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Review scientific paper

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Abstract

Natural stone has been used since the dawn of civilization as a construction material for buildings that are historical and cultural buildings and monuments. The Zagreb Cathedral is an example of such a historical and cultural building and data regarding the extraction of stone for its construction and reconstruction is scientifically underestimated. Based on a review of previously published literature and an investigation on the current state of the sites where stone for construction was previously quarried, this paper presents a systematic overview of challenges regarding stone material that will be faced in the restoration of the Cathedral after the 2020 earthquakes. The autochthonous stone varieties used for the Cathedral, namely lithothamnium limestone, litavac, calcareous sandstone, and vinicite were determined. The description of the locations where they were quarried was emphasized, and the suitability of these sites for re-quarrying the stone blocks during reconstruction after the 2020 earthquake was investigated. In addition, the Cathedral was renovated in the meantime with travertine imported from Italy, which, although it is not of domestic origin, represents an integral part of the Cathedral and whose characteristics must be taken into account in the planning of the current reconstruction of the Cathedral. To preserve the cultural memory of quarrying in the Zagreb area, emphasis is given to the importance of preserving and showing old visual representations of the quarries.

Keywords:
quarries; lithothamnium limestone; litavac; calcareous sandstone; vinicite; travertine

1. Introduction

Stone, as a natural material, has been used for centuries for building purposes, especially in the construction of monumental buildings. Although it is much more difficult to obtain and work with stone when compared to other building materials, it has been used for the construction of important buildings since ancient times due to its resistance and durability (**Bussagli, 2006**). Therefore, the architectural and monumental heritage of cultures and civilizations that were endowed by natural stone is better preserved (**Šimunović, 2002**). Another important factor influencing the durability of buildings is the construction technique, which has changed over the centuries, depending on the way materials were used and the conditions of the area in which they were built. The construction technique refers primarily to the way in which the stone blocks are joined together. With the development of various techniques of surface finishing, the value of stone was increasingly influenced by its decorative properties as a special architectural element. However, a particular building cannot be designed without considering the problem of the area, whether in terms of geographical location, climate, and the available materials, or in terms of the organization of the internal and external surfaces of the construction itself (**Bussagli, 2006**).

Croatia has a long history of using natural stone in construction, particularly in the Adriatic region (**Briševac et al., 2021a)**. The continental part, on the other hand, has some magnificent stone buildings, such as the Cathedral of the Assumption of the Blessed Virgin Mary and Saint Stephen and Saint Ladislaus or the Cathedral of Zagreb. The Cathedral is an important symbol of the city of Zagreb and its wider region. For the construction of the Cathedral, the stone was mined in the immediate vicinity and later in the wider surroundings of Zagreb (**Crnković, 1996**). The beginnings of the construction of the Cathedral are related to the foundation of the Zagreb diocese, but the lack of historical sources and possible forgeries have led to the fact that these events remain largely unexplained (**Szabo 1929; Mohorovičić, 1998**; **Bedenko, 2014; Jezidžić, 2022**). As a result, little is

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Figure 1: The Cathedral from the period before the 1880 great earthquake **(Digitalna.NSK.HR, 2019)**

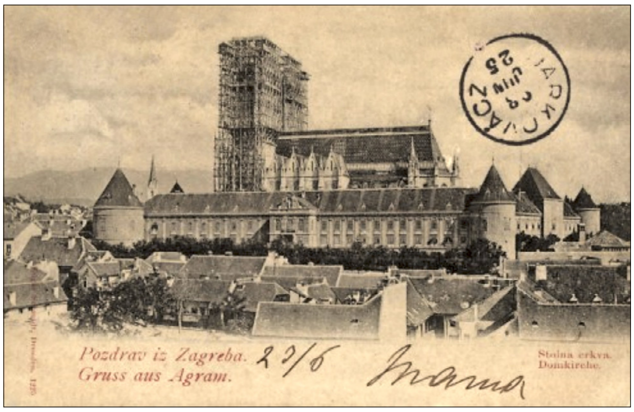

Figure 2: The Cathedral from the period of Bolle's extension in 1898 **(Digitalna.NSK.HR, 2019)**

known about the construction of the Cathedral in the 12th and in early 13th century, as well as about the procurement of stones for construction, additions, and renovations. However, there is an agreement that the construction began in 1102 and was completed in 1217 in the transitional Romanic style (**Crnković, 1996**).

Over the centuries, the original Cathedral was hit by a series of disasters (enemy raids and fires) that led to its damage and was renovated in the Gothic and Renaissance architectural styles. The appearance of the Cathedral can be guessed from several architectural plans and preserved fragments of the Cathedral (**Szabo 1929; Klarić, 2002; Plukavec, 2006; Bedenko, 2014**). More complete graphic representations of the Cathedral from this period are related to techniques of fine art, so they include a dose of painterly experience, as can be noted from the first drawings. The appearance of the Cathedral in the 19th century was immortalized in photographs (see **Figure 1**), which were used as postcards. A turning point in the history of the Cathedral was the great earthquake that struck Zagreb in 1880 after which the Cathedral gained its present appearance.

Since the strong earthquake in 1880, the Cathedral has been rebuilt several times. During its first renovation (see **Figure 2**), which was carried out by the plans of the Austrian architect Friedrich von Schmidt (**Nadilo, 2005**), and under the direction of the Croatian architect of German origin Hermann Bollé, autochthonous stone was used, including lithothamnium limestone, litavac and carbonate sandstone. During the second renovation in 1930/1931, which lasted until World War II, a total of 747 pieces of stone carvings were replaced on the southern bell tower (**Foretić, 2019**). In the renovation during 1967/1968 the top of the northern tower was restored, in which the stone variety from Bizek was used. Renovations which lasted until the earthquakes in 2020 began in 1987. During this most recent renovation, lithothamnium limestone and litavac from Bizek were replaced with travertine, chosen by the Committee for the Restoration of the Cathedral upon the recommendation of Professor Branko Crnković (**Foretić, 2019**).

There is no complete literature on the stone material used for the Zagreb Cathedral. The relatively numerous information was written in a style rather intended for a wide audience, while scientific facts were mentioned only sparsely. The aim of this paper is to provide a scientifically based summary of relevant literature and carried research on the types of natural stone found on the Zagreb Cathedral's facade. Furthermore, the current state of the former quarries from which natural stone was obtained was investigated in order to review mining activities in the Zagreb area. The collected data allowed us to give conclusions about the feasibility of stone extraction for the purpose of restoration and renewal of parts of the Cathedral.

2. Research methodology

The methodology was divided into a few steps, consisting of reviewing the available literature, extracting essential data, and summarizing gained data from a mining and geological perspective.

The first step included collecting and review of data available from the archives of the Zagreb Cathedral and the library of the University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, as well as a search of databases archived in various journals. The research focused on the previous petrographic and physical-mechanical investigations of the stone used in the construction, renovation, and restoration of the Zagreb Cathedral. Special emphasis was placed on the presentation of photographic material, which is poorly available and commonly protected by copyright. For this reason, the research is limited to the photographic material from the public domain that was found in the archives and could be used with a reference. Most of this material is part of the digital collection of the National and University Library in Zagreb (**Digitalna.NSK.HR, 2019**).

The second step involved a survey of the Cathedral's façade through macroscopic identification and photographing of the different varieties of stone. A survey was carried out on the façade parts that were accessible from the ground or from the scaffolding that had been installed for the renovation.

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The third step was field work with an emphasis on prospecting the old quarry locations. Most of the information on stone exploitation was found in papers by **Crnković (1992a and 1996)** and **Malinar (2004)**. However, since exploitation ceased a long time ago, it was necessary to undertake many excursions and works to find these sites. The objective was to find sites and determine what these sites are used for today. Four former quarries were visited: Markuševec, Bizek, Vrapče potok and Vinica. An additional plan was to locate the former Bregovi Quarry near Samobor, but despite intensive search and field work, the exact location of the quarry could not be determined. Sampling and laboratory testing and determining of the properties is planned in the next activity connected with the stone material of the Cathedral. More extensive field research, as a next step, that would lead to more accurate results, such as exploratory drilling or excavation, could not be carried out because it is not possible to obtain permission for such activities in natural areas.

The proposed discussion brings about conclusions regarding the possibility of quarrying or acquiring natural stone for the needed reconstructions of the Zagreb Cathedral.

3. Review of the previous research of stone varieties and the current state of the former quarries

This research focuses on a review of previous research connected to natural stone varieties used in the construction, renovation, and restoration of the Zagreb Cathedral, but also on the current state of the former quarries.

