

## THE DECAY OF TERTIARY SANDSTONE IN A NON-POLLUTED ENVIRONMENT: CARTA CISTERCIAN MONASTERY IN SIBIU COUNTY, ROMANIA

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**Abstract:** Cârța Cistercian Monastery, built in the 13th century during the colonization of Transylvania by Saxons, is the oldest preserved monument in Romania built in the Cistercian style. Tertiary (Sarmatian) calcareous sandstones from the southern part of the Transylvanian Basin were used for construction. The sandstones, rich in quartz, feldspars and rock fragments, are feldspathic litharenites with carbonate cement and bioclasts having a very low porosity. These are not suitable as building stones due to the influence of the CaCO<sub>3</sub> and clay minerals content as opposed to the compact framework of the stone that does not allow expansions; micro fissures and dissolutions occur due to the chemical weathering. The low ultrasonic velocity proves granular disintegration of the sandstones, which presents a medium to high anisotropy. The weathering processes, macroscopically analyzed, belong to Discoloration/Deposits, Detachments, Loss of stone material, and Fissures/Deformations groups. The microscopic analysis evidenced specific weathering processes: fractures parallel to the surface of the stone, fissures running around different types of grains, radial growth of gypsum crystals, formation of crusts in varying generations, and lichens colonization.

**Key words:** weathering, decay, Tertiary sandstone, clay minerals, porosity, anisotropy, Cistercian

### 1. INTRODUCTION

This paper presents the characteristic of the weathering processes identified in the building stones from Cârța Cistercian Monastery, Sibiu County, Romania. We have investigated how geographical orientation influenced the development of some specific weathering processes due to the exposure to insolation, moisture and wind erosion in a non-industrial-polluted environment. The properties inherited by the sandstone from its depositional environment are also part of our discussions.

### 2. HISTORY AND ANAMNESYS

Sibiu (Ger: Hermannstadt) County is located in the south part of Transylvania (Ger: Siebenbürgen), which represents the central part of Romania. Both the historical space of Transylvania and the geographical coordinates of the

Transylvanian Depression bear the marks of long term foreign domination. Being now part of Romania, this territory also had its own evolution. Being situated at a meeting point between the Eastern and the Western world, Transylvania is marked by the cohabitation of three ethnic groups: Romanians, Hungarians (with Szeklers as subgroup) and Germans.

In this frame, during the conquest of Transylvania by Hungarians and the settlement of western colonizers (e.g. Transylvanian Saxons) in the 11-13th centuries, monumental constructions in Romanesque architecture style have been built. The Romanesque style was replaced by the Gothic one, which influenced the region during the 12-14th Centuries. During the colonization process, the Transylvanian Saxons have occupied parts of the already conquered Szeklers territory; nevertheless, they mainly settled in the territories held by Romanians (Pop, 1997). Constructions and monuments have been built by the new populations in

their own architectural style. In southern Transylvania, the oldest preserved monument from this time frame is the Cistercian Monastery in Cârța (Ger: Kerz), built in the 13th Century (Fig. 1) as a result of the existence of a Cistercian site. Cârța Cistercian Monastery was built in the simple and utilitarian Cistercian style.

This unique architectural style is associated to the churches, monasteries and abbeys of the Roman Cistercian Catholic Order. Early Cistercian architecture shows a transition from Romanesque to Gothic styles. The monastery, being situated in a Romanian (Orthodox) environment, did not fulfill its missionary role, being lately abolished by Matthias Corvinus, King of Hungary, and the premises taken over by the Evangelic church in Sibiu (Vătășianu, 2001). Nevertheless, the construction of the monastery pointed the birth of a new architectural movement in the area by enhancing the Gothic style (Pop, 1997). The monastery was established at the beginning of the 13th century by King Andrew II of Hungary, but the actual time of construction is not yet clearly known. The main building (the nave) is 60 m long in E-W direction, the transept is 30 m wide, and the apse is about 25 m high. The length of the whole abbey is about 80 m (N-S direction).

A wide diversity of weathering processes is responsible for the nowadays condition of the historical building. Several events in the history of the abbey caused damage to some parts of the church. On the other hand, only few restoration attempts have been done, depending on the approach of the subsequent authorities the abbey belonged to. An important survey and restoration work took place during 1913-1914. On that occasion, tuffitic rocks were used for the consolidation of dimensional blocks in the choir (apse). Tuffites have been also used for the rehabilitation of some buttress on the northern wall of the nave and for

replacing damaged blocks on the southern wall and the western façade. More recently, during the 1960s, the rehabilitation work concerned the parochial house. At the same time, cement was poured on the top of the chapter hall's western wall, in an attempt to consolidate it. Cement was inadequate for restoration, as it filled-in the cracks, fissures and the empty holes from the façade. Cement also locally covers the ancient mortar, probably as a result of the inappropriate restoration attempts during the '60s and '80s.

### 3. METHODS

In this study, we have used the non-destructive methods of Fitzner & Kownatzki (1991) and Fitzner et al., (1993) for damage evaluation and classification of the weathering processes, as well as for detailed mapping of damages, rock types and moisture content.

The determination of the mineral composition was conducted by XRD-analysis on powdered bulk samples, according to the methods described by Koch & Rothe (1979). Equipment used was a Phillips PW 1310 diffractometer. Nickel-filtered Cu K $\alpha$  radiation was used, and the generator was run at 35 kV and 25 mA. Scanning speed was 2 $\theta$ /min.

Thin sections (thickness < 20  $\mu$ m) were made and studied at the Zeiss Axioskope polarizing microscope to identify the petrographical characteristics of the sandstones and some weathering processes, but also to complete the data regarding the mineralogical composition. To underline the porosity, the samples were impregnated with blue dye before cutting. The microscope images were taken with ProgRes C10 device correlated with the compatible software ProgRes Capture Pro 2.0.

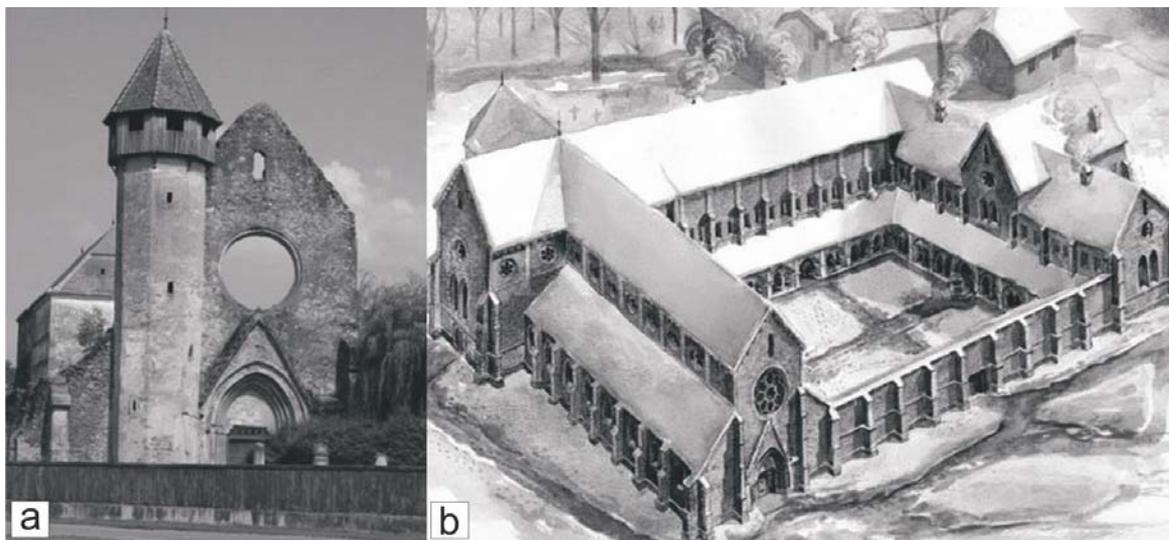


Figure 1. Cârța Cistercian Monastery. (a) main entrance nowadays, west side ; (b) reconstruction sketch by Oltean, 2006

