

Article

Historical Use of the Ashlar Limestone at Piatra Roşie Dacian Fortress; Interdisciplinary Approach in a World Heritage Site

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Abstract: One of the main forms of expression of the power of the Dacian Kingdom, with its capital at Sarmizegetusa Regia, was represented by the monumental constructions built in ashlar stone, the result of a mixture between local traditions and Greek and Roman influences. The fortified acropolis at Piatra Roşie is one of the main components of this center of power and one of the most important archaeological sites from the Late Iron Age in Romania. In 1999 it was inscribed on the World Heritage List as part of the serial site “Dacian Fortresses in the Orăştie Mountains”. This paper presents the most recent data regarding the stones used in the construction of the Piatra Roşie fortress, the most important building material from the point of view of volume and durability. The historiographical and archaeological data, the field investigations and measurements, together with the mineralogical analysis of stone varieties have been corroborated with specific interpretations for construction engineering and 3D modeling applied in the evaluation of the dimension stone volume. The present approach constitutes an absolute novelty for the site of Piatra Roşie, and, also, a model that can be applied to the specific conditions of the other Dacian Fortresses.



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1. Introduction

For the researcher investigating the subject of the fortresses erected in the Transylvanian mountains in the 1st century BC, the task of creating a coherent image from existing or already published data represents not only a complex scientific endeavor, but also requires the ability to identify at least the basic shape of an immense puzzle with a lot of missing pieces. The incomplete previous investigations of any of the fortresses in the Şureanu-Orăştie Mountains drastically limits the information available to be integrated in the evaluation of the stone resources used in their building process.

The present paper focuses on the fortified acropolis of Piatra Roşie, part of the serial site “Dacian fortresses in Orăştie Mountains”, together with the Dacian fortresses of Grădiştea de Munte-Sarmizegetusa Regia, Costeşti-Cetăţuie, Costeşti-Blidaru, Băniţa (Hunedoara County) and Căpâlna (Alba County), listed as UNESCO World Heritage Site. The information presented here is a synthesis of multi and interdisciplinary research made in the last decade by the project team using modern methods and site valorization.

The first stage of the research consisted in an analysis of the site and fortress, in historical context and in various documents, followed by the in situ inventory and measurement (where possible) of the stone building elements. To the observations and the specific geological investigations of the bedrock and of the stone used for different purposes, were added measurements of the limestone blocks used in the initial construction and still visible on the surface of the site within the limits of the fortified enclosure, in order to determine their volume (an essential information in the evaluation of the amount of work needed for their transport and manipulation at the time of the construction). For the first time, have been

estimated the volumes of the ashlar stone used in the construction, through 2D and 3D modeling of the fortress, using specialized software and integrating available information for the constructive elements [1].

Also, for the first time we determined, using modern methodologies [2], the physical-mechanical properties of the limestones from which the stone blocks from Piatra Roşie fortress were made. After detailed petrographic and mineralogical analysis [3] (pp. 819–822), laboratory tests were carried out on samples from the Măgura Călanului historical quarry, the confirmed source of the stone for most of the blocks used for masonry, for the access ways to the enclosure, or as support elements for other structures. This paper also contains a synthesis of the mineralogical and physical-mechanical characteristics, respectively of the workability and durability of the stones found at Piatra Roşie site.

2. History and Heritage Context

The emergence of a center of power in the Şureanu Mountains, sometimes in the first half of the 1st century B.C., marked the height of the Dacian civilization. This will be the heart of the Dacian Kingdom, resulted from the unification of several communities and other smaller structures. The Dacians were a pre-Roman population that lived on the territory of present time Romania during the Late Iron Age. They reached a form of state organization around the middle of the 1st century BC when king Burebista succeeded in unifying several tribes and created a kingdom whose capital was established in Transylvania region, in the Şureanu Mountains (Figure 1).

Its capital, Sarmizegetusa Regia, together with the neighboring fortresses, represents the highest expression of this civilization, translated in material form through monumental architecture: walls, towers, temples, paved roads, and other stone structures.

The Piatra Roşie Dacian fortress is part of this group of fortifications and settlements. It is situated in the Alun village, Boşorod commune, County of Hunedoara, in the Natural Park of Grădiştea Muncelului-Cioclovina (Figure 2a). Taking into consideration the fact that the site has been very little investigated, the timeline of the fortifications is not clear. It is generally considered that the fortification on the plateau, together with the stone stair and the A-D towers (Figure 2b), represent an older construction, dating approximately from the middle of the 1st century BC, during the time of king Burebista, while the second fortification, on the slopes of the hill, represents an extension erected during the time of king Decebal, and deemed necessary for the strengthening of the defensive system in order to face the Roman danger that had appeared at the end of the 1st century AD and the beginning of the next [1] (pp. 124–125). This division into stages, unsupported by clear archaeological arguments, has been criticized by some foreign researchers [4] (pp. 207–208).

The fortress was conquered by the Romans in 106 AD and was never inhabited afterwards. A few traces, dating from the early Middle Ages (11th century AD), bear testimony of the passing or temporary settlement amongst the ruins of a small group of people, but there is no other consistent evidence of the reuse or rebuilding of the fortress.

The hill of the fortress, with its particular shape and reddish rocky slopes, has constituted from the very beginning an important visual landmark. The first written testimony of this toponymy dates from the 15th century [1] (p. 24), but it is definitely older. The ruins were probably known by the locals and by the passing shepherds, but the first documents mentioning it date from the 19th century [5] (p. 317). Systematic archaeological research was concentrated in a single campaign, during the summer of 1949, under the management of Constantin Daicoviciu. During this campaign he also drew a draft plan of the fortress (Figure 2b). For more than half a century, the fortress stirred no interest from the archaeologists. The excavations started again in 2004, with the intention of being continued, but they stopped the next year [6].

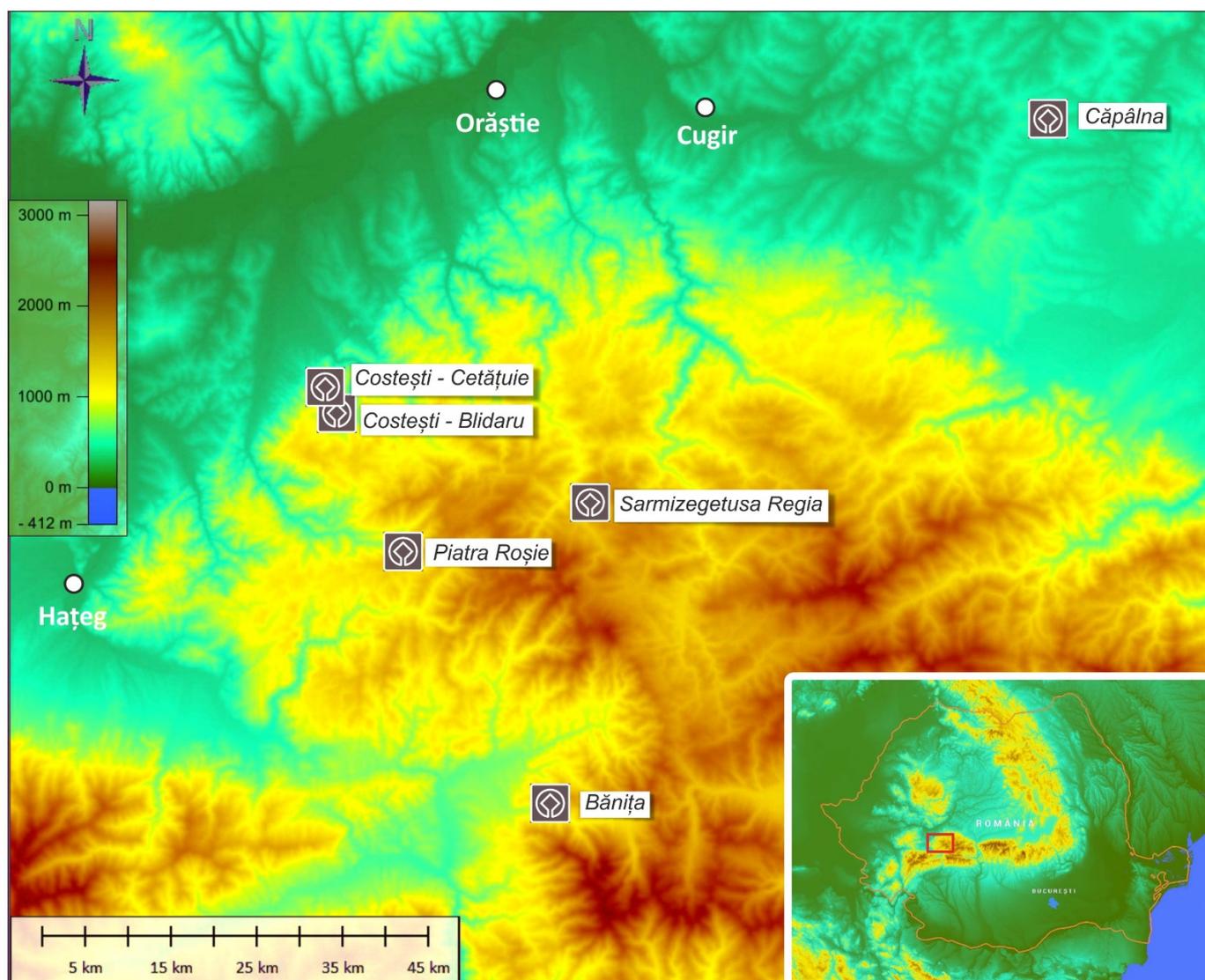


Figure 1. The location of the Dacian fortresses inscribed on the World Heritage List as the serial site “Dacian Fortresses in the Orăștie Mountains” (with red arrow—Piatra Roșie fortress).

The material culture is typical to the Dacian Kingdom, characterized by indigenous types and shapes and Greco-Roman imports. There is also a series of special pieces, unique in the Dacian world: a bronze mask bearing the face of a goddess, a series of iron disks richly ornamented with zoomorphic and vegetal representations.

The research has, obviously, captured only the last stages of the fortress, at the moment of its conquest in the year 106 AD. There are, however, some clues regarding the existence of previous stages, natural for a settlement that lasted a century and a half. However, these stages are very difficult to piece together at the current state of historical knowledge. Since the archaeological research available is very limited, we are forced to work only with the information published in 1949 and 2004 and what is still visible in the field.