3.1. Stone varieties used during the construction, renovation, and restoration

In one of the first scientific papers concerning the Zagreb Cathedral, "Contributions to the Building History of the Zagreb Cathedral", **Szabo (1929)** gave a review on the Cathedral construction and restoration during the time of Hermann Bollé. **Marić (1937)** studied damage to the stone installed on the façade of the Cathedral, by observing a dark crust on the surface of the stone. Marić determined that the crust was composed of calcite with grains of ash and light calcite powder with an abundance of gypsum and related its formation to sulfate acid rain. The author discussed that the main cause of stone deterioration should be sought in the influence of the atmospheric conditions in the Zagreb area. Since gypsum is not present in fresh lithothamnium limestone, the mechanical and technical properties of fresh stone from the quarry meet the required norms for use as a stone material.

In a study made by **Ivandija (1981)**, the author mentions trenches that were made in the floor of the Cathedral in the south and main nave for installation of the heating system. During the excavations of the old walls, different stone varieties and various types of stone processing were discovered. Intensive work on the stone used for and during the restoration of the Cathedral was done by **Crnković (1992b)**. He discussed the restoration of many cultural and sacred heritage buildings destroyed during any war or destruction and proposed a list of different varieties of stone from Croatia (Vinkuran, Valtura, Jadran zeleni, Vinicite, Kornerija) that could be used in the restoration of the cultural heritage in Zagreb. Besides Croatian varieties, Crnković mentions Roman travertine as a possible replacement stone.

In "Restoration works on the Zagreb Cathedral" **Crnković (1992a)** presented parts of "Herman Bollé's program on church renovation" in which Bollé confirms the autochthonousness of the used stone varieties. The litavac and lithothamnium limestones were quarried in Vrapče potok, Podsused (Bizek) and Bregovi near Samobor. Stone from Vinica, today known as "vinicite" (of which many statues were sculpted), and calcareous sandstone from Markuševec were also used. According to its properties and quality, Bizek stone is distinguished. Bollé stated that the stone with which the church was originally built was shaped, and most likely excavated and carved *in situ*, but also imported from the surrounding area. He mentioned that 61.93 m^3 were brought from Bregovi, but that material was also delivered from Vinica (83.74 m^3), and that vinicite was more affordable, and suitable for processing. Since the price depends on the transport, the largest part, 126,078 m^3 of stone, was brought from Podsused. In 1882, Bollé visited the old quarries in Vrapče potok to find suitable building stone for the reconstruction after the earthquake, with small transportation costs. Stone from Vrapče potok was used to restore the entire sanctuary, the stair towers, all the spandrel arches, all the vault ribs and most of the other repairs. The lateral southern finial was built with stones from Samobor, while the sanctuary finials were built with stones from Vinica and Podsused, since they can carry a large load. **Crnković (1992a)** further stated that in 1992 there were no more signs of stone extraction in quarries Bregovi, Markuševec and Vrapče potok, and that they were most likely completely exhausted. He mentions outcrops of the lithothamnium limestone in Bizek, and large deposits of material and about twenty old quarries in Vinica that have potential for further extraction.

Furthermore, **Pollak (1993)** and **Crnković et al. (1994)** noted that the stone of the Cathedral was damaged due to atmospheric conditions and temperature changes. The temperature changes, causing the heating and freezing of water in the pore space, have had a minor effect, while sulfates from acid rain had a major influence on deterioration. Because of the reaction of the sulfates from the rain with the limestone, gypsum was formed on the surface or near the surface of the stone. Shedding, peeling, thinning, and tearing of parts of the stone decorative elements followed. The corrosive damage of the stone and stone elements can occur due to abrasion and deposition and is highly dependent on whether the stone elements are protected from precipitation, or whether the stone is directly influenced by rain, especially on the gallery of the Cathedral. The "exposed" parts are washed away by the rain, while black crusts form on the "shadow" parts that are not exposed to rain. Parts of the stone elements washed by rain are usually sandy, flaky, and ruptured, and do not contain a significant amount of gypsum. According to microscopic, X-ray, thermal and chemical analysis, the scabs contain gypsum, calcite, and soot. The gypsum that develops on the exposed stone elements dissolves and washes away, and the stone elements become thinner, which was clearly visible on the balusters of the gallery. Three types of sulfate black crusts/scabs have developed on the surfaces of parts of the stone elements that are in the "shade". The lithothamnium limestone from Bizek, which had favorable physical and mechanical properties, has black crusts adhering to the stone surface. Limestone from the quarry in Vrapče potok has poorer properties, and black crusts peel off the surface of the stone, causing the crust to fall off the surface together with the stone, which results in losing the original shape of the stone.

During the restoration of the stone of the Zagreb Cathedral, **Crnković (1994)** emphasized the importance of cleaning, strengthening and surface protection of damaged embedded stone (see **Figure 3**). The renovation was planned in a few steps. The first step was to determine the cause, mechanism, type, intensity, and depth of damage. The second step was cleaning, which can include mechanical, chemical, and physical removal of deposited impurities from the surface of the stone. Then as a third step follows the strengthening or consolidation of elements with reduced strength and impregnation of the stone with hardeners. The last step is surface protection with special coatings that prevent water absorption.

As part of research work on the tympanum (**Crnković, 1995, 1996**), 25 boreholes were drilled to determine physical and mechanical properties, including apparent density (mean value 1.97 g/cm^3), water absorption (mean value 5 mas. %), porosity (mean value 27.3 %) and uniaxial compressive strength (mean value 25 MPa). It was also determined that the depths of contamination with sulphate range from 3 to 18 cm, depending on the quality of the stone, exposure to the atmospheric conditions and the thinning of the elements during processing, with the strongest contamination of the stone in the first 0.5 cm of depth.

As a result of all the mentioned reasons that led to the damage and disintegration of stone over time, there was a need to find suitable stone varieties as a replacement material for stone elements made of lithothamnium limestone and carbonate sandstone. Due to its properties, travertine turned out to be a material for the renovation of the Cathedral (**Crković and Poggi, 1995**). The restoration began with the complete replacement of the stone on the first gallery (first and second consoles, cornices, balustrades, and pinnacles), which was completed in 1994, and followed by the replacement of the stone and the restoration of the tympanum. There are two reasons for choosing travertine, and the main one is visual similarity with the lithothamnium limestone/litavac concerning colour – both are yellowish varieties and have significant porosity. The second reason is that travertine has better physical and mechanical properties compared to the previously used varieties. Travertine is resistant to freezing, has a low water absorption and is strong and durable in an urban atmosphere. As a building material, travertine is important on a global scale and has been used since Roman times when the famous Roman architect Vitruvius (active from 46 to 30 BC) recognized it as a stone that "resists the test of time". In addition, travertine has proven itself as a durable material in other buildings in Zagreb (**Crnković and Poggi, 1995; Crnković, 1999**). Nevertheless, each variety of stone, including travertine, can have layers that differ in quality from the rest of the rock, and it should be noted that regardless of all its other characteristics, travertine-type stone is not entirely suitable for stonework, especially for the carving of decorative elements (**Foretić, 2019**). At the same time, bihacite from Bosnia and Hercegovina can be used as a substitute for soft vinicite (**Crnković, 1996**).

Figure 3: The restored portal of the Cathedral

One of the important interventions during the restoration of the Cathedral was the restoration of the damaged sculptures from the naves to the sculpture of the "Virgin with the child and angels" that was on the tympanum of the west façade (**Čorak, 1996**). The sculpture, installed in 1890, was done by Karl Morak according to the plans of the Viennese sculptor Josef Beyer. The sculpture was completely damaged over time and had to be restored. This was done in soft limestone "pietra di Vicenza" (**Crnković, 1996**) with the great skill of Vladimir Herljević, who made a faithful reconstruction according to a photograph of Beyer's sculpture (**Čorak, 1996**).

In the renovation of the first gallery, which took place from 1990 to 1994, Roman travertine was used as the most suitable replacement stone for many damaged gilts, flowers, and finials. As a binding agent, extended mortar, in a ratio of 1:2:5 (cement:lime:sand) was used, and the joints were filled with white cement mortar with swelling additives. All elements were additionally anchored with stainless steel anchors (**Rukavina, 1997**). From 1995 to 1997, the gable (tympanum) building was renovated, and the entire wall was demolished and a new one built. The problem was harmonizing the renovation of tympanum with the regulations on securing the building against a possible earthquake in the IX. earthquake zone of the city of Zagreb (**Herak et al., 2018**). A compromise was the construction of the foundation beams of the gable building walls. Beams were anchored in the bell towers and additionally coupled with a reinforced concrete floor. In 1997, preparatory work began for the restoration of the northern bell tower, as the most damaged part of the Cathedral. The work began on the western facade under the first gallery, and the plan was to replace extremely damaged elements, wash, treat, and protect the stone, and supplement the profiling with the so-called "bizek-mortar", which, resembles the original stone from Bizek after drying (**Rukavina, 1997**).

