CREVICE-TYPE CAVES AS INDICATORS OF SLOPE FAILURES: A REVIEW PAYING A SPECIAL ATTENTION TO THE FLYSCH CARPATHIANS OF CZECHIA, POLAND, AND SLOVAKIA

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ABSTRACT

The occurrence and evolution of crevice-type caves is one of the most spectacular phenomena in the progression of slope failures in distinct types of rocks. Crevices are common manifestations of disintegration of anisotropic flysch rocks in the area of the Carpathians. This paper presents the issues of the close connection between the evolution of gravitational slope deformations and the formation of crevice-type caves. Furthermore, it presents a contemporary view on the regional distribution of crevice-type caves in this area and outlines the recent progress and future possibilities of the investigation of this phenomenon. Based on the vertical distribution of different morphological zones within the caves and the main modes of their evolution, we can distinguish three basic types of crevice-type caves: (i) translational/spreading type, (ii) toppling type and (iii) rotational type.

Keywords: pseudokarst, crevice-type cave, gravitational slope deformations, Carpathians, flysch

1. Introduction

Caves belong to the forms of pseudokarst phenomena (Halliday 2007). Most extensive and widespread pseudokarst caves are crevice-type caves that are formed during the evolution of slope failures by the disintegration of rock blocks (Vítek 1978; Wagner et al. 1990; Baroň et al. 2003a; Margielewski and Urban 2003; Bella 2011). Margielewski and Urban (2003) consider the crevices to be free space between two rock blocks when at least one of them is affected by slope movement. Most commonly, crevice-type caves accompany the evolution of deep-seated gravitational slope deformations (DSGSDs), i.e. types of large-scale mass movements affecting large volumes of rock masses (Němčok 1972; Dramis and Sorriso-Valvo 1994), generally some tens of meters-deep (e.g. Hutchinson 1988: at least 30 m). The mass movements are mostly slow or extremely slow with an average velocity lower than 18 mm per year, but in their catastrophic stage they can reach very high speed (Varnes 1978). However, besides DSGSDs, the crevice-type caves can also be produced within the shallow and medium-deep (<30 m according to Hutchinson 1988) structurally-predisposed landslides (Margielewski 2009). Table 1 specifies the preparatory factors of landslide progression.

The crevice-type caves of equal genesis may occur in distinct types of rocks. The crevices very often open into incoherent sedimentary flysch deposits such as sandstones and conglomerates with intercalations of shales. However, they can be observed also in granites, quartzites, gneiss and other lithologies (Vítek 1978). Crevices originate also in carbonate rocks (limestones and dolomites). Typically, crevices and crevice-type caves occur within the areas built by anisotropic rigid rocks underlain by plastic shales (Pánek et al. 2009b, 2010).

Tab. 1 Preparatory factors of the opening of crevices within the landslide progression

Preparatory factors of opening of crevices within the landslide progression	
long-term	**lithological conditions** – Baroň et al. (2003b, 2004); Bubík et al. (2004); Margielewski (2004); Rybář et al. (2006); Margielewski et al. (2007)
	Tectonics – Pánek and Duras (2002); Pánek et al. (2007); Margielewski et al. (2007); Rybář et al. (2006 a 2008)
	denudation ratio and slope relaxation caused by incision of rivers – Margielewski et al. (2007); Rybář et al. (2008)
	macroclimate – Margielewski (2006b)
short-term	**seismic activity*** – Martino and Mugnozza (2005); Bozzano et al. (2011); Klimeš et al. (2012)
	heavy downpours* – Krejčí et al. (2002); Pánek et al. (2011b)
	groundwater content – Baroň and Kašperáková (2006); Medveďová et al. (2008)
	water from snow melting flushes* – Krejčí et al. (2004)
* also triggering factors	

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This paper presents close connection between the evolution of gravitational slope deformations and crevice-type caves on an example of the flysch Carpathians. In summary, this work:

(1) provides a review of the genesis of crevice-type caves as an important geomorphic element within gravitationally disrupted slopes of the Carpathians;
(2) presents a contemporary view on the regional distribution of crevice-type caves in the flysch Carpathians of Czechia, Poland and Slovakia; and
(3) outlines recent progress and future possibilities and directions in the investigation of this phenomenon.

The terms of movements used in this paper agree with the classification of mass movements by Cruden and Varnes (1996).

2. Crevice-type caves – central topic of pseudokarst phenomena

The term 'pseudokarst' has recently been used to refer to forms resembling karst morphology, but primarily produced by a process other than dissolution (Halliday 2007). A pseudokarst cave is any cave that only originated in insoluble rocks by mechanical forces (Panoš 2001). Pseudokarst caves are then distinguished as fissure caves, cave niches, bedding-type caves, crevice-type caves, talus-type caves and combined-type caves. Crevice pseudokarst is one of eight types of pseudokarsts established in 1997 by the working session within 12th International Congress of Speleology (Kempe and Halliday 1997).

Crevice-type caves originate by the gravitational movement of tectonically or lithologically predisposed rock masses (Panoš 2001). These caves are mostly regularly narrow-shaped ('A' and 'V' or 'H' letter in cross-section) with high walls and flat ceilings or floors. The corridors may reach significant lengths: tens or hundreds of meters (Vítek 1978, 1981; Wagner et al. 1990). Within the crevice-type cave evolution, other processes such as water erosion, frost weathering, rockfall or seasonal temperature change might play an important role (Vítek 1981; Margielewski et al. 2007; Klimeš et al. 2012). Under such circumstances, the crevice-type cave is any cave that originated in soluble or insoluble rocks (including karst) by the influence of gravitationally or tectonically induced widening of fissures (Panoš 2001). The term *rock-slide cave* is closest to the perception of a typical crevice-type cave evolved in the area of the Carpathians (Panoš 2001). Different terminology concerning crevice-type caves is displayed in Table 2.

Tab. 2 Different terminology concerning crevice-type caves

crevice-type cave	Margielewski and Urban (2003); Klassek (2004); Margielewski et al. (2007); Pánek et al. (2007)
joint cave	Wagner et al. (1990)
fissure cave	Kunský (1957); Kirchner and Krejčí (2002); Krejčí et al. (2012)
gull fissure cave	Bella (2011)
cleft cave	Panoš (2001); Pokorný and Holec (2009)
cambering cave	Bella (2011)
crevasse cave	Bella (1998); Baroň et al. (2003a); Petro et al. (2011)
landslide cave	Bella (2011)

3. Crevice-type caves in the flysch Carpathians

The flysch Carpathians are predominantly formed by Mesozoic and Palaeogene sediments which were folded during the lower and middle Miocene alpine orogeny phases (Menčík et al. 1983; Źytko et al. 1989; Lexa et al. 2000; Krejčí et al. 2004). The described mountain range is situated in the territory of the Czech Republic, Slovakia and Poland (Figure 1). Most of the crevice-type caves are situated in the area of the Outer Carpathians, but there are some localities, which pertains to the Inner Carpathians (Figure 1). The flysch rocks consist of thick-bedded sandstones or conglomerates with mica, glauconitic and calcific admixture and thin-bedded intercalations of shales (mudstones, siltstones) with a predominant content of illite and kaolinite clay minerals (Menčík et al. 1983; Eliáš 2000; Margielewski and Urban 2003; Pánek et al. 2011a; Petro et al. 2011). Ridges often have a character of monoclinal ridges and cuestas (Menčík et al. 1983), especially within the Silesian Unit (e.g. Moravskoslezské Beskydy Mts, Beskid Sląski Mts) characterised by steep northern slopes and gentle, long southern slopes predisposed by bedding planes (Krejčí et al. 2004). The flysch massif is strongly disrupted by joints and faults trending in the E-W, N-S, NW-SE and NE-SW directions (Menčík et al. 1983; Krejčí et al. 2002; Bubík et al. 2004; Petro et al. 2011) and WNW-ESE direction (Menčík et al. 1983; Pánek and Duras 2002). In terms of the strike characteristics of the beds, these joints and faults are classified as L (longitudinal), T (transversal) and D1 + D2 (two diagonal systems) (Mastella et al. 1997).

