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EVOLUTION OF THE BYSTREJ VALLEY CAVES (TATRA MTS, POLAND) BASED ON CORROSIVE FORMS, CLASTIC DEPOSITS AND U-SERIES SPELEOTHEM DATING

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Abstract: The origin and age of cave deposits, as well as palaeogeographical changes in the Bystrej catchment during the last ca. 250 ka, were reconstructed in Magurska, Kasprowa Niżnia, Goryczkowa, Kalacka and Bystrej caves (the Bystrej Valley). The reconstruction is based on the study of corrosive forms, heavy mineral analyses and U-series dating of speleothems. Two generations of palaeoflows were distinguished by observations of scallops and heavy mineral analyses. In the older stage, now abandoned caves drained massifs surrounding the Bystrej Valley and part of an adjacent valley. The direction of palaeoflow changed as a result of the water capture after Kasprowa Niżnia Cave came into being. In the later stages, the evolution of cave systems was controlled by glaciation-deglaciation cycles. Probably at this time, some caves located in the lowest parts of the massifs also started to be formed. U-series speleothem dating allows the determination of five phases of speleothem deposition: ca. 220–150 ka, ca. 135–105 ka, ca. 95–70 ka, ca. 40–23 ka and during the Holocene.

Key words: Cave evolution, scallops, heavy minerals, U-series speleothem dating, palaeohydrology, the Tatra Mts.

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INTRODUCTION

The origin and evolution of solution-formed caves is related to geological, geomorphic and climatic conditions. Studies of passage morphology, corrosive forms, and clastic and chemical sediments are important to deciphering these conditions. Corrosive forms enable reconstruction of the palaeoflow direction. Cave deposits provide information on the geological history of a karst region. Mineral composition indicates the alimentation area, the catchment and the transport direction of the deposits (e.g., Turnau-Morawska, 1955; Hercman, 1986; Mange and Maurer, 1992). Speleothems grow in the vadose zone and dating them provides information on the minimum age of cave drainage and the entrenchment of the valley bottom (e.g. Ford *et al.*, 1981; Hercman, 1991; Hercman *et al.*., 1987).

Modern speleological research in the Bystrej Valley (in Polish – Dolina Bystrej) caves began in the second half of the twentieth century. Wójcik (1960), on the basis of the cave sediments in Magurska Cave (in Polish – Jaskinia Magurska), suggested that the palaeoflow had been from an area located to the east of the Kopa Magury massif. Rudnicki (1967) mentioned the age of this cave, which is one of the oldest cave systems draining the Kopa Magury massif. Wójcik (1960, 1966, 1968, 1979) carried out research on the clastic deposits, the development of the cave level and the connection between the ages of moraines in the Bystrej Valley and the deposits in Kasprowa Niżnia, Goryczkowa and Kalacka caves (in Polish Jaskinia Kasprowa Niżnia, Jaskinia Goryczkowa and Jaskinia Kalacka, respectively). Hercman (1985) reconstructed the direction of the palaeoflows and calculated their velocities and discharges from measurements of scallops. Hercman (1986, 1991) reconstructed the palaeotransport directions from heavy mineral assemblages and initiated studies on the evolution of the Bystrej Valley cave systems by means of isotopic dating by ^{14}C, ESR and TL methods. Analyses of heavy minerals and scallops were continued by Kicińska (2002). Tectonic research and morphological observations were investigated by Szczygieł (2015a) and Szczygieł *et al.* (2015).

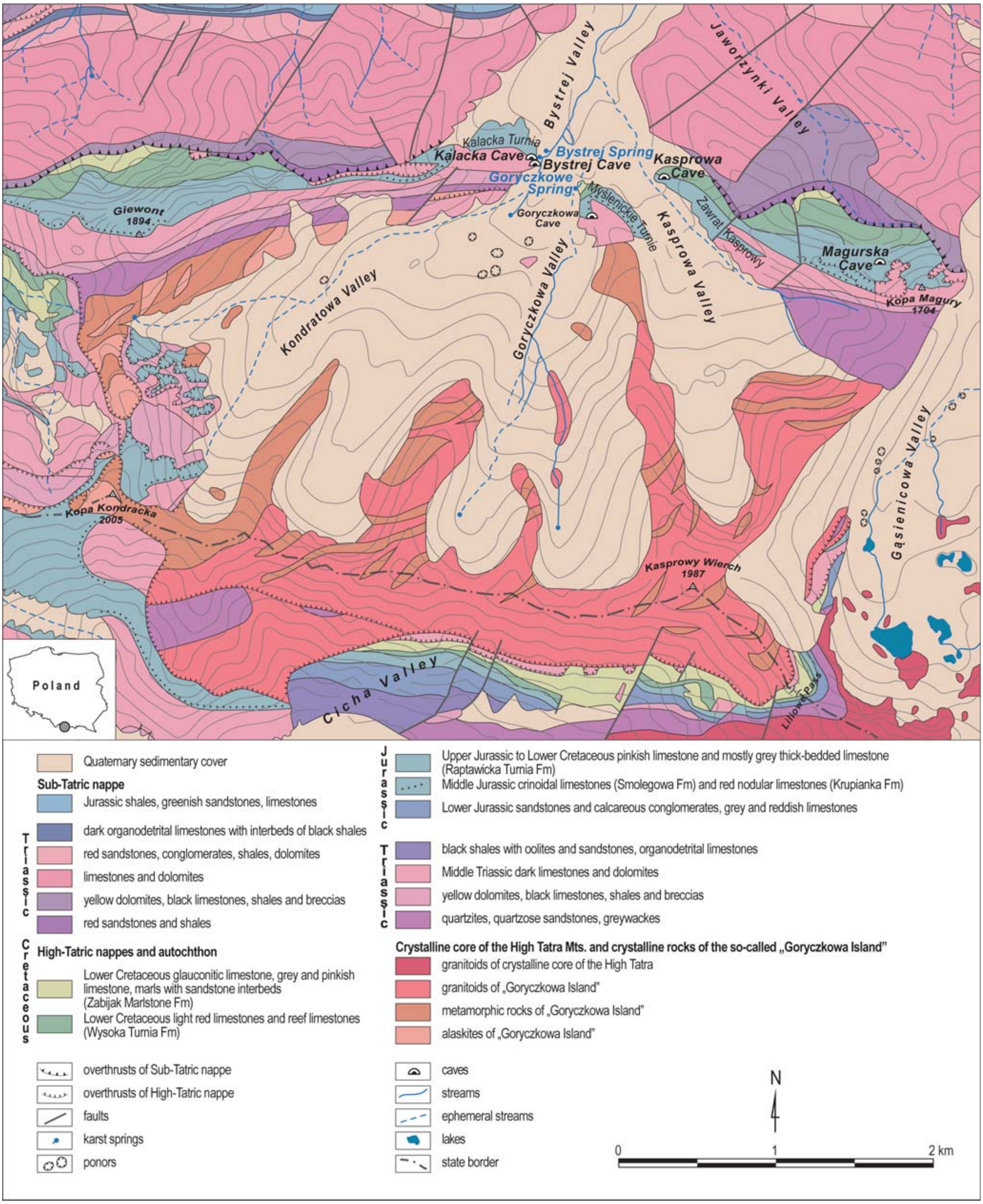

Fig. 1. Geological map of the Bystrej Catchment (modified after Bac-Moszaszwili *et al.*, 1979) with locations of caves studied.

The main aim of this work is to present a model for the evolution of the Bystrej Valley caves on the basis of observations of corrosive forms, analyses of associated clastic deposits and dating of speleothems by the ^{230}Th/ ^{234}U method. Field research was carried out in Magurska, Kasprowa Niżnia, Goryczkowa and Kalacka caves (Fig. 1).

Table 1

Basic morphometric data of Magurska (after Nowicki, 2002), Kasprowa Niżnia, Kalacka (after Luty, 2002), Goryczkowa (after Dudziński, 2013) and Bystrej (after Grodzicki, 2002) caves. Entrance locations of caves after unpublished data of Włodzimierz Porębski

Cave	Entrance location	Entrance altitude/above the valley bottom	Length	Vertical extent	Massif/valley location
Magurska	N 49°14.996′; E 019°59.768′	1460, 1475 m/ca. 135, 150 m	1200 m	-59 m	Kopa Magury-Zawrat Kasprowy massif/Jaworzynka Valley
Kasprowa Niżnia	N 49°15.245′; E 019°58.702′	1228 m/0 m	3020 m	45 m	Zawrat Kasprowy massif/Kasprowa Valley
Goryczkowa	N 49°15.146′; E 019°58.343′	1263 m/ca. 50 m	605 m	31 m	Myślenickie Turnie/Goryczkowa Valley
Kalacka	N 49°15.378′; E 019°58.065′	1230 m/ca. 75 m	345 m	19 m	Kalacka Turnia massif/Bystrej Valley
Bystrej	N 49°15.304′; E 019°58.043′	1182, 1192 m/ ca. 17, 27 m	1480 m	53 m	Kalacka Turnia massif/Bystrej Valley

GEOLOGICAL SETTING

The Bystrej Valley is located in the eastern part of the Western Tatra Mts. The karst of the Bystrej Valley was developed in the Giewont Unit (the High Tatric sequence; Fig. 1). The High Tatric sequence overlies the crystalline core of the High Tatra Mts and is composed of three structural belts: the autochthonous cover (the Kominy Tylkowe Unit) and the allochthonous units (the lower Czerwone Wierchy and the upper Giewont units), according to Bac-Moszaszwili *et al.*, (1979). The Giewont Unit begins with Early Triassic sandstone, claystone, limestone and dolomite with shale interbeds. The Middle Triassic of the Giewont Unit contains partly bioturbated calcilutites with interbeds of crinoidal limestone, bedded dolomite, and dolomitised calcarenites (Lefeld, 1957; Kotański, 1959). The Triassic is penecordantly covered by the Middle Jurassic crinoidal limestone of the Smolegowa Formation (Bajocian) and red nodular limestone of the Krupianka Fm (Bathonian), Upper Jurassic to Lower Cretaceous pinkish limestone and mostly grey thick-bedded limestone (Raptawicka Turnia Limestone Fm), and Lower Cretaceous Urgonian reef limestone (Wysoka Turnia Limestone Fm) and glauconitic limestone, grey and pinkish limestone, marls with sandstone interbeds (Zabijak Marlstone Fm; Lefeld *et al.*, 1985). The Giewont Unit also comprises crystalline rocks in the southern part of the Bystrej Valley with granitoids, migmatites, gneisses, mica schist and amphibolites, known as the "Goryczkowa Island" (Burchart, 1970).

