HABILITATION THESIS

GEOMORPHOLOGY END EVOLUTION OF CREVICE-TYPE CAVES AND ABANDONED UNDERGROUND MINES: STATE OF THE ART AND RESEARCH PERSPECTIVES

(RESTRICTED VERSION WITHOUT SUPPLEMENTED ARTICLES)

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Figure 1: The Cyrilka cave in the Moravskoslezské Beskydy Mountains developed in flysch rocks (conglomerate/sandstone–claystone). Photo: Jan Lenart, 2011

Acknowledgement

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Figure 2: One of the large rooms after clayey slate extraction within the Woodboys mine in the Nízký Jeseník Upland. Photo: Jan Lenart, 2018

ABSTRACT | This habilitation thesis, which comprised ten published studies, contributes to filling the research gap in the genesis, geomorphology, evolution and chronology of crevice-type caves and abandoned underground mines. After the introductory chapters, the research problems are discussed and explained using examples of research articles.

The research articles present exemplary landscapes with a high diversity of crevice-type caves (the Outer Western Carpathians) and abandoned underground mines (the Nízký Jeseník Upland), introduce the essential statistics and parameters, and seek the elementary relations between them. The included review articles summarize current geomorphological knowledge. Other studies address the main geomorphological problems – predispositions, genesis, morphological forms and their types, evolution and dating. The three case studies are interdisciplinary and show the diversity and dynamics of geomorphological forms on the examples of the longest crevice-type cave in Czechia, abandoned collapsed stopes and shallow abandoned underground slate mine. The concluding part of this thesis is devoted to the implications and research perspectives.

KEYWORDS | caves, flysch, mines, Nízký Jeseník, ore, Outer Western Carpathians, pseudokarst, slate

ESSENTIAL DEFINITIONS FOR THE PURPOSE OF THIS THESIS

Crevice-type caves are accessible natural underground cavities situated up to ~10^1 metres deep between semi-independent rock blocks and/or unaffected rock massifs originating from the gravitational extension of rock discontinuities.

Abandoned underground mines are underground cavities situated up to ~10^1 metres deep that originate from man-made rock excavation and are derelict and left to natural processes.

Content

1. An introduction to underground geomorphic systems

The geomorphological properties, genesis and evolution of classical karst caves have traditionally been studied in various karst regions worldwide (e.g., Ballesteros et al., 2019; De Waele et al., 2009; Klimchouk, 2009 and many more). Fewer studies have focused on evaporite karst (De Weale et al., 2017; Gutiérrez et al., 2008), lava caves (Pawar et al., 2016), glacier caves (Małecki et al., 2020) and others. Broad geomorphic references concerning various types of caves were collected by Bella (2011). There are more than five hundred studies concerning topics *caves* and *geomorphology* listed in the Web of Science database. Each of them brings a small piece of the puzzle to the wider picture of **underground geomorphic systems**.

Unlike superficial geomorphic systems, underground geomorphic systems are often closed or semiclosed with clearly identifiable geomorphic catenas (*sensu* Scheidegger, 1973). Whereas a closed underground geomorphic system is completely isolated from the nearest geomorphic system (e.g., Naica cave in Mexico; Forti, 2010), a semiclosed system is connected with the surrounding geomorphic systems through the transfer of material and energy through at least one communication zone or point. Moreover, some underground geomorphic systems connected with the surface through many points or situated shallowly below ground may be considered open geomorphic systems and can be penetrated by liquids, gases or sediments originating from external sources (e.g., Kašing and Lenart, 2020). Many **crevice-type caves** and shallow **underground abandoned mines** belong to that type, and thus, they were omitted from the investigations as presumably less important for scientific research.

In contrast, they can be important for understanding the processes dictating their genesis. For example, underground geomorphic systems may be studied with direct focus on them (e.g., Venezuelan tepuis caves; Aubrecht et al., 2011 and follow-up articles), or they may act as a medium for wider research (e.g., Polish crevice caves for the purpose of access into the interior of landslide bodies; Margielewski and Urban, 2003). The latter case is very important because different underground geomorphic systems serve for research on various scientific topics: geological evolution (Szanyi et al., 2012), climate (Colucci et al., 2016), past biodiversity (Goodfriend and Mitterer, 1993), environmental pollution (Modrá et al., 2017), human history (Goldberg and Sherwood, 2006), landscape evolution (Häuselmann et al., 2015) and natural hazards (Parise et al., 2004).

2. Crevice-type caves and abandoned underground mines – why study them?

As emphasized in the previous chapter, crevice-type caves and abandoned underground mines are rarely researched natural-geographical objects. As of 2022, only a few dozen articles concerning "*crevice-type caves + geomorphology*" and "*abandoned mines + geomorphology*" were listed in the Web of Science database. In contrast, ~200 articles concern the "*karst caves + geomorphology*" topic. Such insufficient publicity is in strong contrast with the fact that crevice-type caves accompany various types of relatively common slope failures (Margielewski and Urban, 2017), and abandoned underground mines can be found in many types of landscapes worldwide (Venkateswarlu et al., 2016). Whereas the genesis, geomorphology and evolution of karst caves is deeply and widely described (Ford and Williams, 2007; De Waele and Gutierrez, 2022), analogous **knowledge about crevice-type caves and abandoned underground mines is rather sparse**.

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As the products of the development of gravitational failures, crevice-type caves belong to geomorphic forms that typically occur within well-developed landslides or deep-seated gravitational slope deformations (Margielewski and Urban, 2003; Lenart and Pánek, 2013). Where gravitational failures dominate as one of the main landscape-forming factors (Alexandrowicz and Margielewski, 2010; Břežný and Pánek, 2017), crevice-type caves can be considered common forms, which contradicts the point of view of many authors describing them as rare or exceptional. They enable entry into the **interior of the gravitational failure**, i.e., to:

- investigate the structure of the landslide (e.g., Lenart et al., 2014)
- access the geological outcrops (e.g., Kašing et al., 2020)
- measure structural parameters (e.g., Lenart and Horáček, 2021)
- get samples (e.g., Lenart et al., 2018)
- detect gravitational movement mechanism and orientation (e.g., Lenart et al., 2018)
- measure rate of gravitational movement (e.g., Klimeš et al., 2011)
- explore infiltration cave sediments (waiting investigation, see Chapter 7.3).

Moreover, crevice-type caves act within the landscape as **natural habitat** with defined parameters (Lenart, 2011; Lenart and Miklín, 2017; Wagner et al., 1990):

- structure and morphology (e.g., Lenart, 2015)
- cave infills (e.g., Urban et al. 2007 and 2015)
- liquids and gasses (e.g., Kašing and Lenart, 2020)
- dynamics of material and energy fluxes (e.g., Kašing and Lenart, 2020)
- biodiversity (e.g., Lenart and Kupka, 2018).

In some areas, crevice-type caves may be preserved as unique and rare (nonzonal) natural habitats with the occurrence of unexpected, rare or endangered species, including troglophiles, as revealed in the Cyrilka cave (Lenart et al., 2018; Lenart and Kupka, 2018). Thus, studying such caves and their geomorphological parameters is important for understanding the geo-ecosystems of such specific areas.

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Abandoned underground mines are perceived as historical monuments or reminders of previous working methods and landscape developments thorough history (Soni, 2020; Schuchová and Lenart, 2020). Similar to crevice-type caves, they stand as **unique geological outcrops** uncovered within various lithologies and structural settings. Overall, they enable us to study the following:

- rock environment (e.g., Wichert, 2020)
- neotectonics (e.g., Stemberk and Košťák, 2008)
- geomechanical and geochemical processes (e.g., Lenart et al., 2017; Melim and Spilde, 2021)
- human history (e.g., Soni, 2020)
- past landscape changes (e.g., Popelka et al., 2016).