Slope deformations are common features in the flysch Carpathians (Kirchner and Krejčí 2002; Baroň et al. 2004; Margielewski 2006b, 2009; Rybář et al. 2008; Petro et al. 2011). The susceptibility of this region to mass movements is given by (i) overall disequilibrium of flysch nappes that are not in balance with the underlying basement consisting of soft Neogene deposits (Krejčí et al. 2004), (ii) strong anisotropy of flysch rocks creating conditions for the evolution of slip surfaces (Margielewski 2006b) and (iii) high precipitation that (also due to summer heavy downpours and rapid snow melt at the end of winter) generate high pore pressures within the rock mass (Pánek et al. 2011b). Typical slope movements are represented by deep-seated gravitational slope deformations and structurally-induced landslides, very often accompanied by crevice-type rock-slide caves (Margielewski 2009). These caves, which were already known during the Wallachian colonization in 16–17th century (Četyna 1966), have systematically been mapped since the mid-20th century. As many as 23 caves were described in the Polish Carpathians in 1954 (Klassek 2004). The centre of exploration in this region was situated in the Beskid Śląski Mts where the first group of cavers was established. At the same time, the first cave in the Czech Carpathians was described in 1953 (Tučník 1953). The Czech group of cavers was established in 1969 (Wagner et al. 1990). In Slovakia, the main research started in the 1990s (Bella et al. 2004). The longest and deepest caves have been detected and explored quite recently. It is for example The Wiślańska cave (explored in 2003; Szura 2009) and Miecharska cave in Poland (explored in 2004; Szura 2006) and The Pod Spišskou cave in Slovakia (explored in 2004, Majerníčková et al. 2005). In the Czech Republic, the largest caves were mapped by Foldyna and Pavlica (Foldyna 1968; Foldyna and Pavlica 1968) and by Wagner et al. (1990). The distribution of the caves is shown in Figure 1. Table 3 summarises the most remarkable caves of surveyed Carpathian flysch. The overall number of crevice-type caves in the area of the flysch Carpathians (Poland, Czechia and Slovakia) is higher than 1520 caves: 1350 caves in Poland (Klassek 2004; Ganszer 2012); 120 caves in Czechia (Wagner et al. 1990; Baroň 2001; Hromas et al. 2009); and 50 caves in Slovakia (Bella et al. 2004; Majerníčková et al. 2005).

Tab. 3 The largest crevice-type caves of the flysch Carpathians in Czechia, Poland and Slovakia

cave	l [m]	d [m]	country	source
Wiślańska	2 275	41	Poland	Ganszer (2012)
Miecharska	1 838	55.8	Poland	Ganszer (2012)
W Trzech Kopcach	1 244	32.6	Poland	Ganszer (2012)
Ostra – Rolling Stones	855.5	60*	Poland	Ganszer (2012)
Pod Spišskou	740	25	Slovakia	Majerníčková et al. (2005)
Drwali – Słowiańska	601	23.8	Poland	Ganszer (2012)
Dująca	582	18	Poland	Ganszer (2012)
Głęboka w Stołowie	554	25	Poland	Ganszer (2012)
Cyrilka	520	16	Czechia	Lenart and Wagner (2012)
Kněhyňská *	280	57.5	Czechia	Wagner et al. (1990)
l – length; d – denivelation; * – the biggest denivelation				

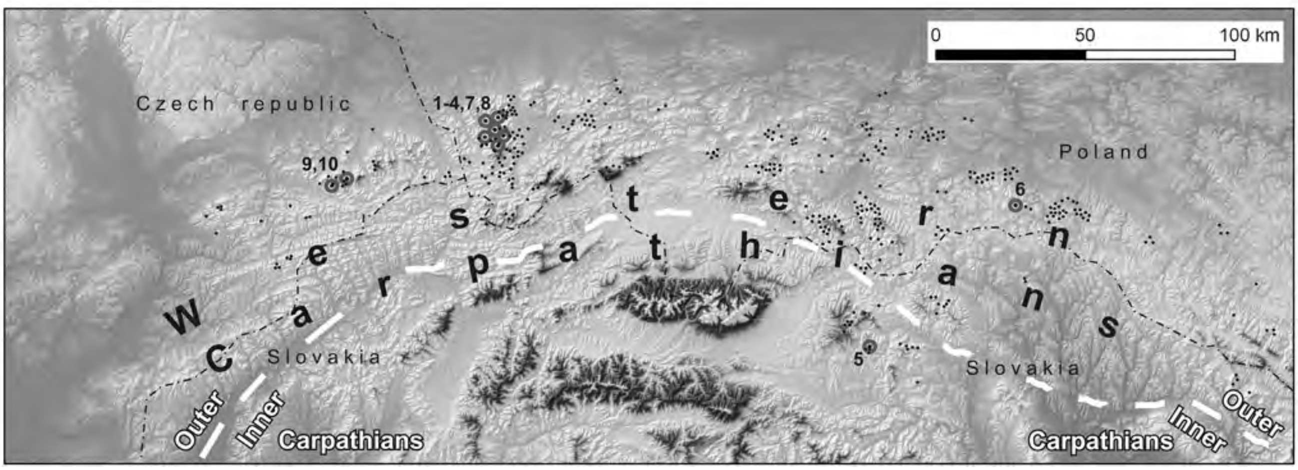

Fig. 1 The approximate distribution of crevice-type caves in the Carpathian flysch of Czechia, Poland and Slovakia – black dots: caves; for 1–10 see Table 3.

4. Evolution and morphology of crevice-type caves

4.1 The origin of crevices in the flysch Carpathians – historical overview

The research of gravitational slope deformations and crevice-type caves has been interconnected in the last ten years (e.g. the case studies of Baroň et al. 2003a; Margielewski and Urban 2003; Pánek et al. 2007, 2010; Klimeš et al. 2012). Thanks to open crevices, we have a unique chance to study the internal structure of landslide bodies from within and to perform a more detailed analysis of slope deformations (Margielewski and Urban 2003; Baroň et al. 2004; Margielewski 2006b). The evolution of slope deformations and occurrence of crevices in anisotropic rock massifs is predisposed by tectonic and lithological discontinuities (e.g. shear fractures, faults, joints, fissures, schistosity and bedding planes; Kirchner and Krejčí 2002; Di Luzio et al. 2004; Margielewski 2006b; Brideau et al. 2009; Jaboyedoff et al. 2009) and driven by various gravitational mechanisms like lateral spreading, toppling, sagging (*sackung*), rotational and translational sliding, and/or composite movement (e.g. Kleczkowski 1955; Němčok et. al. 1972; Varnes 1978; Hutchinson 1988; EPOCH 1993; Cruden and Varnes 1996). Crevice-type caves usually indicate the initial forms of the evolution of gravitational slope deformations (Margielewski and Urban 2003; Margielewski et al. 2007; Margielewski 2009).

