IMPACTS OF COAL MINING ON RELIEF: CASE STUDY OF THE TROJANOVICE MINE AREA, THE MORAVIAN-SILESIAN CARPATHIANS, CZECH REPUBLIC

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Jaromír Demek, Peter Mackovčin, Petr Slavík: Impacts of Coal Mining on Relief: Case Study of the Trojanovice Mine Area, the Moravian-Silesian Carpathians, Czech Republic. Geomorphologia Slovaca et Bohemica, 11, 2011, 2, 6 figs, 26 refs.

The aim of the paper is to predict and estimate the impacts of the planned hard coal mining in Trojanovice mine area underneath the sensitive Moravian-Silesian Carpathians and the impact of mining activities on relief. The planned underground mining activities will accelerate geodynamic processes in the area and cause substantial changes in the young mountainous relief. The impacts of underground hard coal mining in such sensitive young mountains are difficult to predict since actual topographical changes can be significantly different from those predicted by an OKD computer model based on conditions in the lowland part of the Upper Silesian Coal Basin. The authors present a 3D engineering-geomorphological model of expected impacts of the coal mining project on the relief of the western part of the Trojanovice Mine Area.

Key words: impact of underground coal mining on relief, geohazards, engineering geomorphology, the Moravian-Silesian Carpathians, the Trojanovice Mine Area, Czech Republic

INTRODUCTION

Geomorphology is a scientific study of landforms based on cause-and-effect relationships. The understanding of landforms is important for the mitigation of potential risks, connected either with natural or human-induced hazards. Engineering geomorphology concentrates on the prediction and evaluation of impacts of engineering structures on landforms and geomorphological processes and evaluation of these impacts with the aim to find optimal solutions, to avoid potential geohazards and time delays during construction and financial losses resulting from that (FOOKES et al. 2007, SZABÓ et al. 2010). The aim of the present engineering geomorphological study is to estimate and predict the degree of impacts of a possible underground hard coal mining in the Trojanovice Mine Area underneath the sensitive terrain of the young Moravian-Silesian Carpathians on relief. The Trojanovice Mine Area near the Frenštát pod Radhoštěm Town in the eastern part of the Czech Republic was declared officially by Czechoslovak state on 30 June 1980. It is one of the largest mining areas in the Czech Republic due to its surface extent of 63.17 sq. km. The area forms approximately the shape of a rectangle elongated in the direction from southwest to northeast in groundplan (**Fig. 1**). The boundary of the area extends from the Moravian-Silesian Beskids (the Moravskoslezské Beskydy Mts.) in the southwest and west across the Frenštátská brázda Intermontane Depression to the Ondřejník Highland in the northeast.

STUDY AREA

The Trojanovice Mine Area is situated at the Carpathian front, where the northern part of the African and Eurasian lithospheric plates collided from the Upper Cretaceous up to Tertiary. Geologically the area belongs to the Moravian-Silesian terrane that is composed of two structural levels. The lower level forms a crystalline complex (Brunovistulicum – DUDEK 1980, MENČÍK et al., 1983), the upper Variscan level then folded and faulted Devonian-Carboniferous complex (MÜLLER, ed. 2001, MARTINEC et al. 2008). The margin of the Moravian–Silesian terrane bounded and subducted in the deep during Alpine folding at the end of Mesozoic and in the Tertiary (**Fig. 2**). The northern part of the Pannonian block then was thrust over the planated surface of the Moravian-Silesian terrane. Thrust nappes of the Carpathians were over thrust the ancient Mora-

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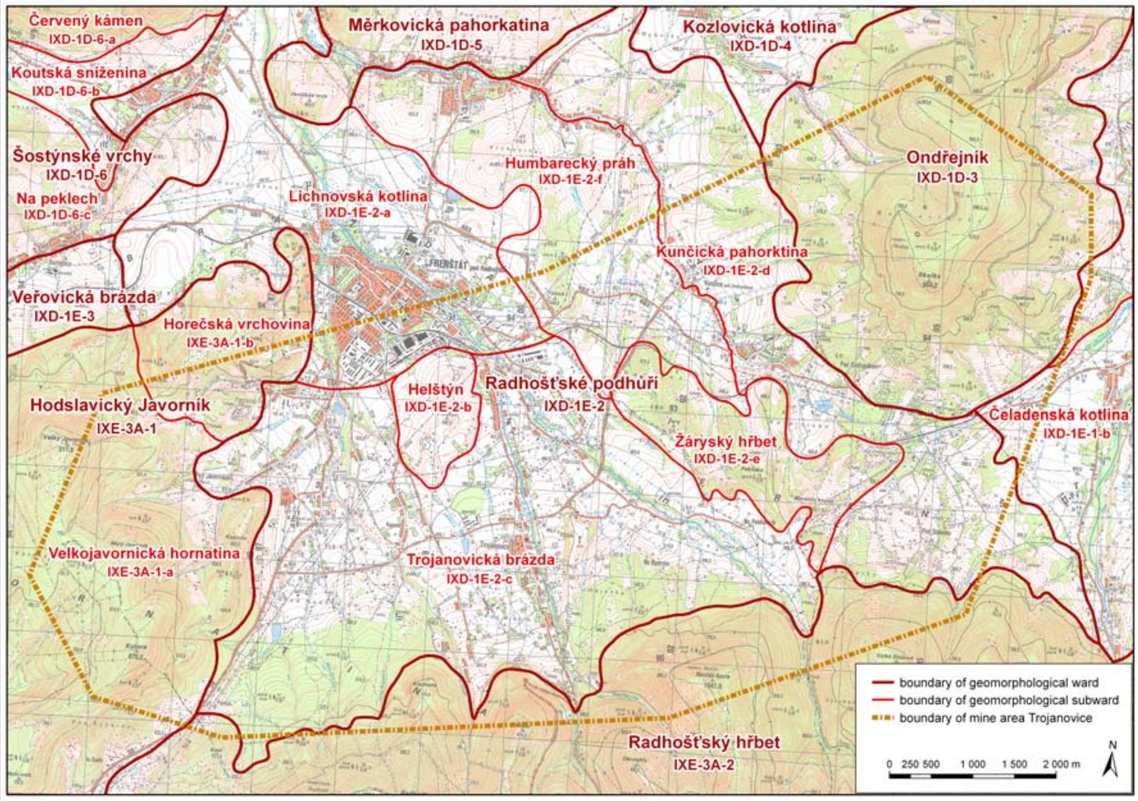


