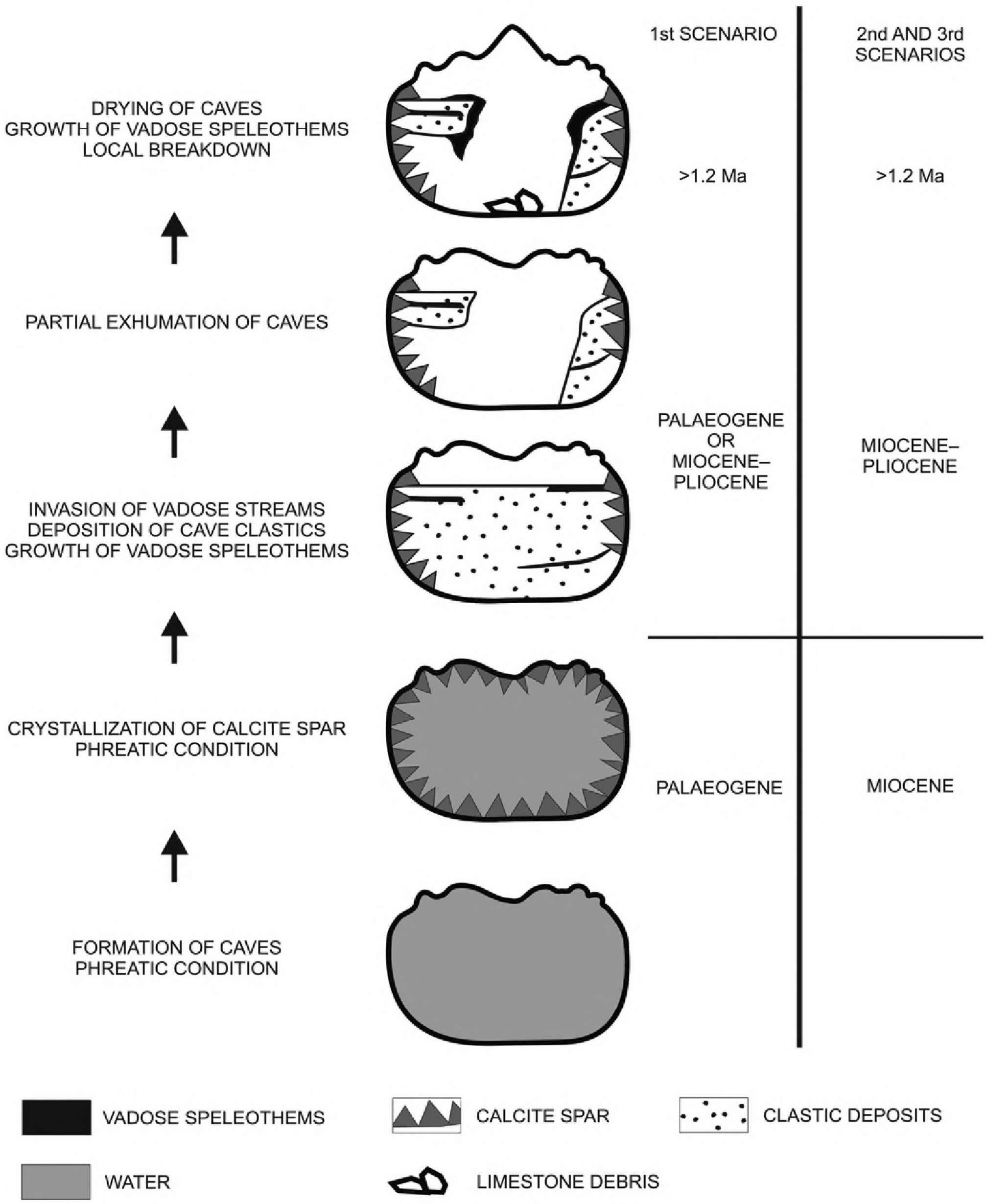
Formation of the caves

The caves in Sokola Hill are fully disconnected from the present-day drainage system and are not related to the present surface relief, hence they originated under hydrological and morphological conditions essentially different from the present ones.

