9th National Conference of the Hellenic Society of Non Destructive Testing Nov 11th, Athens



NDT prospection in the study, implementation and monitoring of the rehabilitation of the Holy Aedicule of the Holy Sepulchre in Jerusalem within the Scientific integrated governance



Jerusalem Patriarchate - National Technical University of Athens

NATIONAL TECHNICAL UNIVERSITY OF ATHENS Interdisciplinary Research Group for the Monuments Protection

Materials & Conservation, Reinforcement and Rehabilitation Interventions in the Holy Aedicule of the Holy Sepulchre

> 27 January 2016, Consulate General of Greece in Jerusalem 19 February 2016, Greek-Orthodox Patriarchate of Jerusalem 8 March 2016, Zappeion Hall, Athens

Scientific Coordinator: Prof. A. Moropoulou

Interdisciplinary Research Group NTUA:

Prof. E. Korres, School of Architecture Engineering NTUA, Former Director of the Interdisciplinary Postgraduate Program "*Protection of Monuments*"

Prof. A. Georgopoulos, School of Rural and Surveying Engineering NTUA, Laboratory of Photogrammetry Prof. A. Moropoulou, Director of Studies in the NTUA Interdisciplinary Postgraduate Programme Direction «Conservation Of Building Materials», School of Chemical Engineering NTUA, Laboratory of Materials Science and Engineering

Prof. C. Spyrakos, School of Civil Engineering NTUA, Laboratory for Earthquake Engineering

Aim of Research



PROPOSAL

Principles, ethics, requirements and instructions for conservation reinforcement and rehabilitation materials and interventions Continual update of the three religious communities of the Holy Church of the Resurrection in Jerusalem and organization of scientific and institutional debate for decision making regarding the most appropriate solution.

Implementation

Decision making upon the study



 Funding Crowdsourcing
 Project implementation by the Technical Bureau under the responsibility of the three religious authorities



High supervision with continual documentation, diagnosis, pilot applications and update of the study by the NTUA interdisciplinary Research Group



In-situ Interscientific Laboratory – Training of the Technical Staff

ORGANISATION MANAGEMENT OF CONSTRUCTION SITE

The continued operation of pilgrimage of the Holy Sepulchre is ensured



2nd Building phase

- 11th c. Byzantine period
- First Crusaders period (1099-1187)

3rd Building phase

The restoration intervention of the Crusaders in the late Romanesque style, gives a new character to the previous intervention of Monomachos, integrating all Holy Shrines below a single building Visualization of entrance to the tomb of Jesus on the basis of current information Gibson, S. and Taylor, J.E. Beneath the Church of the Holy Sepulchre: The Archaeology and Early History of Traditional Golgotha. London: Palestine Exploration Fund; 1994



1st Building phase

- Period of Constantine the Great and construction of Constantinian institutions (326-614 AD)
- The destruction of the Holy Shrines by the Persians (614 AD). The reconstruction of the Church of Resurrection by Patriarch Modestos
- The destruction of the Holy Shrines by Caliph Hakem bi-Amr-Illah on 1009 AD
 The reconstruction of the Church of Resurrection of the Byzantine Emperor Constantine IX Monomachos (1042 - 1048).



The Holy Aedicule of the Holy Sepucihre



The Holy Aedicule (326 AD)



(614AD) after its partial destruction by the Persians



8th c. AD. The rehabilitation of the core of the Aedicule by Patriarch Modestos



(11th c. AD). The rehabilitation in the shape of "pulpit" by Monomachos 1045 AD



Crusaders' phase 12th c. AD De Brun 16th c. AD

© Theo Mitropoulos

The current state of the reconstructed Aedicule by architect Komnenos in 1810 (after the fire of 1808) and the addition of the iron frame from the British rulers in 1947 for addressing the Aedicule's progressive deformation





Holy Aedicule, depicting: a) the present form, b) the earlier latent construction enveloped by the present building's exterior masonry c) the area of possible existence of the Holy Grave's Rock inside the latter (Emm. Korres, 2015) – comparative presentation on the ground plan of the Holy Aedicule by Bernardino Amico, 1609

School of Chemical Engineering Laboratory of Materials Science and Engineering

Documentation of the construction phases and decay diagnosis and pathology (Scientific Responsible: Prof. A. Moropoulou)

Scientific Responsible: Prot. A. More

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Non-destructive prospection / Rendering of the interior structure of the Aedicule of the Holy Sepulchre by use of ground penetrating radar

- **Prospection of the internal structure of the Holy Aedicule:** Holy Rock, Crusaders' construction phase, Komnenos phase
- Documentation of the construction phases





The exterior surfaces of the monument (marble elements and facades) present extensive deformations. These can have a significant impact on the static behavior of the Holy Aedicule, imparting additional loads on building materials contributing negatively to the longevity of the monument, therefore, the cause must be identified and addressed.



School of Chemical Engineering Laboratory of Materials Science and Engineering

Documentation of the construction phases and decay diagnosis and pathology (Scientific Responsible: Prof. A. Moropoulou)



The cause of the deformation is the deterioration of the mortars. Swelling of the masonry:

☆A historic cause of the swelling was the water precipitation through the open oculus of the dome above the Aedicule, until 1870

*Thereafter, as investigated by NTUA, the main source of humidity is the uptake through capillary rise from the surrounding water canals and underground voids.





Horizontal sections of the dome of the Holy Aedicule with the positions of their centers From the three horizontal sections of the dome at the heights 6.00m, 8.00m and 8.80m, it can be deduced that the dome of the Holy Aedicule is vertical and does not deviate from the vertical plane

V

F

:=:-

the marble supports

1

Horizontal sections of the pillars and

The points measured on the two horizontal sections of the pillars nd the marble supports of the Holy Aedicule, show remarkable deformations at these elements and deviations from the vertical from 4cm to 9cm

> The measurements of the points along the ten metal supportive beams revealed that there is strong deformation both vertically as well as horizontally. Vertically deviations up to 23" are observed and horizontally the beams present a bending tendency, i.e. the presence of a stress bow

School of Rural and Surveying Engineering Laboratory of Photogrammetry

Accurate Geodetic Measurements for determining eventual deviations and deformations of the Holy Aedicule (Scientific Responsible: Prof. A. Georgopoulos)

Research Team:

Evangelia Lamprou, Assoc. Professor NTUA George Pantazis, Assoc. Professor NTUA Panagiotis Agrafiotis, Rural and Surveyor Engineer, MSc Lydia Kotoula, Rural and Surveyor Engineer Alexandra Papadaki, Rural and Surveyor Engineer

Deformations of the metal supportive beams

School of Chemical Engineering Laboratory of Material Science and

Engineering **Building Materials' Characterization** (Scientific Coordinator: Prof. A. Moropoulou)



Environment and Quality of Life Center Laboratory School of Chemical Engineering NTUA Laboratory of Strength and Materials, School of Applied Mathematical and Physica Sciences NTUA Institute of Geology and Mineral Exploration (I.G.M.E.)









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12

20

28

36 40



Dept. Mineralogy -Petrography, Institute of Geology and Mineral Exploration (I.G.M.E.). Geologist -Mineralist Dr. G. Economou



CHARACTERIZATION OF HISTORIC MORTARS OF THE AEDICULE

- Binder of calcitic nature
- CO2 (%) * Aggregates are a combination of sands or sand and crushed brick
- The mortars can be characterized as slightly ** hydraulic (pozzolan mortars).



Laboratory of Strenath and Materials, School of Applied Mathematical and Physical Sciences, NTUA, Prof. St. Kourkoulis

School of Chemical Engineering Laboratory of Material Science and

, Engineering

Building Materials' Characterization (Scientific Coordinator: Prof. A. Moropoulou)

Scientific Team: Assistant Prof. Asterios Mpakolas,

Dr. Ekaterini Delegou, Dr. Petros Moundoulas†, PhD Cand. Emmanouil Alexakis, PhD Cand. Mairi Apostolopoulou, MSc Stud. Lamprini Sioula

In collaboration with:

Environment and Quality of Life Center Laboratory School of Chemical Engineering NTUA Laboratory of Strength and Materials, School of Applied Mathematical and Physical

Sciences NTUA Institute of Geology and Mineral Exploration (I.G.M.E.)

Sample Code	Macroscopic Sample Observation	Construction Phase	Petrographic Sample Characterization
JHS_1fa_ys	Yellow Stone – External Façade Building Stone	Komnenos' Phase	Micritic Fossiliferous Limestone
JHS_1fa_ws	White Stone – Masonry Building Stone	Crusaders' Phase	Limestone
JHS_1fa_ws2	White Stone – Masonry Building Stone	Crusaders' Phase	Limestone
JHS_2fl_ps	Pink Stone – Floor Substrate Building Stone	-	Dolomite
JHS_2fl_bs	Black Stone – Floor Building Stone	-	Viomicritic Fossiliferous Limestone
JHS_2fl_ws	White Stone - Rock of Calvary	-	Micritic Limestone
JHS_intss_s3	Building Stone – Internal Staircase	Komnenos' Phase	Dolomite

Indicative Areas of the Building Stones Provenance

IDENTIFICATION AND PROVENANCE INVESTIGATION OF BUILDING STONES



CHARACTERIZATION OF BUILDING STONES OF THE AEDICULE



- External Façade Building Stone Komnenos' Phase (JHS_1fa_ys): Micritic Fossiliferous Limestone
 - Main Composition: Micritic Calcite

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- Secondary Composition: Quartz crystals, clay minerals, opaque metallic minerals and oxides and hydroxides of ferric
- Total Porosity / Special Surface: 0.32% / 0.39 m²/g
- Yield Strength / Young Modulus: 77.8 Mpa / 38.2 GPa
- Masonry Building Stone Crusaders' Phase (JHS_1fa_ws & JHS_1fa_ws2): Limestones
 Main Composition : Micritic and Microsparitic calcite
 - · Secondary Composition: Quartz crystals and oxides and hydroxides of ferric
 - Total Porosity / Special Surface : 18.33% / 0.11 m²/g
 - Yield Strength / Young Modulus: 12.0 Mpa / 0.8 Gpa
- Building Stone from Internal Staircase Komnenos' Phase (JHS_intss_s3): Dolomite
- · Main Composition : Microcrystallic Dolomite
- · Secondary Composition: Calcite, Quartz and Alite crystals
- Total Porosity / Special Surface : 15.82% / 0.14 m²/g