Carbonate rocks extending latitudinally and N–S-trending river valleys influenced the hydrogeology, geomorphology and karst development. While the valleys developed in the Polish part of the Tatra Mts from south to north, the groundwater flowed latitudinally across the river valley. Therefore, the Bystrej catchment is more extensive than the Bystrej Valley (cf. Głazek, 1997). Two principal rising springs are considered to represent the discharge points of the surrounding mountain massifs. The Bystrej vauclusian spring drains the Giewont massif and the eastern part of the Kopa Kondracka massif in the western part of the Bystrej Valley and the Goryczkowe vauclusian spring drains the Kopa Magury and Zawrat Kasprowy massifs and also the Gąsienicowa Valley (in Polish – Dolina Gąsienicowa; Fig. 1). Groundwater tracing tests from a sinkhole located in the Gąsienicowa Valley revealed flow to the Goryczkowe vauclusian spring (1185 m a.s.l.) for 10 to 23.5 hours (Pachla and Żaczkiewicz, 1986; Barczyk, 2003). In the Bystrej Valley, permanent streams flow beneath these springs and transport material from blurred moraines (Wójcik, 1966).

The uplift of the Tatra Mountains started in the Middle to Late Miocene from a depth of at least 5 km, according to apatite fission-track dates (Burchart, 1970; Jurewicz, 2005; Králiková *et al.*, 2014). The present-day relief of the Tatra Mts is related to Neogene uplift. Various authors distinguished different numbers and ages for denudation surfaces in the Tatra Mts (Sawicki, 1909; Klimaszewski, 1988; Zuchiewicz, 1984; Bac-Moszaszwili, 1996). Research on the youngest history of the Tatra uplift indicates that preserved "planation surfaces" could not have formed before ca. 7 Ma and the basic, dome-like, morphostructural formation of the Western Carpathians, which began 4–6 million years ago (Baumgart-Kotarba and Král, 2002; Zuchiewicz, 2011; Minár *et al.*, 2011). Głazek and Wójcik (1963) interpreted the dome-shaped Kopa Magury massif in the Bystrej Valley as a mogote on the Early Pliocene denudation surface.

Wójcik (1966) distinguished eleven cave levels in relation to entrance height above the bottom of every distinctive valley in the Tatra Mountains. Caves in the Bystrej Valley belong to the I (Bystrej, Kasprowa Niżnia), II (Bystrej, Goryczkowa, Kasprowa Niżnia), IV (Kalacka) and V (Magurska) levels. Szczygieł *et al.* (2015), referring to the results of Ford and Ewers (1978) and Häuselmann *et al.* (2003), distinguished three cave levels in the Bystrej Valley: (1) the oldest level, including Magurska, Kasprowa Wyżnia and Kasprowa Średnia caves; (2) the middle level, including Kalacka and Goryczkowa caves, and (3) the youngest and active caves, including Kasprowa Niżnia and Bystrej caves. The passages of caves in the Bystrej Valley have been guided "by tectonic structures, irrespective of lithological differences, indicating that these proto-conduits were formed by "tectonic inception". Differences in the cave pattern in phreatic and epiphreatic zones at a given cave level may be a result of massif relaxation" (Szczygieł *et al.*, 2015, p. 387).

The Bystrej Valley was glaciated during the Pleistocene (Klimaszewski, 1988; Makos *et al.*, 2016). Wójcik (1979) correlated the age of the cave deposits and moraines located near the entrance of Goryczkowa Cave with the main stadial of the Weichselian (Würm) Glacial. He also believed that the cave deposits of Kalacka Cave originated from blurred moraines of the Saalian (Riss) glacial. Rudnicki (1967) claimed that Kalacka and Kasprowa Niżnia caves represent an older stage particularly with regard to the Bystrej and Goryczkowe vauclusian springs.

The speleothems of Bystrej and Kasprowa Niżnia caves were dated at about 100–175 ka, indicating that the caves should be much older than the Late Pleistocene (Duliński and Kuliś, 1989; Hercman, 1991). The TL and ESR ages of speleothems from Goryczkowa and Kalacka caves (Hercman, 1991) have large margins of error, but indicated that deepening of the valley during the last 200 ka was not more than 40 m. Hercman (2000) constructed growth frequency curves for the entire Carpathians from the uranium-thorium dates of speleothems; she identified 8 phases of speleothem deposition over the last 200 ka and proposed a climatic interpretation for them.

Basic morphometric data of the Bystrej Valley caves are listed in Table 1. These caves are located at different heights above the valley bottom. Kasprowa Niżnia Cave is accessible only during the winter, when the water level is low. Most passages of Bystrej Cave are filled with water and in the cave there are five sumps. The Bystrej Valley caves are developed horizontally.

METHODS

Scallops analyses

Scallops are corrosive forms, which develop on the walls, floors and ceilings of caves. They are formed as a result of turbulent flow. Palaeoflow directions have been described on the basis of scallop asymmetry (Coleman, 1949). Scallops could be regarded as dissolution analogues of the current ripples formed in unconsolidated sediments (Lauritzen and Lundberg, 2000). Rudnicki (1960), Curl (1966), Goodchild and Ford (1971) and Blumberg and Curl (1974) pointed out that the size of a scallop is inversely related to the water flow velocity. From experimental research, equations for calculation of flow velocities were derived (Blumberg and Curl, 1974):

for a circular conduit,

$$u = \mathrm{Re}[2.5(\ln \frac{D}{2L_{32}} - 1) + \mathrm{B_L}] \frac{\mu}{\rho L_{32}} \quad (1),$$

and for a rectangle conduit,

$$u = \mathrm{Re}[2.5(\ln \frac{D}{2L_{32}} - 1.5) + \mathrm{B_L}] \quad (2),$$

where

$$\mathrm{L}_{32} = \frac{\sum_{+/-1}^{n} L_i^3}{\sum_{+/-1}^{n} L_i^2} \quad (3)$$

L_{32} = size of a "Sauter-mean",
L = length of an individual scallop,
D = width of conduit,
u = the medium velocity of water flow,
μ = the kinematic viscosity,
ρ = the density of the fluid,
B_L = a fraction factor (for scallops $B_L = 0.013$ cms^{-1}),
Re = the Reinhold's number, based on friction velocity and L_{32} (for scallops, Re = 2000).

On the basis of measurements of scallop length it is possible to calculate water palaeovelocities. A minimum of 100 forms should be measured in a given passage cross-section. Scallops were also measured in areas where a few dozen forms were recognized. In other places, the asymmetry of scallops was observed in order to determine the palaeoflow direction.

Mineral composition of heavy fraction

Analyses of heavy fractions were performed in the Institute of Geology of the Faculty of Geographical and Geological Sciences (the Adam Mickiewicz University, Poznań, Poland). The heavy fractions were separated from the grain-size fraction of 0.125 to 0.25 mm, using standard methods, such as sodium polytungstate ($3Na_2WO_4 \cdot 9WO_3 \cdot H_2O$) of density 2.85 gcm^{-1}. The analyses of minerals were conducted on the basis of their physical and optical properties (Racinowski and Szczypek, 1985; Mange and Maurer, 1992). In each sample, at least 300 grains were recognized. Burkhardt (1978) divided the principal heavy minerals into instable (apatite, amphibole, epidote), mechanostable (garnet, zircon) and chemostable (rutile, staurolite, kyanite, tourmaline).

U-series dating of speleothems

U-series dating of speleothems was performed in the U-series Laboratory of the Institute of Geological Sciences of the Polish Academy of Sciences (Warsaw, Poland). Uranium and thorium were separated using the standard chemical procedure for carbonate samples (Ivanovich and Harmon, 1992). The samples were dissolved in 6 M nitric acid. Uranium and thorium were separated by a chromatographic method using a DOWEX 1x8 ion exchanger. The chemical separation efficiency was controlled by addition of a ^{228}Th-^{232}U spike (UDP10030 tracer solution by Isotrac, AEA Technology) before chemical treatment. Activity measurements by á spectrometry were obtained on a OCTETE PC spectrometer made by the EG&G ORTEC Company. Spectrum analyses and age calculations were performed by means of the "URANOTHOR 2.6" software package (Gorka and Hercman, 2002). Each spectrum was corrected for the background and delay time between chemical separation and measurement.

Table 2

Scallop measurements and calculated flows

Location	Number of forms	Cross-section of conduits (cm)	L32 (cm)	Velocity (cm/s) for circular conduits	Velocity (cm/s) for rectangular conduits
Magurska Cave					
1	80	320 × 200	3.29 ± 0.37	135.40 ± 21.87	144.26 ± 23.65
2	15	140 × 180	5.31 ± 0.37	65.13 ± 7,86	71.86 ± 8.68
3	39	400 × 180	5.90 ± 0.37	70.15 ± 6.45	76.21 ± 7.01
4	30	200 × 320	4.18 ± 0.37	92.89 ± 12.46	101.44 ± 13.61
5	13	200 × 320	0.63 ± 0.34	832.42 ± 688.06	889.22 ± 735.00
Kasprowa Niżnia*					
1	40–80	220 × 300	9.95	21.3 ± 4.3	24.9 ± 5.0
2	40–80	150 × 250	4.48	69.2 ± 13.9	77.2 ± 15.5
3	40–80	200 × 450	6.18	44.2 ± 8.5	51.1 ± 9.8
4	40–80	200 × 250	6.60	41.0 ± 8.2	46.4 ± 9.3
5	40–80	100 × 100	4.46	62.1 ± 12.5	70.1 ± 14.1
Goryczkowa Cave					
1	54	160 × 210	8.97 ± 0.39	35.46 ± 3.11	39.45 ± 3.47
2	41	180 × 150	5.79 ± 0.37	61.78 ± 6,50	67.95 ± 7.15
3	19	250 × 400	4.72 ± 0.37	83.80 ± 9.84	91.37 ± 10.73
4	92	160 × 120	2.41 ± 0.40	170.69 ± 41.01	185.50 ± 44.57
Kalacka Cave					
5	58	50 × 250	0.63 ± 0.34	56.16 ± 12.77	63.39 ± 14.41
5	39	120 × 150	6.90 ± 0.37	55.97 ± 6.1	61.84 ± 6.73
6	10	80 × 100	8.60 ± 0.37	31.57 ± 6.73	35.73 ± 4.96
7	38	250 × 300	13.22 ± 0.40	24.40 ± 1.42	27.07 ± 1.57

*Results published by Hercman (1985)

MATERIALS

Scallops. Observations of scallops were carried out in Magurska (Fig. 2A), Kalacka (Fig. 3A) and Goryczkowa caves (Fig. 3B). Scallops were observed at ten locations in Magurska Cave (Fig. 2A). Scallop size measurements for the estimation of palaeoflow velocity were performed in: Pod Progiem Chamber (1), near the Przekop z Belką Passage (2, 3), between the Przekop z Belką Passage and the Na Rozdzielu Chamber (4, 5). Scallop asymmetry was observed in some places in the middle and end part of the cave (sites 6–10). In Goryczkowa Cave, scallops were observed at six locations (Fig. 3B) and measured near the entrance (1) and in the lower part of the cave (sites 2–5). Observations of scallops in Kalacka Cave were made at nine locations (Fig. 3A) and their size was measured at three locations in the middle part of the cave (sites 5, 6 and 7).