Fig. 1 Location of the Trojanovice Mine Area and geomorphological units

vian-Silesian terrane with its Miocene cover along nearly horizontal over thrust planes (CHLUPÁČ et al. 2002). The thickness of the overthrust flysch nappes reaches 850 – 1,200 m in the Trojanovice Mine Area .

The coal-bearing Carboniferous deposits of the Beskidian part of the Upper Silesian Coal Basin under the Carpathian nappes were discovered in a 1,424.9 m deep borehole to the northwest from the Frenštát pod Radhoštěm Town already back in 1916 – 1919. Further bore holes have uncovered the relict of the Karviná formation coal bearing with areal extent of 46 sq. km and maximal thickness more than 200 m. The coal bearing Carboniferous deposits extending from the Frenštát pod Radhoštěm Town to the south beneath the mountains of the Moravian-Silesian Beskids where the Moravian-Silesian terrane reaches its largest depth (**Fig. 2**). In the borehole situated by the Valašské Meziříčí Town the surface of coal bearing deposits was found at the depth of 2,800 m. The total reserve of black coal reaches 1,568,559 kt in the partial mine areas Frenštát – West and Frenštát – East (parts of the Trojanovice Mine Area). There are five coal seams designated for mining activities in the Karviná formation characterized by medium and large thicknesses (seams No. 36, 37, 38 and 40). Two winding shafts more than 1,000 m deep were built in Trojanovice in the 1980s. These winding shafts are now preserved, but there are still undergoing discussions about the underground mining of hard coal or gas in the Trojanovice Mine Area .

The flysch nappes in the mine area belong to the Silesian unit of the Outer group of the nappes of the Outern Western Carpathians in the Godula development with characteristic stratigraphical structure (**Fig. 2**). The Godula nappe of the Silesian unit is over thrust on the Subsilesian unit and deposits of Miocene age deposited discordantly over the Carboniferous complex. The residual shear stress in the melange of the over thrust surface of Young Styrian Silesian and Young Styrian Subsilesian nappes and also deeper in the Young Styrian Subsilesian nappe caused destruction of the winding shaft No. 4 in Trojanovice despite the fact that over thrusting largely terminated in the Badenian (KREJČÍ et al. 2004, MARTINEC et al. 2008, p. 147). The possible underground hard-coal mining in the of the Trojanovice Mine Area will have impact on the relief due to the increase of the existing imbalance of rocks massifs by undermining and rock bursts that will result in a mobilization of geodynamic processes. Especially the partial mine area of the Trojanovice-West is from the mining-technological point of view situated in