• Floor Substrate Building Stone (JHS_2fl_ps): Dolomite

- Main Composition: Microcrystallic Microsparitic Dolomite
- Secondary Composition: Quartz crystals and oxides of ferric
- Total Porosity / Special Surface: 11.53% / 6.13 m²/g
- Floor Building Stone (JHS_2fl_bs): Biomicritic Fossiliferous Limestone
 - Main Composition : Micritic calcite and plenty fossils
 - Secondary Composition: Quartz crystals, opaque metallic minerals and oxides and hydroxides of ferric, titanium and pyrite (FeS)
 - Total Porosity / Special Surface: 1.85% / 2.21 m²/g
- Rock of Calvary (JHS_2fl_ws): Micritic Limestone
 - Main Composition : Micritic Calcite
 - Secondary Composition: opaque metallic minerals and oxides of ferric
 - Total Porosity / Special Surface: 22.36% / 0.26 m²/g
 - Yield Strength / Young Modulus: 10.3 MPa / 21.7 GPa









Dense point cloud and camera positions of the south facade



Creation of a three dimensional high resolution model through an automated image based method



School of Rural and Surveying Engineering Laboratory of Photogrammetry

Geometric documentation (Scientific Responsible: Prof. A. Georgopoulos)

Research Team:

Evangelia Lamprou, Assoc. Professor NTUA George Pantazis, Assoc. Professor NTUA Panagiotis Agrafiotis, Rural and Surveyor Engineer, MSc Lydia Kotoula, Rural and Surveyor Engineer Alexandra Papadaki, Rural and Surveyor Engineer The colored point cloud of the Holy Aedicule 21 121 12

Main Bearing Structure Mortar of the Crusaders' structural phase Seismic Loading





Current state

Strengthened

Maximum principal stresses Strain stress beyond limits (in red circle)



School of Civil Engineering Laboratory for Earthquake Engineering

Assessment of Current Condition under Static and Seismic Loading for the Holy Aedicule of the Holy Sepulchre (Scientific Responsible: Prof. C. Spyrakos)

<u>Scientific Team</u>: Dipl. Civil Engineer, MSc, PhD Ch. A. Maniatakis

Intervention Scheme

- **1. Removal** of the **metal supporting structure.**
- Mounting of the marble panels with new surface mortar with suitable quality and chemical composition to meet the compatibility requirements.
- 3. Use of **titanium links** to effectively **support** the marble panels.
- **4. Homogenization** of the bearing structure with **grout** of suitable composition and quality and interventions as discussed in the respective sections.
- **5. Strengthening** the supports of the **dome columns**.

COMMON AGREEMENT

Today March 22nd, the three Communities, the historic guardians and servants of the Holy Places, are fulfilling a historic responsibility that has been entrusted to us by the Status Quo, by installing the scaffolding to allow for the necessary conservation, reinforcement and repair interventions to the Holy Aedicule.

Today we mark the formal beginning of the project for the restoration of the Sacred Aedicule in the Church of the Anastasis. This project is being carried out by a team of specialists from the National Technical University of Athens under the supervision of Professor Moropoulou, whose important report has recently been completed and published. This report was submitted to the three Communities here in Jerusalem in February of this year, and the work can now begin.

We wish to acknowledge the consensus that the three Communities have reached so that this project could proceed, following up the meeting of March 19th, at the Greek Orthodox Patriarchate of Jerusalem in order to forward the "Innovative integrated diagnostic research and strategic planning for compatible, performing and sustainable materials and conservation and rehabilitation interventions of the Holy Aedicule of the Holy Sepulcher in the All-Holy Church of the Resurrection in Jerusalem," conducted by the National Technical University of Athens.

The implementation of this project will respect and will not change the rights and the claims of the three Communities.

The consensus achieved implies the following:

- The Project will be implemented within the engineering and scientific framework of specifications as set forward by the NTUA Study.
- 2. The Project will be managed within the following framework:

2.1 The meeting of the Heads of the three major Communities performing as "project owners' committee" (POC) will undertake the responsibility for all strategic decision making.

2.2 Each Community should create separate accounts for contributions in order to collect the necessary funds to cover the cost of completion of the works of the conservation of the Holy Aedicule.

2.3 a. The commencement of the works will begin within a fortnight after the Easter Feast of the Eastern Churches.

2.3 b. The works, which will be completed in approximately eight months to one year, will not prevent the religious services in the Holy Sepulcher or, more specifically, in the Aedicule, nor prevent the access of pilgrims into these places.

2.4 The CTB (Common Technical Bureau of the Church of the Holy Sepulcher), staffed by three Architects by the three Communities, will be responsible for the

correct execution of the project according to the scientific studies and directives realized by the National Technical University of Athens. The representative of the Common Technical Bureau of the Church of the Holy Sepulcher (Dr. Theodosios Mitropoulos), as Construction Site Manager (CSM), will be responsible for the construction site's operation within the directives set forward by the relevant authorities.

2.5 The Scientific Supervision will be performed by the interdisciplinary NTUA Study Team, headed by Professor A. Moropoulou (CSS). She has the overall responsibility for the scientific monitoring of the work and is the director of the interdisciplinary scientific monitoring laboratory which will be set up in the construction site. In collaboration with the interdisciplinary NTUA scientific team, the Project Manager (PM) and the CSM she will monitor and control the work.

2.6 The project management will implement the project charter, report on the work progress according to the schedule and budget, and coordinate the construction and the scientific supervision teams in order to complete the work successfully and on time and to manage risks on regular basis.

2.7 The (POC) project owners' Committee authorizes the Steering Committee (SC) to cope with the current problems of integrated project governance with the participation of the CSS (Chief Scientific Supervisor), the CSM (Construction Site Manager) and the PM (Project Manager). The Patriarch of Jerusalem or His Deputy is chairing the SC with the obligation to inform the project owners Committee.

For the first time in over two centuries, the Sacred Aedicule will receive urgent interventions. This restoration will secure this Holy Place for generations yet to come for all those pilgrims and people of good will who come to this church to seek spiritual renewal. During the entire project, the Holy Tomb will remain accessible to pilgrims without disruption, and for this careful planning and execution we owe the project team a huge debt of gratitude. The Holy Tomb must always be open to all.

May God bless this work and those whose responsibility it is to carry out, and may the renovation of the Holy Tomb of our Lord Jesus Christ be a beacon of hope for a hurting

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THEOPHILOS III Patriarch of Jerusalem

world.

PIERBATTISTA PIZZABALLA Custos of the Hole Land

A NOURHAN MANOUGIAN Armenian Patriarch of Jerusalem According to the common agreement, the interdisciplinary scientific management of the project is recognized as the only prerequisite that can successfully face the risks and the uncertainties that such a unique project presents. The integrated governance of this project is achieved on the basis of the NTUA study.

The <u>restoration and</u> <u>conservation working</u> <u>teams</u> have been established and are now <u>functioning in</u> <u>full capacity</u>, according to the technical and the project management guidelines. Any on-site problems and uncertainties that emerge during the project's execution on a daily basis, are promptly solved through the project's interdisciplinary scientific decision making, and executed by the technical staff. The work done so far has revealed that the **problems in the bearing** structure of the monument surrounding the Holy Rock are extremely serious.

If these problems were not addressed immediately, the net impact on the monument and the Holy Rock would be negative and irreversible

Within this framework, the Technical Bureau of the Holy Sepulchre has up to now taken care for the arrangement of the infrastructure of the construction site, and of the facilities of the Conservation and Monitoring-Documentation Laboratories, according to the NTUA specifications. Dr.Mitropoulos, Osama Hamdan and Irene Babayan are cooperating in partial reports and investigations.



The Common Agreement of the Status Quo Christian communities responsible for the Holy Sepulchre provides the statutory framework for the execution of the project.

The project became possible and is executed under the governance of His Beatitude, Theophilos III, Patriarch of Jerusalem.

Contributions from entities and persons all over the world secure the project's funding.

Worth noting Mica Ertegun's donation through WMF, Aegean Airlines' et als. The work site has been successfully organized without disrupting the flow of pilgrims





Additional support has been installed in order to ensure stability of the Aedicule during the works





The Conservation lab at the Franciscan gallery has been established and is fully functioning

en.





SIDE

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Conservators team

BI 225 225 12

Theodoris Mavridis, M.Sc. in Monuments Protection, B.Sc. in Archaeological Conservation (Team Leader)
Konstantina Karathanou, M.Sc. Archaeologist-Conservator

Ioannis Andritsopoulos, Conservation Technician
 George Palamaris, Stone Technician



The teams of restorers and conservators are working in full capacity in two shifts day and night



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Restorers team •Vasilis Zafeiris, Civil Engineer (Team Leader) •Christos Theodorakis •Athanasios Karydis •Petros Chaloftis •George Anastasiadis, Senior marble technician/restorer The scientific monitoring and documentation laboratory is established and fully functioning under the responsibility of NTUA









The interdisciplinary scientific team of *National Technical University of Athens* (NTUA), using **high technology measuring techniques**, is implementing integrated <u>documentation</u> and <u>monitoring</u>, ensuring **scientific support in decision making**

Governance of the project flow chart



The successful implementation of the works so far has proved that the above governance structure is effective and indispensible to carry out the project as agreed.

Progress of the works

THE MONUMENT HAS NOW BEEN REPAIRED TO A GREAT EXTENT

The **main steps** of the rehabilitation process are the following:

- Dismantling and removal of the stone panels
- Removal of disintegrated and incompatible mortars from the revealed masonry
- Repointing of the masonry
- Partial reconstruction of part of the masonry, where deemed necessary
- Resetting of columns
- Injection of grouts
- Cleaning and Protection of architectural surfaces

DISMANTLING AND REMOVAL OF THE STONE PANELS



The joint of the slabs comprising the stone panels surrounding the Holy Aedicule were sealed by Komnenos with the use of lead, a technique dating to stone buildings of antiquity, but which created severe problems in the specific structure, leading to moisture concentration within the masonry. The lead present in the joints had to be removed, in order to dismantle and remove the slabs of the panels

Prior to the removal of each slab of the panel, supports were designed and constructed in order to ensure the stability of the remaining panels





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The area behind the removed slabs was cleaned of disintegrated mortars and remains from the lead sealing and support was provided. All slabs were coded prior to removal and their dimensions are measured and recorded



The dismantling of the stone slabs, even from the very first panel area



 has revealed that the findings from the NTUA diagnostic study are valid,

• whereas, the knowledge of the historic materials and structures, as well as their decay and damage, are enriched by the ongoing scientific monitoring Head of restoration team, Civil Engineer, V. Zafeiris highlights on June 14th, 2016:



"what we discovered fits what was described in the NTUA study: Disintegrated mortar and concrete of the Komnenos phase and a swollen masonry at its lower part."

