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TECTONIC CONTROL OF CAVE DEVELOPMENT: A CASE STUDY OF THE BYSTRA VALLEY IN THE TATRA MTS., POLAND

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Abstract: Tectonic research and morphological observations were carried out in six caves (Kalacka, Goryczkowa, Kasprowa Niżna, Kasprowa Średnia, Kasprowa Wyżnia and Magurska) in the Bystra Valley, in the Tatra Mountains. There are three cave levels, with the youngest active and the other two inactive, reflecting development partly under epiphreatic and partly under phreatic conditions. These studies demonstrate strong control of the cave pattern by tectonic features, including faults and related fractures that originated or were rejuvenated during uplift, lasting from the Late Miocene. In a few local cases, the cave passages are guided by the combined influence of bedding, joints and fractures in the hinge zone of a chevron anticline. That these cave passages are guided by tectonic structures, irrespective of lithological differences, indicates that these proto-conduits were formed by "tectonic inception". Differences in the cave pattern between the phreatic and epiphreatic zones at a given cave level may be a result of massif relaxation. Below the bottom of the valley, the effect of stress on the rock mass is related to the regional stress field and only individual faults extend below the bottom of the valley. Thus in the phreatic zone, the flow is focused and a single conduit becomes enlarged. The local extension is more intense in the epiphreatic zone above the valley floor and more fractures have been sufficiently extended to allow water to flow. The water migrates along a network of fissures and a maze could be forming. Neotectonic displacements (of up to 15 cm), which are more recent than the passages, were also identified in the caves. Neotectonic activity is no longer believed to have as great an impact on cave morphology as previously was thought. Those faults with displacements of several metres, described as younger than the cave by other authors, should be reclassified as older faults, the surfaces of which have been exposed by speleogenesis. The possible presence of neotectonic faults with greater displacements is not excluded, but they would have had a much greater morphological impact than the observed features suggest.

Key words: Cave morphology, speleogenesis, tectonics, neotectonics, Tatra Mts., Western Carpathians.

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INTRODUCTION

The relationship between tectonics and cave-system development has been investigated by several authors, e.g. Ford and Ewers (1978), Palmer (1991), Klimchouk and Ford (2000), Tognini and Bini (2001), Faulkner (2006) and Sauro *et al.* (2013). This relationship has also been investigated in the Tatra Mts. (e.g., Grodzicki, 1970; Szczygieł and Gaidzik, 2012; Szczygieł, 2013). In the Bystra Valley, however, this type of research has only been conducted in Magurska Cave (Hercman, 1989). The current state of knowledge about tectonic controls is generally adequate, although this topic previously has not been investigated thoroughly in the Tatra karst systems. Moreover, investigations recently have been conducted on cave development and its dependence on recharge and vertical movement (Audra and Palmer, 2013; Gabrovsek *et al.*, 2014). These studies show that, apart from the geometry of the structure, the dynamics of the tectonic/morphotectonic processes have a significant impact on the conditions, under which cave passages are formed and therefore affect conduit morphology and variation in vertical and horizontal cave patterns.

This paper focuses on the structural control of cave passages and attempts to determine the impact of neotectonic processes on passage morphology and general cave pattern. The study area covers the cave system of six caves in the Bystra Valley in the Polish Tatra Mts. These are, from west to east, Kalacka, Goryczkowa, Kasprowa Niżna, Kasprowa

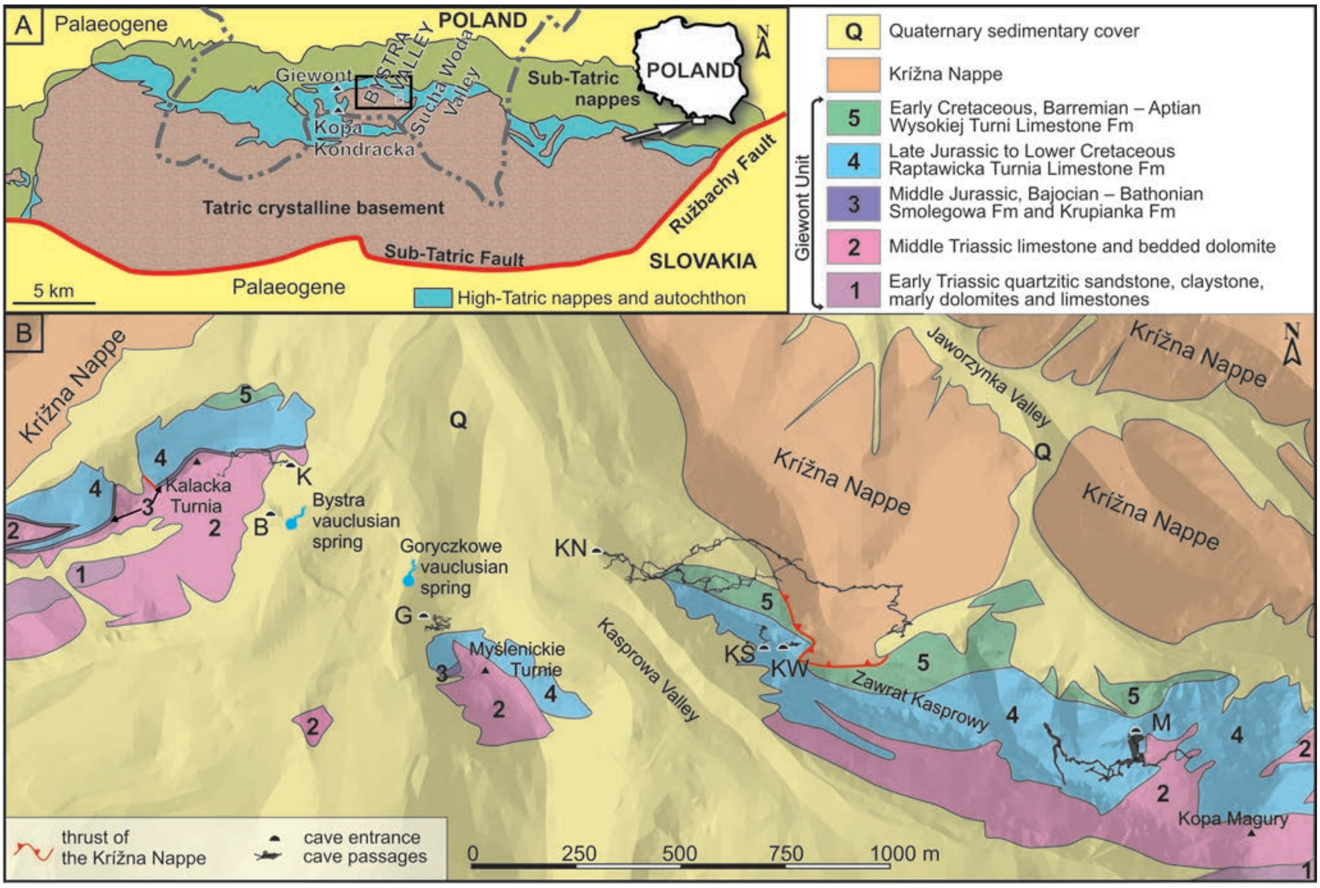

Fig. 1. Location of study area. **A.** Main tectonic units of the Tatra Mts. (after Bac-Moszaszwili *et al.*, 1979). **B.** Surface geological setting of study area (Michalik, 1958; Guzik and Jaczynowska, 1978; modified); K – Kalacka Cave; B – Bystra Cave; G – Goryczkowa Cave; KN – Kasprowa Niżnia Cave; KS – Kasprowa Średnia Cave; KW – Kasprowa Wyżnia Cave; M – Magurska Cave; on background of shaded digital elevation model, azimuth and dip the lighting respectively 90° and 60°.

Średnia, Kasprowa Wyżnia and Magurska caves. These were selected from the 62 known caves in the area (Grodzicki, 2002). The caves are longer than 50 m and are accessible without diving.

STUDY AREA

Geological setting

The Tatra Mts. are the northernmost range of the Central Western Carpathians. They are composed of a pre-alpine crystalline basement overlain by an autochthonous sedimentary covering, the High-Tatric Nappe (Czerwone Wierchy Unit, Giewont Unit) and the Sub-Tatric nappes (Krížna and Choč nappes; Bac-Moszaszwili *et al.*, 1979; Fig. 1A). The Bystra Valley is located in the north-central part of the Tatra Mts. (Fig. 1A). The Bystra Valley caves were formed in Mesozoic limestones of the Giewont Unit (Kotański, 1959; Fig. 1B).

The Giewont Unit consists of a Mesozoic succession, the lower part of which contains Lower Triassic quartzitic sandstones, claystones, marly dolomites and limestones (Michalik, 1958). These deposits are covered by partly bioturbated limestones, bedded dolomites, and dolomitic limestones of Middle Triassic age (Jaglarz and Rychliński, 2010). The Middle Jurassic, overlies the Middle Triassic penacordantly, and is represented by crinoidal limestones (Smolegowa Fm, Bajocian; Lefeld *et al.*, 1985; Łuczyński, 2002) and red, nodular limestones (Krupianka Fm, Bathonian; Lefeld *et al.*, 1985; Łuczyński, 2002). Pinkish limestones (at the bottom) and mostly grey, thick-bedded limestones (Raptawicka Turnia Limestone Fm; Lefeld *et al.*, 1985) represent the Upper Jurassic to Lower Cretaceous (Hauterivian). Further up the profile, the Wysoka Turnia Limestone Fm (Lefeld *et al.*, 1985) occurs, which contains shallow platform limestones that are Late Barremian–Early Aptian in age (Masse and Uchman, 1997). At the top of the carbonate sequence, the Zabijak Marl Fm of Albian–Cenomanian age consists of glauconitic limestone, grey and pinkish limestone, and marls with sandstone interbeds (Lefeld *et al.*, 1985).

The units of the High-Tatric succession are characterized by E–W-trending and narrow, northward-dipping belts, in which carbonate rocks are separated by non-karstic rocks. The Giewont Unit is in the northern belt. River valleys run perpendicular to the karstic belt. This has made a vauclusian spring drain the neighbouring valleys (Głazek, 1997). The northern belt also comprises crystalline rocks in the lower part of the Giewont Unit, i.e. the "Goryczkowa Island", which were detached from the crystalline basement during folding (Burchart, 1970). This distinguishes it from other units. The tectonic outliers of crystalline rocks are the westernmost part of the Giewont Unit. They are found in the upper parts of the Czerwone Wierchy Massif (Kotański, 1961).

