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TOWARDS A NEW FRAMEWORK FOR ANTHROPOGENIC GEOHERITAGE: THE CASE OF OPEN-PIT MINING LANDSCAPES

Abstract. *The concept of geoheritage has traditionally focused on the appreciation of landforms and geological features shaped by natural processes over long periods of time. This study discusses a paradigm shift, proposing that large-scale mining structures, particularly open-pit mines, should be recognized as significant anthropogenic landforms that are crucial for understanding the contemporary state and future of geoheritage. As some of the most visible and extensive manifestations of humanity's ability to reshape the surface and near-surface layers of the Earth, these sites represent an accelerated form of anthropogenic geomorphology. Open-pit mines constitute not only important socioeconomic and cultural landscapes but also embody the collective memory and lifestyle of millions of people worldwide, as numerous towns and cities have developed around and been shaped by mining activity. This research examines the distinct geomorphologies and landscapes of open-pit mines, the unprecedented rates of their formation, and their long-term persistence within the geological record. Through a regional analysis of Sokolov mining site in Czechia, Central Europe, it demonstrates that these landscapes are not merely scars testifying to our technogenic activity but vital sites for interpreting the stratigraphic and anthropological signatures of the Holocene and the advanced human ability to exploit natural resources. The study concludes by proposing a new typology for classifying anthropogenic mining geoheritage, arguing that such a framework is essential for a comprehensive understanding of the transformation of terrestrial landscapes during the Holocene.*

Key words: *open-pit mining, anthropogenic geoheritage, mining geoheritage, cultural landscapes, Sokolov coal basin*.

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К РАЗРАБОТКЕ НОВОЙ КОНЦЕПЦИИ АНТРОПОГЕННОГО ГЕОНАСЛЕДИЯ: НА ПРИМЕРЕ ЛАНДШАФТОВ ОТКРЫТЫХ ГОРНЫХ РАЗРАБОТОК

Аннотация. *Традиционно концепция геокультурного наследия фокусировалась на оценке форм рельефа и геологических особенностей, сформированных природными процессами в течение длительных периодов времени. В данном исследовании рассматривается смена парадигмы, предлагающая признать крупномасштабные горнодобывающие сооружения, особенно карьеры, значимыми антропогенными формами рельефа, имеющими решающее значение для понимания современного и будущего состояния геокультурного наследия. Как одни из наиболее наглядных и масштабных проявлений способности человечества изменять поверхность и приповерхностные слои Земли, эти объекты представляют собой антропогенные геоморфологические структуры. Карьеры являются не только важными социально-экономическими и культурными ландшафтами, но и воплощают коллективную память и образ жизни миллионов людей во всем мире, поскольку многочисленные города и поселки развивались вокруг горнодобывающей деятельности и формировались под ее влиянием. В данном исследовании рассматриваются отличительные геоморфологические особенности и ландшафты карьеров, беспрецедентные темпы их образования и их долгосрочное сохранение в геологической летописи. На основе регионального анализа горнодобывающего участка Соколов в Чехии показано, что эти ландшафты являются не просто «шрамами» на земной поверхности, свидетельствующими о техногенной деятельности, но и жизненно важными местами для*

интерпретации стратиграфических и антропологических признаков голоцена и практики человека по эксплуатации природных ресурсов. В заключение исследования предлагается новая типология классификации антропогенного горнодобывающего геокультурного наследия и утверждается, что такая структура необходима для всестороннего понимания трансформации наземных ландшафтов в течение голоцена.

Ключевые слова: *открытые горные разработки, антропогенное геонаследие, горнопромышленное геонаследие, культурные ландшафты, Соколовский угольный бассейн*.

Introduction and problem statement. Industrial and postindustrial landscapes increasingly occupy a critical position at the intersection of ecological restoration, land-use transformation, and heritage conservation [3]. Processes of planning and remediation often generate tension between the recovery of ecological functions and the preservation of historically significant landforms, spatial configurations, and material traces of industrial activity [16]. In this context, the concepts of authenticity and integrity are essential, as they enable industrial landscapes to be interpreted as material evidence of historical processes, technological development, and landscape transformation [3].

Traditionally in the Western Europe geoheritage has focused on natural geological and geomorphological features formed over long temporal scales. However, human made landforms also represent a significant component of geodiversity. From a geomorphological perspective, anthropogenic landforms can be understood as a form of secondary geodiversity, comprising human-made landforms, their assemblages, and associated systems that may hold scientific, educational, cultural, and heritage value [6; 16]. These elements may therefore be conceptualized as anthropogenic geoheritage.

