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

Integrated Diagnostic Research Project and Strategic Planning for Materials, Interventions Conservation and Rehabilitation of the Holy Edicule of the Holy Sepulchre in the Holy Church of the Resurrection in Jerusalem

Final Report Presentation,
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 Programme "*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

- Framework Agreement (5/10/2015) between the National Technical University of Athens and the **Jerusalem Patriarchate, after initiative of his Beatitude, Patriarch of Jerusalem, Theophilos**

- Participation of more than 25 Faculty members and Researchers, from 7 Laboratories of 5 NTUA Schools (Civil, Arch., Chem., Survey, Appl. Math. Phys.)

Technical Editing
Dr. K. Lampropoulos, NTUA

ΕΛΛΗΝΟΡΘΟΔΟΞΟΝ ΠΑΤΡΙΑΡΧΕΙΟΝ ΙΕΡΟΣΟΛΥΜΩΝ

GREEK ORTHODOX PATRIARCHATE JERUSALEM

No. 70

PROLOGUE

We are honouring the authorization We had from the Christian Communities to urge in program agreement with the National Technical University of Athens for 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," scientifically coordinated by you, esteemed Professor Moropoulou, and performed with the responsibility of the interdisciplinary NTUA research team on "protection of monuments," and more specifically, the esteemed Professors Em. Korres, A. Georgopoulos and K. Spyrakos.

Up to now, the research was performed in continuous reporting, communication, and cooperation with the Christian Communities, finalized by the presentation of the final report by you at the Patriarchate of Jerusalem on February 19th, 2016, where We had the opportunity to elucidate critical points on the preservation state of the Holy Aedicule and to discuss next steps and conclude the way forward.

During this discussion, it became clear that decision making for the implementation of this study has to be based as a whole upon the NTUA research and its proposals. Furthermore, the NTUA scientific responsible and coordinator was committed that the NTUA interdisciplinary research team, within its role of the high supervision of the works, will be in continuous contact with the three Christian Communities, to discuss and approve potential re-adaption of the study, where needed, based on the real data discovered, according to the foreseen continuous in real scale and in real time documentation and diagnosis.

As agreed by all three Christian Communities, it is urgent to proceed with the relevant donations, with the aim to initiate the restoration works immediately.

These works and this process shall have no bearing on the highly guarded "Status Quo" encompassing our various respective rights and customs.

With the acknowledgment of the State of Greece and renowned international supporters, there has been fortunate cooperation with the Polytechnic University, as well as with the Board of the Olympics and Bequests Committee, so that the product of this inter-scientific study of the aforementioned sacred monument of the Holy Sepulcher is the paving of way for the materialization of the initiative we've begun.

With Our Patriarchal blessings and best wishes,

THEOPHILOS III
PATRIARCH OF JERUSALEM

Holy City of Jerusalem
Wednesday, March 2, 2016

NATIONAL TECHNICAL UNIVERSITY OF ATHENS

RECTOR

Athens, 4 March 2016

The National Technical University of Athens, confirming that contributing to the social needs and national targets is an important pillar of its mission, proceeded to the implementation of an innovative Integrated Research Program for the Conservation and Rehabilitation of the Holy Edicule of the Holy Sepulchre in the Holy Church of the Resurrection in Jerusalem, by an interdisciplinary scientific team.

The team is coordinated by the Professor of the School of Chemical Engineering Mrs A. Moropoulou, and also consists of the former Professor of the School of Architecture Mr. M. Korres, the Professor of School of Rural and Surveying Engineering Mr. A. Georgopoulos and the Professor of the School of Civil Engineering Mr C. Spyrakos. I hereby express my sincere thanks to all members of the interdisciplinary scientific team for their generous unselfish contribution.

The project is emblematic and concerns a major monument of global value and glow. Through this initiative, NTUA contributes to the protection of a world cultural heritage monument that is of unique importance for Christianity and Hellenism.

The National Technical University of Athens will continue to be present with the same sensitivity, wherever and whenever its scientific excellence can contribute to the achievement of the social and national objectives of the State.

Professor I. Golias

Rector N.T.U.A.

Aim of Research

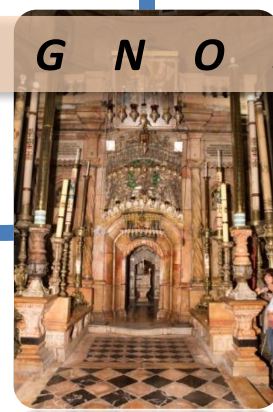
D O C U M E N T A T I O N

Integrated documentation of the problem

Geometric, Structural, Architectural documentation

Documentation and characterization of building materials

D I A G N O S I S



Prospection of building phases and decay diagnosis and pathology

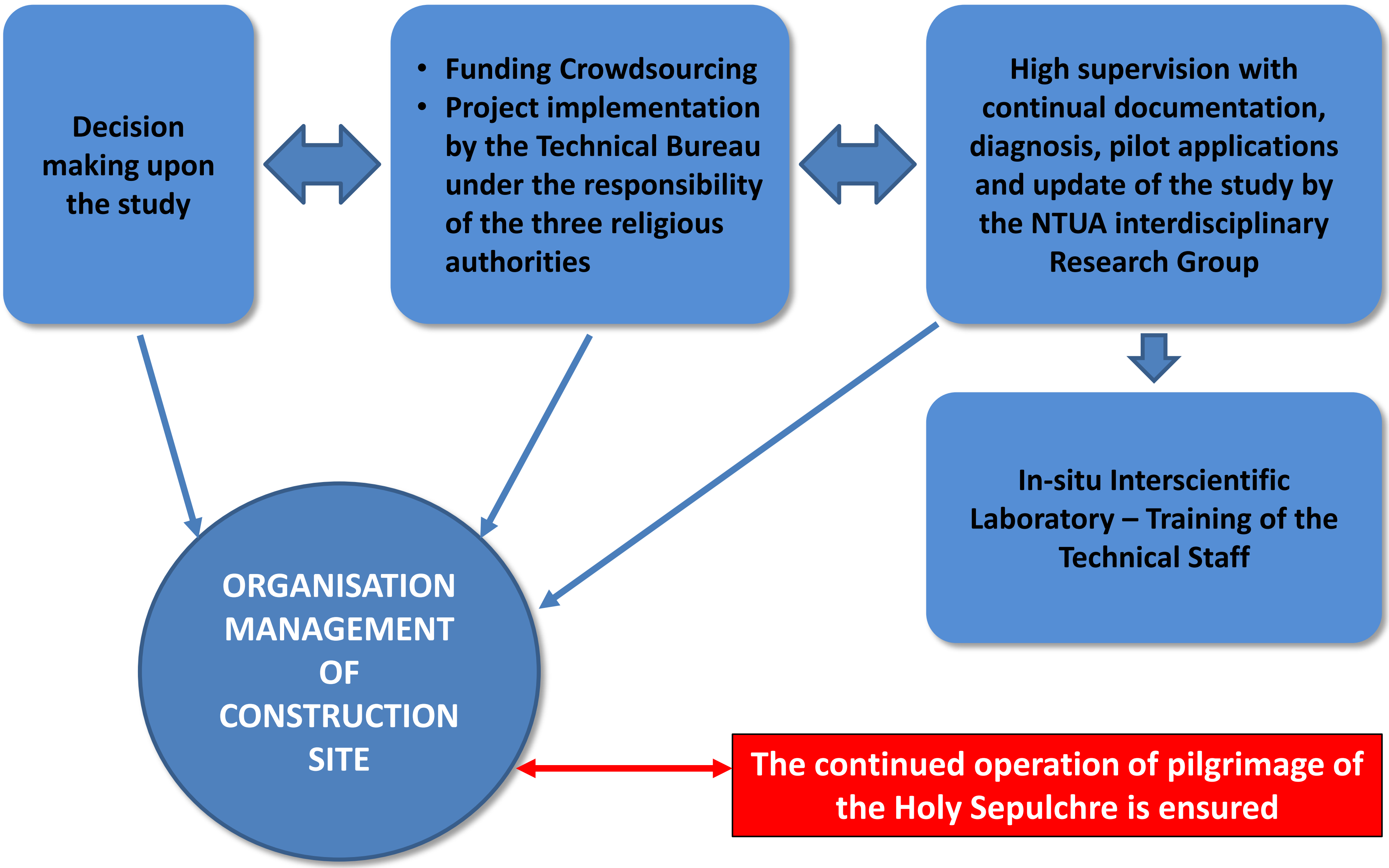
Assessment of current state against static and seismic loads