First researchers dealing with crevice-types caves in the flysch Carpathians attributed their genesis to the joined effect of Pleistocene periglacial climate and mass movements within tectonically jointed rock mass (Novosad 1956, 1966; Foldyna 1968; Foldyna and Pavlica 1968; Wagner et al. 1990). In spite of the fact that Novosad (1956, 1966) attributed the origin of crevice-type caves to mass movements, he stressed the role of periglacial frost weathering during the Pleistocene cold stages. At the turn of a new millennium, there was a significant progress in the ideas concerning both genesis and age of crevice-type caves (e.g. Margielewski and Urban 2000; Baroň et al. 2003a). In accordance with recent observations, the age of crevice-type caves in the flysch Carpathians is placed especially to the humid periods of the Quaternary, including the Holocene (Margielewski 2003, 2006a; Margielewski et al., 2010; Pánek et al. 2011a, 2011b).

During the evolution of landslides along sliding surfaces, the crevices open and the caves are formed (Margielewski 2004). Within a more advanced stage of the progression of slope deformations, the cave begins to be more unstable in connection with fallen rocks, collapses and sediments fillings. According to Margielewski and Urban (2003) and Margielewski et al. (2007), crevice-type caves are generally extensional (dilation-related) fissures developed in the upper part of slope deformations as initial forms of other landslide headscarps. Some crevice-type caves evolve by the process of fissure macro-dilatancy (Reynolds 1985; Kwaśniewski 1986) that is accompanied by abnormal growth of rock volume during the deformation (Margielewski et al. 2007) and that precedes the evolution of sliding surface (Margielewski 2009). However, recent observations have revealed that crevice-type caves do not only develop as initial fissures. Baroň (2000) distinguishes the initial cave stage above or right within the landslide headscarp where narrow but high crevices are still in the opening phase; the mature cave stage with wider passages and gradually collapsing roofs and the senile stage characterised by the cave system downfall due to rock collapse (Figure 2), but this distinction seems to be rather subjective than scientific. Sometimes the opened crevice is consequently narrowing because of secondary movement of blocks (Foldyna 1968; Wagner et al. 1990; Baroň et al. 2003a). In the light of hitherto investigation, crevice-type caves play a role as primary fissures of incipient landslides (e.g. Jaskinia Malinowska cave, Margielewski and Urban 2003), as a secondary opening fissures within the landslide body (initiation of secondary gravitational movement; e.g. Jaskinia Dolny Waserszlog cave, Pánek et al. 2010) or subsequently narrowing fissures within the landslide body (e.g. Zbojnická cave, Baroň 2001).

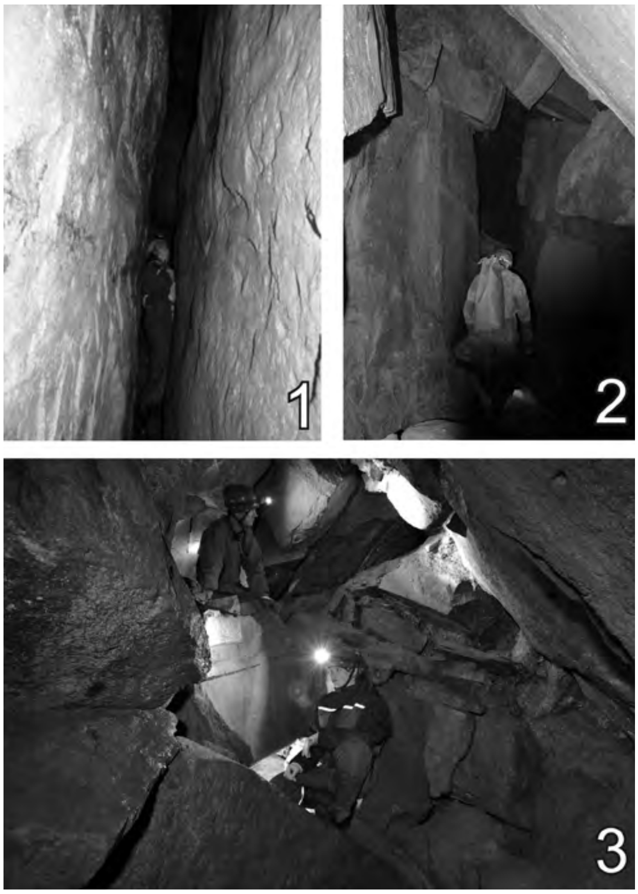

Fig. 2 Stages of cave evolution.

4.2 Basic morphological types and models of the evolution of crevice-type caves

According to recent observations and investigation of crevices, these are frequently present in the internal structure of slope deformations, but only rarely accessible by man. The main crevices are usually narrow but high and narrowing to the bottom or to the top. In some cases the wall face is curved, which is described by the long-term extensional-compressional incidence of tectonic stress (Jaroszewski 1972). With the continuous deformation of the upper part (toppling, lateral spreading and translational slide) the flat ceiling collapses and drops into the opened structure, whereas the rigid beds or boulders form the resulting shape of the ceiling (Margielewski and Urban 2000). According to the vertical distribution of different morphological zones, there are two basic models presented.

(i) Model of translationally, spreading or toppling-induced crevice-type cave:

The simple cross-section of the cave can be presented by an elementary model of the vertical cave (Figure 3) which consists of several levels (Wagner et al. 1990; Margielewski and Urban 2004). First, there is the upper zone of collapsed boulders and debris with small space between them. This zone, which is usually reflected by surface features (sinkholes, trenches), originates from trench walls and overhanging bed collapse. Upslope and downslope walls of crevices are very often disturbed by joints. In such context, main corridors of caves are disturbed joints widened by slope movements. The upper corridors of caves are usually more fissured because of the long-term relaxation of rock massif (Margielewski and Urban 2004). The second layer is described as a zone of wide chambers. This is a rather fissured and relaxed part of massif with longitudinal (L), transversal (T) and diagonal (D_1 and D_2) cracks (terminology after Mastella et al. 1997). The third layer (intermediate zone) is formed by sub-vertical pits with a depth about several meters, connected together by narrowings, filled by boulders and debris. This is followed by the fourth zone which is represented by one narrow crevice described as a tension crack of the landslide (Margielewski and Urban 2004). This is the case of crevice formed by lateral spreading and translational sliding. In the case of toppling process, the crevice narrows to the top and the ceiling is often cluttered with boulders. The fifth (lowermost) vertical layer can be observed in some vertical caves. It is recognizable by narrow crevices, very often differing in their direction from the initial fissure (e.g. Margielewski and Urban 2004). In some specific cases some of the levels are missing or there is a combination of the same type of zones in the caves with a complicated composition (e.g. Wagner et al. 1990).

