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ORIGINAL ARTICLE

Volcanic tuff as a World Heritage Georesource, a Case Study of Tokaj Wine Region UNESCO Cultural Landscape

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Abstract
Volcanic tephra and pyroclastic rocks are common georesources worldwide. Volcanic eruptions produce these materials, and the freshly deposited volcaniclastic sediments undergo variable diagenesis and possible hydrothermal alteration. The rhyolitic pyroclastic rocks of the Carpathian Basin were formed as a result of major silicic volcanism during the Miocene and are exposed in several volcanic regions. The use of these stones depends on their physical properties, such as hardness, colour, and transportability, especially in masonry and ornamental design. The study site, the Tokaj Wine Region (TWR) Historic Cultural Landscape is a UNESCO site located in NE Hungary, which was inscribed on the World Heritage List in 2002. The silicic pyroclastic rocks, here we also referred to them as rhyolite tuffs, are significant geological resources in the UNESCO cultural heritage designation. The pyroclastic formations cover an area of about 100 km^2 and were deposited by three major explosive eruptions (13.1–11.5 Ma). The local varieties are defined by primary volcanological features and secondary (diagenetic, hydrothermal) effects. The stone was extracted from more than 40 open pit quarries dating from the Middle Ages. The wine cellars and dry-built terrace walls are important cultural features of the volcanic tuff use. The geoconservation value of the rhyolite tuff is well illustrated by the exposed special geological features, which represent important sites of volcanic formations. However, only one site has been declared a nature conservation area. Several historic quarries are currently abandoned, and there are many problems due to the lack of their restoration. The most common problems are the instability of quarry walls, illegal dumping, pollution, and dense vegetation covering the geological values. The volcanic tuff has a great potential as a georesource (quarries, cellars, and terrace walls) adding value to World Heritage Site, but special efforts are needed to demonstrate its potential for geoconservation, geotourism, and geo-education.

Keywords Pyroclastic rocks · Rhyolite tuff · Georesource · Cultural landscape · UNESCO world heritage site

Introduction

Throughout human history, the extraction of stone and raw materials has played an important role (Prosser 2018). From the creation of Palaeolithic stone tools to modern building materials, these resources have become increasingly important over time. While some materials, such as obsidian and millstones, have lost their former importance, the large-scale extraction of building stones has significantly impacted the landscape. These changes can be observed in the Mediterranean region (Bloxam 2011; Careddu and Grillo 2018) as well as several areas of the Carpathian Basin (Dávid 2010). Social demands have resulted in significantly modified quarry landscapes, where anthropogenic impacts can transform up to several km^2 (or tens of km^2, coal mining, basalt quarrying, Karancsi et al. 2015). Pyroclastic rocks, in common parlance and here referred to as volcanic tuffs have been the preferred building materials for many places throughout human history (e.g., Mexican tuffs from 2000 BCE, Siegesmund et al. 2022; Rhenish tuffs - medieval ages, Häfner 2022). These materials are derived from explosive volcanic eruptions, and the freshly deposited volcaniclastic sediments have undergone variable diagenesis and/or hydrothermal alteration (Funiciello et al. 2006). The

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non-welded or poorly welded massive ignimbrite deposits are widely used in architecture throughout the world (Arucas stone, Canary Islands - Cárdenes et al. 2022; Bükk region - Hungary – Török et al. 2007). The use of these stones depends on their physical properties, such as hardness, colour, and transportability, especially in masonry and ornamental design. They illustrate how geology can influence society and how culture can influence the perception, use and management of geoheritage over centuries.

The study site, the Tokaj Wine Region (TWR) Historic Cultural Landscape is a UNESCO site located in NE Hungary, which was inscribed on the World Heritage List in 2002. The TWR (total area 881 km^2) consists of 28 villages and 7000 hectares of classified vineyards. Due to the unique geological features and specialized viticultural traditions, the landscape has an exceptionally high geodiversity (Szepesi et al. 2017; Ésik 2021). The TWR is characterized by widespread rhyolite tuffs, which were deposited during the Middle to Late Miocene period (13.1–11.6 Ma, Lukács et al. 2024). The rhyolite tuffs are important geological resource which was recognized early in the TWR (Szabó 1866; Szabó and Török 1867) and was a major milestone in the UNESCO Heritage designation (Szepesi et al. 2017). According to Navarro et al. (2022), there is a global problem of uneven knowledge about building stones and historic quarries that are associated with UNESCO World Heritage sites. The Tokaj World Heritage Management Office also currently lacks a comprehensive database on the subject. Local communities also need help in understanding and preserving the traditions associated with their cultural heritage.

This study aims to provide a comprehensive summary of the volcanic tuff cultural heritage of present in the TWR (Tokaj-Hegyalja) region. To achieve this, extensive geological fieldwork and geoheritage-based mapping of historically important quarry sites have been carried out. In addition, a systematic review of literature was carried out to investigate the historical traditions of the tuffs (e.g., ornamental stone, masonry stone). The study also includes other cultural aspects and anthropogenic features related to the landscape, such as cellars and terrace walls. Finally, the paper concludes with a summary of future perspectives for geoconservation and geotourism.

Geological and Volcanological Framework

Volcanic tuff is a common building material in rhyolitic volcanic areas, including the Carpathian Basin where it is mainly found in the central mountainous region (Fig. 1a). These rocks were formed by major silcicic explosive volcanism during the lithospheric extension of the Pannonian basin and were deposited during several explosive phases between 18 and 11 million years ago (Harangi and Lenkey 2007; Lukács et al. 2018, 2024). The oldest pyroclastic formations (18.1–14.4 Ma) are found in the northern Hungary and in the Bükkalja volcanic field (Lukács et al. 2018, 2022; Hencz et al. 2024). The pyroclastic rocks of the Tokaj Mountains are younger (13,1–11,6 Ma), and similar to the older ones, they represent several eruptive phases (Pécskay et al. 1987; Gyarmati and Szepesi 2007; Lukács et al. 2024). In addition, andesitic and dacitic composite volcanoes, subvolcanic intrusions and dacite-rhyolite lava domes were also active, erupted significant amounts of lava in the Tokaj Volcanic Complex (Selmeczi et al. 2023). The mountain range is interspersed with the products of explosive and effusive volcanism but the rhyolitic pyroclastic rocks (rhyolitic tuff) dominates in the study area (Fig. 1). Two major caldera-forming event associated the Plinian, sub-Plinian explosions (Zelenka et al. 2012; Lukács et al. 2024). Several smaller lava domes are thought to have formed in association with the caldera rim faults (Szepesi et al. 2023), which also led to Vulcanian activity and partial dome collapse, eventually resulting in lithoclast-rich pyroclast density currents. In the early stages of volcanic activity in the Tokaj Mts., the environment was archipelagic and lagoonal according to the fossil record. However, this was later replaced by a terrestrial-limnic character. In certain areas the deposits have experienced continuous hydrothermal activity resulting in variable alteration zones (Fig. 1b). Addition to intense silicification, argillic alteration (kaolinite, montmorillonite) was significant. Other low temperature alteration zones (alunite, adularia-sericite) are also present (Mátyás 1966a; Molnár et al. 1999; Pécskay and Molnár 2002). The paleolakes contained reworked material and layered silica deposits. The present hilly character of the TWR is the result of pediment formation (200–400 m asl. Pliocene) and selective erosion. Uplift during the Pleistocene-Holocene has resulted in the formation of stream terraces and formation of deep erosional gullies. Today, the TWR rhyolite tuff landscape is characterized by gentle hills, semi-circular basins and medium-length valleys. The higher peaks are effusive edifices (e.g. dacite: Tokaj, Sátoraljaújhely, Fig. 1b), rhyolite lava domes (Tolcsva-Erdőbénye) or silicified hydrothermal centres (Megyer Hill).

Methods

The study area includes the rhyolite tuff quarries of TWR, which covers ca. 100 km^2 as shown in Fig. 1. Fieldwork started in 2014, with a primary focus on geological-volcanological relevance. Samples were collected from both working and abandoned quarries. Field data collection included unit thickness, bedding orientation, grain size, and sorting.

