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STABILITY DETERIORATION OF CLIFF FACES DUE TO HISTORICAL MINING IN THE ELBE SANDSTONES PROTECTED AREA

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ABSTRACT

The paper is a methodological study for registering abandoned mining sites and for the assessment of stability of artificial sandstone outcrops. The study presents partial results of the expert cooperation between geologists and historians in the Bohemian Switzerland (Elbe Sandstones) area focused on mapping and documentation of old quarries and mining pits. More than three thousand abandoned quarries for building stone were newly mapped and registered within the study area. Attention was given not only to the preserved relics after mining and their historical context: methods of stone extraction were also described, and the current state of quarries and mining areas was documented. Many of them represent unstable quarry faces prone to rockfall. The present survey and documentation of old quarries identified hitherto unknown sites of potential hazard, where old quarry faces or their parts are endangered by rockfall and can represent a potential risk in populated or tourist-visited areas (e.g., the Elbe River canyon between Děčín and the state border, Suchá Kamenice River valley, Rabštejnské údolí Valley, Kvádrberk Hill, Děčín–Podmokly, Děčín–Dolní Oldřichov, Ludvíkovice and Janská areas, Pekelský důl Valley, etc). Catastrophic events have already occurred in some quarries, and several localities had to be technically secured by stabilizing works recently, fresh rockfalls from 2021/2022 were also registered. One of the aims was therefore to create an inventory map of risk related to old quarries and the assessment of the present-day degree of hazard. Three-dimensional models of selected quarry faces were created using modern technology including calculation of cubic capacity of excavated material and collapsed masses. The complete results are included in the map geodatabase, which is under construction and which will be exploitable for an implementation within the information-educational and state-administration systems.

KEYWORDS

Quarry, Sandstone mining, Rockfall, Rock slope stability, Risk assessment and risk zoning, Map database, 3D modelling

INTRODUCTION

The area of Bohemian Switzerland lies in the north western part of the Bohemian Cretaceous Basin, being represented mainly by quartzose sandstones with isolated occurrences of Tertiary volcanics. Although under a strict supervision by conservationists today with unique sandstone geomorphology (Bohemian Switzerland National Park, Elbe Sandstones Protected Area), this territory was under long-lasting influence of human activities. Their impact has been mostly obscured by natural processes again. An inter-disciplinary survey and a detailed documentation of relics after old mining activities in a broad area of interest was performed in 2021–2022. Attention was given to the extracted rocks, archival materials related to mining history, relict landforms after anthropogenic activities preserved in the landscape, the employed mining techniques, effects on sandstone relief, and possible hazard associated with abandoned quarries. More than 3 000 old quarries and mine workings, including exploratory workings, have been as yet registered in the territories of the National Park (80 km^2 in area) and the Protected Landscape Area (248 km^2 in area). These are represented mainly by quarries exploiting building stone (primarily sandstone), crushed stone (basalt, granitoids), and – to a lesser degree – by workings related to the prospection and exploitation of iron ore (with local extraction of limestone, dolerite, fluorite, quartz, sand and gravel and other minerals).

The area of Bohemian Switzerland is known for the high dynamics of sandstone relief which poses favourable conditions for slope movement activity (especially block movements linked with steep edges of plateaus – e.g. [1]. However, the lack of stability of the local sandstone massifs, manifested *inter alia* by rockfall events in the last few decades, has been largely induced by human interventions, especially by unremediated historical mining. Old mining sites seek their new balance on their way from cultural to natural existence in a succession of natural relief. Around 2 200 abandoned quarries for sandstone building stone (more than 1 380 shelf quarries) are currently registered, many of them being represented by unstable quarry faces. Abandoned quarries are often associated with elevated hazard of catastrophic rockfall, the preparatory stage of which has been shortened considerably relative to that of natural dynamics of rocky-slope evolution [2]. The aim of the study is, in addition to a comprehensive description and characteristics of old quarries, also the identification of possible threats associated with old quarrying. This is achieved through field research with special regard to sedimentary rocks (selection of high-risk areas around quarries, hazard appraisals and basic risks assessment).

METHODS OF BUILDING STONE EXPLOITATION

The former methods of mining, hence also of rock massif disintegration, are directly linked with the present stability state of previously quarried valley slopes. We therefore provide a brief review of the different methods of historical sandstone extraction, primarily based on the observation of the traces they left behind on the former quarry faces (Figure 1).

The oldest encountered mining techniques are derived from observed natural processes of spontaneous rockfall. These early anthropogenic interventions in the landscape are therefore hardly discernible from natural processes in the field. Such old workings are generally revealed only by the presence of unnatural landforms, rare traces of quarryman tools and techniques, or by the occurrence of otherwise improbable rockfall at these sites.

Artificial falls of sandstone blocks

The technique of induced fall of sandstone blocks was usually started by cleaning of joints and scraping of bedding-parallel fissures using forged iron hooks. Boulders and stones from talus-filled joints and fracture zones were then released and removed by iron crowbars and rolled away from the cliff face downhill using nailed wooden bars. Scavenging of transverse and longitudinal joints in the fractured rock massif resulted in the formation of separate rock pillars. The pillars were then forced to a downhill fall by **undercutting – undermining at the level of their bases**. The technique of undercutting of the cliff face created artificial overhangs as much as 20 m in depth and over 40 m in width [3] and was considered a high-risk activity. Fallen blocks were stopped in their downhill movement by drystone terraces and further **disintegrated** mostly by wedging along bedding-parallel fissures or minor tectonic joints. Bags after cutting wedges, earlier wooden ones or later iron ones, have been preserved in some cases in unfinished fallen boulders and blocks, providing valuable evidence of the employed mining technique. Extensive incisions are left behind in the cliff faces, being turned into short gullies due to natural weathering processes. Horizontally levelled rock plateaus are then visible at the cliff bases – floors of the undercuts. Prematurely abandoned mining sites are characterized primarily by the presence of half-disintegrated blocks with undercuts, many tons in weight. Unfinished undercuts have the form of overhangs with flat ceilings and even floors. These unfinished undercuts pose the main hazard of spontaneous rockfall in the future (Figure 2), together with unreclaimed breakups of fracture zones and free-lying fallen boulders on the slope [4]. The extent of this technique of building-stone extraction is exceptional. Its biggest boom dates to the 18–19th century. It was applied especially to the right-bank slopes of the Elbe River canyon from the mouth of the Suchá Kamenice River to the south across Belvedér and Podskalí as far as to Loubí. It was also practiced in the adjacent part of the valley of the Suchá Kamenice River, the channel of which is buried beneath incompletely worked boulders in its lower reach. This mining method can be equally identified in the valleys of the Olešnička and Kamenice rivers, and was widely used also on the Saxonian side of the Elbe River canyon [5].

