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THE COMBINATION OF NDTS FOR THE DIAGNOSTIC STUDY OF HISTORICAL BUILDINGS: THE CASE OF KAISARIANI MONASTERY

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Abstract. *Diagnosis is the first and most crucial step in the process of monument protection. Diagnosis demands a variety of information and can be a complicated procedure especially when dealing with historical buildings and the limitations that these induce; nevertheless when the correct methodology is followed, diagnosis can be carried out whilst minimizing the amount of samples needed, as important features are already revealed and representative samples can be located. This is achieved through a thorough and organized survey of the historical building and the implementation of various non-destructive techniques (NDTs).*

The in-situ optical inspection of a historical building can offer valuable information regarding the preservation state of the building as well as utility problems which might create problems for the masonry, such as humidity problems due to the movement of rainwater. Following the optical inspection, the researchers can apply NDTs on the structure as a whole, focusing however on problematic areas or areas of interest. In this study NDTs were employed in order to investigate the type of masonry structure followed by the original masonry workers, the original building materials, the different construction phases and materials, as well as non-documented conservation interventions.

However, the use of one NDT alone cannot offer the required information; a combination of various NDTs is necessary in order to extract meaningful and useful results. In the case of Kaisariani monastery, presented here, after a thorough in-situ optical inspection, a variety of NDTs were applied: Ground-penetrating Radar (GRP), Infrared Thermography (IR), Fiber Optics Microscopy (FOM) and Schmidt rebound hammer. The results were analyzed and combined in order to extract results regarding the original building materials, the type of masonry construction, the preservation state of the building materials, as well as information regarding non-documented different construction phases and conservation interventions.

1 INTRODUCTION

An integrated diagnostic study includes historic documentation, characterization of the historic materials and study of their provenance, evaluation of previous interventions and assessment of the environmental impact [1].

When dealing with ancient masonry structures certain factors are important and require special attention. The masonries are generally not continuous, homogeneous or isotropic regarding their static and dynamic behavior and the properties of their building materials; in some cases, the wall texture strongly influences the stress distribution [2]. Therefore, an extensive understanding of the historic masonry structure is an essential prerequisite that must precede any intervention, especially when the ultimate aim is the reinstatement of the masonry's seismic response.

Non-Destructive Techniques (NDTs) are a useful tool in assessing the above factors, especially on monument level. Since sampling is restricted and in some cases even prohibited, a combination of NDTs can provide the researcher with valuable information regarding the materials, the structure and the decay mechanisms, thus unveiling the impact of the environment. In this current study, Infrared Thermography (IRT), Ground Penetrating Radar (GPR) and Fiber Optic Microscopy (FOM) were applied. Furthermore, Schmidt hammer test was also applied, in order to evaluate the compressive strength of the building materials [3].

Kaisariani Monastery

The Catholicon of Kaisariani Monastery is a typical mid-byzantine Athenian church structure, its main building elements consisting of carved stones, bricks and mortars. It is a 11th or 12th century monastery, built on the foothills of Hymettus and dedicated to the Presentation of the Virgin to the Temple; the exact date of construction is not known.

The monastery has a rich history, and subsequently many construction phases throughout the centuries. The original building was a complex cross-in-square four-column domed church, without a narthex. The domed narthex was added in the 17th century, and the barrel-vaulted chapel dedicated to Aghios Antonios positioned at the southwest of the Catholicon was an even later addition (Image 1) of the 17th century.

The monastery complex, including the church, has undergone many conservation treatments, which are not fully documented; however two important reconstruction projects took place in the complex in the beginning and the middle of the 20th century. The interventions mostly regarded buildings surrounding the Catholicon, such as the bath installations and the complex containing the kitchen and the refectory [4-6]. The chapel of Agios Antonios was repointed in 2011, using a lime-pozzolan mortar.

2 METHODS AND TECHNIQUES

The exact environmental conditions during the non-destructive testing, as well as the location they were measured at (church interior or exterior), are stated in Table 1.

DATE	Interior/Exterior	Temperature (^oC)	(RH%)
05.02.2014	Exterior	11^oC	65%
17.02.2014	Exterior	12^oC	52%
19.03.2014	Exterior	19^oC	50%
27.03.2014	Exterior	21^oC	50%
	Interior	14^oC	70%

Table 1: Environmental conditions during NDTs

In this current study Infrared Thermography (IRT), Ground Penetrating Radar (GPR) and Fiber Optic Microscopy (FOM) were applied. Furthermore, Schmidt hammer test was also applied, in order to evaluate the compressive strength of the building materials. All NDT results were combined in order to extract information regarding the monument's state of preservation, detect restoration materials and differentiate them from the original building materials and examine the structural techniques of the monument.