Within this framework, a key problem emerges: despite their scale, visibility, and scientific significance, large-scale anthropogenic landforms, particularly those produced by open-pit mining, remain insufficiently recognized and systematically classified within geoheritage studies.

Study of the problem. Open-pit mining landscapes represent some of the most extensive and clearly expressed forms of anthropogenic geomorphology (Fig. 1). Their terraced slopes, benches, excavation voids, spoil heaps, and reconfigured drainage systems are generated through extremely rapid geomorphological processes, transforming relief at rates and scales that often exceed those of natural surface dynamics [22].

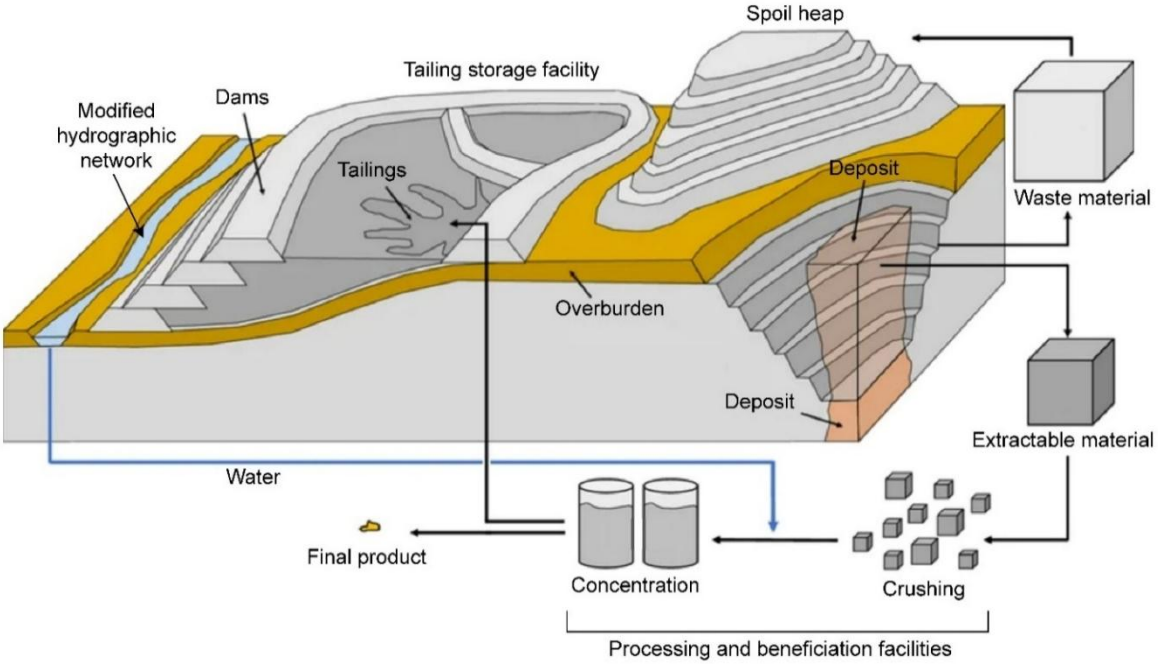


Fig. 1. Simplified schematic representation of the principal functional elements of an open-pit mining system (modified after [17; 22])

These landscapes function not only as sites of resource extraction but also as distinctive geomorphic systems that expose deep geological sequences, reveal stratigraphic relationships, and generate new landform assemblages [16]. Moreover, open-pit mining areas are frequently embedded within broader cultural and social landscapes. Mining regions commonly influence settlement patterns, shape local identity, and contribute to collective memory [8; 18]. They form part of a wider spectrum of mining geoheritage, encompassing extraction structures, technical infrastructure, waste deposits, hydraulic systems, transport networks, and intangible cultural elements.

Despite these characteristics, the role of open-pit mining landscapes as anthropogenic geoheritage remains underexplored. There is a lack of integrative approaches that combine geomorphological, geological, industrial, and cultural perspectives, as well as a need for clearer conceptual frameworks and classification systems.

