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Quaternary faulting in the Tatra Mountains, evidence from cave morphology and fault-slip analysis

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Abstract: Tectonically deformed cave passages in the Tatra Mts (Central Western Carpathians) indicate some fault activity during the Quaternary. Displacements occur in the youngest passages of the caves indicating (based on previous U-series dating of speleothems) an Eemian or younger age for those faults, and so one tectonic stage. On the basis of stress analysis and geomorphological observations, two different mechanisms are proposed as responsible for the development of these displacements. The first mechanism concerns faults that are located above the valley bottom and at a short distance from the surface, with fault planes oriented sub-parallel to the slopes. The radial, horizontal extension and vertical σ_1 which is identical with gravity, indicate that these faults are the result of gravity sliding probably caused by relaxation after incision of valleys, and not directly from tectonic activity. The second mechanism is tilting of the Tatra Mts. The faults operated under WNW-ESE oriented extension with σ_1 plunging steeply toward the west. Such a stress field led to normal dip-slip or oblique-slip displacements. The faults are located under the valley bottom and/or opposite or oblique to the slopes. The process involved the pre-existing weakest planes in the rock complex: (i) in massive limestone mostly faults and fractures, (ii) in thin-bedded limestone mostly inter-bedding planes. Thin-bedded limestones dipping steeply to the south are of particular interest. Tilting toward the N caused the hanging walls to move under the massif and not toward the valley, proving that the cause of these movements was tectonic activity and not gravity.

Key words: neotectonics, Quaternary faults, stress tensor, uplift, cave, Tatra Mts, Western Carpathians.

Introduction

The Tatra Mts form the northernmost part of the Central Western Carpathians and belong to the Tatric–Fatric–Veporic nappe system (Plašienka 2003). The Tatra Mts are composed of a Paleozoic crystalline basement which is overlain by Mesozoic sedimentary rocks to the north and west (Nemčok et al. 1994; Fig. 1). The sedimentary cover consists of the Tatric ("autochthonous" sedimentary cover, Czerwone Wierchy Nappe, Giewont Nappe, Široká Nappe), Fatric (Krížna Nappe) and Hronic units (Choč Nappe — Nemčok et al. 1994). In the north central part of the Tatra Mts, in the Bystra Valley and so-called Czerwone Wierchy massif (Fig. 1b), the Tatric units are exposed for karstification. Most of the caves in the Tatra Mts are located here, including the deepest and one of the longest caves.

Quaternary tectonics in the Tatra Mts have been investigated but previous research was based mostly on remote sensing (e.g. Perski 2008), or on fault geometry and fold orientation analysis from the Tatra edges and surrounding units (e.g. Sperner et al. 2002; Pešková et al. 2009; Vojtko et al. 2010; Tokarski et al. 2012; Králiková et al. 2014). Quaternary deformations in the Tatra caves were recognized by Wójcik & Zwoliński (1959), Grodzicki (1979), Fryś et al. (2006), Szczygieł (2012), Szczygieł et al. (2015). Those studies focused on cave morphology, mainly on displacements in the cross-sections of cave passages and dealt more with cave development rather than with neotectonic movements in a more regional approach. Neotectonics is defined as recent movements generated by the on-going tectonic evolution of the massif. In the Tatra Mts this refers to the Late Pliocene–Quaternary. In other regions from around the world, Quaternary deformations in caves are used as indicators for tectonic activity including seismic activity (e.g. Becker et al. 2006, 2012; Plan et al. 2010; Šebela et al. 2010; Briestenský et al. 2011; Camelbeeck et al. 2012). However, it seems that not all morphological features described as the effects of neotectonic movements are accurately interpreted. For example, breakdowns are not always a result of tectonic movement, they can also be a result of gravity breakdowns, especially in caves developed along the (inactive) fault zones (Szczygieł et al. 2015). Broken speleothems are a frequent phenomenon in caves too but there are many possible causes, including underground glaciers and ice creep (Becker et al. 2006). Nevertheless, unquestionable proof of movement taking place after cave formation is the displacement in the passage profile. This paper focuses on such displacement documented in the Tatra caves. In high mountains such as the Tatra Mts the first trigger mechanism of morphological deformation to be considered is gravity. However some displacements were documented even 400 m under the valley bottom. This allows for the assumption that some of the faults could be affected by tectonic movements on a regional scale and not just by local geomorphology. This article aims to explain the origin of Quaternary faulting located in the Tatra Mts caves. The examined caves are situated in the main karstic regions in the Polish part of the Tatra Mts, the Czerwone Wierchy massif and the Bystra Valley. Geologically, the caves studied are located in the Tatric Unit.