Cave sediments. All of the caves studied are filled with various types of clastic deposits. Altogether, 36 samples from Magurska (14 samples; Fig. 2A), Kalacka (13 samples; Fig. 3A), Kasprowa Niżnia (5 samples; Fig. 2B) and Goryczkowa (4 samples; Fig. 3B) caves were analysed. Two sections were sampled in Magurska Cave. The first one, the Przekop Passage (for the lithology, see section M5 in Fig. 2A), is located ca. 200 m from the entrance (Fig. 2A). The wall of this passage is covered by flowstone (0.5–3.0 cm thick). In the lower part of this section, numerous bones, mostly of cave bear (*Ursus spelaeus* Rosenmüller) were recognized by Ossowski (1882) and were in a sandy matrix with no stratification (cf. Hercman *et al.*, 1987; Hercman, 1991). Three samples of sediment were taken here (Fig. 2A: samples M5.1, M5.2, M5.3). The second section was investigated in the Przekop z Belką Passage (see section M10 in Fig. 2A). Two sediment samples were taken there (samples M10.1 and M10.2). Single samples of cave deposits were also taken from other parts of Magurska Cave (Fig. 2A: samples M3, M7–M9, M11–M15).

In Kasprowa Niżnia Cave, observations were conducted from the entrance up to the Gniazdo Złotej Kaczki Passage (Fig. 2B). Clastic deposits were sampled at three sites (K1, K2, and K3; for the lithology of sections K2 and K3, see Fig. 2B). Two samples were taken from both the K2 (K2.1 and K2.2) and K3 (K3.1 and K3.2) sections for analysis. In Goryczkowa Cave, clastic sediments are not so common. The clastic deposits were sampled for heavy mineral analysis at four locations (sites G1 to G4; Fig. 3B). The entire passage of Kalacka Cave is covered with sediments and six locations were sampled, including four sediment sections (KL4, KL8, KL9, and KL10); their positions, lithology and sampling points are shown in Fig. 3A.

Speleothems. The caves of the Bystrej Valley studied are relatively poor in speleothems. In Magurska Cave, three flowstone samples were taken from the Przekop Passage (Fig. 2A: samples Jma 2, T1 and T9). Bones there are cov-

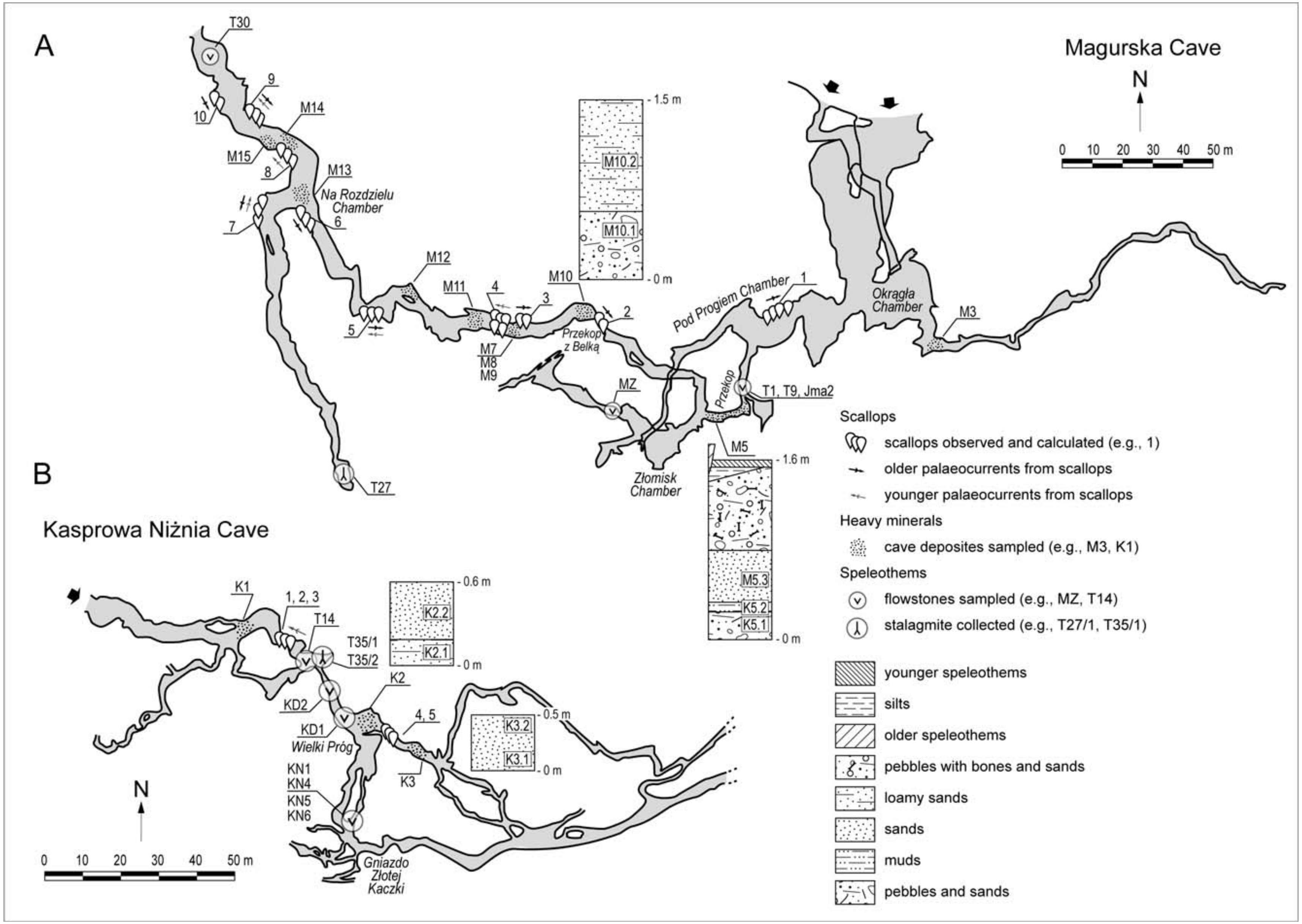

Fig. 2. Maps of the caves studied with locations of sampled clastic deposits and speleothems, areas where scallops were studied, and direction of palaeoflows. **A**. Magurska Cave (morphology after Nowicki, 2002). **B.** Ka- sprowa Niżnia Cave (morphology by Luty, 2002).

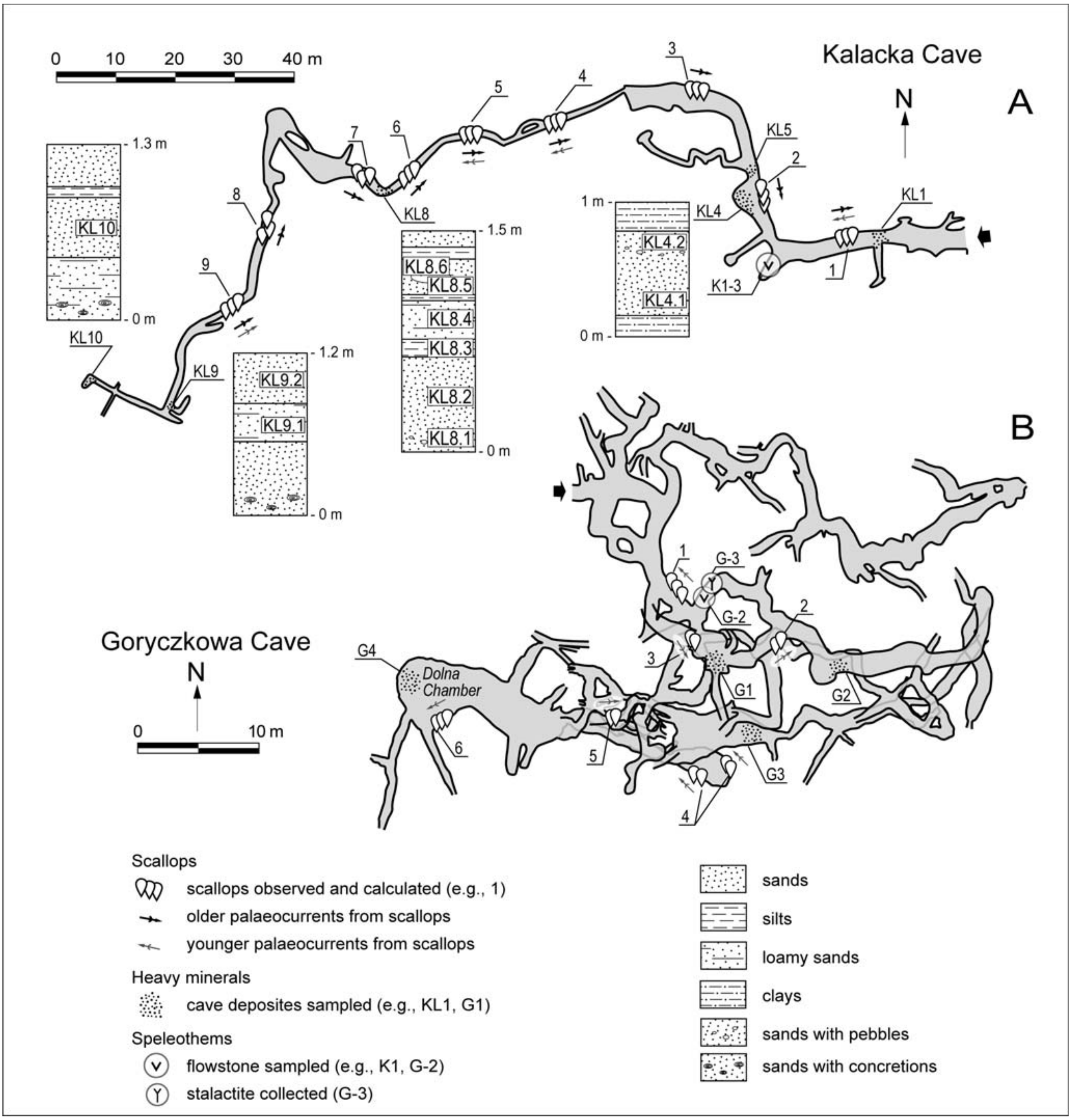

Fig. 3. Maps of the caves studied with locations of sampled clastic deposits and speleothems, areas, where scallops were studied and directions of palaeoflow. **A.** Kalacka Cave (cave morphology by Luty, 2002). **B.** Goryczkowa Cave (cave morphology by Dudziński, 2013).