P R O P O S A L

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.

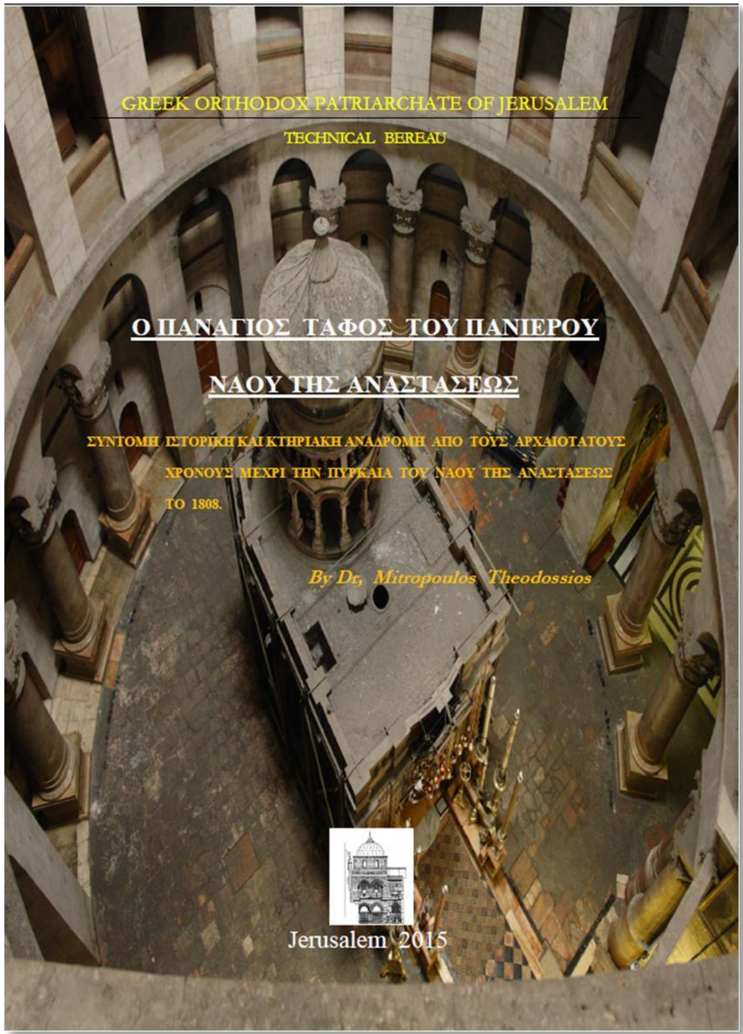
Implementation



NATIONAL TECHNICAL UNIVERSITY OF ATHENS
Interdisciplinary Research Team for the Protection of Monuments
Scientific Coordinator:
Prof. A. Moropoulou
Interdisciplinary Research Group NTUA**:**
Prof. Em. Korres, Prof. A. Georgopoulos, Prof. A. Moropoulou, Prof. C. Spyrakos

DOCUMENTATION

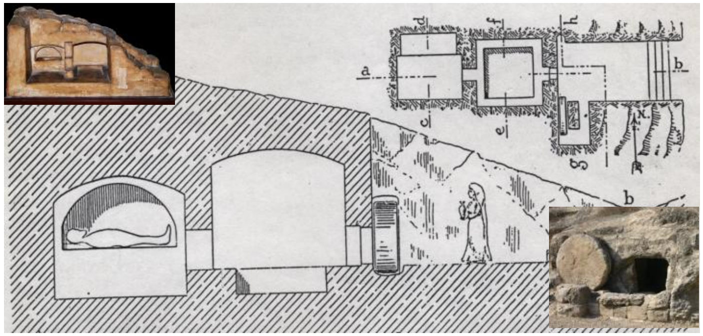
Historic Documentation
Geometric Documentation
Architectural Documentation
Characterization of Materials
Structural Documentation



HISTORIC DOCUMENTATION

The historic documentation was delivered with responsibility of the Jerusalem Patriarchate with the scientific editing of **Dr. Th. Mitropoulos** of the Technical Bureau of the Jerusalem Patriarchate and specifically includes:

- *History of the Holy Sepulchre and its historical significance. Study of historical archives.*
- *List of studies that have been prepared*
- *Collection of data relating to the construction loads (seismic, hydrological, etc.) or damage either during the construction phase or in subsequent periods.*
- *Collection of data for materials and conservation interventions throughout its lifetime*



<u>1st Building phase</u>

- **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 destructio of the Holy Shrines by Caliph Hakem bi-Amr-Illah το1009 AD**
  The reconstruction of the Church of Resurrection of the Byzantine Emperor Constantine IX Monomachos (1042 - 1048).