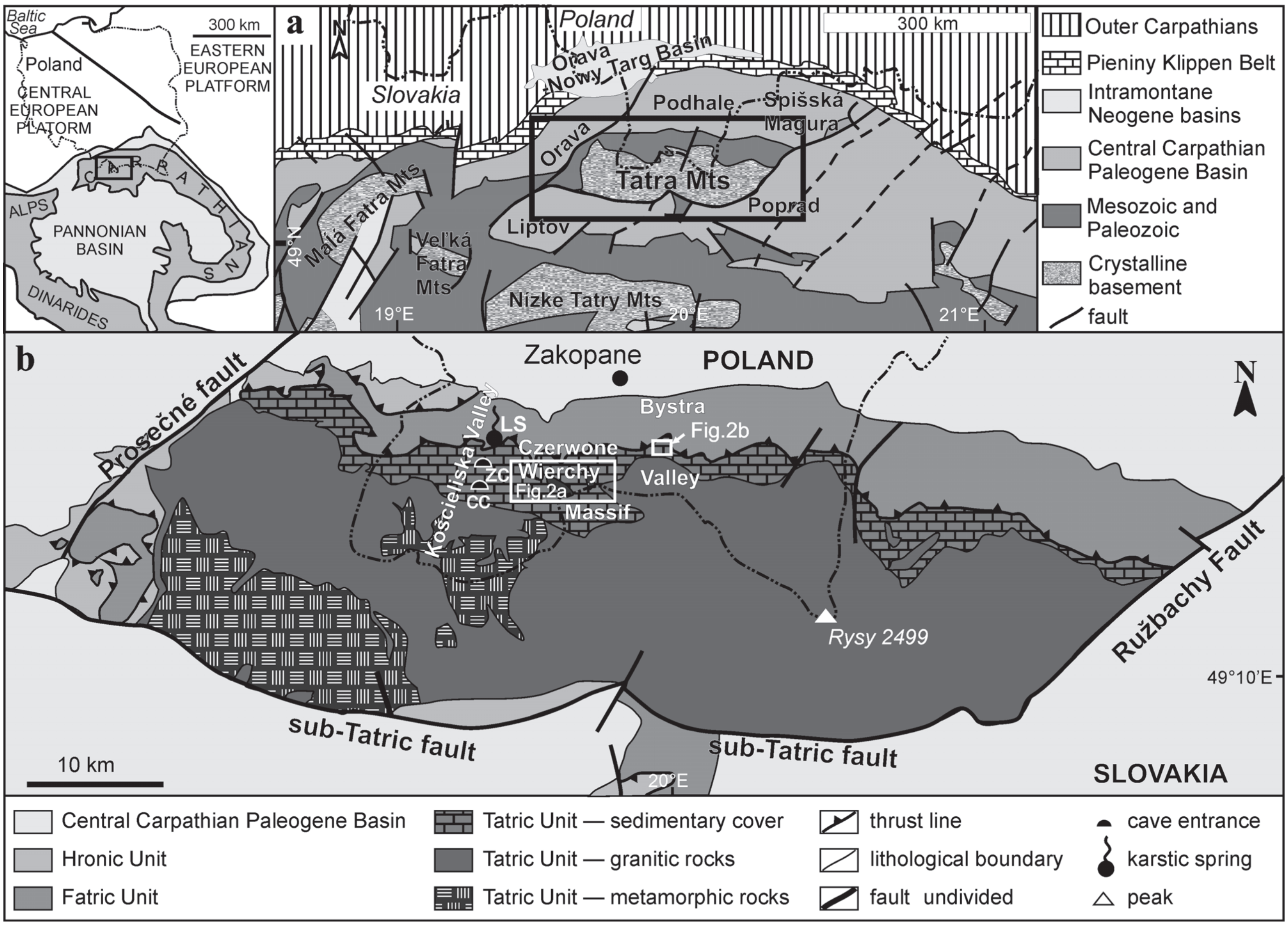


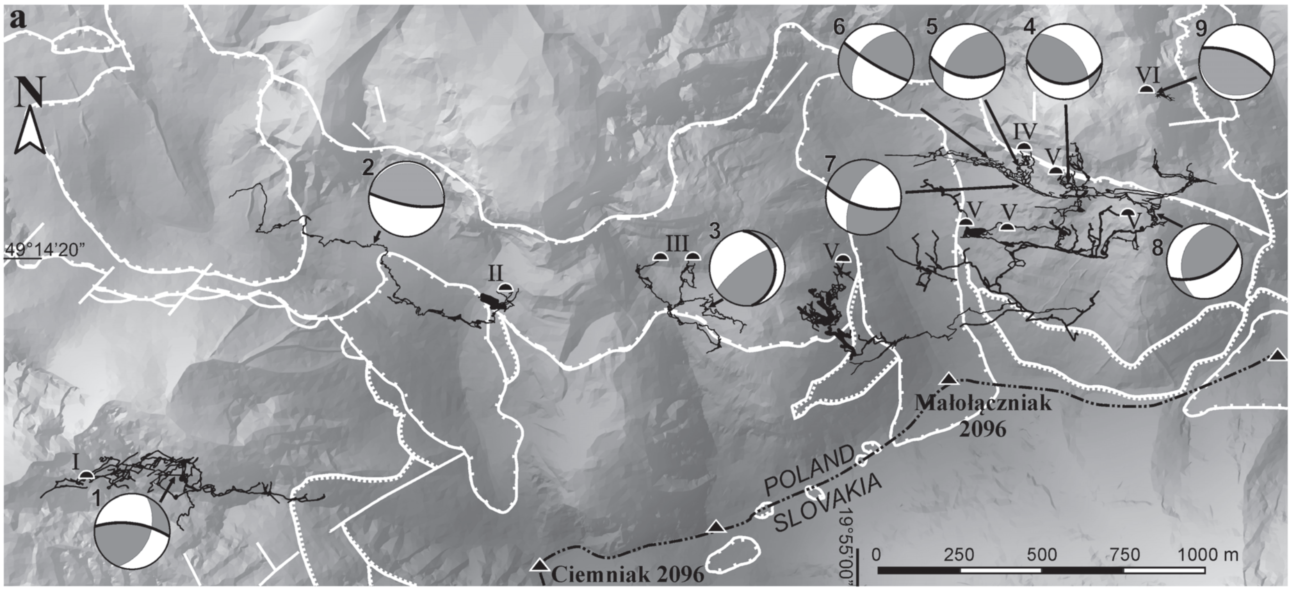
Fig. 1. a — Tectonic sketch of the Central Western Carpathians, after Żytko et al. (1989); black rectangle marks limits of Fig. 1b; location of Fig. 1a against the background of the Carpathians in the upper left corner after Roca et al. (1995). **b** — Tectonic map of the Tatra Mts (after Nemčok et al. 1994, modified) with location (white rectangles) of studied karst areas shown in details on Fig. 2. **Explanations:** LS — Lodowe Spring, zc — Zimna Cave, cc — Czarna Cave.