Porosity measurements were performed on samples collected from the monastery walls and the source area, with a mercury porosimetry analyzer Quantachrome Poremaster device, obtaining measurements for inter and intra-particle porosity and thus the resulted total porosity.

A lab-based GeoTek multi sensor core logger (MSCL) was used for the ultrasonic velocity measurements. The P-wave transmitter of the MSCL is operated at a frequency of 250 kHz. The high frequency implies a shorter wavelength, and therefore the measurements are possible also on thin samples. The measurements were performed both parallel and perpendicular to bedding, where this was possible, in order to calculate anisotropy index.

## 4. RESULTS AND DISCUSSIONS

### 4.1 Geology

Tertiary (Sarmatian) sandstones represent the main building rocks used for the construction of Cârța Cistercian Monastery. We have identified the source area as being Colun quarry (southern part of the Transylvanian Basin), 5 km W of Cârța. There, Miocene deposits with calcareous sandstones have been historically mined (Fig. 2). The age is confirmed by the Sarmatian foraminiferal microfauna (*Bolivina moldavica*, *Bolivina sarmatica*, *Anomalinoidea dividens*, *Nonion*

*bogdanowiczi*, *Tenuitellinata pseudoedita*) identified in the clay deposits interlayered within the calcareous sandstones. Few benthic (e.g. *Nonion* sp.) and planktonic (*Globorotalia* sp.) foraminifera were identified in thin sections, confirming the Miocene age of the sandstones (Plate 2, Fig. 5). Mollusc shell fragments (Plate 2, Fig. 6) indicating shallow marine water environment and other biogenic allochems (miliolids, fragments of coralinaceans and echinoids, and altered bryozoans) occur as well.

The Transylvanian Basin is occupied by equal but nevertheless asymmetrically assigned areas of Sarmatian (coeval with the Serravallian, Middle Miocene) and Pontian (equivalent of Messinian) deposits. The Sarmatian is mainly present in the eastern part of the basin with an extension along the Olt Valley, while in the western part it occupies only a limited area (Fig. 2). Along Valea Mare (Mare Valley) at Colun, as Ilie (1955) indicate, the Sarmatian is represented by sand, grey micaceous and ferruginous sandstones, coarse sandstones, concretions, fine conglomerates with fragments of lamellibranchiate, limestones with *Ervilia* and sandy clays. Our assumption on the source area is based on the fact that the building rock samples from the monastery show mineralogical compositions (including heavy minerals assemblage) and grain sizes similar to those of the samples collected from Colun outcrop.



Figure 2. The geological map of the southern Transylvanian basin (Sibiu-Făgăraș area) with the location of the studied site and the source area of the sandstone deposits (digitalized map after Petrescu & Dăuș, 1968)

## 4.2. Material characteristics

Based on Folk's (1974) classification of sandstones, the samples rich in quartz, feldspars and rock fragments were defined as 'feldspathic litharenites' with carbonate cement and bioclasts, having a F/R ratio between 1:1–1:3. Based on the high frequency of heavy minerals (e.g., zircon, garnet, epidote) (Plate 2, Fig. 7), we assume that most of the rock fragments (R) have a metamorphic source. Additionally, igneous and sedimentary lithoclasts occur. The predominant mineral is quartz (40–55 %), including quartz grains, polycrystalline quartz aggregates, chalcedony and quartz from different rock fragments. The content of plagioclase feldspars is estimated to be between 5–15 %, while microcline has a lower share (3–10 %). The X-ray diffraction analysis indicated a total content of phyllosilicates of 5–15 %, mainly represented by micas (muscovite, biotite), as well as by traces of kaolinite/chlorite (Mihăilă & Benea, 2011).

According to Răcățăianu (2010) the main characteristics of the porous media are porosity, pore geometry, and specific surface, which control the transport of fluids over time and space through the material. These later contribute to chemical changes of the minerals and, implicitly, to the development of some specific weathering processes. Different types of porosities generate different types and degrees of weathering. Therefore, it is necessary to differentiate total porosity into effective porosity (i.e. the porosity defined by interconnected pores) and dead porosity (i.e. isolated pores). The effective porosity is the result of the deduction of clay-bound water (CBW) from the total porosity.

The analyzed sandstones were separated into three groups: sandstones from the eastern wall, sandstones from the western wall - depending on the orientation of the sampling site in the building, and sandstones from the source area, i.e. samples collected from the Colun outcrop. This grouping was aimed to evidence potential differences in porosity resulting from different weathering processes depending on the building orientation, and the source area. The study revealed the interparticle porosity as being characteristic (predominant) for the analyzed sandstone. The values vary from 2.57 % on the eastern wall of the building, to 6.3 % on the western wall, and 1.35 % in the outcrop. Average values were calculated based on the number of samples from each source. Point contacts between grains are present, while micropores are less frequent. In general, the total porosity of the sandstones varies between 8–35 %; nevertheless, the total porosity and interparticle porosity are very low.

The samples collected from the outcrop have low average total porosity, of 4.48 %, and low interparticle porosity, of 1.35 %. These values point out that the rock is not suitable as building stone, given the compact framework of CaCO<sub>3</sub> and the clay minerals content that do not allow expansion. As already mentioned, hydration processes will result in expanding the clay minerals within the compact framework leading to micro fissures in the rock. Meanwhile calcite will be leached, resulting in the spalling (exfoliation) of the rock surface.

The average interparticle porosity of the samples collected from the building (3.46 %) is relatively higher than that of the source rock. This practically represents a secondary porosity as a result of chemical weathering processes in the building (i.e. dissolution, hydration, and oxidation), or of thermal expansions. Therefore, the weathering processes created mechanical stress within the rock framework. Implicitly, micro fissures have developed, providing further access to subsequent, more aggressive chemical and physical weathering processes. Additionally, in this way the decayed sandstone turned into a perfect host for microbial and plants colonization.