Although abandoned underground mines are perceived as devastated and contaminated sites (Schuchová and Lenart, 2020), in reality, they act as nonzonal **natural habitats** with the occurrence of specialized species, e.g., bats (Rydell et al., 2019) or various types of bacteria evolved under unique geochemical conditions (Falteisek and Čepička, 2012). The abandoned underground mine habitat can be characterized by following parameters:

- structure and morphology (waiting for investigation)
- mine infills (e.g., Sawłowicz et al., 2014)
- liquids and gasses (e.g., Lenart et al., 2022)
- dynamics of material and energy fluxes (e.g., Lenart et al., 2022)
- occurrence of archaeological material (Wero and Martin, 2021).

Moreover, abandoned underground mines are sometimes prone to **catastrophic geohazards** (Waltham et al., 2011; Wapwera et al., 2015), i.e.,

- mining-induced seismic event
- mining-induced landslide
- subsidence
- collapse
- flooding
- explosive gas release
- secondary environment contamination.

3. Published contributions

Published studies introduce the typical landscapes with the occurrence of crevice-type caves and abandoned underground mines, summarize the state of the art of geomorphological research, discuss the main geomorphic phenomena and bring the results of particular investigations of representative study sites.
For the purpose of this thesis, articles are divided into two chapters: *Crevice-type caves* and *Abandoned underground mines*. Within both chapters, the articles are arranged in the following logical order: *introduction of exemplary landscape → research review → general geomorphological issues → case studies*.

LIST OF PUBLISHED ARTICLES (SORTED BY ORDER IN THESIS):

- Lenart J, Miklín J, 2017. Pseudokarst Caves of the Outer Western Carpathians, Czechia. Journal of Maps 13:37–46. https://doi.org/10.1080/17445647.2016.1252804

- Lenart J, Pánek T, 2013. Crevice-type caves as indicators of slope failures: a review paying a special attention to the flysch Carpathians of Czechia, Poland and Slovakia. Acta Universitatis Carolinae - Geographica 48:35–50. https://doi.org/10.14712/23361980.2015.3

- Lenart J, Horáček M, 2021. Complex landslides: discrepancy between varied partial movement mechanisms detected in crevice-type caves and by formal investigation. Bulletin of Engineering Geology and the Environment 80:979–992. https://doi.org/10.1007/s10064-020-02033-0

- Lenart J, Pánek T, Dušek R, 2014. Genesis, types and evolution of crevice-type caves in the Flysch Belt of the Western Carpathians (Czech republic). Geomorphology 204:459–476. https://doi.org/10.1016/j.geomorph.2013.08.025

- Lenart J, 2015. Morphological patterns of crevice-type caves in sedimentary rocks of the Outer Western Carpathians (Czech Republic). Journal of Cave and Karst Studies 77:165–176. https://doi.org/10.4311/2014ES0113

- Lenart J, Kašing M, Táborík P, Piotrowska N, Pawlyta J, 2018. The Cyrilka Cave—the longest crevice-type cave in Czechia: structural controls, genesis, and age. International Journal of Speleology 47:379–392. https://doi.org/10.5038/1827-806x.47.3.2210

- Schuchová K, Lenart J, Miklín J, Horáček M, 2023. Abandoned underground mines in Nízký Jeseník Upland (Czechia). Journal of Maps, published online. https://doi.org/10.1080/17445647.2023.2175733

- Schuchová K, Lenart J, 2020. Geomorphology of old and abandoned underground mines: Review and future challenges. Progress in Physical Geography-Earth and Environment 44:791–813. https://doi.org/10.1177/0309133320917314

- Lenart J, Tichavský R, Večeřa J, Kapustová V, Šilhán K, 2017. Genesis and geomorphic evolution of the Velké pinky stopes in the Zlatohorská Highlands, Eastern Sudetes. Geomorphology 296:91–103. https://doi.org/10.1016/j.geomorph.2017.08.031

- Lenart J, Schuchová K, Kašing M, Falteisek L, Cimalová Š, Bílá J, Ličbinská M, Kupka J, 2022. The abandoned underground mine as a semi-natural ecosystem: The story of Flaschar's mine (Czechia). Catena 213:106178. https://doi.org/10.1016/j.catena.2022.106178

4. Research methods

To achieve the goals of investigating the genesis, geomorphology and evolution of crevice-type caves and abandoned underground mines, the following main research methods were used in the attached studies:

a) *Review of existing research results*
The available literature was collected and examined, mainly from scientific databases, archival materials and historical maps but partly also from popular scientific sources. Relevant data and maps were digitized, and derivative outputs were obtained.

b) *Field mapping*
One of the basic research tools was field mapping, specifically, but not exclusively, geomorphological mapping and speleological mapping using the DistoX system (Heeb, 2008). Emphasis was placed on deciphering the underground morphology and the location of the underground cavities in relation to the topography.

c) *Photo documentation, maps and figures*
Morphological macroelements and details were documented with a camera. The work also resulted in a number of speleological and topographical maps, including two large maps on the scale of the regional territory. A number of graphical diagrams and tables were prepared to better understand the presented results.

d) *DEM analyses*
Digital elevation models were built for comparison with maps of caves and underground mines to understand the relation between underground features and topography. Detailed digital elevation models were created using geodetic station.

e) *Structural measurement*
Parameters of joints, bedding planes and faults within the caves and mines were measured with a geological compass, and the data were subsequently processed and visualized stereoscopically.

f) *Electrical resistivity tomography*
Both 2-D and 3-D electrical resistivity tomography surveys (Loke, 1997) were conducted to reveal the geological structure of the rock surroundings of the underground cavities.

g) *Radiocarbon dating*
To help reveal the minimum age of the Cyrilka crevice-type cave, radiocarbon dating of soda-straw stalactites was conducted (see Lenart et al., 2018).

h) *Tree ring chronology*
A dendrogeomorphological approach was used to reveal the recurrence of rock falls and other types of failures disturbing the rocky margins of the Velké Pinky stopes (see Lenart et al., 2017).

i) *Classifications and statistical testing*
The collected data were filtered and qualitatively classified. Quantitative classifications, cluster analyses and dependency testing were used to reveal the relations and dependencies of different datasets.

j) *Designing models*
Design of evolution and morphological models (block diagrams) showing the development of different morphological types of caves or cascades of geomorphological forms in mines was carried out.

k) *Other methods used (in short)*

- rock sampling and mineral composition analyses
- Schmidt hammer testing of rock strength differences
- mine water quality assessment
- microclimatic measurement
- biological inventory.

All main research methods as well as additional methods and analyses are described in detail in the supplemented papers.

5. Crevice-type caves

Crevice-type caves are accessible natural underground cavities situated up to ~10^1 metres deep (for the purpose of this thesis) between semi-independent rock blocks and/or unaffected rock massifs originating from the gravitational extension of rock discontinuities. Margielewski and Urban (2003) define crevice-type caves as underground spaces between two rock blocks when at least one of them is affected by gravitational movement. Due to their low attractivity and poor accessibility, crevice-type caves were traditionally visited and mapped by cavers, with limited research focused on their genesis, geomorphology, evolution and landscape function.
Nevertheless, thorough the history of their investigation, essential milestones were as follows:

- 1983: J. Vítek defined the crevice-type cave in the International Journal of Speleology (Vítek, 1983).
- Early theories underlined the morphogenetic role of ice during cold climatic periods (Novosad, 1956; Kunský, 1957; Demek, 1963; Foldyna, 1968).
- 2003: Various authors clearly connected their occurrence with the development of slope failures (Baroň et al., 2003; Margielewski and Urban, 2003).
- 2013: J. Urban and W. Margielewski classified crevice-type caves according to their geomechanic behaviour and morphogenesis (Urban and Margielewski, 2013; Margielewski and Urban, 2017).
- ~2015: First indirect dating of crevice-type cave formation (Farrant et al., 2015; Urban et al., 2015).