Photos from the dismantling of stone slabs from area N2

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The filling mortar, applied by Komnenos between the stone slabs and the masonry, was found highly disintegrated at the removal of the panels; the rain water entering from the roof caused the mortar to lose coherence and therefore it no further served the purpose it was intended to, having also lost adherence to the masonry and the stone slabs

The removal of the stone slabs allowed for the examination of the original masonry materials



When removing the disintegrated masonry in N5, the northwest corner of the tomb was revealed, thus verifying the NTUA Study regarding the Holy Rock boundaries

Upper stone plate

Lower stone element







Undocumented incompatible modern interventions were discovered

Use of incompatible materials in nondocumented recent restorations: Yellow circle indicates the location in area N5, behind the stone slabs, where Portland cement was used as a filler mortar.

These interventions were **implemented by the Technical Bureau** with the **use of incompatible materials** and **carried out in a manner aiming to cover up the problems arising** due to the swelling and disintegration of the structural materials rather than **correct them, aggravated the state of the structural materials**. This is mainly due to the use of **cement mortars** as detected in many areas of the lower part of the masonries



Use of incompatible materials in nondocumented recent restorations: The removal of the stone slabs around the opening in N1, revealed the use of Portlant cement (area between the yellow curves)

The use of incompatible mortars, such as cement, in addition to multiple other issues it arises, does not allow for the necessary "respiration" of the masonry due to its incompatible microstructure, thus resulting in the aggravation of the masonry swelling.

Finally, the undocumented removal of disintegrated mortars by the technical bureau created further problems to the masonry



ARISING ISSUE:

Therefore, at this point it was deemed essential to **remove all incompatible materials** of the bad undocumented modern interventions, in order to ensure that the degradation processes they enhance and even in some cases provoke are stopped.

The use of new compatible mortars, in accordance to the guidelines and selection as stated in the study, will contribute to the longevity of the monument

ENHANCEMENT OF THE NEED TO IMPLEMENT THE STUDY PROPOSALS CONCERNING MATERIALS, REPAIR, REINFORCEMENT AND CONSERVATION INTERVENTIONS



The removal of the external stone slabs from the areas selected for interventions, and the subsequent revealing of information regarding the type and state of preservation of the masonry, highlighted the need to implement the study proposals concerning materials, repair and reinforcement interventions
In the process of mortar

removal, masonry behind N2-N3

Komnenos filling mortar behind panel N4



Cleaned masonry behind N2 Detail of cleaned masonry behind N2

After the dismantling and removal of the stone slabs of the panels, the inner masonry was revealed. The highly disintegrated Komnenos filling mortar, as described in the previous report, was sampled at different heights, in order to be analyzed (on-going research) and was then entirely removed. Furthermore, the joints of the masonry were cleaned of any disintegrated mortars and dirt, in order to be repointed

VARIETY OF MASONRY JOINT MORTARS



After the removal of the slabs and the Komnenos filling mortar, the masonry structural materials were revealed. <u>A VARIETY OF MORTARS ARE DOCUMENTED</u>. This is <u>IN</u> <u>ACCORDANCE TO THE STUDY PERFORMED BY THE NTUA INTERDISCIPLINARY TEAM</u>, as the mortars revealed and examined, exhibit a different coloration (beize, white and gray) and a different gradation and relative proportion of aggregates, which consist of ceramic fragments and other aggregates frequently of black coloration. The presence of lime lumps, linked to insufficient mixing of the mortar in the production process, is detected even macroscopically in all mortars, however to a different extent.



RESTORATION MORTAR PROPOSAL

Compatible to the original mortars: Lime-pozzolan mortar (High reactivity metakaolin), With river quartz origin aggregates of 2 mm maximum gradation&inorganic mineral fibers. Performing to the structural integrity of the original structure, according to FEM results: compressive strength >15 MPa

classified as a M15 type masonry mortar according to EN 998/2.

The specific characteristics of the proposed mortar are:

- **Cement free:** the total absence of cement makes the proposed mortar compatible with the traditional materials of the masonry that is to be strengthened;
- **High mechanical performance:** the high strength is exceptional for a lime product, which thus succeeds in combining historical and technological requirements with structural and working requirements;
- **High adhesion to masonry:** both shear bond strength (important for bedding) and tensile bond strength (important for reinforced slabs and vaults);
- Very low content of water soluble salts: it presents a very low value of electrical conductivity, does not introduce salts containing sulphates, chlorides, nitrates, potassium and sodium and does not contribute to the chemical-physical decay connected with the formation and crystallization of those salts;
- **Application versatility and simplicity:** applied by trowel or by spraying it is used for strengthening works up to 5 cm thick. For thickness > 5 cm it may also be applied by casting , adding aggregates to the mortar to obtain high strength structural plasters or lime concretes;
- High permeability to water vapor: this is important to allow normal transpiration of the masonry;
- Low capillary water absorption: important to ensure that water does not penetrate the masonry from outside;
- No reaction to fire: the material is not combustible and does not produce fumes (Euroclass A1).



SELECTION OF COMMERCIAL MATERIAL

MASTEREMACO S 285 TIX

The characteristics of the proposed mortar are compatible with the basic building elements of the structure and also within the acceptability limits set for restoration mortars as deduced from the examination of a large number of historical mortars. The proposed joint mortar is a **lime-metakaolin mortar (with high reactivity metakaolin), without the presence of cement, with river quartz origin aggregates of a maximum gradation of 2mm and with the addition of mineral inorganic fibers**. It guarantees compressive strength >15 MPa and is classified as a M15 masonry joint mortar according to EN 998/2

The proposed mortar of beige color exhibits high mechanical strength values, despite being a cement-free lime mortar and is applied by trowel, spaying or casting for the structural reinforcement of masonries. It does not release watersoluble salts or induce the formation of efflorescence. The specific characteristics of the proposed mortar are:

- Material with CE mark: EN 998/2;
- Cement free:
- High mechanical performance:
- High adhesion to masonry:
- Very low content of water soluble salts
- Application versatility and simplicity
- High permeability to water vapor
- Low capillary water absorption
- No reaction to fire:

Table 3: Technical characteristics of the proposed mortar		
Compressive strength EN 1015/11	18 MPa, Class M15	
water vapor permeability, EN 1745	µ<35	
Water-soluble salts (hardened mortar) UNI 11087	Specific electrical conductivity <80µS·cm ⁻¹ SO ₄ ² ~<0.1% Na ⁺ <0.05% K ⁺ <0.05%	
Water absorption coefficient, EN 1015/18	0.2 Kg.m ⁻² .min ^{-0.5}	
Reaction to fire, EN 13501/1	Euroclass A1	
Pullout resistance of steel bars and bars of the line MBar, Rilem-CEM-FIP RC6-78	>6 MPa	
Static modulus of elasticity UNI 6556	16,000 MPa	
Adhesion to substrate – EN 1015/12 (direct tensile strength)	>0.6 MPa (failure type A (mortar-substrate interface)	
EN 1052/3 (shear strength)	τ ₀ >0.80 MPa	

By adding gravel with D_{max} 20 mm to the proposed mortar, a lime concrete is procured with consistence S3, EN 206/1, and compressive strength > 15 MPa.

OPTIMIZATION OF REPAIR MATERIALS

Prof. A. Moropoulou, Assist. Prof. A. Bakolas, Dr. E. Delegou, Phd Cand. M. Apostolopoulou, MSc Stud. V. Volioti

Optimization of repair mortars

The proposed lime-metakaolin mortar is compatible with the Holy Aedicule historic masonry:

- Lime-metakaolin mortars are compatible
- In terms of physicochemical characteristics
- In terms of microstructural characteristics
- In terms of hygric properties
 - Optimum capillary rise coeffficient (0.2 kg/m²min^{0.5}), in order not to aggravate moisture uptake, but allow breathability of the masonry elements

LIme-metakaolin mortars are also serviceable:

Early acquisition of strength

The proposed mortar achieves 15 MPa compressive strength, as demanded by the FEM results

Furthermore, the selected mortar does not introduce soluble salts into the masonry

It is proposed to use the same mortar as the filling material between the panels and the masonry

*****With the addition of gravel, of appropriate gradation, as designed by the NTUA team

Thus compatibility is enhanced



-		CO #/			
	Total Cumulative Volume (mm ³ /g)	Apparent Density (g/cm ³)	Total Porosity (%)	Specific Surface Area (m²/g)	Average Pore Radius (µm)
LM ₁	198.8	1.73	34.3	4.15	0.32
LM ₅	191.6	1.75	33.5	5.56	0.29
NHL	159.8	1.90	30.8	4.43	0.29
ACCEPTABILITY LIMITS	160 - 205	1.6 - 1.9	30 - 42	3 - 14	0.1 - 1.50



REPOINTING OF MASONRY WITH RESTORATION MORTARS



Indicative details of repointed masonry behind panels

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The masonry was then repointed with the use of compatible and serviceable restoration mortar, as selected. The restoration mortar was selected in order to fulfill all compatibility criteria, at the same time ensuring serviceability, as tested by the results of the finite element modeling and analysis.

Masonries behind panels S2, S1, ES, EN, N1, N2 were repointed, whereas the masonries behind panels S3, S4, S5, W, N5, N4 and N3, were reconstructed at their lower parts and repointed at higher levels, where the state of the masonry was assessed as adequate



The masonries revealed after the removal of the Komnenos filling mortar further verified the conclusions of the NTUA study and were in need of repair

The masonry joint mortars appear disintegrated and the masonry appears swollen in its lower part, however <u>the degree of mortar disintegration was found different on</u> <u>the masonry behind each slab</u>.

The masonry revealed behind slabs in areas <u>N2, N3</u>, after the removal of the highly disintegrated outer layer of mortar, was <u>in a relatively good state of preservation</u>, the masonry behind slabs in area <u>N4</u> was found in a <u>moderate state</u> of preservation, however, the masonry behind slabs in area <u>N5</u> was found in an <u>extremely bad state</u> of preservation

- In the implementation study, the NTUA interdisciplinary team was prepared for all arising issues and the implementations which are now deemed a necessity.
- The implementation study is readjusted in full accordance to the findings and will be readjusted continuously as issues and new findings arise

The internal masonry layers become a focal point for the decision making concerning repairs, others being intact and others degrading, and need to be reconstructed

The <u>KEY FINDING</u> that changed the original plan of work is that the masonry surrounding the Holy Rock is in bad shape especially behind slabs N4, N5, S5 and S4, comprises stones of irregular and uneven shapes and needs to be rebuilt from scratch at its lower part, as it is a point of high risk for the stability of the monument and the Holy Rock on which it partially rests.