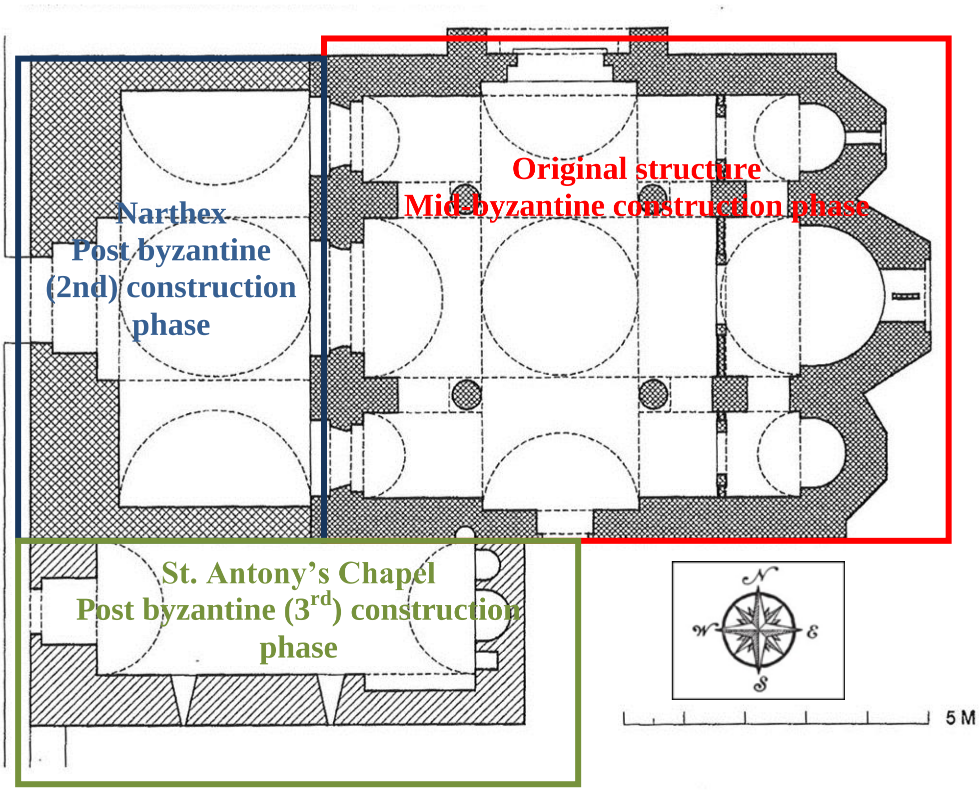

Image 1: Ground plan of the church [7], with probable construction phases

2.1 Fiber Optics Microscopy (FOM)

A Fiber Optics Microscope is a non-destructive microscope that can be utilized in-situ to acquire magnified, visual spectrum images [3]. With FOM, no sampling is required, as the image can be acquired in situ. In this survey a fiber optics microscopy (FOM) i-scope – Moritex was applied in several magnifications (x30, x50 and x120). FOM was employed for an initial material characterization, the assessment of the monuments building materials' decay and the comparison of building materials belonging to different construction phases.

2.2 Infrared Thermography (IRT)

Infrared Thermography is a very useful non-destructive technique, used extensively in the field of monument protection. In the current study, the passive approach was employed, as the area of interest was the masonries of the Catholicon and the materials under investigation are examined in terms of qualitative means [3].

IRT results in the current paper involve the detection of non-documented intervention materials, the examination of masonry interfaces at the interconnection of different construction phases and the comparison of the materials employed for each construction phase. Furthermore moisture transfer phenomena on monumental scale were made evident.

The infrared camera used in the survey was a FLIR Systems Therma Cam B200, with a detector of focal plane array microbolometer in the spectral range of 7.5-12 μm, with thermal sensitivity of 0.08 ^{o}C. All environmental conditions during the conduction of the survey, were measured and are stated in Table 1. During testing, the camera was positioned vertically to the surface under examination. The distance of the camera to the surface (d) was recorder at all measurements. Masonries are complex and non-homogenous materials; the result of a variety of materials with different values of emissivity. In this survey, an average value of 0.86 was selected for the masonry as a whole.

2.3 Ground Penetrating Radar (GPR)

Ground Penetrating Radar (GPR) is an established non-destructive technique [8, 9] that uses radar pulses to image the examined sub-surface. In the field of cultural heritage protection, GPR is used in the assessment of the preservation state of monuments and historic structures. GPR is utilized to locate the position of large voids and inclusions of different materials, to qualify the state of preservation of the structural system, to define the presence and the level of moisture, to control the effectiveness of repair interventions, and to reveal the morphology/geometry of wall sections in multiple-leaf stone and brick masonry structures [3, 10-13].

The ground penetrating radar system used in this survey was a MALÅ Geoscience ProEx system with 1.6GHz and 2.3GHz antennae. The MALÅ Geoscience Groundvision 2 software was used for data acquisition. The MALÅ Geoscience RadExplorer v.1.41 software was used for data processing. Processing of raw files included DC removal, Time-Zero Adjustment, Amplitude Correction, Bandpass filtering and Background removal.

Instead of applying the same mean velocity for the masonry as a whole, the velocity was calculated for each building material of the monument, where the dimensions of each material layer was measurable. The velocity through the stone was calculated at V_{stone} = 11,60 cm.ns^{-1}, the velocity through the mortar was calculated at V_{mortar} = 2,95 cm.ns^{-1}, and the velocity through the bricks is calculated at V_{brick} = 9,28 cm.ns^{-1}.

2.4 Schmidt Hammer Rebound Test

The Schmidt hammer test was initially developed in the late 1940s as an index apparatus for non-destructive testing of concrete in situ. Today it is also used for estimating the uniaxial compressive strength of building stones and bricks [14]. The Schmidt hammer provides a quick and inexpensive measure of surface hardness that is widely used for estimating the mechanical properties of rock material. However, a number of issues such as hammer type, normalization of rebound values, specimen dimensions, surface smoothness, weathering and moisture content, and testing, data reduction and analysis procedures continue to influence the consistency and reliability of the Schmidt hammer test results [15]. Many researchers attempt to uncover correlations for different case scenarios; however in the current study the instrument conversion curve was utilized.

In this survey an N-type Schmidt hammer, manufactured by Proceq, was employed. The impact direction was vertical to the examined surface. The rebound number (R) was utilized in order to estimate the compressive strength of different building materials, through the use of the instrument's conversion curves and in accordance to ASTM C 805. The results can serve as a first indication regarding the type of material tested, the quality of the technology production employed for the production of the brick, as well as limitations regarding the mechanical properties of any future intervention materials that could be utilized without exerting compatibility criteria.

3 RESULTS

The results deriving from all methods were analyzed and combined in order to extract information regarding the original building materials, the type of masonry construction, as well as non-documented construction phases and problematic areas. In this current paper, selected results regarding certain areas of interest will be presented to demonstrate the ability of NDTs to characterize the building materials, to assess the current state of the structure and to identify the construction phases of the building.