The whole sedimentary rock profile of the Giewont Unit occurs in a normal position in the Giewont area (Rabowski, 1959; Kotański, 1961). Further to the east, the geology of the Kalacka Turnia is analogous to that of the Myślenickie Turnie and the Zawrat Kasprowy, which was interpreted by Rabowski (1959) and Kotański (1961) as an anticline. This anticline is the lowermost fold of the Giewont Unit (Kotański, 1961; Bac-Moszaszwili *et al.*, 1979), as confirmed by observations made in Bystra Cave (Grodzicki and Kardaś, 1989). Another secondary fold, a syncline, was documented in the Myślenickie Turnie (Bac-Moszaszwili *et al.*, 1979) and the Zawrat Kasprowy, the hinge zone of which can be observed in Magurska Cave (Hercman, 1989). The present relief of the mountain is a result of uplift that began during the Miocene at 15 Ma (Burchart, 1972; Králiková *et al.,* 2014). The Tatra Mts. were glaciated several times during the Pleistocene (Lindner *et al.*, 2003).

Speleological setting

Sixty two caves have been mapped in the Bystra Valley. The deepest and longest caves are Kasprowa Niżna, Kasprowa Średnia, Kasprowa Wyżnia, Bystra, Magurska, Kalacka and Goryczkowa (Grodzicki, 2002). Most of the caves in this valley are horizontal systems, located at different heights above the valley bottom. Magurska Cave is situated in the Kopa Magury–Zawrat Kasprowy Massif (Fig. 1B). The cave has two entrances, one at 1460 m a.s.l and the other at ca. 1475 m a.s.l. (about 150–200 m above the valley bottom). The total length and denivelation of this cave are about 1200 m and 59 m respectively (Nowicki, 2000). Kasprowa Niżna (denivelation: 45 m; length: 3020 m; Luty, 2002) is situated in the Zawrat Kasprowy Massif at the lowest level of the Kasprowa Valley (1228 m a.s.l.; Fig. 1B). The cave is still active. Kasprowa Średnia Cave (denivelation: 53 m; length: 150 m; Luty, 2000b) and Kasprowa Wyżnia Cave (denivelation: 24.7 m; length: 100 m; Luty, 1979; Fig. 1B) are at higher altitudes in the valley. Kasprowa Średnia Cave is located about. 150 m above the lowest level (1407 m a.s.l.) and Kasprowa Wyżnia Cave has three entrances – at 165, 159 and 140 m (1463, 1467 and 1438 m a.s.l. respectively). Goryczkowa Cave (depth: 31 m; length: 605 m; Dudziński, 2013) is located in the Myślenickie Turnie Massif about 50 m above the valley bottom (1263 m a.s.l.). The entrance is on the eastern slope of the Goryczkowa Valley (Dudziński, 2013; Fig. 1B). Kalacka Cave (denivelation: 19 m; length: 345 m; 1230 m a.s.l.; Luty, 2000a; Fig. 1B) and Bystra Cave (denivelation: 53 m; length: 1480 m; 1182 and 1190 m a.s.l.; Grodzicki, 2002). Bystra Cave is the second longest cave in the Bystra Valley and is still active. The karst phenomena in the Bystra Valley occur only in the W–E extending carbonate rocks (Fig. 1B). The Bystra catchment is bigger than the Bystra Valley, as a result of groundwater flowing from neighbouring valleys to two springs with ascending outflow. The connection between a sinkhole in the Sucha Woda Valley and the Goryczkowe vauclusian spring has been confirmed by tracing underground water (Dąbrowski and Głazek, 1968; Pachla and Żaczkiewicz, 1986; Barczyk, 2003). The other Bystra vauclusian springs probably drains the eastern part of the Kopa Kondracka and Giewont massifs (Barczyk, 2003).

Magurska Cave represents the highest level of the cave conduits explored in the valley. This cave is situated in the dome-shaped Kopa Magury-Zawrat Kasprowy Massif and is considered to be one of the oldest in the Tatra Mountains. The antiquity of Magurska Cave is predicated on the height of the passages above the valley bottom (under the planation palaeosurface) and the spaciousness of the chambers in the near-entrance part. The latter is the result of long-term palaeoflow in warm and wet climatic conditions during the Pliocene Epoch (Hercman, 1991). According to Hercman (1986, 1991), there might have been two independent caves during this time and they could have been connected *via* the Złomisk Chamber after the breakdown of the intervening rocks. This must have happened before the Eemian Interglacial, as estimated from the age of speleothems covered this breakdown (Hercman, 1991).

The longest cave in the Bystra Valley is Kasprowa Niżna (3020 m). The composition of the cave deposits indicates that the palaeotransport direction is from the Sucha Woda Valley (Hercman, 1986; Kicińska, 2002). The formation of Kasprowa Niżna Cave caused underground water capture from the Sucha Woda Valley to the Kasprowa Valley, i.e. the palaeoflow direction was altered. The palaeoflow direction was originally from the Sucha Woda Valley to the Jaworzynka Valley (Hercman, 1991). Later, because of the deepening of the Bystra Valley, Kasprowa Niżna dried up and the Goryczkowe vauclusian spring began to form. The minimum age of the Goryczkowe spring is about 180 ka (Hercman, 1991). The age of the speleothems at Kasprowa Niżna proves that the cave predates the Eemian Interglacial and that it passed into the vadose zone no later than this time.

Goryczkowa and Kalacka caves are considered by Rudnicki (1967) and Wójcik (1966, 1968) to be older counterparts of the Goryczkowe and Bystra vauclusian springs, respectively. Two directions of palaeoflow have been observed in these caves. This was confirmed by the observation of corrosive forms (scallops) in the near-entrance parts (Kicińska, 2002). At this time, Goryczkowa and Kalacka caves were filled by sediments supplied by the palaeoflow from melting glaciers. These caves also contain deposits transported from blurred moraines. One of the flowstone remnants covering these deposits is dated at about 165 ka (Hercman, 1991). This proves that these caves were in the vadose zone during this time. The dating of the speleothems in these caves indicates that glacial-valley deepening did not play a significant role and did not deepen them by more than 100 m (Hercman, 1991).

Wójcik (1968) distinguished eleven levels using the water-table theory, developed by Swinnerton (1932). These levels were assigned according to entrance height above the bottom of each distinctive valley. The cave conduits known in the Bystra Valley caves belong to levels I (Bystra, Kasprowa Niżna), II (Bystra, Goryczkowa, Kasprowa Niżna), IV (Kalacka) and V (Magurska).

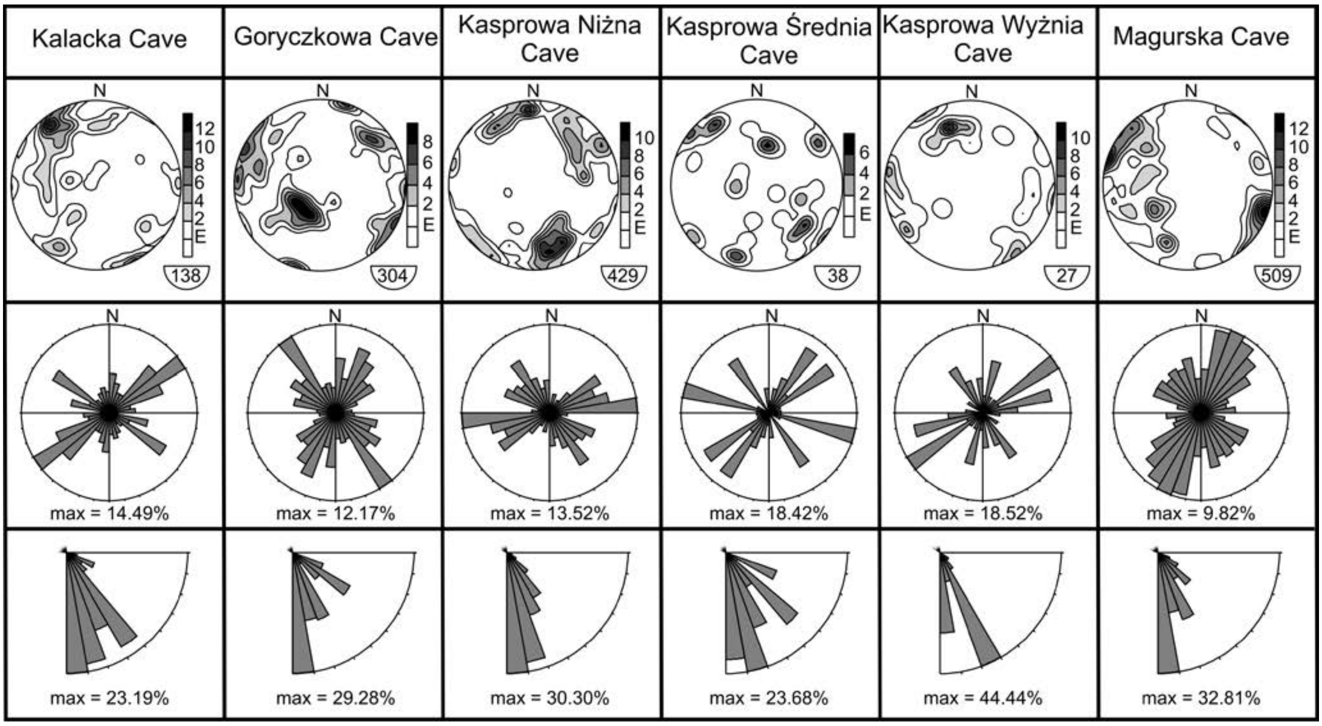

Fig. 2. Spatial orientation (contour density and rose diagrams) of fractures in selected caves in the Bystra Valley.