Pod Sokolą Górą and Studnisko caves comprise chambers whose shape and pattern do not bear any resemblance to typical fluvial caves (cf. Osborne 2007). The relief of the cave ceilings proves that they were formed under phreatic conditions. The hierarchical arrangements of solution cavities in the cave ceilings strongly suggest elevated temperature of the water which formed the caves. The common occurrence of solution cavities in the cave ceilings, arrangement of such cavities in raising chains, along with the presence of blind chimneys and ceiling half-tubes, all testify that the caves were formed by ascending water. Although small solution cavities similar to some observed in caves of Sokola Hill may also be formed in eogenetic caves (Ford and Williams 2007, p. 252; Palmer 2007, p. 211), such a scenario is ruled out because of the reasons given below. Neither the forms of cave relief nor the dimension and shape of the chambers show a relationship to eogenetic karstification. Moreover, eogenetic karstification seems to be improbable, taking into account the depositional milieu of the Oxfordian limestone and the later geological history of the Polish Jura.

The postulated ascending origin of the caves implies that they were formed in a confined setting. This is supported by the lack of scallops on the cave walls, characteristic of wall relief formed in the presence of integrated flow in an unconfined setting (cf. Ford and Williams 2007, p. 241; Klimchouk 2007, p. 30). Hence, the caves were formed when the Jurassic limestone hosting them was covered by confining impermeable beds. The above view contradicts the concept formulated by Skalski and Wójcik (1968), who related the origin of the caves in Sokola Hill to the so-called water-table theory (*sensu* Swinnerton 1932), and claimed that the caves formed in two phases near the water table.

The caves are located a short distance below the present top of the Upper Jurassic limestone and more than 150 m above its base. Thus, the aggressiveness of the water can be attributed to two mechanisms: (i) cooling of thermal water during its upward migration towards the surface, and (ii) interacting of ascending water with water of shallow circulation (cf. Palmer 1991 2007; Dublyansky 2000a, b). It also seems plausible that both mechanisms operated concomitantly. The latter must have been connected with penetration of meteoric water to the Jurassic limestone aquifer, which was possible if there existed vertical connections through the overlying confining beds, for instance along faults or in hydrological windows. Both mechanisms were particularly efficient in a relatively shallow zone but not just below the palaeosurface. It is doubtful that injection of unsaturated water from below into the Upper Jurassic limestone series was involved in the formation of the caves. In such a case the caves would



Text-fig. 12. Simplified history of caves in the Sokola Hill, not to scale, further explanation in the text be located at the base of the limestone series, which is not the case (see discussion in Klimchouk 2009).

Modelling by Andre and Rajaram (2005) suggests that the creation of cave conduits by ascending thermal water is a slow process. A cave which owes its origin to such conditions can attain a traversable size after several hundred thousand years (see also Palmer 1991). Thus, the formation of the caves under discussion, especially the spacious chambers, demanded favourable conditions persisting over a relatively long period of time. Such conditions occurred within a much larger area of the Polish Jura, as is shown by the presence of similar underground forms at many sites over this region (Rudnicki 1978; Głazek and Szynkiewicz 1980; Pulina *et al.* 2005; Tyc 2009 a, b). The palaeohydrological conditions of the phreatic stage of the cave evolution and timing of the cave formation are discussed below in a separate section.

Crystallization of calcite spar

The calcite spar postdates the formation of the caves, but it crystallized when the caves were still under phreatic conditions. However, there is no unequivocal proof that they were still filled with the same water that formed the caves. The euhedral habit of the crystals suggests that they grew slowly deeper below the water table (Ford 1993). The caves were presumably filled with sluggish water, without vigorous flow towards the discharge zone (see discussion in Ford 1989). According to Ford *et al.* (1993) and Dublyansky (1997, 2000a) water loses its aggressiveness near the ground surface and becomes supersaturated with respect to calcium carbonate. When the ground surface is lowered by denudation in the course of geological evolution of an area, the zone of calcite precipitation migrates downward and calcite spar may crystallize in caves formed during earlier stages of speleogenesis (see also Palmer 2007, fig. 8.47). The acceptance of this concept implies that calcite spar was formed under the same palaeohydrological conditions and from the same water which created the caves. This is indirectly supported by calculations suggesting that the calcite spar grew from water of slightly elevated temperature, similar to the water which formed the caves. Nonetheless, the calcite spar may have crystallized from different water during further stages of the cave development, but still when the caves were situated below the water table.

Invasion of vadose streams

The cave clastics containing allochthonous material of sand and gravel size are evidence that the caves were invaded by sinking vadose streams. This marks a new stage in evolution of the phreatic caves, originally formed by ascending water circulation and now included into a completely new karst drainage system. The lack of distinct vadose modelling in the rocky relief of the caves implies that the invasion of surface streams was a relatively short-lasting stage in the evolution of these caves, though the presence of vadose relief cannot be excluded beneath sediments that cover the rock floors of some caves, for instance Pod Sokolą Górą Cave. Vadose modelling is a common phenomenon in caves located in the southern part of the Polish Jura (Gradziński 1962; Madeyska-Niklewska 1969).