3.1 In situ optical inspection – Selection of Areas of Interest

Kaisariani Monastery is a typical mid-byzantine Athenian church structure, its main building elements consisting of carved stones and bricks. Each façade is evidently constructed with a different building technique, depending on the construction phase, as well as the projection of the façade upon entering the monastery complex. The mortars and bricks of each construction phase seem to be of a different technology, and the carved stones are of different origin. The east façade is the only one built in the typical byzantine cloisonné manner, with the carved stones, bricks and mortars presenting perfect symmetry (Image 2). The north and south façade of the Catholicon, attributed to the first construction phase, are also built in the byzantine cloisonné style, however perfect symmetry of form was not followed on these facades to the same extent (Images 3, 4). The walls constructed during the post-byzantine era, are not built in the byzantine construction style, but were constructed as rubble masonry, with asymmetric stones and bricks (Image 3). The in situ optical inspection revealed that the main issues the church is facing are due to humidity problems, intensified by past non-compatible interventions.

After a thorough in situ optical inspection, areas of interest were selected in order to perform non-destructive testing (Images 2-4).

Image 2: East Façade [16] and control areas – Picture of cloisonné style construction and Areas 12.2&12.3

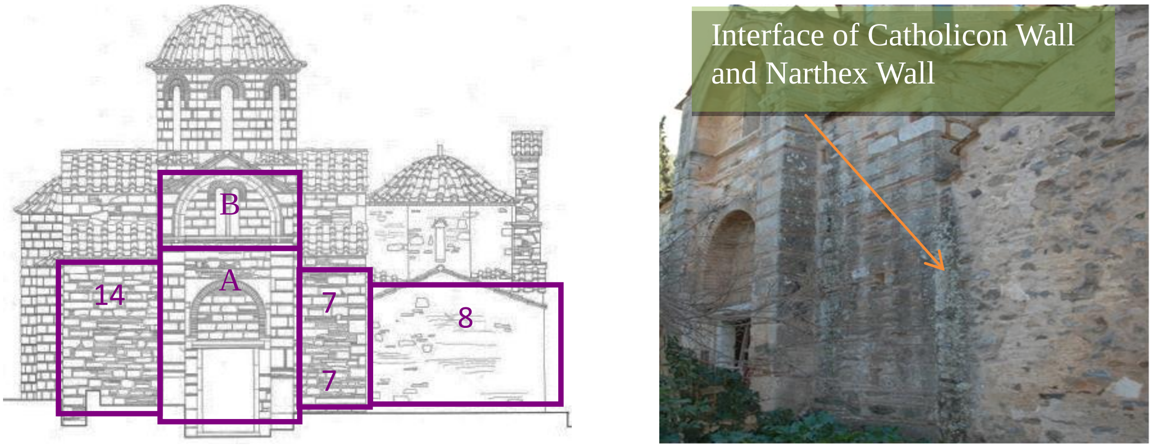

Image 3: North façade [16] and control areas – Picture of Areas 7&8 with distinct construction phases

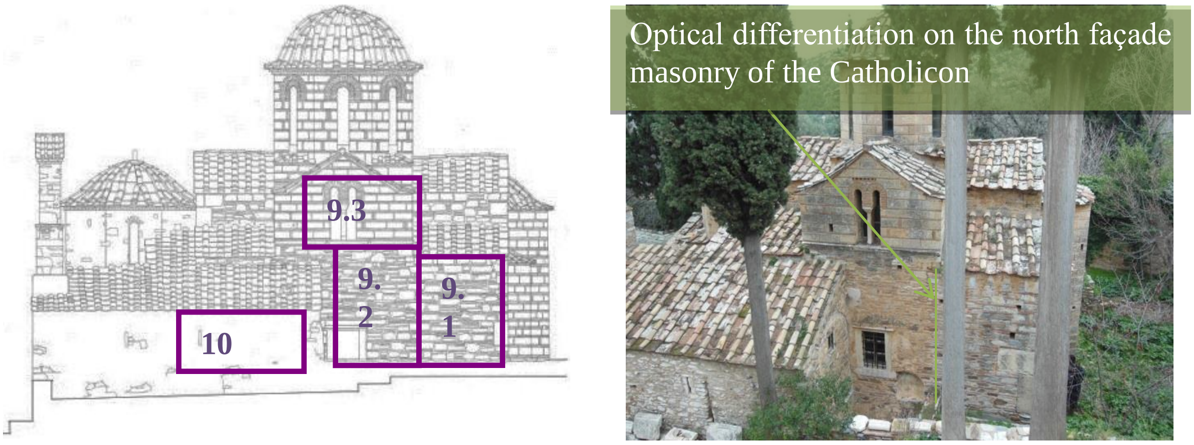

Image 4: South façade [16] and control areas – Picture of Areas 9.1&9.2 with evident differentiation

3.2 East façade – Areas 12.2 &12.3

Areas 12.2 and 12.3 (Image 2) were selected as areas of interest to demonstrate the use of NDTs for the detection of non-documented past interventions, as well as for the examination and characterization of building materials in historic structures. Schmidt hammer rebound testing was implemented to estimate compressive strength the building materials.

The porous stone of the east façade is a fossiliferous stone (Image 5). The original mortar of the east façade, although attributed to the first construction phase, and therefore subjected to environmental factors for a much longer period compared to the subsequent phase materials, is in a good preservation state (Image 6). A different type of mortar was encountered in areas around the windows of areas 12.2 and 12.3 (Image 7), which is most likely a restoration mortar applied during a past, undocumented restoration intervention. Microscopically these mortars seem to exhibit a certain extent of compatibility, although the restoration mortar seems to exhibit better coherence.