Open-pit mining landscapes are also associated with a range of environmental and social consequences that have become an important focus of recent research [3; 6; 8; 16; 18]. The removal of overburden, modification of drainage systems, and creation of extensive excavation voids can strongly alter existing geomorphological and ecological conditions [3; 16]. Consequently, considerable attention has been devoted to the restoration of post mining landscapes, particularly with regard to ecosystem recovery, biodiversity conservation, hydrological rehabilitation, and the development of new land uses [19]. Mining activities may affect local communities through changes in settlement structure, land use patterns, and economic dependency on extractive industries [18]. These impacts are not necessarily uniform in space or time and may persist long after extraction has been stopped. Therefore, contemporary approaches increasingly consider mining landscapes as environments where heritage conservation, ecological restoration, and social development must be evaluated together rather than as separate processes [3; 8; 16].

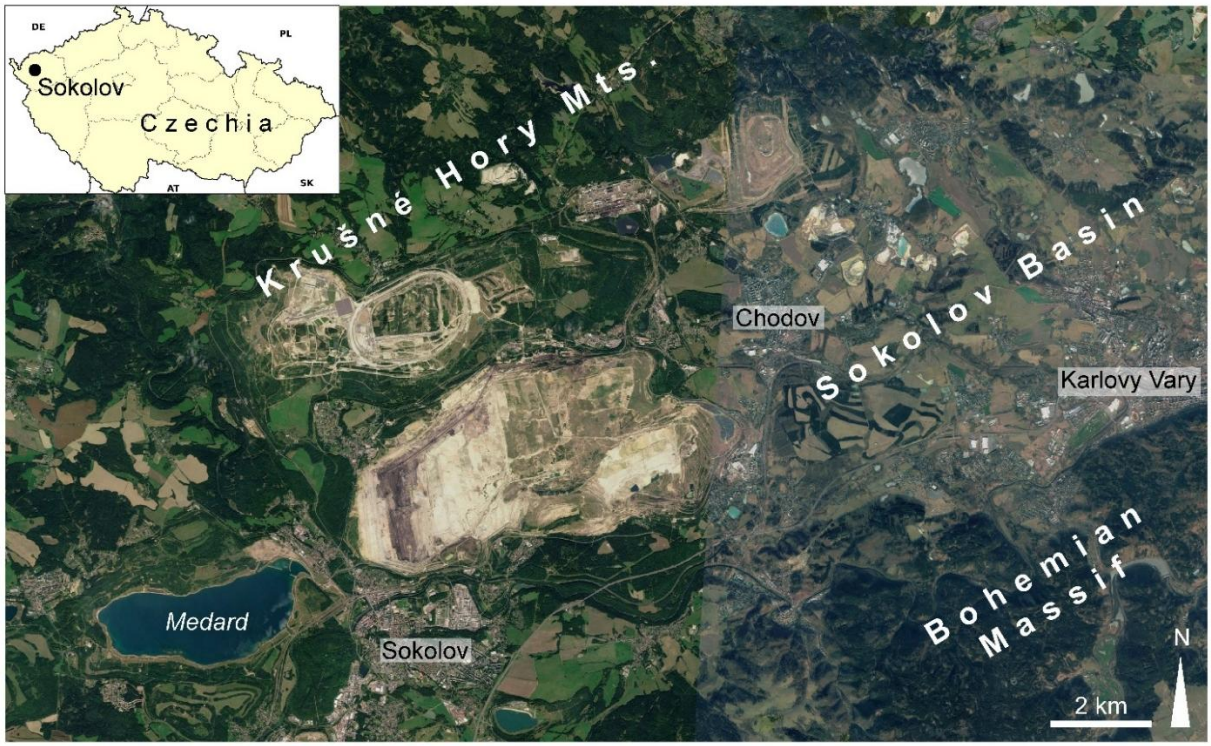


Fig. 2. Orthophoto map of the Sokolov area showing clearly visible open-pit mining sites and water reservoirs formed in reclaimed former pits [13]

Aim and objectives of the research. This study argues that large-scale open-pit mining complexes should be recognized as a distinct category of anthropogenic geoheritage, capable

of preserving stratigraphic, geomorphological, industrial, and cultural signatures of the Holocene. The research focuses on the Sokolov brown coal basin in Czechia, Central Europe (Fig. 2), as a case study to examine the impacts of open-pit mining on landform development, geological exposure, and settlement patterns. The main objectives of the study are: (1) to analyze the geomorphological forms and processes associated with open-pit mining; (2) to assess their significance within the framework of anthropogenic geoheritage; (3) to develop a functional classification of mining related geoheritage elements.