5.1 Flysch Carpathians: Example landscape of crevice-type caves

Study: Lenart J, Miklín J, 2017. Pseudokarst Caves of the Outer Western Carpathians, Czechia. Journal of Maps 13:37–46. https://doi.org/10.1080/17445647.2016.1252804

Commentary: The study analyses the geologically homogenous area with the typical dense occurrence of crevice-type caves. It introduces their basic statistics and parameters and seeks the elementary relations between them. It shows the overall diversity of the caves within a relatively uniform mid-mountain landscape. It is supplemented by the illustrative paper map of the area.

Share of Jan Lenart: 60 %

- *general idea*
- *field investigation*
- *data preparation*
- *text writing*
- *general map preparation.*

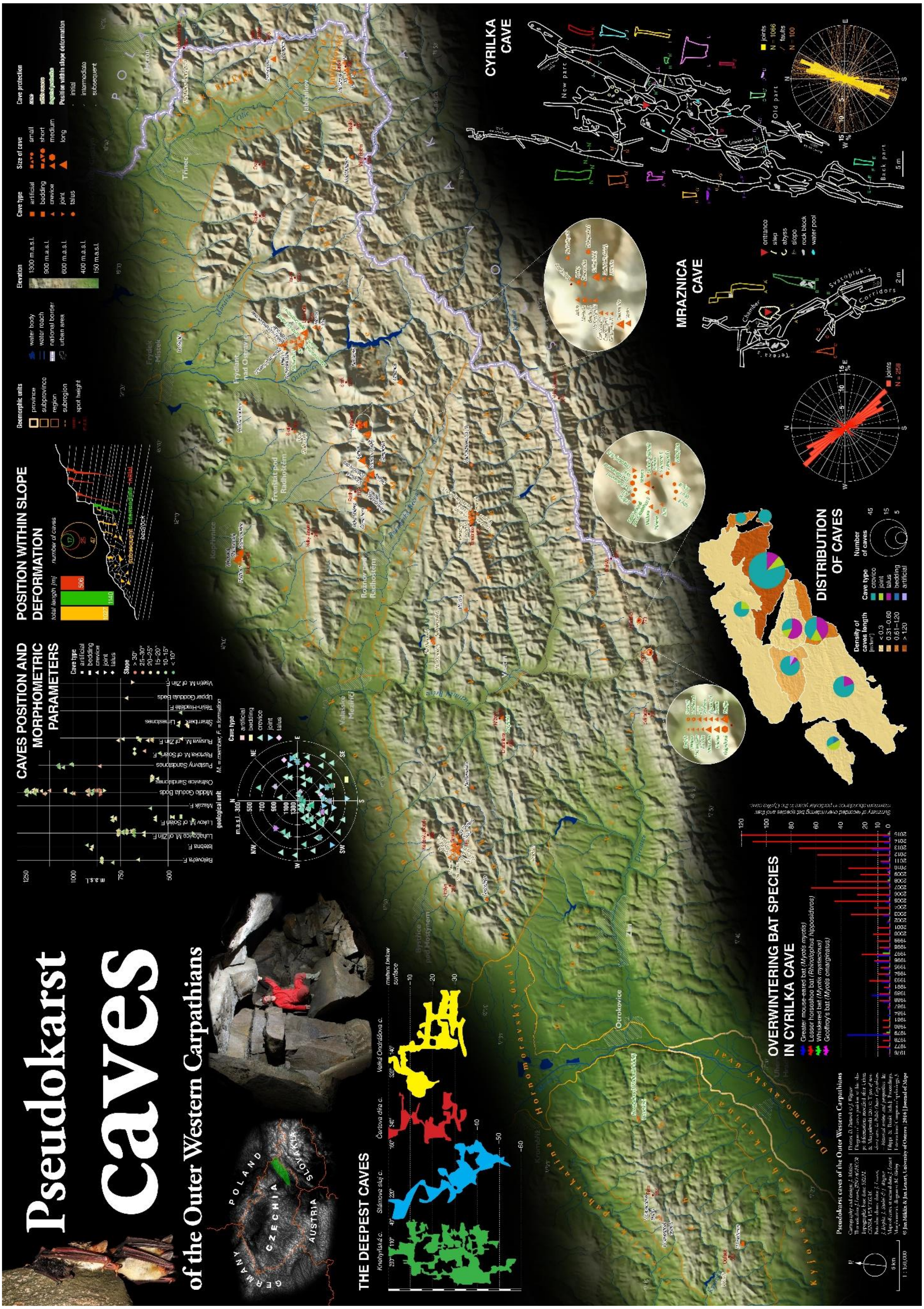

Figure 3: Paper map Pseudokarst caves of the Outer Western Carpathians (Lenart and Miklín, 2017).

5.2 Crevice-type caves and their relation to slope failures

Study: Lenart J, Pánek T, 2013. Crevice-type caves as indicators of slope failures: a review paying a special attention to the flysch Carpathians of Czechia, Poland and Slovakia. Acta Universitatis Carolinae - Geographica 48:35–50. https://doi.org/10.14712/23361980.2015.3

Commentary: Regarding the example of flysch Carpathians, the paper summarizes the hitherto knowledge about the relation of crevice-type caves to slope failures. Recent theories say that slope movements are the main morphogenetical force creating such caves, which is in accordance with the most recent classification by Urban and Margielewski (2013) or Margielewski and Urban (2017). Older theories underlining the influence of ice during cold climatic periods (e.g., Novosad, 1956; Kunský, 1957; Demek, 1963; Foldyna, 1968) are now receded.

Share of Jan Lenart: 90 %

- *general concepts*
- *review data preparation*
- *text writing*
- *graphics.*

Figure 4: The crevice-type abyss within the Velká Ondrášova cave in the Moravskoslezské Beskydy Mountains developed in flysch rocks (sandstone–claystone). Photo: Jan Lenart, 2012

Study: Lenart J, Horáček M, 2021. Complex landslides: discrepancy between varied partial movement mechanisms detected in crevice-type caves and by formal investigation. Bulletin of Engineering Geology and the Environment 80:979–992. https://doi.org/10.1007/s10064-020-02033-0

Commentary: The paper show how varied may be the particular rock movement within the landslide structure and how heterogenous crevice-type caves may develop as a result. Examples from different lithologies and landscapes are included: river canyon in the Bohemian Massif (orthogneiss), coastal cliffs of the Crimean Mountains (limestone), isolated hills (limestone) or mountain ridges (sandstone-dominated flysch rocks). Moreover, the paper shows the limitations of the methodology when evaluating the general slope failure mechanism from the crevice-type cave morphology.

Share of Jan Lenart: 80 %

- *general concepts*
- *field investigation*
- *raw data preparation*
- *text writing*
- *graphics.*

Figure 5: The Brněnská cave in the Znojmo highland developed in orthogneiss. Photo: Jan Lenart, 2013

5.3 Geomorphological phenomenon of crevice-type caves

Study: Lenart J, Pánek T, Dušek R, 2014. Genesis, types and evolution of crevice-type caves in the Flysch Belt of the Western Carpathians (Czech republic). Geomorphology 204:459–476.
https://doi.org/10.1016/j.geomorph.2013.08.025

Commentary: Regarding the example of Czech part of the flysch Western Carpathians, the paper reveals the typical structural, geomorphological and topographical conditions of hillslopes connected with the crevice-type caves occurrence, i.e., predispositions of their development. Moreover, it reveals the main underground geomorphological features and evolution models of such caves. The work follows the previously published article by Margielewski and Urban (2003) from Polish flysch Carpathians.