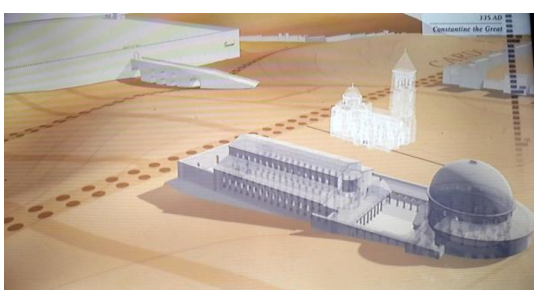
<u>2nd Building phase</u>

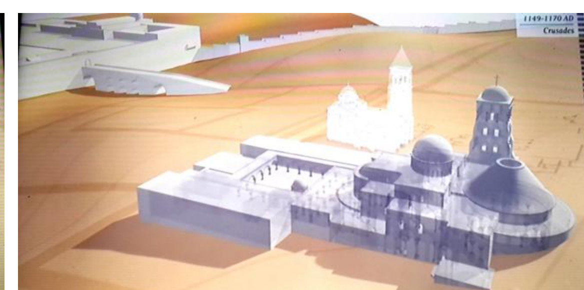
- **11th c. Byzantine period**

- **First Crusaders period (1099-1187)**

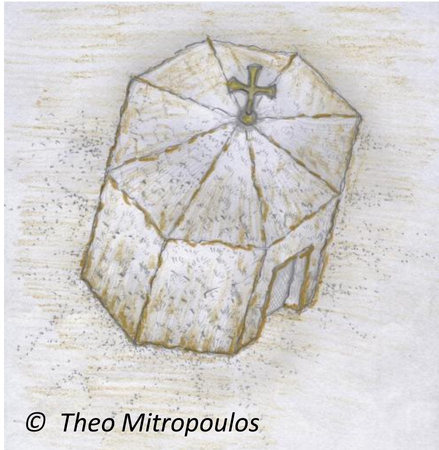
<u>3rd Building phase</u>

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

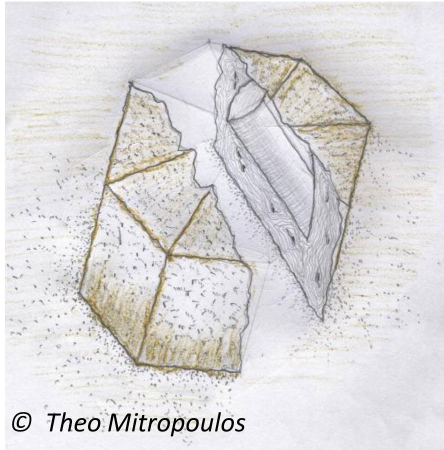




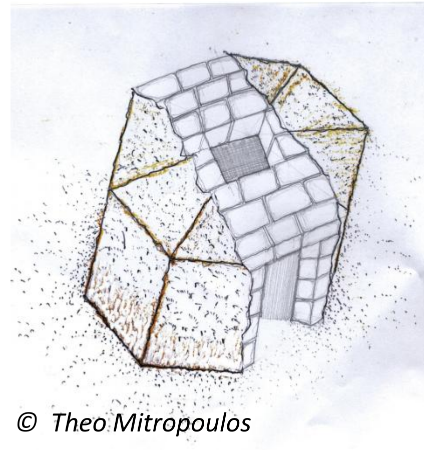
The Holy Aedicule of the Holy Sepuclhre



The Holy Aedicule (326 AD)

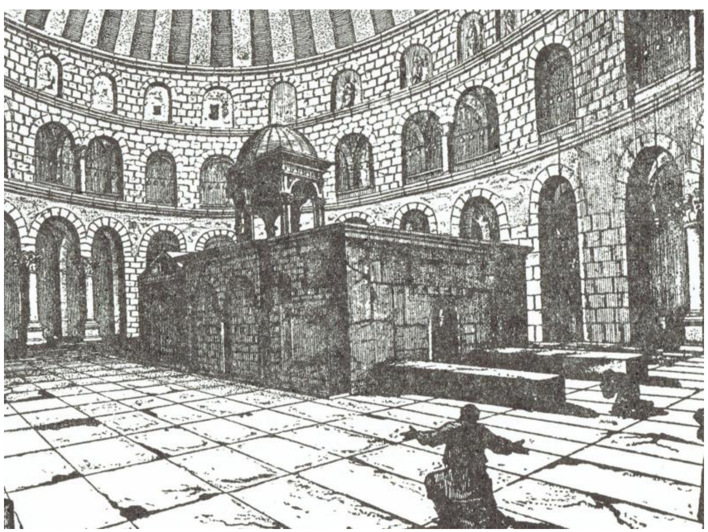


(614AD) after its partial destruction by the Persians



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

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



Crusaders' phase 12^{th} c. AD
De Brun 16^{th} c. AD

© Theo Mitropoulos

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

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Interdisciplinary Research Group NTUA:
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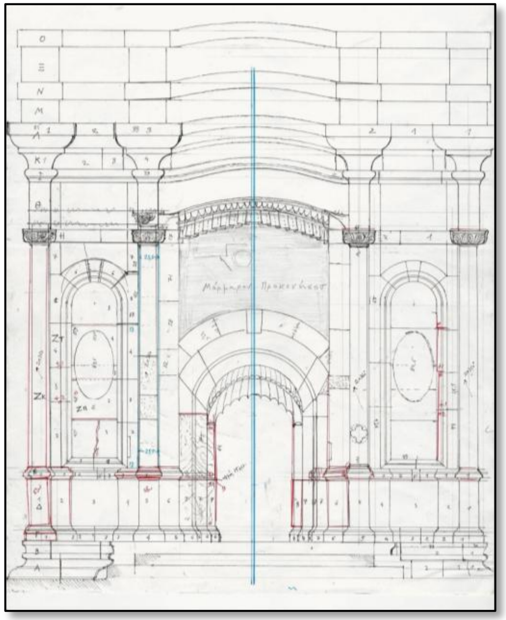
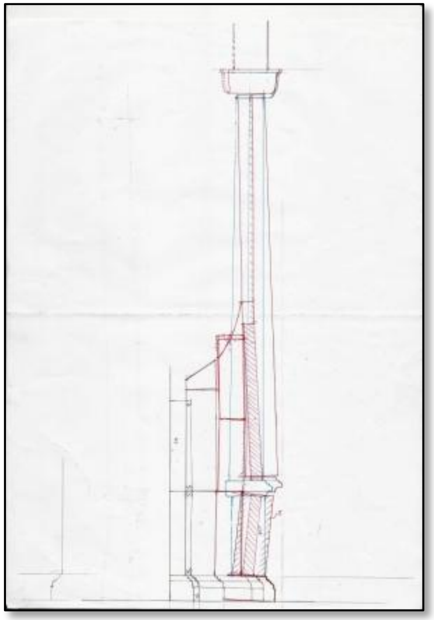
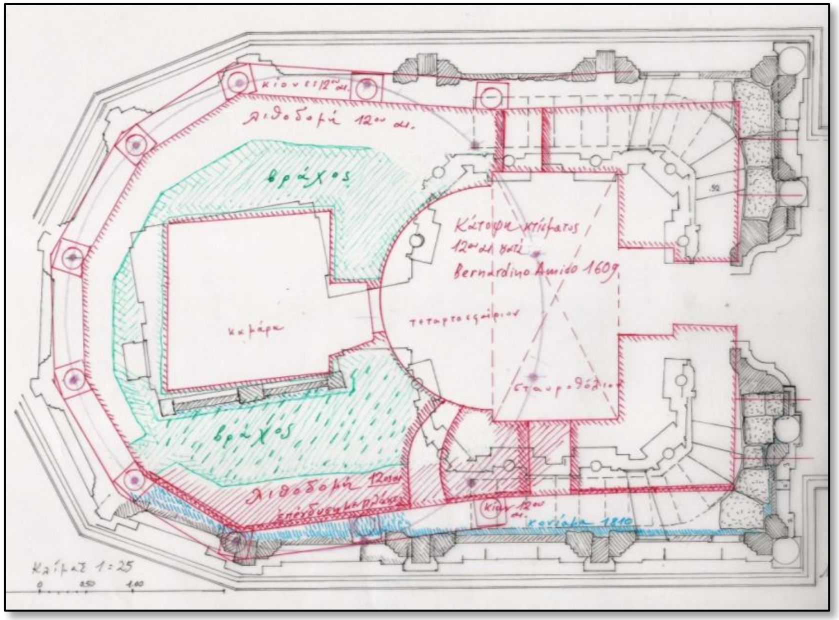
School of Architecture
Department of Architectural Design