Matherials and methods. The methodology combines theoretical and empirical approaches to examine open-pit mines as elements of anthropogenic geoheritage, following the frameworks proposed by Chen et al. (2015) [7] and Bian et al. (2026) [3]. A review of classical concepts of mining heritage and geoheritage is first undertaken. Traditionally, mining has been interpreted primarily as a means of exposing natural geological features of scientific value [12; 14]. This perspective is compared with more recent approaches [15; 16; 19], which recognize mining landscapes as complex systems encompassing both tangible and intangible geoheritage.

Table 1

Functional classification of the anthropogenic mining geoheritage (based on [20; 22])

Functional type	Subtype	Description	Examples
Extraction Structures	Open-pit mines	Large surface excavations created by removal of overburden and ore	Open-pit copper or iron mines
	Underground mines	Subsurface extraction networks including galleries, shafts, and stopes	Medieval silver mines, coal mines
	Quarries	Surface extraction sites for building stone or industrial minerals	Limestone, granite quarries
Mining Infrastructure	Shafts and adits	Vertical or horizontal access structures to underground workings	Ventilation shafts, drainage adits
	Galleries and tunnels	Excavated passages for extraction, transport, or drainage	Roman mining tunnels
	Pillars and chambers	Structural features left to support underground excavations	Room-and-pillar systems
Processing and Beneficiation Sites	Ore dressing facilities	Areas for crushing, grinding, washing, or sorting ore	Stamp mills, washing floors
	Smelting sites	Locations where ores were metallurgically processed	Iron bloomeries, copper smelters
	Slag heaps	Waste accumulations from smelting activities	Ancient slag mounds
Waste and By-products	Spoil heaps	Piles of waste rock from mining operations	Mine dumps
	Tailings	Fine-grained waste from ore processing	Tailings ponds
Hydraulic Mining Systems	Water channels and aqueducts	Engineered systems for water supply to mining areas	Roman aqueducts for gold mining
	Reservoirs and tanks	Water storage for mining and ore processing	Settling tanks
	Drainage systems	Structures controlling groundwater and mine water	Cuniculi, drainage galleries
Transport and Logistics	Haulage roads	Roads built for transporting ore or waste	Mine access roads
	Railways and inclines	Fixed transport systems for ore movement	Narrow-gauge mining railways
	Loading platforms	Areas for transferring material	Ore loading docks
Mining Landscapes	Cultural mining landscapes	Integrated mining areas shaped by long-term human activity	Historic mining districts
	Reclaimed mining areas	Landscapes altered by restoration or abandonment	Post-mining landscapes
Intangible Mining Heritage	Technical knowledge	Traditional mining methods and skills	Hand-drilling techniques
	Social and economic practices	Mining-related community organization	Miners' settlements

A functional classification of anthropogenic mining geoheritage (Table 1) is based on classification which synthesizes established typologies [20; 22] and organizes mining related features into categories including extraction structures, mining infrastructure, processing and beneficiation sites, waste and by-products, hydraulic systems, transport and logistics, mining landscapes, and associated intangible heritage. Open-pits are analysed as integrated systems rather than isolated elements, enabling the identification and assessment of features with geoheritage significance.

The empirical part of this study is based on a case of the Sokolov coal basin (Czechia). Spatial and temporal analyses of landscape transformation are conducted using remote sensing and geospatial datasets (historical maps, archival and contemporary orthophotographs) obtained from Czech Geological Survey [9; 10], State Administration of Land Surveying and Cadastre of Czechia [11] and Google Earth [13]. Landscape change is analysed through a comparative approach, examining successive periods to identify the evolution of mining landforms, the expansion of open-pit excavations, the development of spoil heaps, and changes in drainage systems and infrastructure.