Image 5: Area 12.1 (x30) Typical stone of the east façade

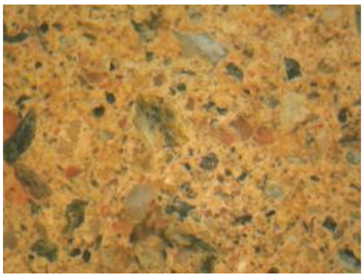
Image 6: Area 12.1 (x50) Mortars

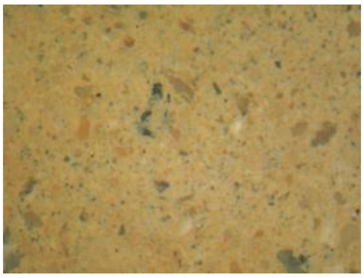
Image 7: Area 12.2 (x50) Restoration mortar

The authentic bricks of the east façade showed relative homogeneity and appear in two different colors, due to a different production technology (Image 8 and 9). Another type of brick was detected, exhibiting a different microstructure (Image 10), which seems to correspond to a newer restoration brick; however, a corresponding intervention using this newer restoration brick was not documented. This type was encountered throughout the east façade around the window of area 12.2 and the window of area 12.3 in accordance to the presence of the restoration mortar described above. The restoration brick seems less porous than the original authentic byzantine brick.

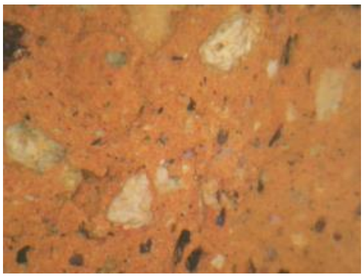
Image 8: Area 12.2 (x50) – Red brick

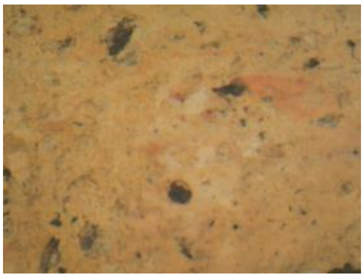
Image 9: Area 12.2 (x50) - Yellow Brick

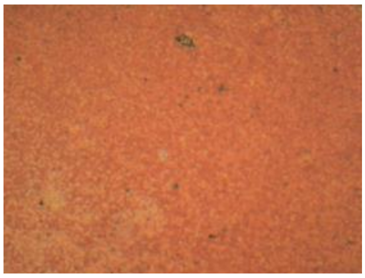
Image 10: Area 12.2 (x50) - New Restoration Brick

Schmidt hammer test was applied only on the carved stones and bricks of the east façade, due to the better conservation state of the materials on this side. A total of 22 bricks were examined. The bricks belonging to the intervention described with the previous methods were excluded, as the original materials of the masonry are of interest. Schmidt hammer test results revealed that the original byzantine bricks are of excellent quality, exhibiting relatively high compressive strength values, varying from 21,8 MPa to 44,6 MPa with an average value of 32,64 MPa and standard deviation of 6,75. The high standard deviation of the measurements, ranging up to 3 for each individual brick, is anticipated, as byzantine bricks were handmade; thus each brick is individual and homogeneity is not complete.

Furthermore, Schmidt hammer test results, deriving from 8 carved stones tested, revealed that the carved stone of the east facade exhibits relatively low values of compressive strength. The stones' compressive strength values, present values from 4,71 MPa to 9,80 MPa, exhibiting an average value of 8,2 MPa and a standard deviation of 1,72. This is anticipated and may be partly due to the roughness of the porous stone surface. Furthermore, as revealed by the FOM images taken during the microscopic examination of the east façade materials (Image 5), the carved stone is quite porous; therefore the Schmidt hammer results are in cohesion. The low compressive strength of the carved stones, imposes limitations regarding the compressive strength that any restoration mortar should have in order to still be deemed compatible with the masonry in any future intervention.

The results from FOM indicated an undocumented intervention evident on the east façade; on the arch of the window of area 12.2 (Image 11), as well as around the window of area 12.3. When examined by Infrared Thermography (Image 12), the majority of the bricks of the east façade, corresponding to authentic bricks, exhibited temperatures well above 20 ^oC and up to 23 ^oC, compared to the bricks of different color above the window in area 12.2, which exhibit much lower temperatures, in the range 18-19 ^oC. The authentic joint mortar between the bricks surrounding the double arched window in area 12.2 exhibits temperatures between 17,3 ^oC and 18,1 ^oC. Again, the joint mortar with a different color exhibits lower temperatures, between 16,5 ^oC and 16,8 ^oC. This was also observed in area 12.3; the temperature differences are due to the different materials used in this undocumented intervention.

Image 11: Detail of area 12.2 - Thermogram area

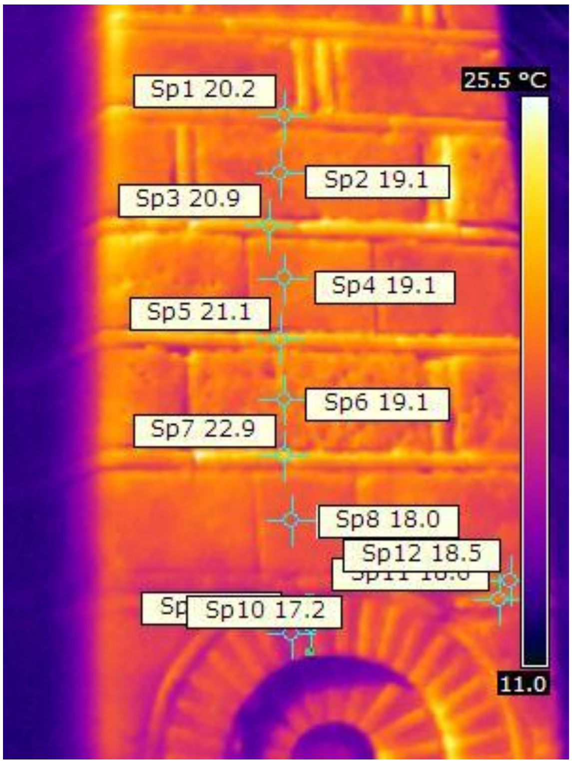

Image 12: IR image [6440], Date: 17/2/2014

3.3 North façade - Areas 7 & 8

Areas 7 and 8 were selected in order to examination the masonry structure and investigate possible construction phases. Areas 7 and 8 of the north wall belong to different construction periods, as area 7 is part of the original Catholicon and area 8 belongs to the Narthex (Image 3). The materials of area 7 appear in a much worse preservation state than the materials of area 8; this is highly evident in the comparison of slate stones in the two areas (Images 13-15) as well as in the comparison of bricks from the two areas (Images 16-18). However, it seems that a similar slate stone was used for the construction of both walls; furthermore, microscopically the bricks of area 7 seem to appear similar to those of area 8.