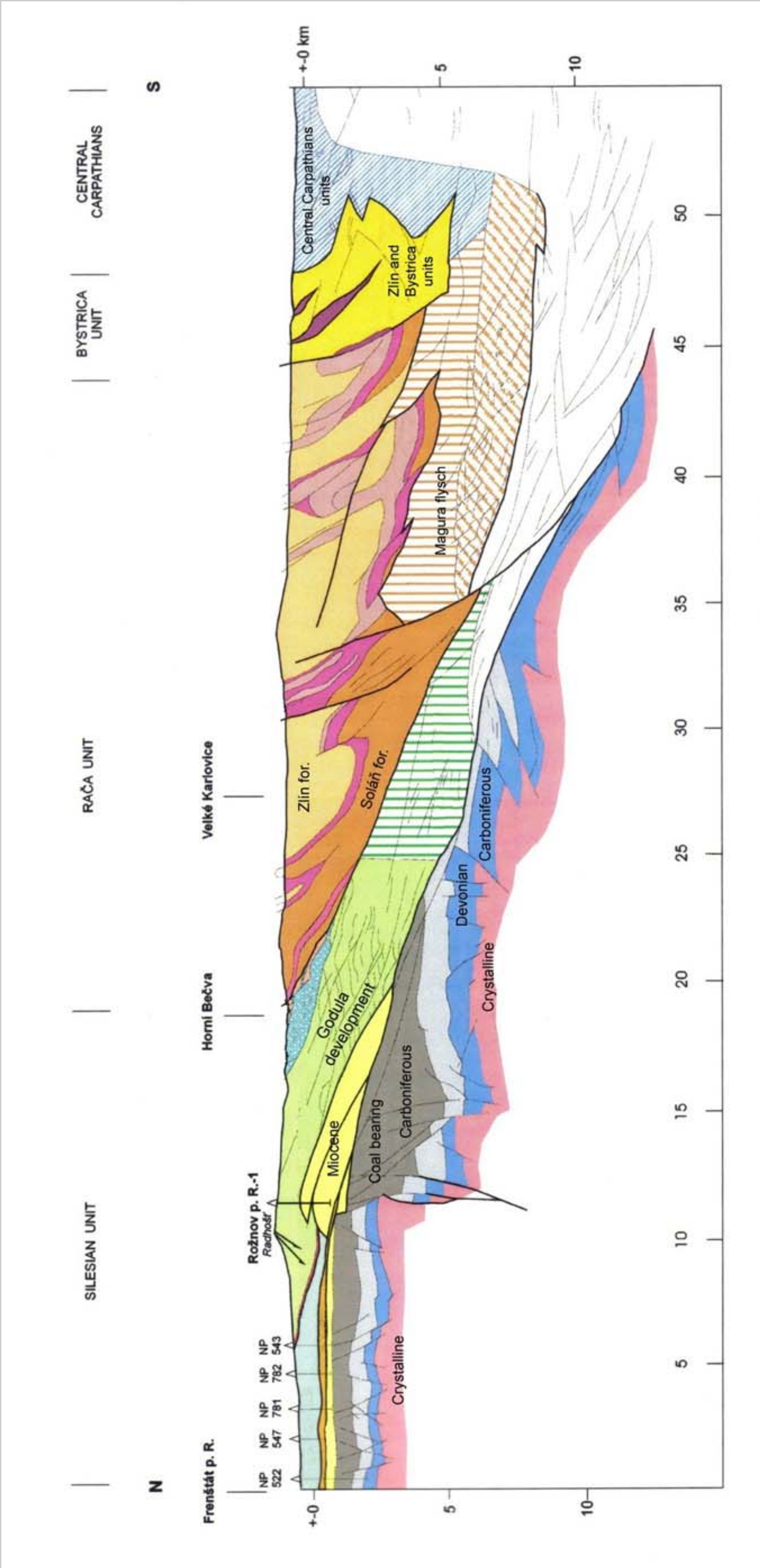


Fig. 2 Subduction of the Moravian-Silesian terrane beneath the nappes of the Outer Western Carpathians (modified after MENČÍK et al. 1983 and KREJČÍ et al. 2004)

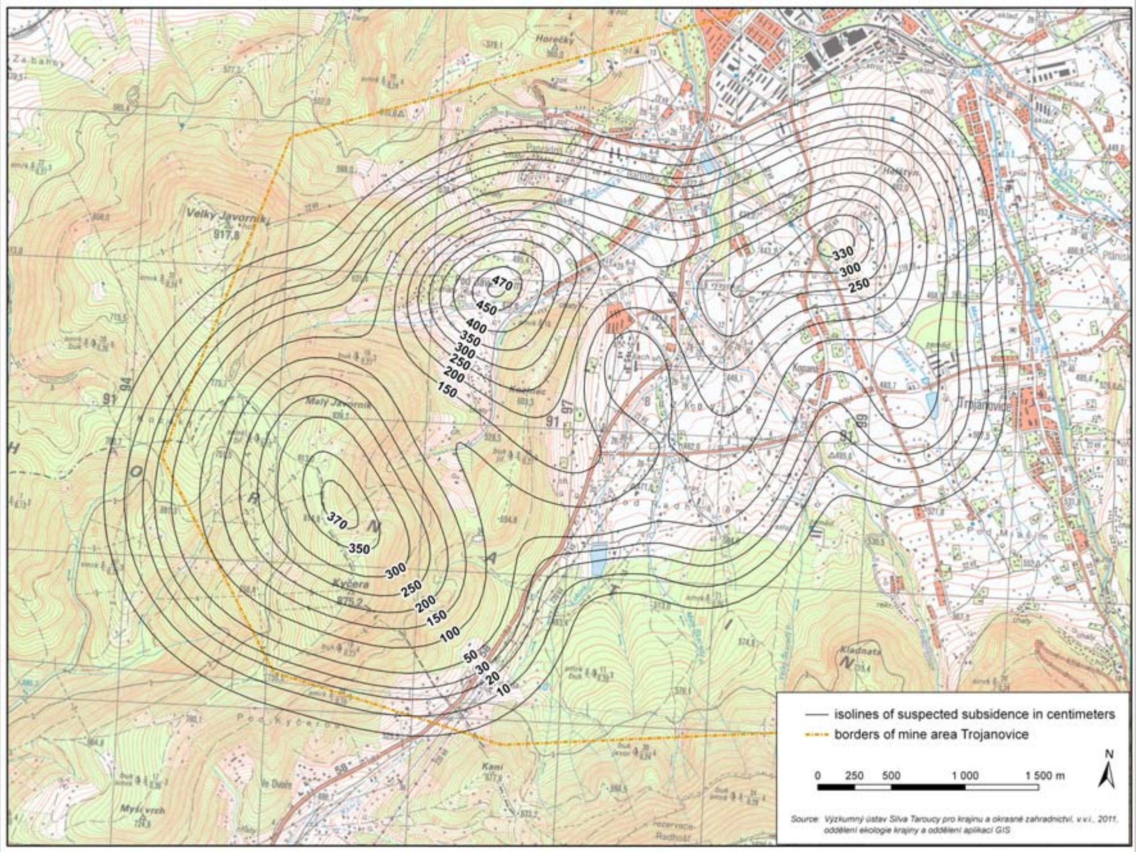


Fig. 3 The Trojanovice Mine Area – western part. Computed prediction of maximal subsiding as impact of underground hard coal mining in centimetres. Source: OKD IMGE joint-stock Company. Topographic map Ministry of defence of the Czech Republic

extremely complex geological situation. The project proposes advance mine adits through heads of the Carpathian nappes crossing a series of important tectonic lines. The OKD IMGE joint–stock company, Ostrava (HYNČICOVÁ 1997) made calculations and cartographical visualization of expected terrain subsidence in relation to underground coal mining in the western part of the Trojanovice Mine Area south of the Frenštát pod Radhoštěm Town and the Trojanovice Village in the east and the Velký Javorník Mt. (917.8 m a. s. l.) in the west in October 1996 (**Fig. 3**). The authors compared this prediction with the engineering-geomorphological prediction based on detailed geomorphological mapping and computer supported modelling of supposed impact of hard-coal mining.