Fig. 1 - Methods of sandstone mining inducing instabilities in rock massifs (examples from the Suchá Kamenice River valley and the adjacent part of the Elbe River canyon: a) a shelf quarry in the valley of the Suchá Kamenice River with well visible traces after quarry-face mining using the technique of undercutting, b) Zlomiskova věž Pillar, produced by extraction of joints and surrounding sandstone blocks, primed for induced fall to the Elbe River canyon by undercutting its base, c) a crevice (dilated tensional joint) formed by unloading of the massif by mining in the Comiteebruch Quarry, d) borings for loading explosive cartridges, e) bags after the insertion of splitters (photo by K. Podroužek)

Bank method

Instabilities of cliff faces are also induced by the bank method, focusing on the extraction of serial rock outcrops. The techniques of building-stone extraction make use of the orthogonal jointing of sandstone. Three techniques were applied in the area under survey. Of the lowest negative impact on cliff-face stability is **chiselling of sandstone ashlars by benches (benching)**. This technique, typical for the 19th century, was applied to the face between two joints. Besides stepped benches, typical anthropogenic traces include rectangular cut-offs with vertical quarry faces, running across the full height of the outcrop [6]. **Wedging along joints and fissures** was applied specially to inclined beds. Cut-offs after this technique are irregular but respect the courses of joints. Extraction of cliff faces by undercutting is common in such cases. Again, the danger of rockfall occurs particularly at sites with unfinished quarrying activities. The third method of disintegration of cliff faces and blocks is blasting with the use of gunpowder and, since 1870s, also dynamite. A typical anthropogenic trace after **blasting** is a spherical blast-firing hole, accompanied by a series of cracks extending radially into the rest of the block. A half-groove after drilling by a borer to lay the explosive cartridge is often preserved. The damage made by the explosives induces secondary disintegration of the massif and a gradual spontaneous deterioration of the block. Such blocks pose a major threat of spontaneous rockfall. The above techniques of cliff-face extraction are well visible in the Elbe River canyon, where they represent the younger layer of mining activities. At upper quarry levels, they produced faces up to 35 m in height.

Fig. 2 - Unfinished mining using the undercutting technique in the Elbe River canyon: left) in the area of the Comiteebruch Quarry, preserved as a deep "overhang" 7×3 m in size; right: unstable rock wall in the whetstone quarry near Podskalí (photo by Z. Vařilová)

Tab. 1 - Basic classification of all mining techniques in the study area

Type of mining object registered	Character of hazard	Degree of threat
Haphazard disintegration of free-lying blocks and boulders	downhill movement due to bedrock weathering / gravity and unloading	none / low
Quarrying and disintegration of small outcrops	falls of disintegrated rock fragments	low
Bank quarry	falls of blocks, rockfalls	moderate / high
Pit quarry, surface pit	---	none
Underground mine working (adit, chamber, shaft)	subsidence	moderate
Cut	minor falls, cave-ins	low

EFFECTS OF MINING ON NATURAL EVOLUTION OF ROCKY SLOPES

The occurrences of rockfall are mostly associated with high cliff faces and outcrops formed by rather resistant quartzose sandstones of Upper Cretaceous age (Lower to Middle Turonian age, corresponding to the Bílá hora and Jizera formations). At places most affected by stone extraction, the cliffs are formed by sub-horizontally stratified fine- to coarse-grained quartzose sandstones with only low amounts of kaolinite matrix. A typical "block" disintegration proceeds along a system of orthogonal joints. The types of rockfalls and their incidence are controlled by the geomorphic character of present relief (degree of rocky slope evolution), the intensity of tectonic fragmentation of the rock massif. The most frequent mass movements of rockfall type are associated with zones of deep-reaching disintegration of the rock massif in the slopes of the of the Elbe River canyon, which are, moreover, affected by long-lasting mining activities. Quarrying of building stone also resulted in changes in the gradient and height of the rocky slopes and in the formation of new discontinuities. The quarry faces, often extending across several natural cliff levels, often reach several tens of metres in height. It is specifically these sites that are endangered by catastrophic waste rockfalls. In contrast with natural evolution, rock massif at such sites is fragmented without being weathered. Therefore, the usual stage of gradual lowering of rock strength is skipped, and the whole process of stability deterioration becomes accelerated [2]. The main reason for mass movement activation in sandstones is the vast redistribution of loading stress, reaching as far as tens of metres beyond the quarry faces. Artificial relief "rejuvenation" by quarrying created conditions favourable for the occurrence of catastrophic rockfalls even in those portions of the rocks slopes where these would never occur under natural conditions.

Tab. 2 - Main hazards in abandoned shelf quarries

Observed phenomenon in parts of rocky slopes affected by historical mining	**Consequence and potential hazards**
Variations in the gradient and height of rocky slopes due to quarrying	Effect on natural development of rocky slopes, resulting in potential deterioration of stability conditions
Extreme height of quarry faces, which often extend across several natural outcrop levels, often reaching several tens of meters (in some parts up to 40 meters)	Loss of cliff-face stability due to unloading and stress redistribution, activation of slope movements in the interior of damaged rock mass (tens of meters behind the quarry face), risk of catastrophic rockfalls of large volumes
Zones of intensive deep weakening of rock massifs	Opening of old tensile fractures, creation of new discontinuities, loosening and falling of blocks
Exposure of surface / subsurface parts of rock massif and fracturing of unweathered rock massif	Acceleration of rock deterioration processes, loss of stability
Undercutting of cliff/quarry faces (artificial overhang)	Loss of rock strength due to prolonged weathering, loss of stability due to the rock weight itself
Secondary failure of rock massifs due to the use explosive methods of rock disintegration	Secondary fissures and cracks with effect on stability, rockfall initiation
Other negative factors and conditions present	**Consequence and potential risk**
Uprooted trees from the cliff/quarry face or the upper edge of the face	Falling of sub-blocks and parts of the cliff/quarry face
Disintegration of quarry facilities (buildings, terraces, unstable piles of unused material from the quarry)	Fall of stones (smaller blocks) in the accumulation parts of the rocky slopes

Historical rockfall events and their remediation

The largest concentrations of unstable cliff faces are clearly located in steep slopes of the Elbe River canyon in areas of intensive building-stone extraction substantially altering the natural cliff-face morphology. Human-induced undercutting and secondary fragmentation of the rock massif are common phenomena here. This is evidenced by catastrophic rockfall events as well as the need of emergency remediation works in recent times. Recurrent threats at almost identical places are not an exception, as indicated by archival sources of information.

