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Review Article

The Volcanic History of the UNESCO Global Geopark Bohemian Paradise

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Abstract

Central Europe and the area of the UNESCO Global Geopark Bohemian Paradise have been affected by global tectonic events, especially during the last 500 million years. Volcanic phenomena are the most striking traces today of such past tectonic events. At the end of the Paleozoic, there were a number of volcanic eruptions connected to the waxing and waning of the Variscan Orogeny. Further volcanic activity came in the Neogene as a distal reaction to Alpine Orogenic processes. All volcanic phases show the variability of volcanic processes and have been studied intensively. In addition, these volcanic events and the production of various volcanic products enabled the emergence of local world-famous mineral deposits. The extraordinarily varied geology and the large number of volcanic features is a great tourist attraction and an excellent opportunity for a vivid interpretation of the geoheritage of Central Europe.

Keywords: Central Europe, UNESCO Global Geopark Bohemian Paradise, Late Paleozoic, Neogene, Volcanic activity, Jičín Volcanic Field, Mineral assemblages, Middle Ages Castles, Collecting, Geoheritage Interpretation

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Introduction

Volcanic activity and its products are among the most striking geological and geomorphological features. As Geoparks target the wider public, the presence of any such attractive features (volcanoes, fossils, caves, crystals, canyons) helps the promotion of the geoheritage. The UNESCO Global Geopark Bohemian Paradise (UGG Bohemian Paradise) offers many of these attractions (e.g. Mencl *et al.* 2021). It is situated in north-eastern Bohemia, in an area with an extraordinarily rich geological history. Although there are no active volcanoes at present, we have recorded several periods of intensive volcanic activity during the Phanerozoic. Besides the presence of metavolcanic rocks with Lower Paleozoic protolith age in the Variscan metamorphic complex (Kachlík 1997; Kachlík & Patočka 1998; Winchester *et al.* 2002), most volcanic activity took place in the Late Palaeozoic (about 300-280 Ma), and in Neogene (16-19 and 4-5 Ma) respectively (e.g., Stárková *et al.* 2011; Rapprich 2012a, b; Petronis *et al.* 2015). While the remains of Paleozoic volcanic bodies can be found mainly in the eastern part of the Geopark, especially in the vicinity of Nová Paka city, Cenozoic volcanic formations are found in the southern and central parts of the Geopark, roughly between Jičín and Turnov cities (Fig. 1). Paleozoic volcanic rocks are usually not well exposed on the surface, but we can study them in some natural and artificial outcrops. In contrast, Cenozoic volcanic bodies often form highly visible and significant landforms and exposures that are very remarkable for visitors and tourists (e.g., Figs. 9-11). Paleozoic rocks in particular are famous and attractive among collectors for their rich content of gemstones and other minerals (Pauliš 2003; Bernard *et al.* 1981) (see Figs. 7-8).

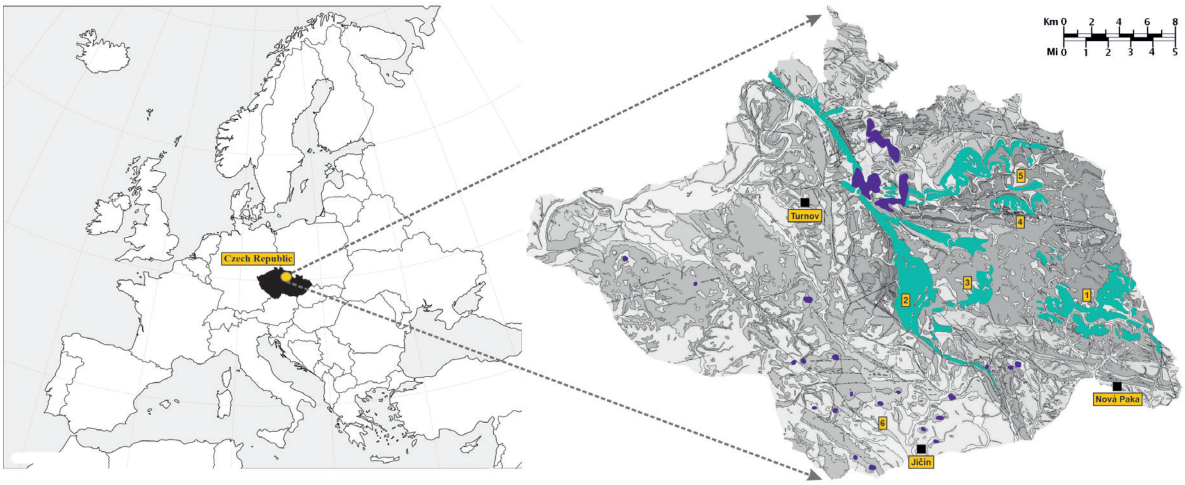

Figure 1. The simplified geological map of the UGG Bohemian Paradise with the volcaniclastic rocks highlighted.
= Late Palaeozoic volcanic bodies
= Cenozoic volcanic bodies
1 = Levín Volcanic Field, 2 = Lomnice Volcanic Complex, 3 = Tábor-Košťálov intrusion, 4 = Těhník lavas, 5 = Strážník sill, 6 = Jičín Volcanic Field.