Share of Jan Lenart: 70 %

- *general concepts*
- *field investigation*
- *data processing*
- *text writing*
- *graphics.*

Figure 6: The Big Abyss within the Kněhyňská cave in the Moravskoslezské Beskydy Mountains. The cave is developed in flysch rocks (sandstone–claystone). Photo: Josef Wagner, 2009

Study: Lenart J, 2015. Morphological patterns of crevice-type caves in sedimentary rocks of the Outer Western Carpathians (Czech Republic). Journal of Cave and Karst Studies 77:165–176.
https://doi.org/10.4311/2014ES0113

Commentary: The paper reveals the regularities of both the horizontal and vertical arrangement of the crevice-type cave passages, typical detailed morphology of crevices and micromorphology of cave walls and ceilings. The paper is supplemented by a series of photographs and schemes.

Share of Jan Lenart: 100 %

- *general concepts*
- *field investigation*
- *data processing*
- *text writing*
- *graphics preparation.*

Figure 7: The Pod Spišskou cave in the Levočské vrchy Mountains in Slovakia, developed in sandstone-dominated flysch rocks. Photo: Jan Lenart, 2012

5.4 Half a kilometre long Late Pleistocene cave

Study: Lenart J, Kašing M, Tábořík P, Piotrowska N, Pawlyta J, 2018. The Cyrilka Cave—the longest crevice-type cave in Czechia: structural controls, genesis, and age. International Journal of Speleology 47:379–392. https://doi.org/10.5038/1827-806x.47.3.2210

Commentary: Regarding the example of the largest crevice-type cave in Czechia, the paper broadly discusses the complex problematics: geological and structural control, geomorphological setting, cave genesis, age and geomorphological evolution. Based on this comprehensive study, the cave is proposed for legislative protection as a natural monument.

Share of Jan Lenart: 80 %

- *general concepts*
- *field investigation*
- *data processing*
- *text writing*
- *graphics preparation.*

Figure 8: The Back part of the Cyrilka cave in the Moravskoslezské Beskydy Mountains. The cave is developed in conglomerate/sandstone dominated flysch rocks. Photo: Martin Kašing, 2019

6. Abandoned underground mines

An abandoned underground mine is an underground cavity situated up to ~10^1 metres deep (for the purpose of this thesis), originating from man-made rock excavation that is derelict and left to natural processes. Unger (2017) defines abandoned underground mines as mines for which mining leases or titles no longer exist and for which the responsibility for their rehabilitation cannot be allocated to any individual, company or organization that has undertaken mining activities. According to UNEP and COCHILCO (2001), there are more than one million abandoned mine lands worldwide.

They were traditionally investigated for the purpose of natural resources, stability of rock mass and natural hazard prevention, with limited research focused on their historical genesis, geomorphology, recent natural evolution and landscape function.

6.1 Nízký Jeseník Upland: Example landscape of abandoned underground mines

Study: Schuchová K, Lenart J, Miklín J, Horáček M, 2023. Abandoned underground mines in Nízký Jeseník Upland (Czechia). Journal of Maps, published online. https://doi.org/10.1080/17445647.2023.2175733

Commentary: The paper analyses the geologically homogenous area with the typical dense occurrence of abandoned underground mines after historical slate and ore extraction. It introduces their basic parameters and seeks the elementary statistical relations between them. It shows the overall diversity of the mines within the relatively uniform Variscan upland. It is supplemented by the illustrative online web map of the area accessible via link:
https://www.arcgis.com/apps/webappviewer/index.html?id=48e5fc661ea44b6bbd59b02d879437e6.

Share of Jan Lenart: 30 %

- *general idea*
- *field investigation*
- *data preparation*
- *text writing.*

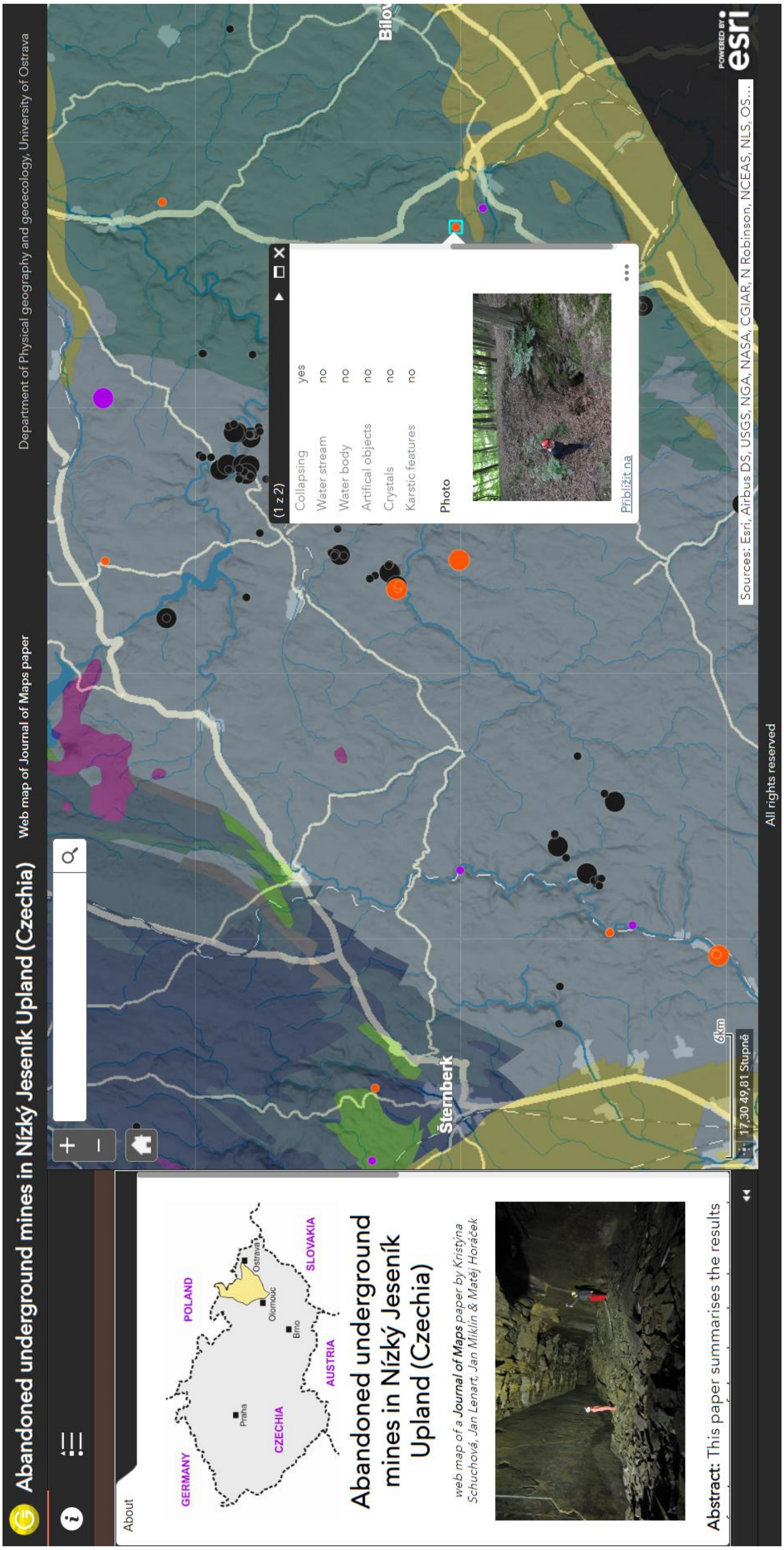

Figure 9: Web map Abandoned underground mines in Nízký Jeseník Upland (Czechia) published together with the article by Schuchová et al. (2023).