This was accomplished in a manner, as to relieve the Holy Rock of vertical loads as much as possible

Effect of the irregular shape of stones on the masonry's strength



Regarding the mechanism of observed deformation of the structure - at its lower level - which is most possibly attributed to the mortars used, and taking into account that the masonry is generally built of irregular shaped stones, it should be noted that <u>EVEN THE WORST QUALITY MORTARS</u> <u>CANNOT BE RESPONSIBLE FOR ANY</u> <u>DEFORMATION DUE TO VERTICAL LOADS, IF</u> <u>THE STONES ARE HEALTHY WITH NARROW</u> <u>HORIZONTAL JOINTS</u>.

Behind certain slabs it is obvious, especially up to a height of four feet from the wall base, that <u>ALL STONES ARE COMPLETELY</u> <u>IRREGULAR WITH STRONGLY INCLINED</u> <u>JOINTS</u>. Furthermore, many of the stones in this area, have suffered extensive decay

Irregular shape of stones (area N2)

This led to the need to install a "vertical lift" structure from panel N4 to panel S4

Preliminary designs of the retaining system that will be used for the construction of the new wall (designs by Assist. Prof. Ch. Mouzakis, Deputy Construction Site Manager)



PARTIAL RECONSTRUCTION OF MASONRY AREAS



Reconstruction of certain masonry areas had to fulfill three basic requirements.

- <u>SAFETY</u>, regarding the structural integrity of the Aedicule. For this purpose a special vertical lift device was designed and constructed, that when installed at certain heights within the masonry, allows the safe dismantling of the masonry below it. Dismantling & reconstruction, was performed panel by panel
- Selection and use of <u>NEW BUILDING STONES THAT ARE COMPATIBLE WITH THE</u> <u>HISTORIC MATERIALS</u>, while imparting the necessary strength to the damaged areas. The new masonry was constructed using orthogonal stone blocks with largely standardized dimensions, to enhance mechanical performance and homogeneity. Jammain stone was selected, a beige limestone from Palestine
 <u>PRESERVATION OF THE HOLY ROCK</u>. To this end, and in order to relieve the Holy Rock of as many vertical loads as possible, the new masonry was constructed to a thickness such that it is in contact with the Holy Rock, without in any way damaging the Holy Rock and conforms to the curvature and shape of the Holy Rock, without the need of carving the historic material.

Jerusalem Patriarchate – National Technical University of Athens Example of reconstructed masonry (S3) conforming to the shape of the Holy Rock. Number indicate the depth from the surface of the new masonry at which the Holy Rock has been identified





RESETTING OF COLUMNS



One of the basic requirements, prior to the reassembly of the panel slabs and the addition of the filling mortar, between the masonry and the stone panels, is the resetting of the dislocated columns.

This procedure has already been initiated, in order to **optimize working time**. In the panels were new masonry was reconstructed, the repositioning of the respective columns had to follow the building schedule.

Process of a column repositioning

Corroded iron support bars







Fully corroded iron support bars in area N1

The removal of the stone slabs, as well as the removal of the disintegrated layer of mortar between the slabs and the masonry, revealed the <u>FULL CORROSION</u> <u>OF THE IRON SUPPORT BARS</u>, which were used to support large stone slabs (e.g, the oval slabs) or embedded within the masonry, connecting external and internal layers.

The corrosion of these iron bars <u>NECESSITATES THEIR COMPLETE</u> <u>REMOVAL, ACCOMPANIED WITH</u> <u>STRENGTHENING (E.G. REBUILDING,</u> <u>GROUTING) OF THE RESULTANT EMPTY</u> <u>SPACE CREATED BY THEIR REMOVAL</u>

This finding necessitates the use of titanium, as proposed by the NTUA interdisciplinary team, in order to avoid such phenomena and ensure the longevity of the structure

Iron connectors between stone slabs for the stabilization of the panels



During the removal of stone slabs, it was evident that <u>THE</u> <u>IRON CONNECTORS</u> between stone slabs that function as stabilization of the panels were corroded too.

<u>THESE CONNECTORS needed</u> to be carefully <u>REMOVED</u> from the slabs, the void created be cleaned appropriately and <u>NEW</u> <u>CONNECTORS NEED TO BE</u> <u>PREPARED, ATTACHED TO</u> <u>THE SLABS WITH A</u> <u>COMPATIBLE MATERIAL</u>

Corroded iron connectors between stone slabs



INTERVENTIONS TO PROTECT METAL ELEMENTS IN THE MASONRY

- If the metallic element is in a parallel position in relation to the masonry surface and in a depth up to 7 centimeters, the use of corrosion inhibitors via spray application are considered as the optimum technique.
- If the metallic element is in a vertical position in relation to the masonry surface or in a parallel position but in a depth greater than 7 centimeters, it is advisable to use corrosion inhibitor "cartridges".
- If the metallic element partially protrudes in the mortars and stones and partially projects into the environment, the protection of the section embedded into the mortars and stones must be protected through the use of VCIs, as previously described. The section exposed directly to the environment can be protected through the use of transparent organic coatings (varnishes). In this case a decision must be made whether the applied varnishes are required to be easily removed (reversible) or not (nonreversible).



The revealing of weak and strong points of the historic materials and structures of the Holy Aedicule enhances the need for the implementation of the study "Conservation, Reinforcement and Repair Interventions for the Rehabilitation of the Holy Aedicule of the Holy Sepulchre in the All-Holy church of Resurrection in Jerusalem" and for its readjustment concerning titanium bolts and anchors, taking into consideration the findings

STRENGTHENING WITH TITANIUM BARS, CONNECTORS AND ANCHORS

Titanium bars will be installed at the columns, after their repositioning and after rebuilding and grouting of the masonry.

The installation of the **titanium bars at the columns**, as well as the corresponding installation of **titanium connectors between the stone slabs** and **titanium anchors between the stone slabs and the masonry**, will <u>RESTORE THE "COHESION" OF THE EXTERNAL</u> <u>STONE LAYER WITH THE MAIN MASONRY AND IMPROVE THE</u> <u>SEISMIC RESPONSE OF THE WHOLE STRUCTURE</u>.

The **option** of introducing, additionally, a **titanium matrix** in the layer between the stone slabs and the rebuilt masonry will be evaluated in due process, after assessment of anchor pull tests

Assist. Prof. Ch. Mouzakis, MSc Stud. Ev. Koukouras, et al

Anchor pull tests have been completed in order to evaluate the different scenarios regarding the use of titanium bolts, anchors and bars in the masonry. The equipment for the anchor pull tests was designed by the deputy construction site manager, Ch. Mouzakis.

A series of tests was conducted using stone slabs from the monument (that were planned to be replaced), as well as new replacement stone slabs, with the aim to determine the stiffness of the connectors which will be implemented to anchor the stones of the outer marble cladding of the monument to the masonry, when reassembling the panels.

These data will be subsequently introduced into a finite element model for the structural assessment of the Holy Aedicule. During the tests, titanium bars of specifications as described in the previous report were used, in combination with the use of Emaco MasterFlow 928. The following figure depicts the test setup.



Design by the deputy construction site manager, Ch. Mouzakis

Typical test setups and stress-strain curves obtained



The values of Springs that have to be adopted by the FEM model for the connection of marbles with masonry are summarized in Table 4

Table 4: Summary of calculated values

Material	Value
Historic slayeb (transverse to the cutting plane): tests 2, 3	E=2288,4 MPa
Historic slayeb (parallel to the cutting plane): tests 4, 5	E=3247,42 MPa
New slayeb (diagonally to the cutting plane): tests 6	E=6621,7 MPa
Anchor at mizzy stone (large side): tests 7, 8	K=1538 N/mm
Anchor at mizzy stone (small side): test 9	K=3107 N/mm
Historic masonry: test 10	K=11261 N/m

The maximum strength of anchored titanium bars are shown in Table 5. These values are much higher than the required ones by FEM for various qualities of marbles and different

anchoring arrangements

Table 5: Description of test conditions and results

TEST	STONE	ORIENTATION OF DRILLED	YIELD STRESS (N)	MAX STRESS (N)	MECHANISM OF FAILURE
		CUTTING PLANE			
1	Historic slayeb	Transverse	20.830	20.830	Brittle fracture of stone
2	Historic slayeb	Transverse	20.000	28.689	Failure of upper thread
3	Historic slayeb	Transverse	18.269	27.980	Yield of titanium bar at the upper
					thread
4	Historic slayeb	Parallel	19.471	27.884	Yield of titanium bar at the lower
					thread
5	Historic slayeb	Parallel	17.067	27.884	Failure of lower thread
6	New slayeb	Diagonally	17.067	26.682	Failure of upper thread
7	New mizzi	Diagonally	13.461	18.269	Yield of titanium bar over the stone
8	New mizzi	Diagonally	15.865	15.865	Yield of titanium bar over the stone
9	New mizzi	Diagonally	14.663	16.826	Yield of titanium bar over the stone
10	Historic masonry	N/A (height 1m, depth 400	19.471	26.682	Yield of titanium bar at the mortar
	(Panel N1)	mm)			

INJECTION OF GROUTS

After the implementation of the repair masonry and the injections of grouts, the Holy Rock will be to a certain level relieved of vertical loads. Even though the Holy Rock will cease to be a bearing element, nevertheless its conservation is an issue of great importance, as the current bad state of the Holy Rock, due to previous stresses it has been subjected to, jeopardizes its longevity and must be addressed

Grout injection aiming at the homogenization of the masonries, using the materials already specified in the NTUA implementation study, will be performed in each of the panel sets, starting with the set N2, N3, N4, N5, W, S5, S4. Grout tubes will be installed after the completion of masonry repair in the respective set of areas. The material used for the grout is fully described in the study and is in accordance to all requirements of compatibility and serviceability, as derived from the NTUA interdisciplinary study, in order to ensure the longevity of the structure.

Preparation for the injection of grouts

Preparation of masonry for grouting Removal of internal facings inside the tomb chamber – visibility of the holy rock Protection of the Arcosolium interior during the grouting process Interventions in the interior staircases Interventions at the chapel of the Angel Interventions regarding the murals and frescoes at the chamber of the Tomb Interventions to protect metal elements in the masonry Detection and sealing of underground channels and voids



MASONRY INJECTION RESTORATION GROUT PROPOSAL

Very fine particle size (<12µm), high flowability and excellent maintenance of workability.

Expansion in the plastic phase, thereby ensuring that even the smallest voids are filled. Guarantees compressive strength >10 MPa.

