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Potential Impacts of Zone-Specific Mining on Karst

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Abstract: This investigation delineates the impacts of mining on karst systems, with a focus on specific karst zones, namely the epikarst, the vadose zone, and the phreatic zone, which includes the epiphreatic zone. Mining activities, regardless of the karst area type, predominantly affect these zones. When mining occurs at the surface or within the epikarst, it results in the destruction of surface features and the disruption of the epikarst, thereby locally halting karstification processes. The extraction in the vadose zone can lead to surface alterations, characterized by collapses, the formation of depressions, and the modification of epikarst activity, ultimately impacting surface karstification and inducing atectonic changes on the surface. The exploitation of the phreatic zone is associated with the artificial lowering of the karst water table and the removal of materials from cavities and depressions. This study emphasizes the importance of understanding the zone-specific impacts of mining on karst systems, highlighting the need for tailored conservation and management strategies to mitigate these effects. The findings contribute to the broader understanding of karst dynamics and provide a foundation for future research on the sustainable management of karst environments in the context of mining activities.

Keywords: Mining; Karst; Farst features; Karst zone; Soil-covered karst; Covered karst

1 Introduction

This study aims to delineate the impacts of mining activities within various karst zones on karst environments and to understand how these zones influence mining operations. Although a diverse range of analyses exists in the scientific literature regarding the effects of mining, the specific impacts of mining within different karst zones on karstification remain underexplored.

Karst rocks, known for their significant permeability, exhibit substantial storage capacity under favorable conditions. It is noted that streams in karst areas are present only when the karst water table aligns with the stream channels developed in the karst region. Infiltration of meteoric water into karst leads to regional storage, predominantly occurring at locations where dissolution capacity diminishes, such as the epikarst, or where aquifuges are present. Additionally, storage development is observed when infiltrated water reaches the elevation of surrounding terrain, signifying the base level of erosion in the phreatic zone.

In the context of carbonate karsts, reservoir water can be categorized into distinct zones based on its movement: the epikarst, the vadose zone, and the epiphreatic-phreatic zone [1, 2]. A notable phenomenon is hypogenic karst, which occurs when regional flow of karst water between the karst and boundary basin is upward under suitable temperature and pressure conditions [3, 4]. This process can lead to the accumulation of valuable ores and hydrocarbons in cavities formed along upwelling waters [5].

The present analysis encompasses effects that are specific to certain karst zones, examining whether mining occurs in one or multiple zones. It is posited that mining's nature, operational characteristics, and even technology are influenced by the specific karst zones in which activities are conducted. Concurrently, this paper elucidates how mining operations impact these karst zones, particularly in terms of their features. Karstification predominantly affects carbonate rocks and evaporites, where karstic rocks tend to dissolve primarily without leaving weathering residues. It is observed that carbonate rocks dissolve at a slower rate than evaporites [1, 6], and the development of epikarst is only partially evident in the latter [7].

The roles of carbonate rocks and evaporites in mining differ: in the case of evaporites, mining is focused on the extraction of these rocks, while with carbonates, mining involves not only the extraction of the rocks but also the mineral resources contained within them. The mineral resources in carbonate karsts are intricately linked to karstification processes, as seen in bauxite, or to geological conditions independent of karstification, such as coal and manganese.

Karst types vary based on the nature of their cover, categorized as soil-covered karst, bare karst, or covered karst. Covered karst can be further divided into concealed karst, characterized by permeable and unconsolidated cover, and cryptokarst, defined by impermeable and consolidated rock cover. The features of karst environments are highly dependent on the properties of the caprock [8–10]. Bare and soil-covered karsts exhibit features like karren, dolines (including dissolution dolines and common variations such as drawdown and collapse dolines), ponors, poljes, karst valleys, and precipitation features. In contrast, typical characteristics of covered karst include caprock dolines in cryptokarst and subsidence dolines like compaction, dropout, suffosion, and sagging dolines in concealed karst [1, 2, 8, 9, 11, 12].

The phenomenon of upwelling water, capable of penetrating the vadose zone and the epikarst, has been observed to extend even into the phreatic zone. This process can override the original zonality of karst systems. In the epikarst, which extends from the surface to a depth that may vary from a few meters to several tens of meters, the infiltrating waters reach saturation [13–19]. This zone is not only characterized by karren but also by a network of cavities formed as water seeps both downwards and laterally. It has been reported that in the epikarst, secondary porosity can reach up to 20%, in contrast to the vadose zone where porosity is typically around 2%. Consequently, the swollen-back water forms the piezometric surface, and the processes within the epikarst contribute significantly to the formation of surface karst features such as drawdown dolines [15].