METHODOLOGY AND MATERIALS

Fieldwork was conducted at more than a hundred sites in six caves in the Bystra Valley. The accessibility of a given cave governed the timing of the fieldwork and the number of points studied in the cave. The observation points were chosen in order to cover the entire cave statistically, with the exception of Magurska and Kasprowa Niżna caves. The areas to the SE of the Rycerska Chamber in Kasprowa Niżna Cave were not studied because of the presence of the Wiszący Sump. Only the easternmost part of Magurska Cave, *viz.* the Stalaktytowy Passage, was excluded, as the sump had been filled in by cave sediments. More than 1500 measurements of the spatial orientation of geological structures (bedding, fractures, and meso-faults with accompanying shear fibres and striations) were taken. Statistical methods were applied to all the gathered tectonic data. The orientations were summarized as structural diagrams (great circles and contour density). These were made in equal-area Lambert-Schmidt projections on the lower hemisphere, using SpheriStat software. Rose diagrams – illustrating the strike directions and dip angles of the structures studied – were drawn, using TectonicsFP software. Angelier diagrams were made for fault slip data, again, using TectonicsFP software.

In order to study the statistical and general relationships between the tectonic structures and the development of the cave network, the tectonic diagrams were compared with the structural plans of each cave and with rose diagrams showing the distribution of conduit directions. The rose diagrams are a compilation of conduit directions weighted by length (Filliponi *et al.*, 2009). If the contour diagrams are presented, then the rose diagrams are not necessary. Rose diagrams, however, better correlate tectonic structures with passage directions on plans and diagrams. This allows the guiding fracture, *i.e.* the fracture that had the most significant impact on the cave pattern and directions, to be determined. Guiding fractures do not always coincide with the master joints, which are the most common fractures in the bedrock.

TECTONIC SETTING OF THE STUDIED CAVES

Kalacka Cave

Kalacka Cave developed within the thin-bedded limestone and dolomite of the Middle Triassic and the massive limestone of the Raptawicka Turnia Fm. The limestone observed in the cave was strongly fractured and faulted, especially in the central and near-entrance sections. Predominant among the brittle features in the cave are joints striking NE–SW (locally also ENE–WSW), dipping steeply and very steeply towards the SE, but much more rarely towards the opposite direction, i.e. NW (Fig. 2). The joints in this set represent the main maximum on the statistical summary fractures contour diagram (Fig. 2) and generally form dense groups that are very clearly marked and have large, smooth, flat surfaces. Significantly, they dominate in the central parts of the cave, but not so much in sections closer to the entrance. Wherever these joints still dominate in the terminal unit, they do so with little change in strike in the NNE–SSW direction. Moreover NW–SE or WNW–ESE fractures, dipping mainly towards the NE, were observed everywhere in the cave as the secondary set faintly visible on the contour diagram. In general, steep, very steep and vertical fractures dominate. Fractures with a dip angle greater than 70° constitute more than 40% of all measured fracture surfaces (Fig. 2). Normal right-lateral and left-lateral strike-slip faults and oblique faults could be observed in Kalacka Cave. These strike NE–SW and ENE–WSW, and dip mostly at moderate angles towards the SE (Fig. 3). The most common tectonic striation (over a quarter of the measured tectonic striations dip at angles between 40° and 50°; Fig. 3) had a slight deflection towards the E or S. Slickenside orientation is therefore usually consistent with the dipping of the fault plane or insignificantly oblique. Also observed in the central parts and in sections close to the entrance were steep faults, striking NW–SE (almost perpendicular to the main set of faults), and N–S vertical faults, where the eastern wall was relatively elevated.

Moreover, normal meso-faults active after the development of the cave were observed. Two striking W–E were observed in the Rozsunięta Chamber and in a high fissure behind the Rozsunięta Chamber, and a third with a NW–SE strike was identified between sumps I and II.

Goryczkowa Cave

This cave was formed in the Middle Triassic limestone and dolomite as well as the limestone of the Raptawicka Turnia Fm. The WNW–ESE, NW–SE striking of beds, dipping moderately towards the NNE and NE, is only noticeable in the areas close to the entrance of the cave.

The limestone and dolomite fractures in the cave are mainly characterized by vertical or very steep dipping surfaces (Fig. 2). Fractures dipping at moderate angles are less common and subhorizontal angles are virtually nonexistent. Those dipping at angles of 25–30° towards the NE, however, comprise the highest density on the fractures contour plot–main maximum. These are normal to the bedding and kathetal joints. The most common steeply dipping fractures on the contour and rose diagrams form two distinct sets. The first set is represented by joints striking in the same direction as the main maximum (NW–SE), but dipping much more steeply in the opposite direction (SW). These are perpendicular to the bedding. The second set is much more differentiated and generally formed by N–S features, with NE–SW strikes that usually dip steeply towards the E and ESE (Fig. 2). The three main sets of joints form an orthogonal system.

As is the case with fractures, steep and very steep faults predominate (Fig. 3). These mainly have N–S strikes and dip eastward. Most of them exhibit biphasic activity, with the normal sense of dip-slip displacement as the younger. They were originally formed as strike-slip or oblique-slip faults with a minor dip-slip component. Normal and strike-slip faults also dominate with only one generation of tectonic striation observed on fault planes. Normal faults of the same strike, but opposite dip direction, are far less frequent. These faults were most probably reactivated during W–E extension. Faults that were gently and moderately inclined towards the NNE, striking WNW–ESE, parallel with the bedding, were also identified. These were most probably formed during the flexural slip, connected with the thrusting processes in the N–S contraction. Normal faults perpendicular to the bedding, steeply dipping towards the SW, were documented too.

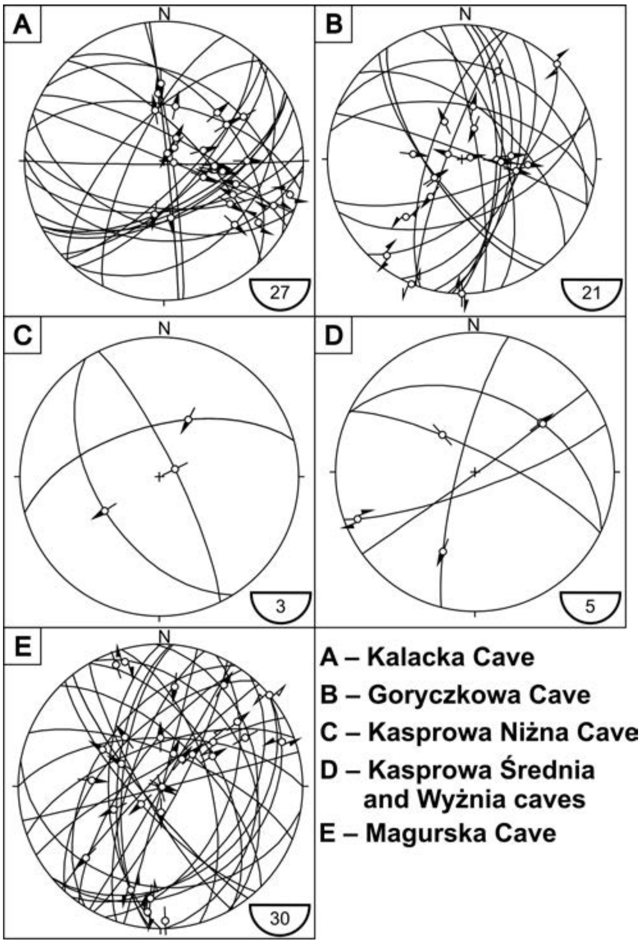

Fig. 3. Spatial orientation (Angelier diagrams) of meso-faults within selected caves in the Bystra Valley.

Kasprowa Niżna Cave

Kasprowa Niżna Cave was developed in the limestone of the Raptawicka Turnia Fm. Very steep W–E and WSW– ENE fractures, dipping towards the S and N, dominate (Fig. 2). These are represented by wide, smooth, straight surfaces, which often form distinct and very dense sets with 10-cm spacing intervals. They are usually accompanied by NW–SE striking fractures which jointly define rhomboidal systems. This sort of pattern is very common and was often found in the parts of the cave studied. Horizontal and moderately dipping fractures are very sparse, and do not generally form clearly separated sets.

Faults striking WNW–ESE and NNE–SSW form two main sets of faults in the cave (Fig. 3). These two groups of faults are characterized by very steep fault planes, a normal sense of displacement and up to 50 cm thick tectonic breccia zone. The sense of the relative displacements was determined on the basis of the low-angle synthetic Riedel shears (Riedel, 1929; Bartlett *et al.*, 1981) that were observed mainly in the hanging wall. Reverse faults were only observed occasionally, e.g. in the Chamber with the hanging lake.

Kasprowa Średnia Cave

Kasprowa Średnia Cave developed within the Raptawicka Turnia Fm. The lateral variability of the fractures on the contour diagram exhibits a rather uniform distribution (Fig. 2). Fractures striking WNW–ESE, dipping moderately towards the NNE, or more rarely, steeply towards the SSW, are the most common. However, steep and very steep fractures with a SW–NE strike occur almost as frequently. Steep fractures, oriented NW–SE, were also observed. Only three striated fault planes were observed (Fig. 3). The steep oblique-slip (normal-sinistral) dislocation, striking WNW–ESE and dipping towards the NNE, is probably of a higher rank. The other measured minor faults are most probably features that are related to the main fault zone and correspond to low-angle synthetic Riedel shears (Riedel, 1929; Bartlett *et al.*, 1981).

Kasprowa Wyżnia Cave

This cave developed within the limestone of the Raptawicka Turnia Fm. As is the case with Kasprowa Śnieżna Cave, which is situated higher, fractures striking NE–SW and ENE–WNW predominate and those oriented NW–SE and NNW–SSE are much less common (Fig. 2). The first set of fractures mainly dip steeply (about 60°) towards the SE, and rarely, very steeply towards the SE and NW. They are perpendicular to the main thrust direction and parallel to the wall orientation of the Zawrat Kasprowy Massif. This suggests their relaxing nature or at least later opening. Very steep fractures that strike NNE–SSW and NNW–SSE, dipping towards both directions, are also frequent.

Owing to the small size of Kasprowa Wyżnia Cave, only three faults on striated fault planes were observed and measured. Two are parallel to the conjugate N–S fracture sets (Fig. 3). The direction and sense of the relative displacements, which were recorded on the basis of observed striations and Riedel shears (Riedel, 1929; Bartlett *et al.*, 1981), seem to prove that they are complementary and formed under N–S contraction. The third is a vertical fault striking ENE–WSW, i.e. parallel to the main fracture set. Dextral oblique-slip displacement was confirmed on the basis of the orientation of the tectonic striations and the high density of the set of Riedel shears (spacing of up to 3 cm near the fault plane).