The worse preservation state of area 7 is also evident during the examination of mortars (Images 19-23); however it must be emphasized that area 8 has undergone many interventions, as the use of many different non-documented restoration mortars evidence. The different mortars used in area 8 seem to exhibit different coherence and microstructure and may not be compatible to the original masonry materials.

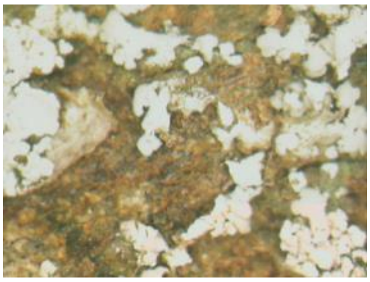

Image 13: Area 7 (x50) - Slate stone with evident decay

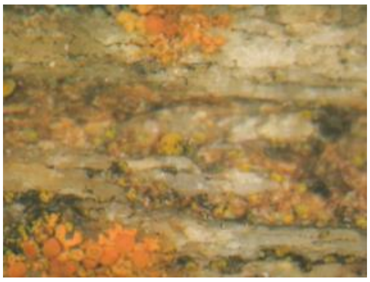

Image 14: Area 7 (x50) - Slate stone with evident decay

Image 15: Area 8 (x50) - Slate stone

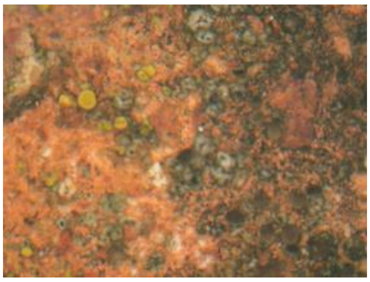

Image 16: Area 7 (x50) - Brick

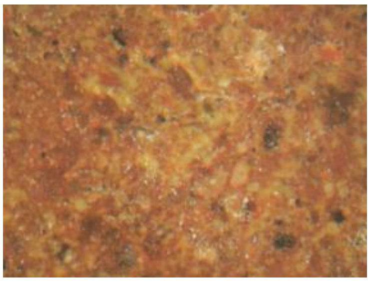

Image 17: Area 8 (x50) - Brick

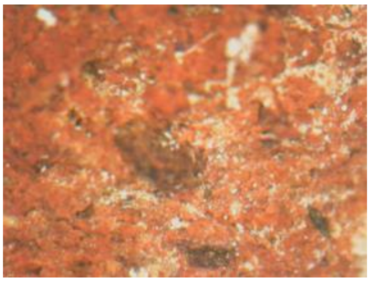

Image 18: Area 8 (x50) – Brick

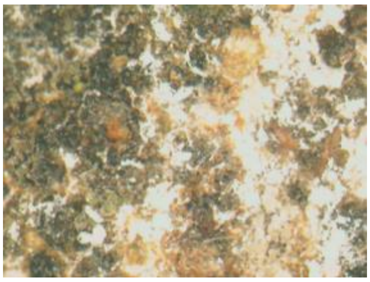

Image 19: Area 7 (x50) - Mortar

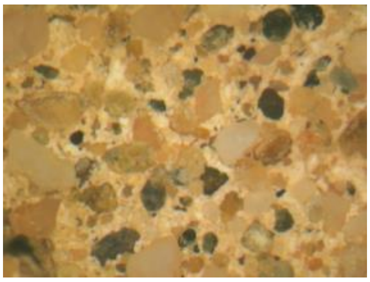

Image 20: Area 8 (x50) - Grey mortar

Image 21: Area 8 (x50) - Grey cementicious mortar

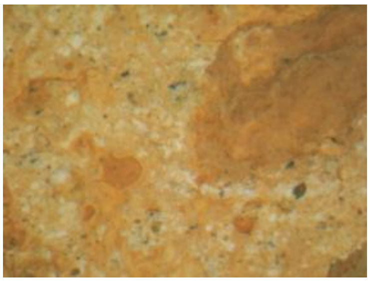

Image 22: Area 8 (x50) - Orange cementicious mortar

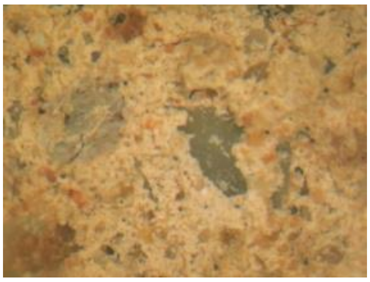

Image 23: Area 8 (x50) – Pink mortar

In order to better examine this area, a IR image was taken (Image 24) depicting the north wall of the Catholicon (area 7) and of the Narthex (area 8) simultaneously. The different construction phases are evident, even by macroscopic observation (Images 25-26), due to the different construction technique of the masonry during the mid-byzantine and post byzantine era. The difference between the two different phases is evident also in the thermogram, through the intense surface temperature difference that the two areas exhibit. The wall of the Catholicon exhibits temperatures ranging from 11,2 °C to 13,2 °C, whilst the Narthex wall exhibits lower temperatures, ranging from 10,7 °C to 12,3 °C. This is due to the different type of construction and the use of different construction materials; however it is unclear through thermography alone whether this is the result of the higher humidity content of the Narthex.