ered by a speleothem, from which sample Jma2 was taken. One sample came from the part between the Złomisk Chamber and the Dolna Chamber (MZ). Other samples were taken from the end part of the cave (T30) and from the passage, which continues on the left from the Na Rozdzielu Chamber (T27). In Kasprowa Niżnia Cave, speleothems were taken from four places (Fig. 2B), near the Wielki Próg location. Samples T14, T35/1 and T25/2 were collected from a small chamber. Samples KD1, KD2 and KG2 were located in the passage, in front of the Wielki Próg site. Samples KN1, KN4, KN5 and KN6 were taken from passages, located behind the Wielki Próg. Single samples were taken from ledges, located in Kalacka (K1–K3; Fig. 3A) and Goryczkowa (G2; Fig. 3B) caves. A small flowstone sample from Goryczkowa Cave (G-2) also was dated.

RESULTS

Scallops

Observations in all caves, except for Kasprowa Niżnia Cave, show two opposite directions of palaeoflow. In

Table 3

Amounts of opaque and translucent heavy minerals and composition of translucent heavy mineral assemblage from sediments in Magurska Cave

Sample	M3	M5.1	M5.2	M5.3	M7	M8	M9	M10.1	M10.2	M11	M12	M13	M14	M15
heavy fraction [weight %]	0.1	0.5	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.6	0.2	0.1	0.1	0.2
opaque minerals	73.6	34.3	29.9	64.5	48.2	53.8	69.6	67.8	72.5	61.5	40.8	71.8	65.0	57.9
translucent minerals	26.4	65.7	70.1	35.5	51.8	46.2	30.4	32.2	27.5	38.5	59.2	28.2	35.0	42.1
amphibole	5.6	0.3	0.7	1.4	4.3	1.5	4.1	7.7	4.2	6.4	1.3	4.2	4.5	4.3
apatite	13.4	0.3	0	6.7	10.1	10.3	20.4	24.6	12.8	0.3	0	0.3	4.5	12.9
biotite	8.7	7.2	3.6	18.2	10.8	16.5	19.0	15.9	17.3	9.9	8.3	18.0	18.1	10.3
chlorite	13.8	4.0	5.5	17.8	19.9	12.9	16.3	21.0	24.2	8.4	2.0	28.0	21.6	12.8
zircon	2.5	0.3	0.5	2.9	0	1.1	2.7	0.5	2.1	1.9	0.3	0.3	0	1.3
kyanite	0	1.1	1.0	5.8	1.2	5.5	3.2	4.6	11.1	5.2	0	0	1.5	0.4
epidote	2.0	0.3	0.6	3.9	3.3	3.6	3.6	4.6	1.4	2.9	1.0	2.3	4.0	4.7
phosphate	6.1	47.2	14.4	21.6	1.1	4.0	8.1	4.1	1.4	0.3	49.6	0.3	0.5	23.8
glauconite	0	0.3	0.5	3.4	0.7	0	0	0	2.4	0	1.3	0.3	0.5	0
garnet	0	0	0	0	2.9	2.2	2.7	0	3.1	2.4	0	2.3	1.5	0.8
muscovite	9.2	15.1	25.6	7.7	36.1	18.8	6.3	7.2	8.3	12.6	19.9	18.6	21.6	20.6
pistacite	0	0.5	0	0	0	0.7	0.5	0	0	0	0.3	0	0	0
rutile	3.1	1.1	0.4	3.4	2.5	8.5	6.8	3.6	3.5	2.1	2.3	2.6	3.5	4.0
chloritized biotite	7.7	0.3	0	0	0	1.1	2.7	0	0	4.2	0	7.7	4.0	0
sillimanite	2.1	0	0.7	1.9	0	2.2	0	0.5	0	0	0	0	1.0	1.1
tourmaline	1.5	0.3	0	0	0	0	0	0	0.4	0.3	0.3	0.7	0	0
carbonates	21.4	20.0	44.3	1.9	3.3	8.5	0	0	2.8	36.3	9.6	14.4	4.5	3.0
others	2.9	1.7	2.2	3.4	3.8	2.6	3.6	5.7	5.0	6.8	3.8	0	8.7	0

Magurska and Kalacka caves, large scallops (50–70 cm) are overlapped by younger, smaller forms (5–10 cm). In other caves, different palaeoflow (with an opposite direction) is marked by scallops that are similar in size, but not overlapping. The larger forms allowed the determination of only palaeoflow directions. Estimates of palaeoflow velocity were made for the younger generation of smaller forms. As the passage shapes at the times of formation of the scallops are not known, calculations were done for both circular and rectangular conduits. Palaeoflow directions are marked by arrows in Fig. 2A (Magurska Cave), Fig. 3A (Kalacka Cave) and Fig. 3B (Goryczkowa Cave). Palaeoflow velocity calculations for all of the caves studied are summarized in Table 2.

The older palaeoflow in Magurska Cave is from the end of the cave towards its entrance (Fig. 2A, sites: 1–3, 5, 6, 7, 9, 10). The large scallops are several dozen centimetres long (40–70 cm) in sites 1, 6 and 7. The younger palaeoflow is from the middle part towards the end of the cave (sites 4, 5, 8, 9). At site 1, there are forms of different lengths, but indicating the same palaeoflow direction towards the entrance. There are two large scallops with a length of 43 and 56 cm in the upper part of the passage, while in the lower part forms have lengths of 2–6 cm. Near the Na Rozdzielu Chamber, scallops with different patterns of asymmetry overlap (site 7). Some forms reach 60–70 cm in length here and indicate a SE palaeoflow direction. They are overlapped by forms 9–10 cm long, showing the opposite palaeoflow direction. The lengths of the dominant scallop morphologies are generally several centimetres at most other locations (e.g., site 6).

Two opposite directions of palaeoflow were distinguished in the upper part of Goryczkowa Cave. In its lower part, all forms show a direction that is consistent with the conduit inclination, except for the forms measured at site 4. Palaeoflow velocity calculations for forms at five locations are summarized in Table 2 (see also Fig. 3B).

Scallop asymmetry was measured at 9 locations in Kalacka Cave (Fig. 3A). Large scallops that are 50–70 cm in length are abundant in all cave sections and indicate flow towards the entrance. These forms in places are overlapped by smaller scallops that indicate flow both towards the entrance (site 9) and towards the end of the cave (site 4). Palaeoflow determinations were made at 3 locations (Fig. 3A, sites 5, 6, 7; Table 2). At all locations within the cave, the older forms indicate palaeocurrents toward the entrance. A few younger forms indicate an opposite palaeoflow direction (sites 1, 4, 5).

The flow velocity calculated from the measurements of scallops in the caves studied show values similar to those for the present streams in the Tatra Mts (Table 2). It is noteworthy that calculations were possible only for the younger

Table 4

Amounts of opaque and translucent heavy minerals and composition of translucent heavy mineral assemblage from sediments in Kasprowa Niżnia Cave

Sample	K1	K2.1	K2.2	K3.1	K3.2
heavy fraction [weight %]	1.2	0.1	0.9	0.1	0.2
opaque minerals	8.1	37.2	4.4	53.3	49.9
translucent minerals	91.9	62.8	95.6	46.7	50.1
amphibole	0	3.4	0	0.5	0.5
apatite	0.8	5.1	0	9.0	8.1
biotite	2.1	11.1	0.7	3.7	2.7
chlorite	6.2	32.7	5.6	18.4	16.2
kyanite	0	0.3	0	0.5	1.1
epidote	0	3.4	0	1.6	2.7
garnet	0.3	0.7	0	2.6	0.5
muscovite	8.5	14.9	3.6	11.1	6.0
chloritized biotite	4.4	3.4	1.3	0.5	0.5
sillimanite	4.4	3.4	1.3	0.5	0.5
tourmaline	0	0	0	0	0
carbonate	72.8	21.6	86.0	50.5	58.4
others	0.5	0	1.5	1.1	2.8

stage of palaeoflow. The same values were obtained in caves of the Kościeliska Valley (in Polish – Dolina Kościeliska; Kicińska, 2005).

Heavy minerals

The results of mineralogical analyses are presented in Tables 3–6. They show the heavy fraction content, the total percentage of translucent and opaque minerals and the percentage of various types of minerals within the translucent minerals group. In most of the samples studied, opaque minerals predominate.

In Magurska Cave, the highest content of heavy minerals typical for metamorphic rocks occurs in samples: M5.3, M8, M10.1, M10.2 and M11. These minerals were not detected in sample M13. In most samples glauconite was recognized, with a high content in sample M5.3. A high percentage of phosphates occurs in the samples from the Przekop section and near the Na Rozdzielu Chamber sediments. Instable and chemostable minerals *sensu* Burkhardt (1978) predominate in the deposits of Magurska Cave.

The near-entrance part of Kasprowa Niżnia Cave contains a high content of heavy minerals that are typical for metamorphic rocks (Table 4, samples K1 and K2.1). Carbonates and muscovite predominate in all samples. Sample K2.2 contains 86 % of carbonates. Instable minerals *sensu* Burkhardt (1978) predominate.

There is a predominance of instable minerals in Goryczkowa Cave, except in sample G4 from the Dolna Chamber with a high percent of chemostable minerals (Table 5). There are high contents of biotite, chlorite and muscovite. The low percentage of minerals typical for metamorphic rocks, with the exception of sample G4, is characteristic for the cave.