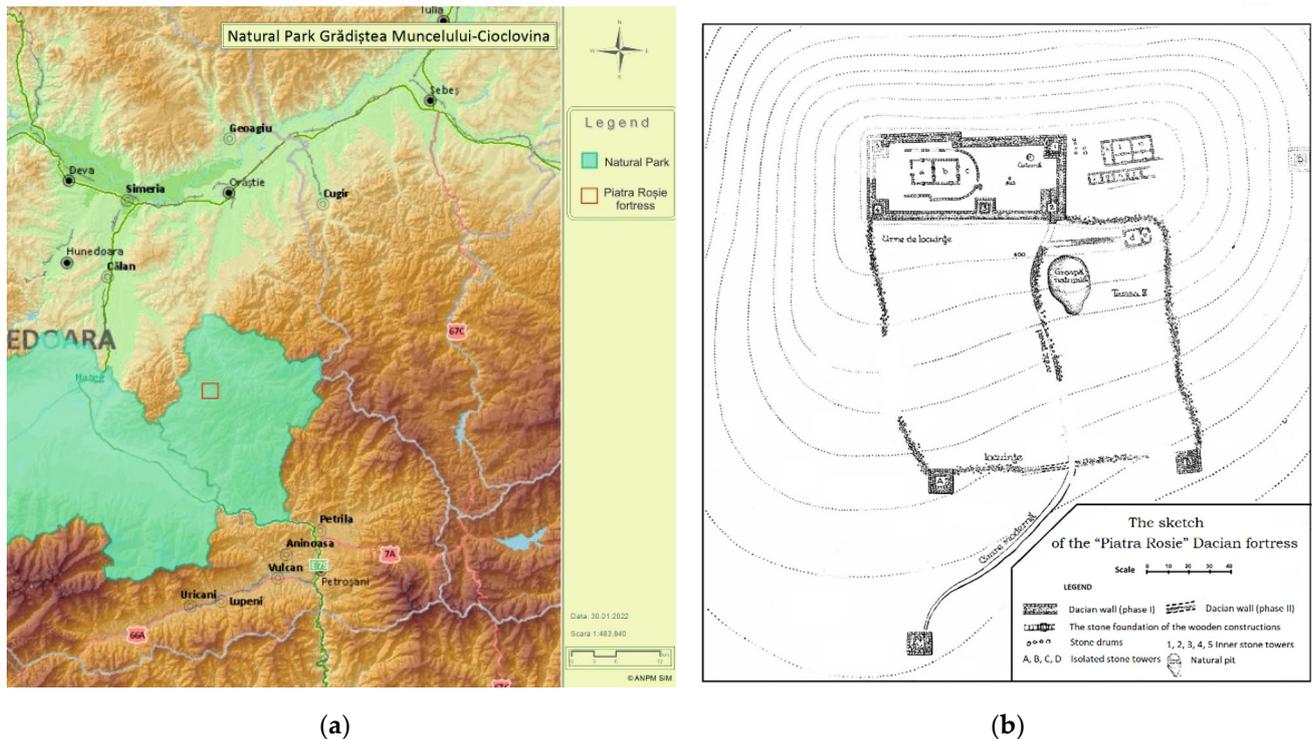


Figure 2. Administrative positioning: (a) The Dacian fortresses from Şureanu Mountains are included in the area of Natural Park of Grădiştea Muncelului-Cioclovina; (b) The first sketch of the Piatra Roşie Dacian fortress, 1954 (The title and legend have been translated into English according to the original, for the purposes of this article—V.C.).

3. Site Description and Geological Setting

Piatra Roşie Fortress occupies an isolated peak (831 m), not easily accessible, in the southwestern sector of the Şureanu Mountains, situated between Valea Alunului, Valea Luncanilor and Valea Roşie water courses. The fortifications are on the upper plateau, that was artificially leveled (Figure 3a), and on the eastern slopes, while various anthropogenic terraces that formed the civilian settlement around the fortress were built both on the hill, where the slopes permitted it (the eastern and northern slopes), and on the valleys and hills in its vicinity.

The western and southern slopes of the hill are rocky and steep (Figure 3b), inaccessible, while the northern slope can be climbed, but with difficulty. On its eastern side (Figure 4), the hill is connected to the surrounding formations through a saddle, the only access-way to the fortress. From here, a path cut in stone by the Dacians themselves leads to the plateau where most of the antique structures are located.

According to the data from the excavations in 1949, on the rocky plateau, leveled and landscaped by the Dacians, was built a rectangular fortification of squared stone that occupied two thirds of the surface of the plateau, with interior towers in the four corners, to which a fifth one was added on the eastern side. The access to the enclosure was secured through the northeastern tower, which could be reached by a monumental stone stair. Inside the fortification, there was a building with two rooms and an apsed porch, while outside the enclosure there was a temple with columns (torn down by the Dacians) and two buildings of unknown purpose. On a lower terrace have been identified the remains of a building with two rooms, one of them apsed, that could be reached via a paved road that branched from the main stairs. Other terraces, situated lower than the plateau and very little investigated, hosted, most probably, living quarters and workshops [7] (p. 405).



Figure 3. The upper plateau of Piatra Roșie hill was artificially leveled: (a) General view from west; (b) The anthropized profile of the hill has become a visual landmark in the area.



Figure 4. Aerial view of the steep western slope of the Piatra Roșie hill and of the only easy access-way to the fortress, from the East.

A second enclosure, built out of local stones, earth, and wooden palisades, was built on the eastern slopes, fencing in the terraces mentioned above and including two towers that were initially isolated (towers A and B). Two more towers that remained isolated have been identified in two points of the fortress: one at the beginning of the access way to the fortress, controlling the access to the plateau (tower C) and another on the northern slopes of the hill (tower D, not investigated till now). An interesting detail is represented by the existence, right in front of the entrance of the plateau enclosure, of a large sinkhole from whose interior the research in 1949 extracted unique artifacts.

The first topographic survey of the Piatra Roșie fortress was done in 2012, by Dacica Foundation (Figure 5). This included the terrain and the architectural elements of the plateau, and also the enclosure on the eastern slope, but was limited by the conservation state of the ruins.



Figure 5. The updated plan of the Piatra Roșie fortress (topographic plan from 2012 superimposed on the sketch from 1950) (processed after România de Vis).

The new surveys have corrected the dimensions existing in the old plans. Thus, it was discovered that the long axis of the fortifications (oriented north to south), measured at the middle of the enclosure from the exterior of the northern side to the exterior of the southern side, is 106.35 m, while the northern side is 46 m. The western and southern sides are incomplete, the southwestern tower (T5) does not exist in the field, and the southeastern one (T4) is only partially unearthed, thus the lengths of these three sides could not be exactly established. Their length cannot be deduced with precision from the long axis of the enclosure and the length of the northern side, because the paths of the walls are irregular and there are clear indications that the enclosure wasn't a perfect rectangle.

From the geological point of view, the area of the Piatra Roșie hill with the Dacian fortifications is comprised exclusively of sedimentary rocks, and is profiled in relief in an emergent position, easily visible due to the mountainsides of reddish limestone (Figures 3b and 6a,b).

It is delimited on the north and northwest side by an important tectonic fault that crosses the region from Streiului valley towards Costești Hill—Vârtoape, over the Grădiștei valley (Figure 7), in a perimeter of no more than 2 km², where the carbonate and arenaceous formations coming into tectonic or natural contact with the crystalline deposits of the Sebeș-Lotru Series.

Actually, the samples taken from the bedrock of the perimeter have been analyzed from the mineralogical and petrographic point of view and have described two types of limestones: (i) the very diaclosed peloidal-bioclastic type, ashen-pink in color with predominantly sparitic cement, and (ii) a compact pink to whitish-purple micritic limestone, quite often with diaclasses filled with calcite and showing sometimes nodular concretions, with some of the holes filled with chalcedony [3] (pp. 813–814).

The ashlar stone used in the Piatra Roșie fortress is the oolitic limestone, extracted mostly from the Dacian quarry at Măgura Călanului, together with some local stone. Although built on a limestone rock, the builders could not use the local stone too much, since its high compactness (Figure 6b) made it difficult to shape. This is the reason why the oolitic limestone from Măgura Călanului was preferred, having highly superior workability, even if its transport from 30 km away required a lot of effort [3] (p. 823).

In time, just as in many other places, the presence of modern human habitations very close to the ruins affected the conservation state of the fortress, because the locals transported high quantities of blocks and slabs from the site to be reused in their constructions.



Figure 6. The Piatra Roșie (=Red Rock) hill. (a) The western slopes; (b) The reddish limestone from upper part of the hill.

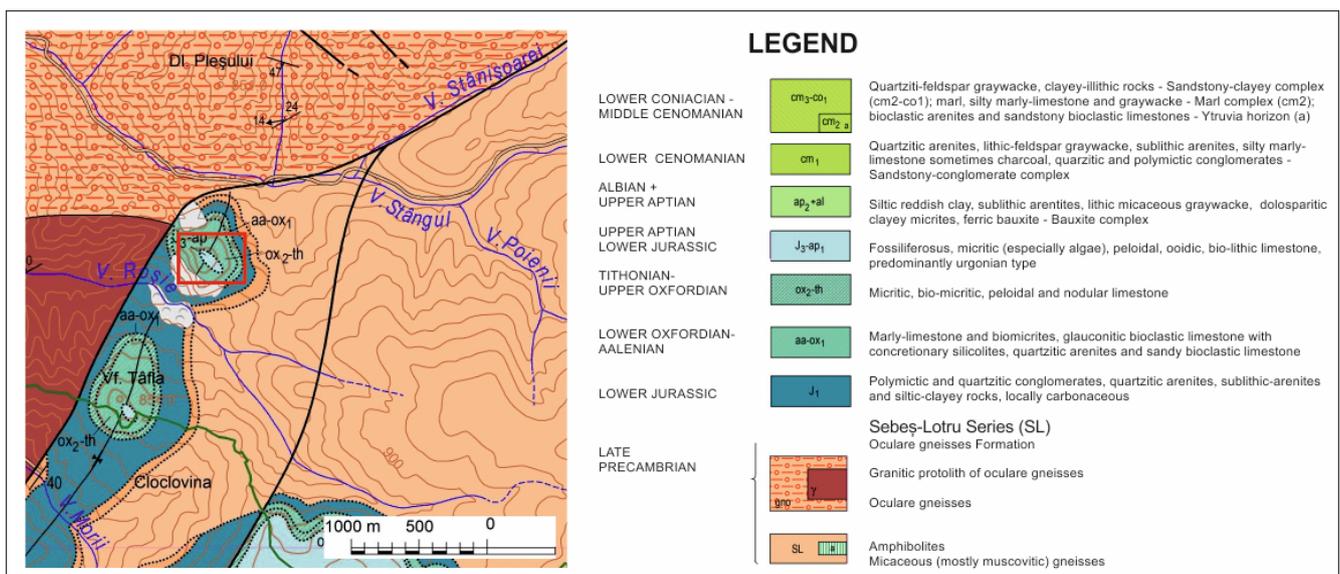


Figure 7. Geological map of the area, Scale 1:50,000, sheet Pui (layout, Geological Institute of Romania, 2012) [8].

4. Materials and Methods

The geo-archaeological research in the Piatra Roșie hill area and of the fortified acropolis, as described in this paper, is part of a larger independent research program of the Dacian fortresses that was developed in the past decade, through the volunteer work and the enthusiasm of the authors involved in its elaboration, depending on their personal interest and competences. The correlation of all the data and information gathered by each member of the team, so that they correspond to the subject of this paper, has required fine tuning, partial evaluations, successive design and correlated interpretations, proving, once again, that complex interdisciplinary studies demand challenging approaches.

The identification and analysis of the architectural and documentary information about the site have been done both centered on Piatra Roșie itself and also in connection

with the data regarding the capital of the Dacian Kingdom [9] (p. 46–48) and the other fortresses surrounding it.

In what regards the data and the geological information concerning the building stones used in the fortress area, starting from the 19th century, most often the documents made reference to the stones from Dealul Grădiștii, at Sarmizegetusa Regia, although there have been some direct observations of the quarry-faced stones in the constructions at Piatra Roșie or of the limestone the blocks are made of. This information, even if unsupported by specific details, can be found in documents like the ones from 1803 and from 1844 [10] (pp. 441–442) and [11] (pp. 25–26), followed by the results of some petrographic research at the beginning of the 20th century [12] (p. 240) and [13] (p. 42), respectively in the monography of the Piatra Roșie fortress containing the results of the archaeological excavations from 1949 or the published results of some independent investigations [3] (pp. 808–809, 816–817).