Spatial and temporal analyses of landscape transformation in the Sokolov area were conducted using remote sensing and geospatial datasets, including historical maps, archival and contemporary orthophotographs, and digital elevation models obtained from the Czech Geological Survey [9; 10], the State Administration of Land Surveying and Cadastre of Czechia [11], and Google Earth [13]. Landscape change was analysed through a comparative approach, in which successive time periods were examined to identify the evolution of mining landforms, the expansion of open-pit excavations, the development of spoil heaps, and changes in drainage systems and infrastructure. This procedure also enabled the assessment of spatial relationships between individual mining elements within the wider mining system. The inventory of anthropogenic mining geoheritage was subsequently conducted through the systematic identification and interpretation of mining related features visible in the analysed datasets. Individual features were classified according to the functional framework presented in Table 1, with particular attention devoted to extraction structures, spoil deposits, hydraulic modifications, transport infrastructure, reclaimed areas, and mining settlement patterns. In addition to the identification of individual geoheritage elements, the analysis focused on their spatial distribution, mutual relationships, and functional interactions within the mining landscape. This approach made it possible to evaluate the Sokolov basin as an integrated anthropogenic geomorphic system shaped by successive phases of extraction, transport, deposition, and reclamation, rather than as a collection of isolated features.

Results and discussion. *Functional classification of mining geoheritage.* The main issue in the interpretation of mining geoheritage concerns the scale and object of analysis. In traditional geoconservation approaches, mining sites were mainly valued for the geological features they expose, such as stratigraphic sections or mineral occurrences [12; 14]. In this perspective, mining activity was treated primarily as a means of access to natural features, while the anthropogenic landforms and associated infrastructure were considered of secondary importance [12; 21]. This reflects an early stage in the development of geoheritage studies, when attention was focused largely on natural geodiversity and its scientific significance [14].

More recent research [3; 15; 16; 19] has expanded this view, recognising that anthropogenic landforms can form an integral part of geodiversity. In open-pit mining areas, large-scale surface modifications create new geomorphological configurations, often exposing geological structures while simultaneously generating distinctive landforms. These landscapes could be analysed in terms of their internal complexity and in relation to their contrast with surrounding natural environments. Such an approach highlights the need for a clearer framework to describe and evaluate mining geoheritage.

The functional classification proposed in this study (Table 1) addresses this need by organising mining related features into 8 categories: extraction structures, mining infrastructure, processing and beneficiation sites, waste and by-products, hydraulic systems, transport and

logistics, mining landscapes, and intangible mining heritage. The purpose of this classification is not simply to list elements, but to emphasise the relationships between them. Mining landscapes are therefore understood as systems in which different components operate together and cannot be fully interpreted in isolation [3; 16].

Open-pit mining complexes provide a clear example of this approach of system with interconnected elements. Their morphology, characterised by terraced slopes, excavation voids, spoil heaps, and modified drainage networks, results from rapid and large-scale transformations of the land surface. These features are closely linked to technical infrastructure, material flows, and patterns of land use, forming a coherent spatial and functional unit [20; 22; 25]. This has direct implications for geoheritage assessment. When individual elements are considered separately, their significance may be reduced, as the relationships that explain their formation and function are not taken into account [25]. A pit wall, a spoil heap, or a drainage structure acquires meaning within the broader system of extraction, processing, and landscape transformation. The classification used here makes it possible to identify these connections and to evaluate mining areas as integrated geoheritage units.

The approach proposed in this paper supports a shift from the protection of isolated features to the conservation of mining systems. This is particularly important in open-pit mining regions, where recultivation and land use change may alter or remove important geomorphological and technical elements. This functional classification also provides a practical framework for analysing mining geoheritage and supports a more consistent approach to its conservation.

Sokolov in the context of mining geoheritage. The Sokolov Basin (NW Czechia) represents a typical large-scale open-pit lignite mining landscape in Central Europe, where mining activity and settlement development is closely interconnected. The basin is part of a Neogene tectonic depression associated with the Ohře Rift and is filled with Eocene to Miocene sediments, including fluvial and lacustrine deposits [5]. Within this sequence, economically significant lignite seams were formed under swamp conditions and later covered by thick claystone overburden [4].

The development of mining in the region shows a clear transition from small-scale underground extraction to large open-pit operations (Fig. 3b-c). Early mining activity, recorded from XVIII and XIX centuries, was spatially limited and closely associated with local settlements.

The second half of XX century was characterised by rapid expansion of surface mining, resulting in the formation of extensive open pits such as the Jiří and Družba mines [23] (Fig. 4c). These sites represent the dominant geomorphological elements of the basin, with large excavation voids, terraced slopes, and internal spoil heaps defining the current landscape.