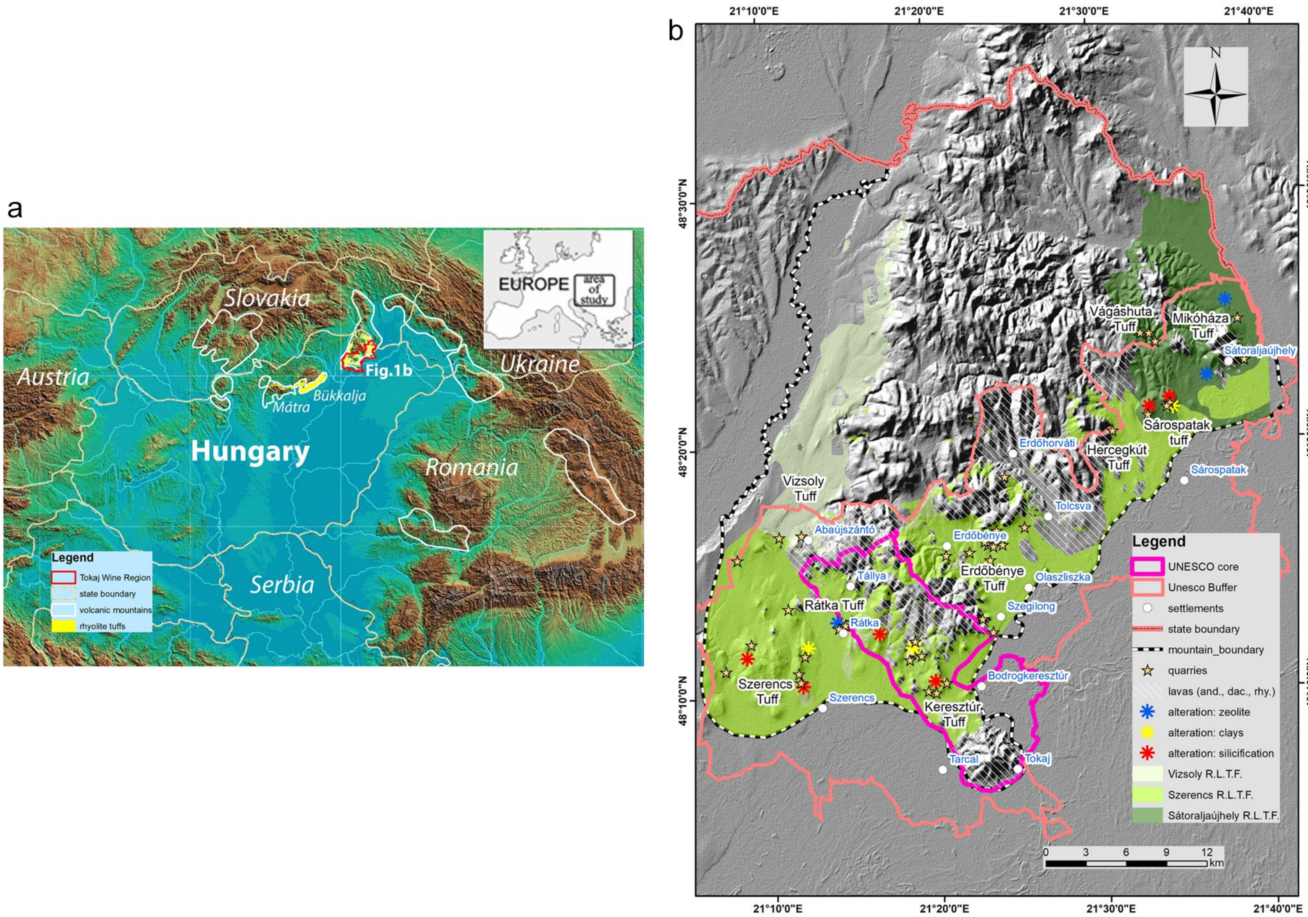

Fig. 1 (**a**) Location of the Tokaj Mountains and Tokaj Wine Region Historic Cultural Landscape in the Carpathian-Pannonian region. (**b**) Digital elevation model of the Tokaj Mountain area highlighting the rhyolite tuff formations (green). The red line is the buffer zone of the Tokaj Wine Region Historic Cultural Landscape. The purple is the core area of the TWR. All of the regional tuff varieties are highlighted on the map

The additional lithological characteristics of the materials were described using hand specimens and thin sections.

The geoheritage-based research (Ésik et al. 2019; Ésik 2021) was focused on the inventory, mapping and evaluation of the quarries as geosites. This involved several assessment criteria, as outlined in (geo)site assessment methods (e.g. Vujičić et al. 2011; Brilha 2016). The criteria included geoconservation purposes, risk of degradation, educational and tourist relevance, and other factors. The research used various indicators, such as representativeness, key locality, scientific knowledge, integrity, geological diversity, rarity, use limitations, accessibility, current observation conditions, vulnerability, educational potential, safety, and association with other values. The fieldwork was partly carried out in conjunction with a special geoconservation-based field survey organized by the Aggtelek National Park from 2015 (Szepesi et al. 2020).

In parallel with the geoheritage inventory work, a comprehensive literature review was undertaken to describe the history of quarrying and significant areas of use. We carried out additional fieldwork in the settlements to identify the various types of tuff used in public and religious buildings, bridges, fences, cemeteries, and ornamental stones. Wherever possible, we tried to determine the origin of the materials used. The final inventory comprises a georesource catalogue that provides a concise summary of the petrography, landscape history, nature conservation, and tourism attributes of the tuffs.

Results

Lithological Characteristics

The rhyolite tuff (rhyolite pyroclastic rocks) is the dominant rock type in the TWR covering an area of about 100 km^2 (Fig. 1b). Our recent study (Lukács et al. 2024) confirmed four major explosive phases (Sátoraljaújhely, Hegyköz, Szerencs and Vizsoly units) between 13.2 and 11.6 Ma in the Tokaj Mts. Three of these phases were documented in

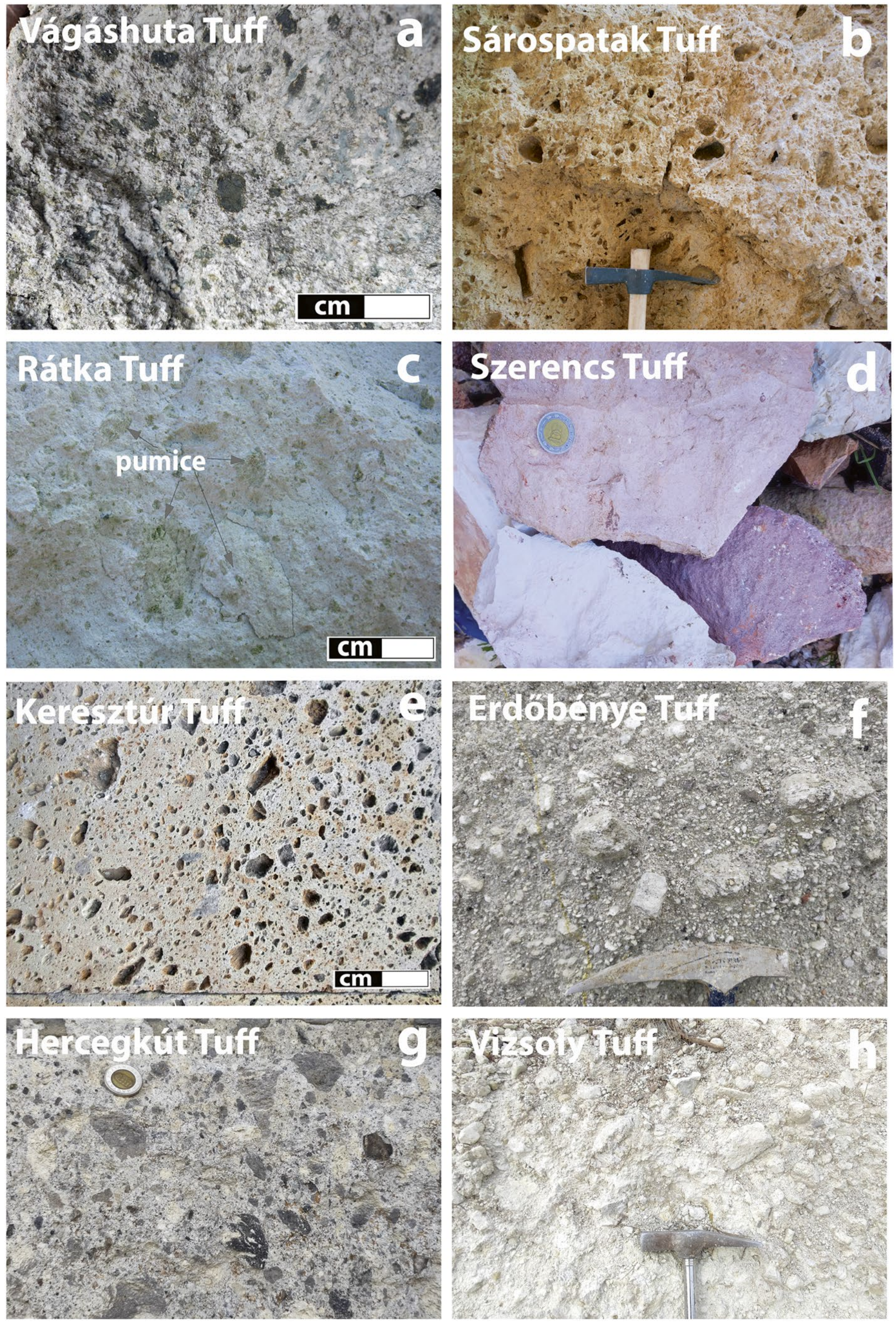

Fig. 2 Lithological characteristics of the tuffs of Tokaj Wine Region. *Sátoraljaújhely Lapilli Tuff Formation (Badenian)*: (**a**) Hand specimen of the Vágáshuta Tuff. The massive lapilli tuff contains non-volcanic lithics (schist -black). (**b**) Coarse-grained pumice breccia character of the Sárospatak (millstone) Tuff. Alteration caused intensive pumice leaching (holes). *Szerencs Rhyolite Lapilli Tuff Formation (Sarmatian)*: (**c**) Greenish colored, zeolitic alteration of the pumices Rátka Tuff. (**d**) Varying (pink, purple) colour of the fine-grained Szerencs Tuff. (**e**) Yellowish, altered character of the Keresztúr Tuff with leached pumices (holes). (**f**) Erdőbénye Tuff: Typical pumice-rich lapilli tuff with rhyolite and obsidian lithics. (**g**) Hercegkút Tuff: Coarse-grained lapilli tuff with pumice and andesitic (grey-black) scoria. *Vizsoly Rhyolite Lapilli Tuff (Pannonian)*: (**h**) Coarse-grained, pumice-rich part of the Vizsoly Tuff, Abaújszántó, Sátor Hill

theTWR quarries (Fig. 1b). From a volcanological point of view, the TWR tuffs are dominantly typical pyroclastic flow deposits, with varying grain size ranges (tuffs, lapilli tuffs, breccias, Table 1). The main regional subtypes are described according to stratigraphic position, age, including local depositional and alteration characteristics.

The oldest pyroclastic formation is the upper Badenian *Sátoraljaújhely Lapilli Tuff* (13.2–13.1 Ma, Lukács et al. 2024), which is exposed in the NE part of the TWR (Fig. 1b). The main lithology of this formation is the massive lapilli tuff (Fig. 2a), but coarser rocks such as lapillistone and pyroclastic breccia are also included. The concentration of lithic and pumice clasts is variable. Among the local varieties, the Vágáshuta Tuff contains variable non-volcanic lithic clasts (gneiss, schist, Lutherán quarry, Fig. 2a), while other pumice-rich varieties are finer grained (Nyilazó quarry). The Mikóháza Tuff (northern part) is characterized by pumice enrichment and zeolitic-argillic alteration (Fig. 1b). The Sárospatak Tuff is characterized by old (pre Miocene), basement-derived lithic clasts, pumice enrichment (Fig. 2b), larger grain size, strong silicification, and argillic alteration