During the research about condition of the stone on the façade of the Cathedral (**Malinar, 2004**) 51 stone blocks of different lithology were analyzed. Each block was graded with a degree of damage from 0 to 3 (healthy, slightly eroded or corroded surface, thin scales, and severe damage). Boreholes, 13 cm wide and 20 cm deep, were made in 51 positions. Powder samples were taken for quantitative analysis of chlorides, sulfates, and nitrates at six different depths. Sulfates were determined in some blocks in a small amount up to a depth of 20 cm, and chlorides and nitrates only on the surface. In addition, the water absorption was determined, and two experiments were carried out, one to conserve stone with a barium hydroxide coating and the other to clean the stone with water under a pressure of 110 bar. It was concluded that in all of the analyzed samples, sulfates were found in harmful amounts on the surface and immediately below the surface, with fine-grained sandstone and lithothamnium limestones being the most polluted with sulfates on the surface. Sulfates were not found in the depth of healthy and slightly damaged varieties. Nitrates and chlorides were found in almost all of the stone blocks, but the values were below harmful limits. During the water absorption test, it was determined that litavac stone has a lower water absorption value than other types of stone. In addition, values of water absorption were correlated with sulphide concentrations at certain depths. A barium hydroxide coating reduced the amount of sulphate on the surface of stone blocks by half, though the sulphate concentration was still above the harmful limits. In addition, after the testing, the values of the water absorption of blocks decreased. It is also noted that surfaces blackened with soot or cemented with calcite and gypsum could not be well cleaned with water under pressure. Only surfaces up to 80 cm high from the ground were cleaned of algae, moss, and loose dirt. At the same time, an attempt of restoration with "bizek-mortar" (repair mortar) gave good results with a satisfactory appearance and good adhesion.

As the renovation continued, at the time of the 120th anniversary of the earthquake in Zagreb, **Aničić (2000)** updated the issue of the state of the Cathedral and listed its weak points in the event of a new earthquake. According to the author, the load-bearing system of the Cathedral is susceptible to damage in an earthquake, and the aging of materials, corrosion of metal parts, the influence of atmospheric conditions and the influence of built-in slender and tall towers, as well as the age of the walls, which have been exposed to multiple mechanical and physical effects, must be considered. **Aničić (2000)** further states that it would be extremely important to determine the compressive and tensile strength of the walls of the most important structural elements, which would serve as basic data for calculating seismic effects on buildings. Seismic risk in Croatia has continuously been investigated (**Atalić et al., 2019**), particularly following the earthquakes in 2020 (**Dasović et al., 2020; Atalić et al., 2021a; Atalić et al., 2021b; Sigmund et al., 2022**).

3.2. Geological and petrographic characteristics of the main stone varieties

According to literature, several different stone varieties were used during the construction and subsequent renovations of the Cathedral. The three main varieties of stone used in the construction are autochthonous (local) varieties extracted from three main quarries which are located in the southwestern part of the Medvednica Mountain (**Crnković, 1992b; 1996**). These are: lithothamnium limestone, quarried in the Vrapče potok Quarry in Gornje Vrapče; litavac, quarried in the Bizek Quarry in Podsused, and calcareous sandstone, quarried in the St. Šimun Quarry in Markuševec. Lithothamnium limestone from the quarry Bregovi near Samobor was also used. In addition to the three main varieties, vinicite stone from Vinica near Varaždin was also used (**Crnković, 1992a; 1996**). All three main varieties, including lithothamnium limestone, litavac and calcareous sandstone, were deposited in the area of the Paratethys Sea that covered a large part of central and southern Europe during the Miocene (Badenian). These stone varieties can be found in various localities in northern Croatia, most often in areas surrounding mountains, which used to be "islands" in the Paratethys Sea (**Crnković, 1996; Vrsaljko et al., 2006; Pavelić and Kovačić, 2018; Fio Firi and Maričić, 2020**). Stone material of the Zagreb Cathedral, according to **Crnković (1996)**, represents a true petrographic collection of Badenian carbonate sedimentary rocks and deposits of the southwestern part of the Medvednica Mountain.

Lithothamnium limestone and litavac (see **Figure 4a**) are varieties of limestone rich in coralline algae (like

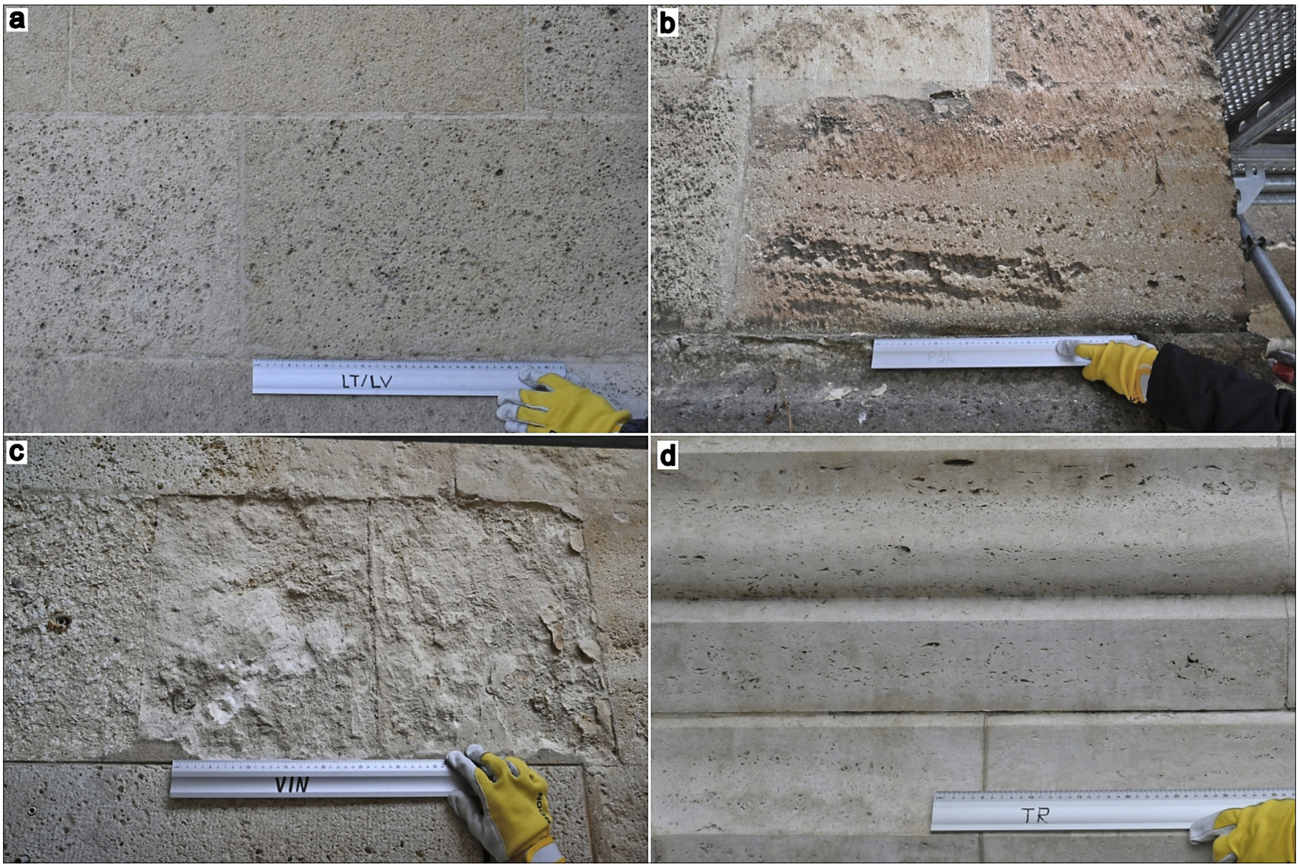

Figure 4: Different varieties of stone used on the façade of the Zagreb Cathedral, **a** – lithothamnium limestone and litavac, **b** – calcareous sandstone, **c** – vinicite, **d** – travertine

Lithothamnion). The stone contains numerous other shallow-marine organisms, i.e. fragments of fossilized bryozoans, bivalves, echinoderms, and foraminifera tests (**Šikić, 1995; Basso et al., 2008; Fio Firi and Maričić, 2020**). Apart from fossil remains, the stone contains fragments of dolomite and siliciclastic detritus, composed of quartz grains and rock fragments (quartzite, chert, etc.) (**Šikić, 1995**). According to the micropetrographic characteristics, the limestones were determined as bioclastic limestones of the wackestone/packstone type with distinct cavities (**Fio Firi and Maričić, 2020**). Lithothamnium limestone and litavac are sometimes considered equivalent, and the litavac was named by shortening the name for lithothamnium limestone (**Basso et al., 2008**). **Fio Firi and Maričić (2020)** consider lithothamnium limestone and litavac as two varieties of limestone, since they differ in terms of lithology (composition and petrological characteristics), origin, use and durability to weathering. Litavac, like lithothamnium limestone, consists of coralline algae and other fossils, but, unlike lithothamnium limestone, includes numerous other clasts and is extremely porous. These pores or cavities used to be fragments of older rocks and minerals, mainly Triassic dolomites, that have dissolved in the meantime, due to different solutions that circulated through already hardened limestone rock (**Zebec, 1975**). Lithothamnium limestone is also porous, but the pores are homogeneously distributed throughout the volume (**Fio Firi and Maričić, 2020**) and cavities are smaller. According to the micropetrographic characteristics, the litavac stone from Bizek was determined as a porous bioclastic limestone, mostly of grainstone type (**Šango, 2019; Fio Firi and Maričić, 2020**).