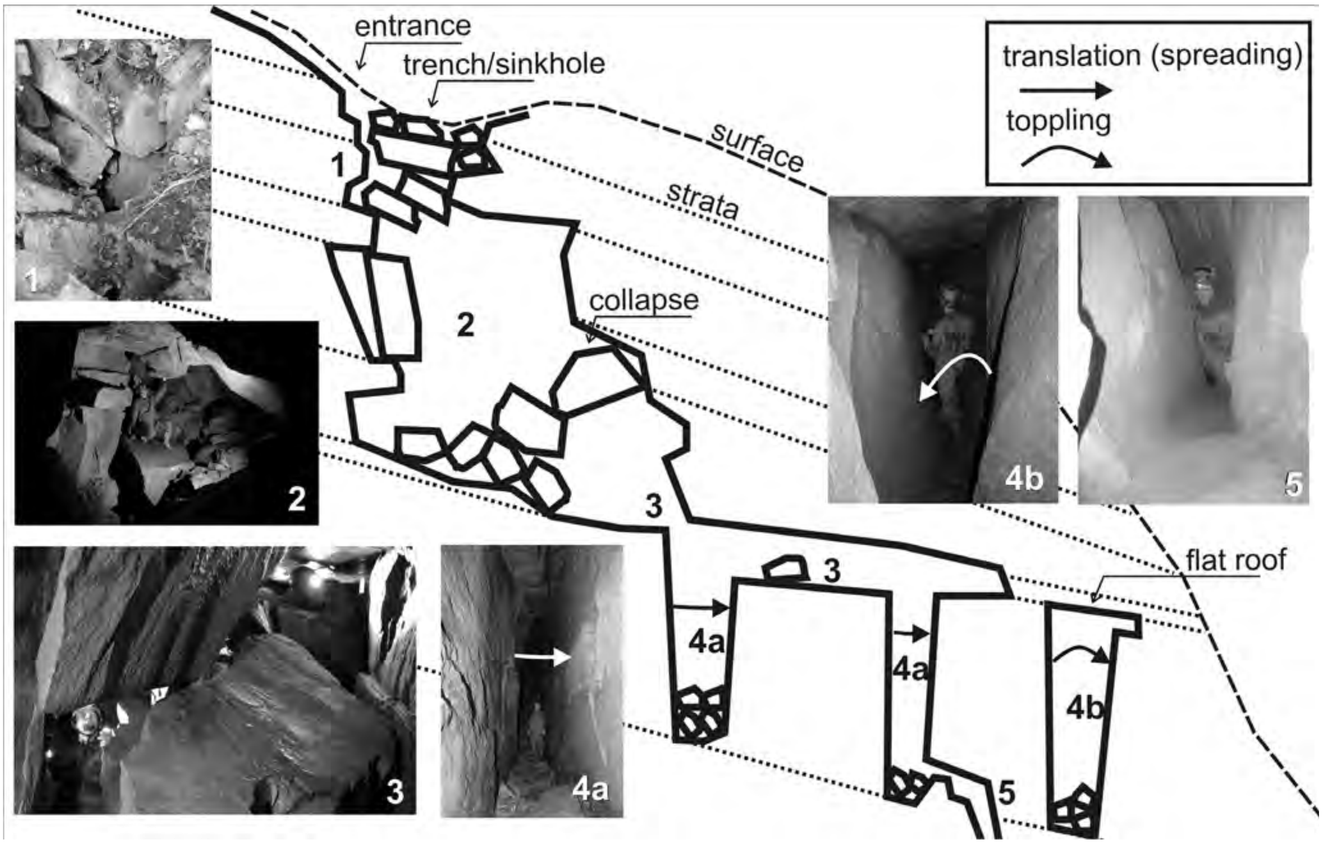

Fig. 3 Model of translationally, spreading, or toppling-induced crevice-type cave – 1: zone of collapsed boulders and debris (the Marná cave, photo: O. Lenart); 2: zone of wide chambers (The Kněhyňská cave, photo: J. Wagner); 3: intermediate zone (The Kněhyňská cave, photo: J. Lenart); 4a: zone of narrow crevices (The Miecharska cave, photo: J. Wagner); 4b: zone of narrow crevices with flat roofs (The Cyrilka cave, photo: O. Lenart); 5: the lowermost vertical layer terminated by narrowing (The Naděje cave, photo: V. Škarpich)

(ii) Model of a rotationally induced crevice-type cave

With the continuous movement of the lower part of crevice (in case of rotational slides), the ordering of vertical zones is different. The ceiling of the cave is narrowing and the bottom is widened and filled with sediments and debris (Figure 4). Sometimes the lower fragments of walls are collapsing. In the first stage of cave, there are often no surface manifestations of deformations and the terrain is flat. This is because the opening of crevices begins from the massif interior and progresses upwards (e.g. Margielewski and Urban 2000).

Due to the frequent subhorizontal bedding of flysch massif (the case e.g. of Silesian Unit in the Outer Western Carpathians), all the types of caves can be combined and blended together. For instance, the zone of rotational-type of crevice-type caves (the zone of debris, boulders and sediment) is followed downwards by the zone of translational-type of crevice-type caves (the zone of wide chambers) within the complex slide. These basic models are complicated by the subsidence of huge rock blocks (10^2–10^3 m^3) in the case of very deep and wide extension of flysch massif. Such vertical zones were distinguished in the Diabla Dziura cave (Rożnów Foothill, Poland) by Margielewski and Urban (2004) and in the Velká Ondrášova jeskyně cave (Moravskoslezské Beskydy Mts, CR) by Kotouč (2011). The upper zone of such caves is highly fissured by the relaxation of rock massif. This zone is followed by the intermediate and lower zones which are created only by a single tension cracks. Finally, there is the lowermost zone of fissures which often differs in the direction contrary to the rest of the cave. Both the presented types of models and their modifications create a typical vertical morphological zonation of crevice-type caves occurring in the area of the flysch Carpathians.