Late Paleozoic volcanic activity

The volcanic bodies in the UNESCO Global Geopark Bohemian Paradise are embedded in sedimentary sequences of late Moscovian/ early Kasimovian (Kumburk Formation), Asselian/Sakmarian (Vrchlabí and Prosečné formations), and late Artinskian (Chotěvice Formation) respectively (Stárková *et al.* 2011; Prouza *et al.* 2013) (see Fig. 2). The most considerable subaerial volcanic activity took place in the Asselian (Stárková *et al.* 2011).

This repeated volcanic activity was connected with post-Variscan evolution of the Bohemian Massif, i.e. transtensional/extensional and rifting activity associated with continental within-plate volcanism. The decay of the Variscan orogen resulted in the formation of intra-montane basins, where both mafic and silicic volcanism occurred frequently. These processes formed several basins within the orogen and its foreland (e.g., Opluštil *et al.* 2016; Žák *et al.* 2018; Van Wees *et al.* 2000). Next to the UGG Bohemian Paradise area, post-Variscan inter-montane basins spread across Europe including NW Bohemia, German Basin, Polish Basin, Oslo Rift and Iberia Messeta (Timmerman 2008).

Coherent volcanic and volcaniclastic rocks of this age are located mostly in the eastern part of the Geopark, represented by the western part of the