The results of the documentation stage were correlated with investigations in situ that included:

- (i) the identification of the areas in the field where the ashlar stone elements can be found and their characterization;
- (ii) geological prospecting and sampling for the characterization of the bedrock, its surrounding rock formations, and of the stone blocks;
- (iii) topographical surveys on 2.5 ha area;
- (iv) study of the stone elements (blocks, slabs, abnormal shapes, the wall with mortar) through direct observations and measurements (208 blocks in 2020, to which some measurements performed in the previous years have also been added).

The information regarding the geometry and positioning of the blocks have been completed with a contextual interpretation of the data, and with the results of the mineralogical and petrographic studies of the limestones from which the dressed stone elements at Piatra Roșie were made, but also of the bedrock. For these analyses of samples, the following equipments were used:

1. binocular magnifying glass analysis, with Zeiss STEMI 508 stereographic microscope, with magnifying power up to $50\times$ ($10\times$ eyepiece), and the lens from $0.63\times$ to $5\times$, equipped with a Zeiss digital camera—for about 50 samples;
2. Zeiss-Jena Jenapol optical microscope was used for mineralogical identification and characterization under polarized light made on thin sections, and the Zeiss AXIO IMAGER A2m optical microscope, with a magnifying power up to $500\times$ with magnifying power up to $50\times$ ($10\times$ eyepiece), and the lens from $0.63\times$ to $5\times$ and equipped with 4 lenses with different levels of magnification such as $10\times \div 50\times$, and eyepieces with $10\times$ magnifying power, also equipped with Zeiss digital camera—analysis on 28 thin sections;
3. electronic microscope equipped with Hitachi TM3030 Tabletop Scanning Electron Microscope (SEM) with a magnification index from 15 to $30,000\times$ (Digital zoom $\times 2$, $\times 4$), equipped with BSE and EDX detectors and 15 kV Accelerating Voltage—for 3 samples.

Special attention was paid to 2D and 3D modeling of the terrain and the walls, with a view of determining the volume of ashlar stone used in the Piatra Roșie fortress. The subject led to spirited debates inside the team, due to the fact that direct information was scarce (the only archaeological excavation that took place on the plateau with the fortress had only partly unearthed the area), for some of the aspects being necessary to adapt, by analogy, data from other fortresses around the Sarmizegetusa Regia capital.

Previous independent projects carried out so far by each author of this paper had an essential role in the modeling and correlations required by the present subject. One of the most important of these was the virtual 3D restoration of Dacian fortresses, conducted by România de Vis [14] and scientifically supported for the Piatra Roșie fortress by the information provided by the Study Centre of the Dacica Foundation. The software used (SketchUp and LayOut) allowed as input the necessary values for the spatial representa-

tions, and also the volumetric evaluation for each construction unit as they are known in the present (Figures 2b and 5).

All the working hypotheses and constructed models have been conditioned by the existence and the degree of reliability of the essential input data. The actual conformation of the surface of the terrain on which the fortress was built is based on the topographical surveys from 2012 provided by the Dacica Foundation. The data regarding the height of the walls and towers and the width of the wall openings were taken from the site monography [1] (pp. 134–135), and those for the upper ending of the walls and the position of the encircling road are based on the bibliography and the analogy with other similar sites. The direct observations in the field, respectively measurements of the stone blocks for the volumetric evaluation, were done both in the fortress perimeter, and also in the historic quarry at Măgura Călanului, the main source of stone for the Piatra Roșie Dacian fortress.

The information regarding the durability of the stone dimensioned in the form of blocks has been obtained by direct observations in the field and from the physical-mechanical analysis in the laboratory, performed on samples extracted from Măgura Călanului (Figure 8), as part of the project RoQ-Stone [15] coordinated by the Romanian Geological Institute. Their conclusions have been corroborated and integrated in the final image suggested for the Piatra Roșie fortress, respectively in the volumetric evaluation of the stone resource used at its construction at the middle of the 1st century BC.



Figure 8. The Măgura Călanului historical quarry. (a) The highest exploitation side, western slope; (b) Partially squared limestone block in the quarry area.

5. Results

5.1. Stone Elements

The ashlar blocks have been used in many types of monuments inside the fortified enclosure: walls (Figure 9a), towers (Figure 9b), foundations of wooden buildings, the bases of residential towers made of bricks, the bases of temple columns, stairs and paving stones. Below, we present an inventory of these.

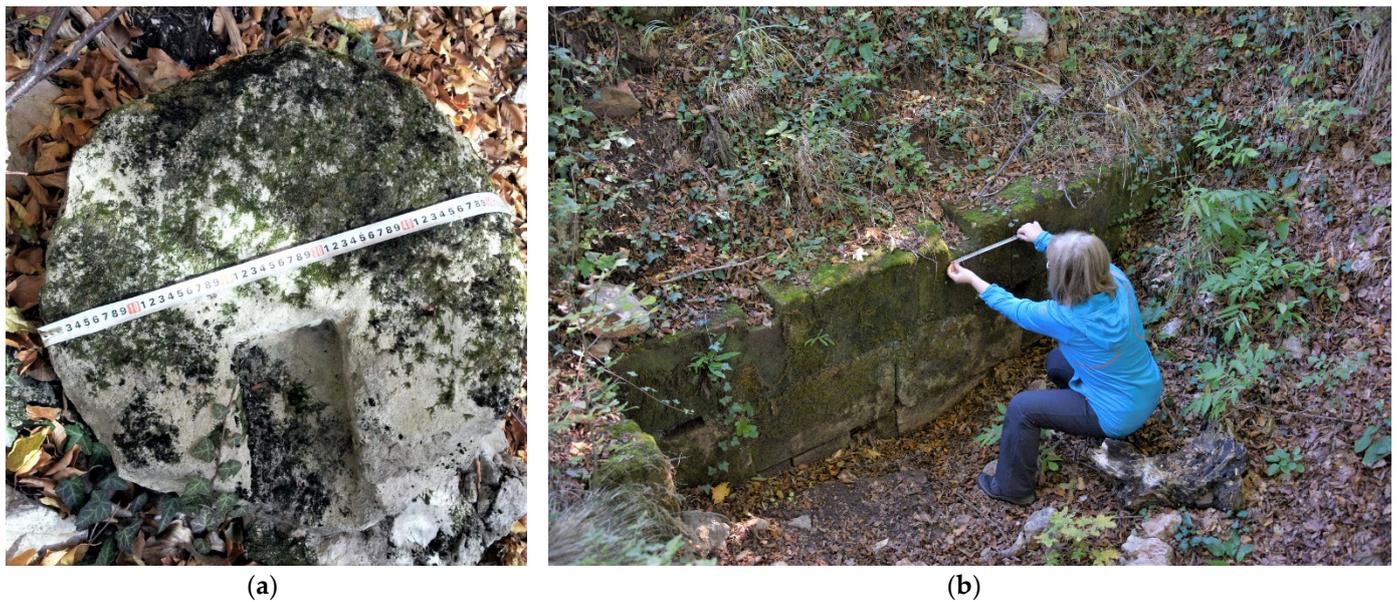


Figure 9. Ashlar blocks at Piatra Roşie Dacian fortress: (a) Limestone block from walls; (b) Measurements inside of the northwestern tower T1.

5.1.1. Walls

The highest quantity of squared stone blocks was used in the construction of the walls of the plateau fortifications. The construction technique was of Hellenistic inspiration: double external wall of close-fitting stonework made of quarry limestone held together with transversal wooden beams and emplecton made from local stones and earth (Figure 10). It had a total thickness of about 3.50 m.



Figure 10. *Murrus dacicus* was the construction technique for the walls and towers of fortification from enclosure I: (a) 3D reconstruction of the eastern side of the enclosure I; (b) Horizontal section through the wall, with the two paraments, the connecting wooden beams and emplecton.

The northern side was 46 m long, and the length of the fortification measured at the middle of the enclosure, from the exterior of the northern wall to the exterior of the southern wall was 106.35 m. The western side had collapsed in several places and the southern side measured only 15.80 m.

The long sides of the fortification acted, almost certainly, also as supporting walls, their batter being placed 3.40 m (west), respectively 4.50 m (east) below the level of the plateau. It is difficult to estimate the height of the walls above the plateau, but existing data suggests a minimum height of 4.40 m.

The second fortification, that enclosed the space on the eastern slope, was built from local stones and earth and had an external wooden palisade. On the southern side has been identified an inner parament of dressed masonry, but reused from older constructions. Although in the sections done on the other side the parament cannot be seen, one can suppose that they existed on all sides of the fortification. In any case, the entrance, situated on the western side, had been reinforced with a segment of wall on each side of the gate. The segment to the south of the entrance has been researched in 1949 and it was found that it was 15 m long with a thickness of 1.80 m. It had two paraments, the emplecton was mixed here with mortar (here defined as “small-sized aggregate material mostly used as a structural binder between masonry units”—[16] (p. 49), and the stone blocks were of various dimensions: $50 \times 32 \times 18$ cm, $54 \times 36 \times 25$ cm, $50 \times 47 \times 25$ cm or $40 \times 34 \times 22$ cm. The segment to the north of the entrance gate has not been investigated, but a few stone blocks are still visible in the field, and it is possible that the length of this wall was similar to the one of the southern segments. The height of the wall must have been here of at least 3 m.

5.1.2. Defensive Towers

Four interior defensive towers have been identified in the field, part of the plateau fortifications: one in each of the northwestern (T1) (Figure 10b), northeastern (T2), and southeastern corners (T4), and the curtain tower (T3) on the eastern side, the one most exposed to the enemy. The tower no. T2 was also a gate tower, being the place where one entered the enclosure (Figure 11). It is supposed that there was a fifth tower (T5), in the southwestern corner of the fortification that must have collapsed when the corner of the plateau collapsed. However, topographical measurements have shown that the southern and western side do not meet up, and, at least in the last stages of the fortification, there could not have been a tower in that position. It is possible that this tower existed in one of the earlier stages of the fortress and then it had collapsed, and the configuration of the fortification has been modified and adapted to the new terrain realities.



Figure 11. The gate tower T2, the entrance to enclosure I on the fortified acropolis of Piatra Roşie.

The towers were not equal in size; their walls were 3 m thick. Tower no. 1 was square and on the exterior its sides measured 9.10 m. Tower no. 2 was 12×11.60 m, and towers

3 and 4 had sides of 10.80×11.20 m. The height of these towers was estimated to 4–5 m above the level of the walls.

5.1.3. Bases of Dwelling Towers

There are four known dwelling towers in the area of the fortress (A–D), out of which one has not been investigated, only identified. Two of these (A and B) were, at some point, integrated in the second fortification, in its northeastern and southeastern corners. Tower C, situated to the east of the fortress, is the most advanced, and controlled the access inside the fortified area. Tower D has not been investigated. The extremely rich inventory of these towers and analogies with other towers of the same type in the area of the capital, plead for their use for housing. However, they also had a defensive role.

All three towers that had been investigated had a square plan, and their bases were built using the same embleton technique, with double wall of dressed stone masonry and embleton. The height of the foundation was of 3–4 rows. The superstructure was made of clay bricks dried in the sun (adobe), while the roof was made of Hellenistic type tiles and shingles. The base of such a tower was 11.30 m on the outside, and the walls were three meters thick. The interior was used as food storage area. The living space itself was on the upper floor.