METHODS

Authors used as the basic method the detailed geomorphological mapping in the field, evaluation of boreholes and remote sensing materials. Information obtained in the field and by remote sensing were visualised in the digital geomorphological map in the scale 1:10 000: The software ArcGIS 9.2 of the ESRI company was used during the process of the geomorphological map compilation. Obtained data were stored in 3 layers of the database (areal, linear and point layer) in the format ESRI shape. Other used methods were structural geomorphological analysis and engineering geomorphological analysis in GIS environment.

GEOMORPHOLOGICAL CONDITIONS

The mine area extends from the Moravian-Silesian Beskids in the southwest and west across the intermountane depression of the Frenštátská brázda Furrow to the Ondřejník Highland in the northeast (**Fig. 1**). The different geomorphological properties of rocks of the Silesian unit influence the relief of the mine area. Mountains and highlands of the Moravian-Silesian Beskids and the Ondřejník Highland are composed of resistant Godula sandstones of the Upper Cretaceous age. The depression of the Frenštátská brázda Furrow developed in less resistant layers of the Upper Cretaceous and Paleogene age with higher proportion of claystones and marls.

The mining area includes the eastern section of the Hodslavický Javorník Mts. (a part of the Moravian-Silesian Beskids). The relief of the Hodslavický Javorník Mts. is distinctive stepped (ŽIŽKOVÁ and PÁNEK 2006). The elevations of individual steps (blocks) sink from the highest Velký Javorník Mt. (917.8 m a. s. l.) in the direction to the east to the Pindula Mountain Saddle and to the depression of the Frenštátská brázda Furrow. Particular flat topped blocks are divided by steep scarps (**Fig. 3**). At the foot of scarps pseudokarst landforms (closed drain-less depressions, pseudokarst dolines) as evidence of deep-seated slip planes are common. The borders of mountains are dissected by deep valleys of left tributaries of the Lubina River. There are many landslides on steep valley sides.

The southern part of the mining area reaches into the Radhošťský hřbet Ridge (a part of the Moravian-Silesian Beskids). The northern front escarpment of the Moravian-Silesian Beskids is traditionally interpreted as a structural scarp on the head of the Godula nappe. The author's analysis has shown that some parts of this escarpment are neotectonic fault scarps controlled by movements of block along faults parallel with the escarpment. These rejuvenated faults were detected in the Variscan basement and propagated through the flysch nappes to the Earth surface. The fault systems are also represented on the geological map of MENČÍK and TYRÁČEK (1985 – see also **Fig. 2**). The striking steps on the front escarpment are subsided blocks of resistant Middle Godula sandstones. The steep northern front escarpment of the mountains is dissected by deep valleys of the Lubina River and its tributaries (the Radhoštnice River, the Bystrá River). Pediments developed at the foot of the front scarp in the Pliocene.

The core of the mining area lies in the depression of the Frenštátská brázda Furrow. The Frenštátská brázda Furrow is an intermontane depression situated between the Moravian-Silesian Beskids in south and west and the Štramberská vrchovina Highland in north. The central part of the Frenštátská brázda Furrow to the south of the Frenštát pod Radhoštěm Town is called the Trojanovická brázda Furrow (**Fig. 1**). The flat bottom of the depression of the Trojanovická brázda Furrow forms three rock pediment levels partly covered by gravels of alluvial cones of the Lubina River and its tributaries (BUZEK 1969, 1972, 1973, IVAN 1987). The Quaternary alluvial cones coalesced into a bajada (DEMEK et al. 2011). The Frenštát pod Radhoštěm Town is situated on the bajada. The Helštýn Monadnock (482,1 m a. s. l) rises above the town and above the flat bottom of the depression of the Trojanovická brázda Furrow controlled by Cretaceous volcanic rocks (**Fig. 1**).

The steep slopes of the Žáryský hřbet Structural Ridge limit the depression of the Trojanovická brázda Furrow on the east (**Fig. 1**). The flat tops of the ridge are structural surfaces bounded on more resistant sandstone layers. Landslides, partly active, are common on steep slopes of the Žáryský hřbet Ridge. The less distinctive subward Humpolecký práh Sill forms the NE continuation of the Žáryský hřbet Ridge. The Kunčická pahorkatina Depression drained by the Tichávka River, flanks the foot of the Ondřejník Highland and also the foot of the Radhošťský hřbet Ridge. The bottom of the Kunčická pahorkatina Depression form both rock pediments and alluvial cones coalescing into a bajada.

The Ondřejník Highland represents a distinctive part of the Štramberská vrchovina Highland (**Fig. 1**) in the Beskids piedmont. The highland reaches 964.2 m a. s. l. with the Skalka Mt. and it forms the central synclinal ridge composed of the resistant middle Godula sandstones. The ridge is spread and struck by several types of geodynamic processes (RYBÁŘ et al. 2006, PÁNEK et al. 2011). Due to retreat of slopes developed cuestas on the western slope of the ridge (BUZEK 1969, RYBÁŘ et al. 2006). On the slopes of the highland also many extensive landslides developed. In the disrupted top part there are several pseudokarst landforms (including pseudokarst caves – HROMAS et al. 2009).