Each of the main varieties of stone has its own subvarieties. Apart from those mentioned, some authors distinguish the transitional form of lithothamnium limestone and litavac (cavities in size between those of lithothamnium and litavac varieties), or siltose lithothamnium limestone, i.e. marly limestone (**Crnković, 1996**; **Malinar, 2004**).

Calcareous sandstone is the third variety (**Crnković, 1996; Fio Firi and Maričić, 2020**), which is the least durable. Sandstones are mostly dark yellow to reddish but can also be gray in color. Varieties of sandstone differ according to grain size (fine to coarse grained; **Malinar, 2004**) and mineralogy (carbonate sandstones with siliciclastic components, such as quartz grains and rock fragments). Sandstones are often laminated/layered and varieties of red sandstone where laminae/layers of fine-grained and coarse-grained sandstone alternate can often be observed (see **Figure 4b**).

Vinicite (**Figure 4c**), as the fourth variety mentioned in the literature (**Crnković, 1992a, 1996; Marković, 2002**) is petrographically determined as a very soft and porous limestone, which is easy to process. Stone was frequently used in the construction of many baroque buildings in the city of Varaždin. Since vinicite is not durable to external influences and weather conditions, during the first renovation it was proposed to use bihacite from Bihać (Bosnia and Hercegovina) for statues, which is similar but more durable (**Crnković, 1996**).

During further reconstructions, an imported variety of travertine called Travertino Romano San Pietro classico (see **Figure 4d**) from the deposits in the Acque Albule Basin from Tivoli near Rome was also used (**Crnković and Poggi, 1995; Crnković, 1996; Dunda et al., 2005; Fio Firi and Maričić, 2020**). This porous stone is terrestrial calcitic limestone with layered/laminated pores. The laminae with pores are interchanging with dense compact laminae that are well-cemented and compacted. The visual difference between travertine and lithothamnium limestone and litavac can be seen through its color, because travertine is whitish, while the lithothamnium limestone and litavac varieties are gray to yellowish in color. Also, lithothamnium limestone has homogeneously distributed pores on the surface, while the travertine is "layered", i.e. travertine shows anisotropy in its structural characteristics (**Fio Firi and Maričić, 2020**). Travertine has small thermal expansion during insolation, is resistant to atmospheric influences and frost and has shown stability and durability to atmospheric conditions in urban environments (**Crnković and Poggi, 1995**).

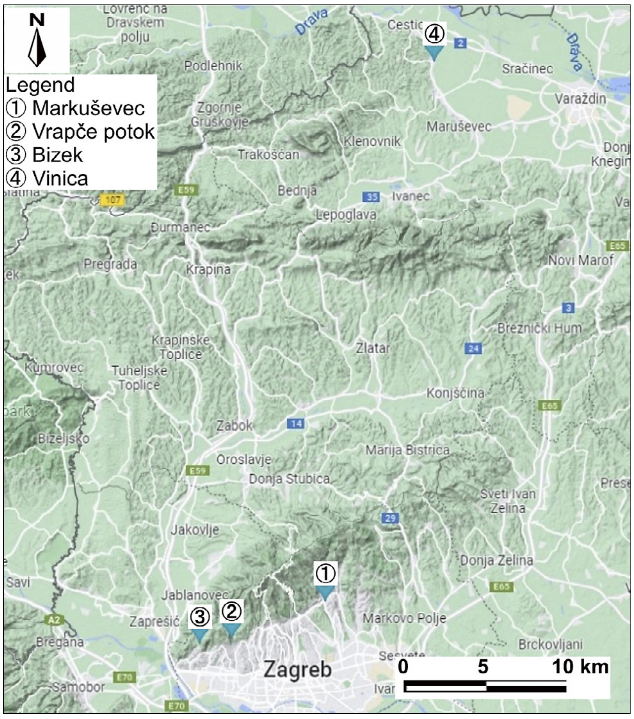

Figure 5: Locations of former quarries connected with the construction and renovation of the Zagreb Cathedral, on the map base at **URL1**

3.3. The current situation around the former quarries

A literature review revealed four domestic quarries which were important for the construction of the Cathedral (see **Figure 5**): Markuševec, Vrapče potok, Bizek and Vinica. These sites were investigated in search of traces of a former quarry.

Since the oldest parts of the Cathedral were built out of stone from the closest quarries, the order of prospecting was identical, and the places closest to the Cathedral were visited first. Each site is marked on the graphic background used by the Ministry of Economy and Sustainable Development in its e-service "United Information System of Mineral Raw Materials" (**URL2, 2022**); shown in **Figures 6a, 7a, 8a** and **9a**.

The first location is an abandoned quarry west of Markuševec (see **Figure 6a**). The remains of the quarry extend over a width of 204 m and a 90 m high slope (see **Figure 6b**). On the base plateau there are several irregularly shaped blocks (see **Figure 6c**). The complex structural set of discontinuities indicates that this site is not suitable for the further extraction of natural building stone. The location, but even more the surroundings of the Markuševec Quarry is significant for the early history of the Cathedral **(Crnković 1992a; 1996**). However, the calcareous sandstone variety was quarried not only in this quarry, but probably also in the surrounding territory of the Archdiocese of Zagreb, i.e. wherever the suitable stone for construction was found. From the 19th century on, the stone from this quarry was not used for the reconstruction of the Cathedral, but (especially in the socialist period) for the extraction of crushed stone. The planned extraction stopped in 1978, and significant rehabilitation of the Markuševec Quarry was never carried out. As this area is part of the Medvednica Nature Park, further mining is not planned, but the area of the former quarry should be used for forest purposes and therefore rehabilitated and reforested (**URL3, 2019**).

The second site is the former Vrapče potok Quarry (see **Figure 7a**). It can be reached by hiking trail No. 4 of the Medvednica Nature Park (**URL4, 2023**), which passes through the former quarry. Although the area is covered with vegetation, the remains of the former quarry slopes are still visible (see **Figure 8b and 8c**). It covers an approximately 370 meter wide and 460 meter long area, with a height difference of 40 meters. The lithothamnium limestone can clearly be recognized (see **Figure 7d**). Nowadays, the shooting range Vrapčanski potok is located next to the former quarry (see **Figure 7a**). It is one of the best European shooting ranges with civil and military purposes (**URL5, 2017**). It is a special and protected building, and according to the spatial plan of the Medvednica Nature Park (**URL6, 2014**), stone quarrying is not allowed near it, making this site unsuitable for the restoration of stone quarrying for any purpose.