5.1.4. Stone Foundations of Wooden Houses

All the four buildings identified were made of wood, with wickerwork and clay walls, and had as foundation a single row of stones. In three of the four cases these are quarry blocks, while in the fourth local stone was used, with only the doorsteps made of dressed masonry.

The building inside the enclosure on the plateau measured 22.50×13.20 m and was divided into two rooms. The blocks in its foundation had variable dimensions but were relatively similar: $48 \times 40 \times 20$ cm, $43 \times 28 \times 18$ cm or $43 \times 30 \times 18$ cm. This building was surrounded on three sides by an apsed porch with foundation blocks of similar dimensions. The perimeter of the porch measured approximately 85 m.

The destination of the two buildings on the outside of the plateau enclosure is unknown (might have been store houses or living quarters) and had big dimensions. The western one was 22.50×13.50 m and was divided into five grouped rooms. The dimensions of the foundation stones vary slightly around the values of $44 \times 30 \times 22$ cm. The building on the east side measured 26×5 m and contained four rooms in line.

Finally, the building on the terrace immediately below the plateau contains two rooms, one rectangular and one with an apse, measuring 7.50×7.80 m (the rectangular room), respectively 7.80×3.20 m (the maximum depth of the apse). Its foundation blocks measure $45 \times 22 \times 18$ cm.

5.1.5. The Monumental Stair

It is situated inside enclosure II and seems to have connected the entrance to this enclosure with the entrance to enclosure I (Figure 11). Only its upper side has been conserved, just before entering the plateau, on a length of about 40 m (Figure 12). According to C. Daicoviciu, the stairs started right before the entrance to enclosure II, went through the tower gate of enclosure I, and climbed on the plateau. The total length between the two gates is of about 127 m, and its width is of about 3 m [7]. The stair was made of blocks of various dimensions: $40\text{--}50(60)$ cm \times $40\text{--}45(50)$ cm \times $30\text{--}40$ cm, with a tolerance of 1–3 cm around these values.

The blocks were embedded in the slope on $\frac{3}{4}$ of their height, the only part remaining outside being a strip of stone that straddled the block in front (Figure 12b,c). Thus, they looked like partly overlapping slabs. On the portion that is still conserved, the stair had 4–5 such rows of blocks (Figure 12d) that form shallow steps. On the flat portions of terrain, the steps alternated with platforms.

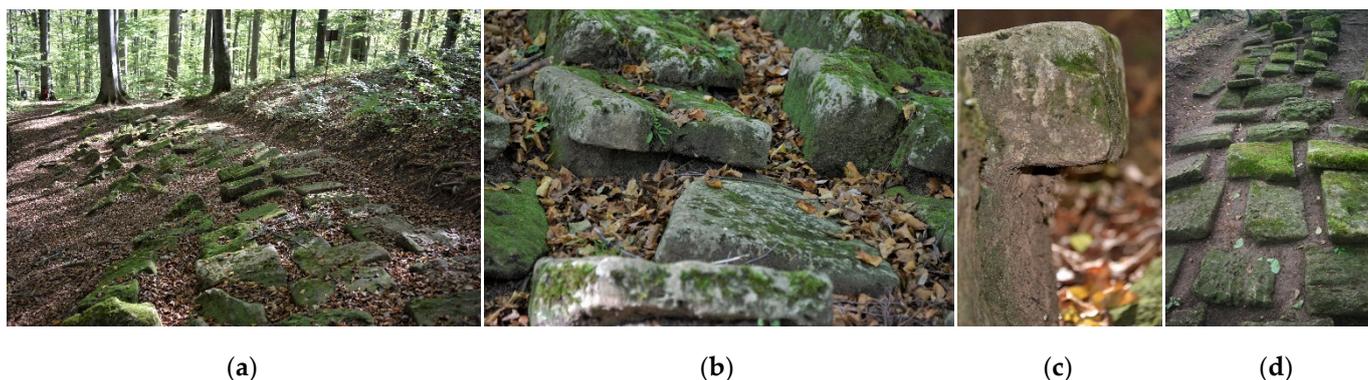


Figure 12. The monumental stair; (a) View just before entering the plateau; (b), (c) Particular shape of blocks, allowing the embedding in the hill slope; (d) There are still visible 4–5 rows of blocks.

5.1.6. The Paved Walkway

Before reaching the gate, a paved walkway branches from the stone stairs, leading to the east towards the apsed building. The walkway stopped on the threshold of the building and is almost completely conserved. Its width is of 1–1.20 m, and its length of about 27 m. It was made of limestone blocks disposed in two rows. The visible side of these blocks measures 40–60 cm × 32–50 cm.

5.1.7. Column Bases

On the plateau, outside the enclosure, there was a temple with wooden columns placed on cylindrical limestone plinths. Their number is not known, because the temple had been dismantled by the Dacians themselves, and some of the stone elements have been reused. Six plinths have been identified in the field, arranged in two rows (2, respectively 4 on each row). The plinths have a diameter of 60 cm, and a height of 40 cm. It is generally considered that it had 4 × 6 columns [17] (p. 168).

5.1.8. Ruins of Uninvestigated Constructions

In the fortress area, there are several artificial terraces where ruins of uninvestigated ancient constructions with stone foundations, or stone blocks scattered around, the remains of such constructions, can be observed. The number of these blocks is difficult to estimate, but it is most certainly in the range of several hundreds. There is no certainty that they were contemporary with the structures on the upper side of the hill.

5.2. Selection of Resource

The selection of the stone resource for the Dacian fortresses in the Șureanu-Orăștie Mountains was a necessity, determined, in fact, by the type of geological substrate. Despite the morphology of the areas where they have been built, most of them at over 800–1000 m altitude, no source of stone fit for the purpose could be found in the near vicinity for any of the fortresses on the list of the UNESCO Heritage Site (and neither for the ones around them).

A primary analysis of the geology of these perimeters shows that these fortified acropolises were placed mainly in areas with crystalline rocks of gneiss and mica-schist and secondarily on carbonate sedimentary deposits, even these having a structure and characteristics improper for obtaining geometrically shaped construction elements. Finally, the local rock has only been used as fragments of various dimensions [7] (p. 395), as strengthening elements, fillings, or in consolidated mixtures with other materials.

The source area for the construction stone had to fulfill, cumulatively, several conditions: (i) to represent an accessible perimeter suitable for the development of a quarry and for its logistics, (ii) the stone had to be found in sufficient quantity [18], (p.40), (iii) to be eas-

ily quarry-faced as blocks or other dimensioned construction elements, and (iv) to present resistance and durability at least acceptable for their intended use [19] (pp. 676–682).

As we have previously detailed in this paper, this location was represented by the perimeter of carbonate rocks disposed in quasi horizontal strata in Măgura hill (Figure 8) [20], close to the present-day village of Călan, known during the Roman times under the name of Aquae, due to the thermal springs in the area. The fact that it was situated at a rather long distance (20–35 km) from the surrounding fortresses proved to be, in the end, just a problem of logistics, that was handled successfully, if we take into consideration the volume of stone blocks visible today on the sites, notwithstanding that which has not yet been unearthed.

The ruins of the fortresses still visible in the present in the Șureanu-Orăștie Mountains prove an aspect that would not have been assumed at a simple glance over the limestones used. These are light colored, in shades of creamy white, varying to yellowish and even reddish shades (this last case is a unique situation that is only found at Piatra Roșie). The stone has predominantly oolitic to intraclastic and bioclastic structure, and even though it does not present special ornamental characteristics, its behavior in time proved high durability, considering the climatic conditions, with at least 20–30 freeze-thaw cycles every year and probably over 50–60 days annually with temperatures below 0 degrees Celsius, at least for some of them.

The natural way in which these stones have kept their resistance properties was, in some cases, the deposition of a clayey and biomineral layer that filled the small cavities and covered the surface of the blocks (Figures 8b and 12) [21] (pp. 23–25), insulating the interior and protecting it from significant chemical transformations and physical degradation [22] (pp. 61–65). In other cases, the change in surface properties under the effect of insolation and humidity led to successive processes of dissolution and redeposition of carbonate material of millimetric thickness, even though there have been found blocks (mainly limestones with increased fossil content) whose surfaces appear to be unaltered. The fact that it is not yet known if these have been exposed to the weather for thousands of years or have been unearthed only in the last century means that this aspect could not be completely explained and needs in-depth analysis in the future.

Another characteristic of the limestones used, supported by the first compression and bending tests on the source rocks at Măgura Călanului (PROCEMA CERCETARE—Testing report no. 1751/20.10.2020, Laboratorul de Construcții CCF—testing report no. 6171/17.11.2020—unpublished), is represented by the load-bearing value of the stone. In construction, this term defines the property of masonry elements to support loads and/or forces in excess to their own weight [23] (p. 328). For the limestone tested, the average value of the compression strength was 40–60 MPa, and its flexural strength was of 6.80 MPa.

The compression strength value is normal for this type of limestone [24,25], but the flexural strengths obtained on the specimens are lower than the expected values. In order to compensate the potential fragility, the ancient masons applied special constructions techniques. The wall was, in fact, a double wall with the two paraments connected with transversal wooden beams, while the space between them was filled with an emplecton made of local stone and clayey material (Figure 10). For a wall thickness of about 3.50 m, its resistance was not just doubled, but increased at least 3–5 times, compensating the lower resistance of some varieties of limestone used and reaching values typical for the types of rocks that can be used in erecting walls even of 8–10 m tall.

This is another clear example of how a stone with medium physical-mechanical properties could become a resource suitable as construction material [26] in a given morphological areal.

5.3. Petrography and Mineralogy

The limestones from which the ashlar stone masonry was made for the fortifications on the Piatra Roșie peak have been investigated from the petrographic and mineralogical point of view, initially just for a brief qualitative characterization, later also in order to determine what elements contributed to the stone durability over millennia. Part of them,

especially those from the walls, were covered, till the last century, by soil and vegetation. Also, a great number of blocks have fallen, directly or after rolling, both at the base of the steep western slope and on the eastern, softer, slope, or in the area of the northern terraces.

After the archaeological campaign in 1949, some areas have remained unearthened, with the morphology of the plateau modified by mounds of earth remaining on the field from digs, ditches and the other excavations. In those areas the weathering processes were the most intense, including physical degradation and biochemical changes of the stone blocks' surfaces.

Petrographic observations in the field, on more than 50 blocks, have revealed a variety of limestones where the macroscopic differences consisted not just in differences in color and compactness, but also in structure and texture. On the surfaces not covered with crusts or mosses were identified two predominant limestone types: (a) oolitic and oolitic-fossiliferous limestones, with more or less carbonate binding, but with granulations clearly varying from sub-millimetric to millimetric, with quartz centers or completely carbonate, and (b) fossiliferous limestones.

A number of 19 optical mineralogical analyses were performed in polarized light on the limestones used for the ashlar masonry and they have showed most clearly the high number of varieties and subtypes present at Piatra Roşie. Respective to the time of the publication of the first results of the mineralogical petrographic analysis [3] (pp. 820–822), some supplementary groups have been selected. This action took place as a result of recent mineralogical analyzes on samples of limestones from the Dacian quarry at Măgura Călanului studied during the years 2017–2022.

The criteria selected for the classification and comparative evaluations has been the proportion of allochemic constituents (clasts, oolites, fossils, peloids, lumps, secondary minerals) and not the type of carbonate binding (micritic or sparitic). Thus, the names of the principal categories identified reflect this aspect by grouping in four classes, each of them including more subtypes.