Table 1 Characteristics of the major rhyolite tuff varieties in the Tokaj Wine Region Historic Cultural Landscape

name, identification (classification)		quarries	lithology	stone material	historic, cultural aspects	geoconservation	geotourism aspects	scientific relevance
Sátoraljaújhely Lapilli Tuff Formations	Mikóháza Tuff	Torzsás, Néma Hill, Boglyaska quarries	pumice rich massive lapilli tuff, fine grained lapilli tuff	pozzolanic material, concrete additive	20th century excavations	no active action	Zemplén Adventure Park route	Wessely 1959
	Vágáshuta Tuff Figure 2a	Óbánya, Lutherán, Lower and Upper Nyilazó quarries	lithoclast rich (non volcanic), / pumice rich massive lapilli tuff,	carved bricks, variable (usally poor) frost resistance	used in Sárospatak medieval castle (1534-37), major excavations in 19th century	geoconservation survey for national monument designation 2017	-	
	Sárospatak (millstone) Tuff Figure 2b	Megyer, Király Cinegés, Botkő quarries	pumice and lithic rich altered (silicified, argillic) lapilli tuff and breccia	whole curve and tiled millstone	from 15th century first-order medal, 1862 World Expo London, major excavation 19th-20th last millstone constructed in 1979	Megyer Hill Nature Conservation area of national interest, 1977 1.1 ha	nature trail, panoramic viewpoint	quarrying: Láczay-Szabó 1864; Hála 1993 Geoconservation chapter (Szepesi and Ésik 2015),
Szerencs Lapilli Tuff Formations	Rátka Tuff Fig. 2c	Rátka village Koldu, Hercegköves, quarries	fine-grained zeolitic lapilli tuff, silicified rhyolite tuff	pozzolanic material, concrete additive bulding stone / decorative stone, quartzite - masonry stone	mainly in 20th century, active excavation in Rátka quarries,	no active action	-	pozzolanic use Wessely 1959; Varjú 1966
	Szerencs/Keresztúr Tuff Fig. 2de	*Abaújszántó*: Fehérkő, Süveges *B.keresztúr*: Kakas, Hangács, Führer *Mád*: Király, Bomboly, Suba quarries	altered massive lapilli tuff with variable lithic and pumice content, high K_2O in Szerencs area	masonry stone (buildings, terrace walls), clay minerals extraction, recently bulding stone, carved and cut decorative stone, cellar excavations (Mád)	from second half of 19th century, mainly surface mulit level, open pit, but there are underground adits. active excavation in Mád and Bodrogkeresztúr	Mád Király Hill quarry bat colony protection, geoconservation survey for Aggtelek National Park	wine tourism without geoheritage relevance	Hoffer 1937, hydrothermal alteration review Mátyás 1966ab, 1967 Molnár et al. 1999 Pécskay and Molnár 2002, Jugovics 1954,1958
	Erdőbénye Tuff Figure 2f	*Szegi*: cellars - underground quarry, *Szegilong* II. quarry, *Erdőbénye*: Dongó, Mulató, Spitzer, Sajgó quarries (over 10 excavations)	lithic and/or pumice-rich lapilli tuff	non-cohesive material: grinded stone dust, cellar excavation. cohesive material: masonry/ bulding stone, decorative stone,	decorative stone industry in late 19th and early 20 th century intermittent excavations in Szegilong II, and Erdőbénye III.	no active action	wine tourism without geoheritage relevance	historical quarrying Szakáll 1997; Fehér 1997; Viga 1997
	Hercegkút Tuff Figure 2g	Kőporos quarry, Gombos Hill (cellars)	lithic-rich lapilli tuff with dark scoria	carved bricks, cellar excavations	from 1972, abandoned in 1990 years	no active action	wine tourism without geoheritage relevance	

Table 1 (continued)

name, identification (classification)		quarries	lithology	stone material	historic, cultural aspects	geoconservation	geotourism aspects	scientific relevance
Vizsoly Lapilli Tuff Formation	Vizsoly Tuff Figure 2h	Hidegoldal quarry	fine-grained lapilli tuff, pumice-rich lapilli tuff	building stone, concrete additive	mainly in 20th century, abandoned, small excavation	no active action	-	physical volcanology studies Hoffer 1937

(Szepesi and Ésik 2015). Submarine deposition is confirmed by mollusc shells.

The *Szerencs Rhyolite Lapille Tuff* is the second formation that dominates the TWR in terms of volume (up to 500 m thick) and surface area (Fig. 1b). It was deposited by several explosive phases around 12 Ma ago. Besides the massive character bedded varieties are also typical. There are several local varieties including the greenish, zeolitic Rátka Tuff (central part, Fig. 2c) and the argillic-silicified Szerencs Tuff (Fig. 2d) in the southwestern and the Keresztúr Tuff in the southeastern part (Fig. 2e). The *Erdőbénye Tuff* is an unaltered, non-welded ignimbrite containing obsidian and rhyolite lithics (Fig. 2f). In addition, the unique *Hercegkút Tuff* is rich in andesitic scoria (dark, Fig. 2g) but this is found locally (Fig. 1b).

The Vizsoly Rhyolite Lapilli Tuff, which is 11.6 million years old, is found only in the northwestern part of the TWR near Abaújszántó (Fig. 1b). It has a variable grain size and pumice enrichment (Fig. 2h), reaching up to dm in size.

The petrography of the three formations is broadly similar. They are rhyolitic in compositions (70–75% SiO2). The average phenocryst content is typically 5–10%, with a high abundance of quartz and plagioclase.The groundmass is mainly composed of ash components, with varying amounts of vesicular pumice (Fig. 3). In the case of the Sátoraljaújhely Formation, the groundmass is typically altered (e.g. zeolitic, silicified, Fig. 3a). The samples of Szerencs formation samples are poor in phenocrysts (< 5%, Fig. 3b) but contain sanidine, while the Vizsoly Formation is usually contains biotite (Fig. 3c) and pyroxene.

The Quarries

The total number of quarries is over 40 (Figs. 1b and 4). The quarries can be classified based on their current status and level of protection, as shown in Table 1. Most of the sites are inactive quarries (e.g. Abaújszántó: Fig. 4a). Only the Geoproduct and Colas quarries (Rátka, Mád, Bodrogkeresztúr) are still in operation (riolittufa.hu, zeomineralproduct.hu; Fig. 4b-d). In Erdőbénye (Fig. 4e) and Szegi intermittent quarrying take place. Only the Megyer Hill (Sárospatak Tuff) has been granted protection status (since 1977, Fig. 4f), where the old quarry walls are well-preserved. The abandoned quarries lack administrative protection, but they have been surveyed by Aggtelek National Park to be declared a natural monument (Fig. 4a and g). The work of the Hungarian Stratigraphic Committee has recently revised the stratigraphic units (Selmeczi et al. 2023) of the area. Some of the quarries are defined as key localities of the pyroclastic formations (Fig. 4a and c-e). Most have recently been dated by zircon U/Pb geochronology (Lukács et al. 2024). The scientific knowledge is also underlined by the geotechnical characterization of the quarried materials (Újhelyi 1957ab; Wessely 1959; Ilkey-Perlaki 1966) and the historical relevance of some building, ornamental and millstone (Hála 1993; Fehér 1997; Szakáll 1997; Viga 1997). The quarries located near residential areas (e.g., Bodrogkeresztúr, Rátka Figs. 1b and 4c and d) are easily accessible, which makes them highly vulnerable to illegal or legal dumping (e.g. Szerencs Fig. 4g, h), which may compromise their integrity. The current observation conditions of these quarries vary greatly, as a dense growth of vegetation often

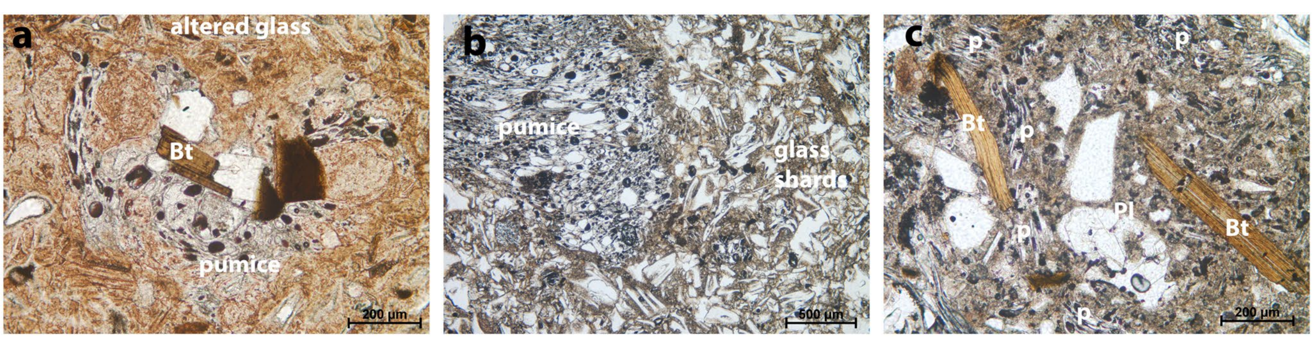

Fig. 3 Photomicrographs of tuff formations. (**a**) Sátoraljaújhely tuff: Altered glass shards (brown), in the fine grained matrix, colourless pumice with biotite (Bt, center). (**b**) Szerencs tuff: Unaltered lapilli tuff with a large pumice (p, left) and characteristic glass fragments. (**c**) Vizsoly tuff: Ash-rich (dark matrix) lapilli tuff with pumice fragments (p) biotite (Bt) and plagioclase (Pl) crystals