The time of clastic deposition cannot be determined directly. The age of flowstone cover on the conglomerates proves that the latter were laid down earlier than 1.2 Ma. This is in line with the absence of glacigenic deposits in the caves (cf. Krysowska-Iwaszkiewicz 1974; Madeyska 2009). The reddish colour of the clastics resembles that of Pliocene/Lower Pleistocene deposits cropping out in the northern part of the Polish Jura, palaeontologically dated to Ruscinian, Villányian and Biharian (Głazek 1989). The nearest cave with Villányian faunal remains is Urwista Cave (Jaskinia Urwista) located 1 km east of Sokola Hill (Horáček and Hanák 1983–1984). However, they may be also isochronous with mouldic sands that is, at least partly, deposited in Palaeogene time (cf. Gradziński 1977).

Drying of the caves

After the deposition of the clastics, the caves were abandoned by underground streams due to the entrenchment of neighbouring valleys. Breakdowns modified cave interiors. Although there are no precisely dated speleothems, we may infer, based on the conclusions drawn by Hercman (2000), that they could have grown in the warm period of the Pleistocene and presumably also in the Pliocene (see also Głazek 1989).

The lack of glacially derived material in the caves can be explained in two ways. Firstly, the caves may have been effectively sealed, but still void, before the advance of the Scandinavian glaciers. If the caves were isolated, they could have endured in this state for several hundred thousand years. They were reconnected to the surface by slope erosion, ceiling collapse and human action, but without erosive activity of streams, which would have washed glacially-derived sands from the vicinity into the caves. The individual caves were reopened at various times and the time of their reopening cannot be determined precisely. Some suggestions are nevertheless possible. Pod Sokolą Górą Cave is a stable cold-cave type. Its microclimate regime is controlled by the spacious entrance located in the topmost part of the cave. Such conditions have persisted at least since the last glacial period, as proved by the occurrence of psychrophilic organisms, regarded as glacial relicts (Szymczakowski 1959). Studnisko and Pod Sokolą Górą caves were entered by bats in the mid-Holocene, as documented by radiocarbon AMS dating of the bat bones (Postawa 2004).

The location of the caves above the level reached by the streams that carried the glacially-derived material is a second possible explanation for the lack of this material in the caves. However, glacially-derived sands are scattered over the Polish Jura at altitudes higher than that of the caves. Różycki (1960) mentions their occurrence up to an altitude of 400 m, whereas Lewandowski (1994, 2009) quotes the presence of aeolian sands, derived probably from older glacifluvial sands, up to an altitude of 380–400 m. Thin sheets of aeolian sands occur 0.5 km east of Sokola Hill in the top part of Donica Hill (Sokole Hills), at an altitude of 370–380 m, that is, higher than the altitude of the caves investigated (Urban and Gradziński 2004).