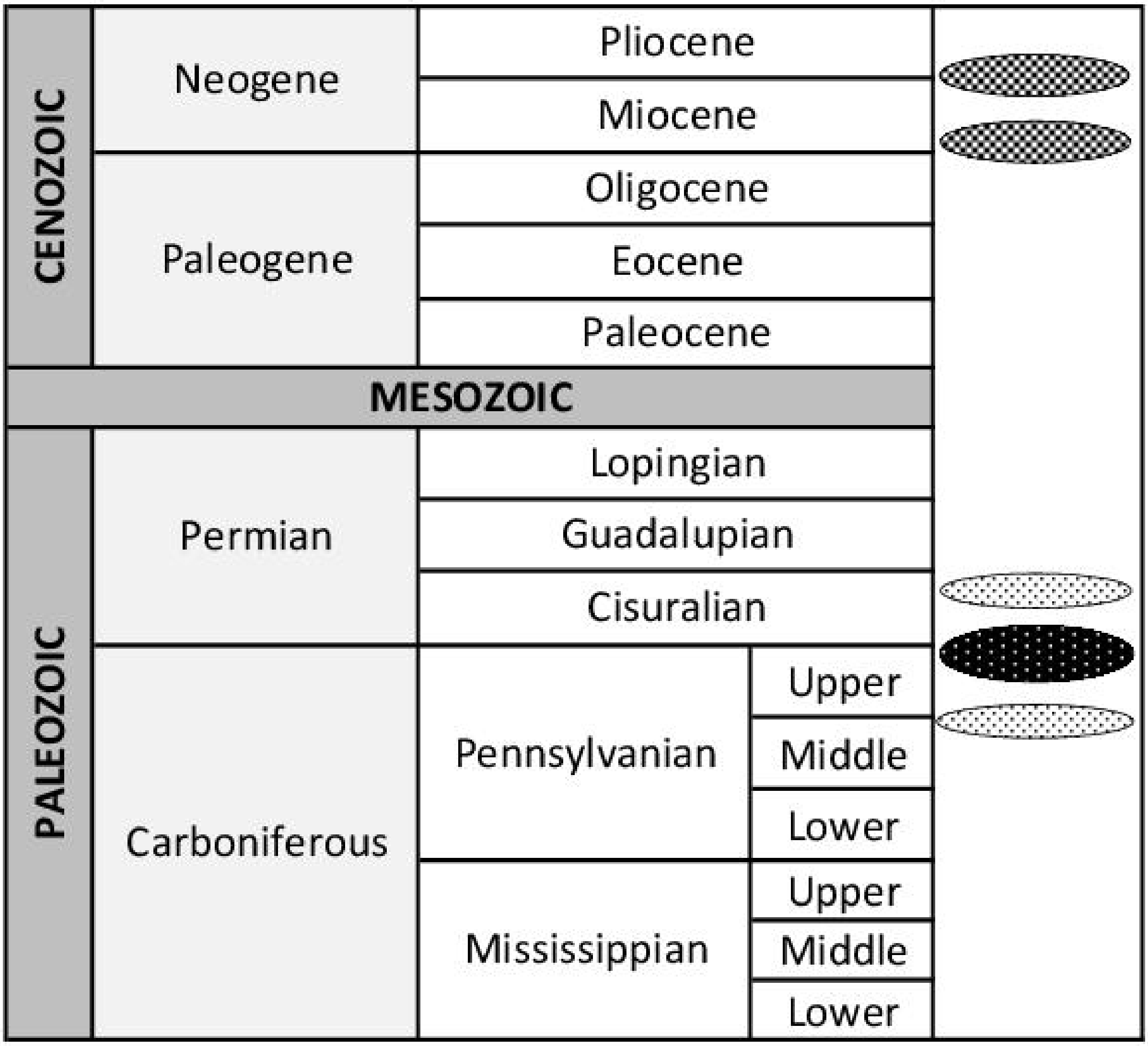

Figure 2. Stratigraphic range of the volcanic activity within the UGG Bohemian Paradise.
= mafic volcanics with a small portion of silicica (dacite, rhyolitic ignimbrite)
= mafic volcanics (dolerites, olivine basanites, andesites) and their pyroclastics
= alkaline basalts

Krkonoše Piedmont Basin. The total thickness of volcano-sedimentary infill in this basin reaches ca 1800 m and it covers an area of 1100 km2 (Pešek *et al.* 2001). Freshwater deposits of the Basin are often intercalated with the products of volcanic activity, mostly mafic rocks traditionally called melaphyres derived from the collision-modified upper mantle, e. g., olivine basalts, basaltic andesites, trachybasalts with associated pyroclastic deposits and small amounts of silicic volcanic rocks (Ulrych *et al.* 2016). There are several separate volcanic units: i) Lomnice Volcanic Complex, Levín Volcanic Field and Těhník lavas composed of mafic effusives (aphanitic or porphyritic lavas), and ii) high-level intrusions (Tábor-Košťálov intrusion, Strážník sill) composed of dolerites and olivine dolerites (Stárková *et al.* 2011) (see Fig. 1). Sedimentary formations (i.e. mainly Vrchlabí and Prosečné formations) intercalated with mafic volcanic rocks – lavas, volcaniclastic deposits and intruded by basalt dykes, consist mostly of reddish, coarse- to fine-grained fluvial, alluvial and lacustrine deposits (Pešek *et al.* 2001).

Upper Paleozoic volcanic rocks often form conspicuous landscapes (Fig. 3), and some of them are well exposed in former or active quarries, as well as in a few natural and artificial outcrops (Fig. 4).

For now, the best-described unit is probably the Levín Volcanic Field (see Fig. 1). It covers an area of approximately 25 km2 along the eastern border of the Geopark, close to Nová Paka city. The total thickness of the volcanic sequences including pyroclastic intercalations is about 60 m, and the suc-

Figure 3. Kozákov Hill, a famous historical landmark of the UGG Bohemian Paradise, formed by Paleozoic and Cenozoic volcanics. Photo by UGG Bohemian Paradise.

Figure 4. Doubravice quarry, an example of artificial outcrops of Paleozoic lavas and a locality famous for the abundant occurrence of gemstones. Photo by J. Bubal.

cession consists of at least five lava horizons. Basalt andesite lavas were accompanied by explosive eruptions of phreatomagmatic, Strombolian, and Hawaiian styles (Stárková *et al.* 2011). Pyroclastic deposits comprise also volcanic bombs or volcanic ash with accretionary lapilli (Fig. 5A). Some Permian lavas flowed into shallow water reservoirs and smaller lakes of the Permian alluvial plain. The evidence of this process are pillow lava textures and hyaloclastite breccias with angular fragments of lava with chilled margins, which document strong cooling of lavas during their interaction with water (Fig. 5B). One of the best examples of the succession is exposed in the former quarry Hvězda, which is typical of the alternation of lavas and products of phreatomagmatic and Strombolian eruptions (Stárková *et al.* 2011), and in the active quarry Studenec too (Fig. 5A, B).