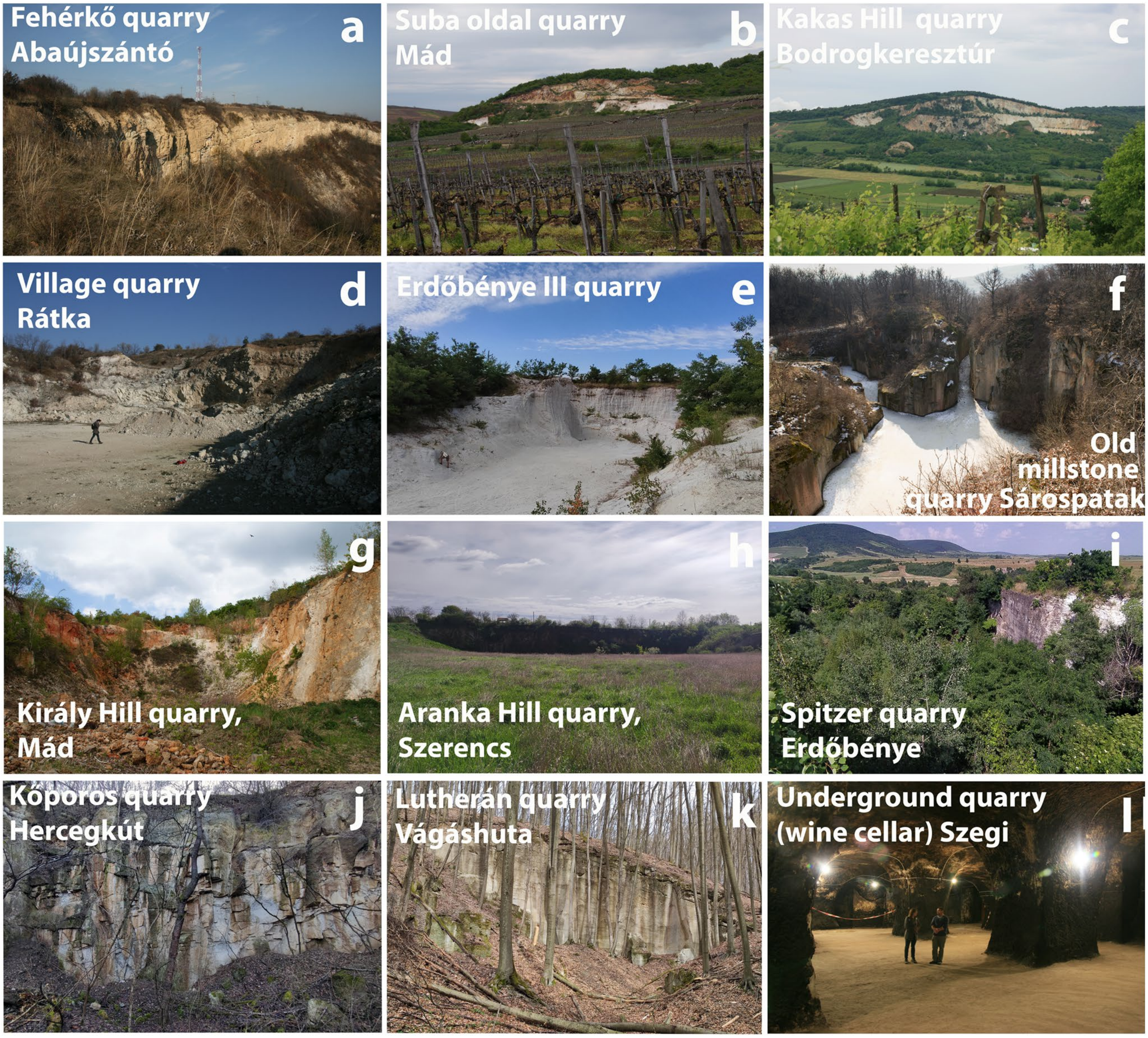

Fig. 4 Quarry landscape of the TWR with the indication of the quarried local tuff varieties (details in Table 1). (**a**) Fehérkő quarry, Abaújszántó (Keresztúr Tuff). (**b**) Suba-oldal quarry, Mád (Keresztúr Tuff). (**c**) Kakas Hill quarry, Bodrogkeresztúr (Keresztúr Tuff). (**d**) Village quarry (Rátka, Rátka Tuff). (**e**) Erdőbénye III quarry (Erdőbénye Tuff). (**f**) Old millstone quarry, Megyer Hill (Sárospatak Tuff). (**g**) Király Hill quarry, Mád (Keresztúr Tuff). (**h**) Aranka quarry with restored dumping, Szerencs (Szerencs Tuff). (**I**) Spitzer quarry, Erdőbénye (Erdőbénye Tuff). (**j**) Kőporos quarry (Hercegkút Tuff). (**k**) Lutherán quarry (Vágáshuta Tuff). (**I**) Underground quarry (Szegi, Erdőbénye Tuff)

follows abandonment (Fig. 4i-k). The touristic potential is variable, study trail has been built in the areas of Sárospatak (Fig. 4f) and Sátoraljaújhely. Some of the historical quarries can be reached by hiking trails, but there is usually no tourist interpretation (Vágáshuta quarries Fig. 4k). The underground quarry of Szegi is a famous wine cellar that focuses exclusively on wine tourism (Fig. 4l).

Use of Stone

Building Stones

Rhyolite tuffs of the TWR had four main uses: building stone (masonry stone), ornamental stone (decorative stone) utilitarian stone, and powder, grinded material (Table 2). The physical rock properties compiled in Table 3. The local varieties reflect well the suitability of the different lithologies and are named after the larger settlements (Szerencs,

Table 2 The major commodity uses of the TWR tuff varieties

Commodity	Uses	Tuff varieties	Important aspects
Building stone (masonry stone) Figure 2a, d,e, g, h Figure 5	brickwork (houses, defence walls, stone fences, bridges) dry built terrace walls	Vágáshuta tuff Szerencs tuff, Keresztúr tuff Erdőbénye tuff Hercegkút tuff Vizsoly tuff	frost resistance availability transportation
Ornamental stone (decorative stone) (Figs. 6 and 7)	Sculptures Columns Gravestone	Vágáshuta tuff Erdőbénye tuff Keresztúr tuff (recently)	grain size – aesthetic appearance carving properties
Utilitarian stone Figs. 2b and 6a	Grinding stone, millstone	Sárospatak tuff Keresztúr tuff	hardness
Powder, grinded material Figure 2c and f	Concrete additive, pozzolanic material	Mikóháza tuff Rátka Tuff Erdőbénye Tuff	water absorbance, porosity

Table 3 Physical rock properties of TWR tuff materials (compiled from Ilkey-Perlaki 1966)

	gravimetric density g/cm^3	overall porosity %	efficient porosity %	average water absorption %	ultimate tensile strenght kp/cm^3
Mikóháza Tuff	1.85	37.1	16.1	9.5	35–188
Vágáshuta Tuff	2.06	31.3	18.5	9.8	140–155
Sárospatak Tuff	not investigated				
Rátka Tuff	1.7	39.4	23.0	14.0	22–30
Szerencs Tuff	1.57	46.6	24.5	17.3	128–149
Keresztúr Tuff	1.6	43.6	20.7	13.1	39–195
Erdőbénye Tuff	1.61	42.2	18.0	11.5	22.9–198
Hercegkút Tuff	1.55	48.8	24.8	18.1	24–107
Vizsoly Tuff	1.55	57.8	31.6	25.7	4.3-9

Mád, Rátka, Erdőbénye, Sárospatak, Sátoraljaújhely Tuffs, Fig. 1b; Table 1). The Vágáshuta quarries are located outside the boundaries of the TWR, but the area of their exploitation was also connected to the largest towns. Quarrying was initially served the ore processing (Ésik et al. 2019) and grain milling. The stones became the raw material for construction (Fig. 5a, b) and elaborate stone carvings of the fortresses and aristocratic residences. The main excavations date from the 18th century when it became a common building stone in local houses (Keresztúr, Szerencs Tuff: Fig. 5c), as the use of local wood for construction was restricted. It was also used to build the famous stone bridges of the region (Olaszliszka, Szegilong, Vámosújfalu, Fig. 5d, e). The Mikóháza and Rátka variants have similar characteristics (zeolitic alteration, pumice enrichment, Figs. 2c and 3a), so they were used as pozzolanic material and concrete additives in the second half of the 20th century. The local Hercegkút Tuff was quarried from 1972 to 1990 (Fig. 4j) and is a representative masonry stone of World Heritage cellars (Fig. 2g). The petrophysical properties based on the lithofacies are very diverse. Porosity, pore size distribution and bulk density are the main determinants of the durability of the stone. The best varieties are characterised by high porosity with high resistance to salt weathering and the influence of water on their strength properties is considerably low (Ilkey-Perlaki 1966).

Millstones, Ornamental Stones

The millstone is one of the oldest products of the TWR mining industry (Fig. 6a). It was essential for grinding wheat, but medieval precious metal mining also required wear-resistant stones. They occur in the central part of hydrothermal alteration zones, mostly associated with clay deposits (Fig. 1b). Mining has the longest tradition in Sárospatak region. It started on the Megyer Hill (from 15th century until 1907, Fig. 4f) and the centre of the industry moved to the Király Hill (1835–1994). Initially, round stones were carved (Fig. 6a), later French-style millstones were made from cemented pieces (Hála 1993; Szepesi and Ésik 2015). The high-quality stones were awarded the "Medal of the First Order" at the World Exhibition in London in 1862 (Láczay-Szabó 1864).

Statues, religous monuments (crucifixes, tombstones) and stonefences are the dominant elements of the TWR landscape (Fig. 6b-f). The ornamental stones were mainly used to decorate castles and larger public buildings in the Middle Ages. Rákóczi Castle (Sárospatak) stands out as the most beautiful surviving example of late Renaissance architecture in Hungary. Here the stonemasons used the fine-grained, white-coloured Vágáshuta Tuff (Fig. 6b). It was used to make the gate of Red Tower, windowsills and other interior and exterior decorations (Fig. 7a-d). Later, in the 19th century, Erdőbénye became the centre of the stonemasonry trade. Here, ornamental stones (Fig. 6c-f) were made from the unaltered pumice rich Erdőbénye tuff, which was a popular stone material even 150–200 km away.

Stone Weathering

The way in which building stones are damaged is the result of a very complex process, which was recognized early on. The weathering forms of the tuff include selective erosion, crumbling, crust and flake formation (Fig. 7). In the case of the Sárospatak castle, the degraded external decorative elements (gate, window, cornice) were placed in the museum (Fig. 7a-d) and the original stone carvings were replaced by artificial stone (Fig. 7d). The famous Erdőbénye Tuff also suffers from several damages (Fig. 7e-h). The stone breaks along the cracks (columns). The surface of the