GRAVITATIONAL SPREADING AND BREAK-UP OF MOUNTAIN AND HIGHLAND ROCK MASSIFS

The gravitational spreading and break-up of the Moravian-Silesian Beskids and the Ondřejník Highland represents the most important problem of relief stability in relation to mining of hard coal in the Trojanovice Mine Area. Gravitational deformations of rock massifs are very common in this area and often extend very deep (KREJČÍ et al. 2004, RYBÁŘ et al. 2006). Very surprising is the fact that the largest gravitational disturbances were found in areas of geomorphologically very resistant sandstones of the middle Godula development that belongs to the hardest and the most resistant rocks in the study area. Massive beds of the Godula sandstones of the Moravian-Silesian Beskids that reach altitudes over 1,000 m in the Radhošť Mt. and the Kněhyně Mt. are thrust over the unstable claystones of the col-

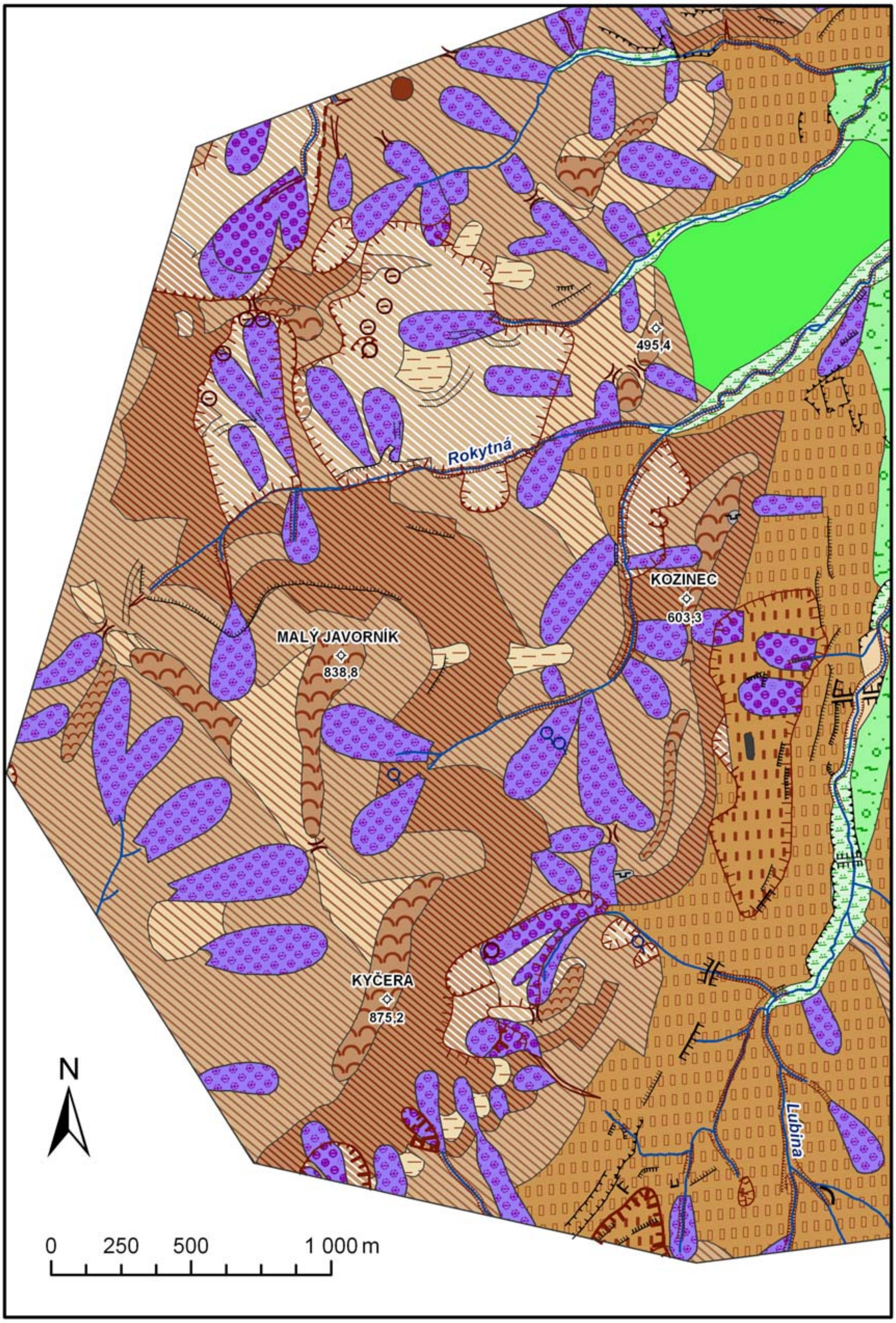
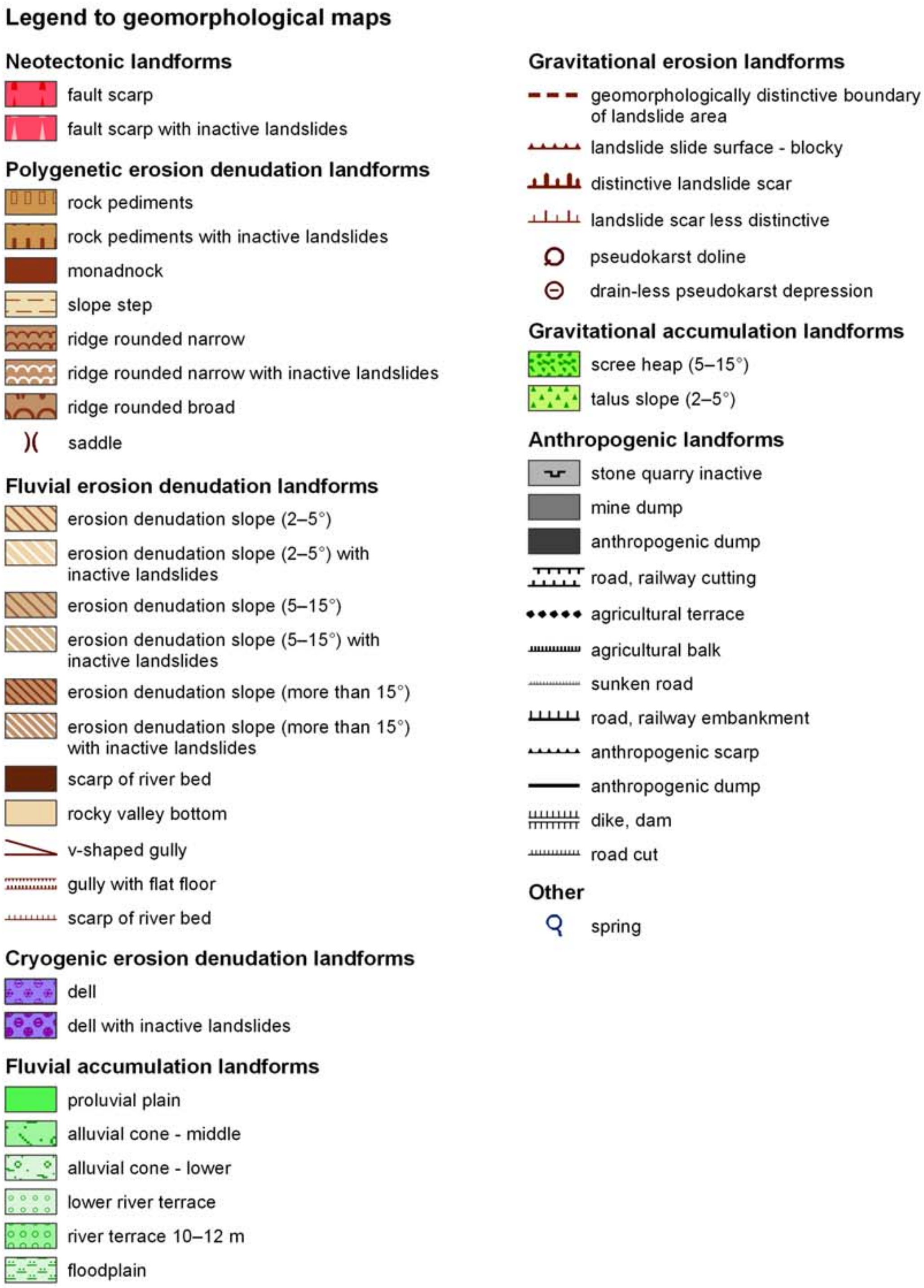