6.2 Geomorphology of abandoned underground mines – state of the art review

Study: Schuchová K, Lenart J, 2020. Geomorphology of old and abandoned underground mines: Review and future challenges. Progress in Physical Geography-Earth and Environment 44:791–813. https://doi.org/10.1177/0309133320917314

Commentary: The paper reviews the thus far little summarized issues of geomorphology of abandoned underground mines in the topics: (i) detection of mines, (ii) subsidence and collapses, (iii) inside-mine motions, (iv) geomorphic reclamation and remediation, (v) geodiversity. To date, this is the first comprehensive review of this topic. It also summarizes the specific geomorphic forms of abandoned underground mines and challenges their future research.

Share of Jan Lenart: 50 %

- *general concepts*
- *text preparation*
- *graphics preparation.*

Figure 10: The inclined shaft of the Soví mine after clayey slate extraction in the Nízký Jeseník Upland. Photo: Jan Lenart, 2019

6.3 Collapsed ore stopes and fragile underground slate mine

Study: Lenart J, Tichavský R, Večeřa J, Kapustová V, Šilhán K, 2017. Genesis and geomorphic evolution of the Velké pinky stopes in the Zlatohorská Highlands, Eastern Sudetes. Geomorphology 296:91–103. https://doi.org/10.1016/j.geomorph.2017.08.031

Commentary: The complex research including historical-geomorphological investigation of the well-known postmining site and evaluation of recent gravitational processes revealed the gradual evolution of specific postmining landforms – distinct shafts and superficial stopes with rocky margins, preserved within the historical ore mining landscape. The study shows how such landforms evolved during the time since their abandonment.

Share of Jan Lenart: 50 %

- *general concepts*
- *field investigation*
- *data processing*
- *text writing*
- *graphics preparation.*

Figure 11: Winze within the abandoned ore mine in the Zlatohorská Highland. The mine was established in crystalline rocks. Photo: Josef Wagner, 2012

Study: Lenart J, Schuchová K, Kašing M, Falteisek L, Cimalová Š, Bílá J, Ličbinská M, Kupka J, 2022. The abandoned underground mine as a semi-natural ecosystem: The story of Flaschar's mine (Czechia). Catena 213:106178. https://doi.org/10.1016/j.catena.2022.106178

Commentary: An interdisciplinary comprehensive study showed how important the geomorphology of an abandoned underground mine is for the functioning and evolution of its other physical-geographic parameters, such as microclimate. It has also been shown that the ecosystem of an abandoned underground mine is fragile and prone to change and that it forms an integral whole together with the surrounding surface environment.

Share of Jan Lenart: 70 %

- *general concepts*
- *field investigation*
- *data processing*
- *text writing*
- *graphics preparation.*

Figure 12: The ceiling of large room in the Flaschar's mine formed by geological fold. The mine extracted clayey slate rocks of the Nízký Jeseník Upland. Photo: Josef Wagner, 2017

7. Implications

7.1 Environmental and cultural values

If we consider the crevice-type caves and abandoned underground mines as geomorphic mezoforms, we can proceed to assess their importance and value. From the ecosystem point of view, crevice-type caves and underground mines should be perceived as nonzonal natural habitats with specific physical geography parameters – air temperature, relative air humidity, air ventilation, illumination or water chemistry, as documented in the examples of Cyrilka cave (Lenart et al., 2018) and Flaschar's mine (Lenart et al., 2022). The flow of nutrients and other elementary substances is also unique there (e.g., Falteisek and Čepička, 2012).

As rocks or wetlands, crevice-type caves and abandoned underground mines are (semi)natural habitats with the occurrence of specialized or endangered and protected fauna (Mysłajek and Szura, 2008; Armstrong et al., 2022; Diamond and Diamond, 2014). Some of these species lost their original habitat due to climate warming after the retreat of Pleistocene glaciers (Lenart and Kupka, 2018), or they found recent alternate habitats after they survived quaternary climatic fluctuations (Marin and Palatov, 2021).

In addition to their environmental values, both types of underground cavities also reveal cultural values, as documented by comprehensive studies (Lenart et al., 2018 and 2022). Crevice-type caves were used by mountain shepherds as storages of milk products (Wagner et al., 1990), or they stood as attractive objects in the early beginning of tourism (Kozdas, 2007). Abandoned underground mines are an important source of knowledge about the working methods of human ancestors and about their customs and spirituality (Machado and Figueirôa, 2022; Soni, 2020). Moreover, they reveal data about past land use changes (Popelka et al., 2016) and are attractive for underground guided tours (Koudelková et al., 2022).

7.2 Problems of preservation and legislative protection

Although both evaluated types of underground cavities are already described in the available literature and their individual components, properties and role in the ecosystem are gradually investigated, it should be noted that their natural and cultural values are not sufficiently appreciated and protected by human society. Using the example of Czechia, it can be shown that although all caves are protected according to the Nature and Landscape Protection Act (Act No. 114), in reality, many of the crevice-type caves are not registered in the databases of protected natural objects, e.g., JESO database, and the entrances to them are neither known to the landowners nor are they marked in the field.

In the case of abandoned mine workings, the situation is dire, as despite their undisputed cultural and natural values, their protection is not legislated for, and only a fraction of the almost two thousand historical mine workings (ČGS, 2022) are protected. Thus, they are rapidly disappearing from the landscape by collapsing, as we showed in a study summarizing 137 mines in a regional-scale area (Schuchová et al., 2023). Nevertheless, I assume that the situation with the protection and preservation of both types of underground cavities is much worse in many countries worldwide.

If crevice-type caves or abandoned mines already enjoy some type of protection, it is usually set insufficiently or incorrectly, regardless of spatial relationships and flows of substances. Common shortcomings include:

1. *Insufficient or incorrect definition of the protection zone on the surface above the underground cavity*
   This common error is based on insufficiently accurate delineation of the underground cavity or incorrect projection of a cavity map with a digital elevation model or other type of surface representation. Another common error is the protection of only part of the surface above the underground cavity due to the unknown total extent of the underground object.

2. *Failure to recognize or neglect values*
   This negative phenomenon manifests itself in both crevice-type caves and abandoned mine workings. Both types of underground cavities are often perceived as uninteresting, drab, unworthy of protection, and lacking significant natural and cultural values. This often stems from insufficient exploration or one-sidedness of the survey, where only biological values are considered, for example, or in the case of mine workings, only historical ones. Other values (geological, geomorphological, hydrological, microclimatic, sedimentological, architectural, technological, ecosystem) are often not assessed.

3. *Taken out of context*
   Related to the previous point. Where values are assessed, it is often done in isolation, without spatial, chronological or ecosystem context. Thus, in practice, subterranean objects of which individual parts do not reach significant individual values but where there are measurable, e.g., significant contrasts, transitions, gradients, cascades of processes and substances, atypical relationships or, on the contrary, the absence of typical forms or processes, are assessed incorrectly as having little value.

4. *Blind protection*
   This error occurs when we protect a particular feature only underground but do not notice that the source of its significance lies outside the protected area (e.g., we protect the water stream flowing through the cave or mine but do not realize that its unprotected spring is situated within the neighbouring unprotected forest).
   A similar error is the protection of only a part of the underground cavity, where especially in the case of mines, the destruction of the remaining part (e.g., burying a shaft) threatens the collapse of the entire underground ecosystem (e.g., by stopping the ventilation system).

5. *Exclusion from the landscape*
   It is important to recognize that individual historical and natural objects were formed in a historical, natural and landscape context and are therefore an integral part of a large stretch of landscape. It is a mistake to consider them out of context with the wider surrounding landscape and its natural and cultural history. The landscape should always be seen as a complex system, not only as a sum of isolated objects.