The grout's specific characteristics are:

- **Cement free:** the total absence of cement makes the proposed grout compatible with the traditional materials of the masonry that is to be strengthened;
- Very low content of water soluble salts: it presents a very low value of electrical conductivity, does not introduce salts containing sulphates, chlorides, nitrates, potassium and sodium and does not contribute to the chemical-physical decay connected with the formation and crystallization of those salts;
- **High fineness, high flowability, high water retention:** these characteristics permit the grout to be easily injected even into the smallest voids and does not easily release mixing water into the masonry, thereby avoiding inhibition of hydration of the grout;
- **Excellent maintenance and workability:** this property allows the contractor adequate working times
- Very low hydration temperature: this is fundamental to avoid cracks forming due to states of thermal coaction inside the masonry;
- **Mechanical performance:** despite being a highly fluid lime grout, the mechanical performance is entirely suitable for masonry strengthening
- High permeability to water vapor: this is important to allow normal transpiration of the masonry;
- **Resistance to sulphates:** the material is not susceptible to damaging chemical reactions with any sulphates present in the masonry (in the bricks, stones, bedding mortars or in the capillary rise water)
- No reaction to fire: the material is not combustible and does not produce fumes (Euroclass A1).



SELECTION OF COMMERCIAL MATERIAL

MASTERINJECT 222

The proposed grout is a cement-free, lime-pozzolan grout with a very fine particle size (<12 μ m), high flowability and excellent maintenance of workability. Furthermore, it expands in the plastic phase, thereby ensuring that even the smallest voids are filled. It does not release water-soluble salts or induce the formation of efflorescence. It develops compressive strength >10 MPa and may therefore be classified as a M10 type according to 998/2.

The grout's specific characteristics are:

- Material with CE mark: EN 998/2;
- Cement free:
- Very low content of water soluble salts:
- High fineness, high flowability, high water retention
- Excellent maintenance and workability
- Very low hydration temperature
- Mechanical performance:
- High permeability to water vapor
- Resistance to sulphates
- No reaction to fire

Table 4: Technical features of the proposed injection grout				
Bleeding, Normal 33/87	Absent			
Flowability, Marsh cone	Initial< 30 s 30 min < 30 s 60 min < 30 s			
Vapour diffusion coefficient, EN 1745	μ<35			
Maximum hydration temperature, adiabatic chamber	< 30 °C			
Water-soluble salts (hardened mortar), UNI 11087				
Resistance to <u>sulphates</u>	No loss of resistance for test specimens placed for 90 days in a 5% solution of Na ₂ SO ₄			
Reaction to fire, EN 13501/1	Euroclass A1			
Compressive strength, EN 1015/11	> 10 MPa Class M10			
Static modulus of elasticity, EN 13412	$6,000 \pm 1,000 \text{Mpa}$			
Adhesion to substrate (shear strength), EN 998/2	> 0.15 MPa			
Pull-out resistance of steel bars of the line MBar, RILEM-CEB-FIP RC6-78	> 4 MPa			
Expansion in plastic phase CRD C 621	> 0.4%			

Regarding the cohesion of the reconstructed masonry with the Holy Rock, an issue arises as to the nature of this interface.

- A <u>PROPOSAL TO USE POLYURETHANE SHEETS</u> in order to protect and insulate the Holy Rock was expressed by one of the member of the Technical Bureau <u>was rejected</u>, as <u>past interventions</u> implementing such materials (e.g. in the case of the Milos Catacombs) have shown very bad results, increasing enthalpy and intensifying the development of microorganisms with subsequent intense bio-deterioration.
- Another case scenario that was examined, was the <u>USE OF HOT LIME TECHNOLOGY MORTARS</u> (onsite slacking of the lime), which would be casted on the Rock and would serve as an intermediate layer, at the same time protecting the Holy Rock. However <u>this solution is not feasible</u>, as the <u>entire</u> <u>Aedicule would have to be opened from above</u> in order to cast the hot lime mortar.

Thus, <u>THE USE OF INJECTION GROUTING WAS SELECTED AS THE OPTIMUM INTERVENTION</u>, which will <u>HOMOGENIZE THE HOLY ROCK AND THE STRUCTURE AROUND IT</u>. The injection grout selected fulfills compatibility and serviceability criteria. This is examined through the assessment of its physicochemical characteristics and the achieved mechanical strength that it succeeds when applied.

Requirements set for the grout involved:

- Achievement of adequate flowability,
- Low content of water-soluble salts,
- Resistance to sulphates
- Vapour diffusion coefficient < 35.
- Low hydration temperatures
- Permeability to water vapour is required to be high
- Mechanical characteristics: compressive strength > 10 Mpa, static modulus of elasticity = 6 Gpa,

The grout is lime-pozzolan, same as the restoration mortar applied; therefore compatibility is enhanced. The selected commercial grout fulfills all the above mentioned requirements; is a cement-free, lime-pozzolan grout with a very fine particle size (<12 μ m), high flowability and excellent maintenance of workability. Furthermore, it expands in the plastic phase, thereby ensuring that even the smallest voids are filled.

PREPARATION OF MASONRY FOR GROUTING

It is necessary to have all panels removed at the time of the injection, in order to control and manage the grouting procedure. The revealed masonries must be cleaned of disintegrated mortars and repointing must be complete. Injections pipes must be installed, creating a clear matrix at different depths (in a depth sequence of 1/3, 1/2 and 2/3 of the masonry thickness). THE ABOVE HAVE BEEN ACCOMPLISHED. Injection pipes have also been applied in the cracks and openings of the surface of the Holy Rock.



Masonries ready for grout injections

PREPARATION OF MASONRY FOR GROUTING



REMOVAL OF INTERNAL FACINGS INSIDE THE TOMB CHAMBER – VISIBILITY OF THE HOLY ROCK

The removal of the marble slabs opposite the Holy Tomb is deemed necessary in order to ascertain visibility of the Holy Rock and to control the grouting procedure. A metal frame will be added in order to impart additional support to the structure.

TWO REQUIREMENTS were set:

- 1. Related to the grouting process, which requires <u>fresh air flow</u>, in order to ensure that no moisture is trapped within the Holy Rock; it is a **basic requirement in order to ensure the longevity of the Holy Rock** while allowing the continuous pilgrim flow, as condensation of moisture deriving from the pilgrims and entrapment of this moisture within the Holy Rock is a constant risk that must be dealt with.
- 2. Related to the visibility of the Holy Rock.

The appropriate interior marble slabs opposite the Holy Tomb will first be removed and the remaining load bearing slabs and the damaged column will be supported with a stainless steel metal frame. The metal frame, will thus uptake a load bearing role in the structure.

A glass window will be installed, constructed of a <u>high</u> <u>technology transparent reinforced crystal</u>. Depending on commercial availability, <u>voids will either be included</u> <u>on the glass panel, or the metal frame</u> to facilitate <u>evaporation & removal of moisture</u> from the Holy Rock





PROTECTION OF THE ARCOSOLIUM INTERIOR DURING THE GROUTING PROCESS

The Arcosolium (Holy Tomb) must be opened in order to determine and deal with the presence of possible cracks in the surrounding masonry/rock.

Specifically, during recent inspections at the N5 panel, the northwest corner of the marble plate that covers the Arcosolium was revealed and visible from the exterior. During these investigations it was revealed that the marble panel over the Arcosolium (the two part marble plate where pilgrims pray), is in fact residing over a second stone element plate, which probably originates to an earlier construction period





Jerusalem Patriarchate - National Technical University of Athens

During the same investigation, <u>FRAGMENTS OF BLACK MARBLE</u> <u>MOSAICS WERE DISCOVERED</u> at the north-west corner of the upper marble plate, at the north side of the Arcosolium plate.

- This mosaic correlates well with the presence of the lower stone element, indicating decorations during earlier historic phases of the Arcosolium.
- More important, it indicates, that parts of the historic Aedicule, especially at its lower height were preserved after the destructive fire of 1807, which were effectively embedded in the Komnenos rehabilitation phase.

Currently, it not known whether the marble plate resides over the Holy Rock surface, where the body of Jesus Christ's body was placed. The authentic surface upon which Jesus Christ's body was rest upon, may be at a height level different than the lower stone element, creating a void between the two surfaces.



DURING THE GROUTING PROCESS THERE IS A RISK OF GROUT FLOWING INTO THIS VOID, FILLING IT COMPLETELY.

- To ensure that no material flows into this void, any openings/cracks present on its surrounding structure, must be sealed.
- The **Tomb must be opened** and openings and cracks must be detected, fully documented and dealt with accordingly.
- During the grouting process the Tomb should remain open, however if this is not acceptable, alternative monitoring means will have to be employed.

INTERVENTIONS IN THE INTERIOR STAIRCASES

DUE TO THE BAD STATE OF PRESERVATION OF THE PLASTERS AND JOINT MORTARS AT THE STAIRCASE AREAS (north and south staircases), there was a risk that, during the grouting process, grout would preferentially flow through cracks from the plaster surfaces into the staircases space, as well as flow into the interface between the staircase masonry and the staircase plaster, <u>"flaking out" the plaster layer</u>.

Two solutions were examined:

 a. The use of reinforced plasters with the use of titanium bars in the interior of the staircases on both sidewalls: <u>Selected as the most appropriate and in accordance to the Venice Charter</u> Part of the restoration works have been completed (deteriorated plasters removed; joints cleaned of disintegrated mortars and repointed with the selected restoration mortar used for the masonry;

effectiveness of this solution verified by finite element modeling (FEM).

b. The **reconstruction of the sidewalls with the use of the repair stones** already procured to the site for the masonry reconstruction at the extremely damaged areas:

<u>Ruled out</u>, since the state of preservation of the staircase masonry was evaluated as adequate for the bearing loads calculated for these areas, requiring only minor interventions & against the Venice Charter.



Sequence of interventions on the staircases so far: (left) condition prior to interventions, (middle) after removal of the plaster and disintegrated mortars, (right) after repointing. South staircase (left and middle images), north staircase (right image)

INTERVENTIONS AT THE CHAPEL OF THE ANGEL

Contrary to the interventions implemented at the western part of the Aedicule, the eastern part of the Aedicule, that effectively corresponds to **the Chapel of the Angel requires a different approach**. The **masonry revealed** after the dismantling of the N1, N2, S1, S2, E1, E2 panels, was found in a **better state of preservation**, compared to the western parts of the Aedicule, not requiring any rebuilding with new stones. However, **buckling phenomena were observed** in both the exterior and interior facades of the Chapel of the Angel masonries.

THEREFORE, THE NEED ARISES FOR IMPLEMENTATION OF INTERVENTIONS THAT WILL ADDRESS THE PREVAILING PROBLEMS, WHILE PRESERVING THE VALUES OF THE MONUMENT.

Specifically:

- The <u>interior marble slabs</u> within the Chapel of the Angel <u>will be anchored to the masonry</u> with the use of titanium bars.
- Local interventions will be implemented wherever needed in order to <u>restore all members to their</u> <u>original position</u>, as deformations are observed. The process of repositioning the displaced marble slabs and columns, <u>is not expected to be as "invasive" as</u> <u>that of the exterior columns</u>, which required the use of hydraulic pistons.