The third location is the former quarry of Bizek, located north of the settlement of Bizek (see **Figure 8a**). Although the area is mostly overgrown by forest vegeta-

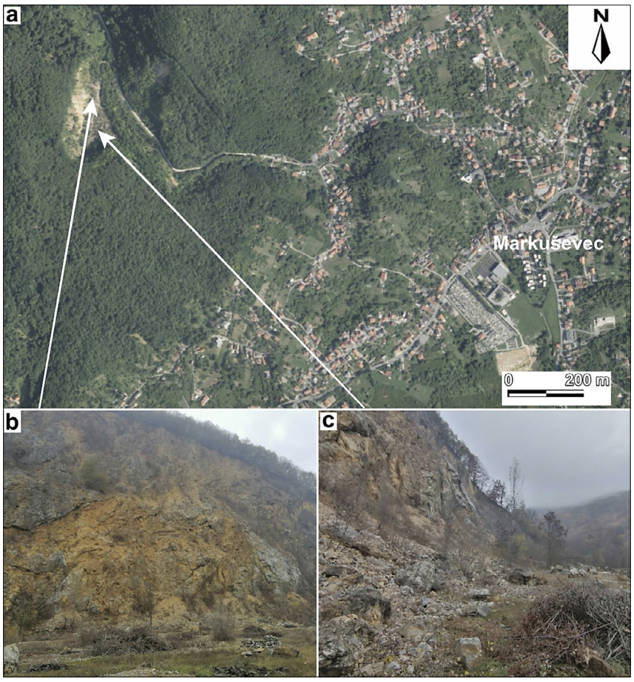

Figure 6: Former Markuševec Quarry, **a** – location on the map base at **URL2**, **b** – slope and rock mass appearance, **c** – the remains of former exploitation

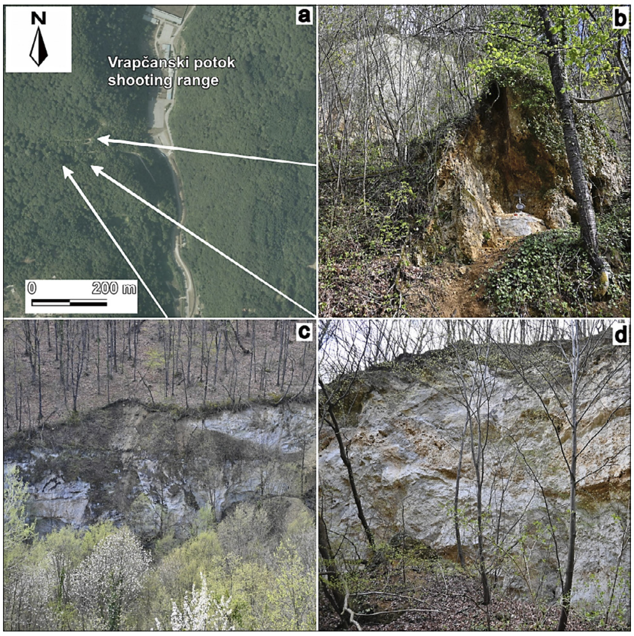

Figure 7: Former Vrapče potok Quarry **a** – location on the map base at **URL2**, **b** – northern slope, **c** – southern slope, **d** – rock mass with the appearance of lithothamnium limestone

tion, traces of exploitation are found in the area 270 m long and 220 m wide. The vertical slopes have a height of 3 to 7 meters (see **Figure 8b**). It is obvious that regularly shaped blocks were extracted from the rock mass (see **Figure 8c**). During the socialist period, the quarry was no longer used for natural stone but for raw materials for the cement industry. However, this decision was

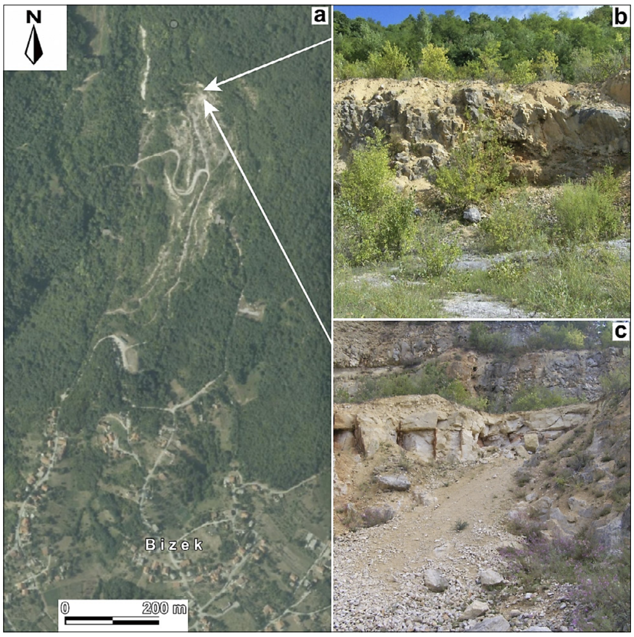

Figure 8: Former Bizek Quarry. **a** – location on the map base at **URL2**, **b** – slope and rock mass appearance, **c** – the remains of former exploitation

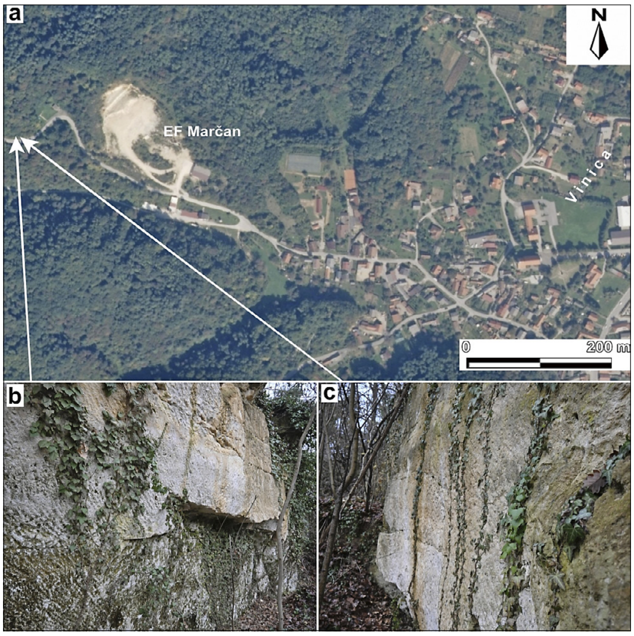

Figure 9: Former Vinica Quarry, **a** – location on the map base at **URL2**, **b** – traces of quarrying, **c** – slope and rock mass appearance

bad, and the result was the impossibility of economically viable production. Although this location has long been mentioned as the only one for quarrying stone for the reconstruction of the Zagreb Cathedral, the spatial plan of the Medvednica Nature Park (**URL6, 2014**) does not allow this possibility.

The fourth location is a former quarry west of Vinica, close to the town of Varaždin, near the current Exploitation field (EF) called Marčan (**Figure 9a**). Former exploitation took place mainly on the open land south of the EF Marčan, but this area has been overgrown with forest vegetation and there are no visible traces of exploitation. However, west of EF Marčan and west of the water reservoir, there are still traces of quarrying of building stones, with visible marks of mining tools and abandoned blocks of regular shapes (see **Figure 9b, 9c**). There is no more exploitation of Vinicite as a natural stone for construction. Zagorje Kamen d.o.o. company has a legal concession on the Marčan exploitation field, but for carbonate mineral raw materials for industrial processing and to produce calcite flour for cattle feed (cattle chalk), calcite for agriculture and calcite fillers (**URL7, 2022**).

The fifth location of the former quarry Bregovi, which should be located between Samobor and Bregana, could not be located. Although we determined the outcrops of lithothamnium limestones we can assume that it was only a minor exploitation area.

4. Discussion

A systematic review of published scientific and professional work, as well as the synthesis of relevant facts and their analysis, are an important element of decision making in all engineering activities and works, especially concerning the restoration of historic buildings. Although the renovation of buildings belongs to the field of civil engineering, this task cannot be well accomplished without knowing and determining the properties of all the materials used, especially stone materials. This paper is therefore describing challenges associated with types of stone materials used during the construction and numerous renovations of the Zagreb Cathedral.

Despite our efforts to study in detail the quarrying of stones for the restoration of the Cathedral, it should be noted that during several parts of history, especially the socialist period, scientific sources were not useful for relevant data. Since religion could not be openly practiced during those times, there was no effort to restore religious buildings. Moreover, the use of stone from the Zagreb region has been repurposed to produce concrete and cement, and not natural stone for construction. For these reasons the Cathedral was not renovated, and scientific papers regarding the renovation of the Cathedral were published in ecclesiastical journals without sufficient scientific orientation. This situation changed to some extent after the Croatian Homeland War and the transition to a democratic society.

In general, the stone blocks used as building material for the Zagreb Cathedral can be classified as soft natural stone. Due to its softness, ease of processing, simple shaping and easy installation, it has been used in construction and sculptures for centuries. It is characterized by high porosity, low durability to atmospheric conditions and low values of compressive strength (**Crnković, 1996**). Since Roman times, soft stone was extracted by creating narrow channels around the future block and then attempting to loosen it from the deposit with metal chisels, wedges, levers, and picks. The block obtained in this way was transported to the construction site, where it was shaped and installed. This technique was used until the advent of cutting machines in the industrial historical period (**Dunda, 2005**; **Jezidžić, 2022**).

Since there are no graphic representations or records of a specific mining method in the wider Zagreb area, it can be assumed that the method of stone extraction did not differ from the technology used in Europe from the Middle Ages to the Industrial Age for the extraction of stones of soft types (**Jezidžić, 2022**).