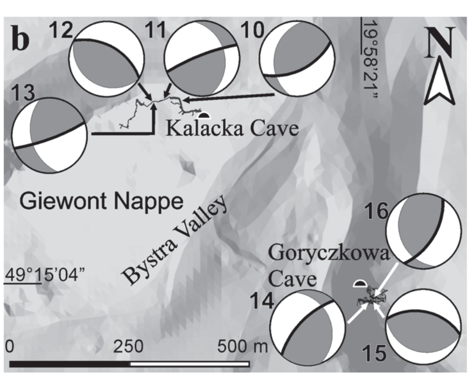
Study area

Geological setting

The Western Carpathians extend between the Alps to the west and the Eastern Carpathians to the east and are subdivided into two main tectonic units: Outer Carpathians and Central Western Carpathians separated by the so-called "Pieniny Klippen Belt", a narrow zone of strongly deformed Mesozoic to Paleogene rocks (e.g. Andrusov et al. 1973; Birkenmajer 1986; Fig. 1a). The Outer Carpathians consist of flysch sediments of Lower Cretaceous to Early Miocene age, thrust northward during the Late Oligocene to Middle Miocene (Oszczypoko & Ślączka 1989). The Central Western Carpathians are composed of Variscan basement units and sedimentary cover deposited from the Late Permian to Early Cretaceous. Both units were deformed by Cretaceous nappe tectonics (e.g. Kotański 1961; Andrusov et al. 1973; Plašienka 2003) and transgressively covered by the so-called Nummulitic Eocene and Paleogene flysh that filled the Central Carpathian Paleogene Basin (Radomski 1958). In the Central Western Carpathians during the Oligocene–Early Miocene, a transpressional tectonic regime commenced vertical movements (Burchart 1972; Kováč et al. 1994). The paleostress field progressively changed followed by a compressional (Early Miocene) to a strike-slip tectonic regime (Middle to Late Miocene) and an extensional tectonic regime (Pliocene to Quaternary — Pešková et al. 2009; Vojtko et al 2010; Králiková et al. 2014). The result of these movements was the recent morphology by uplift and unveiling of the pre-alpine crystalline basement and the Mesozoic successions and deformation of Paleogene flysch (Mastella 1975; Pešková et al. 2009; Vojtko et al. 2010; Králiková et al. 2014). This established the current geological architecture of the Tatra Mts and their surroundings. The rate of uplift in the Tatra Mts is highest along the sub-Tatric fault causing tilting and exposure of the southern and south-eastern part of the Tatra block at first (Bac-Moszaszwili 1995; Anczkiewicz et al. 2005; Králiková et al. 2014). Tilting has a W-E oriented axis and since the Early Miocene the Tatra block has been rotated northward by varying amounts depending on the study; by 20° (Piotrowski 1978), by 30–35° (Bac-Moszaszwili 1995) or by 40° (Jurewicz 2005; Szaniawski et al. 2012). Exhumation of the Tatra Mts split the Central Carpathian Paleogene Basin into the Liptov, Poprad, Podhale basins and the Spišská Magura Mts (Fig. 1a) in the immediate vicinity. Due to rotation of tectonic stress in the northernmost part of the Pieniny Klippen Belt a pull-apart structure formed called the Orava-Nowy Targ basin (Pomianowski 2003) which is filled by a Neogene terrestrial and freshwater sequence (Watycha 1976).

The Paleozoic crystalline basement of the Tatric Unit is composed of the metamorphic sequences of the Western Tatra Mts and granitoid rocks (Nemčok et al. 1994; Fig. 1b). The sedimentary cover of the Tatric Unit consists of Upper Permian–Lower Triassic terrestrial sandstone, conglomerate and shallow marine carbonates, Middle Triassic to Lower Cretaceous limestones with Upper Jurassic sandstone and conglomerate interbeds, and Albian to Cenomanian marls and sandstone. The complete succession occurs in the autochthonous sedimentary cover. The Czerwone Wierchy and Giewont nappes contain hiatuses in the Lower Triassic, Upper Triassic to Lower Jurassic and Upper Jurassic (Rabowski 1959; Kotański 1961, 1963; Lefeld et al. 1985). The strata of the autochthonous sedimentary cover dip about 40° towards the north. The upper parts are folded (but not detached) in the parautochthon (Kotański 1961; Bac-Moszaszwili et al. 1984). In the Czerwone Wierchy massif the parautochthon is situated between Czerwone Wierchy and Giewont nappes (Bac-Moszaszwili et al. 1984; Fig. 2a). The Czerwone Wierchy Nappe is composed of two sub-units, the northern — Organy and the southern — Ździary, and are separated by the Organy Fault (Kotański 1963; Fig. 2a). The Organy and Ździary sub-units have a syncline-style geometry in general. The dip of the axial surface of the folds is recumbent to plunging and the interlimb angle is tight to isoclinal. The folds are open to the north and the lower limbs are steeply to gently inclined towards the north, the upper limbs dip steeply southward. In some parts just one of those main limbs is preserved (Rabowski 1959; Kotański 1961, 1963; Bac-Moszaszwili et al. 1984; Szczygieł 2013; Szczygieł et al. 2014). The Giewont Nappe bears crystalline rocks at the core due to the crystalline basement becoming detached while folding. The klippes of crystalline rock are located in the upper parts of the Czerwone Wierchy Massif (Kotański 1961; Fig. 2a). The sedimentary rocks of the Giewont Nappe dip steeply in a normal position toward the north in the western portion (Rabowski 1959; Kotański 1961). In the eastern





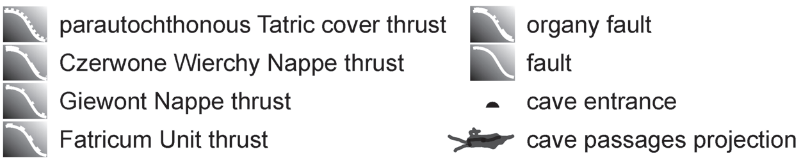


Fig. 2. Shaded digital elevation model (DEM) of studied karst areas (location on Fig. 1b) including location and individual P/T axes of each fault. In the 'beach balls' the grey polygons and the white circle represent the position of the P- and T-axes, respectively. The thicker black line on the 'beach ball' is a projection of the fault plane. Numbers at the 'beach balls' refer to faults in Table 1. **a** — The Czerwone Wierchy massif including: boundary of the main tectonic units (after Piotrowska et al. 2008); **b** — Central part of the Bystra Valley. **Explanations:** I — Wysoka–Za Siedmiu Progami Cave, II — Mała w Mułowej Cave, III — Kozia Cave, IV — Śnieżna Studnia, V — Wielka Śnieżna Cave, VI — Lodowa Małołącka Cave.

outcrops Lefeld (1957) distinguishes three subunits: the main fold of the Giewont Nappe, the Zawrat Kasprowy subunit and the uppermost — Kopa Magury subunit. These subunits are recumbent synclines in general (Lefeld 1957; Hercman 1989). The Fatric Unit consists of an Lower Triassic–Lower Cretaceous succession (Nemčok et al. 1994) and is overthrust (Krížna Nappe) onto the Tatric Unit (Plašienka 2003). The stratigraphic range of the Hronic Units is Middle Triassic to Lower Jurassic (Nemčok et al. 1994) and bears the highest nappe (Choč Nappe) in the Tatra Mts nappe system (Plašienka 2003).