For example, repeated rockfalls were encountered at **Kvádberk Hill** (cadastre of Děčín) at the site of former sandstone quarrying above the municipal pasture of "Kühweg" (Viehweide) in years 1835, 1893 and 1931. Another catastrophic event at the same site was the big rockfall of 1938 (Figure 3) which induced damage to the local water-supply tank and a part of the forest and city park [7, 8]. This event was induced not only by stability degradation due to a giant artificial incision in the rock massif contributed by unfavourable weather conditions but also, most importantly, by the improper location of the quarry at the intersection of two tectonic fractures. Based on an expert opinion from 1960s [9], safety measures were proposed for separate parts of the hill and selected unstable objects. The above-mentioned shelf quarry was evaluated as the highest-risk portion by these reports. Based on an updated stability study (2003), extensive remediation measures were realized in the area of this quarry face degraded by fracturing and shearing to avert the threat of a rockfall thousands of m^3 in volume (removal of high-risk blocks, fixing of blocks by basal walls, rod rock bolting, filling of joints by gunite, construction of a retaining wall). Remediation of another rock pillar in the former quarry took place in 2013. The area of the old quarry continues to pose, despite all realized technical measures, potential risk of fall of stones and smaller loose parts of the rock massif.

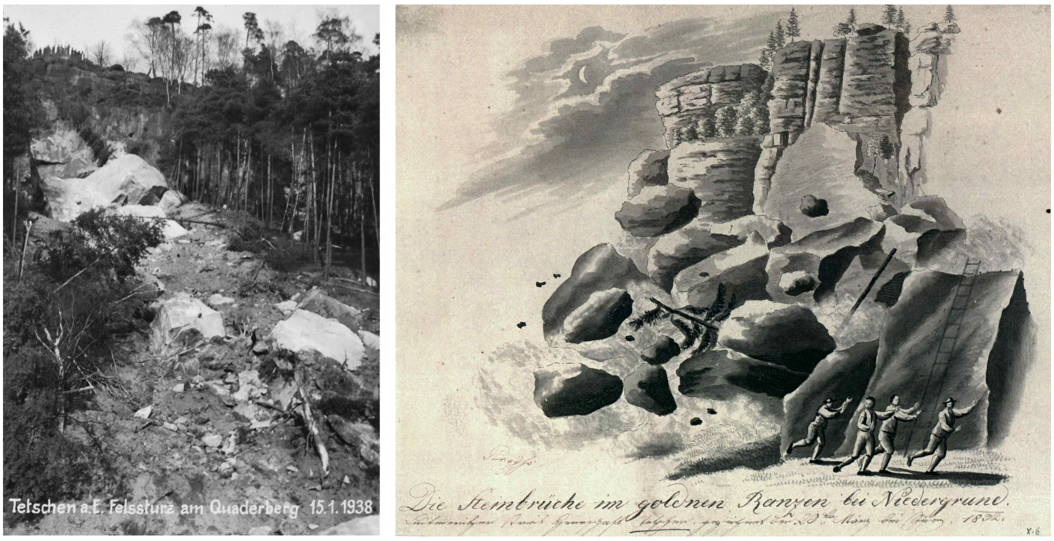

Fig. 3 - Left: A historical photograph of rockfall in a quarry at Kvádrberk Hill in 1938 (archive of P. Joza); Right: A wash drawing by J. Preyss, the parish priest of Hřensko, showing the rockfall of March 20, 1832 in the Goldenen Ranzen Quarry (near the Suchá Kamenice River); then, blocks at the foot of the slope were quarried by wedging, and a spontaneous fall of the quarry face occurred in the upper part of the slope (collections of the Municipal Museum of Ústí nad Labem)

Possibly the best example to demonstrate this type of hazard is the serial rock exposure over 300 m long south of the confluence of the Suchá Kamenice and Elbe rivers. It represents **the area of several quarry faces** known as **Goldene Ranzen (Elbleiten)**. Rock extraction was started in the 18th century here, and the building stone was used, e.g., for the construction of the fort of Terezín or for buildings in the near town of Děčín. The rocky slope is strongly weakened down to considerable depths and, moreover, affected by old quarrying. The intense, deep-reaching disintegration of rock massif is also evidenced by the presence of extensive systems of crevice caves. The area is therefore subject to long-term monitoring by engineering geologists. Repeated rockfall events were encountered here at the time of the quarry operation and thereafter – e.g., in 1832 (Figure 3), 1862, 1864, 1882, 1962 and 1980. One of the last big rockfalls, 1 360 m^3 in volume, in January 1984 (Figure 4) was successfully predicted based on block-movement monitoring, and the affected road could be closed in time [10]. Remediation of a part of the quarry face pillar was made to avert threat to road traffic again in 1986. Two years later, a prelude to another catastrophic rockfall was accelerated by controlled downing of a part of the face. Another emergency remediation (quarries Goldene Ranzen_1 and 2) was realized based on data from revision monitoring in 1999. In a part of the area (“P31” corresponding to quarry Goldene Ranzen_3), technically demanding security measures were adopted for several rock massifs (volume about 3 000 m^3) threatening to fall onto the road in 2007 [11]. Detachment and fall of a fractured portion of the rock massif directly from the face of the former quarry Goldene Ranzen_2 occurred in the neighbourhood of the remediated area in autumn 2010; this event was induced by the degradation of the rock massif by mining, intensive fracturing and saturation with precipitation (Figure 4). Processes like joint dilation, rock deformation and tensional joint formation, loosening and removal of blocks or rock plates continue to the present. The broader area of these old quarry faces still belongs to the most hazardous portions of the Elbe River canyon.

Fig. 4 - Left: A face of the Goldene Ranzen_1 Quarry near the mouth of the Suchá Kamenice River to the Elbe River (a historical photograph from the 1980s during remedial work); Middle/Right: A catastrophic rockfall of 1984 and a smaller-volume rockfall of 2010 at the site of an old quarry face in the Goldene Ranzen_2 mining area (photo from [12] and by Z. Vařilová 2022)

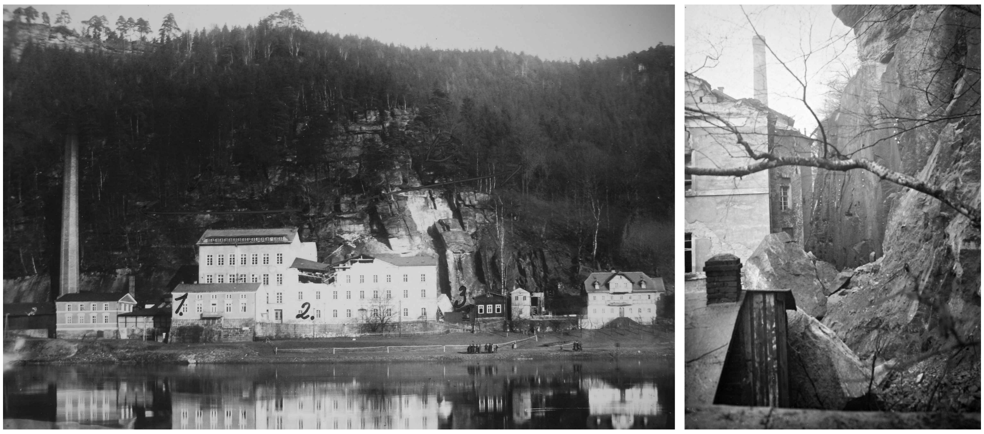

Fig. 5 - Zwirnfabrik Eiselt (Duty free shop) site – photographic documentation is available for the rockfall event of 1938, when sandstone mass from an old quarry face 400 m^3 in volume induced damage to the adjacent building [14]