In the vadose zone, extending to several hundred meters, water saturation occurs, and seepage is predominantly vertical. The phreatic zone, often exceeding 100 meters in thickness, is characterized by water perpetually filling the cavities, unsaturated, with dissolution capacity and lateral flow towards karst springs. The surface of this water constitutes the karst water table. The epiphreatic zone, varying in thickness up to several tens of meters, represents the fluctuation zone of the karst water table. Cavity formation is a predominant feature in these two latter zones.

Mining activities, whether surface or underground, create both negative features (such as mine yards and pits) and positive features (including mine dumps) [20–23]. These activities induce morphological, hydrological, and environmental changes within the karst environment [24, 25]. The high permeability of karst allows for rapid and widespread dissemination of these changes through karstwater. Veress [26], and Veress et al. [27] have specifically addressed the impact of mining on karst in the Bakony Region.

The effects of mining include the transformation of surface morphology, exemplified by the creation of mine yards and dumps, and the development of collapses and subsidences, which lead to the formation of closed depressions and the exhumation of buried surface features. Additionally, alterations in surface hydrology are evident, such as the formation of mine ponds, the drainage of existing ponds, the diversion of streams, and the creation of backwater. The artificial lowering of the karstwater table can result in the drying up of springs and marshes, as well as the removal of filling material from cavities and the opening up and truncation of these cavities.

The location of a mine within a specific karst zone is crucial, both for safety reasons and due to the influence of the zone on mining technology. In carbonate karsts, mining within the epiphreatic-phreatic zone is particularly vulnerable to water attack, especially in zones rich in cavities. However, in the vadose zone, water-related issues are generally limited to trough caves with surface water inflow. The presence of a hypogene branch significantly increases the cavity index near the surface, whereas its absence reduces this risk. In evaporite contexts, the development of breccia poses challenges in the vadose zone, elevating the risk of collapses through caves and breccia pipes. These phenomena also contribute to an increased incidence of surface depressions, potentially intensifying concentrated water inflow into mines.

2 Effects

The methodology section of the paper focuses on understanding the diverse impacts of mining on karst systems, distinguishing between direct and indirect effects [26]. It is imperative to recognize that while direct impacts are manifested in the physical alteration of karst features, such as mineral extraction leading to the exhumation of karst features, indirect impacts predominantly influence karst hydrology, which can also be artificially altered. Exposure processes involve the denudation of the caprock, revealing the underlying bedrock and potentially exposing karst features if the infill material is exploited.

Mining operations in karst environments are observed to take place in various zones, including surface mining in the karst and epikarst (open-pit mining), as well as in the vadose and epiphreatic-phreatic zones. Instances where mining spans two zones, such as the epikarst-vadose zone or the vadose-phreatic (epiphreatic) zone, are also noted (Figure 1).

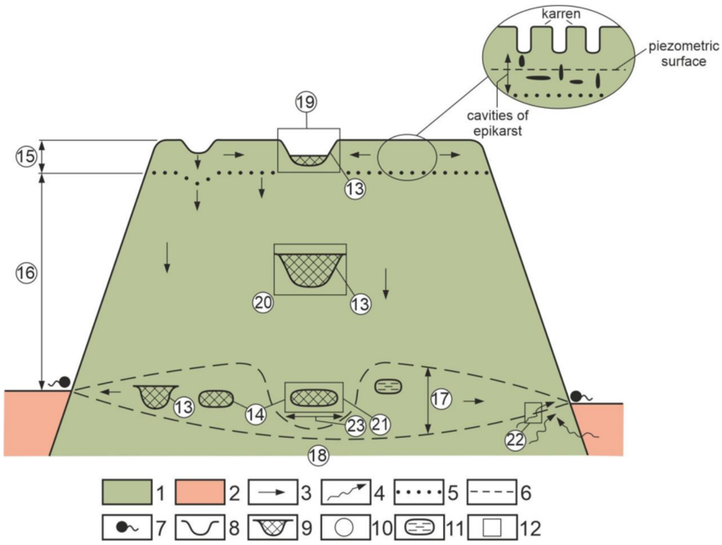

Figure 1. Soil-covered karst zones and possible occurrences of mining sites.