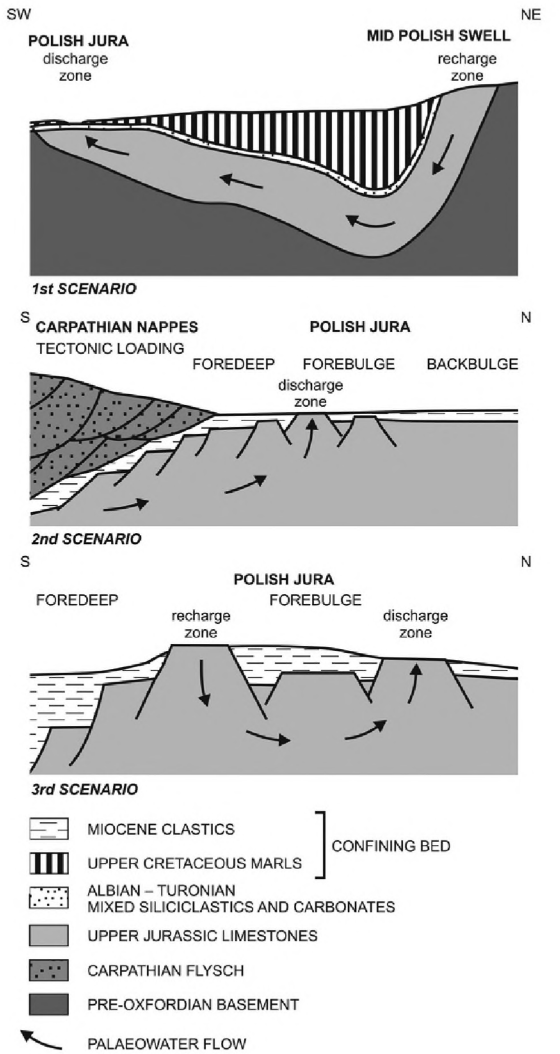
PALAEOHYDROLOGICAL CONDITIONS AND THE AGE OF CAVE FORMATION

The development of ascending caves demands fulfilling at least two conditions: the presence of confining beds over the cave-bearing series; and an upward waterflow regime in the area where the caves originate. We propose three alternative scenarios of the cave development, all taking into account the geological history of the Polish Jura together with all the observed facts (Text-fig. 13). Each scenario explains in a different way the general palaeohydrological pattern and the origin of water which created the caves. The scenarios are valid not only for the relatively small area of Sokola Hill but also for the whole Polish Jura and they aim at providing an adequate explanation for the abundance of ascending caves in this region.

First scenario

The first scenario assumes that low-permeable Upper Cretaceous marls, which were completely covering the Jurassic limestone at the beginning of the Palaeogene, acted as a confining bed. In this scenario, the development of ascending phreatic caves postdates sedimentation of the Cretaceous marls and predates their erosion during the Palaeogene. Hence, the formation of the caves must have preceded the surface karstification of Upper Jurassic limestones, development of dolinas and the sedimentation of the so-called mouldic sands whose precise age is unknown. The mouldic sands were laid down in Palaeogene time, before the Miocene faulting of the Polish Jura (Gradziński 1977). Such an age and origin of some small caves in the Polish Jura have been suggested by Głazek and Szynkiewicz (1980).

A gravity-driven palaeoflow demands the presence of a recharge zone lying higher than the discharge zone. Unambiguous identification of the recharge area in this scenario is not possible, as the topography of the Polish Jura has significantly changed since Palaeogene time. The most feasible candidate for the recharge zone seems



Text-fig. 13. Proposed three possible palaeohydrological scenarios explaining the development of ascending caves in the Polish Jura below discharge zones of deeply circulating water, cross-sections, model of the 2nd scenario is partly based on schematic cross-section published by Jarosiński *et al.* (2009), not to scale, further explanation in the text to be the Middle-Polish Swell (Mid-Polish Anticlinorium) which existed throughout the Palaeogene. It did not develop high-mountain topography because its uplift was compensated by erosion (Kutek and Głazek 1972) but the fact that it provided clastics to adjacent basins testifies that it was rising to some elevation. Thus, it could have served as a possible recharge zone for regional palaeoflow. The palaeoflow within the Upper Jurassic limestone series was gravity-driven by a topographic gradient and oriented south-westward from the Middle-Polish Swell. The swell was subjected to two stages of uplift, at the turn of the Mastrichtian and Danian and in late Palaeocene–early Eocene (Jarosiński *et al.* 2008). The palaeoflow may have taken place after each stage of uplift. The discharge zones were located in places where the confining Cretaceous marls were faulted, or in so-called 'hydrologic windows'. In the former case, water migrated upward along open fissures. In the latter case, ascending water flowed to the surface in those places where Cretaceous marls had been earlier removed by erosion and Jurassic limestone was directly exposed at the surface or covered only by permeable Albian–Turonian deposits, which still overlie Jurassic limestone at the eastern margin of the Polish Jura (Marcinowski 1970, 1974). These deposits facilitated water circulation directly above the Jurassic limestone, whereas the overlying thick sequence of 'Senonian' marls acted as a confining bed.

The Nida Basin, adjacent to the Polish Jura, may serve to some extent as a modern analogue of such a hydrogeological setting. Water from 'Senonian' marls discharges there mainly in faulted or heavily jointed zones where water flow is usually very high (Kleczkowski 1986). However, the discharging water there does not have an elevated temperature.

Second scenario

The second and third scenarios are based on the idea that impermeable clastics of middle Miocene age covered the Polish Jura in late Miocene time. The presence of such deposits has been postulated by Głazek and Szynkiewicz (1987) and Głazek (1989), based on analysis of the age and distribution of the remains of Miocene and Pliocene vertebrate fauna in southern Poland. According to these authors, in the Polish Jura marine Miocene deposits interfingered with floodplain deposits laid down by rivers flowing from the north. Such a contact is still visible in the area of the town of Nysa, more than 100 km west of the Polish Jura (Dyjor and Sadowska 1986). The clastic cover was removed from the Polish Jura in late Miocene time. The above view seems to be consistent with the common opinion that the shore of the Miocene sea was located farther to the north than the present-day erosional boundary of Miocene marine deposits in the Kraków area (Oszczypko *et al.* 2005; see also Jasionowski 1995). The Miocene clastics could have acted as an efficient confining bed over the Jurassic limestone. Migration of ascending water was possible either along faults cutting this cover or through zones of more permeable deposits. Lateral variation of coarse- and fine- grained sediments in the preserved Miocene deposits in the Polish Lowland seems to support the latter possibility.