Magurska Cave

Magurska Cave was formed in Middle Triassic limestone and dolomite, Middle Jurassic limestone, and the limestone of the Raptawicka Turnia Fm. The variability of the spatial orientation of the fractures observed in the cave indicates a pronounced dominance of fractures dipping steeply and very steeply in an easterly direction (from the NE to the SE; Fig. 2). Only a small part of the data is located on the opposite side of the contour diagram, which shows fractures that are almost vertical and dip towards the W and NW. Steep fractures like these dominate the total fracture population. Fractures dipping at angles of more than 80° represent nearly 1/3 of all measured fracture surfaces. Joints striking NNE–SSW dominate inside the cave. These dip very steeply towards the W and E, and represent the main maximum on the statistical contour diagram (Fig. 2). There are also secondary joints striking NE–SW. These are most commonly steep and very steep, and dip towards the SE. These two sets were observed with a similar frequency from every observation point in the cave. They form relatively dense sets with spacing of a few centimetres and often produce wide, smooth straight surfaces. Fractures that do not form wide planes, strike between WNW–ESE and NNW–SSE, and mostly dip steeply towards the NE are much less common.

The variability of the spatial orientation of the observed faults is such that they strike in almost every direction, except W–E and NNW–SSE (Fig. 3). The most common features are near vertical, very steep (nearly 1/3 of all fault-slip data) and moderately dipping normal and oblique-slip faults with a normal sense of displacement of the dominant dip-slip component, and which strike 40–50°, 0–10° and 330–340°. No faults dipping at less than 20° were observed.

LOCAL TECTONICS FROM CAVE DATA *VS.* REGIONAL TECTONICS

Structural studies of the lower part of Bystra Valley are difficult, mainly because of the Quaternary sediments that cover most of the valley bottom and slopes, but also because of the poor preservation of slickensides in the carbonate rocks. Mesozoic rocks can almost only be observed *in situ* on cliffs. In caves, however, tectonic structures are well preserved and more clearly exposed as a result of having been dissected and eroded by water flow. This makes caves “good outcrops” for structural studies.

Comparing the fracture networks of the five domains (Kasprowa Wyżnia and Średnia are treated as a single domain) gives qualitatively similar results. From the Kopa Magura to the Kalacka Turnia massifs, NW- and SE-striking fractures dominate, as do N- and ENE-striking fractures, albeit to a much smaller extent.

A comparison of the observed faults in these domains (Fig. 4) reveals a more diverse result. From the Kopa Magura to the Myślenickie Turnie massifs, the dominant faults trend NNE–SSW and WNW–ESE, and slightly less commonly, NW–SE. These directions differ significantly from those in Kalacka Cave, where the predominant faults trend NW–SE and are sub-parallel. Faults also trend other directions in Kalacka Cave, but there are no NNE–SSW dislocations prevailing on the eastern side of the valley.

All the caves investigated are located in a series of folds in the Giewont Unit, which has a uniform style of folding (Rabowski, 1959; Kotański, 1961; Grodzicki and Kardaś, 1989). The differences in the fault strike directions on the two sides of the valley between the Kalacka Turnia and Myślenickie Turnie massifs may confirm the presence of a fault at the bottom of the Bystra Valley (Fig. 4). This thesis has already been postulated by Goetel and Sokołowski (1930) but should be verified by targeted research in caves and on the surface on both sides of the valley. The bottom of the valley is covered by Quaternary sediments, which prevent direct verification.

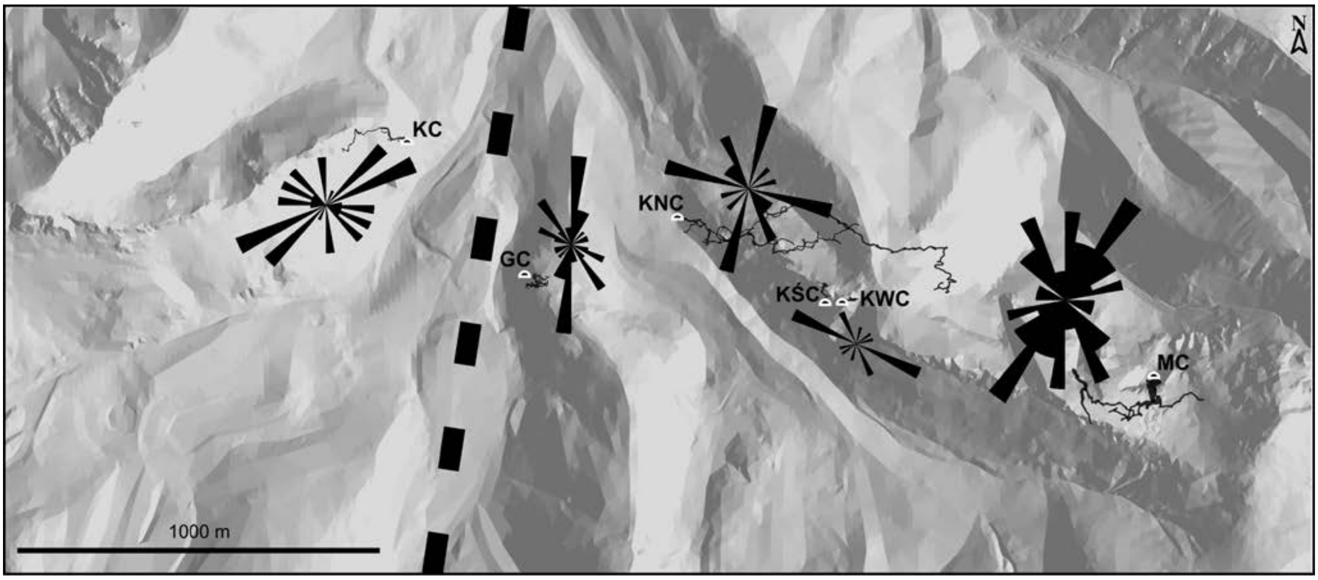

Fig. 4. Shaded digital elevation model of the Bystra Valley including caves studied; rosette diagram shows the strike of faults documented in individual caves with the exception of Kasprowa Wyżnia and Średnia, for which one diagram was made; dotted black line indicates a potential course of the fault in bottom of valley.

RELATIONSHIP BETWEEN TECTONICS AND CAVE DEVELOPMENT

Structural guidance for cave patterns

Most passages in Kalacka Cave were formed on W–E and NE–SW faults (Fig. 5A). Despite the paucity of N–S structures, however, some parts of the cave are oriented N–S. There are also gently dipping W–E structures. It is therefore probable that the water flowed in the dip direction of gently inclined faults and that the passage directions are related to steep fractures. Most of the guiding faults originated at the extension stage, or were initiated at an older compression stage (Pannonian or older; Vojtko *et al.*, 2010; Králiková *et al.,* 2014) and rejuvenated at the extension stage (late Miocene–recent; Burchart, 1972; Vojtko *et al.*, 2010; Králiková *et al.,* 2014). They are manifested by steep normal faults.

Three WNW–ESE main conduits and many linked N–S and NE–SW passages can be observed in the plan view of Goryczkowa Cave (Fig. 5B). Northern and southern conduits oriented WNW–ESE are guided by faults over long distances. The conduit at the middle of the cave is strictly related to the strike of the bedding and the master joints (NW–SE). The passages linking these three conduits were guided by joints and minor faults. The main hall (Fig. 5) is probably the bottom of an “hourglass-shaped” sinkhole, which is located in this area because of the high density of the fault network.

The cave pattern is a 3-D anastomotic maze. It is difficult to say which structures are especially favourable for karstification, as most of the fractures and faults have a similar strike (Figs 2, 3). The passages are clearly oriented along the discontinuities, but nowhere in the cave tectonic features dominate over dissolution ones. The morphology is mostly palaeophreatic. Breakdowns are purely local and just in the main chamber could be correlated with neotectonic movements.

The pattern of Kasprowa Niżna Cave is strongly related to discontinuities. Extensional fault zones with breccia and dense Riedel shears (Fig. 6E) represent guiding structures, characterizing the most common passages oriented WNW–ESE (Fig. 7A) and providing pathways for water migration. Short, but regular conduits orientated NNE–SSW are guided by steep faults throughout the cave. Importantly, these faults were formed under N–S contraction, as were the faults in the short passages in Goryczkowa Cave. Other passages are guided mainly by joints.

In Kasprowa Średnia Cave, the main chamber and the passage leading to the bottom are guided by a steep extensional fault that strikes WNW–ESE and dips towards the NNE. The passages in the upper part are related to joints (Fig. 7B). There are no vadose features in the cave; even the shaft is ellipsoidal in cross-section. This suggests that this cave could be a relic of the palaeophreatic level, which was dissected by glacial erosion.

The passages leading to the main chamber of Kasprowa Wyżnia Cave are guided by W–E joints. The main chamber was developed on the base of conjugate normal faults (Fig. 7B). The most important of these is a vertical NW–SE fault with many accompanying X shears (*sensu* Riedel–Skempton shears; Bartlett *et al.*, 1981). On the east side of the chamber, there is a fault striking perpendicular to the elongation of the hall. This fault might have been a barrier to karstification, as the chamber is much smaller on its eastern side.