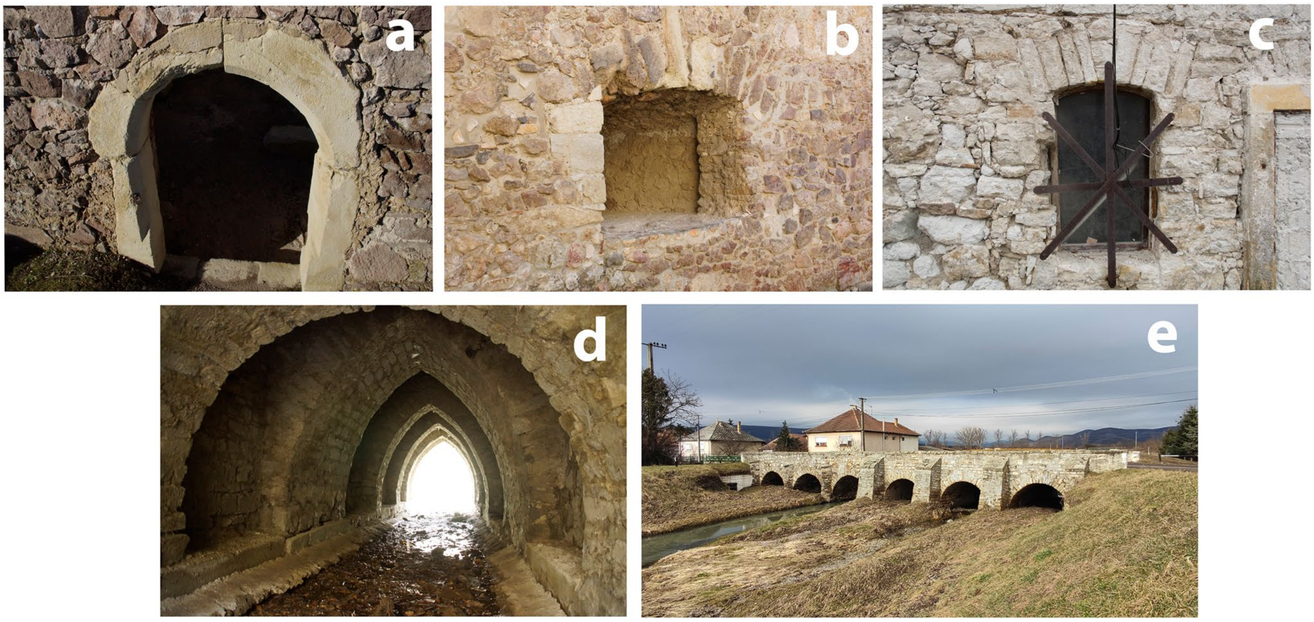

Fig. 5 Use of volcanic tuff as a building stone. (**a**) Original, medieval door frame, Sátoraljaújhely fortress (Vágáshuta Tuff, the wall rock (pink) is dacite. (**b**) Fortified wall, Sárospatak castle (various stones). (**c**) Irregularly shaped masonry bricks (Erdőbénye Tuff). (**d**) 8 m high, temple-like bridge (Olaszliszka, Erdőbénye tuff). (**e**) Six-hole stone bridge (Vámosújfalu, Erdőbénye Tuff)

gravestones is flaking off due to crusting, and the inscriptions are disappearing. The heritage authorities have a role to play in tackling the problems of deterioration. Most of the major primary resource quarries have closed. So when replacements are needed, they have to use other alternatives (Fig. 7e, Keresztúr Tuff).

Other Cultural Landscape Features (Cellars, dry Built Terrace Walls)

A TWR cultural landscape demonstrates the long tradition of wine production, including historic cellars which can be found in almost all municipalities. Underground structures are relatively easy to excavate in the non-welded or slightly altered tuffs. The cellars can be classified into two categories based on their location: (1) the historical network of underground cellars in villages and towns (Mád, Erdőbénye, Sátoraljaújhely, Sárospatak), and (2) cellars carved into the surrounding hills (rows, Hercegkút). The architecture, layout, and length define the main cellar types (Frisnyák 2012; Müller 2013). The most popular is the single branch cellar. The most spectacular World Heritage site is the hillside cellars of Hercegkút (up to 180, Gombos Hill and Kőporos) with triangular entrance (Fig. 8a and b). The large hall cellars have several branches (Fig. 8c, d) and levels. The interesting thing about the Szegi cellar (carved out of Erdőbénye Tuff, Fig. 4l) is that a multi-level tunnel system connects three large underground quarries (used for scrubbing powder). Another important cultural heritage site is the Ungvári Cellar (Sátoraljaújhely), where 27 individual cellars were connected horizontally and vertically to form a 14–16 km long underground attraction (Szepesi et al. 2017). Although the surface is covered by noble mould in most places where it is clear, primary pyroclast accumulation features (bedding, lithic enrichment) are visible (Müller 2013; Szepesi et al. 2017).

Another traditional TWR landscape features are the dry-built terrace walls (Fig. 8e, f). They are considered an important part of the cultural landscape and are valued as architectural and environmental monuments. Their comprehensive scientific study has recently been completed (Incze and Novák 2013, 2016; Incze 2017; Novák and Incze 2014). These walls can reduce soil loss due to erosion and improve the microclimate by modifying the slope. The construction stones are locally sourced and the gaps between them are filled with reworked soil. Terraced slopes and walls occur on about 590 ha (11.3% of TWR) within the wine region, most frequently on steeper (> 17%) slopes (Incze and Novák 2016). According to the distribution of the lithology, tuff walls can be found near the settlements of Mád, Rátka, Szerencs and Erdőbénye. Their average height is 0.7–2 m (Fig. 8e, f) and 0.5–1.5 m wide, but the lack of maintenance is a major problem. Without continuous upkeep, the structure of the walls weakens during heavy rainfall, causing them to collapse.

Fig. 6 Millstone, decorative and ornamental stone carvings: (**a**) Millstone (Megyer Hill, Sárospatak tuff). (**b**) Original window frame removed during restoration, Sárospatak castle (Vágáshuta tuff). (**c**) Churchyard decorative stones (Erdőbénye tuff). (**d**) Vine-leaf carving (Erdőbénye Tuff). (**e**) Cross gravestone (Erdőbénye Tuff). (**f**) Decorative stone (Erdőbénye Tuff)

Discussion

Rhyolite Tuff as Georesource

Georesources are naturally occurring materials with significant geological value and have the potential for exploitation (Gray 2004; Morante-Carballo et al. 2022). The availability and extraction of certain materials represent the impact of geology on society (Prosser 2018). This illustrates how culture can influence the perception, use and management of resources over centuries (Kubalíková and Zapletalová 2021). The unique geological characteristics currently provide important scientific or educational value and support multiple uses (Kubalíková 2017; Kaźmierczak et al. 2024). The characterization of a stone resource includes a number of approaches (Heldal and Bloxam 2008), such as geological features (e.g. lithofacies, fractures, Funiciello et al. 2006), other physical properties, and landscape-forming entity and commodity. Volcanic tuffs are among the most abundant rocks in the world(e.g. Canary Islands – Cárdenes et al. 2022; Mexico- Siegesmund et al. 2022) and are naturally highly heterogeneous in their petrography and petrophysical properties (Pötz et al. 2022). Lithofacies largely determine the potential uses of pyroclastic deposits. These are related to primary volcanological features and secondary (diagenetic, hydrothermal) effects. In the TWR, the most common lithofacies is pumice-rich lapilli tuff (Figs. 2 and 3), which often contains lapilli (volcanic, non-volcanic). The syn-depositional densification and lithification is associated with additional mineralization (zeolite, Figs. 2c and 3a) and hydrothermal alteration (silicification, clays, Fig. 2b, d and e). The disintegrated parts were removed by erosion, leaving the lithified or hydrothermally altered parts as mounds (Fig. 4a-c), which were later quarried. The loose parts were only preserved under a harder cover (e.g. lava) and exploited by underground mining (Szegi, Fig. 4i). The commodity aspects are summarised in the Table 2. The consolidated, usually non or slightly welded and/or

Fig. 7 Degradation of decorative stones. *Vágáshuta Tuff*: (**a**) Large gate of Red Tower (Sárospatak Castle) replaced by artificial material. (**b-c**) Original degraded stones of the gate in the museum. (**d**) Unique combination of original and artificial stone showing the difference in material. (**e**) New window in the Sátoraljaújhely fortress made from Keresztúr tuff currently quarried. *Erdőbénye tuff*: (**f**) crust formation on the gravestone (**g**) Broken gravestone caused by cracking. (**h**) Broken fence post

hydrothermally weakly altered tuffs with variable porosity and water absorption (Table 3) were suitable for carving of masonry stone (almost all major types). They were used for the construction of houses, public buildings, bridges, fences and terrace walls (Figs. 5, 6 and 7). Historically, only the Vágáshuta and Erdőbénye Tuffs were used mainly as ornamental and decorative stones (Fig. 6), nowadays only the Keresztúr Tuff was quarried for decorative works (geoproduct.hu). The Vágáshuta tuff was the raw material for late-Renaissance stone carving (Rákóczi Castle, Sárospatak, Figs. 6b and 7a-d). The Erdőbénye Tuff has been a popular raw material since the 19th century (Figs. 6c-f and 7f-h). The Sárospatak Tuff and the silicified varieties of the Rátka region were used for high-quality millstones from the 15th century. The decomposed varieties were used as abrasive dust, stone dust, while the zeolitic varieties

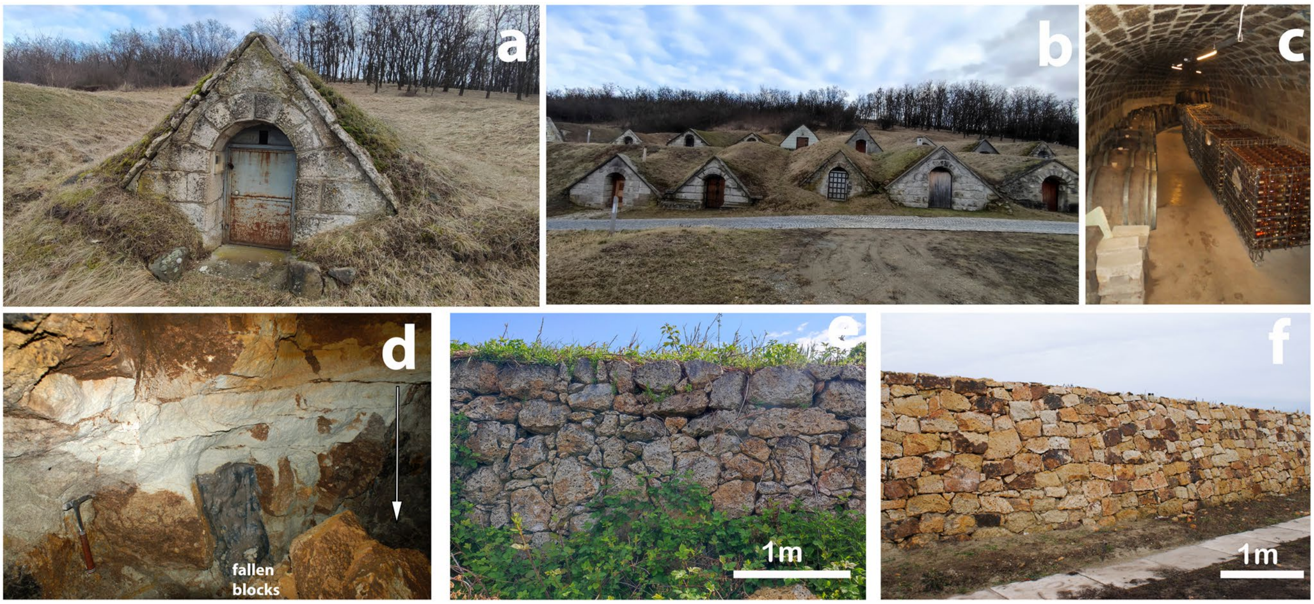

Fig. 8 Cultural landscape features of the rhyolite tuff use. (**a**) Triangular cellar entrance and (**b**) the multiple rows of World Heritage cellars, Hercegkút (Hercegkút Tuff). (**c**) Vaulted cellar and d, fresh cellar collapse (Mád, Keresztúr Tuff). (**e**) Historic dry built terrace wall (Megyer Hill, Sárospatak Tuff). (**e**) Renovated terrace wall (Mád, Keresztúr Tuff)

(hydrovolcanic tuff, Mikóháza, Rátka tuff) were used as pozzolanic material (only in the 20th century, cement, concrete additive). Similar uses have been reported in Italy, especially in Rome and Naples (Funiciello et al. 2006).