Fig. 4 Geomorphological map of the Hodslavický Javorník Mts. in the western part of the Trojanovice Mine Area



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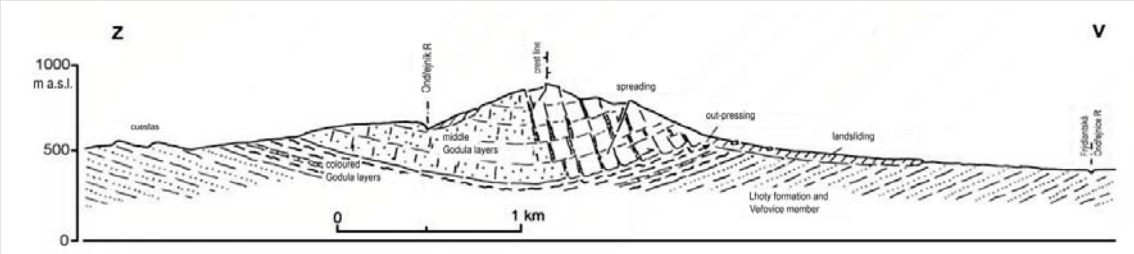


Fig. 5 Cross-section through the Ondřejník Highland showing the spreading of the central sandstone ridge and out-pressing of plastic claystones at the foot. Modified after RYBÁŘ et al. (2006)

oured Godula and Veřovice layers. RYBÁŘ et al. (2006) discovered the outcrop of claystones of coloured Godula layers in the Ondřejník Highland that caused spreading of the superposed very resistant but easily breakable sandstones of the middle Godula development.

The mountain peaks of the Moravian-Silesian Beskids exhibit higher altitudes than expected from simple over thrusting of the Silesian and Subsilesian units along nearly horizontal over thrust planes over the underlying basement of the Moravian-Silesian Terrane and its Neogene cover (CHLUPÁČ et al. 2002, KREJČÍ et al. 2004). Consequently, the whole area must have experienced isostatic uplift, gravitational spreading and break-up. These geodynamic processes caused imbalance in rock massifs and stress in addition to that increased by subaerial erosion. The stress resulted in deep and widespread deformations of rock massifs. Rock deformations manifest themselves in two ways: first in a stepped structure of the surface and second by a deep-seated creep with common pseudokarst features as deep and open crevasses with pseudokarst caves. These processes and landforms are well developed on the front scarp of the Moravian-Silesian Beskids, in the Hodslavický Javorník Mts. and on slopes of the Ondřejník Highland (**Fig. 4**). The pseudokarst Kněhyňská jeskyně Cave on the slope of the Kněhyně Mt. (1256.8 m a. s. l.) can serve as evidence of large depths of spreading. This cave is accessible into the depth of 57.6 m with narrow tensile fissures continuing further into the rock massif. Other pseudokarst caves and abysses on wide open and deep crevasses in Godula sandstones have already been described long ago (WAGNER et al. 1990, HROMAS et al. 2009).