INTERVENTIONS REGARDING THE WALL PAINTINGS OF THE DOME AT THE CHAMBER OF THE TOMB

Prof. A. Moropoulou, Dr. E. T. Delegou, PhD Cand. M. Alexakis, MSc I. Ntoutsi , MSc T. Mavridis, P. Chaloftis, Y. Andritsopoulos Section of Scientific monitoring and documentation issues



The upper part of the Holy Tomb is crowned by a dome that its base is decorated by a wall painting depicting the Myrrhbearers, Angels Michael and Gabriel, as well as Virgin Mary.

The spatial arrangement of the Holy Figures comprising the wall painting is shown

PRESERVATION STATE OF THE WALL PAINTING

FOM Investigation



Aesthetical & physicochemical degradation of the wall painting due to: •Black soot particles •dust fall and •black depositions

Cracks of several and different widths (from capillary size to almost of one centimeter width) can be visually inspected.

Gilding decoration is observed

All the northern part areas (Virgin Mary, Mary of Clopa, Mary of Magda) present 3 horizontal cracks of high width, one in the upper part, one in the middle area, and one in the lower part, where the balusters are depicted.

PRESERVATION STATE OF THE WALL PAINTING IRT Investigation



IRT investigation of Mary Virgin (north) demonstrating detached areas, cracks & joints of the underneath structure

PRESERVATION STATE OF THE WALL PAINTING

GPR & US Investigation



The discovered detachments appearing on different heights of the paintings should be considerably taken into account especially for the case of the Holy Aedicule grouting. Before any intervention the paintings must be consolidated as in a different case the risk to provoke irreversible damage is very high.
PRESERVATION STATE OF THE WALL PAINTING

Raman Investigation of the pigments



Preliminary Raman Spectroscopy results demonstrate the possible use of mineral pigments, since peaks of calcite and hematite are identified (investigated area of reddish hue).

PRESERVATION STATE OF THE WALL PAINTING

Construction Technology

The bedding mortar of the wall painting



•The bedding mortar of the wall painting consists of 2 layers.

•Its total thickness is approximately 1cm, where each layer is around half centimeter thick.

•Poor cohesion between the 2 layers of the bedding mortar

•the substratum is reinforced by straws and fibers.

•Soot and black depositions have been accumulated on the first layer due to crack existence.

Bad Preservation State of the Wall Painting

PILOT CLEANING TESTS

Vulpex/H2O 1:9, washed out with White Spirit

FOM Investigation



In all the examined test areas: •Soot & black depositions were removed

•pigments were not dissolved and preserved their vividness

Vulpex: potassium methylcyclohexyl oleate soap

PROPOSAL OF CONSERVATION INTERVENTIONS

1. Cleaning: brush and vacuum cleaning of the loose depositions, application of deionized water, then application of Vulpex/H2O 1:9 (Vulpex: potassium methylcyclohexyl oleate soap) and finally washing out with white spirit.

- 2. Cracks sealing
- 3. Consolidation of the detached areas of the wall painting to the underneath structure using MasterInject 222 (formerly known as Albaria Iniezione).
- 4. Surface support of the painting using 2 gauze layers and rabbit skin glue (20% in water).
- 5. Installation of a wooden bearing structure with underpins of moving head to withhold the wall painting in its position during the application of masonry grout.
- 6. Final cleaning: removal of the gauze and the rabbit skin glue, and application of aesthetic conservation wherever required.

HISTORIC DOCUMENTATION OF THE CHAPEL OF THE ANGEL AND THE TOMB CHAMBER DECORATIONS



The Technical Bureau conducted a historic documentation of the decorations present in the Chapel of the Angel and the Tomb Chamber.

- Theodosis Mitropoulos has completed the documentation of the marble sculpted decorations
- The marble sculpted decorations of the Holy Aedicule were partially gilded decades after the Komnenos restoration (1839, 1842), therefore the remnants of gold present on the marble sculpted decorations today do not correspond to the Komnenos restoration intervention, but constitute a later addition. The gilded decorations present today on the Holy Aedicule decorations are to a great extent artless, presenting coarse imperfections. Furthermore, the gilding of the marble decoration is not in consistency with the relatively unadorned Holy Aedicule, which was constructed in the austere baroque architectural style of Komnenos and a decision had to be made regarding the extent of the gold coatings' conservation. The gilding corresponds to the rococo architectural style and is considered incompatible with the original style of the Komnenos Holy Aedicule.
- It is suggested to <u>make the decision to emphasize the conservation-restoration of the red and black marbles, thus highlighting the implemented opus sectile technique employed by the Komnenos technicians</u>. The red and black marbles, most probably corresponding to red slayeb, and black Wadi Moussa stones probably from the area of Jericho, are now being analyzed.

MATERIALS AND TECHNIQUES FOR CONSERVATION INTERVENTIONS

Cleaning and protection of the architectural surfaces

MATERIALS AND TECHNIQUES FOR CONSERVATION INTERVENTIONS: SELECTION OF THE OPTIMUM CLEANING INTERVENTION MATERIALS AND METHODS

Prof. A. Moropoulou, Dr. E. Delegou, Th. Mavridis, I. Andritsopoulos

The **main decay patterns** presenting in all the above mentioned architectural surfaces are <u>oily depositions and extended black depositions</u> which are primarily consisted of wax residues and soot particles respectively.

Candles' and hanging oil-lamps' burning close to or even in contact to the architectural surfaces is the major factor for the presence of these decay patterns. Also, it causes strong thermal stresses to the stone facings, despite their aesthetical and physicochemical degradation, due to the accumulation of black and oily depositions.





FOM image of mizzy stone surface of the South façade, presenting black & oily depositions

Materials applied:

- Poultice AB57 (1l deionized water, 30g NH₄HCO₃, 50 g NaHCO₃, 25 g of bisodium EDTA, 10ml Desogen, in sepiolite or carboxy-methyl-cellulose CMC) at different application times;
- Poultice AB57 with ammonia and triethanolamine, (AB57 Plus) at different application times;
- Poultice of NH₄HCO₃ 10%w/v in sepiolite at different application times;
- Enzyme Lipase, pecial enzymes that are consuming fatty & oily substances;

Pilot Cleaning Interventions



- Water solution of Vulpex (1 part of Vulpex diluted in 6 parts of water (~14%v/v)
 (Vulpex: potassium methylcyclohexyl oleate soap;
- Vulpex in white spirit (1 part of Vulpex diluted in 10 parts of white spirit (~9%v/v) - (Vulpex: potassium methylcyclohexyl oleate soap;
- Vaporized water;
- Organic solvents like ethanol and acetone; were applied on the former described representative surfaces.

Criteria and methodology adopted for the evaluation of the pilot cleaning interventions

The criteria used for the evaluation of the applied pilot cleaning interventions, as they are formulated by NTUA and the international research community, concern the following:

- •the chemical-mineralogical composition of the surfaces regarding the preservation of patina, (if it is detected during decay diagnosis), the complete removal of black depositions, and the preservation of authentic material,
- •the preservation of the surface microstructure under similar and/or slightly lower threshold levels, comparing to the ones before cleaning, and
- •the preservation of aesthetics color variations after cleaning to medium intermediate levels

Optimization between

- Cleaning and surface roughness and activation (FOM, SEM)
- ✓ Wettability (Karsten tubes, IR-th)
- ✓ Aesthetic compatibility (colorimetry)



Final proposals for the cleaning of the architectural surfaces of the Holy Aedicule

➢At areas presenting <u>extended & intense black & oily depositions</u> the application of vaporized water & Vulpex water solution is proposed for both mizzy and slayeb facings

➢At areas presenting black & oily depositions of lower quantity, the application of vaporized water & Vulpex water solution is proposed for the slayeb facings, whereas for mizzy facings the poultice of AB57 in sepiolite for 15 minutes application time is recommended.

At areas of **black & oily depositions** of low quantity on fine textured stones the application of vaporized water & Vulpex water solution is proposed for both mizzy and slayeb facings

At the <u>Prokonisos marble</u> architectural surfaces the application of vaporized water & Vulpex water solution is also proposed.



MATERIALS AND TECHNIQUES FOR CONSERVATION INTERVENTIONS PILOT PROTECTION APPLICATIONS

Prof. A. Moropoulou, Dr. E. T. Delegou, MSc I. Ntoutsi, MSc T. Mavridis, Y. Andritsopoulos

Both inorganic - mineral based and organic-based materials were tested

Organic-Based materials:

•TeC is a pure wax material,

•ISO and AGS are wax based materials using water as solvent,

•Bel belongs to the vast category of the commonly used organic coatings

Inorganic – mineral based materials :

•Dibasic Ammonium Phosphate (DAP) was used as precursor for hydroxyapatite (HAP) formation

•Ammonium oxalate (AmOx) & Oxalic Acid (Ox) were used as precursors for calcium oxalate formation

Pilot applications on stone slabs in the conservation lab



Mizzy hammered – N2_Z68



Slayeb smooth – N3_E13



Mizzy smooth – N3_D14



Slayeb smooth – N3_E14

In situ pilot applications







Slayeb hammered – Column N1-Façade

S5_mizzy hammered & fine textured S5_slayeb fine textured The evaluation of the pilot protective applications aims at the selection of an efficient material in order to fulfill the established compatibility criteria for protection interventions, as well as the specific needs of the on-going conservation works in the Holy Aedicule.

Evaluation Criteria

- •Chemical compatibility with the substratum.
- Deposition mechanism: no formation of an impenetrable film. Treatments based on
- chemical reactions should be controlled regarding authentic material loss.
- •Increased water repellency , no change of water vapor permeability
- •No significant aesthetic differences allowed. The total color difference ΔE should be lower than 5, (Colorimetric System of CIELab)

FINAL EVALUATION AND PROPOSAL

500

1000

Raman Shift (cm-1)

2000

<u>AGS</u> (wax based material using water as solvent) <u>exhibited aesthetical</u> <u>compatibility in both lithotypes and textures</u> (hammered/smooth), that is <u> $\Delta E < 5$ in</u> <u>all examined cases</u>. The formed protective layer of AGS (demonstrated in both FOM & Raman Spectroscopy results), did not induce any incompatibility concerning the hygric properties of the stones (Karsten tubes and IRT results).



Raman shift

FINAL EVALUATION AND PROPOSAL

IRT & Karsten tube tests results





AGS, Mizzy, hammered, presenting the lowest average temperature of all treatments, that is the maximum temperature homogeneity



Karsten tube test: good water repellency, no water absorbance

Therefore, the proposal for the final protection of the Holy Aedicule for both stone types mizzy and slayeb, of both textures, hammered and smooth is AGS.