7.3 Research perspectives and challenges

As was also shown in studies attached to this thesis, **crevice-type caves** are now well researched from the perspective of their morphology and recent state functioning. However, there are still many unsolved scientific questions. In particular, the detailed mechanism of their formation is still insufficiently researched. Although Margielewski and Urban (2017) presented their detailed morphogenetic and geomechanical classification, some additional problems are still unresolved:

1. *The trigger*
   The current consensus attributes the development of respective caves along with the hosting landslides, especially during the humid phases of the Holocene (Lenart and Pánek, 2013). Many datings support this assumption (Urban et al., 2015; Margielewski and Urban, 2017), but some do not (Margielewski and Urban, 2017; Lenart et al., 2018). Caves may originate before the main gravitational event as an initial form – gravitationally widened crack (*sensu* Margielewski and Urban, 2003) – or they may evolve later as a product of post-failure relaxation of the slope, which tends to the new equilibrium.

The gravitational opening of crevice-type caves is commonly explained as a phenomenon accompanying failures of rock slopes under the influence of heavy rainfalls (Lenart and Pánek, 2013), but the seismic event remains as the potential trigger. However, such theories suffer from a lack of evidence.

2. *Unsatisfactory dating*
   As previous studies have revealed (Urban et al., 2015; Margielewski and Urban, 2017; Lenart et al., 2018), there is a chronic lack of datable material in crevice-type caves, and existing dating campaigns are sporadic, giving inaccurate results that may be interpreted in various ways. Typically, the obtained ages represent only individual crevices but not the whole cave, which may be of significantly different ages. Moreover, the obtained age may represent only the time of initial gravitational widening of the crack before it became the cave. In fact, we still do not know how old the crevice-type caves are.

3. *Question of tectonic strain*
   Based on direct extensometric measurements in crevice-type caves, few studies suggest the role of tectonic strain changes in their development (Stemberk et al., 2017). The main problem of such point measurement is that gauges are installed only at subjectively selected positions within the larger crevice-type system. These selections will not eliminate the possibility of misleading measurements, detecting only partial gravitational movements between semi-independent gravitationally affected rock blocks (see Lenart and Horáček, 2021).

4. *Active or stabilized*
   Extensometric and dilatometric measurements have revealed slow recent movements within crevice-type caves (Košťák, 2001; Klimeš et al., 2011; Stemberk et al., 2017). The authors usually extrapolate the results to whole cave (i.e., larger system of intersecting crevices) or even to wider gravitationally affected area outside the cave occupied place. This may lead to incorrect general interpretation because the point measurement detects only partial movements between semi-independent gravitationally affected rock blocks, as I show in a comprehensive study from various crevice-type cave environments (Lenart and Horáček, 2021). Thus, some blocks may shift very actively within the rest of the relatively intact blocks.
   Even if the measurement point is selected carefully with regard to the presence of faults (slickensides, tectonic breccia), the fault zone may be discontinuous and disconnected by the complex and long-term evolved gravitational deformations. The measurement may reveal recent movements, but we do not know if it is valid for the whole area, cave or individual rock block only.

5. *Fast or slow*
   Just as we do not know if the cave is still gravitationally active in general, the unresolved question remains if the caves were opened catastrophically during a single gravitational event (i.e., within days) or if they open slowly and gradually under the long-term influence of slow gravitational evolution (i.e., during thousands of years). Dating of materials would help to solve the question, but there is a chronic lack of datable material within crevice-type caves, which we confirmed in the study by Lenart et al. (2018).

6. *The role of periglacial processes*
   As we summarized in the review paper by Lenart and Pánek (2013), the original theories about the crucial cave-shaping role of ice wedges formed during Pleistocene cold stages and periglacial processes in general (Kunský, 1957; Demek, 1963) were fully replaced by gravitational theory. As indicated by some dating results (Lenart et al., 2018), at least some cracks or crevices have been

opened since the Pleistocene. If these ages are accurate, it indicates that periglacial processes may help to shape the cave interior.

The morphogenetic influence of frost action in karst cave environments was described by Lundberg and McFarlane (2012) or Žák et al. (2013). There is no reason to state that shallower crevice-type caves were not affected in that way.

7. *Spatial linkages*

   Crevice-type caves are commonly investigated separately from the surrounding environment. This is also partly valid for studies by Lenart (2015) and Lenart et al. (2014). Future comprehensive studies should focus on linkages to neighbouring geomorphic and other natural phenomena. Margielewski et al. (2008) described the Miecharska cave developed within a vast landslide, which cut the mountain stream channel. The water flows through the cave, forming an intracave channel with waterfall and pools. The understanding of the interaction between hillslopes, crevice-type caves and water streams is crucial for future knowledge about spatially and functionally wider ecosystems.

   Kašing and Lenart (2020) suggested that ventilation and the relationship of the microclimate to the external environment have not been sufficiently studied.

8. *Sediment traps*

   Some particular sites within crevice-type caves (entrances, shallow portions, deepest crevices) are filled with a mixture of both clastic and organic material. However, its detailed composition, stratification and functioning are often unknown, especially compared to the well-investigated sedimentary infills of karst caves (Hajna et al., 2010; Kaufmann et al., 2020). Radiocarbon dating of such material from carefully selected sediment traps may help with the determination of the minimum age of the cave or its individual section. Detailed sediment analysis would potentially reveal past changes in local and regional landscape evolution (e.g., Häuselmann et al., 2015).

9. *Frequency problem*

   Researchers consider crevice-type caves to be rather rare or randomly developed (pers. comm.). However, they meant rarely or randomly accessible, not developed. Presumably, crevice caves commonly accompany various types of gravitational failures, and thus, their frequency is probably much higher than previously supposed.

   As I explained in Lenart et al. (2014) and Lenart (2015), crevice-type caves may develop gradually from depth towards the surface without any changes in topography above them. Only under appropriate circumstances is an accessible connection with the surface established. We can even speculate that the overall number of crevice-type caves is even higher than the number of detected gravitationally affected sites in some areas, and thus, such caves should be considered common, not rare.

10. *Black swan cave*

    As our inventory from Czech flysch Carpathians (Lenart and Miklín, 2017) shows, the most documented caves are relatively short and small. From the total amount of 130 caves, only eight reached a length of more than 100 metres. The largest cave – the Cyrilka cave – recently reached 572 metres (unpublished result). The deepest – the Kněhyňská cave – reached 57.5 metres vertically below the ground (Lenart and Miklín, 2017).

    In other areas, much larger dimensions are documented. Jaskinia Ostra–Rolling Stones cave in the Polish flysch Carpathians reached 60 metres of denivelation (Państwowy Instytut Geologiczny, 2023). Jaskinia Wiślańska cave reaches a surprising length of 2275 metres (Państwowy Instytut Geologiczny, 2023). The question arises as to how deep and how long the exceptionally large crevice-type cave can be developed – an unknown black swan (*sensu* Taleb, 2010).

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Abandoned underground mines are traditionally well investigated from the perspective of human history (e.g., Soni, 2020). As also summarized in a state-of-the-art review (Schuchová and Lenart, 2020), geomorphological problems have been narrowed down chiefly to recent catastrophic processes, e.g., collapses (e.g., Waltham et al., 2011). The recent geomorphic research conducted by our studies (Lenart et al., 2017 and 2022) has brought new research challenges dealing with mine functioning or persistence of processes similar to those investigated in various types of caves:

1. *Tool for historical survey*
   Abandoned underground mines are traditional objects of historical, more precisely archaeological, investigation (e.g., Szychowska-Krąpiec, 2007). However, the relation of particular mining geomorphological forms to the surface topography is less investigated (e.g., Jirásek et al., 2019). As our study by Lenart et al. (2022) shows, this may help to understand historical consequences as well as to date mining forms and reveal their functioning within the mining-affected landscape.

2. *Geomorphological processes*
   Underground mines, as extensive geological outcrops, may serve to investigate the geomorphological and related processes that run below the surface, i.e., weathering, rock deformation, and sediment transport. On the surface, such processes are hardly observable and examinable due to the high rate of erosion, vegetation or human development.