The Cathedral is built out of several different varieties of stone material (**Marić, 1937, Crnković, 1992a, 1994, 1995; Crnković et al., 1994; Crnković and Poggi, 1995; Pollak, 1993; Dunda et al., 2005; Fio Firi and Maričić, 2020**). But various professionals working in construction, restoration, or preservation of monuments, do not pay enough attention to the differences that these stone varieties have. In most cases, only lithothamnium limestone is mentioned, without more precise stone categorization, and determination of the four different carbonate varieties at the Cathedral façade, including do-

Table 1 Basic physical and mechanical properties of lithothamnium limestone and Roman travertine (**Marić, 1937; Crnković, 1995 and 1996; Crnković and Poggie, 1995**)

Stone variety	**Lithothamnium limestone (Marić, 1937)**	**Lithothamnium limestone (Crnković, 1995 and 1996)**	**Roman travertine (Crnković and Poggie, 1995)**
Uniaxial compressive strength (MPa)	5 – 39	25	92.5 – 115.3
Uniaxial compressive strength after freezing (MPa)	-	-	83.3 – 113.2
Flexural strength (MPa)	-	-	12.7 – 14.6
Water absorption (%)	2.23 – 3.48	5	7.3 – 8.85
Porosity (%)	-	27.3	-
Apparent density (kg/m^3)	2003 – 2180	1968	2437 – 2473
Density (kg/m^3)	-	2700	-
Durability	Durable	-	-

mestic lithothamnium limestone, litavac, calcareous sandstone, vinicite and imported travertine. All these carbonate varieties have specific petrographic characteristics and show different durability to weathering conditions. These differences should be taken into account during the use of stone or for restoration purposes.

Unlike previous renovations, the one at the end of the 20th century used an imported stone, Roman travertine (**Crnković and Poogi, 1995**), whose installation brought about certain problems after installation (**Baričević, 2017**; **Foretić, 2019**), suggesting that all varieties should be tested separately and their main physical and mechanical properties, such as density, porosity, water absorption, capillary water absorption, uniaxial compressive strength, flexural and triaxial strength, should be determined. In this way, the best stone properties for replacement of the Cathedral's damaged stone blocks could be identified and properties that are not preferred could be excluded. Even though the attractiveness and decorativity (appearance) of stone types is important, it should not be the main factor in selecting a replacement stone type.

Some basic data about the physical and mechanical properties of stone (see **Table 1**) were given in **Marić (1937)**, **Crnković (1995, 1996)** and **Crnković and Poggie (1995)**. It should be taken into account that five different varieties were used during history in the Cathedral. **Marić (1937)** analysed stone samples from the Vrapče potok and Bizek quarries, while **Crnković (1995, 1996)** tested samples that were previously used in the Cathedral during the tympanum renovation. In addition, three different varieties of Roman travertine samples – chiaro, chiaro fosse and oniciato were tested (**Crnković and Poggie, 1995**). There are big differences in properties between Roman travertine and domestic stone (see **Table 1**), but due to time passing and different testing standards, it is not possible to completely compare properties and to make a conclusion about stone materials and their durability. As literature data about stone materials, including their physical and mechanical properties, are sparse, the need for future detailed determination of their properties influencing durability and usage is apparent. Whether the properties are determined on stone samples from quarries or on the previously used stone material, it is important to test them according to the same procedures.

Since no records were kept in the earliest times, it is not possible to determine the exact amount of each type of stone used in the Cathedral construction. After the restoration guided by Hermann Bollé it was possible to determine the exact quantity of various stone types, as shown in quantitative data published by **Crnković (1992a)**, and in **Figure 10**. The most used variety was lithothamnium from the Vrapče potok Quarry.

The field prospection of the sites where stones were once quarried for the construction of the Zagreb Cathedral has shown that there is actually no possibility of stone recovery at these sites. Although it sounds pessimistic, the situation is presented realistically, taking into account both the legal possibilities and the public perception of stone quarrying in Croatia. Even though there are more positive examples in the world from which we could learn, the fact is that certain solutions cannot simply be transferred to other countries. In neighboring Italy, there are some excellent examples, such as the quarry for the restoration of the "Duomo di Milano" (**URL8, 2023**) and the quarry for the restoration of the city of Matera (**Bonomo et al., 2019**). At the same time, it must be noted that Italy was fortunate that the tradition of quarrying natural stone in a given area was not interrupted by the turn to socialism or for other reasons. Because of this, the quarrying of natural stone for the purpose of the restoration of architectural heritage has been established in Italy relatively easy. Unfortunately, this is not the case in Croatia. During the socialist era, all sites were used for the exploitation of other mineral raw materials, and the natural building stone was no longer quarried. The tradition of extraction and processing of the lithothamnium limestone, which reached its peak during the Bollé restoration, was interrupted. Moreover, the high bureaucratic costs of obtaining permits today, the administrative prohibitions of quarrying in the immediate and wider surroundings of Zagreb (**URL6, 2014**), and the generally negative attitude of the public towards quarrying operations, are invincible obstacles to the resumption of this activity in the Zagreb area. Nevertheless, former quarries should be professionally valorized for tourism and educational purposes, as it has been done in other cases of geotechnological heritage (**Bonomo et al., 2019; Briševac et al., 2021b**).

Even if it is too late for today's renovation and there is not enough time to find autochthonous stones for renovation, it does not mean that one should give up looking for a solution for renovation with local stones. It is necessary to prepare for the next possible disaster and the next renovation and do research, like it was done in the Piemonte Region, which has conducted a survey on ornamental stones used in the architectural heritage (**URL9, 2023**).

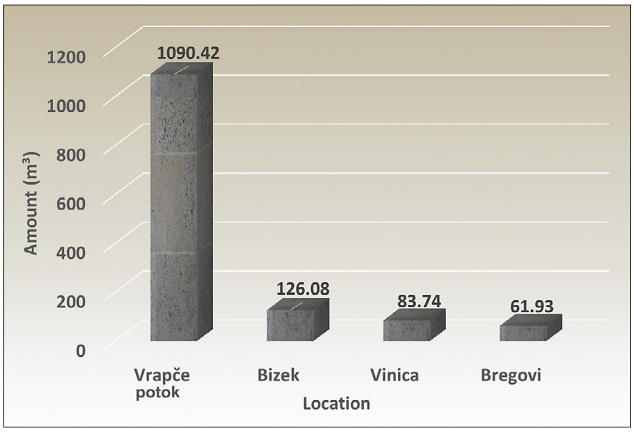

Figure 10: Quantities of stone used during Bollé's restoration

After each major catastrophe, the Zagreb Cathedral was rebuilt with a partial change of its appearance. It is very likely that this will also be the case after the reconstruction caused by the earthquake in 2020. The Cathedral will have to be reconstructed to some extent to withstand earthquakes expected in the future. In this process, the damaged stone parts will probably be replaced by stone that can be found on the market. Of course, this stone will have to visually resemble the current one and meet the physical, mechanical, and other properties required for construction. The emphasis should also be put on durability of stone in the atmospheric conditions that are present in Zagreb, and it should be protected by coatings for the prevention of water absorption. In addition, stone should be easy to process when used for decorative elements. Damaged stones that can no longer be used for the construction of the Cathedral can become valuable artifacts and can be used in museum exhibitions and as various art installations that promote the history of both the Cathedral and the city of Zagreb and represent the geological history of the Zagreb area.

Our research led to the realization that there are only few historical visual representations showing quarries and stone exploitation which are classified as public property and can be used without special copyright protection, of course with citing the source. Only one photograph (see **Figure 11**) showing Slavko Ferković's Quarry in Podsused, taken before 1905, has been found in the Digital Collection of the National and University Library in Zagreb (**Digitalna.NSK.HR, 2019**). Even though no building stone was quarried in this quarry, the photo still deserves to be shown, since it represents an important contribution to the memory of stone quarrying in the Zagreb area.

Figure 11: Slavko Ferković's Quarry in Podsused (**Digitalna.NSK.HR, 2019**)

5. Conclusions

The evaluation of available professional and scientific works, together with the inspection of the Cathedral's façade, suggest that five varieties of carbonate material were used in the construction and numerous renovations of the Zagreb Cathedral: lithothamnium limestone, litavac, calcareous sandstone, vinicite and Roman travertine. A few conclusions can be drawn:

- Lithothamnium limestone, litavac and sandstones are stone materials from the Zagreb area, while the Vinicite comes from the Varaždin area. The imported Roman travertine is used during the ongoing renovation that started in the 90s of the 20th century.
- The similarity of appearance and proclaimed resistance to weathering are not sufficient for choosing a replacement stone material for the Zagreb Cathedral. Physical and mechanical properties, together with stone durability to atmospheric conditions, should be the main criterion of stone selection for restauration and renovation purposes.
- Although certain tests on the physical and mechanical properties of the stone were carried out in the past, these tests cannot serve as a basis for the future reconstruction of the Cathedral after the earthquake in 2020. It is necessary to perform individual tests on all the established varieties of stone. Based on these tests, the type of stone which should be used as a replacement for all the damaged stone blocks can be selected.
- The current bureaucratic obstacles and unfavorable entrepreneurial climate in the field of stone exploitation, as well as the interruption of the tradition of stone extraction and processing in the Zagreb area, mean that exploitation cannot be resumed at the former quarried sites, nor is it possible to exploit building stone at new locations.
- As long as the official prohibitions and negative public perception continues, it is not possible to quarry stones for the restoration of the Cathedral in the Zagreb region.
- It is necessary to make further efforts to find visual representations of stone mining in Zagreb and other areas of Croatia and to categorize these materials as public goods. In this way, the cultural memory of this human activity can be preserved.