Cave characteristics

Tectonic settings have a direct impact on the development of independent karst systems (Rudnicki 1967). The morphology and passage patterns of the Tatra caves are characterized by cave levels that are linked or intersected by series of shafts and meanders. Cave levels are accumulations of subhorizontal passages which originated in phreatic or epiphreatic conditions. Vertical and steep parts of the caves including shafts, meanders, cascades etc. developed in vadose conditions, mostly as a result of the invasion of water which either flowed from a melted glacier (Głazek et al. 1977), or was just meteoric water (as in recent conditions). Some very steep parts are relatively short and located within cave levels amenable to formation in phreatic conditions (Gradziński & Kicińska 2002). Cave systems in the Tatra Mts are not just of the multilevel extended type, often caves systems show just one of the mentioned genetic and morphological types.

Dating of speleothems permits a description of the development of the Lodowe spring system draining the Czerwone Wierchy Massif (Fig. 1b). The highest paleophreatic passages are in the Czarna Cave (Fig. 1b) where the latest phreatic stage ceased no later than 1.2 Ma (Gradziński et al. 2009). Dating of flowstone from caves in the Bystra Valley area indicates that those caves transitioned to the vadose zone during the Eemian Interglacial (Hercman 1991).

Methods

Fieldwork has been conducted in cave passages with diverse morphology — vadose and paleophreatic types. For research purposes only those faults which were not deformed by breakdowns have been chosen. Pre-faulting morphology also had to be clearly visible to establish sense and precise measurement slip. Fault planes, slickenlines with kinematic indicators, superposition of striae, dip and strike, separation were all measured during fieldwork. The orientation of the studied faults and slope nearest to the cave were compared on the basis of the Digital Elevation Model (DEM). The altitude of faults and the nearest valley bottom were also compared.

Fault-slip data were used for reconstruction of the paleostress fields. To identify the orientation of the stress axes (principal maximum compression axis — $\sigma_{1,}$ principal intermediate compressional axis — σ_2 and principal minimum compressional axis — $\sigma_{3,}$ with $\sigma_1 > \sigma_2 > \sigma_3$) two methods were employed: right dihedra (P/T method), and inverse methods (for details see Ramsay & Lisle 2000). These analyses were carried out on TectonicsFP (Reiter & Acs 1996) and MyFault (Pangea Scientific 2005) software. The right dihedra (P/T method) was used to calculate the principal stress axes of the individual faults and are represented in the "beach ball" plots. The reduced stress tensors and the stress ratio Φ or the R $[\Phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)]$ of the fault sets were calculated according to inverse methods. Data sets were separated into subsets, to obtain the homogeneous stresses for each set. The sets were subdivided into fluctuation diagrams and the relationship between the faults and the surface terrain.

Results

Cave morphology

Geological and geomorphological research was conducted in 32 caves situated in the autochthonous sedimentary cover of the Tatric unit, Czerwone Wierchy Nappe and Giewont Nappe. However, only eight caves have morphological features that clearly indicate their deformation after cave development. A review of neotectonics-affected deformation in caves was given by Becker et al. (2006) who have noted that many processes could give the same visual effect in passage morphology, for example, speleothems being broken by earthquakes or creeping ice as mentioned above. Therefore, the faults for this study were very carefully selected. The best for such observations seem to be paleophreatic passages or narrow vadose passages both with well preserved dissolution features such as scallops, solution pockets or anastomoses.

All of the documented faults are normal and right- or left-lateral normal oblique-slip faults. The displacement vectors have a length from 3 to 27 cm. In a few cases a gap of up to 4 cm also accompanies faults. All movements slipped along pre-existing structures: faults, fractures or bedding planes. Comparison of the location and orientation of faults with local topography showed that among the studied fault population two groups can be distinguished. Fault sets are described, for example, as [1,2,3,...] with the numbers in parentheses corresponding to faults in Table 1. The first group includes faults located above the valley bottom and oriented sub-parallel to the nearest slope (Fig. 2, Table 1). The second group comprises faults dipping in the opposite direction or obliquely to the nearby slopes. This group includes, inter alia, fault movement along the interbedded planes (Fig. 2, Table 1).

Fault-slip analysis

Fault-slip data was recorded at 16 sites in eight caves. The orientation of fault planes and their relation to topography as well as slip direction is too diverse to assume one homogeneous population. This is also indicated on the fluctuation diagram for the whole population. Therefore a reconstruction of the stress field was made for two groups subdivided according to topographical relationship. The faults fulfilling the conditions described for each of the two groups were analysed first. The faults that do not fit perfectly but closely

Table 1: Location, geological background and paleostress tensors from fault slip data. **Explanations:** TU — tectonic unit, SU — tectonic subunit, E — elevation, Dip dir — dip direction, Fm — lithostratigraphic formation, A — "autochthonous" Tatric cover sequence, PA — parautochthonous Tatric cover sequence, CWN — Czerwone Wierchy Nappe, ŹU — Ździary Unit, OU — Organy Unit, GN — Giewont Nappe, N — normal fault, ND — dextral oblique-slip fault, NS — sinistral oblique-slip fault, V — vertical displacement, H — horizontal displacement, T_2 — Middle Triassic thin-bedded limestone and dolomite, JCr — Late Jurassic to Lower Cretaceous (Hauterivian) thick-bedded limestone, Cr — Lower Cretaceous (Barremian, Aptian) thick-bedded limestone, σ_1 σ_2 σ_3 — azimuth and plunge of principal stress axes estimated by right dihedra (P/T) method.