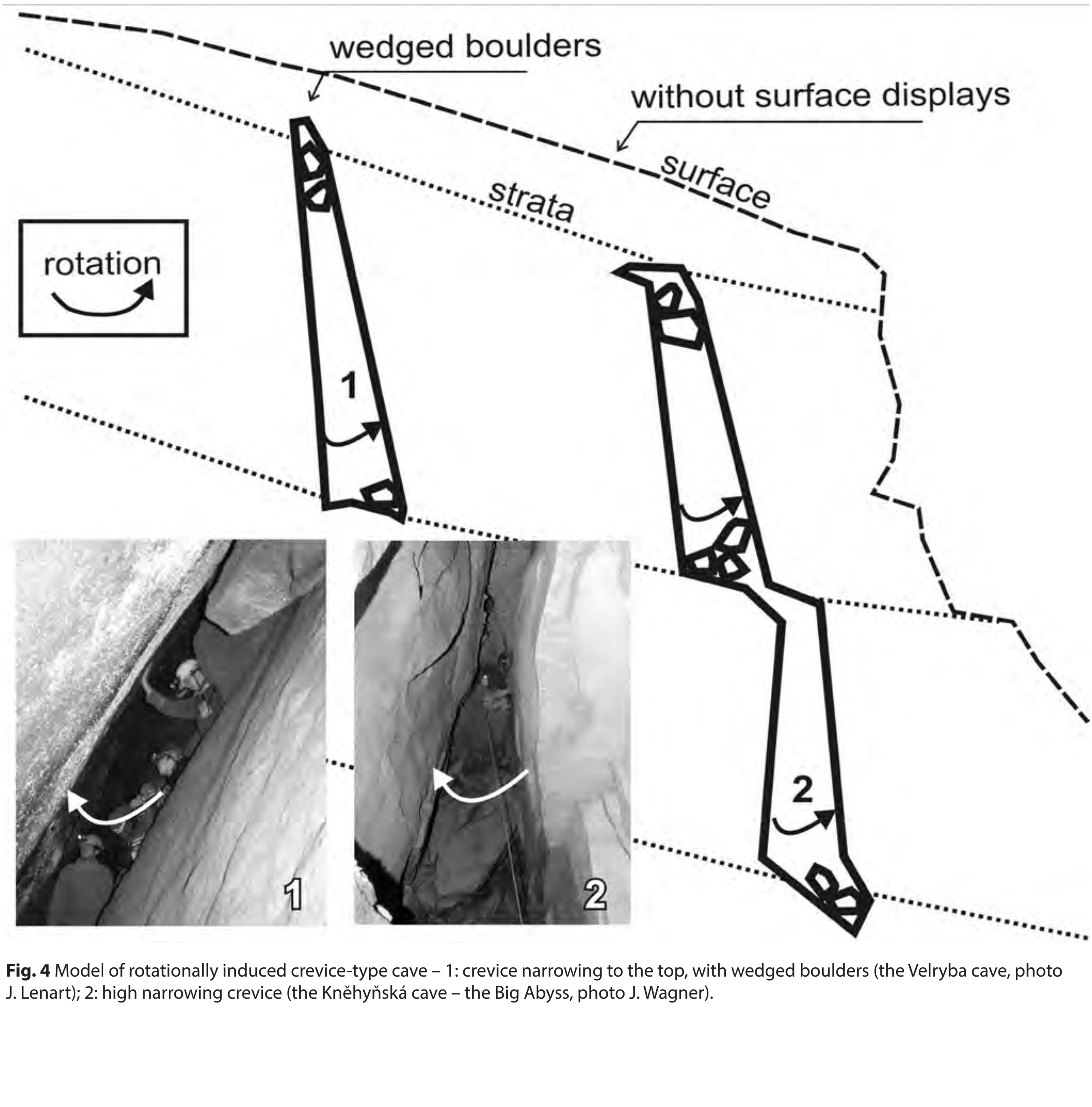

Fig. 4 Model of rotationally induced crevice-type cave – 1: crevice narrowing to the top, with wedged boulders (the Velryba cave, photo J. Lenart); 2: high narrowing crevice (the Kněhyňská cave – the Big Abyss, photo J. Wagner).

4.3 Morphological features and structures within the caves

There are three main types of corridor shapes formed by distinct gravitational movement of flysch massif: (i) 'V-letter-shaped' corridors, where the upper part of crevice is significantly wider than the lower part, (ii) 'A-letter-shaped' crevices, where the ceiling is significantly narrower than the bottom and (iii) 'H-letter-shaped' forms with no difference in the width between the lower and the upper parts of crevice. The first type indicates toppling, the second rotational slides and the third lateral spreading and incipient translational sliding (Margielewski and Urban 2003). Using this approach, there is a problem with large subsided and fissured rock blocks which can indicate a type of movement erroneously. This mistake can partially be eliminated by observing and correlating bedding planes which can usually be detected in the conditions of flysch rocks very well (Figure 3-1, 2, 3 and Figure 5-d, f). Subtle morphology of cave corridors is shaped by water erosion caused by episodic inflows (Urban 2005).

As for the vertical caves, each horizon (cave level detached according to thickness of sandstone/conglomerate beds) is usually shifted staircase (Figure 3 and 4). The elevation of bedding planes, sedimentary intercalations or boundaries in sedimentary sequences between