6. References

Aničić, D. (2000): Zagrebačka katedrala u potresu 1880. i njezina današnja obnova (*Zagreb cathedral in the 1880 earthquake and its present day renovation*). Građevinar, 11, 655–661. (*in Croatian – with English abstract)*

Atalić, J., Šavor Novak, M. and Uroš, M. (2019): Seismic risk for Croatia: overview of research activities and present assessments with guidelines for the future, Građevinar, 71 (10), 923–947. https://doi.org/10.14256/JCE.2732.2019

Atalić, J., Šavor Novak, M., Uroš, M., Demšić, M. and Baniček, M. (2021a): Impacts of Earthquakes in 2020 to Croatian Cultural Heritage. In: GSCAEE-2021: Global Summit on Civil, Architectural and Environmental Engineering. Barcelona, The Scientist, pp. 36.

Atalić, J., Uroš, M., Šavor Novak, M., Demšić, M., Baniček, M., Herak, M., Dasović, I. and Prevolnik, S. (2021b): A. Uvodno o potresu i njegovim učincima - A.3. Potres u Zagrebu u ožujku 2020. Godine *(A. Introduction: The earthquake and its effects - A.3. Zagreb earthquake of 22 March 2020)*. In: Uroš, M., Todorić, M., Crnogorac, M., Atalić, J., Šavor Novak, M. and Lakušić, S. (ed.): POTRESNO INŽENJERSTVO - Obnova zidanih zgrada. Zagreb, Građevinski fakultet Sveučilišta u Zagrebu, 46–68, 594 p. *(in Croatian – without English abstract)*

Baričević, M. (2017): Projekt sanacije pukotina na fijalama i stupovima II i III galerije sjevernog zvonika Zagrebačke katedrale (*Project for the repair of cracks on the phials and columns of the II and III gallery of the north bell tower of the Zagreb Cathedral*), Urbane ideje d.o.o, Samobor, 55 p. (*in Croatian – without English abstract*)

Basso, D., Vrsaljko, D. and Grgasović, T. (2008): The coralline flora of a Miocene maërl: the Croatian "Litavac". Geologia Croatica 61(2–3), 333–340

Bedenko, A. (2014): Povijest izgradnje zagrebačke katedrale Uznesenja Blažene Djevice Marije s posebnim osvrtom na gradnju lađa u 14. i 15. Stoljeću *(The history of the construction of the Zagreb Cathedral of the Assumption of the Blessed Virgin Mary with special reference to the construction of naves in the 14th and 15th centuries).* Diplomski rad. Filozofski fakultet u Zagrebu. 62 p. (*in Croatian – without English abstract*)

Briševac, Z., Maričić, A., Brkić, V. and Bralić, V. (2021a): An overview and future prospects of Croatian geotechnological heritage. Rudarsko-geološko-naftni zbornik, 36 (1), 77–97. https://doi.org/10.17794/rgn.2021.1.7.

Briševac, Z., Maričić, A. and Brkić, V. (2021b): Croatian Geoheritage Sites with the Best-Case Study Analyses Regarding Former Mining and Petroleum Activities. Geoheritage, 13, 95, 15. https://doi.org/10.1007/s12371-021-00620-5.

Bonomo, A.E., Acito, A.M., Prosser, G., Rizzo, G., Munnecke, A., Koch, R., and Bentivenga, M. (2019): Matera's Old Quarries: Geological and Historical Archives That Need Protection and Valorization. Geoheritage, 11, 1603–1619. https://doi.org/10.1007/s12371-019-00413-x

Bussagli, M. (2006): Arhitektura *(Architecture)*. Stanek d.o.o., Varaždin, 383 p. (*in Croatian – without English abstract*)

Crnković, B. (1992a): Restauratorski radovi na Zagrebačkoj katedrali (*Restoration works on the Zagreb Cathedral*). Klesarstvo i graditeljstvo, 1–2, 3, 19–21. (*in Croatian – without English abstract*)

Crnković, B. (1992b): Arhitektonsko-građevni kamen u obnovi (*Dimension stone in restoration works*). Klesarstvo i graditeljstvo, 1–2, 3, 15–18. (*in Croatian – without English abstract*)

Crnković, B. (1994): Obnova zagrebačke katedrale, Klesarstvo i graditeljstvo, V, 1–2, 32–39. (*in Croatian – without English abstract*)

Crnković, B. (1995): Zagrebačka katedrala, Istraživački radovi na timpanonu (*Zagreb Cathedral Research works on the tympanum*). Klesarstvo i graditeljstvo, VI., 1–2, 21–28. (*in Croatian – without English abstract*)

Crnković, B. (1996): Kamen Zagrebačke prvostolnice (*Stone of the Zagreb Cathedral*). Godišnjak zaštite spomenike kulture Hrvatske, 27–34. (*in Croatian – with English abstract*)

Crnković. B., Tadej, N. and Pollak, D. (1994): The Influence of Acid Rains on the Lithothamnian Limestone on the Gallery of the Mary's Ascension Cathedral, Zagreb, Croatia. Rudarsko-geološko-naftni zbornik, 6, 1–9.

Crnković, B. and Poggi, F. (1995): Travertine the restoration stone for the Zagreb Cathedral. Rudarsko-geološko-naftni zbornik, 7, 77–85.

Crnković, B. and Šarić, Lj. (2003): Građenje prirodnim kamenom (*Construction with natural stone*). Institut građevinarstva Hrvatske, Zagreb, 380 p. (*in Croatian – without English abstract*)

Čorak, Ž. (1996): Obnova kipova na zagrebačkoj katedrali: Josef Bayer rukom Vladimira Herljevića (*Restoration of the statues of Zagreb Cathedral - Joseph Beyer by hand of Vladimir Herljević*). Radovi Instituta za povijest umjetnosti, 159–165. (*in Croatian – without English abstract*)

Dasović, I., Herak, D., Herak, M., Latečki, H., Mustać, M. and Tomljenović, B. (2020): O potresima u Hrvatskoj *(On Earthquakes in Croatia)*. Vijesti Hrvatskoga geološkog društva, 57 (1), 4–27. (*in Croatian – without English abstract*)

Digitalna.NSK.HR. (2019): Digitalne zbirke Nacionalne i sveučilišne knjižnice u Zagrebu. Nacionalna i sveučilišna knjižnica, Zagreb. https://digitalna.nsk.hr/pb/

Dunda, S., Kujundžić, T. and Fistrić, M. (2005): Travertine on the Zagreb Cathedral. In: Ozkul, M., Yagiz, S., Jones, B. (Eds.) Proceedings of 1st International Symposium on Travertine. Denizli, Kozan Ofset Matbaacilik San. ve Tic. Ltd. Sti. Ankara, 328–333.

Fio Firi, K. and Maričić, A., (2020): Usage of Natural Stones in the City of Zagreb (Croatia) and its Geotouristical Aspect. Geoheritage, 12, 62, 1–18. https://doi.org/10.1007/s12371-020-00488-x

Foretić, D. (2019): Trideset godina obnove zagrebačke katedrale *(Thirty years of renovation of the Zagreb Cathedral)*. Klesarstvo i graditeljstvo, XXIX, 1–2, 35–53. (*in Croatian – without English abstract*)

Herak, D., Herak, M., Allegretti, I., Fiket, T., Kuk, K., Markušić, S., Prevolnik, S., Sović, I., Dasović, I. and Stipčević, J. (2018): Seismicity of Croatia in the period 2006–2015. Geofizika, 35 (1), 69-98. https://doi.org/10.15233/gfz.2018.35.2.