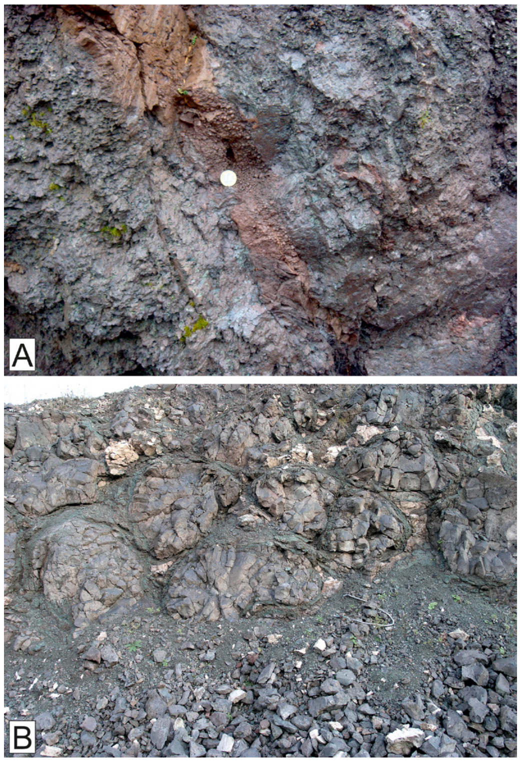

Figure 5. Accretionary lapilli in tuffite preserved in the melaphyre crack in the Hvězda quarry (A) and pillow lavas in the outcrop of Studenec quarry (B), Levín Volcanic Field. Photo by M. Stárková.

Some lavas (melaphyres) were vesiculated because of exsolved volatiles. Some vesicles were filled with hydrothermal siliceous solutions. From these solutions the typical quartz-chalcedony mineralization has crystallized (Fig. 6) and lavas show typical amygdaloid texture (Stárková *et al.* 2011).

Figure 6. Mafic rock (melaphyre) with typical amygdaloid texture. Inside amygdales, there are usually quartz or calcite infilled with blue-green secondary minerals. Scale bar = 5 cm. Courtesy Municipal Museum Nová Paka, photo by V. Mencl.

The most famous local chalcedony varieties are agates (Fig. 7C), as well as colored quartz forms (rock crystal, amethyst, and smoky quartz) (Fig. 7D) and jasper that often fills cracks in the rock (Fig. 7B). These minerals have been very attractive for gemstone collectors for ages. The typical mineral assemblage associated with quartz is calcite and zeolites, more rarely barite, goethite and hematite (Tuček 1975). Zeolites from Kozákov, especially facolite and heulandite (Fig. 8A), are some of the best in Europe (Bouška and Kouřimský 1983; Řídkošil 1996).

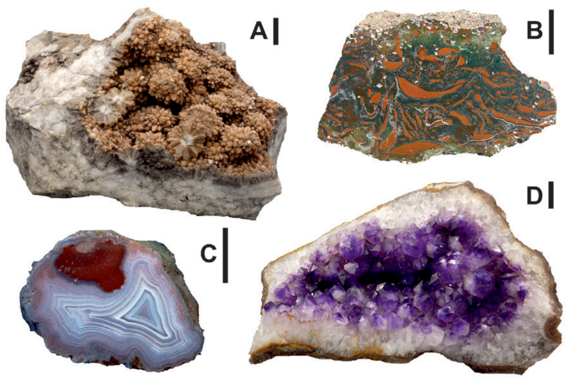

Figure 7. Quartz minerals of Paleozoic volcanic. A) star-shaped quartz, B) jasper, C) agate, D) amethyst. All scale bars = 2 cm. Courtesy Museum of the Bohemian Paradise (A, D) and Municipal Museum Nová Paka (B, C). Photo J. Bubal (A, D) and V. Mencl (B, C).

Moreover, small deposits and occurrences of copper ores are also associated with melaphyres. The most interesting site is the Studenec quarry, where apart from copper and vanadium minerals, Ag-Hg mineralization rarely appears. The typical ores are cuprite (Fig. 8C) and pure copper, which are accompanied by blue-green secondary minerals (Just

1995; Vavřín and Frýda 1996; Pauliš *et al.* 2005).

A different mineral assemblage occurs in the intrusive equivalents of melaphyre lavas (dolerites – subvolcanic melaphyres) located in the western and northern parts of the Krkonoše Piedmont Basin. Veins of pectolite accompanied by zeolites, apophyllite, and prehnite respectively crosscutting the dolerite sill, are considered to be the best in the world (Pauliš 2003; Bernard *et al.* 1981) (Fig. 8B, D).

Strážník hill near Jilemnice town used to be the most important world site of unique star-shaped quartz, with crystals up to 5 cm in diameter (Kunert 1996; Kouřimský *et al.* 1999) (Fig. 7A).

Cenozoic Volcanic Activity

As a result of Alpine Orogenic processes, older tectonic structures were reactivated during the Neogene, and new ones were also created, opening pathways for alkaline melts to ascend towards the surface. Volcanic activity occurred on deep-seated faults, which continued in several stages until the end of the Neogene. The most intense volcanic activity was concentrated along the Eger Rift, which represents the eastern branch of the European Cenozoic Rift System (Rajchl *et al.* 2009). Apart from the main volcanic complexes (Doupovské hory Volcanic Complex, České středohoří Volcanic Complex) in the central part of the rift, several smaller volcanic fields were also formed on its flank (Rapprich *et al.* 2007; Ulrych *et al.* 2016; Rapprich *et al.* 2017).