In general, sedimentary rocks are first deposited as unlithified sediments. Subsequently, their stability to weathering and their quality as building stones are defined by the rock texture, as well as the amount, spatial distribution and morphology (geometry) of pore types. The texture of a rock can often be characterized by grain size distribution and the morphology of the grains. The spatial anisotropy in a building stone is directly related with the different sedimentary structures resulted commonly from the distribution of grains in the sedimentary rocks (Răcățăianu, 2010). According to Heinrichs & Fitzner (2007), low values for ultrasonic velocities perpendicular to the bedding and high anisotropy values in sandstones are results of weathering processes affecting the rock, such as exfoliations (splitting along the bedding plans). Also, the decrease of ultrasonic velocity, both parallel and perpendicular to the bedding is a result of granular disintegration.

For sandstones, the measured ultrasonic velocities - both parallel and perpendicular to the bedding, are generally decreasing with increasing grain/matrix ratio, mean grain size and total rock porosity. During weathering simulation tests (freeze/thaw cycle tests) the coarser-grained sandstones are more vulnerable to granular disintegration than the fine-grained, less porous ones, whereas the fine-grained sandstones are more vulnerable to exfoliation. These mechanisms add

stress to the outer layers of the sandstone, thus weakening the intergranular bonds. Internally, physical separation of the sandstone into layers parallel to the surface leads to exfoliations. In general, this effect is more intense given the anisotropy of sandstones and their internal bedding, in buildings being oriented parallel to the stone surface (Heinrichs & Fitzner, 2007). Several ultrasonic velocity measurements (fig. 3) have been accomplished on four samples: one from the source area (Sample 2) and three from the historical building (Samples 1 and 3 from the west wall and Sample 4 from the eastern wall). The ultrasonic velocities parallel to the bedding range between 1.53 and 2.76 km/s in the weathered rock (Samples 1, 3 and 4), while in the unweathered Sample 2 the value is 1.98 (Table 2). The perpendicular ultrasonic velocities for samples 1, 3 and 4 range between 1.22 and 2.55 km/s; for Sample 2, the ultrasonic velocity is 1.92 km/s.

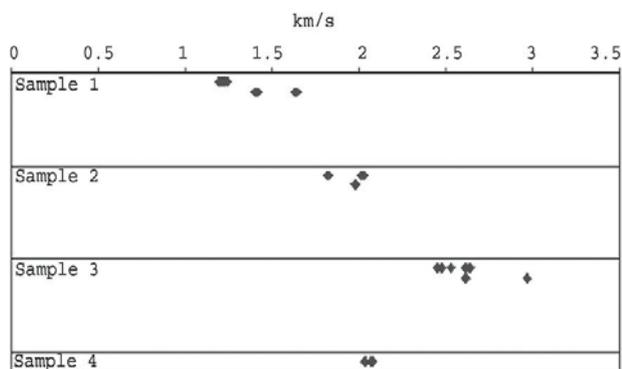


Figure 3. Ultrasonic sound velocity measurements on four sandstone samples from Cârța Cistercian Monastery area (Samples 1, 3 and 4 represent weathered rocks from the historical site, while Sample 2 is the unweathered rock from the source area).

The anisotropy index for the analyzed samples is 1.03 (no anisotropy) for the unweathered sandstone (Sample 2), and ranges between 1.08 and 1.25 (medium to high anisotropy) for the weathered sandstone (Samples 1, 3 and 4). The rock mapping and the microscopic analyses concerned two areas within the building, which differ in the rock used: the sandstones in the eastern side of the portal (fig. 4) show different grain size and sorting coefficient than the rest of the studied sites.

### 4.3. Macroscopic weathering analysis

Stone monuments (buildings, walls, sculptures or statuary) are affected by direct contact with the atmosphere. Complex physical, chemical and biological processes alter the stone in some general or specific way. The weathering is

defined as the rocks', soils' and their minerals decomposition, processes which cause changes in color, texture, strength, chemical composition, or other properties of the natural material due to the action of the weather (Harris, 1975). Therefore, all natural building stones will eventually be weathered, dissolved and/or disintegrated into individual grains, or sand. If the rocks are processed before being used, the chance of deterioration is increasing due to the effects of the intrinsic factors (i.e. lithological constituents, variations in rock composition and particle size, fractures, micro-fissures that occurred during the mechanical processing). These control factors will be of additional importance (Paradise, 2005). The decaying of a building stone begins when a natural rock block is moved from the quarry or outcrop to the stonemasons for cutting and shaping. Later, when it is exposed to wind, sun, rain, snow, moisture and pollutants from the atmosphere, the decay is accelerated by the effect of the physical and chemical weathering processes. During these stages, the sandstone's matrix stability is affected, while oxidation and hydration reactions as well as dissolutions of the carbonatic content corrode the rock-forming minerals (Keller, 1957). Corrosion is amplified by other factors as well, such as the activity of microorganisms which colonize the surface and subsurface of the facade of buildings, monuments and statues (Krumbein, 1972). The microbial colonization of stones depends on environmental factors (presence of water, pH, climatic exposure, or nutrient source). Additional petrological parameters (mineral composition, porosity and permeability) of the building stone have to be taken into account (Warscheid et al., 1989; Arino & Saiz-Jimenez, 1996 in Warscheid & Braams, 2000). Microbial communities interact in many different ways with minerals and their external environment. They can be present on the surface, in fractures and fissures or within the material or its interstitial space. This microbial interaction can lead to biodeterioration. The effect of the microorganisms's metabolism is of chemical nature and later can also influence physical processes (Sand, 2001). In historical monuments, the 'microorganisms are strongly involved in rock decay processes' (Bock & Krumbein, 1989; Warscheid, 1990 in Warscheid et. al, 1991). Generally, all types of microorganisms can be involved in biodeterioration; however, the organisms that contribute most are bacteria and actinomycetes, cyanobacteria, algae, lichens, yeasts, fungi, myxomycetes and protozoa.