Magurska Cave, as demonstrated by Hercman (1989), is located in the hinge zone of a chevron anticline. The strata here therefore have been subjected to specific deformation. Within folded rocks, the highest compression zone (located closer to the core) and the local extension zone (located in the outer zone) can be distinguished. These zones are separated by a neutral surface (Ramsay and Huber, 1987). In the hinge zone, more structures have been formed and the bedding partings have been opened to guide water migration

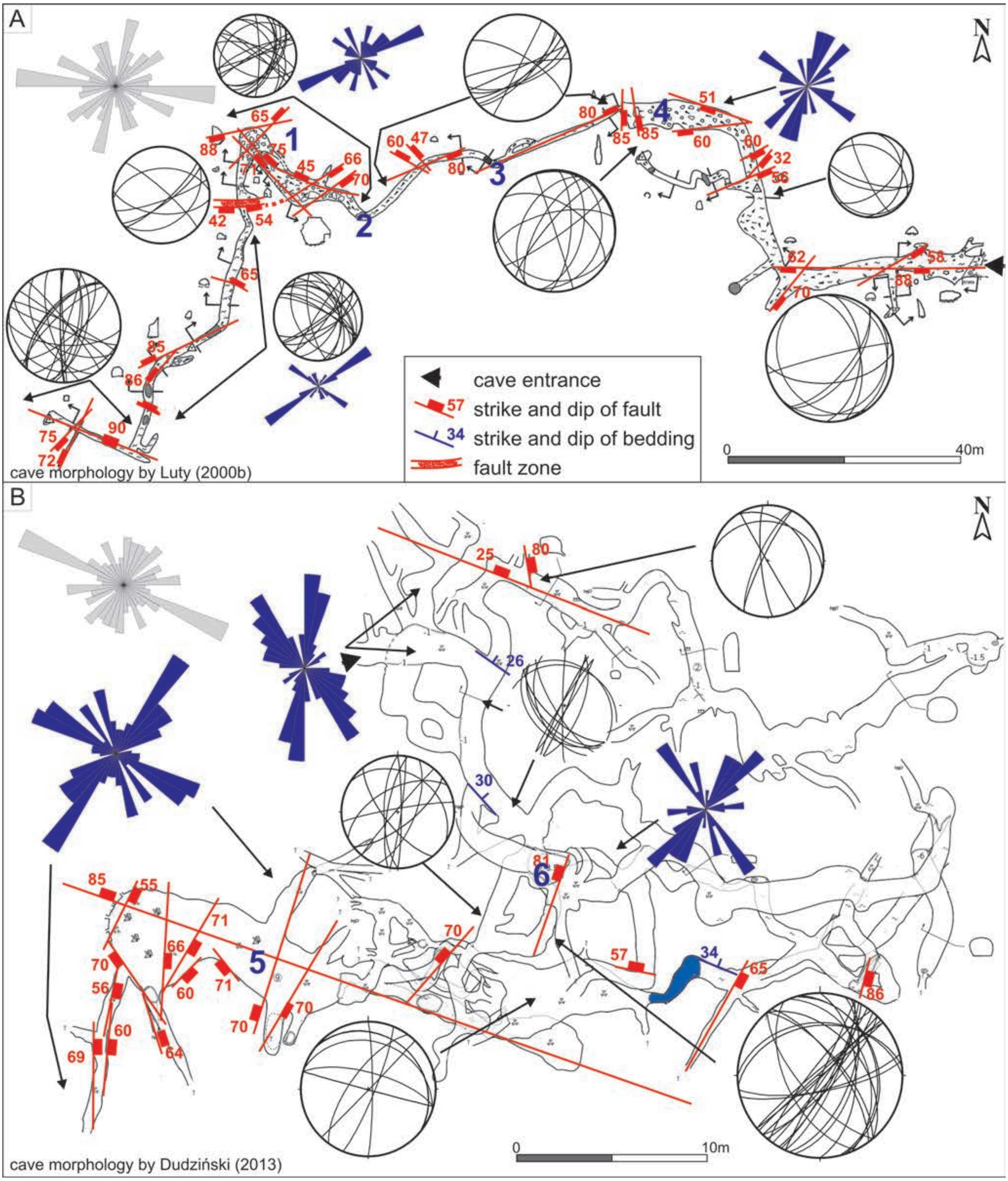

Fig. 5. Structural measurements in Kalacka and Goryczkowa Caves. **A.** Kalacka Cave. **B.** Goryczkowa Cave; blue rosette diagrams show the strike of fractures (joints) at the measurement stations; great circles represent lower-hemisphere stereographic projection of fractures; gray rosette diagram shows the conduit direction weighted by their length; 1 – Za Przekopem Chamber; 2 – Sump 2; 3 – Sump 1; 4 – Rozsunięta Chamber; 5 – Main Chamber; 6 – fault younger then passage (Fig. 6C).

(Hercman, 1989). The location of the Wstępna Chamber (Fig. 8), one of the largest rooms in the Tatra caves, in the hinge zone of this chevron fold, confirms the assertion by Szczygieł (2013), regarding the relationship between the fold geometry and the development of voluminous karstic voids. The Wstępna Chamber in Magurska Cave has evolved mainly as a result of breakdowns, probably from a network of palaeophreatic galleries. The chambers described by Szczygieł (2013) in other caves in the Tatra Mts. developed in vadose conditions. The development of analogous forms in similar geological settings, although from the original palaeophreatic morphologies, additionally may confirm Szczygieł's (2013) conclusion that "Large chambers have been formed in the hinge zones of the chevron folds (...). The relatively large concentration of deformation over small vertical distances induces the development of forms with similar horizontal and vertical dimensions (…)".

Magurska Cave passages are guided by faults and fractures oriented N–S, NE–SW and NNW–SSE. The diagrams of the passage directions (Fig. 8) are clearly correlated with the fault network diagrams (Fig. 3). This testifies to a strong relationship between cave development and tectonic structures. The palaeophreatic morphology of these passages has been obliterated by breakdowns, due to a dense network of discontinuities (Fig. 6F). It is also possible that palaeophreatic morphology did not develop, because the fragile walls and ceiling were partly eroded by water flux. Hercman (1986) and Kicińska (2002) identified two palaeoflow directions in Magurska Cave. Moreover, their velocities and discharges were higher than those in the phreatic zone in the Bystra Valley. Magurska Cave is one of the oldest known caves in the Tatra Mts. (Hercman, 1991). This may indicate that the disintegrated rocks were mechanically eroded, and that the cave evolved over a long period after it had dried-out. It is also highly likely that the original shape of the cave has been remodelled by breakdowns and the flooding that occurred during the later phases of deglaciation. The W–E sections of the cave developed in relation to bedding planes, as well as partly tectonic contacts between the formations (thin-bedded limestone and dolomite of the Middle Triassic, crinoidal limestone of the Middle Jurassic, and massive limestone of the Upper Jurassic; Fig. 8).

Neotectonic phenomena vs. cave morphology

The influence of neotectonic processes on the morphology of Magurska and Kalacka caves already was studied by Wójcik and Zwoliński (1959). The observations of these authors are re-examined here. Wójcik and Zwoliński (1959) describe a 3-m displacement in the western end of the Rozsunięta Chamber (Fig. 5A) in Kalacka Cave. Indeed, there is a fault zone 1.5–2 m thick, where two stages of deformation can be observed. The older striations indicate dextral reverse-oblique-slip movement, while the younger features suggest sinistral reverse-oblique-slip, as evidenced by R shears. This is contrary to the conclusions of Wójcik and Zwoliński (1959), *viz*. that the western limb moved northward and upward. There are no signs of fault deformation in the passage behind the Rozsunięta Chamber. This indicates that a movement of 3 m after the cave had developed, as proposed by these authors, was impossible.

Wójcik and Zwoliński (1959) also described a horst that developed after the formation of the cave in the Za Przekopem Chamber of Kalacka Cave. The present study documents six steep meso-faults with clear fault planes and striations in this part of the cave. There are two faults parallel to the longer axis of the chamber, NW–SE (Fig. 6A). Two generations of striations were documented on the surface of one of these faults. This indicates at least two phases of activity: an older sinistral reverse-oblique-slip and a younger dextral normal-oblique-slip (Fig. 6A). The other faults are more or less perpendicular (NW–SE) or diagonal to the chamber elongation (Fig. 5). These are normal or oblique-slip faults with a normal dip-slip component. This proves the existence of the horst, although not exactly as Wójcik and Zwoliński (1959) described it. Moreover, these authors did not mention anything about faults that appear to be younger structures (preservation of striations, no mineralized steps) running parallel to the chamber. Indeed, this strongly deformed zone did not have any dissolution features on the walls. Despite this, the passages in front of and behind the chamber are palaeophreatic conduits. The water flowing into this area might have encountered so many possibilities for flow directions that the flow spread through the fissures and focused again behind the fault zones. As for inflow, the "barrier", in the form of a fault zone, where the water had to flow along by a network of fissures, may indicate an increase in palaeoflow velocity in the Za Przekopem Chamber, with inflow ranging from 5.55 (±3.06) to 10.58 (±7.31) and 18.83 (±5.98) and changes to outflow from the chamber at 6.16 (±2.63) and further 3.96 (±2.6; the speed in cms^{-1}; see Kicińska, 2002). Wójcik and Zwoliński (1959) argued that the presence of a neotectonic displacement is supported by the lack of phreatic morphological features in the chamber. This can also be explained by the mechanical disintegration of rock fractured by fault zones during periods of cave flooding and breakdowns during dry periods. It has to be noted that dry periods correspond with glacial periods (Hercman, 1991, 2000; Kicińska, 2002), when frost enhanced the breakdown of cave walls and ceilings. The dissolution morphology could not be preserved in these conditions, nor perhaps could it be developed. This is because new surfaces were subjected to dissolution after further breakdowns. The present study concludes that the Za Przekopem Chamber, including the horst described by Wójcik and Zwoliński (1959), is strongly dislocated. The displacement along the fault surfaces noted, however, occurred before the cave was formed. Wójcik and Zwoliński (1959) further described two neotectonic faults that are similarly interpreted here. The first is located in the Rozsunięta Chamber and dips toward the S with a normal-slip displacement of ~15 cm (Fig. 6D). The second used a guiding fracture in the passage between the Rozsunięta Chamber and Sump I. This movement is also normal-slip with a displacement of ~5 cm. Two other faults, not reported by Wójcik and Zwoliński (1959; Fig. 5), were observed between Sumps I and II. The first is parallel to that previously described and is guided by a fracture plane. The second is perpendicular to the passage and is located in the area, where the cross-section of the passage changes from a high fissure to an elongated horizontal ellipse. A high corridor, showing visible relicts of palaeophreatic pipes, has developed along the W–E faults. Phreatic features may have developed during an older phreatic phase of cave formation (Kicińska, 2002). Displacement then occurred. During the younger phreatic stage of the cave (Kicińska, 2002), water from glaciers migrated along the already gaping fissures and remodelled the passages into a more slotted morphology. Where the fault is eroded, the water flowed through palaeophreatic pipes.