Another exemplary site is the cliff face behind the **Duty-free shop** building – the original spinning mill of Zwirnfabrik Eiselt at Hřensko. It experienced repeated catastrophic rockfalls in 1886, 1938 (Figure 5) and 1944. New threat, identified in years 2002/2003, called for technically demanding security measures. Repeated rockfall events and extensive remediation works preclude any precise determination of the original shape and size of the quarry face.

Similarly, the threat of fall of large rock masses from an old quarry face directly **above international Road I/62** in the developed part of the village of Hřensko was observed in 2010–2011. Sandstone extraction at this site was probably conducted in 1938–1945 with the use of reckless blasting operations (numerous explosions in core runs). The quarry forms a trapezoidal niche in a serial outcrop with prominent primary orthogonal jointing. These joints were subjected to dynamic effects of rock extraction, generating secondary detachment planes and cracks. Traffic on the road was constrained for a long time due to the imminent risk of rockfall [15], and an impact bed was constructed in one lane. Multi-stage remediation works were then performed (2011–2013) with the aim to secure the parts of the cliff face endangered by imminent rockfall. As much as 1 200 tonnes of unstable rock were removed, a concrete collar was built in the most fractured part of the quarry face at the height of 25 m, the face was strengthened by bolt mandrels (bolting to a depth of 24 m), joints were injected with gunite and a high-load barrier was installed [16].

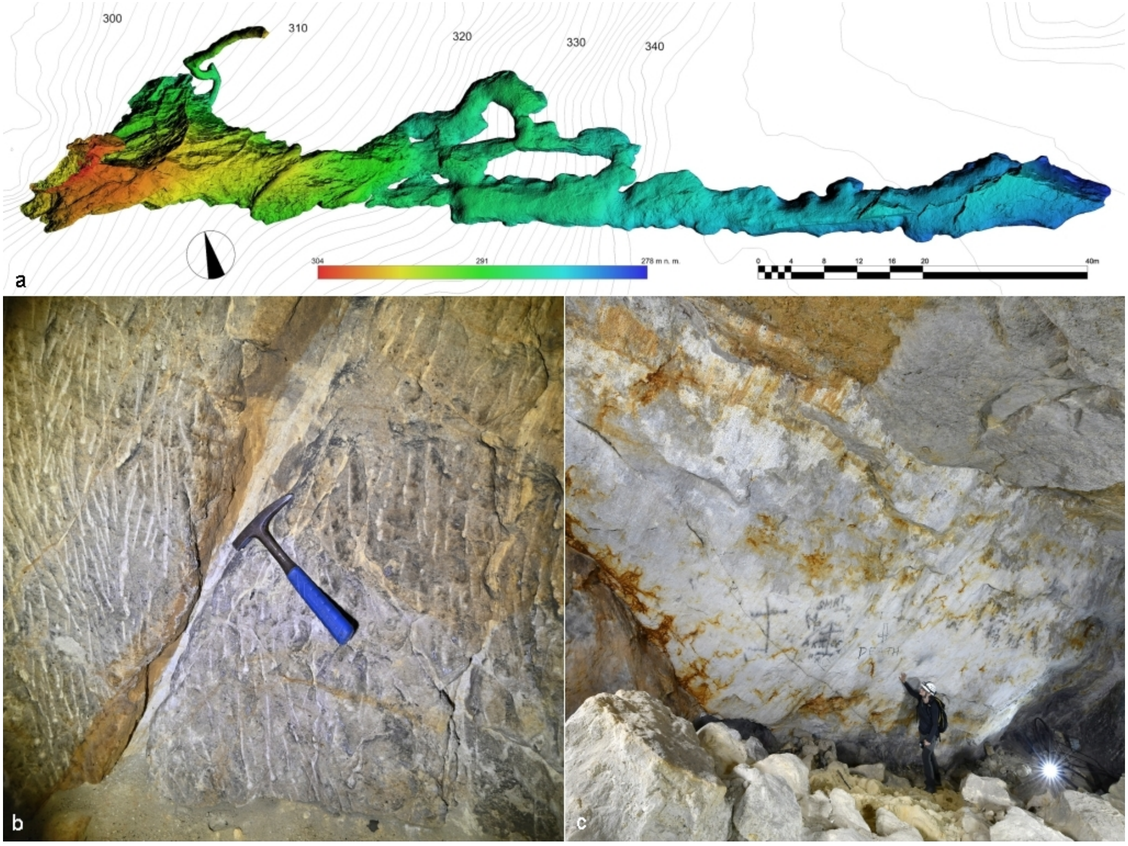

Fig. 6 a) - Hypsometric analysis of surfaces of excavated underground spaces at Ludvíkovice, b) a minor shear fault in a side of the adit, c) an exposed striated shear plane now forming the wall of the terminal dome at the site of repeated ceiling collapses and deadly rockfalls (photo by Z.Vařilová and J. Preclík)

Underground sand pits exploiting friable sandstone represent a specific type of mining objects. One of the largest excavated objects in the area of interest is the Labyrinth or **Sandloch** site (cadastre of Ludvíkovice, Figure 6). This Labyrinth was originally promoted as a point of interest in tourist guidebooks in the second half of the 19th century. After a fatal injury by fallen rock mass during sand extraction in 1914, mining operations were stopped and the entrance to the adit was closed [17, 18]. The entrance to the underground sand pit lies at the foot of a hill in an immediate proximity of the developed area of Ludvíkovice. The overall length of all documented underground spaces is 132 m, maximum height is 6.5 m (height of artificially carved corridor max. 5.5 m). The present size is markedly affected by repeated falls of the ceiling and parts of walls even at recent times (traces of fresh fallout). The extracted material was low-strength quartzose sandstone, showing dips of strata of max. 20° and intensive fracturing. Shear faults and their intersections, fractures and prominent lithological boundaries functioned as detachment surfaces of rockfalls. Fresh-looking detachment surfaces in the entrance dome and the terminal dome confirm the presence of imminent risk. A potential threat of subsidence of a part of the undermined slope cannot be excluded.