RESTORATION INTERVENTIONS ON THE HOLY AEDICULE UPPER STRUCTURE DOME

Prof. A. Moropoulou, Assist. Prof. Ch. Mouzakis, Dr. K. C. Lampropoulos, PhD Cand. M. Alexakis, MSc Stud. M. Kroustallaki

The NTUA diagnosis and protection proposal took into consideration the macroscopic observations report of E. Korres, Ch. Mouzakis and A. Moropoulou, as well as the report submitted by the architect Osama Hamdan

The dome pessaries are mostly comprised of slayeb stones. In order to examine whether there is any metallic connector that retains the pessaries and the upper structure, a GPR scan took place with an Antenna of 2.3 GHz on the surface above the pessary. The reflection appearing in the GPR measurement, approximately in the middle of the scanned distance and 7cm depth, suggests the existence of metallic connectors at this location.





Pessary N 3 (Numbering starts from left to right), the GPR scan took place along the red arrow appearing in the lower right.

GPR measurement suggesting the metallic connector presence.

During the progress of the project, **all the layers of history** were revealed in the internal construction phases

FINDINGS REGARDING THE STRATIGRAPHY



Proposed layering of the Holy Aedicule based on GPR prospection, before the start of restoration Works.

Did Komnenos built a completely new Aedicule around the remains of the Holy Rock or did he embedded parts of the earlier Aedicule that survived the destructive fire?

The question emerges not only in an academic aspect, but has major implications in the continuation and effective implementation of the interventions. After the initiation of the restoration Works, and the removal of the exterior stones from various areas of the north façade, both the architectural and Ground Penetrating Radar analyses were verified, regarding the predicted internal layers



Upper left: The revealed surface of the Holy Rock, in area N3.Right:Endoscopic prospection of the Holy Rock.Lower left: Endoscopy image of the Holy Rock

Matrix of drilled holes in Area N2 to investigate the presence of a filled-in opening dating to the 12c. Aedicule



Endoscopic prospection of drilled hole #7 in Area N2.



- An **internal cavity** was observed, most possibly corresponding to the back surface of the marble stone at the north side of the interior of the Chapel of the Angel
- The fact that the drilled hole #7 managed to reach the back surface of the interior marble indicates that the stone block labeled S1 could be acting as a filler stone of the 12c. masonry opening.
- Removal of stone block S1, revealed another stone block almost the same size as the opening
- The **dimensions and location of this opening coincide** satisfactorily with the one indicated by **Amico's plans** and as predicted by **GPR** prospection.

If this opening indeed corresponds to the 12c. masonry opening, consequently, the masonry below it and at the same level as the opening date back to the 12century, whereas, the masonry at a level above the opening corresponds to the Komnenos construction period.

Two triangular shaped marble pieces with decorative cymatia, characteristic of the Crusader phase, were discovered in the filling mortar between slab N2 and the masonry, obviously placed in the mortar as filling and reinforcement materials by Komnenos, with surface incisions to increase adhesion (A. Moropoulou, E. Korres, et al).





Behind slab S2, a <u>ceramic drain tube</u> was detected in the masonry. An archaeometric investigation is ongoing in order to determine the chronological period it belongs to



In the masonry comprising the west side of the structure, possible remains of the Crusader's construction phase were identified. Two building stones in the masonry are completely different in terms of surface processing in relation to the surrounding stones and are obviously attributed to a different construction period (A. Moropoulou, E. Korres, et al)

Komnenos most probably preserved the core of the masonry, at least at its lower height, which is presumed to have been erected by Monomachos with interventions from the Crusaders, embedding primary materials in his own construction phase. Moreover, the roughly reconstructed masonries of the Komnenos phase, are proof that the reconstruction was implemented in conditions of great haste

PRESERVATION OF THE HOLY ROCK

It must be emphasized, that even with the rebuilding and strengthening of the problematic parts of the masonry, the Holy Rock must still be conserved and treated with grouts, otherwise it will not be preserved.

The danger the Holy Rock is facing is acute and must be dealt with in order to ensure its conservation. The conservation of the Holy Rock is not a structural issue or choice, but a choice to preserve the values of the monument;

THE HOLY ROCK IS THE INITIAL STRUCTURE, IT IS THE CORE OF THE HOLY AEDICULE, THE CENTER OF THE HOLY SEPULCHRE AND THE SYMBOL OF CHRISTIANITY.

It exists both as a physical entity and as a symbol and provides the archetypal meaning to the word Aedicule. The man made structure was put in place after the destruction of the Holy Rock, as a part of it, **in order to complete and protect it**.

Thus, the preservation of the Holy Rock is intertwined with the preservation of the structure surrounding it.



Aspects at the centre of the implementation project

1. PRESERVATION OF THE VALUES, THE SEMANTICS AND THE ORIGINAL MATERIALS INTERTWINED WITH THE TOMB OF CHRIST

Jerusalem Patriarchate - National Technical University of Athens



Design of glass window and metal frame by E. Korres

The installation of the window at the south interior wall of the burial chamber aims to highlight the values of the Tomb of Christ, as pilgrims will be able to gaze upon the original material, the Holy Rock



Opening of the Tomb of Christ

Lifting of the stone of the Tomb

Opening of the Tomb of Christ



Open Arcosolium: The leaders of the three Christian Communities and Prof. A. Moropoulou



Opening of the Tomb of Christ

Second marble plate, beneath the first layer (~3cm) of filling material



The engraved cross symbol indicates that the plate dates to the Crusaders period

Ultrasonic tomography prospection of the Holy Rock





UltraSonic Tomography Findings

From 10 to 30 cm under the surface of the Crusaders plate, along an 1.2 m axis from west to east, there is strong indication of substrate alteration

Ongoing research and combination of Non Destructive Testing methods are employed to validate the findings



Ground penetrating radar prospection of the Holy Rock



Surface of the rock

Feature, 20 cm below the surface and approximately 30cm western to the engraved canal

Indication of an interface 65cm below the rock surface





engraved canal at the eastern side of the Holy rock



The Tomb may have closed but research continues and we will get answers regarding the configuration and morphology of the burial complex



2. STRUCTURAL INTEGRITY

From the very beginning of the project, the structural integrity of the monument was the top priority of the project team. Given that the steel structure in place is already severely deformed, it was decided by the Interdisciplinary Scientific Team following a proposal by Professors M. Korres and H. Mouzakis to provide extensive lateral support to the structure. Four lateral support installations have been completed, one on each of the four sides of the monument, North, South, East, West.

Five lateral "H" support beams have been installed on each of the North and the South sides. These beams lean on the columns of the steel structure encasing the monument.



The East and West sides required the installation of additional vertical beams, as the existing steel structure did not provide adequate vertical support. Four additional vertical "H" steel columns were installed in the east and two "H" steel columns in the west.

GROUTING PROCESS

Application of grouting with assessment of its effectiveness (qualitative & quantitative)

Homogenization of the internal structure






PRESERVATION OF THE HOLY ROCK

53-10

3. SUSTAINABLE REHABILITATION

The study of the interdisciplinary NTUA team and the new findings arising from the implementation of the project and the continuous monitoring of the structure indicate that rules and regulations must be established regarding the management of the pilgrims' attitude regarding the Holy Aedicule.

The most important aspect regards to the burning of candles in the Holy Aedicule. As demonstrated in the diagnostic study the burning of candles in contact or very close to the architectural surfaces of the Holy Aedicule must be abandoned, since it causes strong thermal stresses to the stone facings, despite their aesthetical and physicochemical degradation, due to the accumulation of black and oily depositions. Therefore, special candlesticks should be placed in sufficient distance from the monument, accompanied by suitable ventilation.

50.6 °C

Wood, 40.5°



IRT image demonstrating the high temperature variations on the stone facings, due to candles burning

The goal is to ensure that at the end of the project as well during <u>the three-years monitoring period</u>, which will follow the completion of the works, the Holy Aedicule will be established as a center of innovative applications, research and education.

The three year monitoring period will allow the assessment of:

- The hygric performance
- The structural, dynamic and static health of this important and unique monument

Immediately after the removal of the external stone slabs, in order to assess the condition state of the building materials parting the revealed masonry behind the panels, an in-situ thermographic investigation took place.

The revealed masonry behind panel N2



The temperature difference between the lower and the upper part of the masonry is suggested from the thermograph

Rising damp is still an issue regarding the masonry, as illustrated in the IR-Thermal images The problem must be addressed



- According to the rectangular boxes 1 and in the upper region, the temperature of the building materials presents small variations with maximum, minimum and average values 27.2, 26.4 and 26.9 °C, respectively
- On the contrary, within the rectangular box 3 at the lower part of the revealed masonry, higher temperature variation is observed where the minimum temperature declines from the average up to 0.9 °C (maximum, minimum and average values 26.5, 25.1 and 26.0 °C, respectively)



- The absence of moist in the higher parts of the masonry suggests that there is moisture transfer from the lower parts of the masonry to the higher ones.
- The lower part of the panel is overwhelmed with moisture (blue color) while the only area colored in blue on the upper part is where the corrupted metallic conjunctions; used by Komnenos to stabilize and reinforce the face stones of the panels, lying.

Thus, the need for an interconnected infrastructure project arose, as the voids, underground canals and previous excavations around the Holy Aedicule highlight the need to study and document the historical aspect interlinking an infrastructure project, simultaneously aiming to relieve the structure from the rising damp problem it is facing.

Therefore both of the following are addressed:

- Conservation of the pavement
- Construction of a sewage system



DETECTION AND SEALING OF UNDERGROUND CANALS AND VOIDS

Prof. A. Moropoulou*, Dr. K. C. Lampropoulos*, PhD Cand. Em. Alexakis*, P. Sotiropoulos** * School of Chemical Engineering, National Technical University of Athens ** Terra Marine, Greece

Section of Scientific monitoring and documentation issues

From the pre-restoration stage, as well as during the restoration stage of the project, it has been realized that the Aedicule should not be examined as a "stand-alone" structure within the complex environment of the Church of the Holy Sepulchre.



Indeed, the problems with the masonries deformation and deterioration point out to a close interrelationship between the Aedicule structure and the morphology of the surrounding underground structures and channels, below and in the vicinity of the Aedicule.

Plate 1 in V. Corbo "Il Santo Sepolcro de Gerusalemme, Aspetti archeologici dale origini al period crociato, Parte II" depicting the location of archaeological surveys and part of the underground channel system and cisterns.