Architectural Documentation
(Scientific Responsible: Prof. Em. Korres)

The present form of the Holy Sepulchre, which exists without alterations since1810, is a result of repair and restoration of the earlier building after the catastrophic fire of 1808. The exact form of the earlier building, also a result of a restoration of an even earlier form, which is closer to the initial form surrounding the Holy Grave rock, appears in 1609 drawings together with a brief description, a citation on the dimensions and explanatory notes







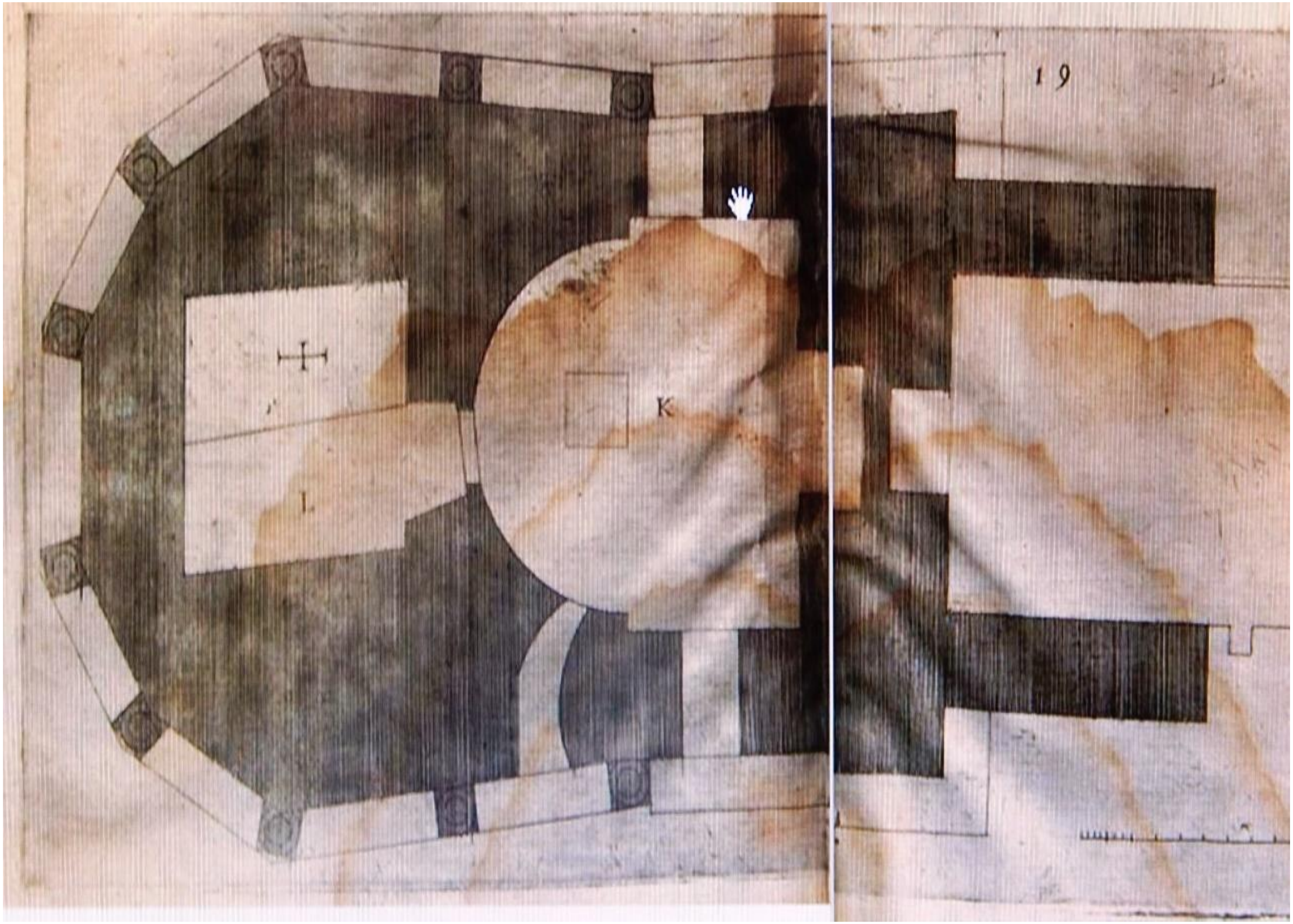


Fig. 1. Bernardino Amico, Plan of the Holy Aedicule, 1609

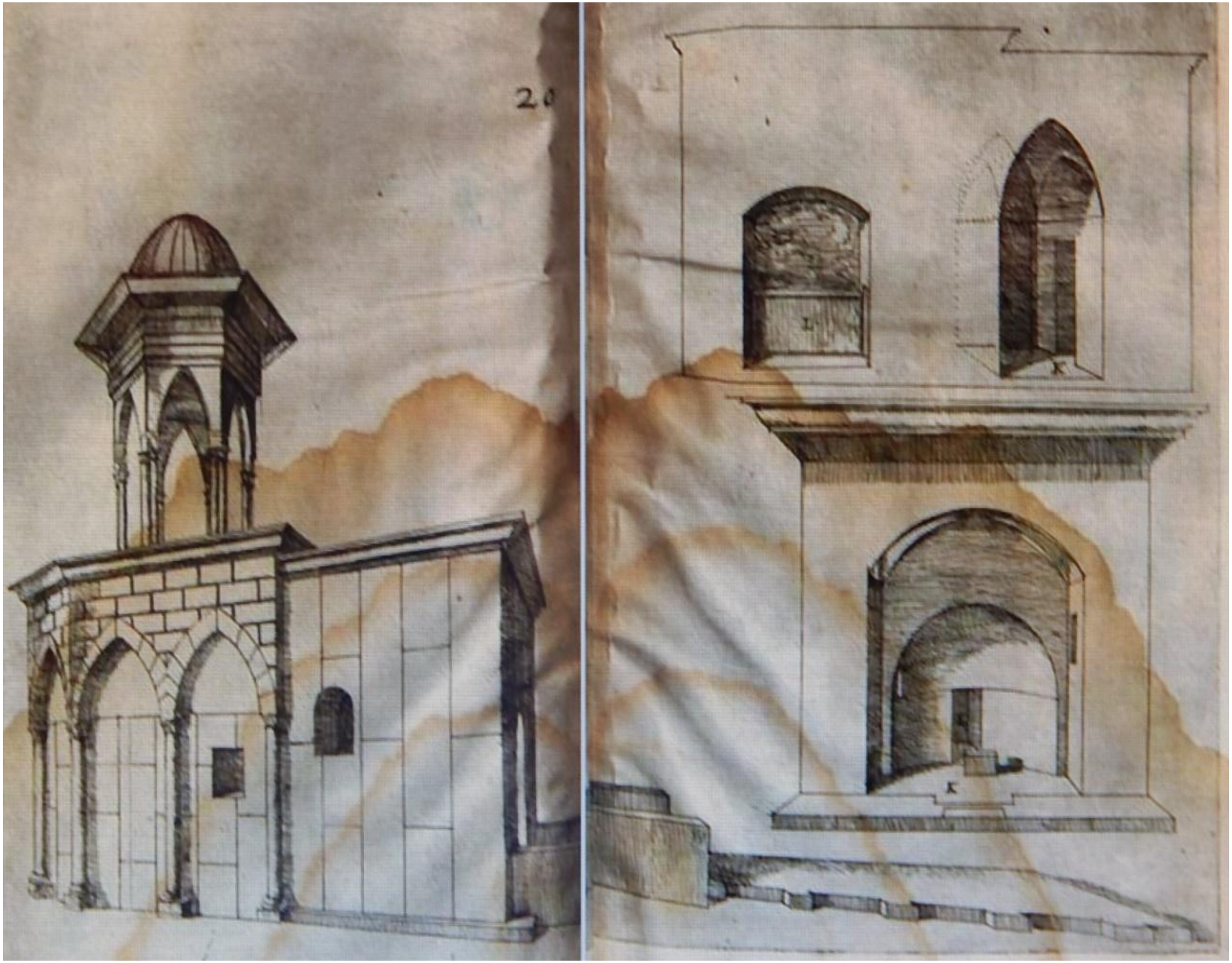
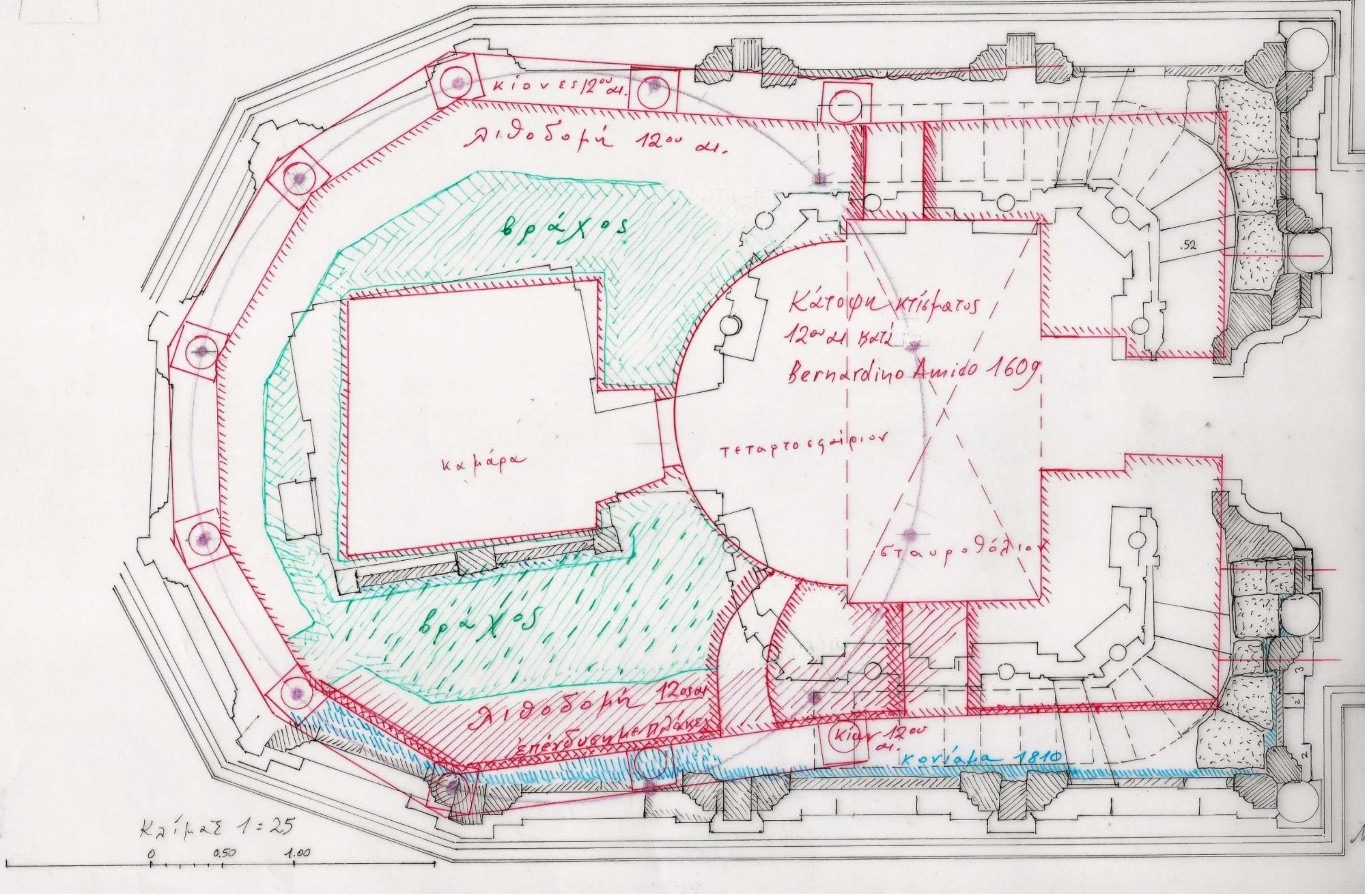
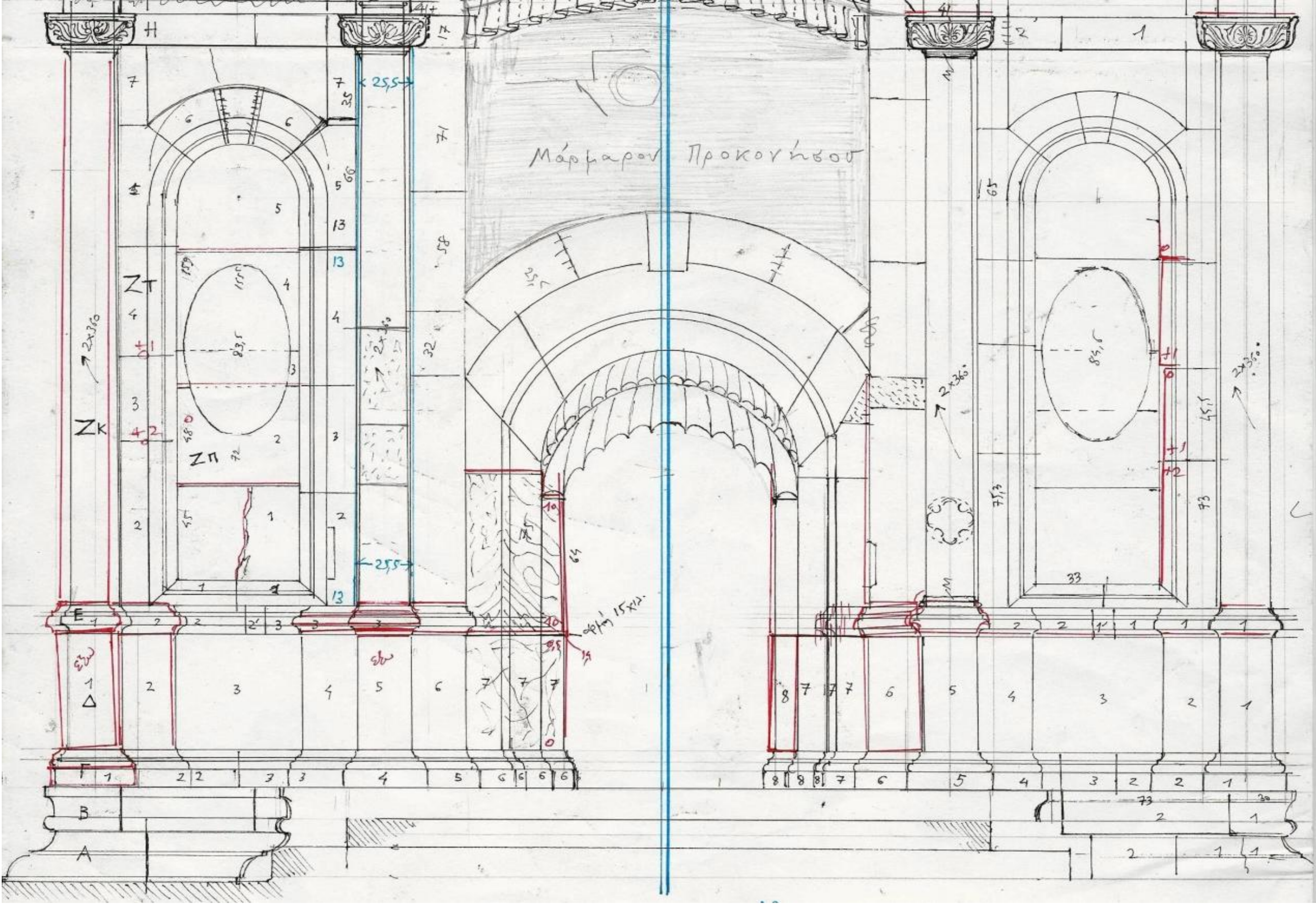