3. *Spatial linkages*
   Similar to crevice-type caves, abandoned underground mines are commonly investigated separately from the surrounding environment. Future interdisciplinary focused studies similar to those conducted by us (Lenart et al., 2017 and 2022) should address the linkages to neighbouring geomorphic phenomena, such as slope or fluvial processes and landforms, weathering, and anthropogenic processes.
   In some cases, unusual combinations may be explored (e.g., stream channel anthropogenically directed into the abandoned mining adit; Schuchová and Lenart, 2018). The relationship between the elements of such a system is all the more important the closer the mines are to urbanized areas. The understanding of interactions between particular geomorphological agents is crucial for future ecosystem-based research.

4. *Sediment traps*
   As we showed in the example of 137 abandoned underground mines (Schuchová et al., 2023), some sites within the mines are filled with a mixture of both clastic and organic material deposited during both anthropogenically driven and nonintentional (almost natural) processes. Similar to crevice-type caves, their detailed composition, stratification and functioning are often unknown. Due to the subrecent age of deposited material, the sedimentary layers may serve as tools for recent geomorphic processes, climate or landscape development studies.

5. *How long they will survive*
   Since mining has terminated, abandoned underground mines will be preserved within the various types of world landscapes for some time until they collapse. Of the 137 investigated mines in our study (Schuchová et al., 2023), 54 exhibited some degree of rock collapse. The common lifetime of abandoned underground mines within various rock/landscape conditions is unknown. From a long-term point of view, mines should behave like stress-hardened mountain slopes (Jarman, 2009). Do abandoned mines completely disappear due to collapsing, erosion and long-term stress hardening?

6. *Transition to caves*

   We refer to an underground mine as an underground cavity that has a definable shape created by deliberate human activity. However, what if a highly collapsed mine begins to resemble non-karst caves (e.g., crevice-type, boulder-type)? The original rooms and walls may fully vanish by destructive geomorphic processes. Is it still mine or something different? Where is the borderline between mine and cave? What if the crevices opened within the back of the collapsing room? Are these newly developed geomorphic forms part of the former mine or not?

   Finally, is the morphogenetic point of view more important than strictly morphological? An almost fully collapsed underground mine may represent a morphology identical to gravitationally induced caves.

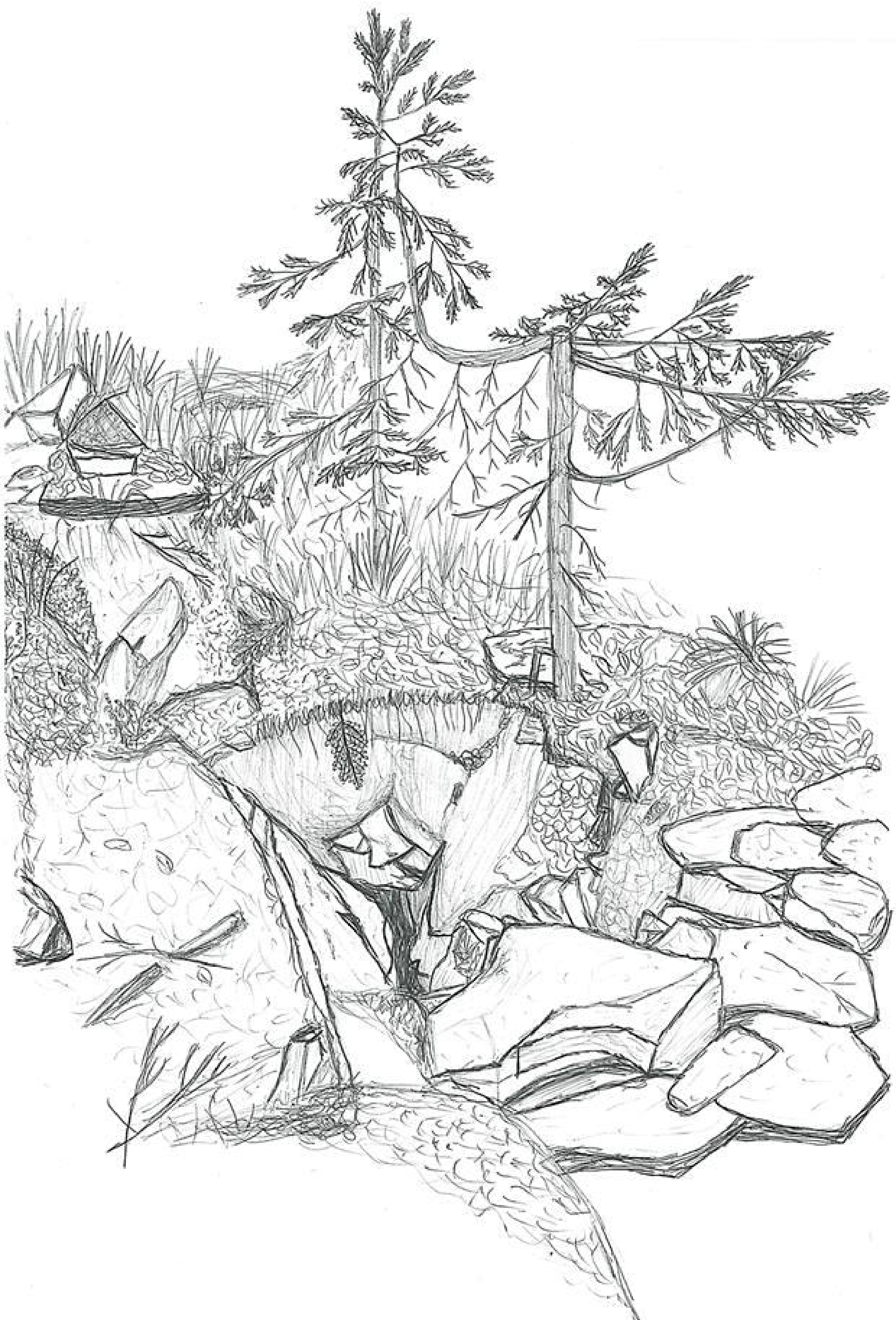

Figure 13: Entrance to the Mraznica cave in the Moravskoslezské Beskydy Mountains. Drawing by Tereza Vlčková, 2014

Conclusion

The geomorphology of crevice-type caves and abandoned underground mines is one of the crucial parameters in their natural and historical research and evaluation, together with their geology, hydrology, microclimate and anthropogenic influence.

The geomorphological research of these underground cavities is directed in two conceptual branches of survey:
1. Deeper into individual topics, with the results of individual geomorphological investigations being continually refined and results being achieved in ever greater detail;
2. In the context of the surrounding environment, individual research results are linked and embedded in a mosaic of interdisciplinary landscapes.

In the future, there should be both very detailed studies that will provide complex analyses (morphometric, chemical) and parameters of individual underground geomorphological forms, as well as interdisciplinary studies that will address the continuity of geomorphological forms, their evolution over time and their relationship to the surrounding landscape ecosystem. Humanities-oriented studies that work with elements of inanimate nature in the context of socioeconomic values and human needs in the landscape are also developing strongly.

Thus, the problems of the geomorphology of underground cavities are applicable to questions of the extent of caves and mines, their development, hydrology and airflow, archaeological research and tourism. After all, caves and mines can be explored together after a certain time of their development. When the abandoned mines succumb to destruction and collapse, their residual geomorphological forms will begin to resemble those of caves.