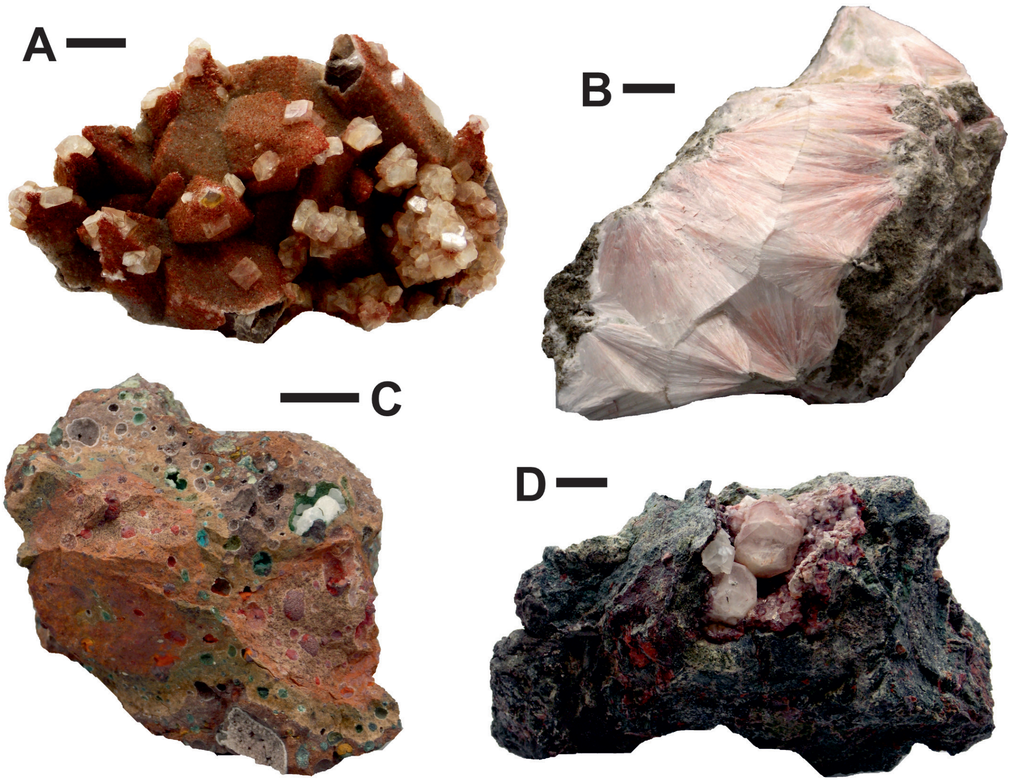

Figure 8. Mineral assemblage of the Paleozoic melaphyres. **A)** heulandite, **B)** pectolite, **C)** cuprite, **D)** analcime. All scale bars = 1 cm. Courtesy Museum of the Bohemian Paradise, Photo J. Bubal.

On the south-eastern edge of the Eger Rift lies the Jičín Volcanic Field, which includes the area between the municipalities of Železný Brod, Turnov, Jičín, Lázně Bělohrad, Nová Paka and Lomnice nad Popelkou (Cajz *et al.* 2009) (see Fig. 1). Volcanic activity in the Jičín Volcanic Field occurred during two separate episodes: i) Early Miocene (16–19 Ma), and ii) Early Pliocene (4–5 Ma) (Rapprich *et al.* 2007; Petronis *et al.* 2015; Rapprich *et al.* 2017) (see Fig. 2). In the Miocene and Pliocene, the Lusatian fault represented a structure significant for the ascent of alkaline magmas, although near the surface these magmas already used less significant faults, often connected with the Lusatian fault, which had a more suitable geometry for the ascent of magmas (Rapprich 2013).

With the exception of erosional remnants of a 12 km long lava flow in the immediate vicinity of Kozákov Hill (Fig. 3), Cenozoic volcanic bodies in the territory of the Bohemian Paradise have the character of scattered isolated dykes, conduits and erosional remnants of pyroclastic cones (Rapprich *et al.* 2007; Cajz *et al.* 2009). Alkaline volcanic rocks are present in the form of various volcanic landforms, often clearly standing out from the surrounding Cretaceous deposits (Fig. 9). Eruptions occurred in the form of lava flows, lava lakes, phreatomagmatic craters (maars), and scoria- and tuff-cones. The rocks are intra-plate alkaline basalts, including picrobasalt, basanite, and olivine nephelinite (Rapprich *et al.* 2007; Petronis *et al.* 2015; Rapprich *et al.* 2017).