Other selected documented rockfall events at sites of old quarrying according to [19–25]:
Dolní Kamenice, Rabštejnské údolí Valley, Vrchnostenský Quarry (Pr_7): April 1912, January 2022
Janská, Rabštejnské údolí Valley: 1861 rockfall at spinning mill
Děčín, Teplická St. – Pastýřský vrch Hill (Lerchenbruch / Kargel Quarry): 1869, fall of a block; 1898, repeated rockfall and rock fragment detachment in 20th century, 2021 rockfall and remediation
Děčín, Spitzhüttel (a historical quarry): 1872, fall of the quarry face and remediation
Děčín, Pastýřská stěna Cliff: 1877, rockfall and remediation

Hřensko (former cadastre of Dolní Žleb), Komitee Steinbruch Quarry: 1874, fatal injury of a quarryman under a suddenly released block
Hřensko, near the Labe Hotel: 1843, fall of a block; 1900, rockfall; 2010–2011 remediation
Hřensko, near the Zlodějská stezka Path: 1876, risk of rockfall from the face
Hřensko, near the Březový důl Valley: 1889, remediation of a high-risk block necessary
Hřensko, near the Malinový důl Valley: 1851 rockfall; 1855 rockfall followed by remediation by chiselling; 1896 fall of a block followed by remediation
Martiněves, Windrich Quarry: 1899, collapse of the face, death of three quarrymen working under the face

Present signs of stability deterioration of quarry faces

Besides rockfalls documented by archival data, several new events from the break of 2021/2022 were identified (e.g. Figure 7, 11). These mass movements were induced by a combination of factors: intensive fracturing of the rock massif and artificial overhangs, saturation with precipitation water or meltwater, often facilitated by uprooting and wedging of the root system of adult trees on top edges of quarry faces. The problem of stability of old quarry faces is, however, not restricted only to the selected sections of the right slopes of the Elbe River canyon between Děčín and the state border. The present survey and documentation of old quarries identified hitherto unknown sites of potential hazard, where old quarry faces or their parts are endangered by rockfall (Suchá Kamenice River valley, Rabštejnské údolí Valley, close to the network of tourist trails leading to the Dolský Mill, above buildings and roads at Děčín-Podmokly and Dolní Oldřichov, Martiněves, Růžová, Ludvíkovice and Janská areas, Pekelský důl Valley and other sites). In only a few cases, however, potential rockfalls pose a threat to inhabited and man-frequented areas.

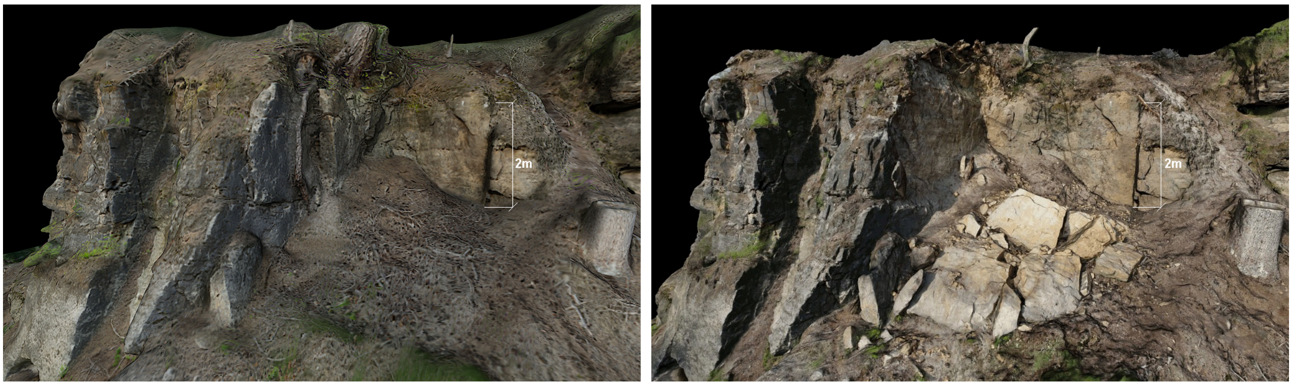

Fig. 7 - A collapse of a part of a cliff face, 2.6 m³ in volume, caused by a tree uprooting at the model site of Bruckgraben (Vysoká Lípa cadastral area) – a comparison with the use of a photogrammetric quarry model (June 2021 and March 2022)

QUARRY DOCUMENTATION AND HAZARD CLASSIFICATION

The existing published methodologies (e.g., [26]) were found to be inadequate for a uniform and representative description of abandoned quarries in sandstone rocks. On the basis of field documentation, a typology and terminology of old quarries and their components was developed in comparison with written sources and literature. All quarries and mine work were described using basic typology and defined parameters: site description (extent of mining activities, size and shape of the quarry, geological description, direction of mining progress, present state) and object type (shelf quarry / pit quarry / artificial disintegration and benching in small outcrops / wedging of boulders / underground mining / prospection etc.), character of the extracted material and the deposit, historical data (time interval of quarry operation, quarry operator/lease-holder), extraction method,

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description of relics of buildings and equipment, semi-finished products and engravings including a list of all recovered archival sources and literature for each registered site.

Representative quarry areas were chosen as model sites and characterized in detail, beyond the extent of routine documentation. At these sites, an inventory of features related to mining history and preserved relics after human activities was extended by the study of the degree of interventions in the sandstone landscape and by the assessment of mining impacts.

Documentation of model quarry faces using photogrammetry

Geodetic documentation of the quarries employed routinely practised techniques, based primarily on the polar method [25]. This was performed with the use of a total station or a stabilized laser range meter (two range meters at known positions allow the use of the forward intersection method). Polar measurement is intended to provide, depending on the desired output for the given site, marker coordinates for subsequent photogrammetry measurement, or laser scanning, or direct determination of detailed points as a basis for the creation of the plans [28]. With respect to the character of relief in quarries, the manual direct linear measuring technique was only rarely used.

Similarly, the coordinate system of the geodetic survey was chosen depending on the requirements stipulated for the given site. If a total station is used, it is advisable to use – apart from the local S-JTSK system. The connection was realized using the GNSS RTK receiver, the limits of which are especially sensible in the environment of historical quarries. Densely forested terrain, narrow valley profiles and underground mine workings preclude any fixation of the measured points at some sites. Planimetry and altitude data were checked against the detailed Digital Elevation Model / DEM [29].

Where a digital 3D model was required for the given site, its creation is based on photogrammetry method SfM (Structure from Motion; [30]; for output examples see Figure 8). This photogrammetry method was based on an automated optical correlation in a series of digital photographs, generating 3D data in the form of a point cloud. The point clouds were evaluated and processed into a form of a polygonal mesh with a photorealistic texture. This method is limited, above all, by the need of good visibility of the photographed object. This implies that some sites are not suitable for processing by this method, and some other sites can be detected by this method only in a vegetation-free period. 3D data obtained by this method were combined with data from a detailed DEM [29] complete the final scene.