Functional components of the mining system are clearly identifiable within the Sokolov Basin and together constitute a complete mining geoheritage assemblage. Extraction structures are represented by open-pit excavations, which form the core of the landscape (Figs. 2, 3). Around these, mining infrastructure such as conveyor systems, access roads, and operational facilities developed as integral elements supporting material extraction and transport. Processing and energy production sites are directly connected to the pits, reflecting the integration of extraction and industrial use. Waste and by-product features, particularly spoil heaps and reworked overburden deposits, occupy large areas and significantly modify the original topography. Hydraulic systems, including drainage networks and post mining water bodies, illustrate the reorganisation of natural hydrological processes. Rail connections, link different parts of the mining system and contribute to its spatial coherence. Post-mining landscapes represent a later stage in the evolution of the system, where new land uses are superimposed on the original mining geomorphology.

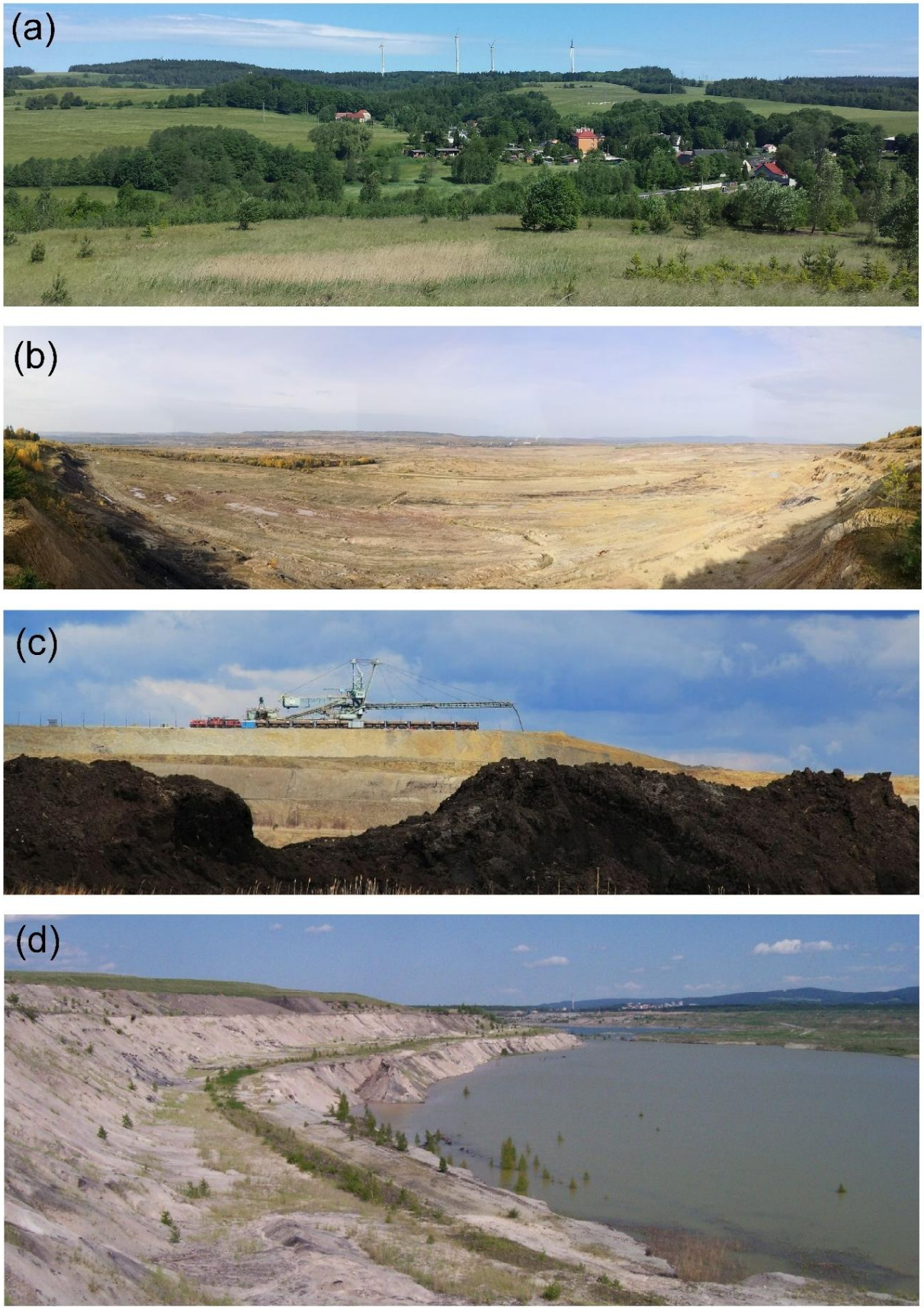


Fig. 3. Landscape transformations around Sokolov, NW Czechia: (a) agricultural and forest areas unaffected by mining; (b) Lom Jiří, the main open-pit coal mine near Sokolov; (c) brown coal transported by train from the open pit; (d) former open-pit mine now submerged under the Medard reservoir