The most representative volcanic bodies in the territory of the Bohemian Paradise are the lava flow at Kozákov (Fig. 3), the Trosky volcano with two conduits (Fig. 10), the Vyskeř volcano with a conduit made of picrite (Fig. 11), and Prackov volcano, which is the best-preserved pyroclastic cone in Bohemia, having still a well-preserved and morphologically obvious crater (Fig. 12).

Figure 9. Zebín Hill, an example of a Miocene tuff cone, located close to Jičín City. Cenozoic volcanoes protruding from the surrounding Cretaceous deposits often form distinctive geomorphological formations and monuments in the landscape. Photo by M. Lavický.

The most significant occurrence of Cenozoic volcanic rocks/remnants is the Kozákov lava flow, divided by erosion into three large and two small relics. In places where the lava flowed down the slopes of Kozákov, it reaches a thickness of several meters, while in the area between Železný Brod and Semily, where basanite lava fills the original Jizera river valley, it reaches a thickness of 40-50 m (Rapprich 2013). A 12 km long lava flowed into the Paleojizera valley, where it covered fluvial siltstones. The interaction of lava with water created hyaloclastite breccias and rootless craters.

In places with the largest accumulations of basalt

Figure 10. Two rock towers of the Trosky castle, the most famous landmark of the UGG Bohemian Paradise, formed by two conduits of basalt magma. Photo by UGG Bohemian Paradise.

lava, numerous quarries were established. Except for the famous site of Podmoklice near Semily, there are a number of active and abandoned quarries, e.g., Proseč, Záhoří, Železný Brod, Smrčí and Pelechov. In the quarries, the prismatic columnar jointing of basanite is often very well exposed (Fig. 13). The cooling of the lava created two systems of prismatic jointing - the upper and lower

Figure 11. Vyskeř Hill, a remnant of a volcano made of picrite. Photo by UGG Bohemian Paradise.

Figure 12. Morphologically preserved crater of the Prackov volcano. Photo by J. Bubal.

colonnade (Rapprich 2013). The lava flow is significant due to the abundant occurrence of mantle xenoliths, so-called olivine nodules (Fig. 14). Xenoliths of mantle rocks, which are up to several decimetres in size, are composed of yellow-green olivine, black-brown bronzite, deep green clinopyroxene, and brown to green spinels (Pauliš 2000).

Olivine (91.5% forsterite component) was broken out of the coarse-grained parts and collected as a precious stone intended for jewelry purposes. The richest find dates from 1910, when around 160 carats of high-quality chrysolite raw material were found in the Smrčí quarry. Together with these, a piece was found that after grinding weighs 15.67 carats and is now in the collections of the National Museum in Prague (Bouška and Kouřimský 1983; Pauliš 2000). In Smrčí and Chuchelna quarries, ol-

Figure 13. Well-preserved columnar jointing of the melaphyre in the former Pelechov quarry. Photo by J. Bubal.

ivine mining used to operate for jewelry purposes (Jeriová 1988).

Even though the Prackov volcano is not very well known, it is morphologically the best-preserved volcano in Bohemia. The depression in the top part is interpreted as a remnant of the original volcanic crater (Fig. 12). A number of small outcrops on its slopes perfectly reveal the eruptive history of this small volcano (Rapprich 2012a, b). The lowermost part contains relatively fine-grained pyroclastic deposits with numerous xenoliths of Cretaceous sedi-