Georesources of the Cultural Landcspe

Quarrying is typically associated with opencast mining. Many UNESCO cultural landscapes have been significantly impacted by quarrying, yet there is often a lack of awareness and appreciation of their cultural and historical significance (Navarro et al. 2022; Kubalíková and Zapletalová 2021). An inventory of quarry sites and landscapes within a region or nation is valuable for the holistic management of this heritage. For example, the Quarryscapes project cataloged ancient Egyptian quarry sites (Abu-Jaber et al. 2008). A similar project has been undertaken in Spain for UNESCO World Heritage sites (Navarro et al. 2022). Quarrying also had a long tradition in the Carpathian Basin (Dávid 2010). The first comprehensive cadastre was established during the Austro-Hungarian Empire (Schafarzik 1904; ace.hu). It was later supplemented by explanatory notes to geological maps at various scales (1:25000, 1:200 000 e.g. Bóczán et al. 1966). The most recent regional work of this kind is the cadastre by settlements of Miskolc Mining Department (Izsó 2011). Based on this, a preliminary inventory of the quarries in the TWR was compiled, followed by detailed field surveys by Szepesi et al. (2017), Ésik (2021), and Lukács et al. (2024). The results (Table 1; Fig. 4) suggest that rhyolite tuff has been the main quarry product in the TWR for centuries both in terms of the number and area of quarry sites. The number of identified quarryies is over 40. They cover an area of more than 100 ha and the total excavated volume is more than 8 million m^3 (Incze 2017). The total quarried volume of andesite and dacite building stone (16–18 million m^3), significantly exceeds the rhyolitic tuffs, shows the change in demand. The largest concentration of quarries can be found in the counties of Szerencs, Rátka, Mád, Bodrogkeresztúr, Erdőbénye, Sátoraljújhely and Vágáshuta (Fig. 1b). In reality, this means that when you arrive in the World Heritage area, these abandoned quarries are part of the landscape almost everywhere (Fig. 4). Most of the quarries were worked by hand. Mechanized techniques were introduced in the second half of the 20th century. As mentioned above, the tuffs have been used for centuries, but they are not well known to the World Heritage authorities or to the local population. Only a few historical quarry sites are well documented and recognized (Megyer Hill, Sárospatak —Hála 1993; Szepesi and Ésik 2015, Ésik et al. 2019; Erdőbénye quarries—Fehér 1997; Szakáll 1997; Viga 1997).

The underground spaces are also important cultural landscape features (e.g. Cappadocia Turkey, Aydan and Ulusay 2003; Armenia- Davtyian 2013; Rome, Italy Funiciello et al. 2006). The Carpathian Basin provides an ideal climate for grape growing, but achieving high-quality wine ageing requires specific conditions, including carving wine cellars into stone. This practice has been documented in medieval sources, particularly in the cellars of northern Hungary such as Eger and the Mátra region (Juhász and Csanády 2016).

However, many wine-producing regions face challenges due to their old cellar systems. Although the municipalities have data that can be used to create a database of cellars, unfortunately there is no register that covers the World Heritage area. A large number of the TWR cellars are cut into rhyolite tuff, which is easy to shape and inherently stable (Fig. 8). As a result, no additional support is required for the cellar slab. Unfortunately, the presence of fracture networks can lead to cellar collapse (Fig. 8d). Owners of such cellars are responsible for repairing them and preventing any accidental damage.

Terraced landscapes are also a common feature of agricultural cultivation worldwide, from rice plantations in Asia to arable farming in South America and viticulture in Europe (Petit et al. 2012). In Hungary, the terraces with retaining walls are evidence of the viticulture using historical cultivation techniques. These landscapes are particularly valuable with 11% (590 ha) of area of TWR. Recently, a systematic field survey was conducted (Novák and Incze 2014; Incze and Novák 2013, 2016; Incze 2017) to determine the length of the terraces by rock type and to assess their condition. Since the abandonment of cultivation secondary succession has started on the fallow land. This has resulted in the presence of semi-natural grasslands in various stages of succession, along with woody shrubs, scrub, and species-rich mowing. Due to the favourable exposure, several protected and valuable herbaceous plants of conservation importance have been established on the abandoned terraces (Novák et al. 2014).

Geoconservation, Geotourism Perspectives

Georesources have a great potential for geoconservation, geotourism and geo-education (Szepesi et al. 2017, 2018ő et al. 2023). In this regard, historic quarries are the most extensive and impressive structures of the TWR and can be defined as geosites (Szepesi et al. 2017; Ésik 2021). The conservation value is well illustrated by the exposed special geological features which represent key localities of volcanic formations (Selmeczi et al. 2023; Lukács et al. 2024). The quarries can be classified based on their current status and level of protection, as shown in Table 1. Currently, only the quarries in Bodrogkeresztúr, Mád, Rátka are in operation (Keresztúr and Rátka Tuff, Fig. 4b, c). The quarries in Szegi and Erdőbénye (Erdőbénye Tuff) occasional intermittent workings so the possibilities for active geoconservation are limited. Most of the sites are inactive quarries (Vágáshuta, Szerencs, Hercegkút) without administrative protection. Successful geoconservation activities have only been achieved at Megyer Hill, Sárospatak (Fig. 4f). The amazing quarry yard was declared a nature reserve of national interest in 1997. Unfortunately, several historic quarries (Fehérkő–Abaújszántó – Fig. 4a, Nyilazó–Sárospatak) have been abandoned and many problems have arisen due to the lack restoration. The main and most frequent problems are the instability of quarry walls, illegal dumping and pollution and the dense vegetation covering the geological interests of the quarries (Fig. 4). There has been conservation study (Act 55/2015, Szepesi et al. 2020) by the Aggtelek National Park for further protection (2015-19, e.g. Abaújszántó, Mád quarries) but no protection has been granted so far. From a touristic point of view, Bachinska et al. (2018) categorized the quarries into four groups, which can also be applied in our case. These are the very attractive, attractive, slightly unattractive and unattractive quarry landscapes. The *very attractive* category is applied to the Megyer Hill millstone quarry (Fig. 4f). The picturesque lake in the abandoned quarry was selected Hungary's most beautiful natural attraction in 2011 (Szepesi and Ésik 2015). The tourism infrastructure has been significantly upgraded in recent years (Ésik et al. 2019), including infrastructure improvements (parking lots, access routes, lookout tower) and the renewal of the information panels on the trail. The interpretation includes aspects of geology, quarrying and millstone history. The *attractive quarries* (Mikóháza, Vágáshuta Tuff, Fig. 4k) have good to moderate accessibility (e.g. nature trail), but the vertical differentiation is not so impressive, and the natural succession is somewhat faster. In the *slightly attractive* category, the quarry walls are hindered by natural succession, and the contrast with the surrounding areas is low, but these areas have a great potential for presentation and tourism (Abaújszántó, Fig. 4a). The last category contains *unattractive quarry* landscapes with poor preservation state and dense natural succession. They are almost invisible in the landscape (Erdőbénye, Spitzer quarry Fig. 4i), and their exploitation requires a lot of effort (Szerencs Tuff quarries, Fig. 4h). In this respect, the attractive and slightly attractive quarries could be the possible sites for tourist development. These are relatively accessible (tourist routes) and the removal of the cover (vegetation, debris) would expose the geological features and provide greater landscape contrast. The quarries have a high scientific value and can be used for geotourism and education (Kubalíková 2017; Kaźmierczak et al. 2024) through traditional on-site interpretation and innovative smartphone applications. It is important to establish a link between quarries and the material extracted (building stones, decorative stones, terrace walls).

The cellars and dry-built terrace walls have no effective legal protection (Müller 2013; Szepesi et al. 2018), although some sites are listed by UNESCO (e.g., Hercegkút cellars, Fig. 7a, b). These are geodiversity sites according to this international methodology (Brilha 2016). In Hungary, they are listed in the settlement based cadastre of 'unique landscape values' (Szepesi et al. 2018, 2020). These objects have limited or no scientific value. The cellars are used for wine and heritage tourism without geo-interpretation (Szepesi et al. 2017). The terraces are also characteristic elements of the cultural landscape, but their preservation is a crucial and complex task. Drawing attention to geodiversity objects (cellars, terraces) requires interpretation of geology, landscape, nature conservation, local history possibly linked to thematic nature trails (geology, viticulture based).

These aspects are essential for local communities to connect with their landscape heritage (Prosser 2019). Protecting local interests and values against global phenomena with negative impacts (environmental, social or other) is a key issue of social sustainability (Fodor 2017). In this regard enhancing geoheritage can effectively enhance the resilience of local communities and tourists (Vereb et al. 2020; Moradipour et al. 2024). Local authorities and municipal environmental programs can play an important role here.

Conclusion

There are several link between the described rhyolite tuffs and the UNESCO cultural landscape. The quarries have been used for centuries to extract natural stone that were used in the construction of many historic buildings, including churches, castle walls, and local buildings. These buildings hold historical significance in the UNESCO World Heritage Site. Religious sculptures, gravestones, and decorative stones are also important parts of the cultural heritage. The terraces and carved underground spaces are of great importance for viticulture and local wineries.

Although the georesources play a special role in the geodiversity and land use of the cultural site, they are undervalued by the local communities and the UNESCO World Heritage authorities. It is necessary to raise awareness and establish links between World Heritage authorities, geoscientific research, and geosconservation for further development. Initially, we focused on demonstrating the significance of the predominant volcanic tuff. However, the intermediate to silicic lavas (andesite, dacite, rhyolite) would require a similar approach. The compiled georesource inventory can then be incorporated into future development strategies.

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Data Availability Data are available from the corresponding author upon request.

Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

References

Abu-Jaber N, Bloxam EG, Degryse P, Heldal T (eds) (2008) QuarryScapes: ancient stone quarry landscapes in the the Eastern Mediterranean Eastern Mediterranean Geological Survey of Norway Special Publication 12:1-185

ace.hu A magyar szent korona országainak területén létező kőbányák Schafarzik Ferenc bányakatalógusának és gyűjteményének revíziója http://www.ace.hu/schaf/accessed: 04.28.

Aydan Ö, Ulusay R (2003) Geotechnical and geoenvironmental characteristics of man-made underground structures in Cappadocia, Turkey. Eng Geol 69:245–272. https://doi.org/10.1016/S0013-7952(02)00285-5

Baczyńska E, Lorenc MW, Kaźmierczak U (2018) The Landscape attractiveness of abandoned quarries. Geoheritage 10:271–285. https://doi.org/10.1007/s12371-017-0231-6

Bloxam EG (2011) Ancient quarries in mind: pathways to a more accessible significance ancient quarries in mind : pathways to a more accessible significance. World Archeol 37–41. https://doi.org/10.1080/00438243.2011.579481

Bóczán B, Franyó F, Frits J, Láng S, Moldvay L, Pantó G, Rónai A, Stefanovits P, Budapest (1966) M-34-XXXIV. Sátoraljaújhely. Magyarázó Magyarország 200 000-es földtani térképsorozatához. (Explanatory for the 200 000 geological map series of Hungary) 1–132. (in Hungarian)

Brilha J (2016) Inventory and quantitative Assessment of Geosites and Geodiversity Sites: a review. Geoheritage 8:119–134. https://doi.org/10.1007/s12371-014-0139-3

Cárdenes V, Cabrera-Guillén D, López-Piñeiro S, Ruiz de Argandoña VG, Rubio-Ordóñez A (2022) The historical significance of the Welded Tuffs from Arucas, Canary Islands. Geoheritage 14:46. https://doi.org/10.1007/s12371-022-00680-1

Careddu N, Grillo SM (2018) Sardinian basalt—an ancient georesource still en Vogue. Geoheritage 11:35–45. https://doi.org/10.1007/s12371-018-0285-0

Dávid L (2010) Quarrying and other minerals. In: Szabó J, Dávid L, Lóczy D (eds) Anthropogenic geomorphology. Springer, Dordrecht. https://doi.org/10.1007/978-90-481-3058-0_9

Davtyan (2013) The ethno-cultural features of man-made caves carved in the Neogene pyroclastic formation within the Armenian highland and neighboring areas Proceedings of the 16th International

Congress of Speleology, Czech Republic, Brno, July 21–28, 2013 Volume 2
Ésik Z (2021) Evaluation of volcanic geoheritage of the Tokaj mountains Phd thesis University of Debrecen 1-153. http://hdl.handle.net/2437/328112 (in Hungarian with english summary)
Ésik Z, Rózsa P, Szepesi J (2019) Geoheritage elements of millstone manufactory, Tokaj Mountains, Hungary. Eur Geologist J 48:8–42. https://doi.org/10.1007/s12371-018-0285-0
Fehér J (1997) Az erdőbényei kőfaragómesterség története (The history of the stonemasonry in Erdőbénye) Hermann Ottó Múzeum Évkönyve. 35–36:447–462 (in Hungarian)
Fodor L, Bányai O (2017) A települési önkorményzatok szerepe a környezeti jog és politika alakításában (The role of municipalities in shaping environmental law and policy) 1–157 (in Hungarian)
Frisnyák S (2012) A Tokaj-Hegyaljai borpincék földrajzi vázlata (Geographical sketch of the Tokaj-Hegyalja wine cellars) in Frisnyák S, Gál A (eds) Tokaj-hegyaljai borvidék hazánk első történeti tája:157–171 (In Hungarian)
Funiciello R, Heiken G, Levich R, Obenholzner J, Petrov V (2006) Construction in regions with tuff deposits in Heiken G (ed) Tuffs: their poperties, uses, hydrology, and resources Geol Soc Am Spec 408: 119–127 https://doi.org/10.1130/0-8137-2408-2.1
Gray M (2004) Geodiversity: valuing and conserving abiotic nature. John Wiley & Sons Ltd
Gyarmati P, Szepesi J (2007) Fejlődéstörténet, földtani felépítés, földtani értékek (History, geology, and geological values) In: Baráz Cs, Kiss G (eds) Zempléni Tájvédelmi Körzet The Zemplén Landscape Protection Area, Bükki Nemzeti Park, Eger, 15–44. (in Hungarian)
Häfner F (2022) Rhenish Tuffs in Ehling A, Häfner F, Siedel H (eds) Natural stone and world heritage: UNESCO sites in Germany Taylor & Francis Group, London, UK 133–138
Hála J (1993) A sárospataki francia malomkő (French millstones of Sárospatak) Hermann Ottó Múzeum Évkönyve 30–31 (1): 485–511 (in Hungarian)
Harangi S, Lenkey L (2007) Genesis of the Neogene to Quaternary Volcanism in the Carpatian Pannonian region : role of subduction, extension, and mantle plume. Geol Soc Am Spec 67–92. https://doi.org/10.1130/2007.2418(04)
Heldal T, Bloxam E (2008) Quarryscapes guide to ancient stone quarry landscapes: documentation, interpretation and statement of significance Geological Survey of Norway, Work Package 9, Deliverable No. 11: 1–85
Hencz M, Biró T, Németh K, Szakács A, Portnyagin M, Cseri Z, Pécskay Z, Szabó C, Müller S, Karátson D (2024) Lithostratigraphy of the ignimbrite-dominated Miocene Bükk Foreland Volcanic Area (Central Europe). J Volcanol Geotherm Res 445:107960. https://doi.org/10.1016/j.jvolgeores.2023.107960
Hoffer A (1937) A Szerencsi-sziget földtani viszonyai (The geology of Szerencs Inland) Közlemények a Debreceni Tisza István Tudományegyetem Ásvány- és Földtani Intézetéből. 8(2):1–304
https:/ /riolittufa.hu/ accessed: 2024.04.28
https://zeomineralproduct.hu accessed: 2024.06.29
Ilkey-Perlaki E (1966) Tokaj-hegységi riolittufák alkalmazási kőzetjellegei (Investigating the rock characteristics of rhyolite tuffs in the Tokaj Mts. Bull Hung Geol Soc 96:2:155–170 (in Hungarian)
Incze J (2017) Investigation of anthropogenic geomorphological processes in connection with the traditional land use in the area of Tokaj-Hegyalja Phd thesis University of Debrecen 1-147
Incze J, Novák TJ (2013) Geomorphological characteristic and significance of dry constructed terrace stone walls on abandoned vine-plantations in Tokaj Big-Hill (In: Novotny J, Lehotsky M, Raczkowska Z, Machova Z (eds.) Carpatho-Balkan-Dinaric Conference on Geomorphology Book of Abstracts, Geomorphologia Slovaca et Bohemica, 13: 33
Incze J, Novák TJ (2016) Identification of extent, topographic characteristics and land abandonment process of vineyard terraces in the Tokaj-Hegyalja wine region between 1784 and 2010. J Maps 12:507–513. https://doi.org/10.1080/17445647.2016.1195295
Izsó I (2011) A Miskolci Bányakapitányság kerületének bányaipara (Mining industry of Miskolc Mining Station district) 1-83 (in Hungarian)
Jugovics L (1954) A vulkáni tufák, mint építőkőzetek (Volcanic tuffs as building stones) Építőanyag 6 (11): 399–407 (in Hungarian)
Jugovics L (1958) Néhány építésre és falazótömb előállítására alkalmas vulkáni tufaterületünk kőzetanyagának sajátságai és bányászatunk (Characteristics of some volcanic tuffs suitable for construction and masonry block production and mining) Építőanyag 10 (12): 431–446 (in Hungarian)
Juhász P, Csanády GM (2016) Tuff in Eger and the surrounding area. Int J Eng Manage Sci (IJEMS) 1(2016 2):153–161. https://doi.org/10.21791/IJEMS.2016.2.20
Karancsi Z, Horváth G, Sütő L, Csüllög G (2015) Anthropogenic geomorphosites in the Karancs–Medves Region. In: Lóczy D ed. Landscapes and landforms of Hungary. World Geomorphological Landscapes. Springer, Cham. https://doi.org/10.1007/978-3-319-08997-3_17
Kaźmierczak U, Lorenc MW, Marek P, Rajczakowska D (2024) Examples of Good practices in the reclamation and use of abandoned quarries. Geoheritage 16:32. https://doi.org/10.1007/s12371-024-00934-0
Kubalíková L (2017) Mining landforms: an Integrated Approach for assessing the Geotourism and Geoeducational potential. Czech J Tour 6:131–154. https://doi.org/10.1515/cjot-2017-0007
Kubalíková L, Zapletalová D (2021) Geo – Cultural aspects of Building Stone extracted within Brno City (Czech Republic): a Bridge between. Nat Cult Herit Geoheritage 13:78. https://doi.org/10.1007/s12371-021-00585-5
Láczay-Szabó K (1864) A sárospataki kova malomkőgyártásnak legújabb, megbecsülhetetlen vívmányai (The latest achievements of Sárospatak's silicified millstone production). Pesti Napló 15(268):2 (in Hungarian)
Lukács R, Harangi S, Guillong M, Bachmann O, Fodor L, Buret Y, Dunkl I, Sliwinski J, von Quadt A, Peytcheva I, Zimmerer M (2018) Early to mid-miocene syn-extensional massive silicic volcanism in the Pannonian Basin (East-Central Europe): eruption chronology, correlation potential and geodynamic implications. Earth Sci Rev 179:1–19. https://doi.org/10.1016/j.earscirev.2018.02.005
Lukács R, Harangi S, Gál P, Szepesi J, Di Capua A, Norini G, Sulpizio R, Groppelli G, Fodor L (2022) Formal definition and description of lithostratigraphic units related to the Miocene silicic pyroclastic rocks outcropping in Northern Hungary: a revision. Geol Carp 73:137–158. https://doi.org/10.31577/GeolCarp.73.2.3
Lukács R, Guillong M, Szepesi J, Szymanowski D, Portnyagin M, Józsa S, Bachmann O, Petrelli M, Müller S, Schiller D, Fodor L, Chelle-Michou C, Harangi Sz (2024) Mid-miocene silicic explosive volcanism of the Tokaj Mts., eastern-central Europe: eruption chronology, geochemical fingerprints and petrogenesis. Gondwana Res 130:53–77. https://doi.org/10.1016/j.gr.2024.01.004
Mátyás E (1966a) A Mád környéki felsőszarmata vulkáni utóműködés (The Upper Sarmatian hydrothermal volcanic activity around Mád) Földtani Kutatás 9(2):17–27 (in Hungarian)
Mátyás E (1966b) A rátkai felsőszarmata édesvízi medence földtani és teleptani viszonyai (Geology and depositional charactheristics of the Upper Sarmatian limnic basin of Ratka. Bull Hung Geol Soc 96(1):27–42 (in Hungarian)
Mátyás E (1967) A szerencs-feketehegyi „fehér kálitufa a tokajhegységi ásványbányászati nyersanyagkutatások újabb földtani eredményei tükrében (the white potassic tuff of Szerencs-Feketehegy in the light of recent geological results of mineral exploration