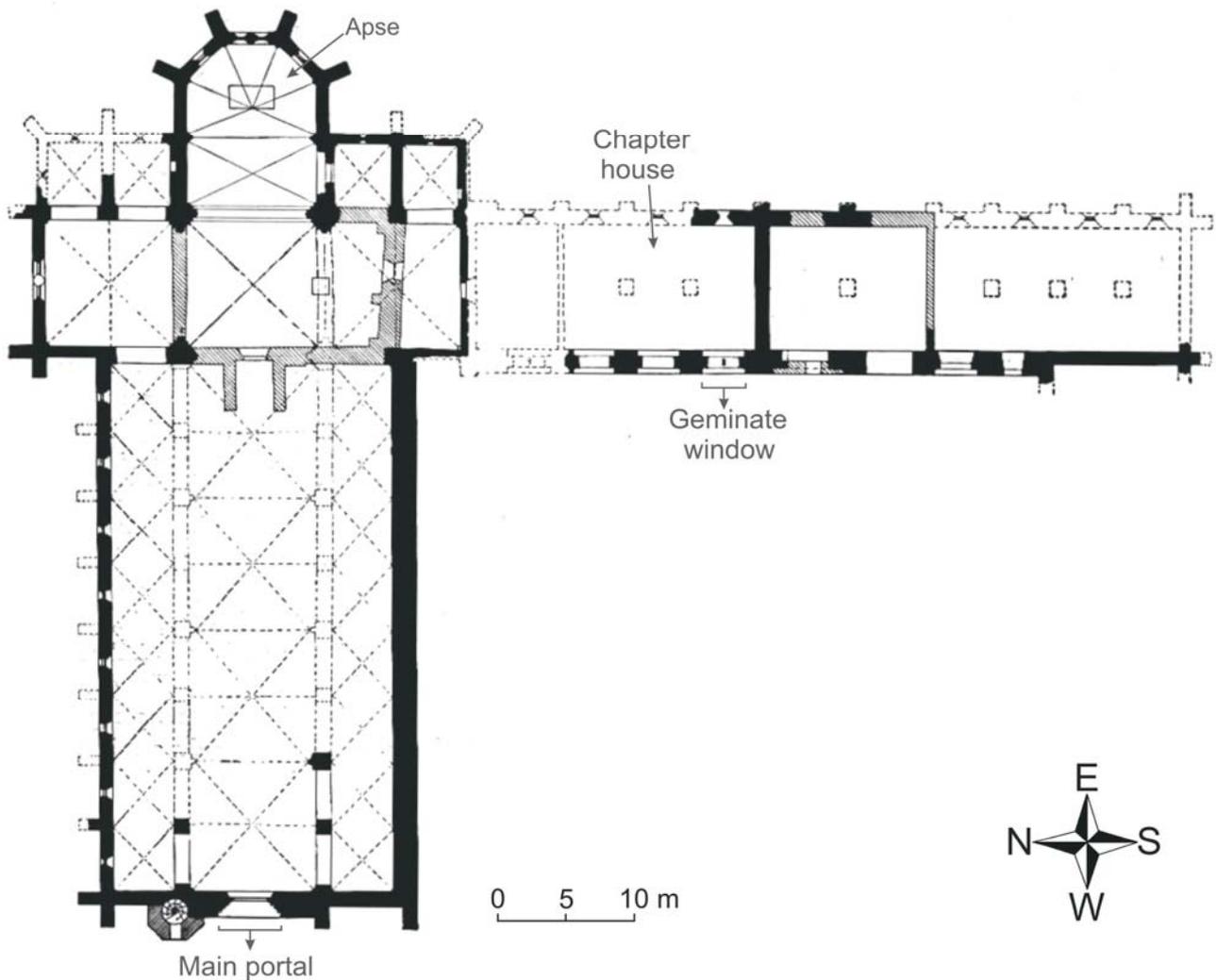


Figure 4. Architectural plan of the Cârța Cistercian Monastery - location of the studied areas (modified after Entz, 1963)

They can act separately or jointly, via complex interaction patterns. Among these, in some cases, cyanobacteria and fungi can be the dominant biomass (Gaylarde & Gaylarde, 2005 in Crispim et. al, 2006). These organisms can cause rock degradation by the production of aggressive acid or alkaline metabolites and surfactants, as well as by physical penetration of their cells into the substrate (Gaylarde & Morton, 1999; Warscheid & Braams, 2000 in Crispim et. al, 2006).

Soiling, crusting, as well as specific chemical processes by which patina forms on rocks are features that commonly occur on stone surfaces in polluted environments. In such cases, expensive cleaning actions are required. The crusts can either protect the stone surface, by acting as protective outer skins, or they may act as reservoirs for potentially damaging salts that can migrate into the underlying stone body. Therefore, the nature of black gypsum crusts and the genetic importance of

surface sulphation in  $\text{SO}_2$ -rich atmospheres should be analyzed in particular for every different case (McAlister et al., 2006). As a rule, 'the formation of gypsum crusts or the surface modification take place in the presence of particulate (dust) deposition especially in areas sheltered from rain and rainwash, where crust formation is prevalent' (Răcățăianu, 2010).

The western part of the Cârța Cistercian Monastery offers the perfect climate for microbial colonization. The constant moisture and the climatic exposure (to sun, wind) combined with the porosity of the sandstones used allow massive colonization with yellow, grey and black lichens, as shown in Plate 1, figures 1 and 5 and Plate 2, figure 2. This colonization, mostly located on the harder and probably less porous sandstone blocks, generates dark crusts that trace the surface (Plate 1, Fig. 5). This micro-environment is also adequate for the colonization by higher plants, which benefit from the

presence of the constant moisture (Plate 1, Fig. 1). The constant moisture changes the sandstone by expanding the clay minerals, causing stress and weakening the rock. On the geminate window and chapter house, these processes increase the overall permeability of the stone and generate weathering processes such as exfoliations, or granular disintegrations as flakes and multiple flakes to multiple scales (Plate 1, Fig. 6 and Plate 2, Fig. 5). The western parts of the portal (facade), the chapter house and the geminate window are also affected by insolation. This, combined with the dissolution of the carbonatic components of the sandstone are weakening the bonds between the minerals, creating micro-fissures. The hydration and insulation processes enlarge the original micro-fissures, thus creating larger pores. Subsequently, they lead to loss of material via detached crusts, weathering out, breaking out, and back weathering (Plate 1, Figs. 1, 5, and 6). On the western part of the portal the intense alveolar weathering of the sandstone led to disintegration into sand and to back weathering of the protruding architectural elements (Plate 1, Fig. 2). Depending on the rock structure, the micro-fissures resulted from the processes described above generate detachments of crusts and back weathering due to loss of crust and weathering out (Plate 1, Fig. 5). Moisture changes the sandstone by increasing the mineral compound structure during the re-hydration of dehydrated clay minerals, causing expansion (Ritchie, 1975), leading to stress and finally, weakening of the rock. These processes increase the overall permeability of the rock and generate weathering processes such as pitting (Plate 1, Fig. 4). Changes in color take place as well, as a consequence of hydrations or/and oxidations (Plate 1, Fig. 4). The intensive weathering is also influenced by the high anisotropy of the sandstones.

While on the west-oriented walls of the monastery the sandstone blocks are mostly bacterially weathered, on the eastwards ones the presence and detachment of crusts is more common, as well as colorations. Light- and dark-colored crusts tracing the surface occur due to the high moisture content from rain water on the surface of the apparently more porous sandstone. In all the studied sites, i.e. the geminate window, the church's portal and the chapter house, this is a result of inner dissolution (Plate 1, Figs. 3 and 7 and Plate 2, Figs. 2, 3 and 4). The micro-fissures parallel to the surface resulted after the bonds inside mineral compounds were broken by dissolution, leading to the detachment of the dark-colored crust tracing the surface (Plate 2, Fig. 4). Because of the oxidation process, iron from the Fe-rich phases (e.g. clay

minerals) gives birth to red oxides, pigmenting the sandstone (Plate 1, Fig. 8). This process probably took place during an intensive fire that affected the monastery, when calcination occurred. Also, as a result of hydration, discoloration (bleaching) occurs on large areas on the blocks (Plate 2, Fig. 1). Oxidation can result in an increase of the mineral structure volume, thus the weakening of the rock, which later becomes granular and is disintegrated into grains and single flakes (Plate 1, Fig. 8 and Plate 2, Fig. 4). As result of disintegrations, large parts of the more porous sandstone are breaking out along the internal micro-fissures developed parallel to the surface. Also, crumbling disintegration to single scale products occur as indicated in Plate 1, figure 7 and Plate 2, figure 4. The decay continues with the smoothing of the blocks' corners, via rounding and notching processes (Plate 1, Fig. 7). As a consequence of their loss of structural integrity (by inside dissolutions, oxidations, hydrations and mechanical stress leading to the formation of large fissures), the sandstones are breaking out (Plate 1, Fig. 6 and Plate 2, Fig. 1). For example, higher plants and microbiological crusts colonize the chapter house blocks along the N-S direction (Plate 2, Fig. 2).