Table 5

Amounts of opaque and translucent heavy minerals and composition of translucent heavy mineral assemblage from sediments in Goryczkowa Cave

Sample	G1	G2	G3	G4
heavy fraction [weight %]	0.1762	0.2086	0.3485	0.3743
opaque minerals	41.5	19.5	28.9	19.4
translucent minerals	58.5	80.5	71.1	80.6
amphibole	9.4	0.5	2.1	1.5
apatite	8.0	0.8	5.0	0
biotite	23.3	1.9	16.8	1.5
chlorite	14.6	6.5	20.4	19.6
zircon	0	0	0	0.4
kyanite	0	0.3	1.1	17.1
epidote	3.5	0.5	3.6	0.7
phosphate	1.0	0	0	0
glauconite	0	0	0	0.7
garnet	5.9	0.3	0.7	13.8
muscovite	24.3	4.9	27.1	23.1
rutile	1.7	0	0.4	2.5
chloritized biotite	5.2	0	12.5	6.5
sillimanite	0	0.8	1.4	0
tourmaline	0	0	0	0.7
carbonate	2.1	82.6	7.9	9.5
others	1.0	0.9	1.0	2.4

The predominance of instable minerals *sensu* Burkhardt (1978) occurs in the deposits of Kalacka Cave, except for samples KL2.2 and KL5 (Table 6). In samples KL4, KL8 and KL9, there are high amphibole contents. High glauconite content is typical for samples KL1, KL4.1, KL8.3 and KL9.1 (Fig. 3A, Table 6).

U-series dating of speleothems

The results of U-series dating are presented in Table 7 and Figures 2, 3. Reported errors are in the range of 1 standard deviation. Samples with $^{230}Th/^{232}Th$ activity ratio below 20 were treated as contaminated. The most frequent contaminants are detrital admixtures, such as clay minerals and iron oxides or hydroxides. For these samples, reliable age estimation needs correction for the contamination. It is difficult to correct data, for which a single measurement was performed; only the so-called "B0 method" may be used. It assumes knowledge (or an arbitrary assumption) of isotopic uranium and thorium composition in the contaminant. The most popular solutions are the assumption that only thorium is introduced from a contaminant with a known/assumed $^{230}Th/^{232}Th$ activity ratio (B0) or the use of corrections with a U and Th isotopic composition that is characteristic for lithosphere. The mean value calculated from analyses of "dirty carbonates" of a known age may be used as an estimate of the $^{230}Th/^{232}Th$ activity ratio in detrital contaminant (Kaufman and Brocker, 1965; Schwarcz,

Table 6

Amounts of opaque and translucent heavy minerals and composition of translucent heavy mineral assemblage from sediments in Kalacka Cave

Sample	KL1	KL4.1	KL4.2	KL5	KL8.1	KL8.2	KL8.3	KL8.4	KL8.5	KL8.6	KL9.1	KL9.2	KL10
Heavy fraction [weight %]	0.3	0.3	0.8	1.6	0.1	0.1	0.1	0.2	0.1	0.03	0.1	0.1	0.1
opaque minerals	87.8	91.2	93.2	96.5	54.6	70.7	43.0	92.1	90.2	87.4	86.2	94.7	93.8
translucent minerals	12.2	8.8	6.8	3.5	45.4	29.3	57.0	7.9	9.8	12.6	13.8	5.3	6.2
amphibole	4.70	9.73	0.88	0	8.0	24.3	7.0	17.30	9.19	19.30	9.44	7.67	3.97
apatite	8.46	2.43	0.87	0.67	4.7	2.9	3.8	6.15	5.87	11.20	6.44	12.30	3.24
biotite	21.0	18.20	0	17.30	9.4	11.7	3.2	17.30	13.40	14.80	16.30	17.0	14.0
chlorite	21.32	14.29	17.47	15.25	4.0	2.9	9.5	18.85	22.92	20.26	20.17	28.30	22.43
zircon	0	0	0	0	0	0	0	0	0	0	3.0	0	0
kyanite	1.25	0	13.10	0	1.3	1.9	1.3	0	0.56	0	0.43	0	0.23
epidote	0.31	0.30	0	0	4.0	2.9	0	3.85	1.96	2.57	0.43	2.33	0.70
phosphate	1.60	6.38	0.44	0.45	0	0	0	0.38	5.59	2.89	6.86	3.33	1.17
glauconite	2.51	3.34	2.18	0.40	2.7	3.9	1.9	0	0	0	0	0	0
garnet	10.70	5.78	0.87	0	26.2	26.3	8.2	10.0	3.63	3.54	9.29	2.67	0.70
muscovite	18.80	25.23	48.91	57.80	33.6	12.6	50.5	11.54	29.89	15.11	17.67	16.67	45.79
rutile	0.63	1.82	0.44	2.57	0.7	1.9	0	1.15	1.12	2.57	2.58	0	0
chloritized biotite	5.96	4.86	9.17	6.05	0.7	0	2.5	8.85	0.28	2.89	6.44	4.33	5.37
sillimanite	0.31	0	4.37	0	2.7	1.9	5.1	1.92	0.28	0.97	0	0.67	0.70
tourmaline	0	0	0	0	0.7	1.9	3.2	0	0.28	0.32	0	0	0
carbonate	1.90	5.17	0.87	0.67	0	3.9	0	2.69	1.40	1.92	2.15	3.0	0.70
others	0.55	2.47	0.41	1.41	1.3	1.0	3.8	0.02	3.63	1.66	8.87	1.63	1.0

1980, 1986; Kaufman, 1993; Lin *et al.,* 1996). Taking into account the dispersion of the ^{230}Th/^{232}Th values calculated, it is reasonable to assume a ^{230}s24 Th/^{232}Th value in contaminant equal to B0 = 1.5 ± 0.5. Corrected ages (Table 6) have much larger errors that are due to the rough knowledge of the ^{230}Th/^{232}Th value for the correction. The corrected ages presented in Table 7 should be treated with caution as being only rough age estimates.

DISSCUSION

Palaeoflow direction

The analysis of corrosive forms and the mineral composition of the cave deposits allowed the reconstruction of the palaeoflow history and the alimentation zone of the cave deposits. For example, in Magurska and Kalacka caves, overlapping forms were detected, the asymmetry of which indicates opposite palaeoflow directions. The mineralogical composition of cave sediments depends on the lithology in the alimentation/catchment zone, which is composed of igneous rocks of the crystalline core under a cover of sedimentary rocks (e.g., limestones, dolomites, marls), granitoids and metamorphic rocks of the Giewont Unit (Fig. 1).

In Magurska Cave, large scallops are preserved in the near-entrance part and smaller forms in the middle section of that cave. They indicate an older palaeoflow direction from the south-west (the Gąsienicowa Valley) toward the north (the Jaworzynki Valley; in Polish – Dolina Jaworzynki). The different lengths of scallops (Fig. 2A) indicate changes in the velocity of the flow toward the Jaworzynki Valley in the past or local differences, depending on the passage shape. Traces of slower palaeoflow are marked by large scallops, located in the upper part of the passage. The younger palaeoflow direction from east to west, that is, from the Gąsienicowa Valley toward the Kasprowa Valley (in Polish – Dolina Kasprowa), is indicated by scallops in the middle and end parts of Magurska Cave (Fig. 1). Two generations of forms overlap at site 7 (Fig. 2A), with the younger and smaller ones occurring within the larger forms that represent the older palaeoflow direction (NW–SE).

The composition of the heavy minerals in Magurska Cave confirms the direction of palaeoflow from the Gąsienicowa Valley and from the southern part of the Bystrej Valley. In the near-entrance part (sample M5.3), the high glauconite content most probably was derived from the Cretaceous glauconite-bearing limestones in the vicinity of the Liliowe Pass (in Polish – Przełęcz Liliowe; Fig. 1). This is consistent with the results of Hercman (1986), who found glauconite in the highest layer of sandy limestone gravel with bones of *Ursus spelaeus*. A high content of heavy minerals typical for metamorphic rocks occurs in samples along the main passage, indicating that the material could have been transported within the caves from the "Goryczkowa Island". The occurrence of phosphate is unique to the sediments of Magurska Cave. In the Przekop Passage section,