5.3.1. Ooidic Limestones

They represent the main type of limestones used for the stone masonry at Piatra Roşie, with a general coloring ranging from yellowish-cream to whitish-cream (Figure 13), sometimes presenting light-brown films of limonite, and have medium compactness and resistance. The percentage of oolites (regardless if they have a central core of quartz, fossil, feldspar, muscovite, etc.) is higher than 40–50%. The identified subtypes are as follows: oolitic limestones, bio-oolitic limestones (fossils over 5–10%), intraclastic-oolitic limestones, intraclastic sub-oolitic limestones (oolites below 30% of all allochems), light-fossil oolitic limestones (fossil content below 5%), all these sub-varieties being found also in the samples from Măgura Călanului antic quarry (Figure 8).

In what regards the stone from tower no.1, the oolitic to intraclastic-oolitic limestone is, in both aspect and constituent allochems, visually distinguishable from all the others by its intense purple-reddish color (Figure 14) and has high compactness, apparently superior to the other varieties identified so far at Piatra Roşie or Măgura Călanului. In case the hypothesis of its provenance from Măgura Călanului is correct, its rather massive appearance could be the consequence of the existence of a very compact stratiform layer that might have been quarried and depleted before reaching the present morphological level. As for the reddish color, it might be due to in situ secondary limonitization on a far more advanced level than all the other subtypes found in the Dacian fortresses or in the ancient quarry, a hypothesis supported by the higher percentage of iron found in the soil, a fact that also gave the name of the peak (Piatra Roşie = Red Rock).

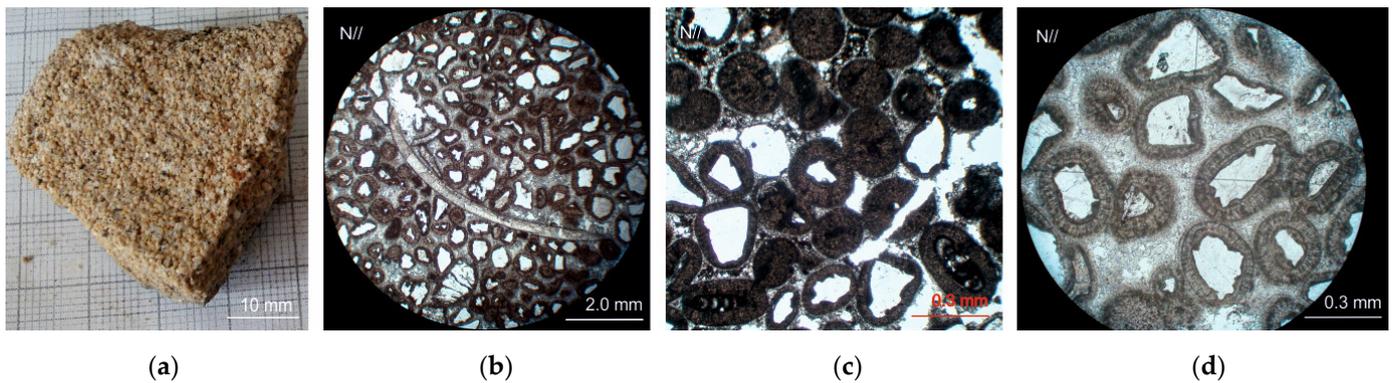


Figure 13. Ooidic limestone—the most widespread variety of limestone used in the walls of Dacian fortresses: (a) Sandy texture, yellowish-cream color; (b) Microscopic image of fossil-poor oolitic limestone; (c,d) Types of oolites with and without central core, in a mass of sparitic binder.

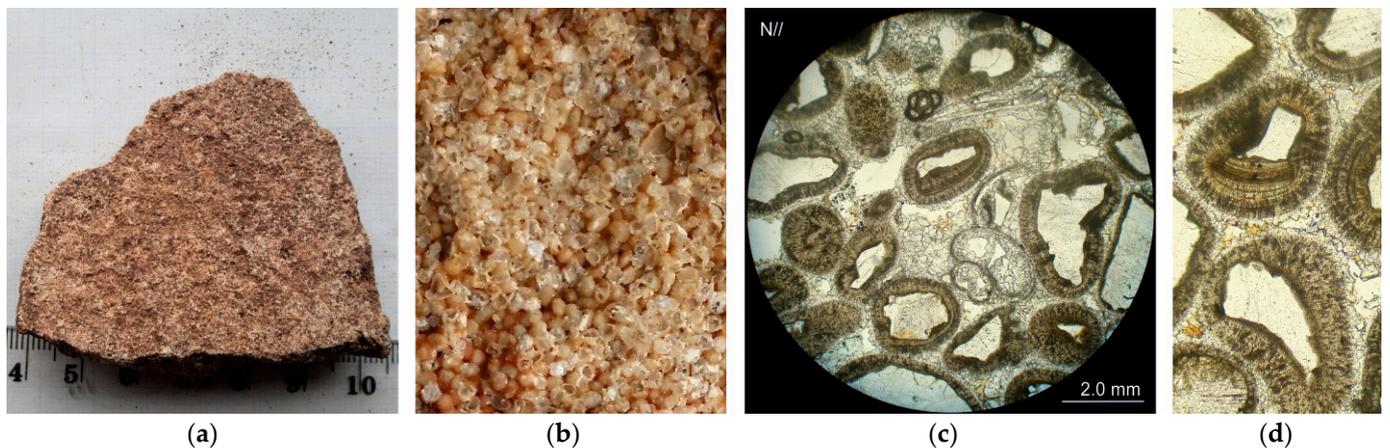


Figure 14. Highly compact reddish intraclastic oolitic limestone: (a) The macroscopic appearance is influenced by the predominant color and the sandy-size of the allochemes; (b) Mesoscopic view, in which the reduced percentage of the binder in the rock can be observed. (c) The oolites, which are predominantly subangular shape, generally have a quartzite center; it may be missing in rounded or subrounded oolites; (d) Films of iron hydroxides could be observed in the voids of the pore sparitic cement, contributing to the overall reddish appearance.

Proof of the process of alteration in contact with exogenous factors can be found in several samples from both areas, but at Piatra Roşie, around tower 1, it seems to either have been more intense (more than 1–2 cm inside the stone block), or the source of this petrographic variety differs from the known ones. Future archeological excavations are expected to expose blocks that might bring further information and clarification on genetic varieties of limestones, but, for sure, a similar type has not yet been identified in the area of Măgura Călanului historical quarry.

5.3.2. Intraclastic Limestones

They are stones colored from whitish to creamy-white (Figure 15a) and light-brown on the exposed areas, with a brittle structure and low resistance. We have identified intraclastic limestones, oolitic/oolitic intraclastic limestones (the clasts present successive ooidic layers, but have a high degree of angularity), sub-oolitic intraclastic limestones, and also light fossiliferous or bio-oidal clastic limestones. These varieties have also been identified in the samples from Măgura Călanului historical quarry, and have been analyzed both under stereomicroscope and an optical microscope (Figure 15).

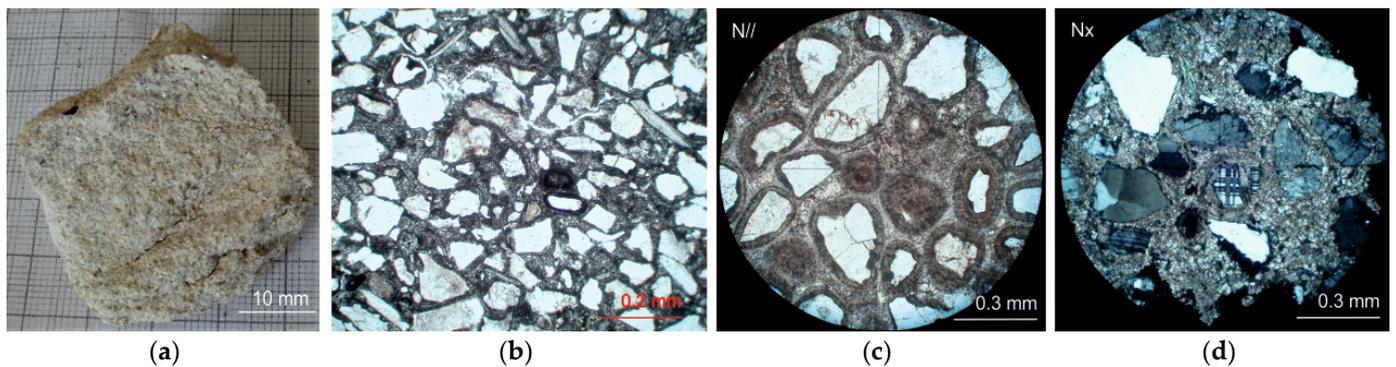


Figure 15. The intraclastic limestones: (a) Usually is colored from whitish to creamy-white and the appearance is slightly more friable on the mineralogically analyzed samples; (b) the size of the clasts varies, but generally they are submillimeter; (c,d) There are also transitional varieties, such as oolitic intraclastic limestones, sometimes slightly fossiliferous.

5.3.3. Bio-Pelletoidal Limestones (Lump)

With a more porous structure than previous types, these types of limestones (Figure 16) contain more than 30–40% pellets/peloids (algae remains or microorganism waste that went through a process of diagenesis) or lumps (granular aggregates of bio-peloids, ooids, fossils, or intraclasts). Their base coloring is yellow-cream to white, but supergene alterations with film deposits of limonite and the bio-mineral deposit processes often lend them a red-scarlet aspect. Sometimes, the ooidic aspect of the samples is more visible, a fact that determined the hypothesis that it might have been possible that this type of limestone could have existed in the strata at Măgura Călanului, even if it had not been confirmed so far.

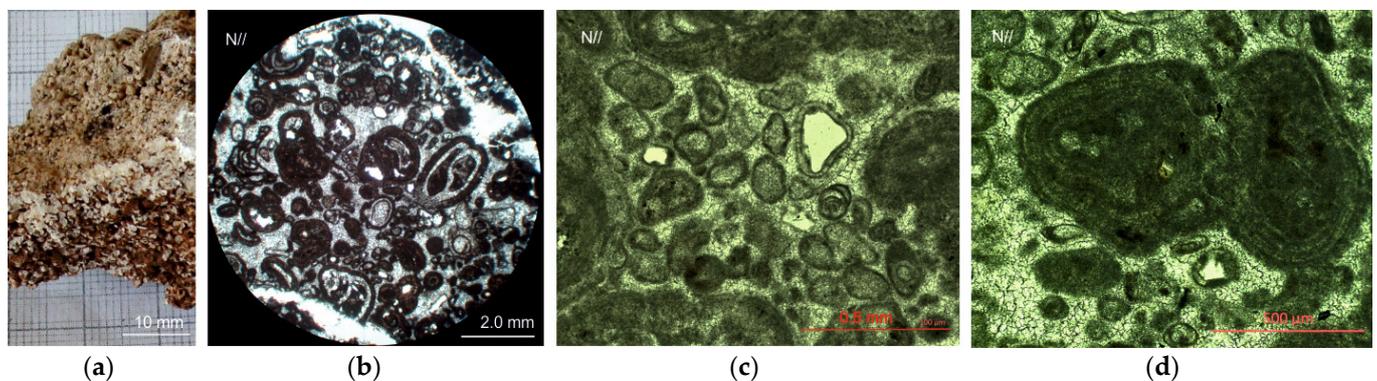


Figure 16. The bio-pelletoidal (sometimes and sub-oolitic) limestones: (a) The limestone presents a more porous structure; the color is influenced by the supergene alterations, changing from yellow-cream to reddish; (b–d) Microscopic images of some varieties of bio-peloidal limestone.