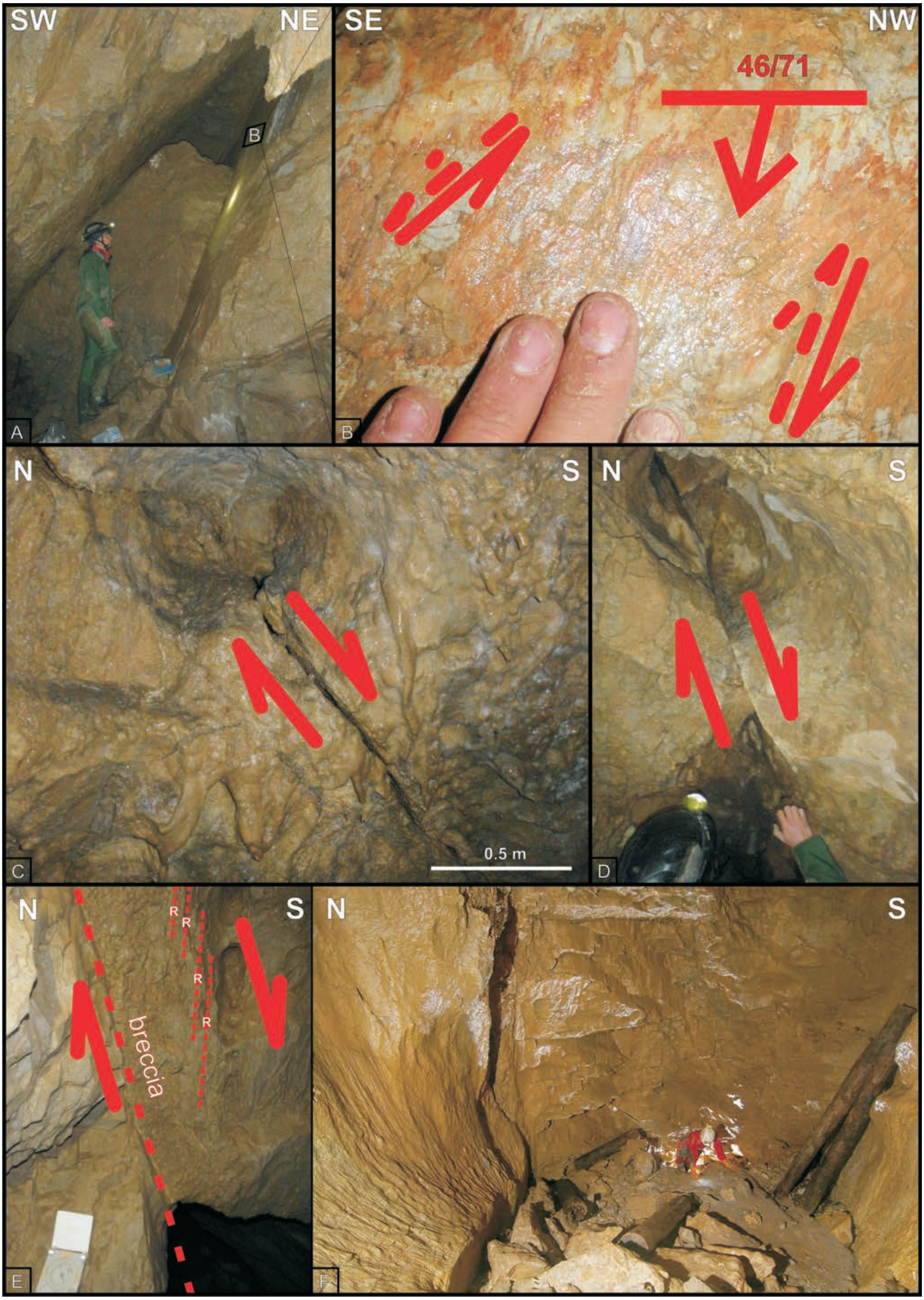
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Fig. 6. Selected tectonic features from caves studied in the Bystra Valley, Tatra Mts. **A.** Two steep fault planes parallel to the chamber elongation; NW part of Za Przekopem Chamber, Kalacka Cave; **B.** Slickenside with two generations of striation; NW part of Za Przekopem Chamber, Kalacka Cave; **C.** Visible 4-cm displacement caused by meso-fault younger than passage; Goryczkowa Cave, location of photography on Fig. 5B; **D.** Clearly seen ~15-cm displacement generated by meso-fault younger than passage; Kalacka Cave, Rozsunięta Chamber; **E.** 10–50 cm normal fault zone with breccia and R shears, proving its normal displacement; Kasprowa Niżna Cave, location of photograph on Fig. 8A; **F.** Palaeophreatic conduit with undamaged scallops on the bedrock wall, and "non-karstic" morphology of the wall in fault zone; Przekop z Belkami, Magurska Cave; photo. A–E by J. Szczygieł, F by J. Nowak.

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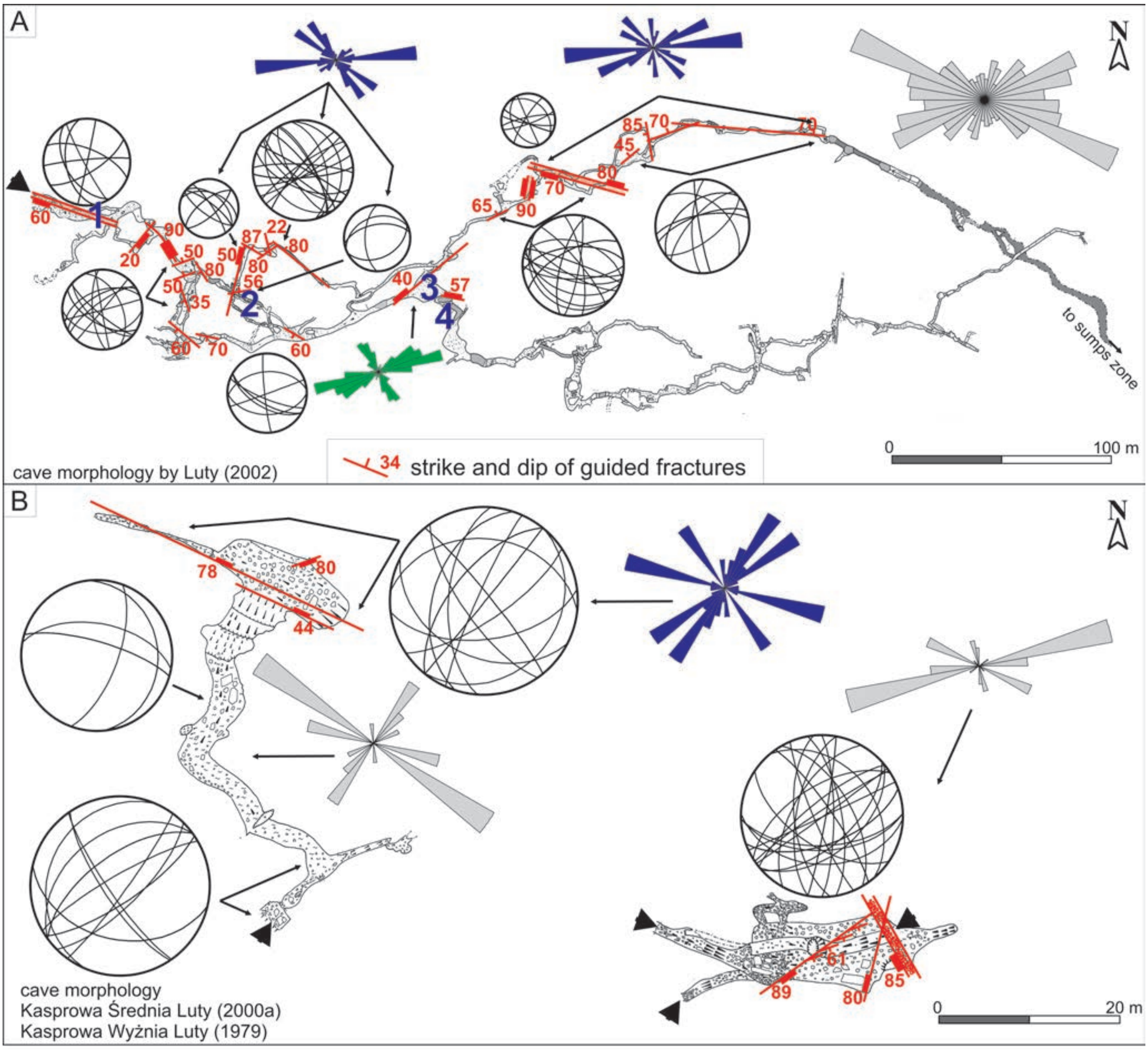

Fig. 7. Structural measurements in Kasprowa Cave. **A.** Kasprowa Niżnia Cave, **B.** Kasprowa Średnia Cave and Kasprowa Wyżnia Cave; green rosette diagram shows the strike of fractures and faults in Rycerska Chamber; 1 – Fault with breccia (Fig. 6E); 2 – Gąbczaste Passages; 3 – Rycerska Chamber; 4 – chamber with hanging lake; unexplained symbols as in Fig. 5.

There is so far no report of displacement, younger than the passages in Goryczkowa Cave. During the field studies, however, these sorts of neotectonic displacements were identified at four observation points, all in the southern part of the cave. In three cases, the movement occurred along faults striking NE–SW, and in one, WNW–ESE. All the faults are characterized by steep surfaces and 4 cm displacements, often combined with a 2–3 cm gap (Fig. 6C). All these neotectonic displacements are re-activated faults guided by fissures. Morphologically, only a small displace-