3D models were used not only for presentation purposes but also as a basis for the creation of other outputs. These include especially plan documentation, which can show a much closer detail, if aided by 3D models, than plans constructed solely on the basis of geodetic measurements. The plan documentation was created in the environment of CAD system and other vector graphic editors. 3D models were further used to create orthophoto mosaics, DEMs with hypsometric analyses, to compare models and to calculate areas and volumes [31]. The task to calculate the volume of wasted or excavated part of the quarry is relatively straightforward if models of the quarry before and after the event are available (see Figure 7): the differential body has to be created first at the given level of detail (post-modelling is sometimes needed to eliminate the effect of spaces covered with fallen material in the post-event model), and its volume is subsequently calculated using at least two different programs independent of each other for its corroboration (for large-scale projects with periodically surveyed areas, automated procedures are available; [32]). If the volume of fallen / excavated part is to be calculated without a prior geodetic documentation, collaboration of the surveyor with a geologist is necessary to produce a qualified estimate of this volume.

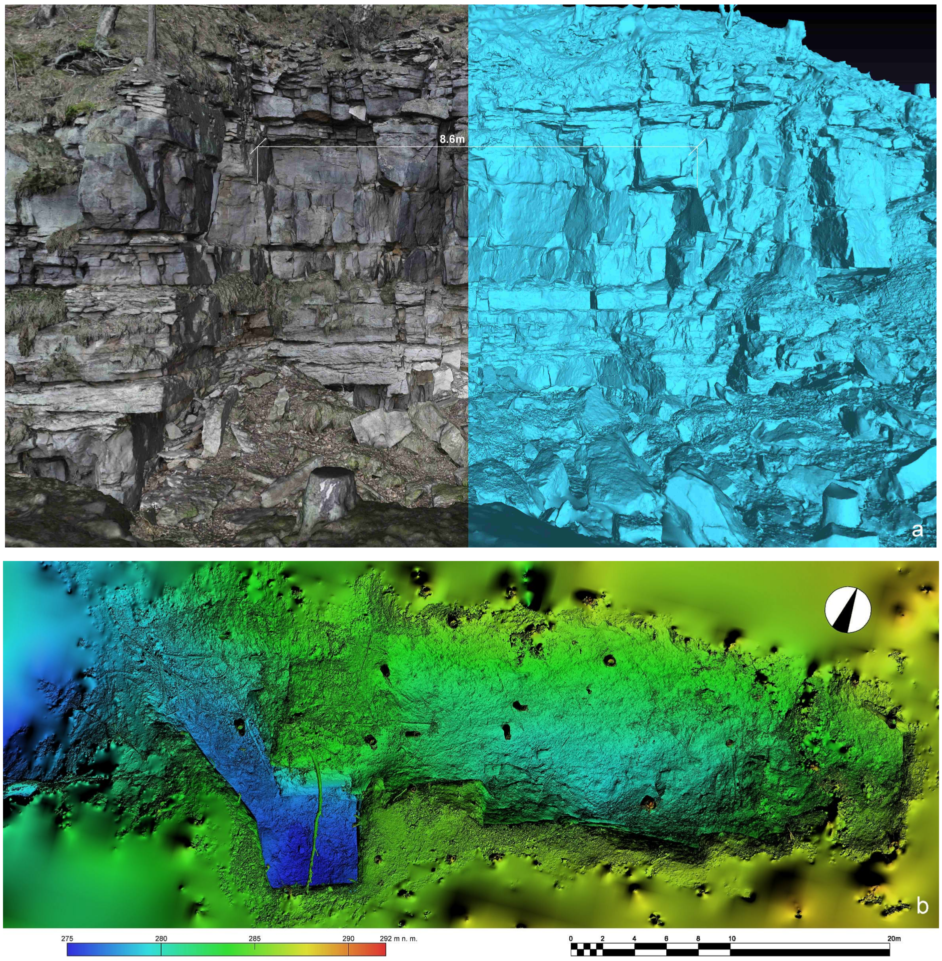

Fig. 8. a) - A 3-D computer model of a whetstone quarry near Podskalí in the Děčín area – an image with phototexture (left) compared with monochrome colour with simple shading (right); b) A digital model of the surface of an excavated quarry near Janská with a hypsometric visualization of relief.

Assessment of present-day stability and risk classification

An assessment of potential risk from mass movements was made, and present-day stability degrees were attributed to different sites. Due to the large quantity of mining sites, the risk evaluation was made for whole quarries or mining areas within the full limits of their exploitation. Only the sections of rocks massif affected by human activity and their integral parts were assessed. A more detailed risk classification was performed for selected model sites, distinguishing among individual risk zones within the quarry area/quarry face – e.g., the Goldene Ranzen and Comiteebruch quarries in the Elbe River canyon or the Vrchnostenský Quarry in the Rabštejnské údolí Valley. Unlike in a detailed engineering-geological study of stability conditions (e.g. [33]), the aim of the present activity was to provide a basic assessment of the degree of present-day risk and the presumed damage inflicted. Therefore, the main evaluation criterion was the probability of damage to the road network, buildings, local population or visitors by rockfalls. Other classification criteria included local conditions and controlling factors, such as the position, height and character of cliff faces (intensity of tectonic and human-induced fragmentation of outcrops, intensity of weathering, etc.), slope gradient or the presence of spontaneously established woody plants. Last but not least, the documented history of rockfall events and data on previous remediation measures were also considered. A specific type of threat related to sandstone mining relicts is represented by waste stone deposits, remains of retaining walls or disintegrating relics of buildings, which may release smaller sandstone blocks. On the other hand, major slope adjustments (e.g., artificial terraces or protective ramparts of quarried stone) can play a positive role in retaining the loose masses in some cases.

The degrees of risk (0 to 3) were assessed individually based on field reconnaissance considering the specific conditions at each site, making use of basic point evaluation. A list of all evaluated parameters is given in Table 3.