No.	Cave	Site	TU/SU	E [m a.s.l.]	Dip dir/dip	Sense	D [cm]	σ_1	σ_2	σ_3	Bedding	Fm
1	Wysoka–Za Siedmiu Progami	Stary Kanion	A	1340	6/70	ND	27	233/41	79/46	335/13	~ 10/45	JCr
2	Mała w Mułowej	Meander TPKC	PA	1297	190/82	N	15	10/54	280/00	190/36	—	Cr
3	Kozia	Niska Galeryjka	CWN/ŹU	1683	88/25	ND	12	172/53	48/23	306/27	154/45	T_2
4	Wielka Śnieżna	Partie za Kolanekim	CWN/ŹU	1655	185/40	ND	9	278/65	123/23	28/10	185/40	T_2
5	Śnieżna Studnia	Kacza Łapa	CWN/OU	1521	186/55	NS	V-15/H-15	66/55	251/35	160/03	186/55	T_2
6	Śnieżna Studnia	Dziki Zachód	CWN/OU	1340	209/80	NS	V-15/H-15	71/33	292/49	176/22	209/80	T_2
7	Śnieżna Studnia	Bottom of the Wazeliniarzy Shaft	CWN/OU	1271	196/70	NS	V-15/H-15	65/28	254/62	157/04	196/70	T_2
8	Śnieżna Studnia	Czekoladowe Shafts	CWN/OU	1250	152/60	NS	4	21/62	228/25	133/11	152/60	T_2
9	Lodowa Małołącka	the entrance area	CWN/OU	1634	22/75	N	18	201/60	112/00	22/30	—	JCr
10	Kalacka	Rozsunięta Chamber	GN	1235	152/63	N	15	18/59	229/27	132/14	~ N/60	T_2
11	Kalacka	between sump 1 and Rozsunięta	GN	1230	337/80	NS	V-3/H-2	193/40	63/38	309/27	~ N/60	T_2
12	Kalacka	between sump 1 and 2	GN	1235	30/60	ND	V-7/H-2	210/75	300/00	30/15	~ N/60	T_2
13	Kalacka	between sump 1 and 2	GN	1235	158/80	NS	V-8/H-3	20/34	241/49	125/21	~ N/60	T_2
14	Goryczkowa	above Main Chamber	GN	1258	312/70	NS	4	173/52	32/31	290/20	~ 30/30	T_2
15	Goryczkowa	lower passege	GN	1254	12/57	N	4	192/78	282/00	12/12	~ 30/30	T_2
16	Goryczkowa	lower passege	GN	1265	120/65	N	3	342/60	199/25	101/16	~ 30/30	T_2

enough were also considered because it can be argued that they were formed as a result of the same process.

The first population includes the faults numbered 10, 11, 13 and 14 (Table 1). These faults originated under an extensional tectonic regime. The radial extension can be characterized by W-E oriented, horizontal σ_3 (sigma 3) and vertical σ_1 (sigma 1) (Fig. 3a). Other faults from Kalacka and Goryczkowa caves [12, 15 and 16] are located close enough to the surface and to faults 10, 11, 13 and 14 to assume that they also could have been caused by the same trigger. Examination of the fault sets [10, 11, 13 and 14] and [10–16] showed very similar stress fields with the same trend of the principal stress axes (Fig. 3b). It may prove this assumption.

The faults numbered 4–8 (Table 1) best meet the conditions of the second group. Stress analysis showed that σ_3 is gently inclined towards the SE while σ_1 plunges steeply toward the west (Fig. 3c). This may indicate a transition regime between the extensions and the transtension. As well as in the first group, the rest of matching faults [1–3 and 9] were added to the set. Results of the analysis of set [4–8] were compared with set [1–9] including all faults within the Czerwone Wierchy Nappe and the autochthonous sedimentary cover. Outcomes differ slightly but the general trend is similar (Fig. 3c,d). This may suggest that faults numbered 1–3 and No. 9 were developed as an effect of similar processes as faults 4–8.

Interpretation and discussion

Most of the neotectonic movements in the Carpathians are resolved by relaxation (e.g. Zuchiewicz 1998). However, movements which took place a few hundred meters from the nearest slopes or even under the bottom of the nearest valley, could be related to the stress which influences the whole orogen and not only to gravitation in an interaction of relaxation.

The maximum horizontal stress in the Central Western Carpathians is NE-SW oriented on the regional scale (Jarosiński 2006). However, for individual units it is more diverse, for example, in the Central Carpathian Paleogene Basin sub-units surrounding the Tatra Mts. To the west and northwest in the Orava Basin and western portion of the Podhale Basin the Quaternary stress field is characterized by E-W oriented S_h (minimum horizontal compression) and N-S oriented S_H (maximum horizontal compression) (Pešková et al. 2009). In the eastern portion of Podhale and the Spišská Magura Mts the most recently operating was ENE-SWS oriented tension (Vojtko et al. 2010). In contrast, to the south of the Tatra Mts in the Hornád Depression, the last and youngest tectonic phase consisted of NNW-SSE oriented tension (Sůkalová et al. 2011). The kinematic of the Tatric block exhumation has also changed since the Miocene (Králiková et al. 2014). Most recently the Tatra Block has been horst limited by Prosečné, sub-Tatra, and Ružbachy normal faults (Nemčok et al. 1994) and is tilting northward as is also confirmed by geodetic surveying (Makowska & Jaroszewski 1987; Bac-Moszaszwili 1995). On the Slovakian side of the Tatra Mts near the sub-Tatric fault, vertical movements were observed to reach speeds of up to +8.4 mm/year (Makowska & Jaroszewski 1987); in