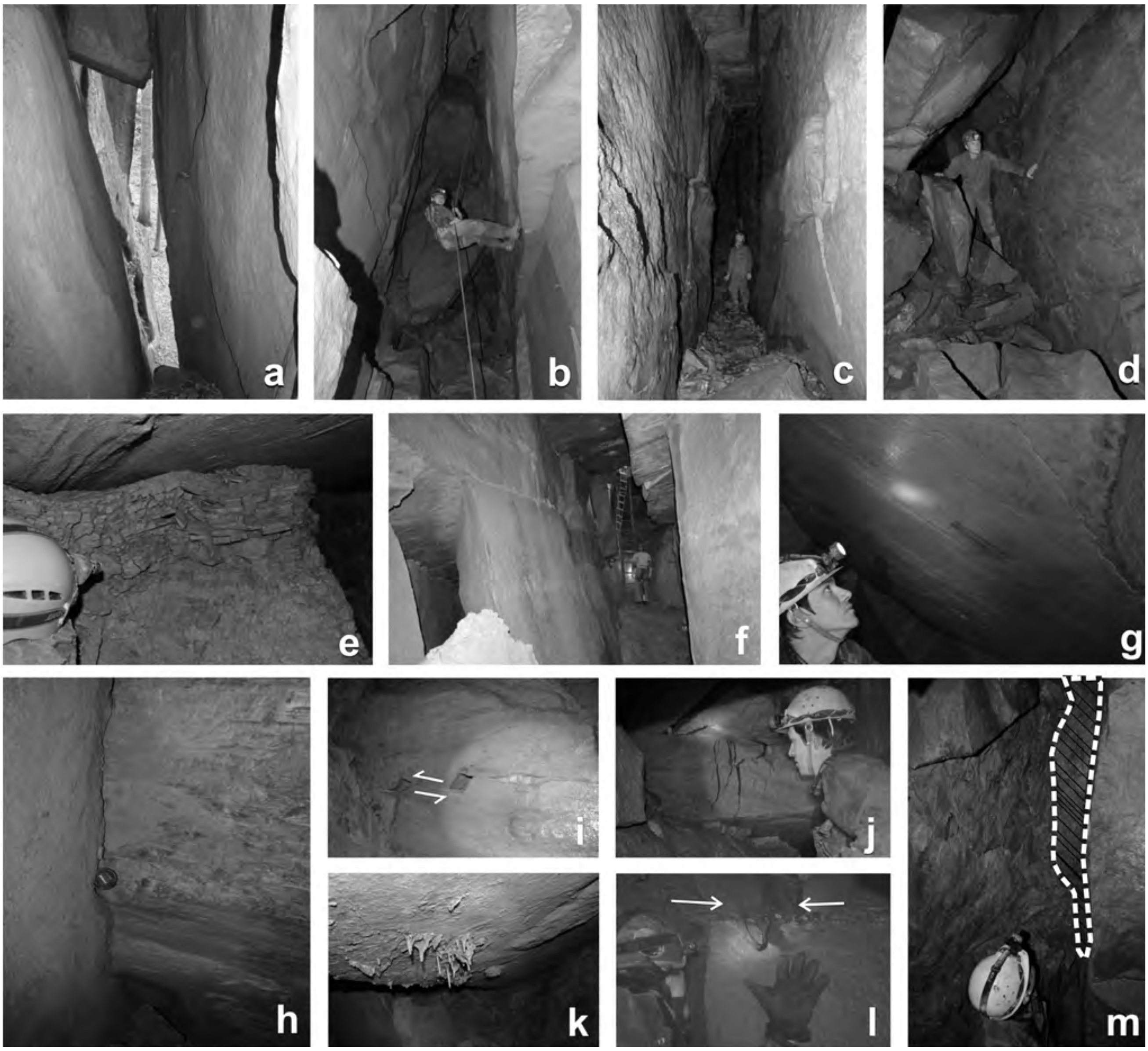

Fig. 5 Morphological features and structures within the caves – a: V-letter-shaped corridor (the Velryba cave); b: A-letter-shaped corridor (the Kněhyňská cave); c: H-letter-shaped corridor (the Miecharska cave); d: corridor filled with fallen blocks (the Kněhyňská cave); e: strata of shales folded by the movement of sandstone block (the Pod Spišskou cave); f: corridor created by interbedded movement of blocks (the Pod Spišskou cave); g: striations on lower surface (the Wiślańska cave); h: slickensided surface with secondarily produced minerals (the Čertova díra cave); i: disrupted walls with the signs of strike-slip movement (the Pod Spišskou cave); j: stressed material of sandstone block (the Wiślańska cave); k: small stalactites (the Pod Spišskou cave); l: compressed root within a narrowing crack (the Salajka cave); m: zones of tectonic breccia within the fault zone (the Kněhyňská cave); photo: a, e–m: J. Lenart; b–d: J. Wagner.

Fig. 6 Different types of ceilings within the crevices – 1: flat ceiling with the strata of shales (the Cyrilka cave, photo J. Lenart); 2: flat sandstone ceiling (the Pod Spišskou cave, photo J. Lenart); 3: flat sandstone ceiling (the Čertova díra cave, photo J. Lenart); 4: partly collapsed and fissured ceiling (the Salajka cave, photo J. Lenart); 5: ceiling created by wedged boulders (the Pod Úplazem cave, photo J. Wagner).

two opposite walls sometimes significantly change along the crevice. These are signs of vertical displacement or rotational movements (Margielewski and Urban 2003). A typical feature of horizontally established caves is a creep (translation) between sandstone/conglomerate beds. During this process, regularly shaped rooms with flat roofs are created by the movement of blocks along the bedding planes (Figure 6-1, 2, 3). In the case of advanced and combined stage of cave evolution, there could be 'corridor-like' areas created between fallen, tilted and cracked rock blocks and boulders (Figure 6-4, 5). Extensive rooms, horizons and corridors are typically connected with each other only by narrow and small crawl spaces (Figure 3-3, 5).

Generally, we can distinguish several microforms and structures commonly occurring in the crevice-type caves (Figure 5). They include (i) forms and structures related to tectonic and gravitational movements within the rock mass, (ii) forms and structures related to fluvial activity, (iii) speleothems and other secondary cave infill and (iv) forms related to biogenic activity.

(i) Faults and fault zones represent shearing planes originated by tectonic deformations. Cave systems are very often laterally limited by them, or the fault zones cross the cave. There are zones of mylonites and tectonic breccia occurring sporadically at the margins of the caves where the fault zone enters the massif (Figure 5-m). The direction of tectonic pressure is expressed by the presence of striations and slickensides, tectoglyphs with ribs, hackle marks and Riedel shears (Davis et al. 1999; Katz et al. 2004; Margielewski et al. 2007). Locally, the whole walls of cave chambers are covered by these features, sometimes with more than one generation of striations (Figure 5-g, h). The direction of striations is often sub-horizontal (on cave walls) or there is a concordant direction of striations with the dip of strata (these are visible on cave ceilings). Faults pass to main corridors and crevices almost perpendicularly. Gravitationally induced movement can trigger the detachment of huge regularly-shaped boulders by pressure incidence on rock wall. While the boulders wedge into the widened crevice, small sub-vertical striations can occur on the walls, what indicates the widening of corridor. The displacement of sedimentary layers and intercalations, striations and other markers can be detectable along fractures analogously to fresh breaks affecting speleothems in karst caves (Jurková and Briestenský 2008). Within the tectonic jointing and gravitational sliding and rotating of blocks, there can also be two types of folding of shales (Figure 5-e): a) folding induced by the pressure of sliding blocks as a reduced form of compression folds (Baroň et al. 2006; Margielewski et al. 2007; Margielewski et al. 2008); b) folding induced by the subsidence of strata into the crevice. Margielewski (2004) reconstructed the rotational character of slope deformation based on the observation of gravitationally induced folds within the Muronka Mt. cave (Beskid Śląski Mts).

(ii) The forms and structures related to fluvial activity are represented by small shallow pools in many caves (proportions usually < 100 × 100 cm) filled with sand or mud (Kotouč 2011; Lenart and Wagner 2012). Underground spring water can create gutters, whereas egutation pits are often created in mud and sand. In some specific cases systems of subterranean drainage evolve with underground fluxes of water and sediments along sliding surfaces (Margielewski et al. 2007).

(iii) Secondary speleothems are sometimes represented in crevice-type caves (Figure 5-k.; e.g. Bosák 2003; Cílek et al. 2003; Majerníčková et al. 2005; Urban et al. 2007a; Bruthans et al. 2009; Lenart and Wagner 2012). The composition of cement within flysch rocks is highly variable – from pure siliceous to calcareous ($CaCO_3$ around 18%) (Urban et al. 2007a). Fruticose sinters of this origin were also mentioned by Demek (1963). Having discovered the same sinters, Cílek et al. (2003) supposed their origin in calcific soils of the early and middle Holocene period and considered them senile now. Out of the crevice-type caves of Polish Carpathians, Urban et al. (2007a) mentioned 7 types of secondary speleothems according to the terminology proposed by Hill and Forti (1997): (1) small (less than 10 cm long) stalactites with a thinly-laminated external part and a soft amorphous internal part with organic matter, (2) crenulated flowstones, (3) moonmilk, (4) crusts, (5) coatings, (6) crystals and (7) helictites. Besides precipitated speleothems, corridors are filled with rock debris, gravel, sand or clay (Wagner et al. 1990). In some microclimatically anomalous and periodically iced caves there are large sand accumulations caused by frost weathering and erosion due to water frozen in the cave (Lenart 2011). Entrance parts of caves (in some specific cases also the deeper parts) very often contain accumulations of organic material (leaves, wood, bones, and guano) (Wagner et al. 1990).

(iv) Biogenic indicators of movements occur in the caves only rarely. For example, the roots of trees which get into the cave are U-letter-shaped by the pressure of blocks in a narrowing crack (Figure 5-l). By contrast, the roots tensed between two opposite walls indicate the widening of crack.