5.3.4. Fossiliferous Limestones

There have been identified some varieties of limestone with a predominantly fossiliferous to sub-oolitic aspect, where the dimensions of the skeletal shapes allow for easy microscopic identification (Figure 17).

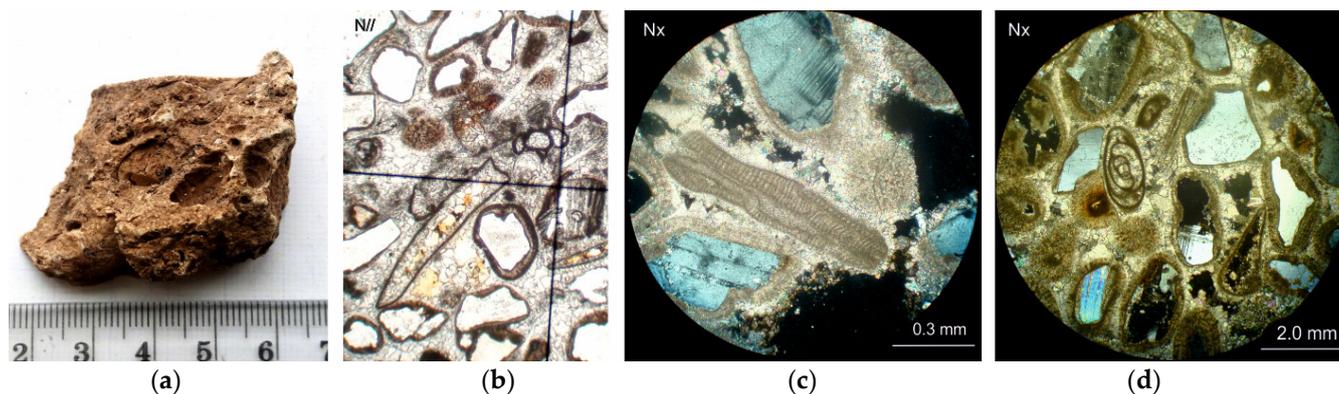


Figure 17. More subtypes of fossiliferous limestones were identified in the area of fortress, depending of the predominant type of fossils: (a), (b) bivalves, (c) crinoid, (d) foraminifer; limestone with gastropods were also highlighted.

5.4. Durability of Stone

When conducting research in an area of archaeological value, it is important to select investigation techniques adapted to the necessity of preserving such a site. Thus, in order to find the qualitative characteristics [27] (p. 3) of the rocks used for the fortress blocks, we had to use nondestructive laboratory tests [28] (p. 60) on the samples obtained from the Piatra Roşie, instead, all the destructive laboratory tests were done until now on limestones from the ancient quarry of Măgura Călanului, the main source of stone for the fortifications.

In 2020, the first analyses performed on samples from a stone block from the area of the Măgura Călanului quarry (Figures 8 and 18) led to the physical-mechanical characterization, for the first time in the research of the site, of a variety of oolitic-fossiliferous limestone used for the fortress blocks and identified in tower no. 2.



Figure 18. Laboratory analyses were conducted on samples from a stone block from the area of the Măgura Călanului quarry, for the first time in the research of the site: identification of the strata with fossiliferous limestone in the main quarry, sampling made of limestone block from the abandoned quarry and laboratory mechanical tests (compression strength and flexural strength).

The results were obtained according to modern investigation techniques following European harmonized standards [2,29,30], and the values have been inputted in the analysis of rock durability. Moreover, the medium relative density of the rock of 2230 kg/m^3 (Table 1) has been used both in the calculation of the weight of the ashlar blocks measured inside the fortress and in the evaluation of the total mass of rock transported for building it.

Table 1. Physical-mechanical properties of fossiliferous-suboolitic limestone.

Parameter	Unit Measure	Value
Water absorption	%	1.61–7.18
Real density	kg/m^3	2650
Apparent density	kg/m^3	2198–2270
Open porosity	%	4.82–14.10
Compression strength	MPa	63.26
Flexural strengths	MPa	6.80
Compression strength after 56 freeze-thaw cycles	MPa	61.65

The laboratory analyses have been performed in two Romanian laboratories certified for this type of tests, the results being interpreted both individually and also comparatively and cumulatively, in order to obtain the most representative average values for the rocks tested and for lab tests. This was necessary because the rocks from the Măgura hill present also a very high variability, as shown in the previous chapter. Even if these values are just the first in their series, new laboratory analyses are in 2022 on their way using the variety of oolitic limestone.

For the limestone from Măgura Călanului under investigation, the laboratory results have indicated normal values for a carbonate rock [31]. The sometimes-significant differences between the individual values for the mechanical tests are due to the textural variability from inside the block where the samples have been collected, respectively to the random presence of holes created by the decomposition of the carbonated skeleton of the bivalve fossils (Figures 8b and 18).

Another preliminary conclusion from the analysis of the laboratory results is the very good behavior of the stone after freeze-thaw cycles. Both the loss of mass and the lowering of the mechanical strengths are very low, another aspect that indicates a good behavior of the rock in terms of durability, and one that supports the observations that we have made on all the sites.

5.5. Workability

Regarding the property of the limestones from the Măgura hill of being easily dimensioned into masonry blocks and having work done on the exposed surface, this is very clear from the aspect of the sedimentary stratification visible in the quarry (Figure 9). Stone quarrying involved the extraction of rough blocks from horizontal and sub-horizontal layers, thus the relative evenness of 40 cm of one of their sizes (width, thickness or even length). Then the rough blocks were dressed through specific techniques [32] with mallet [33] (p. 96), chisel and wooden wedges to the maximum resultant sizes (Figure 19).

Locally, on the vertical sides of extraction points, chisel-dressing of the stone can be observed (similar with some of the blocks from the area of the Piatra Roșie fortress), made by chisels with various point thicknesses (Figure 19a,c). The traces left suggest localized hammering or longer lines, sometimes a little curved (Figure 19d). The texture of the rock facilitated the process of splitting (Figure 19b), but all actions followed the direction of strata (Figure 19a) and respected the way the stone cracked under unique directional strokes, for minimal processing work. Indeed, this is also the most important selection criteria [34] for a rock used in construction work, and one that defines its property of “workability”. The limestones from the Măgura Călanului area [35] fit well in this category, unlike the carbonate bedrocks from the Piatra Roșie or Bănița hills, or the crystalline rocks on which the other Dacian fortresses from the Șureanu—Orăștie Mountains were built.

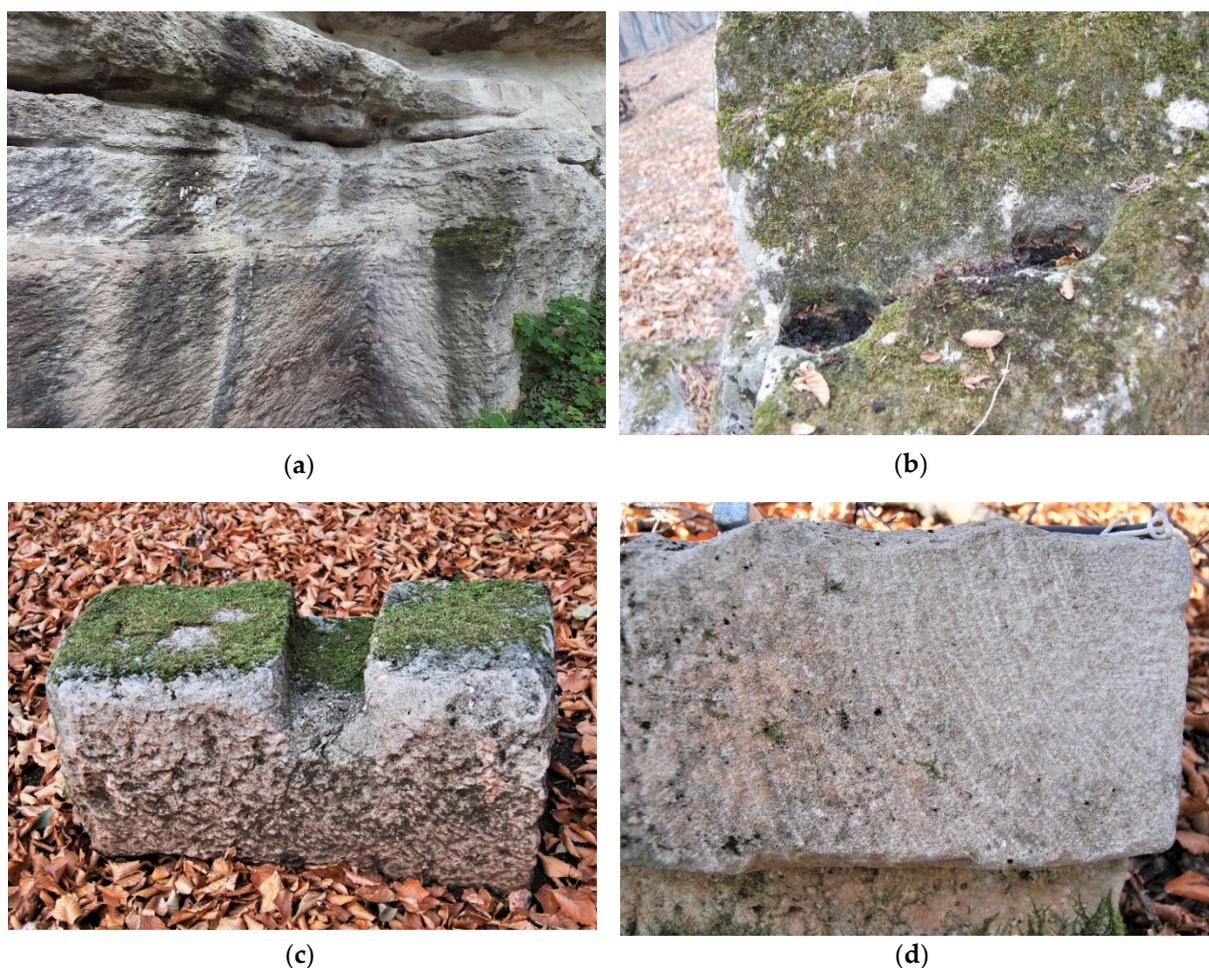


Figure 19. The main property of limestones from the Măgura Călanului quarry is the workability: (a) Traces of quarry-facing on stone and splitting at Măgura; (b) Chisel marks for detaching the blocks; (c) Stone block from Piatra Roșie fortress with ditch for wooden anchoring beam, dressed by hammering; (d) Fine chisel-dressed face of a limestone block at Piatra Roșie.

The first processing stages of the stone were done inside the quarry, including quarry-facing of stone and removing of all unevenness of the block sides. As no block with ditches for wooden anchoring beams and for other connecting or mounting elements was found in the quarry area, most probably these holes were made in situ, where the scrap from processing could be included in the wall infills (Figure 11) [1] (p. 62), together with clay, fragments of local rocks and other binding agents.