#### 4.4. Microscopic weathering analysis

The in situ macroscopic identification of weathering forms could be performed on all monument building stones, since it is a non-destructive method. Microscopic studies could only be made on few small samples that were collected from the most weathered blocks in the sites of high interest. Many of the studied samples have frequent fissures and cracks running around different grains (e.g., Plate 2, Fig. 8; Plate 4, Fig. 5). Other types of secondary porosity occur, mostly due to dissolution of different carbonate grains. The partial dissolution of foraminifera can lead to the formation of biomolding porosity (Plate 2, Fig. 8). Generally, the dissolution process is enforced by fracture zones. Besides weak intergranular porosity, secondary porosity can occur due to the break out of different grains, as shown in Plate 3, figure 2, where relics of ooid cortices on the edge of a large pore indicate the detachment of the ooid's central part.

Many of the weathering processes macroscopically identified at the surface of the rock can be identified also in thin sections. For example, microbiological colonization, crust formation, granular disintegration, multiple flaking and other weathering processes are illustrated also at microscopic scale. In the lower and uppermost parts

### **Plate 1. Macroscopic analyses of damages:**

Figure 1. Detailed picture of the geminate window - western side. Microbial colonization (C) and colonization by higher plants (B) are visible on the blocks at the bottom of the windows. Yellow lichens settle on the hard sandstone. Also, back weathering due to loss of scales (A) occurs.

Figure 2. Detailed picture of the church's portal (facade) - western side. The intense alveolar weathering of the sandstone led to disintegration into sand and to back weathering of the protruding parts of the portal.

Figure 3. Detailed picture of the church's portal (façade, the frieze) - eastern part. The softer sandstone is disintegrating into sand and grains because of the weak bonds between the mineral grains, and inner dissolutions (A). Also superficial dark crust occurs locally (B).

Figure 4. Detail picture of the church's portal (facade) - western side. The presence of constant moisture affects the sandstone by expanding the mineral aggregates?, causing stress and weakening the rock. This increases the overall permeability of the stone and generates weathering processes such as pitting (upper part) and flaking (bottom). Changes of color take place as well.

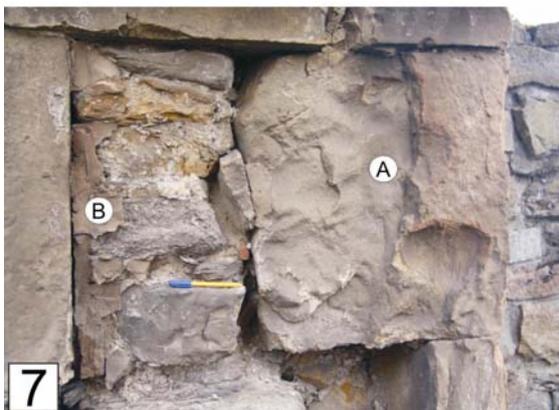
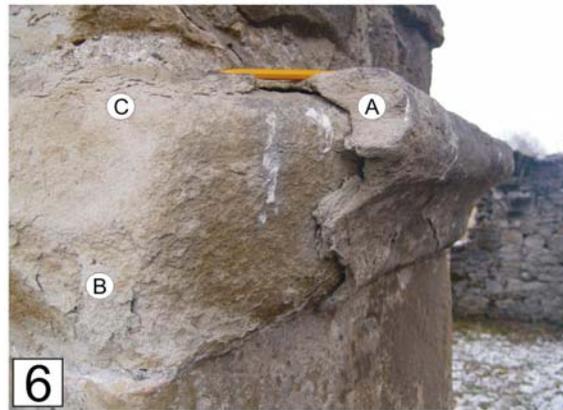
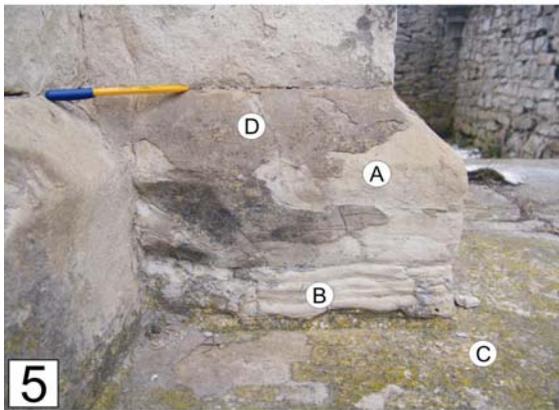
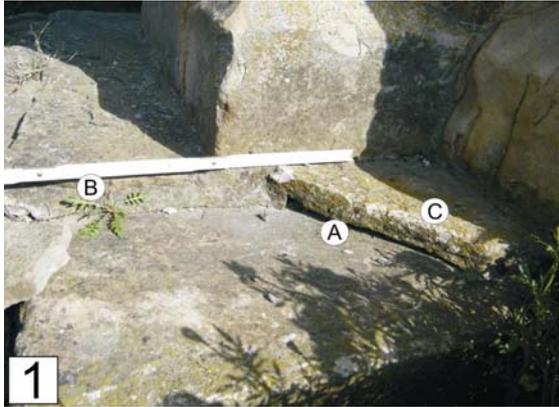
Figure 5. Detailed picture of the geminate window - western part. Intensive formation of dark-coloured crust tracing the surface (D) due to the high moisture. The detachment of the crusts leads to back weathering (A). Subsequently, new types of weathering can easily occur, depending on the rock structure (B). At the bottom, yellow and grey lichens cover the harder, and probably less porous, sandstone (C).

Figure 6. Detailed picture of the geminate window - western part. Intensive weathering of the weak sandstone, which lost large masses due to breaking out (A). Dissolution of calcite under constant high moisture led to surface spalling, as multiple flakes and scales (B). The consequence is the granular disintegration into single flakes (C).

Figure 7. Detailed picture of the chapter house – the interior, eastern part. Large areas of the porous sandstone broke out along the internal microfissures developed parallel to the surface, generating crumbling disintegrations to single scales (A). The high moisture controls the formation of superficial, coloured crust (B). The decay continues with the smoothing of the block corners due to disintegrations resulting in rounding and notching processes.