5. Recent progress in crevice-type caves investigation in the light of new geochronological, monitoring and prospecting methods

5.1 Chronology of crevices

Last decades have been characterized by rapid development of geochronological techniques (Walker 2005). Suitable materials used for the determination of minimum ages of crevice-type caves are secondary speleothems originating especially within sandstones and conglomerates containing calcareous cement (e.g. Middle Godula beds, Eliáš 2000). The ages were stated for small stalactites from the crevice-type caves in the Polish Carpathians using radiocarbon and U/Th-series dating (Urban et al. 2007a, 2007b; Margielewski et al. 2012). These ages correspond with the Late Glacial and humid Holocene phases: Preboreal-Boreal transition, Atlantic, Early Subboreal and Subboreal-Subatlantic transition (Starkel 1977; Margielewski 2003, 2006a; Margielewski et al. 2010; Pánek et al. 2011a, 2011b). The dating of speleothems within pseudokarst caves is also underway in other regions. Bruthans et al. (2009) analyzed the calcite sinters of sandstone caves in the Bohemian paradise (Bohemian Massif, Czech Republic) using ^{14}C and/or U/Th dating methods. Sanjurjo-Sánchez and Vidal Romaní (2011) dated two opal-A speleothem samples taken from the NW Spain granites. The results of the TL and OSL dating show their Upper Pleistocene and Holocene age. All these methods supplement ordinary dating methods of mass movements (e.g. Lang et al. 1999) and make crevice-type caves potentially important elements for relative dating and minimal age estimation within the landslide bodies.

There are some possibilities of how to estimate the relative age of crevices. Examples from the Outer Western Carpathians show a relation between the lithology and secondary features occurring within the crevices. The walls of crevices are composed of turbidites of thick-bedded sandstones, conglomerates and thin-bedded shales exposed to water erosion (e.g. Bruthans et al. 2012). Fresh (erosive) or fossil (sometimes secondarily mantled by mineral covers) character of opened crevices is also an indirect indicator of cave (landslide) age. Margielewski and Urban (2004) supposed several generations of crevices according to the occurrence of mineral crusts on walls. Bruthans et al. (2009) used cave walls covered by sinter to observe the erosional rate of rock surface.

5.2 Recent movements and forms

Recent movements forming crevice-type caves are evidenced by (i) glass indicator cracking, (ii) measuring movements by optical-mechanical crack gauges, (iii) dilatometry measuring and (iv) direct observations of fallen boulders, collapses or slumps. A very simple, yet inaccurate technique of how to identify recent movements of rock massif and boulders in caves is by placing glass indicators on sites where the movement of blocks and boulders is expected (Figure 7; Wagner et al. 1990). Since 1978 many of these indicators have been installed into the caves of the Czech Outer Western Carpathians and they are presently cracked or destroyed by the movement of rocks and subsidence of blocks and boulders. In some cases the crack in the broken glass is in the orders of a few centimetres (e.g. the Kněhyňská jeskyně cave). This is an actual proof of recent gravitational movements, but it is often an example only of secondary movements within the cave. Long-term investigation of slow gravitational and tectonical movements is provided with the use of the optical-mechanical crack gauge TM-71 (Stemberk and Jánoš 2002; Stemberk et al. 2008; Petro et al. 2011; Klimeš et al. 2012). In this sense, the movements are detected in three axes (crack dilation, horizontal shear displacement, and vertical displacement) and two types of rotation (Klimeš et al. 2012). This method is also suitable to measure the activity of recent faults (Briestenský and Stemberk 2008). Klimeš et al. (2012) distinguished gravitationally and tectonically induced movement with seasonal fluctuations in the Cyrilka cave (Moravskoslezské Beskydy Mts, Czech Repuiblic) following the results of crack gauge measurement. Baroň et al. (2003a) used the methods of dilatometry – direct measuring of distances between cave walls. He detected seasonal fluctuations of movements depending on sudden precipitation following a dry period. He also measured the subsidence of rock blocks wedged in crevasses.

Fig. 7 Glass indicator installed in the Cyrilka cave; photo: M. Řezák.

Recent movements within crevice-type caves can be summarized in three groups (according to the type of movement): (i) movements induced by landslide, (ii) seasonal movements and (iii) secondary movements of blocks and boulders. The gravitational movement determines the main trend of movements – their direction and velocity. The proper movement for crevice-type cave creation is very slow (creep) and the crevices are formed perpendicular to the movement direction (Baroň et al. 2003a; Margielewski and Urban 2003). Seasonal movements measured within the massif are caused by the volumetric change of rocks which are partly elastic. These cyclically fluctuating movements become evident as narrowing and widening of crevices. The rate of movements depends on the season (annual temperature dilations) and water content in rocks (Klimeš et al. 2012) and decreases with depth (Briestenský et al. 2010). The main gravitationally induced movement and seasonal elastic movement are accompanied by secondary movements of relaxed blocks, boulders and sediments. These collapses are triggered by the slow movement of landslide body and by seasonal changes in the volume of rocks (Wagner et al. 1990).

5.3 Detection of crevices

Recent progress in the exploration of new crevice-type caves in the flysch Carpathians is partly connected with the introduction of new prospecting methods (Lenart et al. 2011; Baroň et al. 2012). Underground crevices without (or with a small amount of) surface features can be detected by various techniques. These are especially: (i) microclimatic methods based on the temperature contrast and air flow measurement and (ii) geophysical sounding.

(i) Microclimatic methods

Every underground crevice cumulates warm air during summer (Hromas et al. 2009). In winter time this air rises up from the subsurface structures and melts the snow (Figure 8; Baroň et al. 2012). According to the occurrence of these places and their temperature, high resolution detection of caverns can be realized. The examples from the Outer Western Carpathians show that the largest cave systems have an average air temperature around 7 °C (Wagner et al. 1990). Therefore, the temperature measured above the anticipated cave reveals the dimensions of subsurface structures (Baroň 2004). Since there is usually a debris layer overlapping and masking crevices, ascending warm air is the unique evidence of the occurrence of crevice-type caves and other relaxed zones within the bedrock. It can be demonstrated on the example of the Čertův Mlýn Mt. slope deformation (Moravskoslezské Beskydy Mts), where there is a string of melting spots running diagonally to the ridge outlines main gravitational morphostructures (e.g. scarps, trenches, and cracks) and a large extent of relaxed bedrock with potentially numerous crevice-type caves (Tábořík 2007).

Dimensions of subsurface structures are also evidenced by the time necessary for the compensation of temperature between the surface and the cave interior (Lenart 2013). In the case of small caves, warm air gets exhausted during the winter, whereas in the case of large cave systems, warm air is usually never spent (Lenart 2013). There is also a difference between the places where the snow is only melted on debris and places where the warm air rises up by chimney-like effect actively – i.e. the case of blow holes (Baroň 2004). If a cave is accessible for man, the circulation of air can be surveyed within the cave system. The directions of air flow indicate the connections between the crevices and corridors and the lakes of cold air indicate the lowermost places of crevices or inflow of cold air from the outside through the fissures (Komárková et al. 2008; Hromas 2009; Lenart 2013). In the Outer Western Carpathians there are some localities, where underground crevices are characterised by strong outflow of cold air onto the surface (Lenart 2011). As for the future investigation of these phenomena, there is a great potential of thermography methods (Nakládal 2006; Baroň et al. 2012). Jian-Hong at al. (2005) and Tsung-Lin et al. (2009) used thermography for the location of weathered zones within concrete walls and for the estimation of the depth of fissures. Analogically, this method could be useful in the detection of subsurface crevices and their extent in natural conditions (Baroň et al. 2012).