Table 7

U-series dating results

Sample	Cave	Lab. No.	U cont. [ppm]	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$	Age [ka]	* Corr. Age [ka]
G-3	Goryczkowa	J638	0.128 ± 0.003	2.08 ± 0.05	0.32 ± 0.02	10.5	40 ± 3	35 ± 6
G-2	Goryczkowa	J627	0.176 ± 0.006	1.42 ± 0.04	0.72 ± 0.03	646	128 ± 8	
T 14	Kasprowa Niżnia	J789	0.103 ± 0.002	1.96 ± 0.05	0.94 ± 0.03	431	200^{+14}_{-13}	
T 35/1	Kasprowa Niżnia	J797	0.147 ± 0.003	1.92 ± 0.04	0.95 ± 0.03	630	210^{+13}_{-12}	
T 35/2	Kasprowa Niżnia	J750	0.132 ± 0.03	1.67 ± 0.04	0.90 ± 0.04	150	190^{+19}_{-15}	
KN 1	Kasprowa Niżnia	J626	0.133 ± 0.004	1.97 ± 0.06	0.93 ± 0.03	34	190^{+16}_{-14}	
KN 4	Kasprowa Niżnia	J632	0.127 ± 0.03	1.98 ± 0.05	0.90 ± 0.03	20	180^{+12}_{-11}	
KN 5	Kasprowa Niżnia	J763	0.092 ± 0.002	1.57 ± 0.05	0.96 ± 0.04	9	230^{+28}_{-23}	210^{+35}_{-33}
KN 6	Kasprowa Niżnia	J777	0.137 ± 0.003	2.42 ± 0.06	0.93 ± 0.03	>1000	187^{+11}_{-10}	
KD 1	Kasprowa Niżnia	J583	0.198 ± 0.007	1.49 ± 0.07	0.66 ± 0.03	8	110 ± 8	100^{+16}_{-17}
KD 2	Kasprowa Niżnia	J596	0.124 ± 0.007	2.23 ± 0.14	0.56 ± 0.03	>1000	82 ± 7	
KG 2	Kasprowa Niżnia	J596	0.170 ± 0.004	1.59 ± 0.04	0.90 ± 0.03	2.5	191^{+15}_{-13}	130^{+57}_{-80}
T 27/1	Magurska	J738	0.078 ± 0.004	2.07 ± 0.13	0.58 ± 0.05	31	86^{+10}_{-9}	
T 27/2	Magurska	J799	0.078 ± 0.002	2.02 ± 0.07	0.51 ± 0.02	106	73 ± 5	
T 27/3	Magurska	J816	0.093 ± 0.004	2.70 ± 0.12	0.088 ± 0.009	56	10 ± 1	
T 27/4	Magurska	J737	0.057 ± 0.002	3.44 ± 0.15	0.07 ± 0.01	39	7.2 ± 1.3	
T9	Magurska	J619	0.089 ± 0.003	1.49 ± 0.05	0.68 ± 0.03	28	114 ± 8	
Jma 2	Magurska	J634	0.157 ± 0.006	2.08 ± 0.09	0.40 ± 0.03	2.4	53 ± 5	24 ± 26
T 30	Magurska	J798	0.094 ± 0.002	1.68 ± 0.05	0.75 ± 0.03	5.5	130^{+10}_{-9}	110^{+22}_{-25}
MZ	Magurska	J614	0.116 ± 0.003	1.71 ± 0.05	0.52 ± 0.02	>1000	76 ± 4	
T 1	Magurska	J751	0.054 ± 0.002	2.28 ± 0.07	0.07 ± 0.01	13.7	8 ± 2	7 ± 2
K 2	Kalacka	J637	0.094 ± 0.003	2.63 ± 0.08	0.84 ± 0.05	61	160^{+15}_{-14}	
K 3	Kalacka	J1049	0.099 ± 0.003	2.59 ± 0.08	0.81 ± 0.06	4.7	160^{+20}_{-18}	120^{+35}_{-100}
K1	Kalacka	W 165	0.108 ± 0.008	2.1 ± 0.2	0.86 ± 0.04	2.6	140^{+15}_{-14}	130^{+80}_{-100}
** KG 17-II	Bystra		0.214 ± 0.007	1.75 ± 0.07	0.68 ± 0.04	58	116 ± 10	
** KG 16-II	Bystra		0.244 ± 0.005	1.94 ± 0.05	0.04 ± 0.01	4	4.7 ± 0.3	3 ± 2

* Age correction assuming Th contamination with initial $^{230}Th/^{232}Th$ activities ratio in contaminant 1.5 ± 0.5
** Data from: Duliński and Kuliś (1989)

the phosphate content is due to a large amount of Pleistocene animal bones. In the terminal part of the cave, the high phosphate content could be the result of the large number of bat bones, mentioned by first explorers (Zwoliński, 1987).

Observations of scallops and measurements of them were carried out in Kasprowa Niżnia Cave by Hercman (1985). The scallops occupy the surfaces of the walls, ceiling and speleothems. The average length of the scallops is a few centimetres, indicating a rapid water flow. The direction of palaeoflow is toward the entrance (Fig. 2B).

In Kasprowa Niżnia Cave, a very high content of heavy minerals typical for metamorphic rocks is in the near-entrance sediments. The source area for this material is in the "Goryczkowa Island", south of the Bystrej Valley. Kowalski (1953) drew attention to the occurrence in Kasprowa Niżnia Cave of "granite sand", derived from the Gąsienicowa Valley. The high carbonate content, typical for the Kasprowa Niżnia Cave deposits, may indicate a water flow path through Triassic dolomites, as already mentioned by Hercman (1986). On the other hand, instable minerals *sensu* Burkhardt (1978) predominate, indicating only short sediment transport in the absence of weathering. The source of these materials could be from blurred moraines in the upper part of the Kasprowa Valley or the upper part of the Bystrej Valley.

Scallops are not so common in Goryczkowa Cave. All of the forms encountered are a few centimetres in length. The older direction of palaeoflow from the inside of the cave toward the entrance is indicated. It reflects the drainage stage of the Myślenickie Turnie Peak. There is a high content of minerals typical for metamorphic rocks. Instable minerals predominate, except in sample G4 from the Dolna Chamber (more than 60% of chemostable minerals). The development of Goryczkowa Cave probably was complicated. The northern part of the cave has a maze pattern, whereas a large chamber (the Dolna Chamber) modified by ceiling collapse is in the southern part. Water from melting glaciers could have entered the Dolna Chamber independently from the main entrance through sinkholes (Fig. 3B). The sinkholes recently were filled by moraine deposits containing granitoid blocks (Lipiec, 1990). The younger palaeocurrent direction evidences the inflow of water from melting glaciers into the cave. The circulation of water could have changed many times, depending on the altitude of glaciers above or below the cave entrance.

In Kalacka Cave, most of the scallops observed show a single palaeoflow direction from the inside of the cave toward the entrance. There are forms of two sizes, indicating differences in water flow velocity. Only in the middle part of the cave (Fig. 3A, site 4 and 5), large scallops are occupied by smaller forms of different asymmetry, probably as a consequence of changes in the inclination of the downward passage (cf. Palmer, 2007). Several forms with asymmetry that indicates a flow direction into the cave occur additionally in the near-entrance part. At site 8, a large form is occupied by smaller ones and both indicate the same direction of flow toward the entrance. The asymmetry of scallops indicates that the older stage of palaeoflow was connected with drainage of the Giewont massif and probably the eastern part of the Kopa Kondracka massif. The younger and faster one is marked by smaller scallops with asymmetry indicating a direction of flow toward the entrance.

Glauconite from deposits near the cave entrance and the profile in the middle of the cave indicate an alimentation area in the upper part of the Kondratowa Valley (in Polish – Dolina Kondratowa), the Giewont massif and probably the north part of the Cicha Valley (in Slovak – Tichá dolina, in Polish – Dolina Cicha) in Slovakia (water flow under the "Goryczkowa Island"), where Cretaceous glauconite-bearing limestones occur (Fig. 1). The high amphibole content of samples KL8, KL9 and KL4 indicates transport from the "Goryczkowa Island" in the upper part of the Kondratowa Valley, where amphibolites are common. Instable minerals *sensu* Burkhardt (1978) predominate in Kalacka Cave, except in samples K2.2 and K5.

The observations of scallops and analysis of the composition of the heavy minerals in general prove a minimum of two palaeoflow directions in all caves of the Bystrej Valley. There is evidence in many places for two opposite directions of palaeoflow. The first, older one was connected with drainage of the mountain massifs that surrounded the Bystrej Valley and the second, younger one, with the water from melting glaciers. The calculated flow rates for the younger generation of scallops are similar to contemporary rates of underground flow in the Tatra Mountains (Barczyk, 2003). It should be noted that these values were calculated with reference to the present sizes and shapes of passages.

Speleothems crystallization phases

Speleothem crystallization generally is controlled by climatic conditions. The periods of intensive speleothem growth are interpreted as being warm and humid, while cold and/or dry periods are less favourable for speleothem deposition. The speleothem growth-frequency curve (deposition phases) shows maxima for periods that were favourable for speleothem deposition (warm and humid) and minima for less favourable periods, usually interpreted as being cold and/or dry (e.g., Hercman, 2000).

The dating of speleothems from caves in the Bystrej Valley permitted the recognition of five maxima on the speleothem growth-frequency curve (Fig. 4A and B, Table 7). The oldest (1) phase covers the period of 220–150 ka (speleothems from Kasprowa Niżnia and Kalacka caves) and corresponds to phase I of speleothem crystallization in the Carpathians (Hercman, 2000). It may be correlated with the Lubelski Interglacial (Lindner *et al.*, 2003) and 7–6 Marine Isotopic Stage (MIS; Imbrie *et al.*, 1984; Pisias *et al.*, 1984; Martinson *et al.*, 1987; Lisiecki and Raymo, 2005). The next period (2) of speleothem deposition (samples from Goryczkowa, Magurska and Bystrej caves) is dated as 135–105 ka. It is correlated with phases II and/or III in the Carpathians and the Eemian Interglacial. The third phase (samples from Magurska and Kasprowa Niżnia caves) lasted from 95 until 70 ka. It may be correlated with phase V of speleothem deposition in the Carpathians and with the MIS sub-stage 5a. The next (4) phase (samples from Magurska and Goryczkowa caves) covers the period from 40 to 23 ka. It is correlated with the Carpathian phase VII and the warm sub-stages of the Vistulian. The youngest (5), Holocene