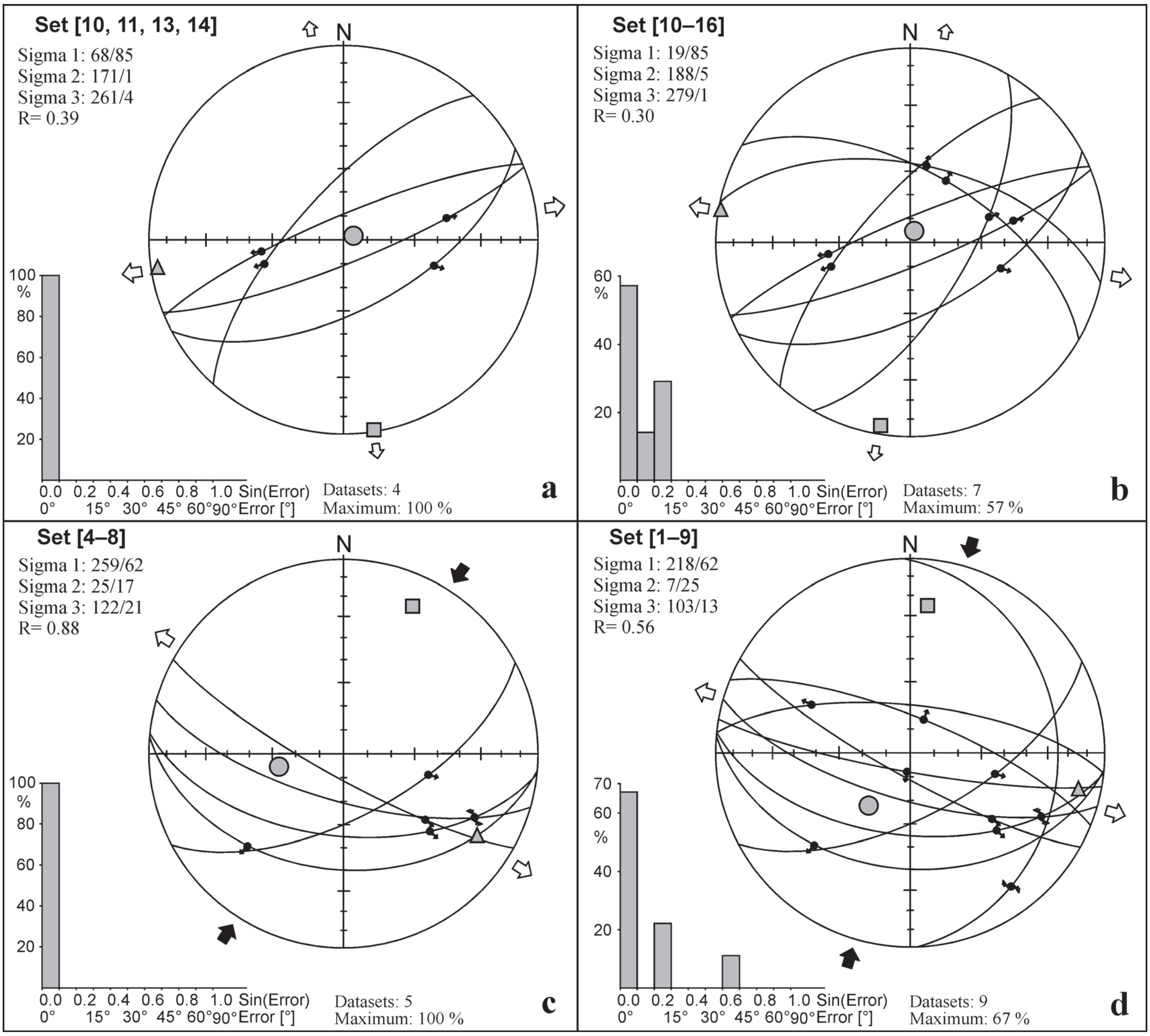


Fig. 3. Paleostress reconstruction for selected sets of faults-slip data from Tatra Mts caves. **Explanation:** Numbers of faults in individual sets correspond to faults in Table 1, Stereogram (Lambert's net, lower hemisphere) with projection of fault planes, observed slip lines and slip senses and principal paleostress axes: circle — σ_1 (Sigma 1), square — σ_2 (Sigma 2) and triangle — σ_3 (Sigma 3), R-Φ — stress ratio (σ_2-σ_3/σ_1-σ_3), fluctuation histogram shows the dihedral angle between the measured lineation and the stress vector for each fault plane.

Zakopane the speed was calculated to +0.3 mm/year, and 20 km to the north in Nowy Targ — 0.75 mm/year (Perski 2008). From the foregoing, the neotectonic stage in the Tatra Mts is determined as Late Pliocene–Quaternary (e.g. Vojtko et al. 2010) or even Late Miocene–Quaternary (Králiková et al. 2014). So if the stress field and the rate of uplift has changed over time, it is necessary to determine the approximate age of the investigated movements. The maximum or the minimum age of deformation in a cave can be determined by the U-series dating of speleothems, which were destroyed or cover the deformed surface (e.g. Becker et al. 2006, 2012; Plan et al. 2010). This study was based only on structural measurements and the following interpretation of the age is based on published data, often dealing with other aspects.

The development of the Goryczkowa and Kalacka caves took place simultaneously (Rudnicki 1967) so the transition to the vadose zone could be correlated. No dating of speleothems from the Kalacka Cave has been carried out so far, but the dating of flowstone from the Goryczkowa Cave indicates an age of ca. 160 ka. This suggests that these caves were drying out during the Eemian interglacial (Hercman 1991) corresponding to the Riss/Würm interglacial in the Alps (Lindner et al. 2003). Cracked flowstone at fault No. 16 from the Goryczkowa Cave indicates that this fault operated after the speleothems had grown. There are no forms indicating erosion in phreatic conditions on the fault planes in the Goryczkowa and Kalacka caves. It can be assumed that all examined faults in these caves developed after the change of conditions from phreatic to vadose, between the late Eemian and recent.

In the Czerwone Wierchy Massif there are no speleothem dates available from the caves where neotectonic faults have been found. Faults occur in passages of both main types: vadose and paleophreatic. Dislocations among the paleophreatic conduits are found at the high-altitude level (e.g. fault No. 4, Table 1) as well as in the lowest cave level in this area (e.g. fault No. 1, Table 1, Fig. 4b). Paleophreatic passages at an altitude of more than 1600 m are probably older than the passages in the Czarna Cave (see chapter "*Cave characteristic*"). Furthermore, the lowest cave level can be correlated with the lowest level of the Zimna Cave (Fig. 1b), where the transition of the youngest conduit from the phreatic to vadose zone took place ca. 120 ka ago (Gradziński et al. 2009). The occurrence of faults in passages of different ages may indicate that this deformation originated after the development of the cave in its current state. It means that faults from the Czerwone Wierchy Massif as well as the faults from the Bystra Valley were active in the Eemian Interglacial or later. So it is too short a time span to look upon each fault group as a separate, successive tectonic stages. However, by comparing the faults and morphology of the studied area two groups of faults were determined. Fault-slip analysis showed generally the same tectonic regime — extensional, but the orientation of principal stress axes differs in detail. The type of extension was also different. In the first group it was radial extension, in the second it was a transitional tectonic regime between extension and transtension. It is possible to assume that the morphological setting and asymmetry of uplift could affect the presence of different types of movements in the Tatra caves.