Fig. 2. Bernardino Amico, Exterior form and interior of the Holy Aedicule, 1609



dr. T1 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).



dr. T2 . Holy Aedicule describes the boundaries and the movement of each stone, vertical and horizontal design sections (Emm. Korres, 2015).

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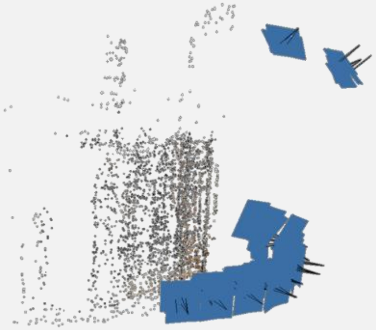
School of Rural and Surveying Engineering
Laboratory of Photogrammetry

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

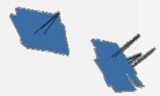
Research Team:
Evangelia Lamprou, *Assoc. Professor NTUA*
George Panatzis, *Assoc. Professor NTUA*
Panagiotis Agrafiotis, *Rural and Surveyor Engineer, MSc*
Lydia Kotoula, *Rural and Surveyor Engineer*
Alexandra Papadaki, *Rural and Surveyor Engineer*

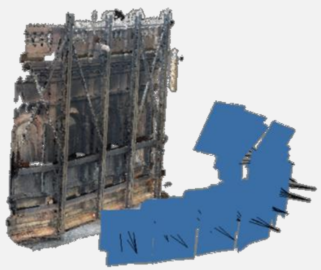
Aims of the Research

- The production of a **three dimensional high resolution model**, from which it is possible to extract the eventually necessary conventional **two dimensional products**, as e.g. horizontal and vertical sections, facades etc
- The performance of particular **geodetic measurements of high accuracy** for (a) the reference of the three dimensional model in the common reference system and (b) the determination of eventual deformations and micro movements on the Holy Aedicule



Sparse point cloud and camera positions of the south facade





Dense point cloud and camera positions of the south facade

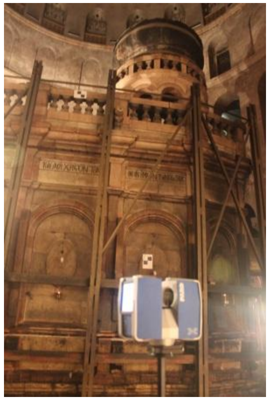
Creation of a three dimensional high resolution model through an automated image based method