in the Tokaj Mountains) Földtani Kutatás. 10(2):14–23 (in Hungarian)
Molnár F, Zelenka T, Mátyás E, Pécskay Z, Bajnóczi B, Kiss J, Horváth I (1999) Epithermal Mineralization of the Tokaj Mtns., Northeast Hungary: shallow levels of low-sulfidation. In: Molnár F, Lexa J, Hedenquist J (eds) Epithermal mineralization of the western carpathians. Society Of Economic Geologists, Guidebook series 109–155
Moradipour F, Moradi A, Yamani M Geoheritage Resilience Assessment for Geoconservation Planning in Lorestan Province. Iran Geoheritage 16, 7 https://doi.org/10.1007/s12371-023-00909-7
Morante-Carballo F, Gurumendi-Noriega M, Cumbe-Vásquez J, Bravo-Montero F, Carrión-Mero P (2022) Georesources as an alternative for Sustainable Development in COVID-19 Times—A Study Case in Ecuador. Sustain 14. https://doi.org/10.3390/su14137856
Müller I (2013) A Tokaj-Hegyaljai pincék múltja, értékei és sorsa (the past, values and fate of the Tokaj-Hegyalja cellars) 1–22. (in Hungarian)
Navarro R, Martínez-Martínez J, Fernández-Suárez JF, Areces-Álvarez J, Baltuille-Martín JM (2022) Comparative analysis of the current uneven situation of historical quarries associated with the UNESCO world heritage sites in Spain. Resour Policy 75:102471. https://doi.org/10.1016/j.resourpol.2021.102471
Novák TJ, Incze J (2014) Retaining walls of abandoned vineyard terraces on Tokaj Nagy Hill. 4D J Landsc Archit 35:20–35
Novák TJ, Incze J, Spohn M, Glina B, Giani L (2014) Soil and vegetation transformation in abandoned vineyards of the Tokaj Nagy-Hill. CATENA 123:88–89. https://doi.org/10.1016/j.catena.2014.07.017
Pécskay Z, Molnár F (2002) Relationships between Volcanism and hydrothermal activity in the Tokaj Mountains, Northeast Hungary. Geol Carp 53:303–314
Pécskay Z, Balogh K, Székyné FV, Gyarmati P (1987) A Tokaji-hegység miocén vulkánosságának K/Ar geokronológiája (K/Ar gechronology of the Miocene volcanism in the Tokaj Mts). Bull Hung Geol Soc 117:237–253
Petit C, Konold W, Höchtl F (2012) Historic terraced vineyards: impressive witnesses of vernacular architecture. Landsc Hist 33(1):16–22. https://doi.org/10.1080/01433768.2012.671029
Pötzl C, Siegesmund S, López R, Reiner D (2022) Key parameters of volcanic tuffs used as building stone: a statistical approach. Environ Earth Sci 81:1–29. https://doi.org/10.1007/s12665-021-10114-w
Prosser CD (2018) Geoconservation, Quarrying and Mining: opportunities and challenges Illustrated through Working in Partnership with the Mineral extraction industry in England. Geoheritage 10:259–270. https://doi.org/10.1007/s12371-016-0206-z
Prosser CD (2019) Communities, quarries and Geoheritage — Making the Connections Geoheritage 11:1277–1289. https://doi.org/10.1007/s12371-019-00355-4
Schafarzik F (1904) A magyar korona országai területén létező kőbányák részletes ismertetése (Detailed description of the existing quarries in the countries of the Hungarian Crown) Geological Institute of Hungary, Budapest 1-487 (in Hungarian)
Selmeczi I, Fodor L, Lukács R, Szepesi J, Sebe K, Prakfalvi P, Sztanó O (2023) Neogén: Alsó és középső Miocén (Neogene: Lower and Middle Miocene) in Babinszki E, Piros O, Csillag G, Fodor L, Gyalog L, Kercsmár Z, Less G, Lukács R, Sebe K, Selmeczi I, Szepesi J, Sztanó O (eds) Magyarország litosztratigráfiai egységeinek leírása II: Kainozoos képződmények (Description of the lithostratigraphic units of Hungary II: Cenozoic formations) Szabályozott Tevékenységek Felügyeleti Hatósága 52–116. (in Hungarian)
Siegesmund S, Pötzl C, López-Doncel R, Gross CJ, Dohrmann, Ufer K (2022) Overview and quality assessment of volcanic tuffs in the Mexican building heritage. Environ Earth Sci 81:426. https://doi.org/10.1144/GSL.SP.2007.271.01.24
Sütő L, Szepesi J, Kozics A, Utasi Z, Kajati Gy, Patkós C (2023) Geotúra-vezető képzés tapasztalatai a Bükk-vidék Geoparkban (Experiences of geotour guide training in the Bükk-Vidék Geopark) In: Szalai K, Michalkó G, Rátz T (eds): A turizmus válságjelenségei (Crisis phenomena in tourism) Székesfehérvár, Magyarország, Budapest, Magyarország: Kodolányi János Egyetem, Csillagászati és Földtudományi Kutatóközpont Földrajztudományi Intézet, Magyar Földrajzi Társaság 117–133
Szabó J (1866) Tokaj – Hegyalja és környékének földtani viszonyai. (Geology of Tokaj- Hegyalja and its environs)– Matematikai és Természet Tudományi Közlemények 4:226–303 (in Hungarian)
Szabó J, Török S (1867) Album of Tokay-Hegyalja, Vinicultural Society by Tokay-Hegyalja, Pest 1-244
Szakáll S (1997) Az erdőbényei kőbányák és egyéb kőanyagok. (Erdőbénye quarries and other quarry materials.) Hermann Ottó Múzeum Évkönyve 35–36:441–446
Szepesi J, Ésik Z (2015) Megyer Hill: Old Millstone Quarry. In: Lóczy D (ed) Landscapes and landforms of Hungary. World Geomorphological Landscapes. Springer, Cham. https://doi.org/10.1007/978-3-319-08997-3_26
Szepesi J, Harangi S, Ésik Z, Novák TJ, Lukács R (2017) Volcanic geoheritage and geotourism perspectives in Hungary: a case of an UNESCO World Heritage Site, Tokaj Wine Region Historic Cultural Landscape, Hungary. Geoheritage 9:329–349. https://doi.org/10.1007/s12371-016-0205-0
Szepesi J, Ésik Z, Soós I, Novák TJ, Sütő L, Rózsa P, Lukács R, Harangi S (2018) Földtani objektumok értékminősítése: módszertani értékelés a védelem, bemutatás, fenntarthatóság és a geoturisztikai fejlesztések tükrében. (Methodological review of geosite inventory and assessment work in the light of protection, sustainability and the development of geotourism) Bull Hung Geol Soc 148:143–160. https://doi.org/10.23928/foldt.kozl.2018.148.2.143(in Hungarian with English abstract)
Szepesi J, Ésik Zs, Soós I, Németh B, Sütő L, Novák J, Harangi S, Lukács R (2020) Identification of geoheritage elements in a Cultural Landscape: a case study from Tokaj Mts. Hung Geoheritage 12(4):89. https://doi.org/10.1007/s12371-020-00516-
Szepesi J, Vona A, Kovács IJ, Fintor K, Molnár K, Scarani A, Giordano G, Lukács R (2023) Lava – substrate interaction: constraints on flow emplacement and basal sintering, Lebuj rhyolitic flow, Tokaj Mountains, Carpathian-Pannonian region. J Volcanol Geotherm Res 441:1–18. https://doi.org/10.1016/j.jvolgeores.2023.107878
Török Á, Forgó LZ, Vogt T, Löbens S, Siegesmund S, Weiss T (2007) The influence of lithology and pore-size distribution on the durability of acid volcanic tuffs, Hungary. Geol Soc Spec Publ 271:251–260. https://doi.org/10.1144/gsl.sp.2007.271.01.24
Újhelyi J (1957a) A tufa építőipari felhasználása (The use of volcanic tuff in construction) Építőanyag 9 (6): 298–310 (in Hungarian)
Újhelyi J (1957b) A traszanyagok vizsgálatának módszereiről (Methods for the analysis of trass tuff substances) Építőanyag 9 (2): 80–90 (in Hungarian)
Varjú G (1966) Rátkai traszelőfordulás földtani viszonyai (Geological conditions of the Rátka trass deposit) Földtani Kutatás 9 (3):21–30 (in Hungarian)
Vereb V, van Wyk de Vries B, Hagos M, Karatson D (2020) Geoheritage and Resilience of Dallol and the Northern Danakil Depression in Ethiopia. 82. https://doi.org/10.1007/s12371-020-00499-8. Geoheritage 12,:
Viga G (1997) Az erdőbényei kőipar néprajzi vonatkozásai (Ethnographic aspects of the stone industry in Erdőbénye)Hermann Ottó Múzeum Évkönyve. 35–36:463–485 (in Hungarian)
Vujičić MD, Vasiljevic DE, Markovic SB, Hose TA, Lukic T, Hadzi O, Janicevic S (2011) Preliminary Geosite Assessment Model (GAM) and its application on Fruska Gora Mountain, potential

geotourism destination of Serbia. — Acta Geogr Slov, 51 (2):361–377. https://doi.org/10.3986/ags51303
Wessely I (1959) A trasz hidraulikus kiegészítő kötőanyag kémiai-fizikai vizsgálata, értékelése, gyártástechnológiája és felhasználása (Chemical-physical testing, evaluation, production technology and use of trass hydraulic supplementary binder. Építőanyag 11(11):397–412 (in Hungarian)
Zelenka T, Gyarmati P, Kiss J (2012) Paleovolcanic reconstruction in the Tokaj Mountains. Cent Eur Geol 55:49–83. https://doi.org/10.1556/CEuGeol.55.2012.1.4

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