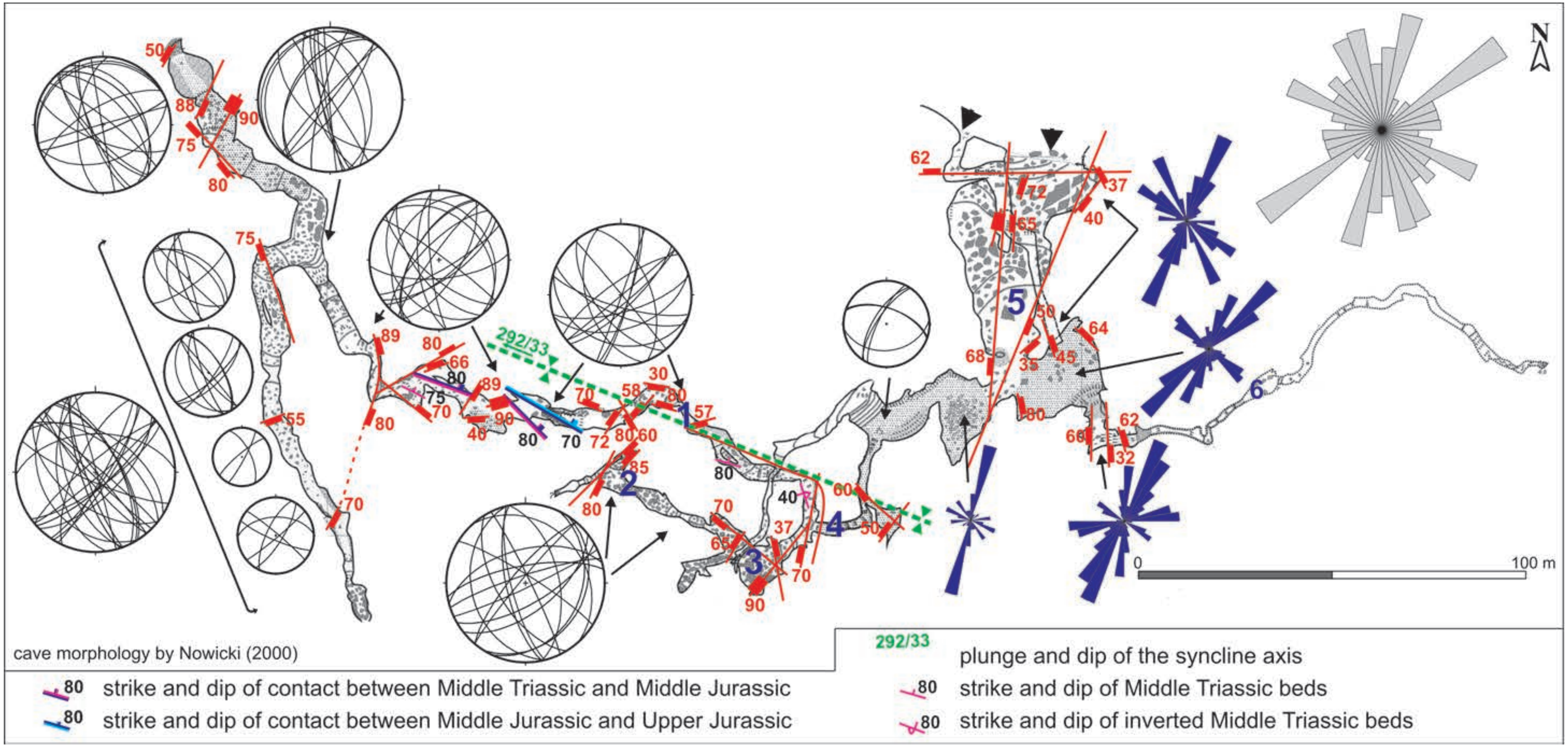

Fig. 8. Structural measurements in Magurska Cave; 1 – Przekop z Belkami; 2 – Dolna Chamber; 3 – Złomisk Chamber; 4 – Ślizgawka; 5 – inner Chamber; 6 – Stalaktytowy Passage; unexplained symbols as in Fig. 5.

ment is visible in the passage cross-section; there are no R shears or breakdowns. Normal faults dipping toward the NW and the NNE run parallel to the slopes. Their activity can therefore be associated with relaxation or gravitational processes.

Wójcik and Zwoliński's (1959) interpretation of neotectonic displacements from Magurska Cave has also been re-examined. The authors described a number of neotectonic displacements to the west, which were "younger than the cave passages and having a decisive influence on its morphology". Wójcik and Zwoliński (1959) defined the slip of the fault on the NW wall of the Dolna Chamber as sinistral, assigned it a strike-slip value of ~10 m, and correlated it with the dislocation at the Przekop z Belkami site. Hercman (1989) confirmed the slip of the fault by displacement of lithostratigraphic formations. The present study found that striations, steps and Riedel shears indicated sinistral movement. These sorts of movements were not found at the Przekop z Belkami site (Fig. 6F), which is 15 m in a straight line from the Dolna Chamber (Fig. 8).Wójcik and Zwoliński (1959) also marked the neotectonic displacements in the Złomisk Chamber and the Ślizgawka site (Fig. 8) on the plan of Magurska Cave. These dislocations, however, are not described in the text, which makes discussion of them impossible. No displacements younger than the passages in this part of the cave were recorded during the field studies for the present research. Hercman (1991) dated the speleothems from the passages between the Dolna and the Złomisk chambers (Fig. 8). These had grown on breakdown gravel over the past 60 ka. These sediments, however, are not unequivocal evidence, as gravity breakdowns often occur, especially near inactive fault zones. These data indicate the minimum age of the collapse, but give no indication of what caused it. A displacement visible in the cross section of a conduit, such as that described by Wójcik and Zwoliński (1959) in the Stalaktytowy Passage in Magurska Cave, is proof of movements younger than the cave passages. Similar displacements have been observed in other caves in the Tatra Mts. (e.g. Szczygieł, 2012). The slip amplitude of these movements is about 10–30 cm. A similar displacement has been described in Hirschgruben Cave in the Eastern Alps (Plan *et al.*, 2010), where a slip of ~25 cm was dated as from the last glacial cycle. This dislocation was correlated with the activity of one of the main faults in the SEMP Fault System in the Alps. Wójcik and Zwoliński (1959), however, described a number of displacements younger than the cave passages with slips of 3–4 m and even 10 m. The origin of such displacements, especially in mountains, is movement inside deep landslides (*e.g.* Baron *et al.*, 2013). Although a landslide was documented in the upper part of the Bystra Valley (Wójcik *et al.*, 2013), there is no indication for its impact on the caves. Another explanation is that these displacements took place along the currently active faults as a result of earthquakes (e.g., Kao and Chenw, 2000). However, such strong earthquakes would have led to the complete collapse of the cave. The marks left by an historical earthquake with an estimated magnitude of 6.9 in a cave, situated 3–4 km from the earthquake fault line, have been studied by Becker *et al.* (2011). The changes to caves that result from earthquakes are broken or inclined speleothems and breakdowns. There was no wall movement, even though the cave was formed along a related thrust.

On the other hand, it can be assumed that the displacement did not result from such events, but occurred during long-term microtectonic displacements. By way of analogy, recent measurements of microtectonical displacements show an average rate of movement of 0.03–0.07 mm/year in the Carpathians (Briestenský *et al.*, 2011) and in the much more tectonically active Dinaric Alps (Šebala *et al.*, 2010). A displacement of 10 m would take 200 ka. Theoretically, this displacement would be possible in relation to the entire history of the cave. However, brittle faults of such dimensions are formed as a result of tectonic events.

These analogous examples from the caves (Plan *et al.*, 2010; Becker *et al.*, 2011; Szczygieł, 2012) indicate that some faults in the Bystra Valley were active during the Quaternary and have left their mark in the caves. However, these are not the 3–10 m displacements described by Wójcik and Zwoliński (1959), but are much smaller (~5–30 cm).

In the Bystra Valley, displacement younger than cave passages occurred along pre-existing faults or fractures oriented more or less parallel to the ridges, but the dip direction is not always the same as that of the nearest slope. Such faults only occur in caves above the bottom of the valley. This fact, together with the regularity in the orientation of such faults, can prove that the mechanism of displacement younger than caves is gravity faulting, due to relaxation after deglaciation and/or valley deepening.

CONDITIONS OF SPELEOGENESIS

All the caves studied were established during phreatic or epiphreatic conditions and their subsequent transition to the vadose zone. In similar cases (e.g. Filliponi *et al.*, 2009), inception horizons (Lowe and Gunn, 1997) are presumed to be the main factor responsible for the geometry of phreatic passages. According to the authors mentioned above, inception horizons are "especially favourable to karstification by virtue of physical, lithological or chemical deviation from the predominant carbonate facies". Although these detailed lithological analyses have not been the focus of the present study, any relationship between cave passage patterns and lithology, *sensu* Lowe and Gunn (1997), can be ruled out in the Bystra Valley, since the cave passages are mostly guided by structural discontinuities and only rarely by bedding planes. Even in Magurska Cave, where two lithological contacts are present, the passages are oriented obliquely to them (Hercman, 1989). Conduit development was therefore initiated along tectonic discontinuities, not with respect to lithological differences, as is evidenced by field observation of the caves, especially given that the vast majority of the "guiding faults" were created or rejuvenated in an extension regime during the uplift (Vojtko *et al.*, 2010; Králiková *et al.,* 2014). The key issue is that extension can open a tectonic void, large enough to allow turbulent flow, thereby promoting the development of conduits along specific pathways (0.005–0.01 cm; see Palmer, 1991). This process of initiating phreatic conduits along tectonic fissures is called tectonic inception (Faulkner, 2006). A similar situation was described by Sauro *et al.* (2013) for the caves in the Dolomites, where "the tectonic inception features of the karst system started to open, when the Piani Eterni area was uplifted during the middle-late Miocene". The karst processes probably began in the Pliocene Epoch. If so, then the proto-conduit network of at least the higher levels in the caves was developed before the Quaternary Period. It is noteworthy that Hercman (1991) postulated that the conduits of Magurska Cave were initiated during the Pliocene Epoch.

The phreatic conditions of cave development in the Bystra Valley and their high dependence on tectonics support using a model that takes these factors into account. The four-stage model is a model of cave origins in phreatic conditions that can determine cave patterns in the dimensions of length and depth related to fissure frequency (Ford and Ewers, 1978). When fissure frequency is low, deep phreatic loops evolve (stage 1). When it is high, caves develop along the water table (stage 4). Stages 2 and 3 are intermediate cases. As for the caves in the Tatra Mts., the stage 2 phreatic loops in Czarna Cave (Gradziński and Kicińska, 2002) and the stage 3 ones in Miętusia Wyżnia Cave (Fryś *et al.*, 2006) have been documented for the four-stage model (Ford and Ewers, 1978). A dense network of discontinuity sets that had a significant impact on their development was identified in the caves studied. The relatively small denivelation of the caves (19–59 m) and the dense network of initial fissures may indicate that some of the studied caves could have been formed in stage 3 of the model (Ford and Ewers, 1978). This means that separation within one cave of more than one cave level corresponding to the water table, as suggested by Wójcik (1968) with reference to Swinnerton (1932), is unlikely. However, not all caves were developed in phreatic conditions. For example, Kasprowa Niżna Cave, which is still active and periodically flooded, and the Gąbczaste Passages meet the definition of soutirages (Häuselmann *et al.*, 2003). This indicates that epiphreatic conditions caused the development of Kasprowa Niżna Cave. Bystra Cave also developed partly under phreatic and partly under epiphreatic conditions. This may indicate that other caves developed (at least partially) under epiphreatic conditions. According to Audra and Palmer (2013), "Many epiphreatic passages, which form above the low-flow water table under hydraulic pressure, also have irregular profiles with high-amplitude loops". The passage morphology in those two zones is generally similar. Nevertheless, Palmer (1991) suggests that "flood water can form angular networks in fractured rock, anastomotic mazes along low-angle partings, or sponge- work where intergranular pores are dominant". Through the research in Alpine multilevel cave systems, it was shown that the simultaneous development of different stages (four-stage model) and epiphreatic passages is possible at the same cave level (Plan *et al.*, 2009). Moreover, recent studies have shown a strong relationship between the vertical organization of karst conduit networks, base-level changes and recharge variations (Gabrovšek *et al.*, 2014).