Image 24: The north wall - different construction phases

Image 25: Detail of the thermo gram area

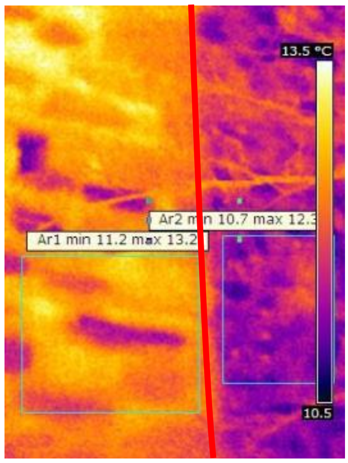

Image 26: Thermo gram [6357], Date: 5/2/2014

The ground penetrating radar was used at different areas of the north wall (Image 27), in order to better investigate areas 7 & 8 and to investigate the structural continuity of the wall between the two construction phases. The horizontal scans 581H and 582H (Image 28) were performed at the exterior of the north masonry, at a height of 100 cm and 150 cm above the ground level respectively, whereas scans 583 and 586 were performed at the interior of the building, to aid in the identification of the masonry features.

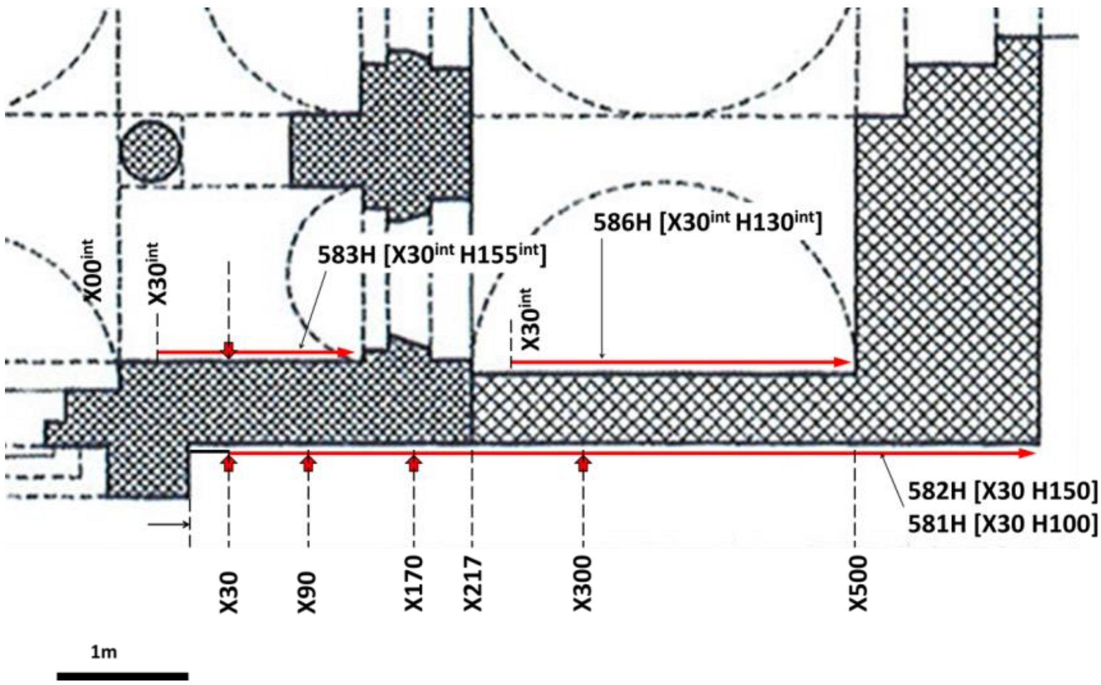

Image 27: Ground plan and GPR scan positions

The scans run across both the Catholicon and the Narthex wall, as well as across both sides of the north wall; therefore it is deemed possible to perceive discontinuities in the structure, even in the core of the masonry.