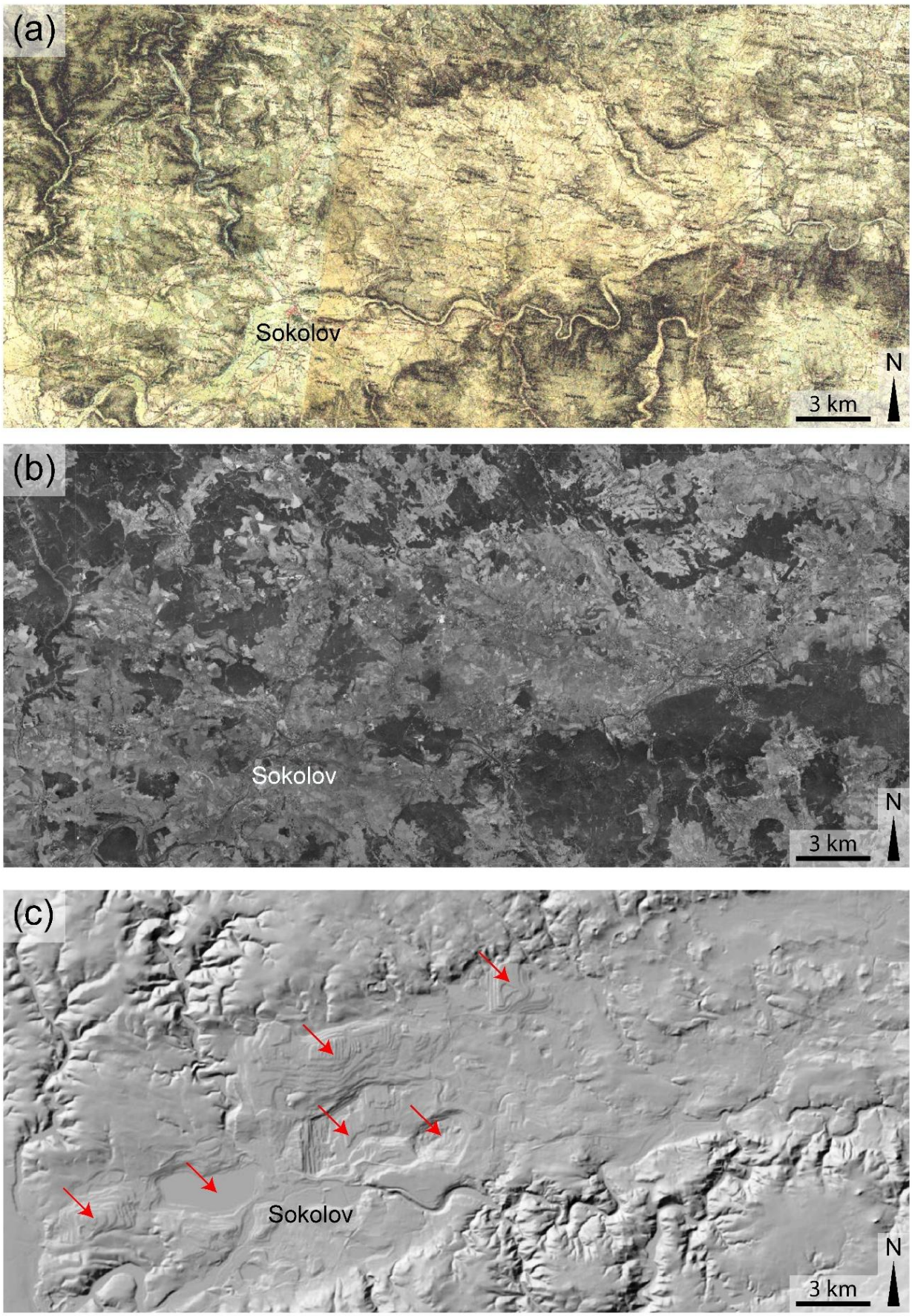


Fig. 4. Historical landscape changes of Sokolov area: (a) military map from the 1830s [9]; (b) historical orthophoto from the 1950s [10]; (c) DEM-derived hillshade map highlighting open-pit mining structures and anthropogenic landforms by red arrows [11]