Deeper into the topic

The following articles with the author's participation allow us to delve deeper into the issues of discussed topics:

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Selected Maps and Photographs

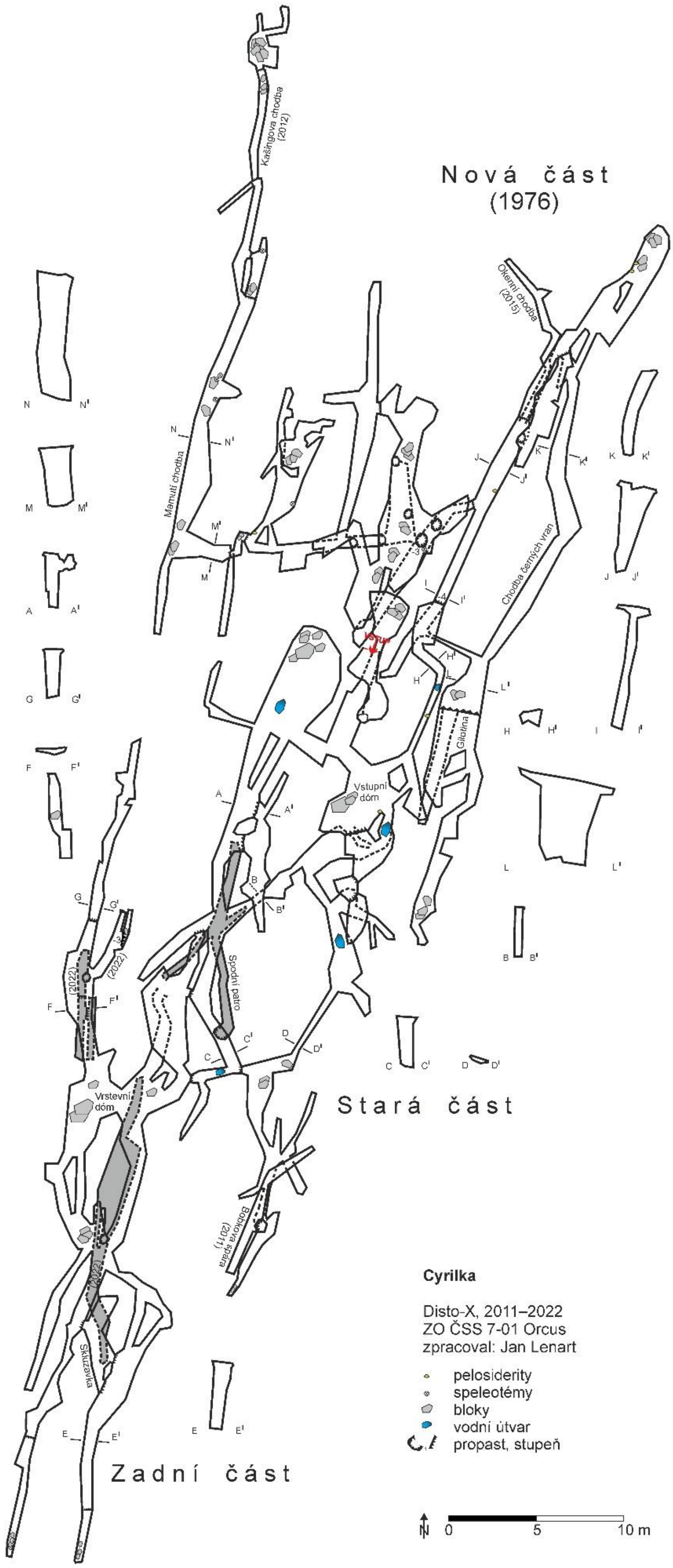

Figure 14: The Cyrilka cave – the longest crevice-type cave of Czechia, speleological map from 2022.

Figure 15: The interior of the Old part of the Cyrilka cave in the Moravskoslezské Beskydy Mts. Photo: Josef Wagner, 2020

Figure 16: Collapsed blocks in the Nad Lučinou cave developed in Carboniferous sandstone in Ostrava basin. Photo: Martin Kašing, 2020

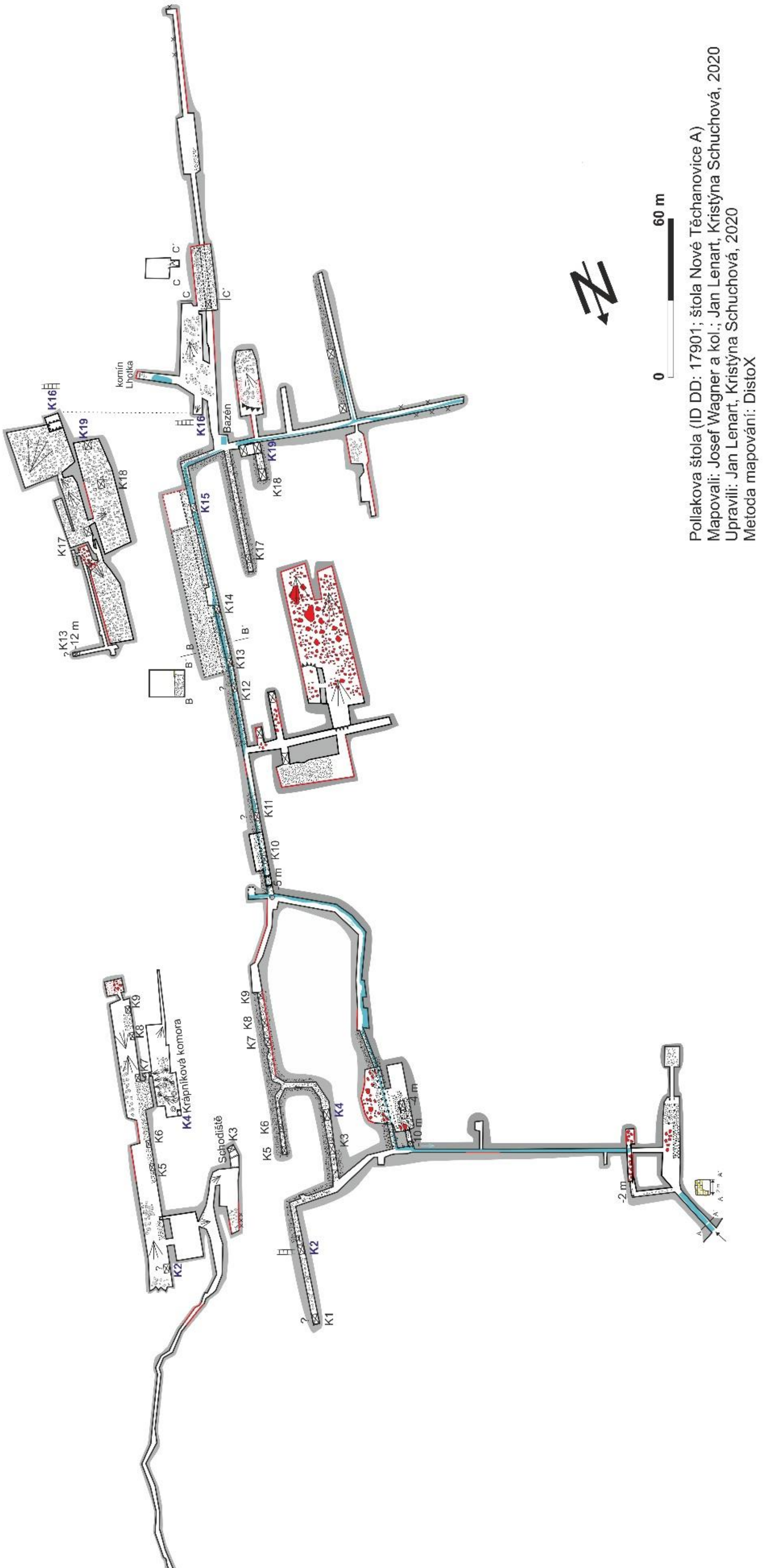

Figure 17: The Pollakova štola mine – one of the largest abandoned underground clayey slate mine in the Nízký Jeseník Upland, map from 2020.

Figure 18: The interior of the Nittmann's mine developed after clayey slate extraction in the Nízký Jeseník Upland. Photo: Jan Lenart, 2020

Figure 19: The interior of the Gold's mine (also Černý mine) developed after clayey slate extraction in the Nízký Jeseník Upland. Photo: Josef Wagner, 2017