Legend: 1. karstic rock, 2. non-karstic rock, 3. water flow direction, 4. the hypogenic branch, 5. saturation level of epikarst water, 6. karst water table, 7. spring, 8. surface karstic feature, 9. mineral, 10. cavity, 11. water in cavity, 12. mine, 13. paleokarst surface karstic feature, 14. paleokarst cavity, 15. epikarst, 16. vadose zone, 17. phreatic zone, 18. deep karst, 19. surface mine, 20. mine in vadose zone, 21. mine in phreatic zone, 22. mine at hypogenic branch, 23. artificial subsidence site of the karst water table in phreatic zone

2.1 Zone-Specific Mining

Zone-specific mining strategies are explored, with open-pit mines extracting karstic rock or fill from paleokarstic surface features, such as bauxite, manganese [26], or gold [28]. This mining activity leads to the exhumation of paleokarstic depressions. However, it is recognized that such practices can result in the destruction of surface karst features and even the epikarst, particularly when mines expand over large areas. Challenges in mining operations due to epikarst cavities, such as the presence of barren rock, necessitate consideration in mining strategies. Post-mining landscape reclamation is addressed, highlighting that while reclamation can obscure scars in the landscape, the regeneration of the epikarst in carbonate karsts does not occur, rendering these areas inactive in terms of karstification. Conversely, in evaporite environments, mining does not inhibit but can stimulate the development of surface features.

In the context of this study, the focus is placed on mining activities within the vadose zone and their consequent effects, both within this zone and on the epikarst. It is observed that mining operations in this region may target the extraction of karstic rock or minerals associated with karstic features. The diversity of infill within karst depressions is noted, ranging from bauxite [26] to iron ore [2], and including interbedded materials such as coal [27].

The process of mining leads to the exhumation of paleokarst features. In these scenarios, the risk of water intrusion into the mines is mitigated. It is crucial to note that the size of the mine plays a pivotal role in determining the extent of its impact. Larger mines have the potential to significantly alter vertical water movement. Such changes are particularly pronounced in mines located close to the surface or those with considerable vertical extension. These alterations extend to the epikarst, thereby influencing surface karstification processes.

First, in covered karst environments, an increase in drainage towards mining sites has been observed when the mine's backwall extends to the lower boundary of the epikarst. Research indicates that a decrease in the water table leads to the development of multiple subsidence dolines within the overlying cover [29–31]. This phenomenon is attributed to the loss of water in the cover, resulting in its compaction and the drying of cavities within it, consequently leading to an increase in suffosion material rearrangement. In such scenarios, various types of dolines may form: compaction dolines due to cover compaction, dropout dolines as a result of cavity collapse, and suffusion dolines due to increased suffosion. The intensity of doline formation is amplified when superficial deposits are directly transported into the vadose zone or the mine through epikarstic passages. This process is particularly pronounced in cases where mining activities contribute to the lowering of the water level [32]. For instance, in Zambia, the transport of 700,000 cubic meters of overlying bed material into the karst, with 300,000 cubic meters directed to a mine, resulted in the formation of a subsidence doline [33]. Such doline formation is especially prevalent when the water table resides below the bedrock surface [34–36].

Second, in bare karst or soil-covered karst scenarios, the increase in vertical drainage from the epikarst occurs when the mining backwall reaches its lower surface. This leads to a subsidence of the piezometric surface, thereby reducing or completely eliminating water filling in the epikarst. As a result, the epikarst becomes inactive, halting or diminishing its development. Consequently, this inactivation transforms surface karst processes; for example, the typical development of dolines is replaced by the formation of karren.

Third, the rapid and extensive development of surface features above evaporite mines has been directly attributed to the formation of mine cavities by collapse. A notable instance is the Berezniki caprock doline in the Ural Mountains, which formed over a large potash mine in 1986. In this case, the infiltration of water from the caprock led to the collapse of the material into the mine, subsequently causing the collapse of the caprock itself [37]. This event resulted in the formation of a depression measuring 40×80 meters in diameter and 150 meters in depth, extending to the water level of the lake at the bottom. Accompanying this collapse were phenomena such as explosions, light flashes, sound effects, material ejection, and seismic activity. A similar occurrence has been documented at the Solotvina salt mine in Ukraine, representing one of the most significant post-closure surface transformations in recent times [38].

Finally, subsidence of rocks above mine cavities has been observed, along with the development of atectonic extension fissures at the margins [39–41]. This process is not limited to karstic rocks but can also occur in other non-karstic rock types. The material from the overlying beds is known to enter these fissures either by suffosion, leading to the formation of pseudokarstic suffosion dolines, or by collapse, resulting in pseudokarstic dropout dolines. Such mechanisms have been identified in the formation of subsidence dolines at Bocskor Hill in Hungary [27].

In the phreatic zone, the exposure of paleokarst depressions and cavities is often observed. To ensure the safety of mining operations, activities are typically preceded by a drawdown of the karst water table. This alteration in the water table modifies the flow regime within the karst system, often leading to the drying up of karst springs.