From the above findings, it follows that there are no loops or anastomoses in the pattern of Kalacka Cave; the cave is a low-amplitude single passage. Since the recharge area was located 2–3 km away on the Giewont Massif and the E slopes of Kopa Kondracka (Fig. 1), the flux probably reached a water table far from the spring, so that near the spring water migrated under phreatic conditions. Goryczkowa Cave has a 3-D anastomotic maze pattern. The hydraulic gradient was almost the same as in Kalacka Cave, but the distance between the recharge area (Sucha Woda Valley) and the cave was shorter (1–1.5 km; Fig. 1). This means that descending water may not have reached the water table before outflow, or reached this level close to the spring, where the epiphreatic zone is thicker. The oldest cave level in the Bystra Valley includes Magurska, Kasprowa Wyżnia and Średnia caves. Hercman (1991) considers that this level was initiated at the Pliocene, *i.e.* before glaciations when the geomorphology was gentle and hydraulic gradients were smaller. Moreover, palaeoflow direction in Magurska Cave was from the bottom to the entrance, *i.e.* slightly upward, during the initial phase. There are two loops in the cave, with denivelations of 15 m and 35 m. This may indicate that Magurska Cave developed under phreatic conditions. However, the cave has been remodelled since then by a few processes, so it is hard to be sure.

Plan *et al.* (2009) suggest that "(...) the change of preferred conduit directions at different levels indicates the flow direction that initial fissures or have changed over time. This latter could be explained by a change of the stress fields due to the ongoing Alpine deformation". It follows that these variations in hydrological conditions and cave patterns could result from exposure of the bedrock to relaxation of the massif. The phreatic zone is located below the bottom of the valleys. The effect of stress on the rock mass is therefore related to the regional stress field, or the individual relaxational faults extended under the valley bottom (Fig. 9B). Thus, only individual structures allow the migration of water (Fig. 9C). The flow is focused and the single conduit is becoming enlarged. The epiphreatic zone is above the valley bottom, where local extensions, caused by the relaxation of the massif, are more intense (Fig. 9B). Hence, more fractures are sufficiently extended to allow flow. A maze could be forming as flood water migrates along a network of fissures (Fig. 9C). The cave systems were formed during stable periods, when the rate of erosion was higher than the rate of uplift. In the Bystra Valley three stable periods, related to the cave levels developed under partly phreatic and partly epiphreatic conditions, can be observed. Periods of simultaneously faster uplifting and valley deepening followed. This resulted in a transition of cave passages to the vadose zone (Fig. 9E). During this uplift, some faults were reactivated and some new ones appeared (Fig. 9E). Most probably, the results of this loosening were displacements of up to 15 cm in already dried-out passages and openings of new fissures that allowed new conduits to develop under the water table and in the epiphreatic zone (Fig. 9E, F).

CONCLUSIONS

The cave pattern is strongly controlled by tectonic features, mainly faults and related fractures that originated, or were rejuvenated during extension from the Late Miocene onwards (Burchart, 1972; Jurewicz, 2005). The hydrogeological conditions that determine flow directions seem to be

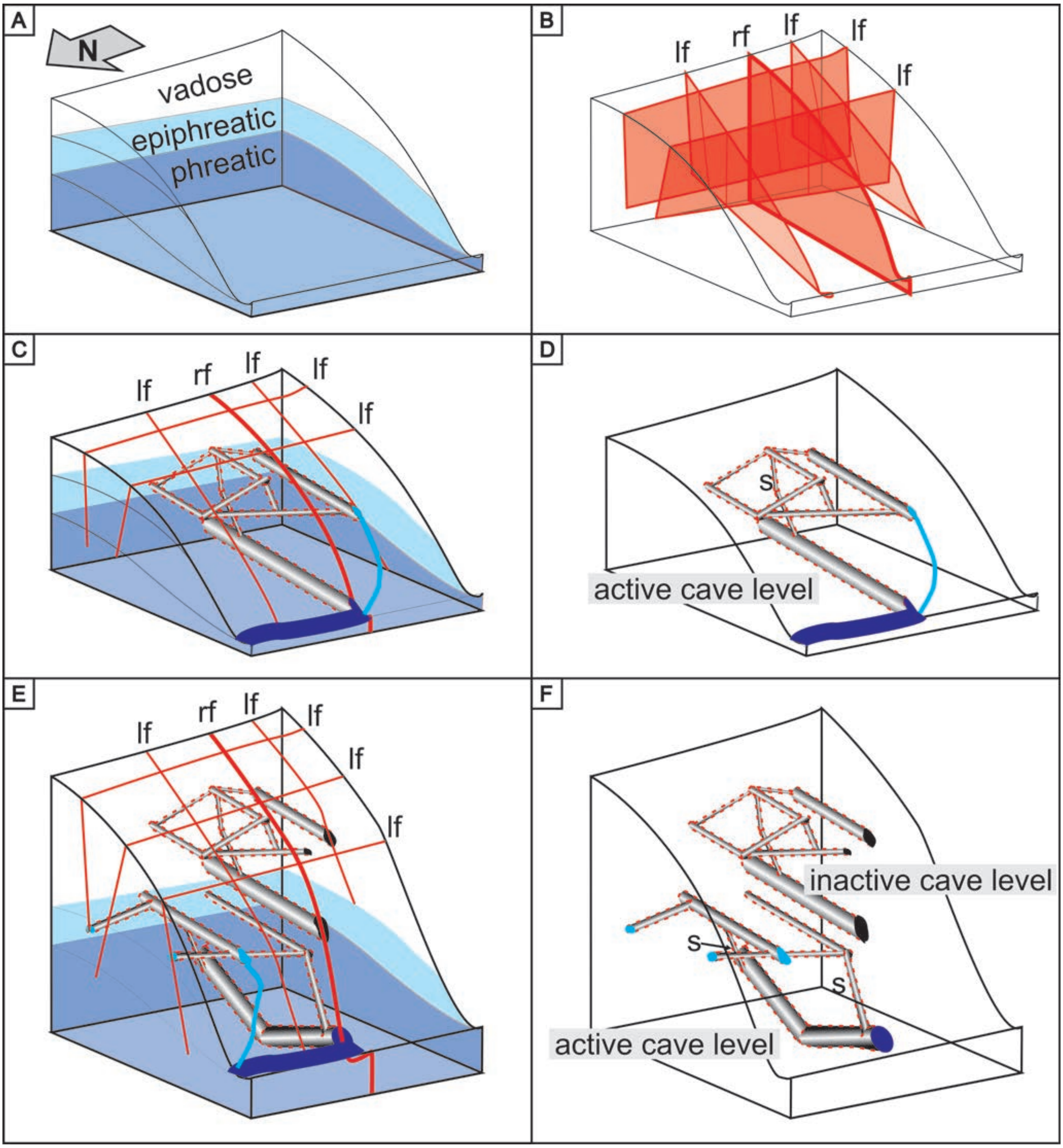

Fig. 9. Simplified schematic of cave development and its dependence on the neotectonic and morphotectonic processes in the Bystra Valley; **A.** Hydrogeological conditions, **B.** Tectonic setting, **C** and **E**. Development of cave conduit along initial fissures, **D** and **F**. Cave pattern at earlier (D) and later (F) stage of cave development in Bystra Valley; dark blue – phreatic zone; light blue – epiphreatic zone; rf – fault extended under the valley bottom, owing to regional stress; lf – fault extended, owing to relaxation of the massif; s – soutirages *sensu* Häuselmann *et al.* (2003).

equally significant, as they cause water to flow at a slight angle, even in vertical fissures. This does not change the fact that corrosive water flowed along tectonic structures during phreatic and/or epiphreatic conditions and that these proto-conduits were formed by "tectonic inception". The tectonic structures favoured by inception were mainly faults and in few local cases combinations of bedding and joints.

Neotectonic features, identified in the caves as being younger than the passages, are characterized by relatively small displacements (up to 15 cm) and did not have any significant impact on cave morphology. No breakdowns or highly fractured zones occur in the areas of neotectonic faults. It is the authors' opinion that faults with displacements of several meters were mistakenly interpreted by Wójcik and

Zwoliński (1959) as being younger than the caves. Given the present state of knowledge and armed with the results of this study, these faults should now be classified as older structures, the surfaces of which have been commandeered and exposed by speleogenesis. The presence of neotectonic faults with greater displacements has not been excluded, but they would have had a much greater impact on morphology than the observed features.

There are three cave levels in the Bystra valley: (1) the youngest and currently active caves, including Kasprowa Niżnia and Bystra caves, which are developing partly under phreatic and partly under epiphreatic conditions; (2) the middle and inactive caves, including Kalacka Cave, which developed under phreatic conditions in stage 3 of the four-stage model (Ford and Ewers, 1978) and Goryczkowa Caves, which developed under epiphreatic conditions; and (3) the oldest and inactive caves, including Magurska, Kasprowa Wyżnia and Średnia caves, which most probably developed in stage 3 of the four-stage model (Ford and Ewers, 1978).

Differences in cave pattern between the phreatic and epiphreatic zones in a given cave level could have resulted from exposure of the bedrock to relaxation of the massif. The phreatic zone is located below the bottom of the valleys. Hence the effect of stress on the rock mass is related to the regional stress field, or to individual relaxational faults extended under the valley bottom. Thus, only individual structures allow the migration of water. The flow is focused and the single conduit is becoming enlarged. The epiphreatic zone is above the valley bottom, where local extensions caused by the relaxation of the massif are more intense. Hence, more fractures are sufficiently extended to allow flow. A maze could be forming as flood water migrates along a network of fissures.

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