The colored point cloud of the Holy Aedicule

Part of the textured 3D model of the south facade

Part of the not textured 3D model of the south facade

The 3D model of the dome textured (left) and untextured (right)



Scanning in the North side of the Holy Aedicule

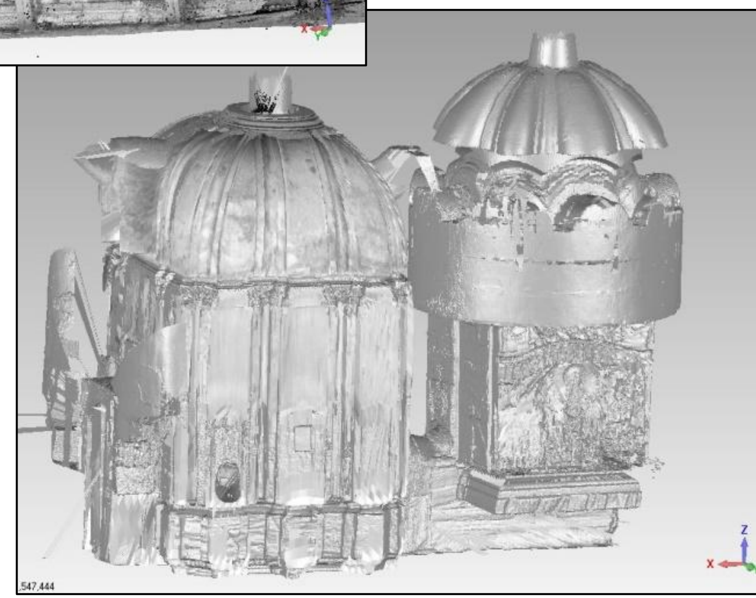
Scanning in the Coptic Chapel in the West side of the Holy Aedicule

Part of the registered point clouds outside the Holy Aedicule

Scanning from the roof openings of the Holy Aedicule

Creation of a three dimensional model using Terrestrial laser scanning

Part of the registered point clouds inside the Holy Aedicule

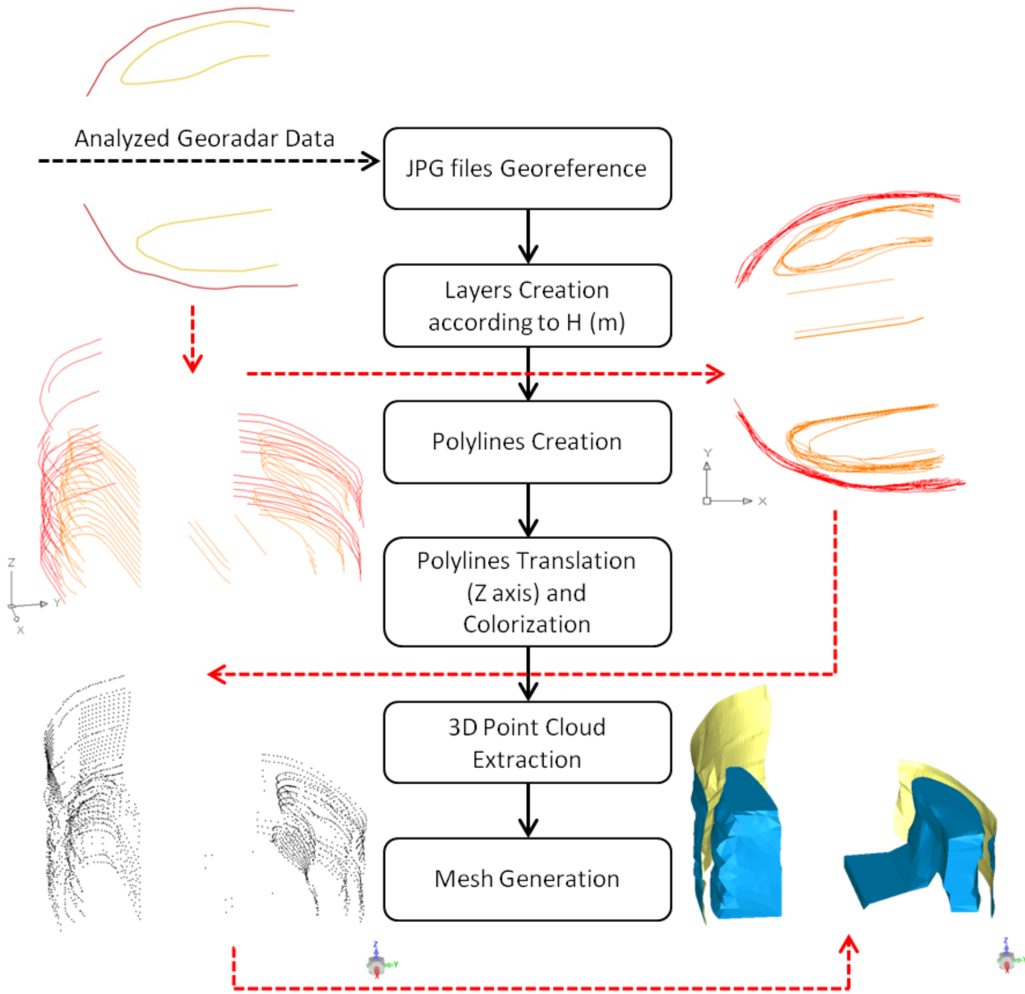


The registered point clouds were delivered to the members of the team from the Laboratory of Earthquake Engineering in order to be used for their structural studies of the Holy Aedicule.

Exploitation of the geometric documentation products

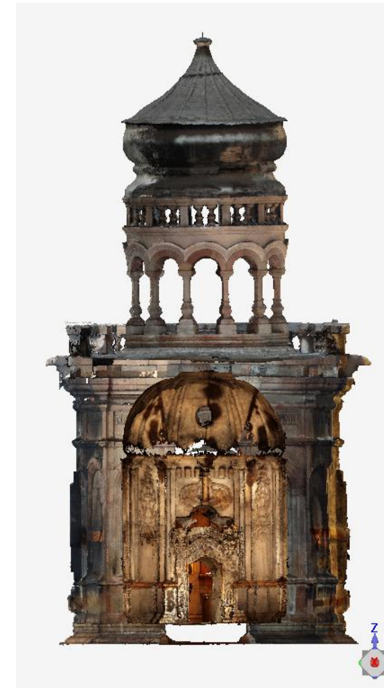
1. In the framework of the non-destructive testing/study of the internal structure of the Holy Aedicule with ground penetrating radar *(Prospection of the Holy Aedicule using GPR, **A. Moropoulou, K. Lampropoulos**)* **techniques for the 3D representation of the internal structure of the Holy Aedicule were developed by A. Georgopoulos** and his Research Team