Faults of the first group (10–16) that run sub-parallel to the slopes are spaced from the surface to several tens of meters. Stress analysis showed that these faults are the result of horizontal widening, which can usually be correlated with slope orientation. It is very important that σ_1 is vertical, so synonymous with gravity. These factors indicate that these faults formed as the result of gravity sliding. This process may be related to the extension which followed the contraction, as in the Outer Carpathians (Zuchiewicz 1998) or just relaxation after deglaciation and valley incision, so it is not directly from tectonic activity. Gravity could also have caused the movements if the weakest plane is not parallel to the slope. It is enough for the strike direction to be sub-parallel to the ridge course (Beck 1968). Evidence of this process can be seen at fault No. 11 where there is a ~4 cm displacement, combined with a 2–3 cm gap (Fig. 4a). However, these movements should not be equated with landslides. Although in the upper part of the Bystra Valley landslides were documented by Wójcik et al. (2013), the morphology of slopes near caves has not indicated the presence of landslides. This stress analysis confirms the assumptions of Szczygieł et al. (2015).

The origin of the second faults group (1–9) by gravity sliding is unlikely. The displacement also occurred ~450 m below the bottom of the valley (e.g. No. 8). After that, the hanging walls moved under the massif and not toward the valley (Fig. 2a). The cause of movements in this direction may be tilting of the Tatra block due to recent uplift.

Fault set (1–9) was developed under a transitional regime, between the extensions of the transtension with NW–SE to WNW–ESE oriented S_h and NE–SW to NNE–SSW oriented S_H. The computed directions are consistent with Králiková et al. (2014) results. However, they differ from the surrounding units, for example, they are similar to the results of Pešková et al. (2009) but the regime is not purely extensional as in the Orava region, especially as some dislocations have strike-slip component. Thus a process of uplift that directly affects

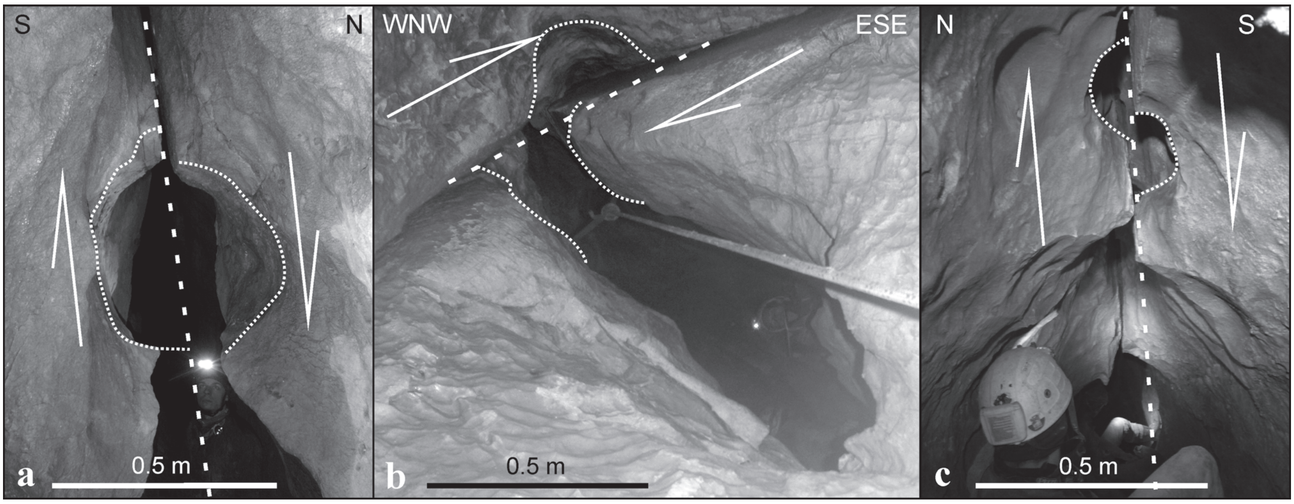


Fig. 4. Chosen faults from studied caves in the Tatra Mts. **a** — oblique-slip faults combined with a 2–3 cm gap with strike direction parallel to the nearest slope, fault No. 11, the Kalacka Cave, passage between Rozsunięta Chamber and sump 1; **b** — oblique-slip fault developed in massive limestone under the bottom of the nearest valley, fault No. 1, Wysoka–Za Siedmiu Progami Cave, the Stary Kanion passage; upward view; **c** — oblique-slip fault developed in thin-bedded limestone along inter-bedding plane and located under the bottom of the nearest valley, fault No. 6, the Śnieżna Studnia Cave, Spełnionych Marzeń passage. **Explanations:** White thick dotted line — orientation of the fault plane, white thin dotted line — cross section of the passage. Photos "a and b" by Jacek Szczygieł, photo "c" by Ewa Wójcik.