Ivandija, A. (1981): Prilozi za građevnu povijest zagrebačke katedrale *(Contributions to the building history of the Zagreb Cathedral)*. Croatica christiana periodica, V, 8, 1–13. (*in Croatian without English abstract*)

Klarić, J. (2002): Požari u Zagrebu i katedrali *(The fires in Zagreb and the cathedral).* Naša Katedrala, 45(7), 21–22. (*in Croatian – without English abstract*)

Jezidžić, H. (2022): Povijesni pregled dobivanja kamenog materijala za potrebe izgradnje zagrebačke katedrale *(Historical overview of obtaining stone material for the construction of the Zagreb Cathedral)*. Završni rad, Rudarsko-geološko-naftni Fakultet, Zagreb, 32 p. (*in Croatian – with English abstract*)

Malinar, H. (2004): Konzervacija kamena Zagrebačke katedrale *(Conservation of the stone of Zagreb Cathedral)*. Godišnjak zaštite spomenika kulture Hrvatske, 28, 123–136. (*in Croatian – with English abstract*)

Marić, L. (1937): Litotamnijski vapnenjak (krečnjak) u prirodi i u građevini *(Lithothamnium limestone in nature and in construction)*. Tehn. list, 19/21−22, 296−300. (*in Croatian – without English abstract*)

Marković, S. (2002): Hrvatske mineralne sirovine (*Mineral resources in Croatia*). Institut za geološka istraživanja, Zagreb, 544 p. (*in Croatian – without English abstract*)

Mohorovičić, A. (1998): Zagrebačka katedrala *(The Zagreb Cathedral)*. Naša Katedrala, 32(1), 6–7. (*in Croatian – without English abstract*)

Nadilo, B. (2005): Herman Bolle – veliki hrvatski graditelj i pedagog *(Herman Bolle – great Croatian builder and pedagogue)*. Građevinar, 57, 801–807. (*in Croatian – without English abstract*)

Pavelić, D., and Kovačić, M. (2018): Sedimentology and stratigraphy of the Neogene rift-type North Croatian Basin (Pannonian Basin System, Croatia): A review. Marine and Petroleum Geology, 91, 455–469.

Plukavec, S.L. (2006): Glavni oltar zagrebačke katedrale *(The main altar of the Zagreb Cathedral)*. Naša Katedrala, 51(10), 43. (*in Croatian – without English abstract*)

Pollak, D. (1993): Utjecaj sulfatnokisele kiše na litotamnijski vapnenac ugrađen u galeriju Zagrebačke prvostolnice (The influence of acid rains on the lithothamnian limestone on the gallery of the Zagreb cathedral). Graduation thesis, RGN fakultet, Zagreb, 54 p. (*in Croatian – without English abstract*)

Rukavina, Z. (1997): O obnovi zagrebačke katedrale 1990. – 1997. *(About the renovation of the Zagreb Cathedral in 1990-1997).* Godišnjak zaštite spomenika kulture Hrvatske 22, 23, 19–26. (*in Croatian – with English abstract*)

Sigmund, Z., Radujković, M. and Atalić, J. (2022): The Role of Disaster Risk Governance for Effective Post-Disaster Risk Management – Case of Croatia. Buildings, 12 (4), 420, 17. https://doi.org/10.3390/buildings12040420.

Szabo, G. (1929): Prilozi za građevnu povijest zagrebačke katedrale (Contributions to the building history of the Zagreb Cathedral). Narodna starina, 65–77. (*in Croatian – without English abstract*)

Šango, M. (2019): Petrografska determinacija kamenih varijeteta iz hrvatske koji na tržištu pripadaju skupini „mramora" (Petrographic determination of Croatian stone varieties that on the market belong to the "marble" group). Završni rad, RGN fakultet, 35 p. (*in Croatian – with English abstract*)

Šikić, K. (1995): Geološki vodič Medvednice *(Mt. Medvednica guide book).* Institut za geološka istraživanja Zagreb i INA-industrija nafte d.d. Zagreb, 199 p. Zagreb. (*in Croatian – without English abstract*)

Šimunović, P. (2002): Hvalorijek Bračkom kamenu *(Praise to the Brač stone)*. Brač-Jadrankamen (ed. Vrandečić, S). Jadrankamen d.o.o, Pučišća, 9–33, 271 p. (*in Croatian – without English abstract*)

Vrsaljko, D., Pavelić, D., Miknić, M., Brkić, M., Kovačić, M., Hećimović, I., Hajek-Tadesse, V., Avanić, R. and Kurtanjek, N. (2006): Middle Miocene (Upper Badeninan/Sarmatian) palaeoecology and evolution of the environments in the area of Medvednica Mt. (North Croatia). Geologia Croatica 59(1), 51–63.

Zebec, V. (1975): Kalcit i dolomit iz okolice sela Bizek i Dolje kod Podsuseda u Medvednici (Zagrebačka gora) (Calcite and dolomite from the surroundings of villages Bizek and Dolje near Podsused on Medvednica (Zagrebačka mountain)). Acta Geol Prirodoslovna istraživanja 41, 287–314. (*in Croatian – without English abstract*)

URL1: https://www.google.com/maps (accessed 21st December 2022)

URL2: https://jisms.gospodarstvo.gov.hr/#/maps (accessed 21st December 2022)

URL3:https://mingor.gov.hr/UserDocsImages/UPRAVA-ZA-PROCJENU-UTJECAJA-NA-OKOLIS-ODRZIVO-GOSPODARENJ-OTPADOM/Opuo/27_02_2019_Elaborat_Sanacija_EP_Markusevec.pdf (accessed 21st December 2022)

URL4: http://www.medvednica.info/2010/10/planinarska-staza-4.html (accessed 21st December 2022)

URL5: https://hrvatski-vojnik.hr/wp-content/uploads/2017/10/hv_289.pdf (accessed 21st December 2022)

URL6: https://mpgi.gov.hr/o-ministarstvu-15/djelokrug/prostorno-uredjenje-3335/prostorni-planovi-8193/prostorni-planovi-drzavne-razine/prostorni-planovi-parkova-prirode/prostorni-plan-pp-medvednica/3393 (accessed 21st December 2022)

URL7: https://zagorje-kamen.hr/ (accessed 21st December 2022)

URL8: https://www.duomomilano.it/en/article/2022/06/16/the-origins-of-the-duomo-candoglia-quarry/439/ (accessed 21st May 2023)

URL9: https://www.regione.piemonte.it/web/temi/sviluppo/attivita-estrattive/pietre-ornamentali (accessed 21st May 2023)

SAŽETAK

Prirodni kamen korišten prilikom gradnje i obnove zagrebačke katedrale

Prirodni kamen kao građevinski materijal koristi se od početka civilizacije prilikom gradnje građevina koje danas zovemo povijesno-kulturnim građevinama i spomenicima. Zagrebačka katedrala primjer je jedne takve građevine, ali podatci o vađenju kamena za njezinu izgradnju rijetko su objavljivani u znanstvenim časopisima. Na temelju pregleda dosad objavljene literature te provedenoga istraživanja trenutačnoga stanja lokacija na kojima se prije vadio kamen za gradnju katedrale, ovaj rad predstavlja sustavan pregled izazova u vezi s kamenim materijalima o kojima treba voditi računa prilikom obnove katedrale nakon potresa 2020. godine. Utvrđeno je koji su autohtoni varijeteti kamena korišteni prilikom gradnje katedrale: litotamnijski vapnenac, litavac, vapnenački pješčenjak i vinicit. Naglasak je bio na opisu lokacija na kojima su navedeni varijeteti eksploatirani te je istražena prikladnost tih mjesta za ponovno vađenje kamenih blokova tijekom obnove nakon potresa u 2020. godini. Osim toga, katedrala je obnovljena uvezenim travertinom iz Italije, koji je sastavni dio građevine iako nije domaćega podrijetla, pa se njegove karakteristike moraju uzeti u obzir pri planiranju sadašnje obnove katedrale. Posebno je istaknuta potreba pronalaženja starih vizualnih prikaza kamenoloma na području Zagreba kako bi se očuvala kultura sjećanja na ovu ljudsku djelatnost.

Ključne riječi:
kamenolomi, litotamnijski vapnenac, litavac, vapnenački pješčenjak, vinicit, travertin

Author’s contribution

Ana Maričić (1) (Ph.D. in geological engineering, Associate Professor at the Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb) conducted an analysis of published works on stone material and determined the varieties of stone built into the Cathedral. She also participated in the field work. **Zlatko Briševac (2)** (Ph.D. in mining engineering, Associate Professor at the Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb) participated in the analysis of published papers on the construction and restoration of the Cathedral, participated in field research and wrote chapters on the places where the stone was once quarried, and created graphic representations on paper. **Petar Hrženjak (3)** (Ph.D. in mining engineering, Associate Professor at the Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb) participated in the collection and analysis of published and unpublished data, as well as in field work. **Helena Jezidžić (4)** (graduate student at the Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb) analyzed the history of construction and exploitation in the Zagreb area based on research for the preparation of a Bachelor’s thesis and participated in the creation of some graphic representations on paper.