Dilatometric measurements proved recent movements on tensile fissures (NOVOSAD and KOŠŤÁK 2002, STEMBERK and RYBÁŘ 2005, RYBÁŘ et al. 2006, KLIMEŠ and STEMBERK 2007). WAGNER (2004) described opening of tensile fissures on the Lukšinec Ridge near the Lysá hora Mt. after extreme precipitations in 2007. The data about the imbalance of the rock massifs in the Trojanovice Mine Area obtained by KREJČÍ et al. (2004) in the Moravian-Silesian Beskids and RYBÁŘ et al. (2006) in the Ondřejník Highland are therefore confirmed.

In addition to that, there are widespread extensive fossil, subrecent and recent landslides with deep seated deformations on slopes of the Trojanovice Mine Area. In the Moravian-Silesian Beskids there is probably the highest density of landslides in the Czech Republic.

ENGINEERING – GEOMORPHOLOGICAL MODEL OF RELIEF DEFORMATIONS RELATED TO IMPACT OF MINING IN THE PARTIAL FRENŠTÁT – WEST MINE AREA

Based on geomorphological mapping the largest impact on relief can be expected in the forested eastern part of the Hodslavický Javorník Mts. (**Fig. 6**). The relief of the geomorphological unit is distinctly stepped. Flat surfaces of subsided or rotated blocks are irregularly alternating with steep slopes (JANOŠ 2004). The altitude decreases in large steps from the highest Velký Javorník Mt. (1017.8 m) to the east to the Pindula Saddle and to the depression of the Frenštátská brázda Furrow. The northern slope of the Velký Javorník Mt. is stricken by a large step-like arranged landslide with slip plane in bedrock. At the foot of the northern slope of the Velký Javorník Mt. there is a counterslope escarpment interpreted as a fossil deep seated slope deformation. At the foot of the slip plane of 2 – 6 m height there are open tensile fractures, distinctive closed depressions without outlet and pseudokarst dolines (**Fig. 4**). Fossil slope deformation also represents another lower scarp on the edge of the subsiding depression around the elevation of 495.4 m in the upper reaches of the Myslivecký potok Stream (Pod Javorníkem on the 1:25 000 scale map of the Czech Army). The slip plane reaches a height of 15 m. Other slope deformations were described on the

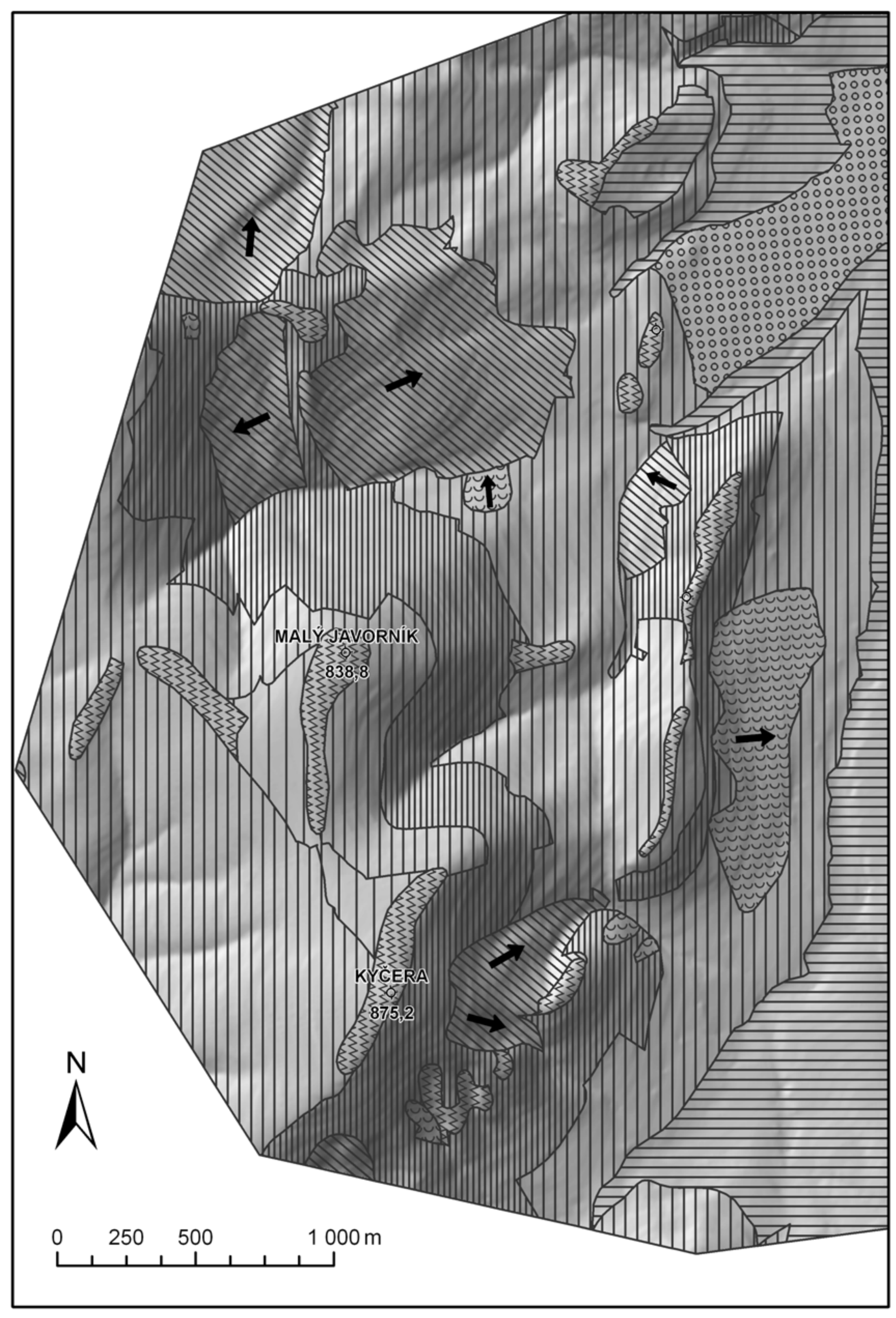
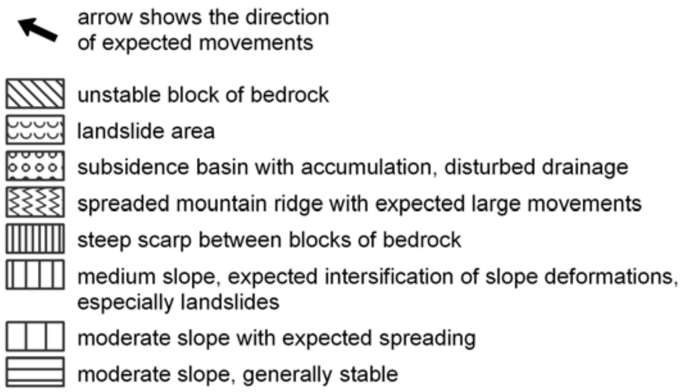