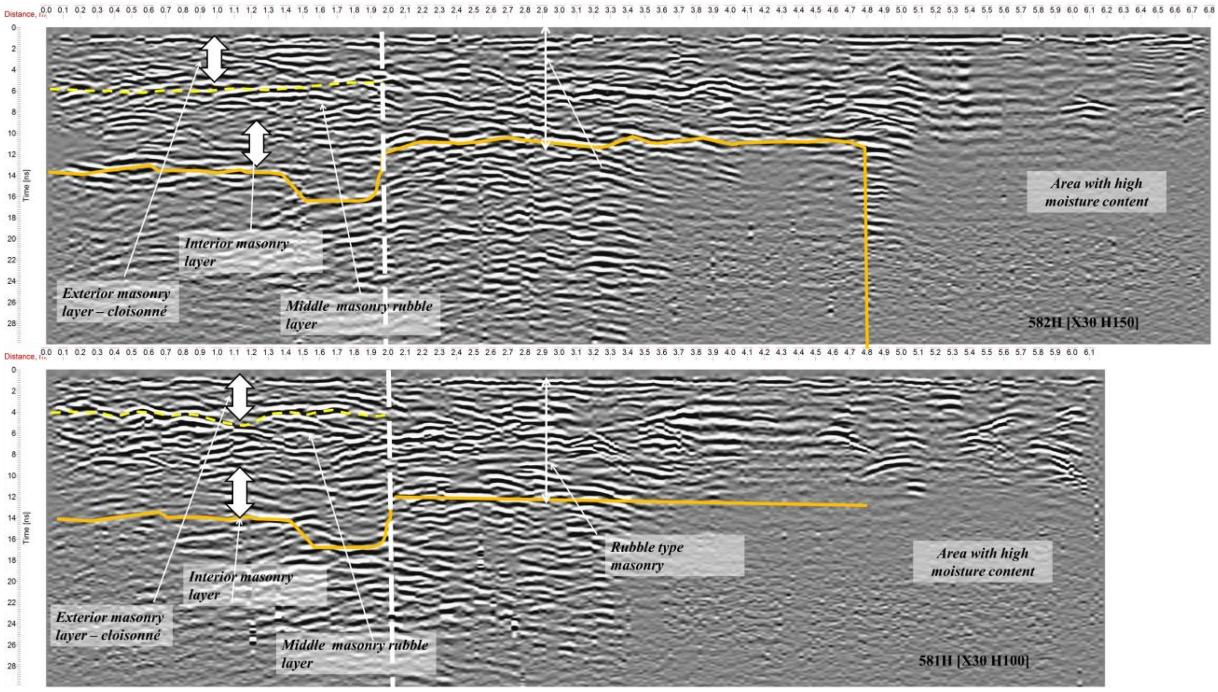

Image 28: Horizontal GPR scans H581 and H582 respectively

The GPR scans reveal interesting information. A discontinuity at the interface of the Catholicon wall and the Narthex wall is evident, at exactly 2 m from the beginning of the scan, confirming the IR results; furthermore, it is evident that the wall corresponding to the original mid-byzantine structure corresponds to a three leaf cloisonné masonry, whereas the wall corresponding to the Narthex clearly corresponds to rubble masonry extending to the core of the structure. Another interesting aspect that the GPR revealed is the presence of a high content of moisture in the Narthex wall; this explains the presence of several restoration mortars on the Narthex wall. It is also possible, that due to the incompatibility of the restoration mortars with the original masonry materials, transpiration of the masonry is difficult and humidity is trapped in the core of the Narthex wall, intensifying the problem.

3.4 South façade – Areas 9.1 & 9.2

On the south façade, Areas 9.1 and 9.2 were selected as areas of interest, in order to investigate the masonry structural continuity and possibly document a lost construction phase. The south façade of the Catholicon is optically divided into two areas, 9.1 and 9.2. Area 9.2 is characterized by its orange hue and spattered appearance. Areas 9.1. and 9.2 of the north wall, seem to be distinctly different (Image 4). The microscopic examination of the bricks, mortars and stones however does not offer a clear image, as all building materials of area 9.2 seem to be covered by an orange plaster residue (Images 31, 34, 36-37).

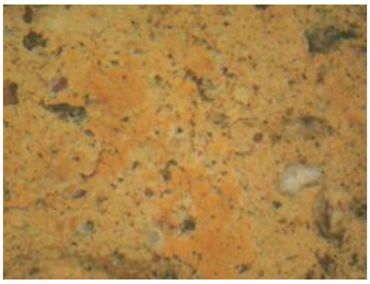

Image 29: Area 9.1 (x50) - Brick

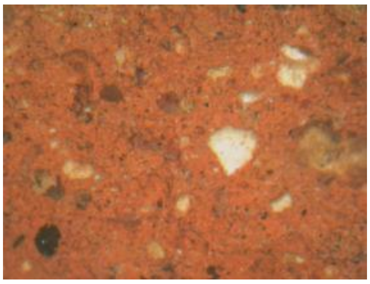

Image 30: Area 9.1 (x50) – Brick

Image 31: Area 9.2 (x50) – Brick

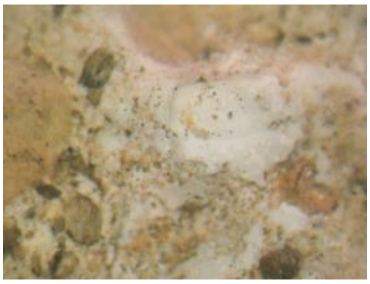

Image 32: Area 9.1 (x50) – Mortar

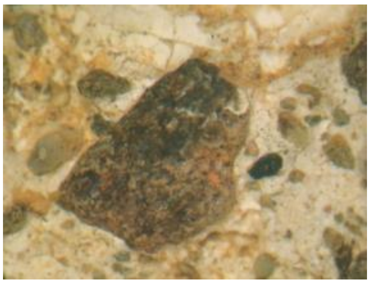

Image 33: Area 9.1 (x50) – Mortar

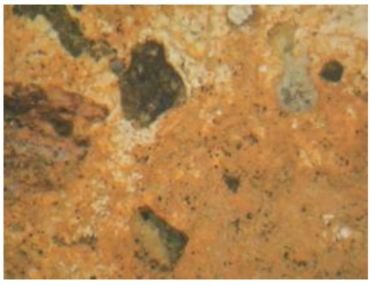

Image 34: Area 9.2 (x50) - Mortar

Image 35: Area 9.1 (x30) – Porous stone

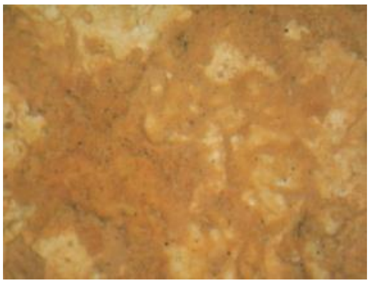

Image 36: Area 9.2 (x50) - Porous stone

Image 37: Area 9.2 (x50) - Mortar

An IR image (Image 39) was taken in order to include both areas 9.1 and 9.2, simultaneously (Image 38). The surface temperature of the stones of both areas exhibit similar values, indicating that the same type of stone was used. The same applies in the case of the brick elements. However, in the case of the joint mortars, this is not the case; the temperature of the mortar in area 9.1 ranges from 29,1 ^oC to 29,5 ^oC, whereas in area 9.2 the temperature of the joint mortar ranges from 31,4 ^oC to 34,1 ^oC. This is an indication that a different mortar was used in the two areas. An explanation of this would be that the chapel used to extend further to the east, and therefore area 9.2 was at some point the interior of the chapel. In addition, the remains of a tile roof, which is observed by optical observation on the upper limit of area 9.2, exhibits the same temperature as the bricks, indicating that this is part of the older structure; perhaps it was the roof of the chapel when it extended further to the east. However, with IR thermography, the surface of the structure is examined; the masonry structure must be examined as to assess whether the different mortar is only on the surface or whether the use of the different material extends to the masonry core.