(ii) Geophysical techniques

Air-filled voids and caverns represent major subsurface geophysical anomalies (Milsom 2005; Ezersky 2008; Pánek et al. 2010; Gambetta et al. 2011). In the last few years, near-surface geophysical methods (especially ground penetrating radar-GPR, electrical resistivity tomography-ERT, seismic refraction and

Fig. 8 Melting spot, NE slope of the Kněhyně Mt.; photo: P. Tábořík.

microgravimetry) have become widely introduced into geomorphology (Schrott and Sass 2008). Recently there has been extensive geophysical investigation in crevice-type caves, especially in the context of the research of gravitational slope deformations (e.g. Baroň 2004; Pánek et al. 2010; Kotouč 2011). The most useful techniques seem to be ERT and GPR techniques (potentially, also microgravimetry), which are useful in the detection of the geometry of important subsurface structures connected with crevice-type caves such as sliding surfaces, relaxed zones, cavities, lithological boundaries, aquifers and faults (El-Qady et al. 2005; Hradecký at al. 2005; Pánek et al. 2010 and 2011a; Lenart et al. 2011).

Results of recent 2D and 3D ERT measurements in the sites of crevice-type cave show several challenges and limitations (Tábořík 2009). Future investigation and testing of ERT for the detection of crevice-type caves should be conducted using a combination of other methods – especially GPR and microgravimetry as recently usefully tested, for example, in karst terrains (e.g. Gambetta et al. 2011; Gómez-Ortiz and Martín-Crespo 2012).

6. Future challenges in the investigation of crevice-type caves

Many questions remain unanswered concerning the relationships between crevice-type caves and gravitational slope deformations. First, there is a problem of the absolute age of crevice-type forms and their relative age with respect to the succession of slope deformations. The question is, in which stage of slope deformation evolution the cave is established. Is it the early initial stage, as Margielewski and Urban (2003) suppose, or the advanced stage connected with the retrograde progression of an older landslide? Do crevice-type caves evolve just during the main (catastrophic) stage of landslide activity or during the creeping phase of the evolution of a slope failure (initial stage)? This could be revealed by the absolute dating of crevices (to date unrealizable). Very rewarding fact would be the information on relative tendencies of cave progression. Some of the caves evolve directly within the landslide body, some of them are established before the slope moved down rapidly and some of them originate above the landslide headscarp as a result of retrograde progression of slope deformation. Is there any rule stating which type of crevice will occur in a particular stage of slope failure evolution? The age of cave could be determined by investigation of the cave sediments (Hromas et al. 2009). In theory, there are two possible types of sediments to explore. Firstly, there are sediments containing both minerogenic and organic material washed down into the caves from the surface. In the location of a proper sedimentary profile we could use the method of biostratigraphy (Bosák 2003). Organic material would be dated directly by conventional and AMS radiocarbon methods (Bosák 2003). The second type of sediments is chemogenic speleothems, which could be numerically dated by radiocarbon and/or U/Th-series techniques. In spite of the fact that the dating of secondary infill within crevice-type caves only reveals its minimum age (Bosák 2003; Urban et al. 2007a), it brings valuable information on the evolutionary stages of caves and their relation to the succession of slope failures. In the near future, we can expect the expansion of the database of dated speleothems from crevices in the flysch Carpathians bringing important data on the chronology of slope failures and correlation between the genesis of crevice-type caves and palaeoclimatological conditions.

There is also an important question related to the importance of karst processes during the evolution of crevice-type caves (Panoš 1963). Palaeogene sandstones and conglomerates susceptible to karstification are known from crevice-type caves in Slovakia and Poland (e.g. Urban et al. 2007a; Miháľ 2010). There are strong indicators of karstification of sandstones and conglomerates with calcium-rich cement within these crevices (Otvos 1976). Moreover, there is a possibility of coupling these processes with mechanical activity during slope movements. Could the dissolution of calcium-rich cement be one of the preparatory factors for sliding activity in non-karstic rocks? Experience from several world regions reveals that the dissolution of carbonate rocks decreases shear strength of rocks by reducing contact surfaces along bedding planes and other discontinuities (Chigira et al. 2012).

7. Conclusion

The research of gravitational slope deformations and crevice-type caves has become interconnected in the last ten years. Crevice-type caves in the flysch Carpathians of Czechia, Poland and Slovakia are formed by the propagation of both deep-seated and shallow, structurally predisposed gravitational slopes deformations. The crevice-type caves of the same genesis may occur in distinct types of rocks like incoherent sedimentary flysch rocks (sandstones and conglomerates with intercalations of shales), but examples from other settings reveal that they can also affect granites, quartzites, gneiss and other lithologies. Crevice-type caves are mostly regularly narrow-shaped ('A' and 'V' or 'H' letter in cross-section) with high walls and flat roofs or floors. Thanks to crevices, we can study the internal structure of the landslide body from the inside and make an analysis of slope deformations with more precise facts by means of speleological techniques. During the evolution of the slope movement along sliding surfaces the crevices open and caves are formed (i) as primary initial fissures of future landslides, (ii) as secondary opening fissures within the landslide body (initiation of secondary gravitational movement) or (iii) successively closing fissures within the landslide body. Based on the vertical distribution of different morphological zones within caves, there are two basic modes of cave evolution- translation (spreading)- or toppling-induced crevice-type caves and rotationally-induced crevice-type caves. Hitherto dating of speleothems within crevice-type caves of the flysch Carpathians point to their genesis during the humid phases of the Late Glacial and the Holocene and their evolution continues during the present times. Actual movements in the caves detected by various monitoring techniques involve major gravitational downslope activity of landslides, seasonal, pulsation-type movements detected between the cave walls and secondary movements of blocks and boulders within cave passages and chambers.

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RÉSUMÉ

Rozsedlinové jeskyně jako indikátory svahových poruch: Přehled s důrazem na flyšové Karpaty Česka, Polska a Slovenska

Vznik a vývoj rozsedlinových jeskyní je jedním z nejviditelnějších fenoménů spojených s výskytem svahových defomrací v nejrůznějších typech hornin. Rozsedliny se velice často vytvářejí ve flyšových horninách jako například v oblasti Karpat, které jsou tvořeny střídáním subhorizontálně uložených vrstev pískovců, prachovců a jílovců. Článek prezentuje propojení mezi vývojem svahových deformací a výskytem a vývojem rozsedlinových jeskyní, poskytuje přehled o genezi a vývoji rozsedlinových jeskyní jakožto důležitého geomorfologického elementu gravitačně rozrušených svahů flyšových Karpat, prezentuje náhled na soudobou problematiku výzkumu a odhaduje cesty jeho budoucího vývoje.