The spatial distribution of these elements demonstrates that the Sokolov Basin functions as an integrated mining landscape rather than a collection of isolated features. The relative extent of individual components has changed over time. During the period of intensive extraction in the late XX century, the area occupied by open-pits and active industrial surfaces increased significantly, while agricultural and semi natural landscapes declined [23] (Fig. 3a). In XXI century the extent of active mining areas has stabilised or decreased locally, while reclaimed areas, water bodies, and new land uses have expanded [1]. These changes reflect a shift from extraction dominated to post mining landscape structures (Fig. 3d), although the geomorphological imprint of mining remains significant.

The category of mining landscapes is particularly well represented within the Sokolov basin [1; 2]. Rather than occurring as isolated landforms, extraction pits, spoil heaps, transport corridors, industrial facilities, reclaimed surfaces, and newly formed water bodies occur as interconnected elements of a single spatial system. Figure 2 shows the scale of these transformations, where former extraction areas coexist with reclaimed reservoirs and newly established land uses. Such spatial relationships indicate that the geomorphological significance of the basin cannot be understood just through individual mining features. The landscape represents the cumulative result of successive phases of extraction, deposition, reclamation, and redevelopment that have progressively reshaped the original terrain.

Sokolov region is characterised by a strong presence of intangible mining heritage. Settlement patterns in the region developed largely in response to mining activity. New towns, housing estates, industrial zones, and transport corridors were established in direct relation to open-pit operations, forming a spatial structure oriented towards extraction sites [24] (Fig. 4a-b). This differs from many historic mining regions in Czechia where extraction activities were superimposed onto existing settlement networks. In the Sokolov basin, urban development and mining progressed in parallel during the socialist period, resulting in a landscape in which social and industrial structures became closely interconnected. As a consequence, the organisation of settlements, transport infrastructure, and public services can be interpreted as part of a broader mining system rather than as independent components of regional development.

The influence of mining extended beyond the physical transformation of the landscape and contributed to the formation of a distinct social and professional environment. Universities, vocational schools, and specialised training institutions historically supported the workforce required for lignite extraction and processing [2; 24]. At the same time, mining activities shaped patterns of employment, labour organisation, and community development throughout the basin. The transmission of technical knowledge, professional skills, and occupational traditions between generations contributed to the formation of a mining identity that remained closely associated with regional development. Although such relationships are less visible than the physical landforms produced by mining, they provide an important interpretative framework for understanding the landscape.

In this context, intangible mining heritage may be understood as the collective expression of knowledge systems, professional practices, social memory, and community identity associated with long term resource extraction. These elements persist through educational institutions, museums, archival collections, local narratives, and place-based cultural traditions, even where the original economic functions of mining have diminished. Consequently, the geoheritage significance of the Sokolov basin is not limited to its anthropogenic landforms and mining infrastructure, but also encompasses the social and cultural processes that developed in response to sustained interaction between society and the mining environment. Such relationships indicate that mining landscapes may be interpreted not only as products of geomorphological transformation but also as cultural landscapes shaped by the co-evolution of extractive activities and human communities.

Conclusion. Open-pit mining landscapes, such as areas in Sokolov Basin, present a complex record of human interaction with the Earth's geological environment, where rapid extraction and industrial activity have reshaped relief, exposed stratigraphic sequences, and

generated new geomorphic forms. Though often approached primarily for their geological value, these landscapes encompass more than scientific interest: terraced pit walls, spoil heaps, hydraulic modifications, transport networks, and associated infrastructure together form a coherent system, whose significance is only fully appreciated when considered in relation to one another. The case of Sokolov mining area demonstrates that these features are conected to broader social and cultural contexts, where settlement patterns, professional practices, and community identity evolved alongside industrial operations. In this sense, the landscape is a material expression of a modified environment, where technological ambition, resource use, and social organization intersect. Recognizing open-pit mining complexes as anthropogenic geoheritage allows us to deepen the interpretation that integrates geomorphology, industrial history, and cultural meaning, providing a framework for their assessment, conservation, and post mining transformation.

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