Figure 8. Detailed picture of the geminate window - eastern part. Oxidation processes of iron in Fe-rich phases (e.g., clay minerals) led to the formation of red oxide that pigment the sandstone (A). This process probably took place during an intensive fire, when calcination occurred. Oxidation can also cause increase in the volume of the mineral aggregate, thus weakening the stone, which later disintegrated into grains and single flakes (B)

PLATE 1



## **Plate 2. Macroscopic analyses of damages:**

Figure 1. Detailed picture of the geminate window - eastern part. Large fissures (A) occur in the weaker, more porous sandstone from the bottom part of the wall due to inner dissolution and mechanical stress. Bleaching is noticeable on large parts of the blocks as result of hydration (B).

Figure 2. Detailed picture of the eastern wall of the chapter house. Along N-S direction, the lower part of the wall is colonized by higher plants and covered by microbiological crusts due to the constant moisture. Also, dark crust traces the surface of the non-colonized blocks.

Figure 3. Detailed picture of the interior of the chapter house - eastern part. The high and constant moisture content at the bottom of the wall led to intensive calcite dissolution and implicitly to the formation of light-colored crust tracing the surface (A). The weakening of the bonds between the mineral components due to dissolution generates micro-fissures parallel to the surface, which result in the detachment of the light colored crust tracing the surface (B).

Figure 4. Detailed picture of the geminate window - eastern part. Due to the large amount of moisture from the rain water on the surface of the apparently more porous sandstone, dark-colored crust tracing the surface (A) occurs as result of inner dissolutions. The resulting micro-fissures parallel to the leading to the detachment of the superficial dark-colored crust (B). The decay process continues, and as consequence there is a loss of material, as multiple flakes (C).

## **Microscopic analyses of damages:**

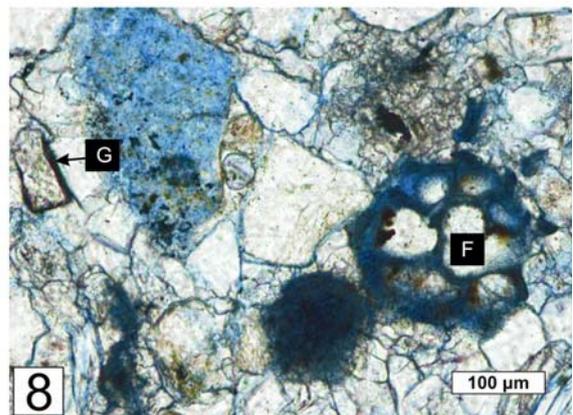
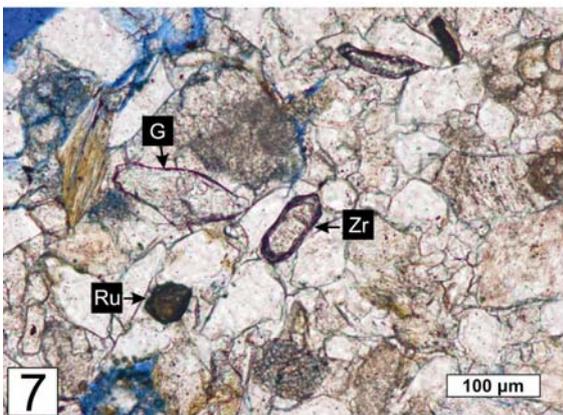
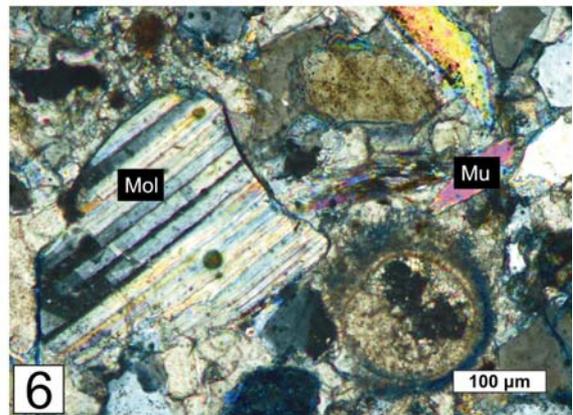
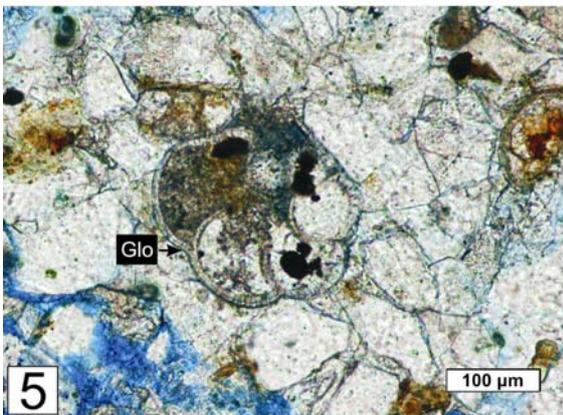
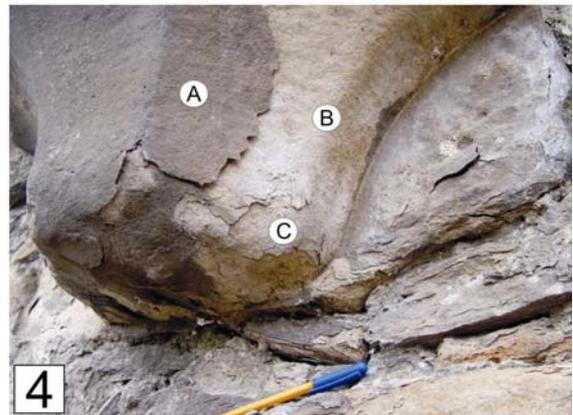
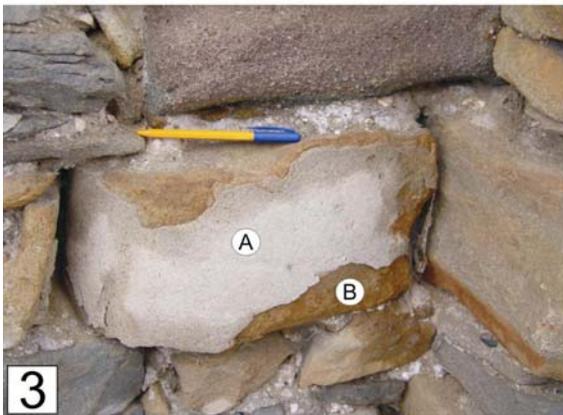
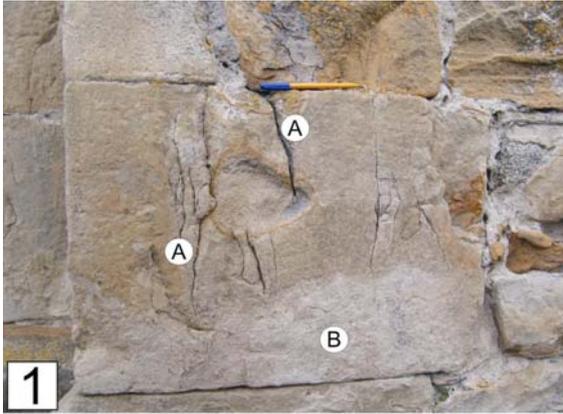
Figure 5. Portal sample- eastern side. The planktonic foraminifera *Globorotalia* Sp.(Glo) is an indicator for the Miocene age of the studied sandstones. The intense blue color is due to the pigment added for enhancing the pores (single polar).