2.2 Impacts of Non-Zone-Specific Mining

In instances of non-zone-specific mining, the activities are less influenced by the particular characteristics of karst zones. This includes quarrying, the formation of breccia pipes related to mining, hydrocarbon extraction, and mining associated with hypogenic branches.

Quarrying conducted on carbonate rocks, especially at plateau margins, valley sides, and small mountain summits, can lead to the destruction, shortening, or opening of existing caves. In Hungary, notable examples include the phreatic or former phreatic cavities uncovered during mining activities on Mount Esztramos [42] (Figure 2) and in the Bükkösd area of the Mecsek Mountains [43] (Figure 3).

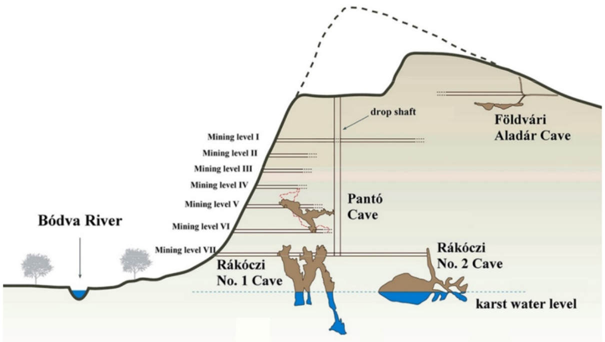

Figure 2. Mining levels and associated excavated and preserved caves in Mount Esztramos (Hungary) [42]

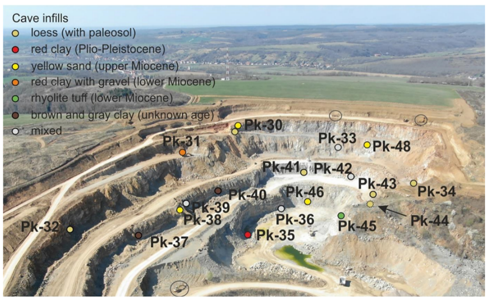

Figure 3. Paleokarst cavities eroded by mining [43]

The formation of breccia pipes, a phenomenon observed in evaporite environments, is characterized by a process of mutual dependence between dissolution and collapse. These structures typically originate at the base and develop upwards, potentially reaching mining areas and increasing the risk of water intrusion [44]. The formation of caprock or dropout dolines above breccia pipes is contingent upon the composition of the overlying caprock and is further stimulated in the presence of surrounding paleokarst cavities or mines that can accommodate the falling rock. This process is particularly pronounced when water from the surface permeates into the evaporites that encompass or support the mine. An illustrative example occurred in Texas, where water injected during oil prospecting drilling dissolved the salt, leading to the creation of cavities in the rock. Subsequent to the cementing of casing pipes, which was of questionable quality, and the cessation of work, additional water influx into the cracks and cavities of the concrete triggered the collapse of the rock salt cavity. This collapse initiated the development of a breccia pipe and culminated in the formation of a caprock doline on the surface [45].

A significant portion of Earth's hydrocarbons are stored in karstic cavities (limestone) or within fractures and fissures (dolomite), located below the current water table. The extraction of hydrocarbons from these karstic reservoir rocks does not result in significant nor negligible impacts on karst. In deep, pressurized hydrocarbon reservoirs, typically found in buried karstic rocks, confined water tends to fill the reservoir as hydrocarbons are depleted, maintaining the stability of the karstified rock. Conversely, in shallow, low-pressured oil reservoirs, where there is no material to fill the depleted hydrocarbon space, subsidence dolines may form on the surface due to cavity collapse.

3 Conclusions

The study's exploration of zone-specific mining has facilitated a novel approach in elucidating the interplay between mining activities and karst environments. Through this analysis, a more nuanced, in-depth, and categorically distinct representation of mining's effects has been enabled. In the context of mine planning, a more comprehensive consideration of the impacts on karst, as well as the influences of karst on mining operations, is now achievable. Consequently, this leads to the selection of more appropriate and effective mining technologies.

The nature and magnitude of mining's impact on karst are found to be significantly contingent upon the specific karst zone where the mining activity occurs. Surface mining predominantly affects recent and paleokarst forms, as well as the epikarst. Conversely, mining in deeper strata influences former paleokarstic surface features, the epikarst, and both recent and paleokarstic cavities. The extent of these impacts is determined by a variety of factors, including the type of karst, the nature, scale, and duration of mining activities, and the size of the mining operation.

Data Availability

The data used to support the findings of this study are available form the corrsponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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