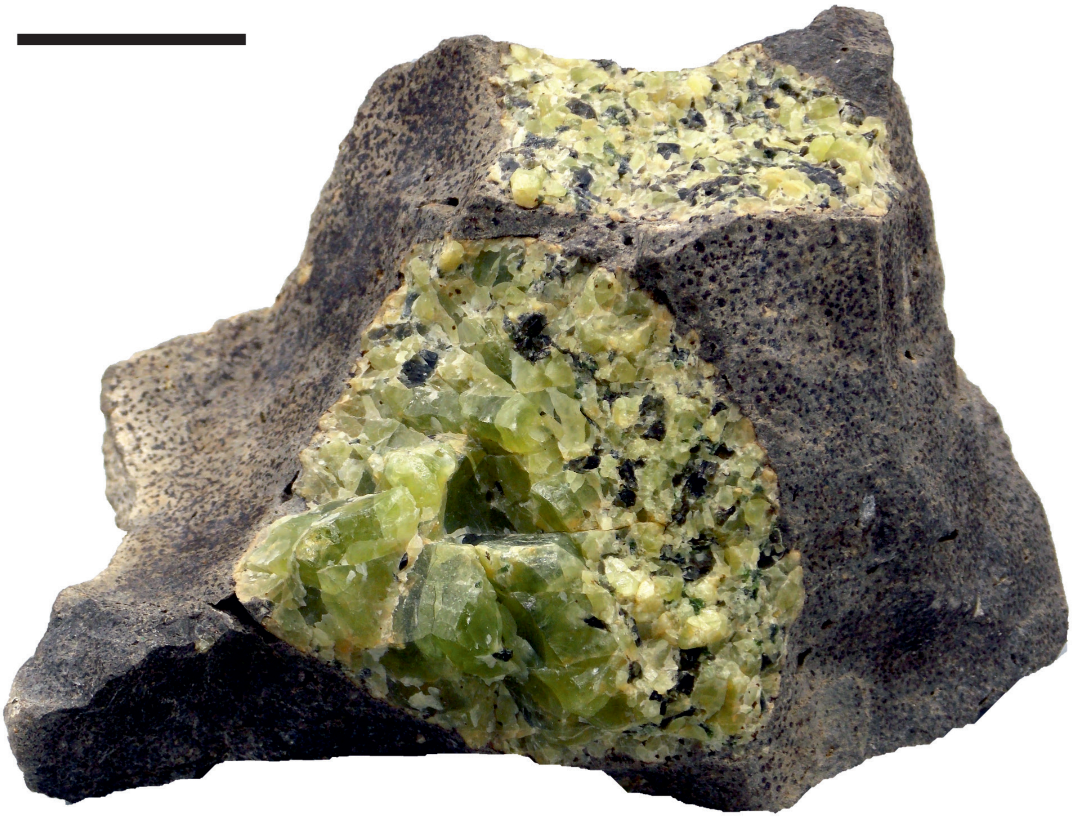

Figure 14. An example of Cenozoic mantle xenoliths composed of yellow-green olivine. Scale bar = 3 cm. Photo by J. Bubal.

ments, which represent the initial phreatomagmatic phase; an eruption which, in addition to magmatic gases, was also influenced by surface water. In the higher parts of the slope, the number of xenoliths decreases; the volcanic material starts to coarsen and is also more densely vesiculated. This change marks the transition from a phreatomagmatic to a Strombolian type of eruption. Larger shreds of lava are locally found in the top part, which are significantly deformed or even welded together; this marks the transition to the Hawaiian style of eruption. The activity ended with a lava flow, which currently covers the pyroclastic deposits from above (Rapprich 2012a, b; Rapprich 2013). The age of the Prackov basanite is 4.92 My (Cajz *et al.* 2009). Evidence suggests that 5 Ma (Pliocene) there were two active volcanoes: Kozákov with a long lava flow and the mainly eruptive Prackov (Rapprich 2012a).

The most famous feature of the Geopark is the Trosky volcano (Fig. 10). Two rock towers, on which the remains of the medieval castle stand, represent the dissected conduits of basalt magma that solidified inside the two volcanic cones. Scoria deposits from the Strombolian style eruptions, also used to build the castle, can be seen in the rim of both basalt towers (Rapprich 2012b; Petronis *et al.* 2015). Both towers, formed by compact basanite, are more resistant to erosion and weathering than the surrounding Cretaceous sediments and pyroclastic deposits (Rapprich 2012a). Basanite has a pronounced columnar jointing, with the columns in towers oriented sub-horizontally. Between the two towers, there is another sub-horizontally placed plate-like body with a sub-vertically oriented columnar jointing (Čech *et al.* 2013). Using the K-Ar method, the age of the basanite lava was determined to be 16.5 My (Rapprich *et al.* 2007).

A significant relic of a monogenetic volcano is Vyskeř Hill (Fig. 11), which is interesting for its conduit made of picrite, which is a rare and exceptional rock in the geopark area. This picrite has a partly cumulate character, as the magma was enriched with approx. 15% olivine compared to the original basanite melt. The rock is strongly alkaline and has the highest magnesium and chromium contents (Rapprich 2012b). Due to the low potassium content, the picrite rock could not be dated, but it is probable that the activity of the volcano corresponds to the surrounding basanites, with an age of around 17 My. The conduit formed by picrite is rimmed by medium-grained volcaniclastic deposits with a low content of small xenoliths of Cretaceous rocks indicating intense fragmentation caused by contact of magma with water on surface. This corresponds to the Surtseyan type of tuff cone eruption in a wetland to shallow lacustrine environment (Čech *et al.* 2013).