According to the second scenario, the ascending circulation would be connected with regional northward palaeoflow driven by tectonic loading. This concept refers to the idea of fluid expulsion in the frontal part of the overthrusting orogenic belt (Olivier 1986). Machel and Cavell (1999) identified this mechanism in the foreland of the Rocky Mountains, where fluids migrated up to 150 km outward from the deformation front. Thus, it seems probable that water expelled by the tectonic loading of the Carpathian nappes migrated under confined conditions below the impermeable Miocene clastics. This scenario satisfactorily accounts for the widespread occurrence of ascending caves in the central part of the Polish Jura, where the discharge zones could have been located. It can also explain a local zinc-lead mineralization along faults in Upper Jurassic limestone there (Bednarek *et al.* 1985). Accepting this scenario one must rule out the deposition of calcite spar from the same water that formed the caves. Values of $\delta^{13}C$ of the calcite spar indicate its precipitation from water charged with soil CO_2.

In this scenario, the development of the caves was coeval or only shortly postdated the stages of overthrusting of the Carpathian nappes towards the foreland. Oszczypko *et al.* (2005) list three main stages, namely between the Ottnangian and Karpathian, in late Badenian and after Sarmatian time. Of these three stages, the first preceded the deposition of the potential confining beds over Jurassic limestones and hence should not be taken into consideration. Consequently, a Badenian, Sarmatian or Pannonian age of the ascending caves seems to be probable according to this scenario.

Third scenario

The third scenario refers to more local, topography-driven palaeoflow systems. The potential recharge zones were located on elevated parts of the Polish Jura, from which Miocene clastics were earlier removed. Such an area lay, for example, near Podlesice, c. 25 km southeast of Sokola Hill. There, in Podlesicka Cave (Polish: Jaskinia Podlesicka), a rich assemblage of vertebrate bones dated to the ?Upper Miocene–Lower Pliocene (Turolian–Ruscinian; MN13–MN14 zones) was found (Stefaniak *et al.* 2009 and literature quoted therein). It clearly documents that Upper Jurassic limestone in this area was exposed at that time. The presence of elevated parts within the Polish Jura may be related to tectonic deformation of this area, located in a forebulge zone in front of the Carpathian orogenic belt (cf. DeCelles and Giles 1996). The forebulge consisted of several tectonic blocks (cf. Jarosiński *et al.* 2009). Exposed blocks could have served as local recharge zones feeding gravity-driven ascending circulation. The ascending caves developed below neighbouring discharge zones. Smocza Jama cave, in the city of Kraków, developed due to ascending circulation in an analogous setting (Gradziński *et al.* 2009). This scenario, similarly to the second one, associates the widespread occurrence of ascending caves in the central part of the Polish Jura with tectonic deformation in front of the Carpathians.

CONCLUSIONS

1. The caves in Sokola Hill abound in solution cavities in their ceilings and walls, blind chimneys and ceiling half tubes. The solution cavities display hierarchic organization or form rising sets.
2. The caves were formed by ascending water, probably of elevated temperature, under confined conditions. During the cave formation, Upper Jurassic limestones were covered by impermeable deposits which formed a confining bed. Cretaceous marls or Miocene clastics may have acted as this bed. The caves were formed in the Palaeogene or at the turn of the Miocene and Pliocene.
3. The calcite spar, commonly found in the caves, is the oldest recognized cave deposit. It crystallized under phreatic conditions from water of elevated temperatures. During subsequent stages of development, the caves were invaded by vadose streams depositing cave clastics. This took place before 1.2 Ma, probably in Pliocene time.
4. The caves were isolated during the Pleistocene glaciations and were not invaded by surface streams carrying glacially-derived clastics.
5. There are three possible scenarios explaining the origin of the caves. They refer to: (i) ascending circulation confined by Cretaceous marls in Palaeogene time, (ii) regional palaeoflow driven by tectonic loading of the Carpathian nappes, and (iii) local topography-driven circulation beneath impermeable Miocene clastics.

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