5.6. 3D Evaluation of the Volume of Limestone Blocks

The 3D modeling of the Piatra Roșie fortifications have required the integration of several unknown construction information. Although some terrain profiles from archaeological excavations were available, the public data did not include any specific data regarding the surface morphology on which the walls were built. Consequently, it is unknown at what depth under the surface the first blocks of ashlar masonry were placed for each wall section, an information that is essential in the evaluation of the volume of stone. Moreover, nowhere was the masonry preserved at its original height, so this value had to be evaluated by correlating information from the site monography [1] with data specific to other Dacian fortresses [5].

A specific stage was represented by the measurement of all stone blocks visible in the area of the fortified acropolis (Figures 9 and 20), for volumetric evaluations and for the

approximation of the probable number of blocks that had to be transported for the erection of the fortress.



Figure 20. Ashlar blocks in the area of fortified acropolis: (a) In the sinkhole, before the entrance in the Enclosure I; (b) The western wall of the plateau fortification.

5.6.1. The Foundation Ground

Accurate topographical information was limited until 2012, when Dacica Foundation made the first topographical survey of the area and drew a detailed plan of the fortress. As a starting point for the representation for the purpose of this paper, the sketch of the plateau (done by direct measurements during the archaeological excavation from 1949) was superimposed on this updated topographical plan (Figure 5) and then scaled to coordinates.

It became clear that the older sketch could not be completely overlapped on the current situation in the field. On the whole, the terrain morphology for both enclosures (I and II) no longer corresponds with the situation in antiquity. The differences are quite important, if we take into consideration only the fact that after the walls were destroyed, the soil and the supporting stone structure probably spilled on the slopes, thus changing also the terrain configuration.

In the first stage of the 3D reconstruction of the terrain surface, we chose a flat reference level for the whole of Enclosure I. This was probably the case in reality, being achieved at that moment through filling that acted at the same time as a support for the walls (Figure 11). However, the excavations from 2004 (stopped next year) have shown that there were some slight level differences on the plateau. Thus, it became clear that building 2 was positioned at a higher level than the entrance, indicating the existence of a step. This aspect has been custom integrated in the 2D and 3D models of the fortification.

In the absence of any information about the ground terrain under the four exterior towers (two from Enclosure II and the other two lone towers) this was considered as flat, even if it would have required a leveling process. The topographical measurements from 2012 have also indicated the fact that the base of the walls wasn't at the same level on all sides of the fortress. On the northern and southern sides, they presented the smallest height, thus being considered as a reference in the modeling processes. In the same way, we decided to conduct the modeling process using the option where the towers had, on the inside, the same stepping level as the plateau, marked by the level of the last visible slab of stone of the access stairs.

5.6.2. The Dimensions of the Geometric Construction Elements

In order to perform the 2D/3D modeling of the stone constructions, as an efficient tool to represent and manage information of Cultural Heritage [36–38] (p. 258), the first stage was to place the towers, buildings and walls, and the access stairs on the topographic

plan (scale 1:200, Stereo '70 coordinates), as they could be seen in the field (as they were left by the incomplete covering with earth of the archaeological excavations from 1949). This is, indeed, the most certain element from the models, as it can be verified in the field at present. Of course, the proposed model for the site is not to be considered the final version, because a detailed investigation might offer differences from the image we have at present. For now, though, it can be considered that all elements and measurements mentioned in reference documents or measured in the field have been interpreted and integrated with the highest possible accuracy.

The next step was to determine the most probable dimensions of the walls and towers, so that they can be used as input in the spatial projections (Figure 21).

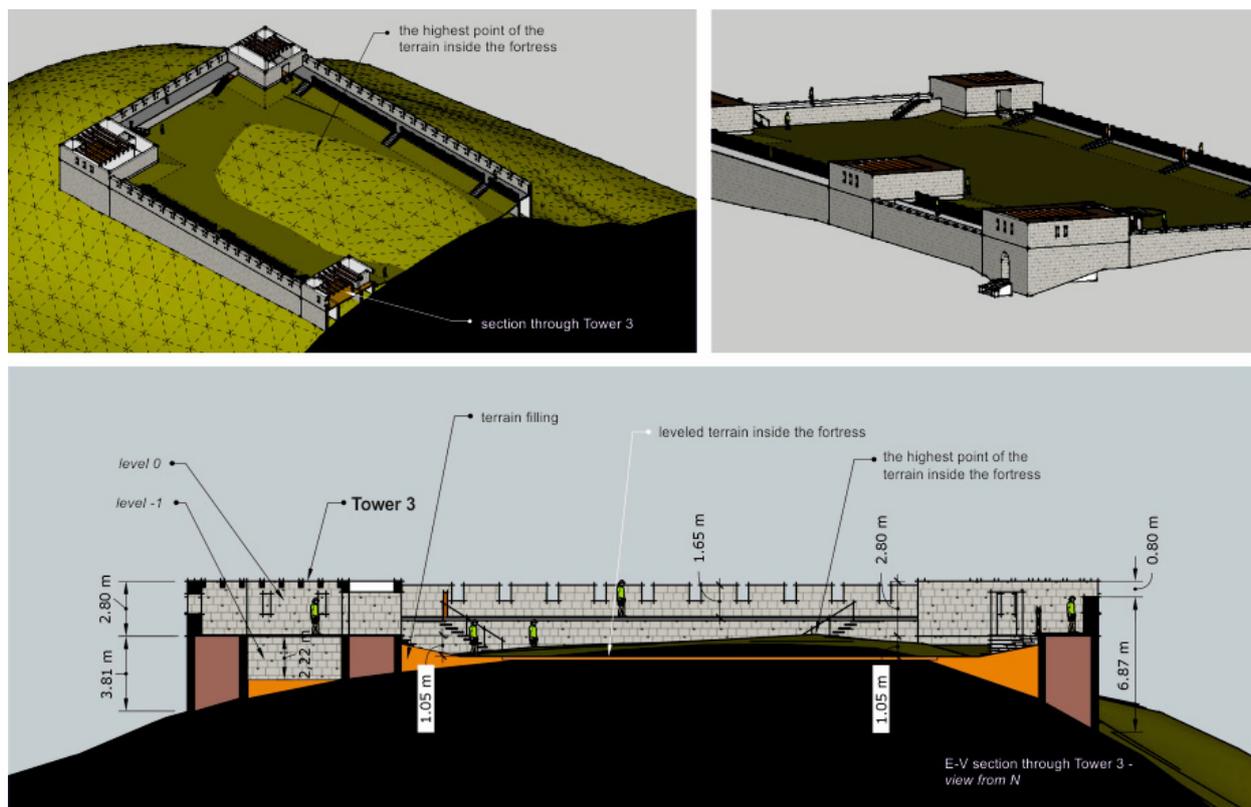


Figure 21. 3D images of the fortified enclosure during the designing stage for the evaluation of the stone volume.

If the 3 m thickness of the walls is clear (Figure 22a), their height was more difficult to determine, due to the bad stage of conservation of the fortifications. The towers used to dominate the fortress walls, rising at least 4–5 m above them [1] (p. 44). In the end, in the 3D image obtained, we considered that the maximum height of the stone structure was 10 m, which determined that the minimum height had to be of 5.6 m on the western side, depending, of course, on the surface of the terrain.

The data was also inferred from the iconographical information offered by the representations of Dacian fortresses on Trajan's Column [39] that suggested (by number of stone rows) a height of the towers 3–5 m above the level of the walls. In their turn, the walls had, for sure, both a defensive and a delimitation role and also the role to support the plateau on which the fortified enclosure was built.

The modeling of the 3D image included, for the purpose of volumetric evaluation, both the guard road and the battlements and crenellations. Obviously, we also performed an analysis without these elements, but the difference in values were small when compared to the scale of the fortress.

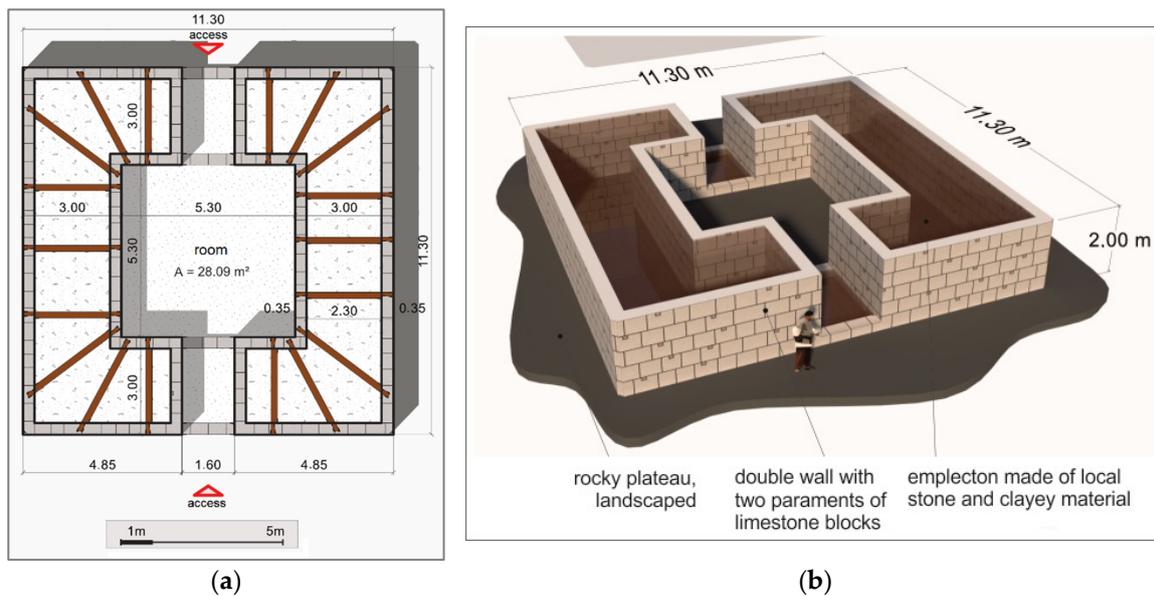


Figure 22. 2D and 3D construction models of dwelling towers (source: Romania De Vis): (a) Plan view of the base level of a dwelling tower, highlighting the system of strengthening the two paraments of the walls of dressed stone masonry, through wooden beams and emplecton; (b) 3D view of the double walls of a dwelling-tower, which had 1 or 2 entrances on the lower level and up to 4–5 rows.

In order to evaluate the theoretical number of blocks and slabs, we performed measurements of the elements visible in situ in the enclosure on the acropolis and on the other side of the eastern slope of the Piatra Roşie hill, and also from inside the stone quarry from Măgura Călanului. At Piatra Roşie, their dimensions vary between 60 and 110 cm long (sometimes even 140 cm), 40–80 cm wide (with values predominantly between 60 and 70 cm) and a thickness from 20 to 60 cm (predominantly 30–40 cm, similar with the blocks in the stone quarry).

For 3D modeling purpose only, we used a thickness and a height of 40 cm for the limestone blocks, resulting in a maximum number of 13 rows for walls and 23–25 rows for tower no. 4, the highest one.

Another important architectonic element was represented by the stone stair that ran from the entrance to enclosure II to the entrance to enclosure I. Thus, we introduced into the graphical representation the 127 m evaluated for its length, with an average width of 3 m [7] (pp. 412–413). In what regards the dimensions of the slab blocks used in building the stairs, we averaged the measurements for two sides for 104 blocks found at present on the terrain surface (even if they were in various locations—Figure 11), respectively on three sides for the seven elements of the stairs found in the pile of blocks rolled in the sinkhole near the stairs (Figure 21). It resulted an average dimension of the blocks of 50 × 40 × 30 cm (including the overlapping strip) to be used in the volumetric calculations.