The Importance of Volcanic Geoheritage for Human History and Tourism

Historical and Economic Aspects

The landscape of the UGG Bohemian Paradise was inhabited since the beginning of the Early Stone Age (Prostředník and Šída 2010; Šída *et al.* 2014). Around the year 2000 BC, the area of the Bohemian Paradise was inhabited by people of the Urnfield Culture, who used the morphologically distinct volcanic formations and volcanic rocks to build fortresses and tower houses, the remains of which survive (e.g. Mužský). Later, especially in the late Middle Ages, fortresses and castles (e.g. Kumburk, Trosky, Pecka, etc.) and sacred buildings, especially in the Gothic style (e.g. Zebín, Vyskeř, Sv. Anna, etc.) were built on a number of Paleozoic and Neogene volcanic peaks. Some castles have been rebuilt into more modern castles in recent times, e.g. Humprecht, Sychrov, etc. (Prostředník and Šída 2010). In recent years, significant volcanic elevations have also been used for the construction of observation towers and vantage points.

The economic use of local raw materials continued from prehistoric times to the present day. There are several active quarries extracting volcanic rocks in the area of the UGG Bohemian Paradise, and several other quarries have only recently ceased operations. The raw material is mainly used as a building material. The collection and extraction of precious stones is a separate chapter. Their abundant occurrence in local Paleozoic igneous rocks has been known since the Middle Ages, and especially during the reign of Emperor Charles IV. Even later, during the reign of Rudolph II, these were processed and used mainly for decorative purposes. We find them in many period jewels and artefacts in collections around the world (Urban 1976, Barták 2021). Currently, local gemstones are very popular, especially in the last 100 years when they were often collected and processed by private collectors, as well as some local jewel-producing companies.

Geological Heritage and Tourist Potential

UGG Bohemian Paradise is actively involved in the protection of natural and geological heritage, especially through education and information for visitors. In cooperation with other organizations, information boards and educational trails have been built (Fig. 15), and various events and excursions are organized for the public.

From the point of view of an ordinary visitor to the Bohemian Paradise, castles, chateaux and other cultural monuments are undoubtedly some of the most attractive phenomena. Their location on top of volcanic features is a great opportunity to inform visitors about the geology and geological history of the area. In the areas of many of these buildings, the bedrock with various rocks and geological structures is excellently exposed, on which many geological phenomena can be clearly shown. Another benefit is the possibility of a panoramic view from these points, which stands out significantly from the surrounding terrain. Thanks to this, there is an opportunity for an excellent interpretation of the geological history and landscape morphology.

From the point of view of geological heritage interpretation, active and abandoned quarries, which are often popular gemstone localities, e.g. Doubravice and Frýdštejn, are also useful. Although

Figure 15. An example of an informative board explaining local geomorphology and the origin of the volcanoes. Photo by V. Mencl.

mining in many cases irreversibly damages the landscape, it offers a unique opportunity to examine the underlying rocks and obtain geological material for scientific and collecting purposes. The UGG Bohemian Paradise cannot influence the mining and collection of geological material in any way according to the Czech legal system, but we do not consider the collection of gemstones in quarries to be problematic because this enables the preservation of geological material that would otherwise be destroyed. The material may end up in professional institutions or private collections, and it is important to preserve it for later research and processing. Geologists of the UGG Bohemian Paradise are in contact and cooperate with local private collectors, and so have an overview and access to the most important finds from this area.

Conclusion

The strikingly diverse morphology of the UNESCO Global Geopark Bohemian Paradise territory reflects its extremely rich geological history. The area has been affected by at least three periods of significant volcanic eruptions that are recorded in landscape morphology. These events took place in the Late Paleozoic and Neogene.

Research shows that the rock sequence demonstrates high variability of volcanic activities in the Paleozoic, from the Moscovian to Artinskian. There were several types of volcanic eruptions that created various volcanic bodies and produced dozens of types of volcanic and volcanoclastic rocks that cover large parts of the geopark. Many of these were buried by younger deposits, but occasionally they are well excavated in some quarries and outcrops. Mafic basaltic rocks, historically called melaphyres, often have amygdaloid texture and contain attractive and rare minerals, e.g., natural copper, zeolites, pectolite, as well as a large number of gemstones, including agates, chalcedony, crystal-quartz, amethysts, unique star-shaped quartz, etc. In the Neogene, two significant periods of volcanic activity took place, in the Miocene and early Pliocene. These volcanic bodies are quite small, but many are clearly recognizable in the landscape morphology from their well-preserved structures. Because they are excavated in many places, they are great for studying monogenetic volcanism and volcanic products, as well as e.g., feeding conduits.

All volcanic periods were crucial for creating the landscape character of the UNESCO Global Geopark Bohemian Paradise. According to its volcanic history, various products of distinct types of volcanic activity are concentrated in a relatively small area. This offers not only great opportunities for the scientific study of volcanic processes but also represents excellent potential to present volcanic activity to the wider public. Geological interpretations can be linked with presentation on the history of human settlement and the use of raw materials in the area, including recent mining and collecting activities.

Conflict of Interest

The authors declare that there is no conflict of interest in their work.

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