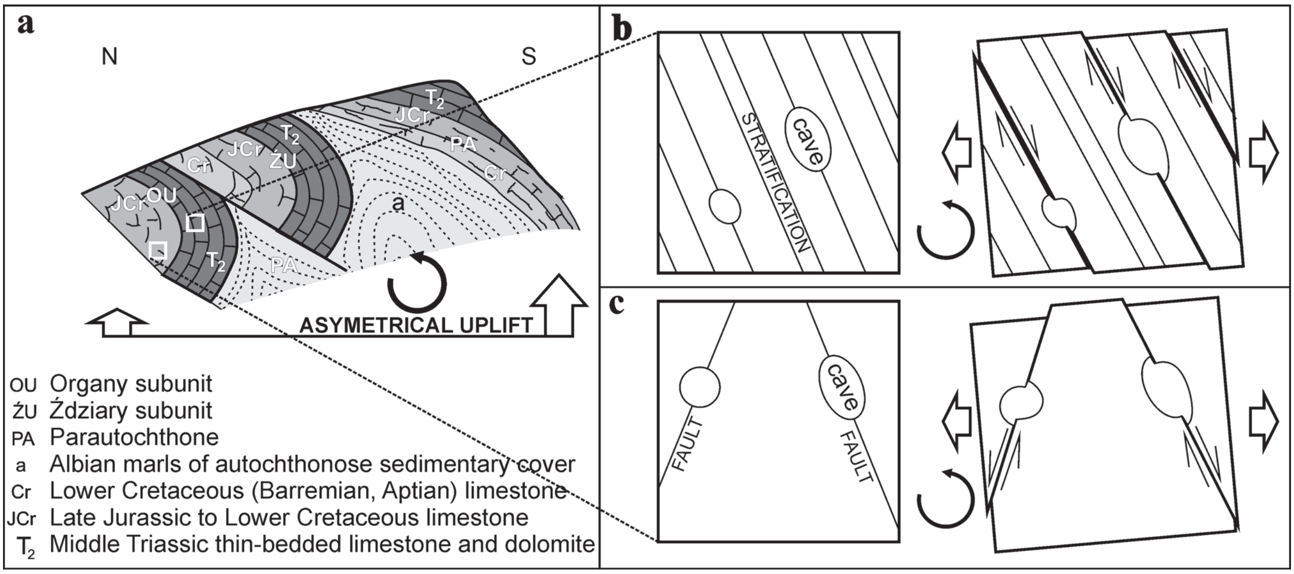


Fig. 5. Schematic presentation of development of the faults shifting cave passages. **a** — schematic geological cross section of the Czerwone Wierchy massif based on Kotański (1963); results of the asymmetrical uplift in thin-bedded limestone (**b**) and massive limestone (**c**).

the Tatra block is responsible for the youngest displacement in the Tatra Mts.

Displacement of all the studied faults occurred along planes of weakness, meaning pre-existing surfaces: fractures, inter-bed or fault planes. This might mean that the orientation of a particular fault plane may depend on a structural pattern and not be formed at ideal angles relative to the principal compression axes. Assuming that in the Tatra nappes the general strike trend of the structures is latitudinal, two cases can be specified in this setting: when the planes of weakness are dipping toward the S, or to the N. All the faults of the second group match this pattern, except for the fault No. 3. In the caves faults operated in limestone and in the study area two significant limestone types could affect the direction of the stress relaxation: massive and thin-bedded limestones. In massive limestone faults and fractures are the weakest planes. Then the stress was relaxed along normal dip-slip or oblique-slip faults depending on the orientation of the weakest planes (e.g. faults Nos. 1, 2 and 9; Figs. 4b, 5b). In the thin-bedded limestone stress relaxed along the pre-existing fault if it was the weakest plane (e.g. fault No. 3). The thin-bedded limestones are represented by Middle Triassic limestone and occur mostly in the upper limbs of the major folds of the Organy and Ździary subunits (Czerwone Wierchy Nappe) which dip steeply to the south (Fig. 5). The biggest caves in the Czerwone Wierchy massif developed in that complex (Szczygieł 2013). The inter-bedding planes are the main weakening planes in this carbonate complex. The layers, steeply inclined southward, have been tilted northward, which resulted in the movement of the layers relative to each other in a similar way to flexural slip (Fig. 5c). Numbers 4–8 are such faults (Fig. 4c).

Another important problem is whether this deformational history is the result of one single event or a series of events, or due to uninterrupted microtectonic movements that have been observed in caves in other areas (Šebela et al. 2010; Briestenský et al. 2011). No breakdowns in the nearest areas of deformation (Fig. 4) may indicate that this could be uninterrupted microtectonic movement. On the other hand, descriptions of eye-witness accounts of earthquakes in caves reviewed by Becker et al. (2006) indicate that seismic events did "not trigger any damage or rock falls in the cave, they (cavers) felt the ground shaking and air blowing, they heard noises and could see fluctuations in water levels". Additionally even if the earthquake caused the breakdown faults would be unrecognizable or there would not be a transition for a speleologist. Earthquake activity is possible in the studied area; for example, seismic activity in the Tatra region may have caused the earthquake of 30 November 2004, which measured 4.7 on the macroseismic scale (Wiejacz & Dębski 2009). However, at present this is mere speculation. To resolve this issue, observations of microtectonic movement need to be carried out as demonstrated by Šebela et al. (2010) and Briestenský et al. (2011). In addition, the dating of speleothems and detailed observations of the breakdowns located in the Tatra caves would need to be completed.

Conclusions

The occurrence of faults dislocating cave passages, strongly indicates fault activity during the Quaternary in the Tatra Mts. Displacement occurs in the passages of the older, as well as the youngest levels of caves in the Tatra Mts. U-series dating of speleothems from these caves done by other authors (eg. Hercman 1991) indicate an Eemian or younger age for this displacement. Stress reconstructions show that all the examined faults were operated under extensional tectonic regimes. However, comparison of location and orientation of faults with local topography showed that among the studied fault population two groups can be distinguished. (I) The faults of the first group are located above the valley bottom and at a short distance from the surface (tens of meters), and fault planes are oriented sub-parallel to the slopes. The radial, horizontal extension and vertical σ_1, which can be identified with gravity, indicate that these faults are the result of gravity sliding, probably caused by relaxation after deglaciation and valley incision, so it is not directly from tectonic activity; (II) Faulting of the second group is a result of active tectonics. The tilting of the Tatra Mts block led to displacements located under the valley bottom and/or oriented opposite or obliquely to the slope. General WNW-ESE oriented extension is quite compatible with previous research (Králiková et al. 2014). The process involved the pre-existing weakest planes in the rock complex: (i) in massive limestone mostly faults and fractures, (ii) in thin-bedded limestone where the most prone were inter-bedding planes.

To be able to precisely assess the age, the nature and rate of such deformation in the Tatra Mts further observations of cave morphology, measurements of microtectonic displacement such as that carried out by Šebela et al. (2010) and Briestenský et al. (2011), and the dating of speleothems such as done by Plan et al. (2010) and Becker et al. (2012) have to be conducted.

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