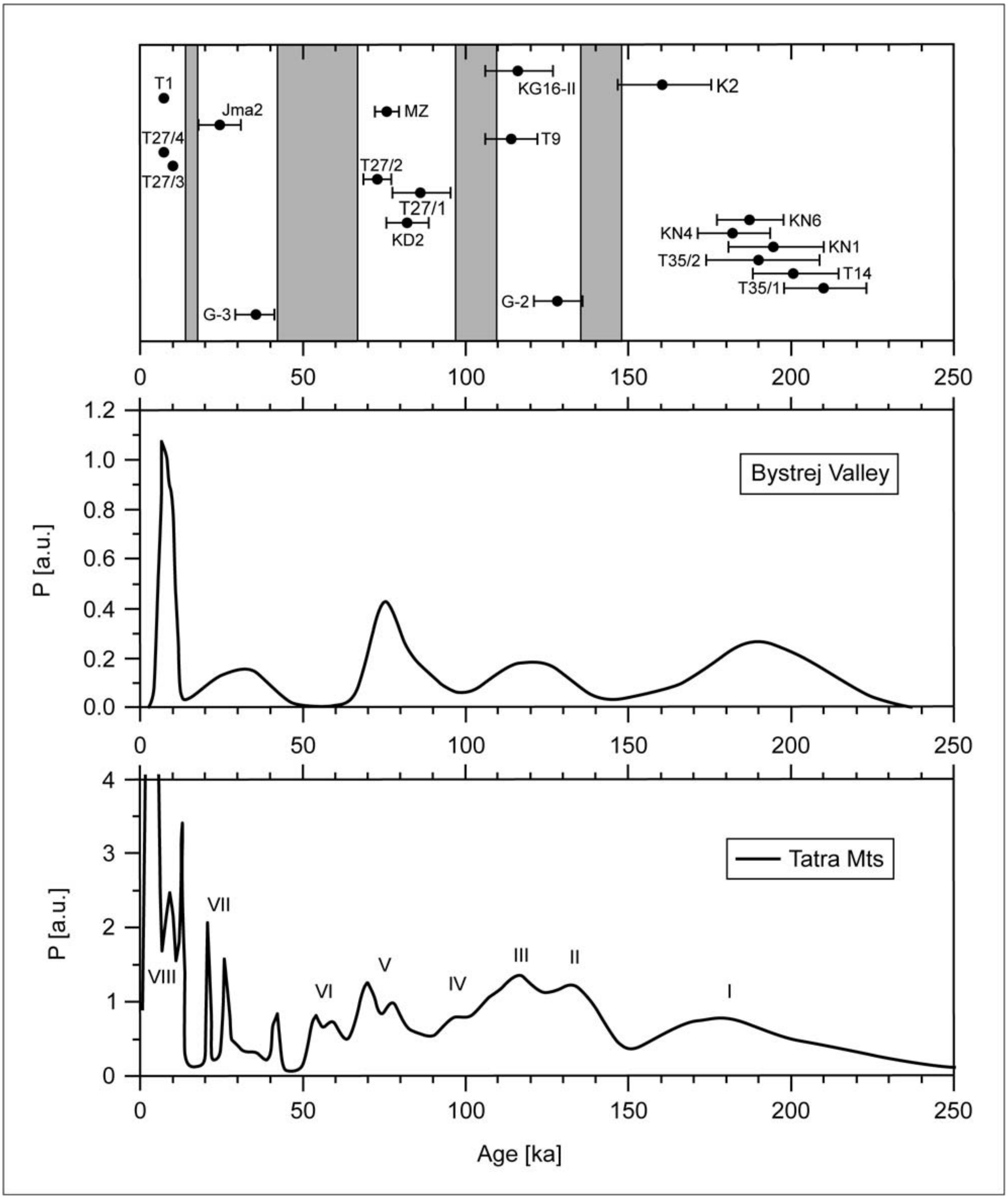

Fig. 4. Speleothem-growth frequency curve for the Bystrej Valley and the Tatra Mts caves and correlation of it with oxygen isotope stages.

phase is represented by samples from Magurska and Bystrej caves.

Age of valley incisions

Three cave levels in the Bystrej Valley (Szczygieł *et al.,* 2015) were formed in periods when uplift of the Tatra Mts had ceased and they reflect the base level of erosion (cf. Calvet *et al.,* 2015; Szczygieł, 2015b). Kasprowa Niżnia and Bystrej caves belong to the youngest, lowermost level, still active and flooded after snowmelt and high precipitation. Kasprowa Niżnia Cave is located at the bottom of the Kasprowa Valley. The age of the oldest speleothems, ca. 230 ka (Table 7), indicates the minimum age of cave drainage; at that time the cave was in the vadose zone. This means that the valley was incised at that time, approximately to the same level as its present position (Hercman, 1991). A similar age is evidenced in the Lodowe Źródło Cave system in the Kościeliska Valley (Nowicki, 2003) and in Brestovská Cave in the Studený Stream Valley (Hercman *et al.*, 2008).

The entrance of Goryczkowa Cave is located 50 m above the bottom of the Goryczkowa Valley (in Polish – Dolina Goryczkowa). The age of the oldest speleothem from Goryczkowa Cave is ca. 128 ka, indicating that the valley bottom could have been incised not more than 50 m downwards during the last 128 ka. An even older date of speleothem formation was identified in Szczelina Chochołowska Cave, which is located at similar height (Hercman *et al.*, 1998). Hercman (1991) calculated the maximum average incision rate of valleys in the Western Tatra Mts to be 0.2 m/1 ka. This is in disagreement with the data of Králiková *et al.* (2014), which the authors attributed to various factors, for example, the N-S asymmetry of uplift of the Tatra Mts, the intensive widening of the valleys in comparison with their deepening, etc. The entrances of Bystrej Cave are located 17 and 27 m above the bottom of the Bystrej Valley. The age of the upper layer of a stalagmite collected between the IV and V sumps is ca. 116 ka (Duliński and Kuliś, 1989). It proves that before the Eemian Interglacial, Bystrej Cave was dry and speleothems were deposited. Because of the presence of moraines, the water level has risen and in recent time the cave is not normally accessible (cf. Audra and Palmer, 2013).

The incision of the Bystrej Valley is deeper than that of the neighbouring valleys, as a result of both palaeoflows and present flows from the east and west and probably from the south. Generally, the evolution of a cave system is related to the local cave level and associated geomorphic conditions. Observations of palaeohydrology and hydrogeology in the Bystrej Valley catchment indicate that the evolution of the cave system also could have exerted an influence on valley development.

EVOLUTION OF THE BYSTREJ VALLEY CAVE SYSTEMS

The karst phenomena of the Tatra Mountains probably began to develop 6–5 Ma ago (Głazek, 2000). Development of the Bystrej Valley cave systems probably began before the Early Pleistocene. In the first stage, horizontal caves were created in the phreatic or epiphreatic zone. The scallops on the walls and ceilings of passages were formed in both zones and in most cases represent the last period of water flow into the cave systems. The age of the oldest speleothems in a cave can be used to estimate the minimal age of transition from phreatic to vadose conditions in any particular part of the cave (Ford *et al.*, 1981). It should be noted that the time between cave creation, the transition from phreatic to vadose conditions and speleothem crystallization may differ substantially. In addition, the samples collected may not represent the oldest depositional phases for speleothems or the transition to vadose conditions.

The oldest cave with the highest altitude in the Bystrej Valley is Magurska Cave. It is located in the dome-shaped Kopa Magury massif, which supposedly was a mogote rising above the early Pliocene denudation surface (Głazek and Wójcik, 1963). The origin of this cave is connected with the axial zone of the anticline, which was subjected to tensile stresses during folding (Hercman, 1989). Unfortunately, the authors did not sample speleothems older than 120 ka there. In Czarna Cave (in Polish – Jaskinia Czarna), located in the Kościeliska Valley at a similar altitude, there were speleothems dated as more than 1,200 ka, as indicated by the equilibrium between ^{234}U and ^{238}U (Nowicki *et al.*, 2000; Nowicki, 2003). Therefore, it might be expected that the older speleothems in Magurska Cave were destroyed during the Pleistocene. The antiquity of Magurska Cave (Fig. 5A, phase I) is evidenced by the location of passages above the valley bottom, the location under the Pliocene denudation surface and the large size of chambers in its near-entrance part. The cave developed under phreatic condition, as evidenced by a few large ceiling pockets in the main passage of the Na Rozdzielu Chamber. Large scallops occurring near the entrance and the Na Rozdzielu Chamber indicate slow palaeoflow toward the Jaworzynki Valley. Two stages of palaeoflow with different flow velocities toward the Jaworzynki Valley were documented in the cave. The older one is expressed by large scallops and the younger one by smaller ones. At the end of the cave and in the middle parts of the cave, conduits with a subcircular cross-section were remodelled continually. Szczygieł *et al.* (2015) suggested the existence of two phreatic loops. In the part near the entrance, the palaeophreatic morphology was obliterated by ceiling collapse, facilitated by a dense network of discontinuities (Szczygieł *et al.*, 2015). According to Hercman (1986, 1991), large chambers located near the entrance of Magurska Cave were formed during a long period of stable climatic conditions, favourable for karstification, probably in the warm and wet Pliocene. At the same time, an independent cave probably existed and represented a path for water flow from the crystalline rocks of the "Goryczkowa Island" toward the Jaworzynki Valley (Fig. 5B). The idea that these caves could form separate parts of a system is indicated in the sediments of the main passage of Magurska Cave by heavy minerals, typical for metamorphic rocks. Minerals of this type are not present in the sediments filling the large chambers near the entrance of the cave (Hercman, 1986). However, samples taken from the lower layers of the Przekop Passage, the Przekop z Belką sections and from other places indicate that the sediments in the cave are more mixed. Minerals typical for metamorphic rocks also occur in lower layers of the Przekop section. A big rock-fall in the Złomisk Chamber probably represents a connection between both independent caves. Speleothem-cemented blocks (ca. 76 ka) indicate the age of this collapse as Eemian or pre-Eemian (Fig. 5A, phase V). During Eemian Interglacial and Vistulian time, Magurska Cave had easy access from the surface and was inhabited by cave bears (Fig. 5A, phase IV).

Goryczkowa and Kalacka caves belong to the second cave level of the Bystrej Valley. Goryczkowa Cave was formed under phreatic and epiphreatic conditions (Fig. 5A, phase II). Most passages have sub-circular cross-sections.