Figure 6. Geminate window sample - western side. Biogenic fragments (e.g., broken mollusk shell, Mol) indicate a shallow marine depositional environment for the sandstone (cross polars).

Figure 7. Geminate window sample - western side. Areas with abundant heavy minerals: zircon (Zr) with high relief, rutile (Ru) presenting typical pleochroism and garnet (G), which is dominant. The heavy minerals enrichment can be related to seams present in a coastal environment (single polar).

Figure 8. Geminate window sample - eastern side. Besides fissures and cracks (blue-stained) mostly located inter-grains, other types of secondary porosity occur, e.g., small biomolds due to partial dissolution of foraminifera (F) and of other grains. Garnet (G) fragment is also recognizable (single polar).

PLATE 2



### **Plate 3. Microscopic analyses of damages:**

Figure 1. A. Geminata window sample - western side. The surface of the rock is covered by microbiological colonization by fungi and other microorganisms, leading to a thin carbonatic crust. The crust itself might document a former conservation attempt with silica ester (single polar). The intense blue color is due to the pigment added for enhancing the pores. B. Portal sample - eastern side. A more detailed image of a similar carbonatic brownish crust with a zone of secondary solution porosity (blue-stained) and round holes due to organic etching was formed parallel to the crust surface. Therein green lichens are settling (single polar).

Figure 2. Portal sample. Low intergranular porosity and large pores (blue-stained) formed due to partial dissolution of carbonate grains. Dissolution was enforced by a fracture zone. The larger pore (P) probably formed by the break out of the central part of an ooid, as indicated by surrounding relics of ooid cortices (single polar).

Figure 3. Geminata window sample - western side. A relatively thick layer of radial growing gypsum crystals is located at the surface of the building stone, probably representing dirt deposits or relics of some ancient paintings (single polar).

Figure 4. Geminata window sample - western side. Due to the high moisture in the lower part of the geminata window, a proper environment for microbiological colonization by fungi and lichens was developed (single polar).

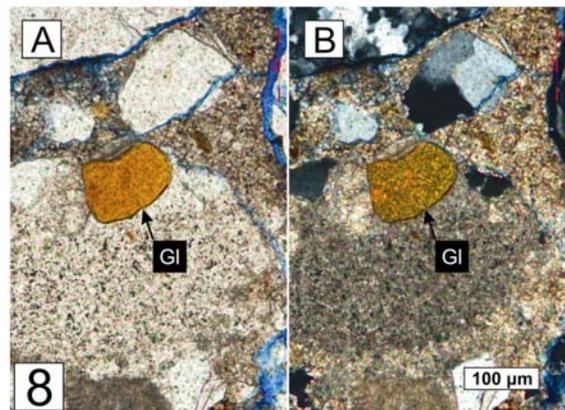
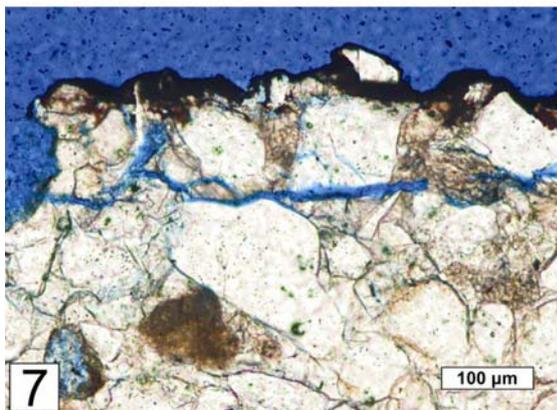
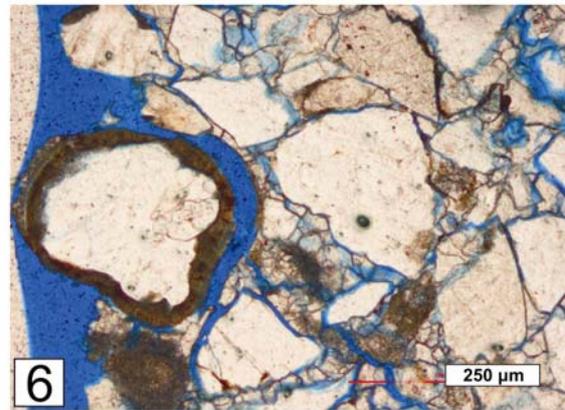
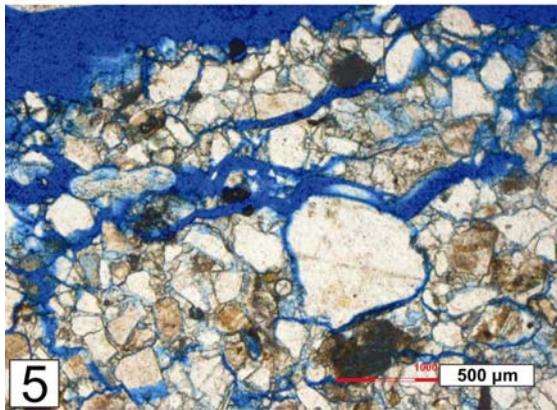
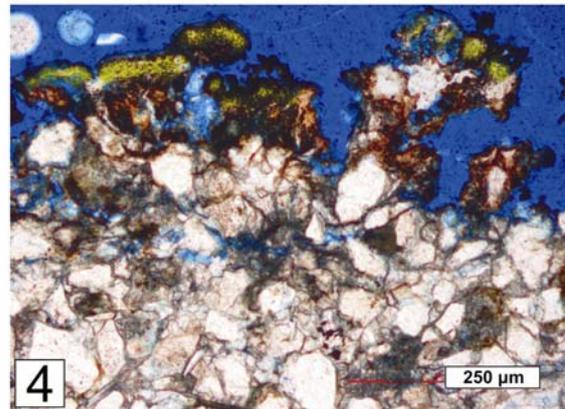
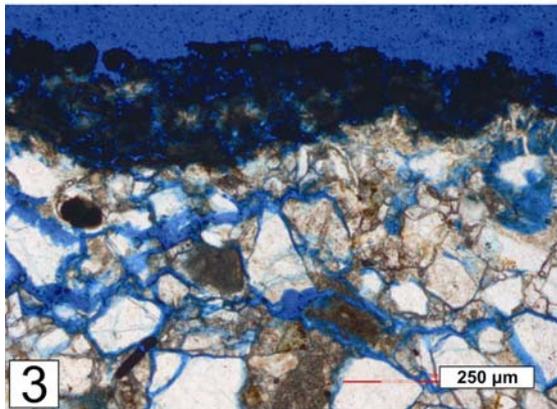
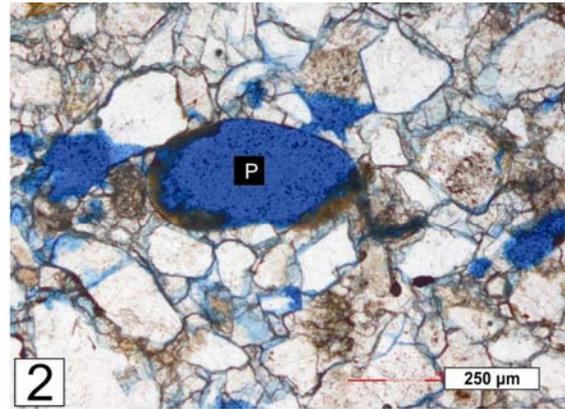
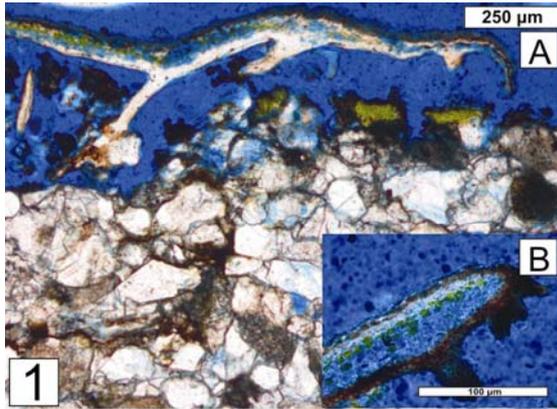
Figure 5. Portal sample. The small fractures parallel to the surface of the rock (blue-stained) and the dissolution of the matrix lead to the weathering process represented by detachment of multiple flakes (single polar).