Black color = Constantinian structures; Blue color = 11th c. restorations of Constantine Monomachus; Red color = Crusader period (12th c.) The presence of this complex drain network and its state of preservation, may be the cause of some of the problems that the Holy Aedicule faced and even faces today; RISING DAMP AND LOCALIZED HUMIDITY CONCENTRATIONS.

A comprehensive ground penetrating radar (GPR) and electric resonance tomography (ERT) survey was conducted to the areas shown:

- Areas A, and B have been analyzed in the previous scientific report,
- GPR surveys with 750MHz antenna E, F and G
- ERT surveys CN and CS.





GPR survey at area F, using the 750MHz antenna attached to a distance measuring cart

MALÅ GX controller (MALÅ Geoscience, Sweden) with a GX 750 MHz (MALÅ Geoscience) antenna Data processing software used was MALÅ RadExplorer and GPR-SLICE (Geophysical Archaeometry Laboratory Inc, USA).

General overview of the ground penetrating radar (GPR) [A, B, E, F, G] and electric resonance tomography (ERT) [CN, CS] survey areas overlaid at the plan of the Church of the Holy Sepulchre, for the detection of underground channels and voids



Plate 16 from V. Corbo , with overlay of the GPR survey boundaries at the western part of area F.



3D GPR Slice (depth = 0.75m) with indication of the targets (red color) identified in the relevant area. These targets correspond to walls M2 and M4

As shown in plate 16 from V. Corbo overlaid with the GPR survey boundaries at the western part of area F, a cluster of targets present in various depths at this area correspond to the <u>ROCKY SURFACE WITH</u> <u>STONE CUTTING OF A QUARRY</u> upon which the eastern flank of apse 16 (Pl. 3, 14 V. Corbo, indicated as wall M6 in Pl. 16) and to the <u>FOUNDATION OF A HADRIANIC WALL (M1)</u>, that continues under the <u>CONSTANTINIAN FACADE OF ANASTASIS (WALL M4)</u> and under the <u>CONSTANTINIAN WALL M2</u>. Scanty remains, possibly of masonry, are discerned under column **51** (Pl. 3 in V. Corbo) here marked as M7, which are becoming more intense (red color) in the GPR survey at depth even down to 4,75m



Figure indicates the <u>LOCATION AND</u> EXTENT OF THE CHANNEL THAT RUNS THROUGH THE WESTERN AND MID-PARTS OF AREA F, TOWARDS THE SOUTH ATRIUM.

The red targets on the west side of the channel, at the section of the south entrance of the building, correspond to the foundation of the Crusaders' period columns at the doorway.

The foundations of the south wall of Katholikon can be identified, reaching a depth of almost 2,50m.

There exist indications of another channel, along the corridor between the south side of Katholikon and Golgotha. The series of four intense targets at the eastern side of the same corridor correspond to floor accessibility covers, probably related to the same channel

54 zscan≈35 z≍144.73cm 40 3 GPR zscan=19 z=1.5m 0. -3 6.8 1.5-5 Depth = 1.50m 2.3.7 3.9 3.8 (m) Hotel AF -130 5 7 9 11 13 15 17 -11 -9 -7 -5 -3 -1 1 3 2 x (m) 2 1

30

60

6

4

100)1000

50

00 20

200

250

00º

Figure shows the intense target that corresponds to the **CHANNEL RUNNING ALONG THE NORTH-**SOUTH DIRECTION, THAT PASSES **BELOW AND IN FRONT OF THE ENTRANCE OF THE HOLY AEDICULE.** Results correlate well with the excavations of V. Corbo

Electrical Resistivity Survey (Areas CN and CS)

Relative positions of the **excavation by V. Corbo** in the South side of the Rotunda (Pl. 19, ibid) and of the **Hadrianic underground chamber** in the area of the Anastasis (Pl. 18, ibid), in relation to the ERT surveyed areas CS and CN respectively.







(Insert) The resistivity meter Terrameter LS with the Lund cables and the cable connectors. (Left) he setup at area CN of the Rotunda (Upper & lower Right) Setup at area CS of the Rotunda

Due to the space limitations (the configuration of the work site), it was not possible to make more extended measurements with ERT and GPR. After the removal of the work site, it is deemed necessary to conduct a more systematic and extended survey, mapping all underground features beneath the Rotunda floor

CS Area



CN Area

Analysis of the ERT surveys indicate potential areas with high risk of "grout escape".

At the middle of area CN, there exists an area with very low resistivity, that is either attributed to the potential presence of a canal or a fracture of the bed rock.

This canal appears to pass below the northeast corner of the Aedicule. The canal may date to earlier historic periods. It may not be functional nowadays (actually it could be filled with sediments), however, its presence is related with high relative humidity, thus lowering the area's resistance. Notice that this low resistivity area starts at a depth of approximately 20cm from Rotunda floor.

If this area is correlated with a fracture of the bed rock, it is still risky for grout escape

It should be noted <u>that this area does not coincide</u> <u>with the Hadrianic underground chamber</u>.



In area CS, there seems to exist a "low resistivity canal shaped area" starting approximately from the base between panels S2 and S1 and with a SE direction, reaching the northern boundary of the Corbo's excavation area.

It should be noticed that the <u>ceramic tube revealed at</u> <u>the western side of panel S2, could correlate</u> <u>satisfactory</u>, regarding its position, with the northern end of this "channel shaped area", indicating that problably the drain tube is connected with this area.





Athens Water Supply and Sewerage Company (EYDAP S.A.): Documentation and mapping of underground sewerage network using an electromagnetic probe system.

Insertion of the probe into the canal



Electromagnetic wave

Transmitter probe inside the water filled canal

Receiver unit



<u>The underground water canal</u> that runs at the north east and east sides of the Rotunda floor <u>does not pass below the Aedicule</u>.



Athens Water Supply and Sewerage Company (EYDAP S.A.):

Assessment of the state of preservation of the underground sewerage network around the Aedicule, using robotic cameras to inspect the interior of the canals



These results of the underground investigation comply and might be interpreted by bibliographic findings concerning historic topography and ground plans of Jerusalem



GENERAL TOPOGRAPHY Plan of modern Jerusalem

Pierotti E. Jerusalem Explored, Vol. I -Text Being a Description of the Ancient and Modern City, with Numerous Illustrations Consisting of Views, Ground Plans and Sections. Vol. II – Plates. Transl. by T. G. Bonney. Cambridge. Deighton, Bell & Co—London. Bell & Daldy; 1864



The Church of the Holy Sepulchre is located on the Gareb Hill.

Underground constructions in comparison with the present level of the city



Pierotti E. Jerusalem Explored, Vol. I -Text Being a Description of the Ancient and Modern City, with Numerous Illustrations Consisting of Views, Ground Plans and Sections. Vol. II – Plates. Transl. by T. G. Bonney. Cambridge. Deighton, Bell & Co—London. Bell & Daldy; 1864

SUSTAINABILITY

The Tomb has been closed but Research remains open

GIVE ANSWERS TO KEEP THE TOMB OF CHRIST ALIVE

SCIENTIFIC MONITORING AND DOCUMENTATION

Scientific monitoring and documentation is operational regarding all issues at the center of the implementation project, as described above.

In this direction, scientific monitoring is opening new research themes and demands the cross-fertilizing synergies amongst scholars and Christian communities at an international level. It is an ongoing process, that will be implemented throughout the project and for a three-year period after its completion Key processes of the project are:

The interdisciplinarity among the different disciplines

❑the *multi-interface interactions* between the scientific teams, the working groups, the Technical Bureau of the Patriarchate and the three Christian communities, all under the authority of His Beatitude, Theophilos III

SCIENTIFIC DECISION MAKING

The above findings and issues that arise deem continuous decision support as mandatory in the specific project, as the Holy Aedicule is the most important monument of the Christian World, with a rich history and many construction periods. The NTUA interdisciplinary team constantly acquires new data; thus the ongoing monitoring is essential in supporting the decision making progress.

It is also important that no information is lost from one research team to another. This is possible through the **use of an innovative platform, on which all information will be uploaded, classified and assessed**. Thus, the decision making process will incorporate all findings from all members of the NTUA interdisciplinary team.

Through the assessment of the findings, issues emerge; the only way to address these issues is through scientifically supported decision making processes.

Data Organization and Management – Scientific Decision making

Prof. A. Moropoulou ,Assis. Prof. A. Doulamis, Assis. D. Kyriazis, D. PhD Cand. Emm. Alexakis et al

Integrated documentation and continuous monitoring of the works and research

> A Sophisticated Information System is currently under development:

- ✓ Optimized spatial database (3D GIS)
- ✓ Time series of data
- ✓ Thematic data
- ✓ Serve the existing needs

✓ Serve needs that might arise with respect to data storage and query answering

 ✓ Allow spatial data registration and enable the spatial data querying Thus, various researchers from different disciplines, can register their data directly to the location/area where the measurements were made

***** The findings and issues that arise demand continuous decision support

Data Organization and Management – Scientific Decision making

Prof. A. Moropoulou , Assis. Prof. A. Doulamis, Assis. D. Kyriazis, D. PhD Cand. Emm. Alexakis et al

A shift from data management to Content Management through Semantic Data Integration is applied

• Spatial/time multilayer management of information



ISSUES

Data Integration in 5 D

- Non destructive Testing
- Analytical Techniques
- Spatial
- Historic
- Time
- etc

DATA ORGANIZATION AND MANAGEMENT



SCIENTIFICALLY SUPPORTED DECISION MAKING

Data Organization and Management – Scientific Decision making

An **example of the interdisciplinarity** and the need for data organization and management in order to support decision making:

> examination of the structure as an integrated entity, rather than focusing on discipline related issues independently



Architectural documentation of masonry surfaces prior to repointing



Design of repair filling mortar



Documentation of the gap between panels & restored masonry



Evaluation of the strengthened structure with finite element modeling





Geometrical 3-D documentation of stone slabs



Through the implementation of this project, the integrated governance with the responsibility of the three Christian communities and the scientific supervision and monitoring by the NTUA interdisciplinary team, the Holy Aedicule becomes an international center of innovative applications, research and education, in addition to its religious, cultural and political significance for the three religions and the two people of Jerusalem.





The Holy Aedicule becomes a center of innovative applications, research and education

Contractor and the

Thus, the implementation of this project, highlighting the values of Anastasis, is highly interconnected with the values mutual communication, understanding and peaceful coexistence, between different people with different religious, cultural and political backgrounds

Framework Agreement (29/05/2016) between the National Technical University of Athens and the Jerusalem Patriarchate, after initiative of his Beatitude, Patriarch of Jerusalem, Theophilos III, according to the Common Agreement of the 3 Christian Communities.

NTUA Interdisciplinary Team

PILTOS

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