Tab. 3 - Evaluation criteria for a quarry face risk assessment

Parameter (controlling factor / condition)	Point
Presence of roads, tourist trails and forest roads or developed areas in the presumed rockfall trajectory (targets of potential threat)	1
Documented history of rockfall / relatively frequent rockfall events above 3 m^3 in volume	1
Presence of tectonic fractures affecting stability (faults, joints) / gravitational dilation / tensional joints / fracturing / intensive weathering of inner parts of rock massif	1
Overhanging portions of cliff face / artificial undercutting	1
Adult trees and vegetation growing on the cliff face or its upper edge (wedging by roots)	1
Larger volume of unstable parts of the cliff face or individual blocks (with a potential catastrophic impact, 5 m^3 to tens of m^3)	1
Position of unstable components of the rock massif in upper part of the quarry face or at its upper edge (higher energy of the fall can be expected)	1
Slope gradient (above 30°) and aspect allowing for the movement of fallen masses, blocks moving downhill will probably reach its base, with a minimum possibility of their stopping	1
Presence of safety and retaining elements (impact bed – e.g., horizontal manipulation terraces or prominent terrain depressions under the quarry, prominent rock steps and a dense cover of adult trees, a.o.)	-1
Completed technical remediation, installed functional safety elements	-1

Tab. 4 - Assessment and classification of rockfall risk

Risk degree	Colour of symbol in map	Points
0	white	0
1	yellow	1–2
2	orange	3–5
3	red	6–8

GIS-aided presentation of results and their applications

Collection and processing of geo-spatial data for quarry sites adopted an approach based on collaborative mapping in the ArcGIS technological environment, the solution is based on the cloud platform of ArcGIS Online. The emerging information database is based on various types of background maps together with a DEM. The emerging map database contains, besides the inventory of old mine workings and their geological and mining-historical characteristics, the assessment of stability of old quarries.

Besides point- and polygon-defined registries of old quarries (Figure 9) and mining-related anthropogenic relict landforms, the database also includes an independent data layer called “Stability of cliff faces”, reflecting the attributed present-day rockfall risk together with a description of any potential threat (Figure 10). Places of high risk, endangered by falls of old quarry faces into populated or man-used areas were indicated. Potential risk was identified not only in the deeply incised canyon of the Elbe River and its tributaries, but also at other sites in a broader region of interest. The selected model mining areas were documented in detail using geodetical and photogrammetric methods (Figure 11).

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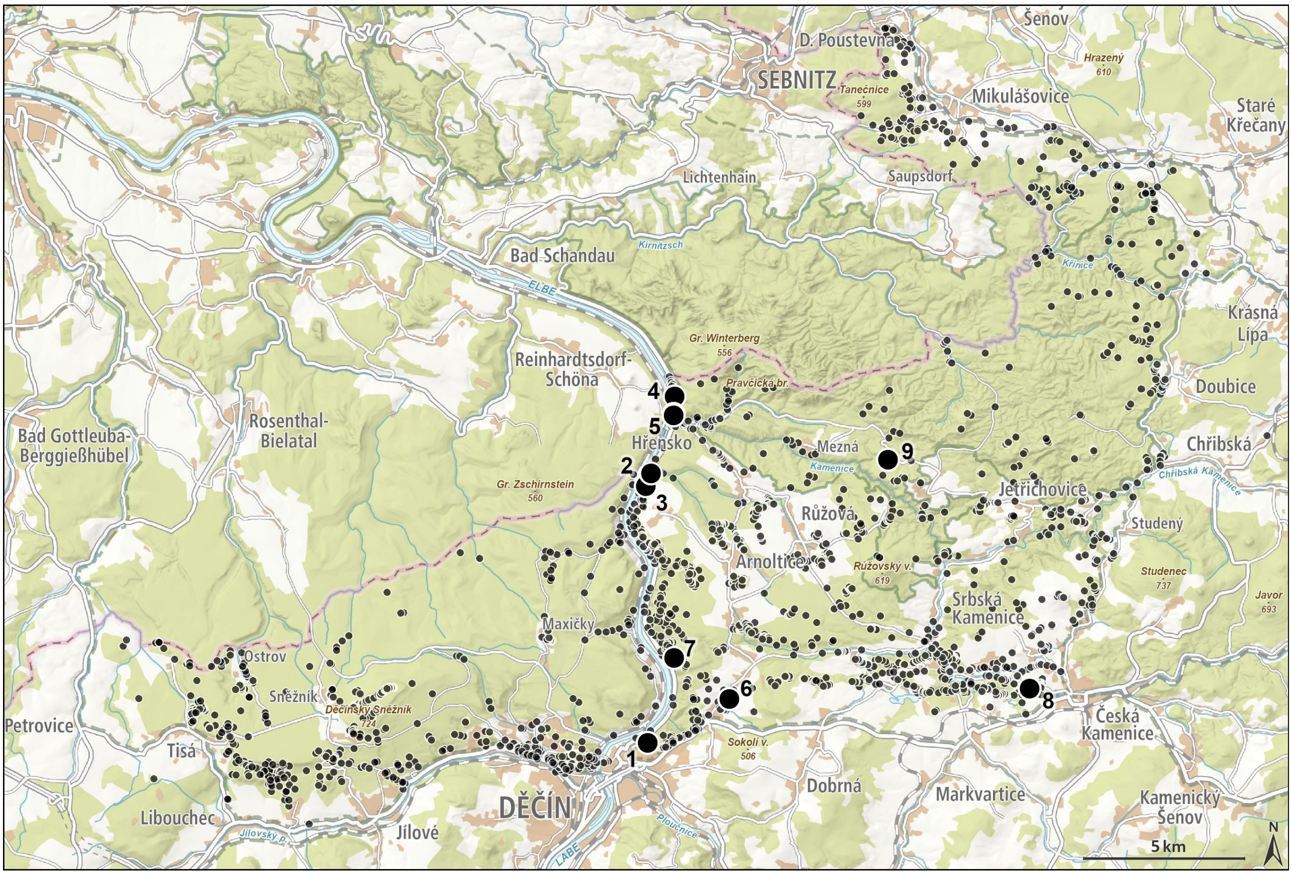

Fig. 9 - A map of the study area with identified quarries (black points) and selected localities: 1) Kvádberk Hill (Děčín), 2) Goldene Ranzen Quarry, 3) Comiteebruch Quarry, 4) Duty free shop (Hřensko), 5) Quarry above Road I/62 (Hřensko), 6) Sandloch (Ludvíkovice), 7) Quarry near Podskalí, 8) Vrchnostenský Quarry (Rabštejnské údolí Valley), 9) Bruckgraben (Vysoká Lípa); Map: © Bohemian Switzerland NP Administration; Source data: © ČÚZK, © IPF TUD, © GeoSN, © BKG, © LFULG

RESULTS AND DISCUSSION

Rock massifs of the Bohemian Switzerland NP and Elbe Sandstones PLA have been extensively affected by historical mining – although this fact is not visible at a first look. The number of currently mapped quarries exceeded initial expectations of the research team by an order of magnitude. The results of study provide an integral set of information on the distribution of quarries in the landscape and the history of minerals utilization. For the purpose of uniform and representative characteristics of quarries in this specific sandstone region, it was necessary to create a new methodology using the sporadic existing literature (e.g., [26, 34]). The emerging map database contains, besides the inventory of old mine workings and their geological and mining-historical characteristics, the assessment of stability of old quarries. Extraction-induced areas of instability of rocky slopes were recognized during the field mapping, for which we recommend an additional detailed engineering-geological evaluation of massifs, risk analysis and rockfall simulations (e.g., [34, 35, 36, 37]). The threat was not determined for a number of old sandstone quarries (and for quarries in other types of rocks) because there were no objects at risk identified.