Image 38: South wall - Areas 9.1 and 9.2

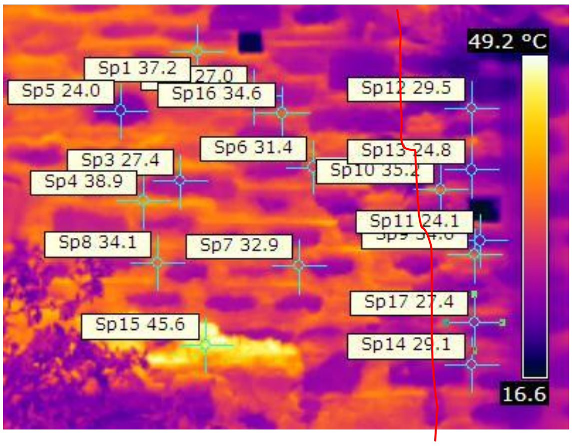

Image 39: Thermogram [7182], Date: 27/3/2014

Ground penetrating radar was employed in order to assess whether the differentiation of the masonry between these two areas is structural or only at the surface. Specifically, horizontal scans were carried out on the exterior of the south wall of the Catholicon, across area 9.2 and area 9.1., in order to assess whether the optical differentiation corresponds to a structural differentiation. Furthermore at the interface of area 9.1 and 9.2 it seems as though a crack is present; however this is not confirmed during a close optical investigation. This area of the south wall is where the pillars receiving the compressive forces from the dome are; through GPR scanning, it will be possible to examine whether these elements are constructed in a different manner than the rest of the masonry. Scans were conducted from the east side of the window to the corner of the east façade (Image 40).

Image 40: Exact positions of GPR scans on the south wall – depiction of the differentiation

The result (Image 41) shows that the differentiation of area 9.1 and 9.2 is due to the use of different materials in area 9.2 and area 9.1. This is obvious in the scan, as a diversification of the signal is evident at 1 m from the beginning of the scan; this is also where the optical differentiation occurs. However, this differentiation is at the surface; from 10 cm from the surface and below, the materials and the structure are continuous throughout the scan and therefore throughout the two areas. The end of the scan corresponds to a large carved stone at the southeast corner. Again the structure of the wall corresponds to the byzantine type of building, where three layers are evident; the outer layer, the middle rubble layer and the inner layer of the wall, thus indicating a three leaf masonry. Therefore, in the case of the south wall the middle layer and the interior layer are homogenous and continuous, whereas the joint mortar of area 9.2 is different, but only on the exterior layer, which is 10 cm deep.

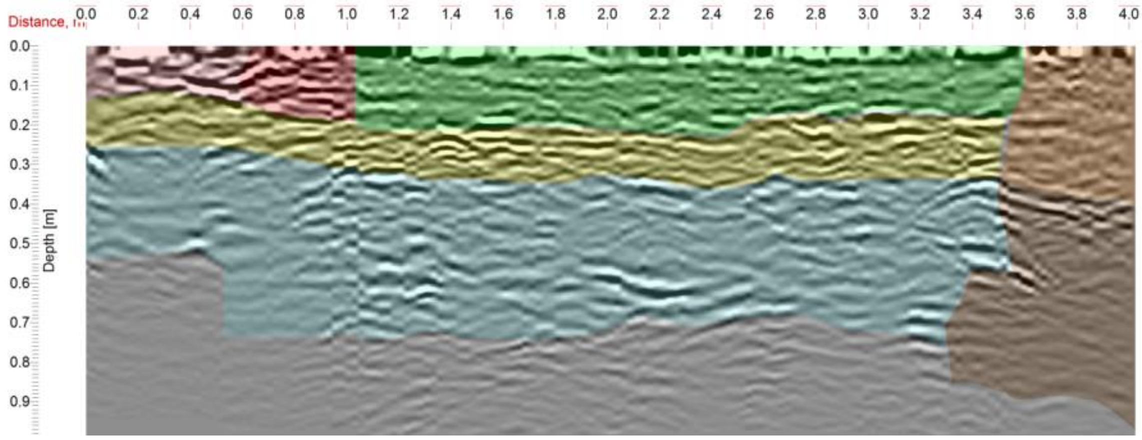

Image 41: GPR scan of south wall

4 CONCLUSIONS

- The carved stone of the first byzantine construction phase is a porous fossiliferous stone, with low values of compressive strength
- The building bricks of the east façade are of excellent quality and exhibit relatively high values compressive strength
- In the case of the Kaisariani Catholicon, the low compressive strength of the carved stones, imposes limitations regarding the compressive strength that any restoration mortar should have and still be deemed compatible with the masonry in any future intervention
- An undocumented intervention was revealed around the windows of the east façade
- The north wall of the Catholicon is a typical byzantine three leaf cloisonné masonry, whereas the north wall of the Narthex is obviously a rubble masonry. The temperature differentiation between the two areas is due to the different construction techniques of the two parts, as well as the high humidity of the Narthex wall
- The undocumented restoration mortars present on the north wall of the Narthex seem to enhance humidity problems, due to incompatibility with the original materials of the masonry
- The optical differentiation of the two areas of the south wall of the Catholicon is due to the different joint mortar of area 9.1 and area 9.2; the building stones and bricks are the same in both areas

- This differentiation does not extend to the core of the masonry; the middle layer and the interior layer are homogenous and continuous, whereas the joint mortar of area 9.2 is different than the mortar of area 9.2, but only on the exterior layer of the three leaf masonry, which in the case of the Catholicon of Kaisariani Monastery is 10 cm deep
- It is possible that the chapel extended further to the east, and therefore the difference of area 9.2 is due to the fact that it was once the interior of the chapel; this is further suggested due to the remain of a brick roof, the remains of which are evident in area 9.2
- The combination of different NDTs can reveal important information that would have been otherwise disregarded; furthermore it can confirm or disregard scenarios regarding non-documented construction phases
- NDTs can detect non-documented past interventions, as well as examine and characterize building materials in historic structures, as demonstrated on the east façade of the Catholicon; furthermore they can assist in the examination of the masonry structure as in the case of the north and south façade
- Schmidt hammer test results can be utilized as a first approximate limitation regarding the compressive strength that any restoration mortar should have in compatibility terms

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