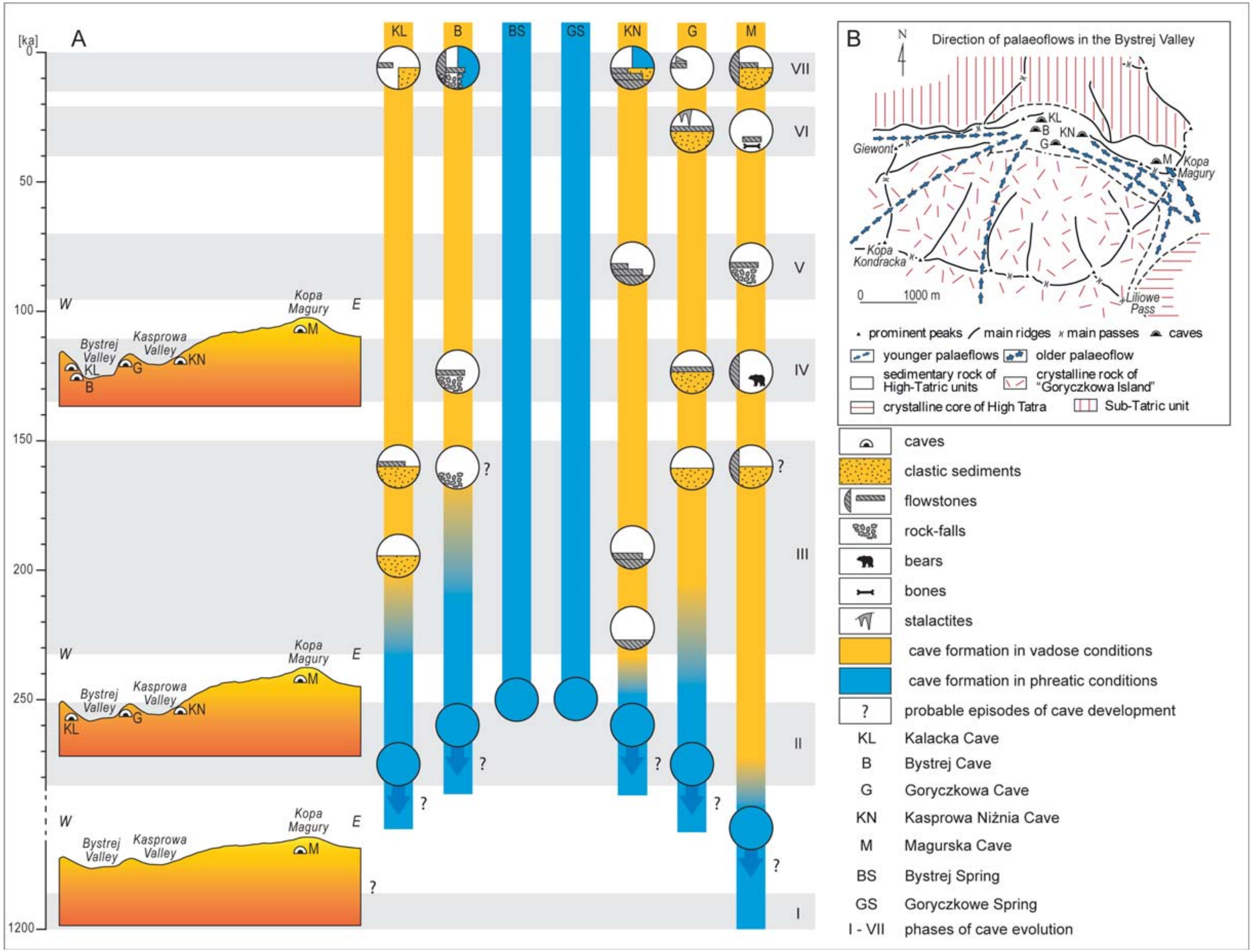

Fig. 5. Geomorphic evolution of the Bystrej Valley. **A.** Evolution of Kalacka, Bystrej, Goryczkowa, Kasprowa Niżnia and Magurska caves with stages of phreatic and vadose conditions, crystallization of speleothems and deposition of cave clastics (marked as I – VII – detailed description in text). **B.** Directions of palaeoflow in the Bystrej Valley (geological sketch map after Hercman, 1991).

Szczygieł *et al.* (2015) stated that the passages are oriented along discontinuities, but dissolution features dominate over tectonic ones. According to these authors, Goryczkowa Cave is a 3-D anastomosing maze type. In Goryczkowa Cave, there are also closed loops and labyrinths of phreatic tubes. There are two palaeoflow directions marked by scallops. The older one is from the inside of the cave toward the entrance. The later evolution of Goryczkowa Cave was connected with glaciation-deglaciation cycles. The Myślenickie Turnie Peak was surrounded by glaciers of the Goryczkowa and Kasprowa valleys (Klimaszewski, 1988), which caused the frequent flooding of Goryczkowa Cave. This means that the genesis and evolution of Goryczkowa Cave was influenced by many factors. Additionally, sinkholes found East of Myślenickie Turnie Peak (cf. Wójcik *et al.*, 2013) might represent entrances for short-lived, increased water inflow into the cave from the Kasprowa Valley. In Goryczkowa Cave, sediments were mostly removed by the invasion of water from the melting glaciers surrounding the Myślenickie Turnie Peak (Fig. 5A, phase VII). Water could have entered the cave through its entrance and probably also through sinkholes located above the Dolna Chamber.

The origin of Kalacka Cave is connected with drainage of the Giewont and probably the Kopa Kondracka massifs and the north part of the Cicha Valley in Slovakia (under crystalline rocks of the Giewont Unit, i.e., "Goryczkowa Island"). This direction is indicated also for recent flows (Małecka, 1997; Holúbek, 2008, Gradziński *et al.*, 2009; Barczyk, 2013). Kalacka Cave was created under phreatic conditions, as evidenced by the phreatic cross-section of conduits and the large scallops on its walls and ceilings (Fig. 5A, phase II). The scallops indicate relatively slow palaeoflow towards the entrance. Small younger scallops on the larger forms in three places document a second generation of high-velocity palaeoflow. They show both directions, that is, toward the end of the cave and toward the entrance. The direction indicating palaeoflow into the cave could have been caused by local turbulence. Later, Kalacka Cave was filled by sands and loam, particularly in the narrow parts, depressions and sumps (Fig. 5A, phase III). According to the Hjulstrom diagram (1935), this type of sediment is deposited at velocities of less than 20 cm/s (cf. Wójcik, 1966). This means that small scallops were formed before deposition of the sediment, because the high velocity of palaeoflow, indicated by scallop size, could have caused sediment erosion. In the near-entrance part, clastic deposits filled the entire passage and the cave was not explored by humans until 1948 (Zwoliński, 1987). In front of this part, sediments are covered by speleothems, dated at ca. 160 ka (K2 sample, Fig. 5A, phase III), that is, after the penultimate glaciation (Saalian, resp. Riss II, according to Lindner *et al.*, 2003). The age of speleothems indicates an older age of deposition for the clastic sediments (cf. Głazek, 1989; Hercman, 2000). These data contradict the views of Wójcik (1979) that these deposits were formed after the penultimate glaciation. In the literature, there are different views with regard to the glaciation of the Kondratowa Valley. Klimaszewski (1988) considered the Kondratowa Valley to have been without glaciers during last glaciation. Wójcik (1979) found moraines of Saalian (Riss) age on the slope of the Kalacka Turnia massif, to the SW of the entrance of Kalacka Cave. Recent reconstruction of the last glaciation of the Bystrej Valley (Zasadni *et al.*, 2015; Makos *et al.*, 2016) shows that the entrance of Kalacka Cave was located within the periglacial zone. It confirms that water circulation in Kalacka Cave was not influenced by the last deglaciation or any earlier one.

Kasprowa Niżnia and Bystrej caves represent the youngest (third) cave level of the Bystrej Valley. The deepening of the Kasprowa Valley and Kasprowa Niżnia Cave development caused underground capture of flow from the Gąsienicowa Valley. As a result of this capture, a down-cutting of about 20 m occurred in the passage, located downstream of the Na Rozdzielu Chamber in Magurska Cave. The minimum age of the underground capture is indicated by the oldest speleothems in Kasprowa Niżnia Cave (ca. 230 ka), referable to the Middle Pleistocene. It means that before 230 ka ago, Kasprowa Niżnia Cave became the main water outflow from the system (Hercman, 1991). In the Middle Pleistocene, after creation of the Goryczkowe vauclusian spring, the Kasprowa Niżnia Cave system occurred in vadose conditions and speleothem deposition there was intensive (Fig. 5A, phase III). Scallops and the composition of heavy minerals in the Kasprowa Niżnia deposits indicate a palaeotransport direction from the Gąsienicowa Valley and the southern part of the Bystrej Valley, except for in its near-entrance part, where there are deposits that were transported from the blurred moraines (Fig. 5B). The cave now exhibits active water out-flow from the karst system at high water levels. In recent times, the Goryczkowe vauclusian spring drains the western part of the Gąsienicowa Valley and the Kopa Magury and Zawrat Kasprowy massifs (Dąbrowski and Głazek, 1968; Barczyk, 2003). Thus Kasprowa Niżnia Cave presents an older stage of the Goryczkowe vauclusian spring, as does Kalacka Cave for the Bystrej Cave systems and the Bystrej vauclusian spring.

There was intensive speleothem deposition in all caves during the Eemian Interglacial (Fig. 5A, phase IV), as in other caves in the Tatra Mountains (Hercman, 1991, 2000; Nowicki, 2003; Hercman *et al*, 2008). In Magurska Cave, the Eemian speleothems cover walls of the Przekop Passage. This proves the post-Eemian age of the thick pile of deposits with bones here (Fig. 5A, phase VII). Sediments were probably deposited during the last glacial. Rounded limestone blocks show the effects of corrosion and the sediments probably were re-deposited from the large near-entrance part, resulting in mixing of them (Hercman, 1986, 1991). These sediments represent a diamictite facies, according to the classification of Bosch and White (2007). The upper layer of sediment shows traces of water flow and the washing of the fine-grained matrix of the deposits. After a blockage to water flow at the final stage, a layer of silt was deposited, probably from stagnant water (Hercman, 1986, 1991).

In the other caves, the period of water inflow is marked by the destruction of the speleothem surfaces, the removal of older sediments (Goryczkowa Cave and the near-entrance part of Kalacka Cave, Fig. 5A, phase VI) and the deposition of clays (Bystrej Cave). A similar destruction of speleothems were noted in the Lodowe Źródło Cave System (Nowicki, 2003) and in Brestovská Cave (Hercman *et al.*, 2008). The last stage in the cave system history is represented by Holocene speleothem deposition, which is still active currently (Fig. 5A, phase VII).

CONCLUSIONS

At least two generations of palaeoflow were recognized in the caves of the Bystrej Valley studied. Older paleoflows were associated with the drainage of carbonate massifs, while the younger ones are related to glaciation-deglaciation cycles.

As a consequence of valley incision, the palaeoflows moved to lower levels of the cave systems. In the Magurska–Kasprowa Niżnia cave system, the underground capture of karst water could have taken place before the Middle Pleistocene.

On the basis of the analysis of heavy minerals, it is possible to identify the alimentation zone and transport routes. A special case is possible palaeoflow from the Cicha Valley in Slovakia to Kalacka Cave, which could confirm the earlier suggestion about present-day transboundary karst flows in the region of Kasprowy Wierch–Skrajna Turnia.

The vauclusian springs in the Bystrej Valley were created within the present-day morphology. The Goryczkowe vauclusian spring was created before ca. 230 ka, which caused the drainage of Kasprowa Niżnia Cave. The Bystrej vauclusian spring is located on the same level, which might indicate that it was formed at the same time.

Speleothems in the Bystrej Valley caves crystallized in periods of 220–150, 135–105, 95–70, 40–23 ka ago and in the Holocene. The oldest speleothems of Kasprowa Niżnia, Goryczkowa, Kalacka and Bystrej caves were dated respectively at ca. 230, 116, 160 and 128 ka, i.e. these caves are much older than the Late Pleistocene. The age of the Kasprowa Niżnia speleothem confirms early studies that the Kasprowa Valley was incised ca. 250 ka ago to approximately the same level as at present. Since at least the Middle Pleistocene, the caves of the Bystrej Valley developed under similar conditions to those of the present day.

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