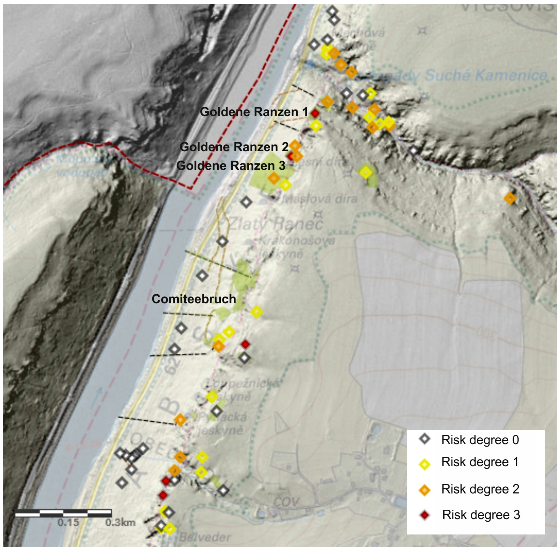

Fig. 10 - The Suchá Kamenice River valley and a part of the right bank of the Elbe River canyon with marked positions of surveyed quarries with inferred rockfall risk degrees (the green polygons correspond to the Goldene Ranzen_1–3 and Comiteebruch mining areas); based on the DEM of Bohemian Switzerland [29]

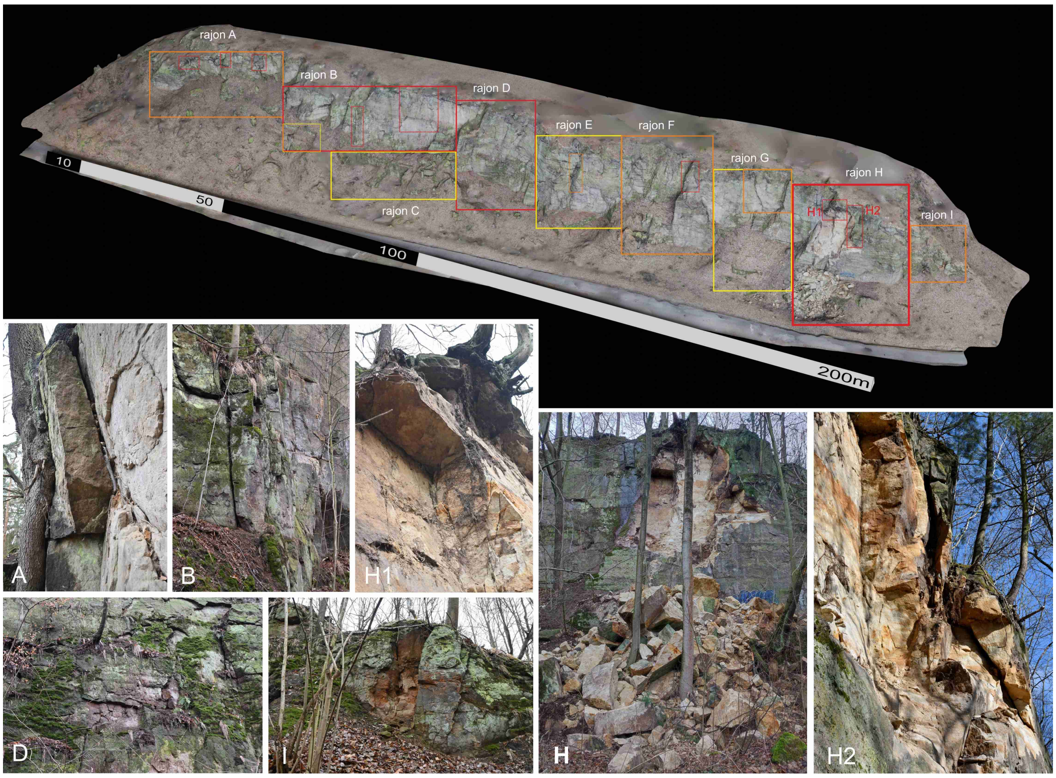

Fig. 11 - Model locality – a quarry face in Rabštejnské údolí Valley divided into individual parts according to the determined degree of risk, and examples of unstable parts of the cliff face (old parts of rock wall A, B, D, I and fresh risk zones H1, H2 corresponding to the shear surface of the rockfall); a rockfall 78 m³ in volume occured here in February 2022 (H) (cadastral area of Dolní Kamenice, photo by Z.Vařilová)

High-risk areas and sites should be given more attention by the users/managers of the potentially affected land. The main recommendations include: Awareness of land owners, authorities, forest managers, nature protection authorities; continuous monitoring of the state of high-risk sites (3–5 years); elimination of mature trees from quarry faces and their upper edges; proper marking of risk and safeguarding the entrances to dangerous quarries /underground spaces. Recommendations in the case of endangering buildings, roads/railways, and frequented tourist routes: detailed engineering-geological survey of selected quarry sites; securing the slopes under the quarry faces (impact beds, terraces, retaining walls and fences); control monitoring of the faces of abandoned quarries (e.g. [38]); remediation of immediately dangerous parts of the rock massif; revitalization and repair of original structures (buildings, retaining walls, roads, skids, etc.); taking into consideration old mining remains in the management of forestry interventions.

CONCLUSION

The set of knowledge will be further extended by consequential research. The current study targeted at maximum applicability of the obtained results and their implementation in the information-educational system. Presentation of the complex results via an online map database (scheduled for the turn of the year 2023/2024) will be guided by practical needs of the Administration of the PLA and NP, local governments and administrative bodies.

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The herein presented results were achieved within the project TL05000407 "Database of old quarries and mine workings in the territories of the Bohemian Switzerland National Park and the Elbe Sandstones Protected Area". This project is co-financed from the state budget by the Technology agency of the Czech Republic under the ÉTA Progamme.

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List of symbols:

BKG – Bundesamt für Kartographie und Geodäsie, Datenlizenz Deutschland
CAD – Computer-Aided Design
ČÚZK – Český úřad zeměměřický a katastrální
DEM – Digital Elevation Model
IPF TUD – Institute of Photogrammetry and Remote Sensing, Technische Universität Dresden
GeoSN – Staatsbetrieb Geobasisinformation und Vermessung Sachsen
GIS – Geographic information system

GNSS – Global Navigation Satellite System
LFULG – Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie
NP – National Park; PLA – Protected Area
RTK – Real-Time Kinematic positioning
SfM – Structure from Motion
S-JTSK – System of the Unified Trigonometric Cadastral Network (geodetic system, mandatory for the territory of the Czech Republic)
SOA – State Regional Archive; SOkA – State District Archive