Fig. 6 Digital engineering-geomorphological 3D model of expected terrain deformations and geohazards in relation to planned deep mining of black coal in the western part of the Trojanovice Mining Area derived from the digital geomorphological map



Legend to **Fig. 6**

Kozinec Mountain Ridge (**Fig. 4**). The mining can rejuvenate fossil slope deformations on this locality and threaten the important road No. 58 from the Rožnov pod Radhoštěm Town through the Pindula Saddle to the Frenštát pod Radhoštěm Town (**Fig. 4**). Terrain subsidence between the Malý Javorník Mt. (838,8 m a. s. l.) and the Kyčera Mt. (875.2 m a. s. l.) could cause horizontal movement of the spread bedrock. In addition, the eastern slope of the Kyčera Mt. is affected by fossil slope deformation with the a slip plane of 15 m height which is an evidence of sandstone blocks movements (**Fig. 4**). The subsidence on the Helštýn Monadnock above the Frenštát pod Radhoštěm Town could threaten the factories situated on its northern slope.

As yet there is no prediction for terrain deformation caused by mining in the eastern part of the Trojanovice Mine Area. In relation to extensive spreading the whole central ridge of the Ondřejník Highland (**Fig. 5**), the outcrop of claystones of coloured Godula layers at the foot of the sandstone ridge and the presence of large landslides authors express the opinion that even a small anthropogenic impact can involve extensive geohazards.

CONCLUSIONS

The authors carried out the detailed engineering-geomorphological survey of the whole Trojanovice Mine Area in connection with planned underground hard coal mining. The authors compared the prediction of mountains and highlands relief changes due to underground hard coal mining in the western part of the Trojanovice Mine Area computed by the OKD IMGE joint-stock Company with results of their detailed engineering - geomorphological survey. Actual changes of relief due to properties of flysch rock massifs can be significantly different from those obtained from the computer analysis based on the experience and software from the lowland part of the Upper Silesian Coal Basin. The engineering-geomorphological analysis of the Trojanovice Mine Area has shown that underground mining activities can cause up to catastrophic changes in the relief of the Moravian-Silesian Carpathians. Authors present a digital 3D model of expected relief changes of the western part of the Trojanovice Mine Area due to planned coal mining based on their engineering-geomorphological analysis. Unfortunately there are no technological data from OKD for the eastern part of the Trojanovice Mine Area. But the detailed geomorphological mapping carried out by authors has shown that in relation to extensive spreading the whole central ridge of the Ondřejník Highland and the presence of large landslides even a small anthropogenic impact connected with coal mining can involve extensive geohazards also in the eastern part of the mine area. The consequences of underground hard coal mining in such a sensitive young mountain and highland terrain in the Czech Republic need further survey of the whole Trojanovice Mine Area and a complex prediction of landscape changes connected with planned coal mining.

ACKNOWLEDGEMENTS

The research was carried out by The Silva Tarouca Research Institute for Landscape and Ornamental Gardening p. r. i. Průhonice and funded by the Research programme of MSM 6293359101 Research into sources and indicators of biodiversity in cultural landscape in the context of its fragmentation dynamics. Authors would like to thank to the Ministry of Environ-

ment of the Czech Republic and to Czech Geological Survey for lending Engineering-geological map of slope stability 1:10 000 and explanatory texts used during the research and preparation of this paper. Authors thank to Professor Dr. Petr Martinec DrSc. and two anonymous reviewers for their valuable comments. Authors are also indebted to Dr. T. M. Rush (London, U. K.) for linguistic corrections.

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