The stairs were not continuous. The steps alternated with platforms on the flat portions of terrain, assumed, by the geometry of the terrain, to have been at least 3. For a difference in level of 33 m [7] (p. 407) on a length of 127 m and an average slope of 16°, resulted a theoretical number of 307 steps, with a depth of 50 cm and a height of 11 cm. If we take into consideration 2–3 platforms (one of which at the entrance to tower T2), the number can probably be reduced to 280–290 steps, but the amount of stone had to be similar, as the platforms were also built of limestone slab blocks.

Each step was, in fact, constructed from blocks placed close to each other, the general aspect being more of rows (Figure 12d). It can be assumed that there were also joints between the slabs, thus we assumed that each step contained about seven blocks. Measurements in the field have shown dimensional variations in the limit of 20% compared with the average value used in our representation (Figure 22a), but it is probable that most of

the changes that can be seen today in the field (only 40 m are still visible) were due to the short amount of time lapsed from their construction to the moment when natural processes occurred, involving slippage on the embedment, shifts on the surface of the terrain after periods of heavy precipitations, possibly even some strong earthquakes or processes of variable compression due to the proximity of the sinkhole that can be found 2–3 m away from the stair, in the area right before the entrance to enclosure I.

Because of the limited amount of archaeological research, some novel stone constructions have not been measured or put in an inventory list, but their remains or traces are still visible in the field. The research remains open, and the volume of stone blocks used will be updated every time new information will become available from field research or at least from non-invasive ones.

5.6.3. The Proposed 3D Model and the Volumetric Evaluation

The proposed 2D/3D images of the stone structures are presented in Figures 21–23. In what regards the dimensions of each component of the fortified enclosure where dressed stone was used, these were detailed in the Stone elements chapter, as walls, towers, foundations of wooden buildings, foundations of housing towers with a brick superstructure, temple column pedestals, stairs, platforms, and pavements.



Figure 23. 3D model of Piatra Roșie fortified acropolis (source: Romania De Vis) [9].

Making a summary of the dimensional measurements from the last two-year field campaigns, the following net sizes (the greater, medium and smaller side [29]) for the geometry of the stone masonry blocks from the Piatra Roșie fortress were obtained:

- the length of the blocks (greater side in a natural layer where appropriate) ranges between 60–140 cm, with the majority measuring 60–110 cm in the area of the towers, respectively 40–50 cm in the area around the entrance and for the blocks scattered inside the two enclosures;
- the height of the blocks (side at right angles to the plane containing length and width) ranges between 40–80 cm, with a slight majority measuring between 60–70 cm;
- the width (the smaller side at right angles to length) of the blocks ranges between 20–60 cm, while the majority measures 30–40(45) cm.

The average volume of the measured blocks is of 0.083 mc, with a minimum of 0.036 mc and the maximum of 0.432 mc. For a density of stone of 2234 Kg/mc according to the laboratory tests, and using a computation formula where the mass is the volume multiplied by the density of the rock, results a weight varying between 80 and 960 kg/block, respectively almost 200 kg/block of average size.

For the paved road that leads from the stairs towards one of the buildings in Enclosure II, only the visible surfaces could be measured. The length of the blocks varies between 40–60 cm, and the width is between 3050 cm.

Regarding the slabs from the access stairs, visible on the last 40 m before the fortress plateau or fallen in the nearby sinkhole, for the 104 blocks measured, the length varies in range of 40–70 cm, but 60% of them have a length of 50–60 cm. Only in the case of 5 of the blocks/(from the sinkhole) we could measure the third dimension (their thickness) in the range of 30–35 cm. By extrapolation of these values to all the blocks of the stair, would result that the volume of the blocks varies between 0.036–0.090 mc, with an average of 0.060 mc. However, in order to construct the graphical representation, we used average dimensions and volumes, respectively 0.052 mc, resulting in a number of 307 steps on a stair that was 3 m wide, every step containing 7 blocks.

All the other measured elements, besides the ones grouped above (like the paved alley, the horseshoe, isolated blocks) fit in the limits mentioned above.

From the analysis of all the measured sizes of the 208 stone blocks it is noteworthy that 75–80% of them have at least one side equal to 40 cm \pm 3 cm, and even a larger percent can be assumed, if we consider that for some of them only 2 sides could be measured. Consequently, the same value has been used in calculating the volume of blocks whose sides could not all be measured. Likewise, the height of the masonry rows in the 2D/3D representations was 40 cm.

Using these dimensions and the architecture agreed according to bibliographical data, the following volumes of stone resulted, while excepting from evaluation the stone structures that are partly visible in the field, but have not yet been investigated (Table 2):

Table 2. The volume of the constructive elements of the fortress.

Name of the Area	Volume (m ³)	Name of the Area	Volume (m ³)
Tower A	47.68	North Battlement	31.50
Tower B	47.68	South Battlement	32.76
Tower C	48.94	East Battlement	89.99
Tower D	47.68	West Battlement	109.42
Tower 1-stone parament	126.13	T2-Stone Platform	7.92
Tower 2-stone parament	228.88	Steps at T1	0.32
Tower 3-stone parament	168.51	Steps at T2	0.32
Tower 4-stone parament	197.11	Steps at T3	0.32
Tower 5-stone parament	126.13	Steps at T4	0.32
North Wall	46.78	Steps at T5	0.32
South Wall	47.01	T2-Exterior steps	1.18
East Wall	198.85	T2-Exterior steps N	0.90
West Wall	204.52	T2-interior steps	3.20
Wall Pavement	76.73	T2-exterior banister	1.72
Stone Stair and platforms	121.57	T2-interior banister	2.41
Total volume of stone = 2016.80 m³			
Total mass of stone = 4497 t			

Taking an average volume of 0.083 mc/block calculated from individual measurements of 208 limestone blocks, it results in a number of 24,300 blocks (about 24,000 blocks) transported to the fortress at Piatra Roşie, this representing only the constructions that have been included in the 3D model (Figure 23) and are officially known and recognized at present.

This amount of finely dressed stone blocks used for a single small size fortress, is proof of the huge effort for those times and an example of organization and resource investment in the extracting and shaping of the limestone blocks and their transport to the fortified acropolis of Piatra Roşie, one of the fortresses from the seat of power of the Dacian Kingdom in the 1st century BC.

6. Discussion and Conclusions

The subject of the present article became increasingly relevant and important in the past two years, while its authors made progress in their research and in the spatial representations, independently, or as a team [40], according to the availability and field of specialization of each of the authors. The further the research and interdisciplinary processing of the data progressed, the more we discovered how little data we have indeed on the complexity of the construction of the Piatra Roşie fortress and, implicitly, on the stone used in its erection.

For the purpose of this paper, there have been correlated, interpreted and processed data from:

- observations in the field, both archaeological and geological;
- historiographical data, the results of the only thorough archaeological excavation at the beginning of the 20th century [1] and new data and interpretations [5];
- results of petrographical, mineralogical and physical-mechanical laboratory analyses;
- 2D and 3D modeling of different Dacian fortresses from Romania, based on the public data;
- results of the geological research that took place in the past two years at Măgura Călanului [15] ancient limestone quarry, the main source of stone for all the Dacian fortresses in the area.

The limestone used for the ashlar blocks at the Piatra Roşie fortified acropolis, but also at Sarmizegetusa Regia, Costeşti-Cetăţuie, Costeşti-Blidaru and Băniţa fortresses originates mainly from the ancient quarry at Măgura Călanului. The historical value assessment [41] made for this quarry and the analyze of its significance in human culture [42] have demonstrated this stone fulfills all the requirements for international designation as global heritage stone [43]: it have been extracted for almost 150 years, widely used in historical sites, World Heritage listed, deeply tied to the national identity [20], and presenting ongoing availability of material for quarrying, at least for restoration purposes [44].

In the quarry area, the limestones disposed in quasi-horizontal strata (layers) bear a wide typological variety: ooidic limestones, intraclastic limestones, fossiliferous clastic limestones, pelletoidal oolitic, bio-pelletoidal and micritic-sparitic fossiliferous limestones, with numerous transitions between them that have been listed as subtypes. In this paper there were briefly presented only those identified so far inside the perimeter of the Piatra Roşie fortress.

As an absolute novelty, this paper includes two types of results:

1. the physical-mechanical properties of a fossiliferous variety of the limestone used as a source of stone for the ashlar masonry at Dacian fortresses in Şureanu-Orăştie Mountains, and
2. the first evaluation of the volume of stone used in the erection of the Piatra Roşie fortress, based on the 3D modeling of the constructions revealed by the archaeological excavations from 1949 and updated by field observations and topographical measurements.

The most laborious work, due to the need to realize numerous projections and models, was the representation of the 2D/3D images of the site, respectively of the constructions erected from stone or which contained stone in their structure. For this approach, I am deeply grateful to my article colleagues Aurora Peţan and Mihai Stancu, who had numerous debates (prior to this publication, but also throughout its duration) on the basis of each construction included, to integrate in the best possible way the available historical

information, measurements and field observations with the graphical projection, to allow the evaluation of the ashlar stone volume (V.C.).

For the stone elements present on the plateau that are still in position, we could analyze various elements of geometry and positioning. We cannot ascribe the same degree of certainty to the access stairs and the connection between the entrance to enclosure II and the entrance to enclosure I, and even less about the exterior dwelling towers A, B, C, and D. These have almost completely disappeared, being destroyed either in the events associated with the second Dacian-Roman war, due to the passage of time, and also because of the reuse of some stone blocks from the ruins by locals, in modern times.

Successive observations and measurements in the field and their correlated interpretation led to the conclusion that the evaluated volume of almost 4500 cubic meters of stone blocks represents a good approximation of the masonry from the archaeological area. The average number of 24,000 ashlar blocks resulted for this perimeter is an impressive value, representative of the human effort during the century and a half before the Roman conquest, underlining the degree of development and power that the Dacian Kingdom had at the time.

We consider that the applied methodology for the evaluation of the volume of stone used in the construction of the Piatra Rosie fortress has successfully achieved its goal. It was necessary to complete the limited archaeological information, through topographic surveys, numerous campaigns in the field, intense documentation and successive modeling of the constructions in the fortified area. Thus, an evaluation methodology, used predominantly in the mining area to calculate the volumes of rock reserves [45], can also be applied for the incompletely researched archaeological sites, obviously, after adapting to their specific data. This can only be achieved in multidisciplinary teams [46] (p.110), which ensure as much as possible the accuracy of the primary data and enhance the effort to obtain 2D/3D models of the masonry structures as closer to those from the moment they were built.

Regarding the structures that have not yet been investigated and are in the perimeter of the fortified acropolis, it remains for future researchers to reveal them, by any suitable method, from non-invasive measurements, as electrometry and Global Penetration Radar (GPR), to surveys and archaeological excavations. This might help elucidate many unknowns about the construction and positioning solutions dictated by the morphology of the terrain, about the real magnitude of the defensive system, about the destination of each building or the role this fortress really played during the wars between the Dacians and the Romans.

This type of interdisciplinary study also contributes to smooth the line between the scientific and technical information derived from heritage sites incompletely researched or little-known to the public, and the global community, as the final recipient of cultural data [47].

The Piatra Rosie fortified acropolis, located to the West of Sarmizegetusa Regia, the capital of the Dacian Kingdom, represents not just a historical monument of global importance, but also a special place where the stories and the beauty of the natural landscape preserves an air of mystery beyond the millennia.

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