Figure 6. Portal sample. Abundant fractures and fissures (blue) network around grains due to dissolution of the rock matrix. The disintegration of the outer rock surface into grains/sand is one of the most important weathering processes in sandstones. Note ooid with a quartz grain as core expelled from the rock (single polar).

Figure 7. Geminata window sample - eastern side. Relic of historical painting or a previous attempt of conservation builds up as a thin crust visible as dark colored (black/brownish) deposits on the surface of the sandstone. The harder, elastic crust could weaken the rock and lead to the formation of fractures parallel to the surface (single polar).

Figure 8. Portal sample. Although glauconite (G1) is scarce in the analyzed sandstone, it bears important features such as the brown color of the grain. This might indicate heat damage related to historical firing that occurred inside the former abbey (A - single polar), (B - cross polars).

PLATE 3



of the studied areas, especially on the western side, typical process of biological colonization by fungi and other microorganisms occur, mostly because the blocks are highly exposed to moisture. In some cases, moisture can lead to the formation of a thin carbonatic crust (Plate 3, Fig. 1A). In a more detailed image of such a crust (Plate 3, Fig. 1B), a zone of secondary solution porosity (blue-stained) and round holes due to organic etching can be seen. These are formed parallel to the crust surface allowing green lichens to settle inside. A thicker layer of lichens and fungi colonization occurs at the surface of the samples collected from the lowermost part of the geminate window (Plate 3, Fig. 4). Thick black crust deposits also occur (Plate 3, Fig. 3). The radially growing small crystals might be gypsum, as this is the regular secondary product of calcite dissolution in similar crusts. Some other, thinner black-brownish deposits identified on a sample from the eastern side of the geminate window may be interpreted as relicts from ancient paintings (Plate 3, Fig. 7). Because of crust development, fractures parallel to the rock's surface may occur, weakening its structure. Flaking is one of the most frequent weathering forms identified in situ. The process consists of the detachment of small, thin rock layers (flakes) parallel to the stone surface. Small fractures (blue stained) parallel to the surface lead to the detachment by flaking (Plate 3, Fig. 5). Another detachment weathering process is the granular disintegration into sand and/or grains. Probably due to the dissolution of the carbonate cement, fractures and fissures occur at the surface and run around individual grains (Plate 3, Fig. 6).

Moisture and water circulation are relevant decay factors for porous stones, since water generates decay depending on the chemical and mineralogical composition of the rock (Franzini et al., 2007 in Benavente et al., 2008). Clay minerals, as common components of the clastic fraction of sedimentary rocks are among the most susceptible phases to change in the presence of water. Thus, they play an important role in the decay of building stones. Their 'peculiar crystalline structure can include water molecules within the lattice'. When water interacts with clay 'aggregation-disaggregation or swelling-contraction processes of clayey particles' occur (Veniale et al., 2001). This induces deformation and fractures in the framework of the stone, reducing stone's resistance to total breakdown (Delgado Rodrigues, 2001 in Benavente et al., 2008); therefore the clay-containing heterogeneous stones show the lowest degree of durability. In opposite, clay-free homogeneous siliceous stones show the highest durability (Benavente et al., 2008).

Throughout its history, the monastery suffered many invasions; on those occasions, several known fires occurred (Fabini, 1998), especially inside the former church. The eastern side of the main portal presents obvious macroscopical fire marks such as changes of the outside rock colour into more intense red hues. This feature usually occurs because of the dehydration of the iron compounds, at temperatures above 300° C (Chakrabarti et al., 1996). For example, glauconite (Fe-rich mica frequent in sandstones) changes its colour from green to brown at 450° C and to dark brownish-red at 900° C, when it turns into hematite according to Hajpál & Török (2004). The brownish colour of the glauconite grains was identified in several samples from the eastern side of the portal (Plate 3, fig. 8 A, B), suggesting a firing temperature higher than 450° C. In comparison, the glauconite grains found in samples from the western side of the portal (outer part) appear green.

Tertiary (Sarmatian) calcareous sandstones from Colun (southern part of the Transylvanian Basin) were the rocks used for the construction of the Cârța Cistercian Monastery. The age of the sandstones was confirmed by the Sarmatian foraminiferal microfauna identified in the interlayered clays. In the rock, other biogenic allochems occur as well. The building material sampled from the monastery walls shows close similarities in mineralogical composition (including heavy minerals) with the rock samples collected in the outcrop. The analyzed sandstones are rich in quartz, feldspars (F) and rock fragments (R); we define them as feldspathic litharenites with carbonate cement and bioclasts, with F/R ratio between 1:1–1:3. Most of the rock fragments are of metamorphic origin, based on the frequent occurrence of heavy minerals. Nevertheless, igneous and sedimentary lithoclasts are also present. The predominant mineral is quartz (40–55 %). Plagioclase feldspars represent between 5–15%, and microcline 3–10 % of the rock. The X-ray diffraction analysis indicated 5–15 % total content of phyllosilicates; micas (muscovite, biotite) are dominant, accompanied by traces of kaolinite/chlorite.

## 5. CONCLUSIONS

As a consequence of the loss of their structural integrity following inside dissolution, oxidation, hydration and mechanical stress, the sandstones break out. The intensive weathering is the result of the action of multiple factors, which have a direct impact on the rock. These factors are:

the high anisotropy of the sandstones, the low porosity, the compact framework of the rock, and the CaCO<sub>3</sub> and clay minerals content. All these intrinsic factors, as well as the extrinsic factors (e.g., climate, spatial orientation etc.), are the cause of the moderate to severe decay of the building stone used at the Cârța Cistercian monastery. The in situ investigations and the laboratory analysis are of high value evaluating the current state of the monument in order to provide restorers the optimum preservation solutions.

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