Flowchart of the methodology developed for the creation of the 3D model of the internal structure of the Holy Aedicule

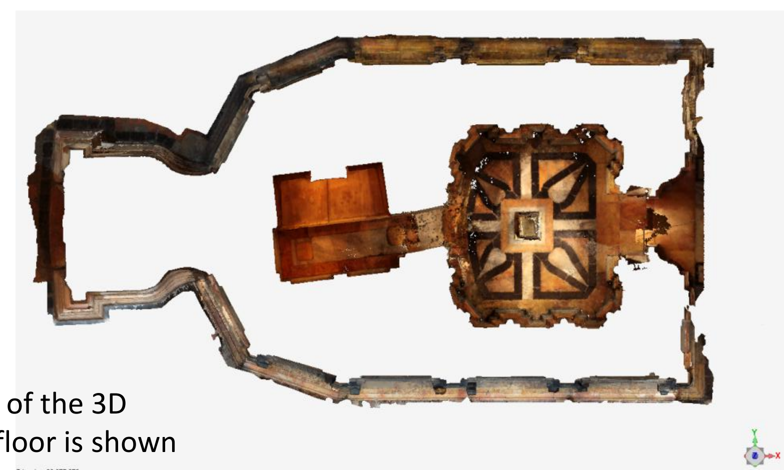


2. Visualizations from the 3D model to support the design of restoration interventions

Visualization of a vertical section from the 3D model without texture (left) and with texture (right)



Section of the Holy Aedicule in order to show its internal structure



Horizontal section of the 3D model where the floor is shown

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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

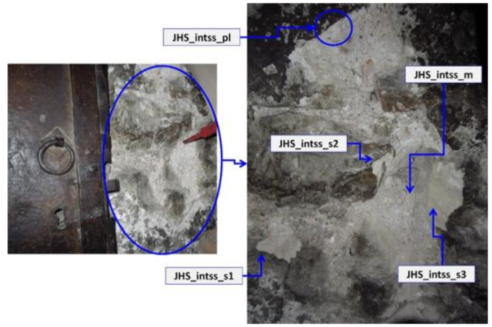
In collaboration with:

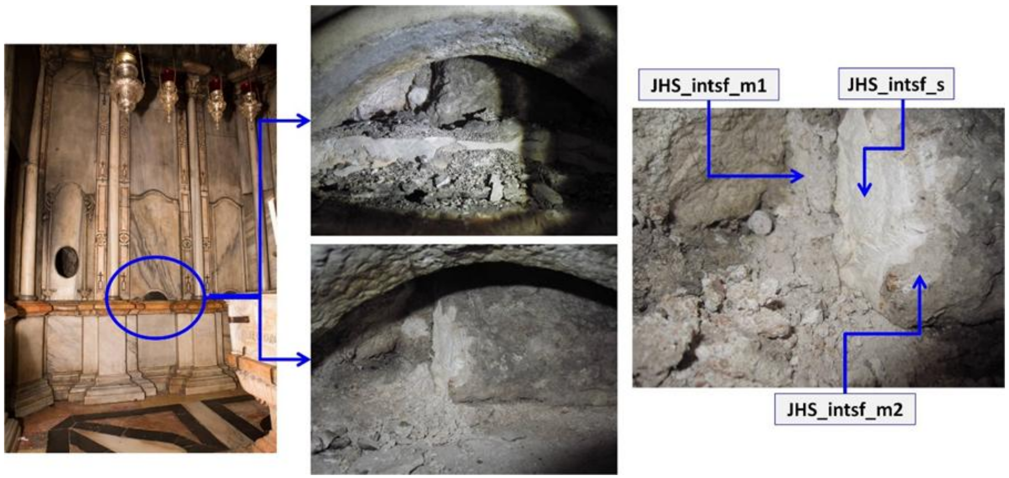
Environment and Quality of Life Center Laboratory School of Chemical Engineering NTUA
Laboratory of Strength and Materials, School of Applied Mathematical and Physical Sciences NTUA
Institute of Geology and Mineral Exploration (I.G.M.E.)

Research Topics

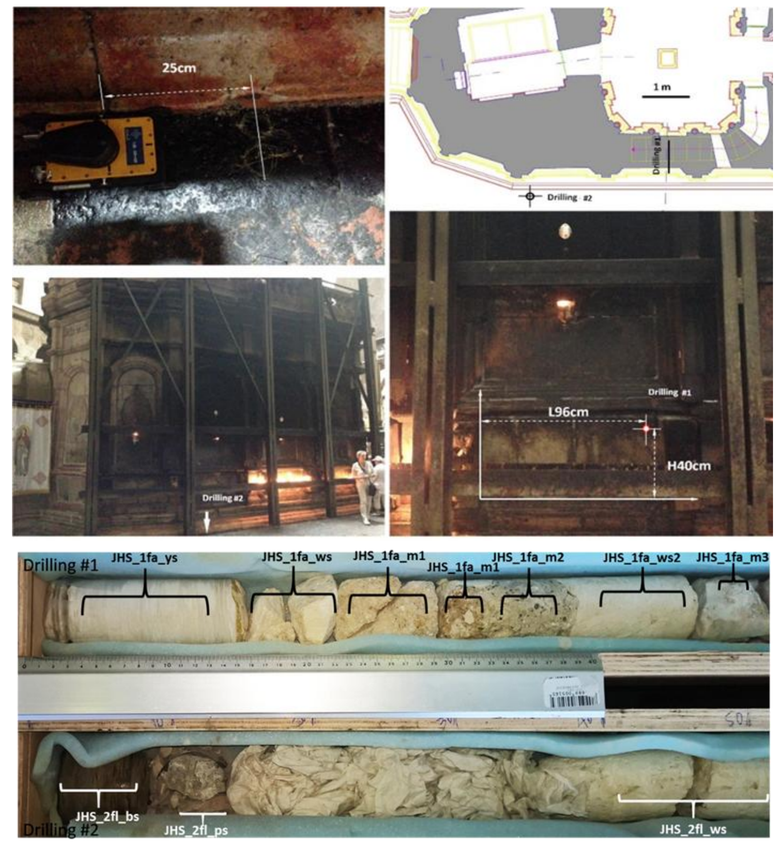
- Sampling
- In-Situ Non Destructive Testing
  (Optical Microscopy, Infra-Red Thermography, Schmidt – Hammer Testing),
- Analytic Materials Characterization Methods (qualitative and quantitative analysis of the mineral, petrographic chemical, physical and mechanical materials properties as well as microstructure analysis)
- Identification and provenance Investigation of Building Stones
  (Based on the Israel's Geological Maps)

SAMPLING



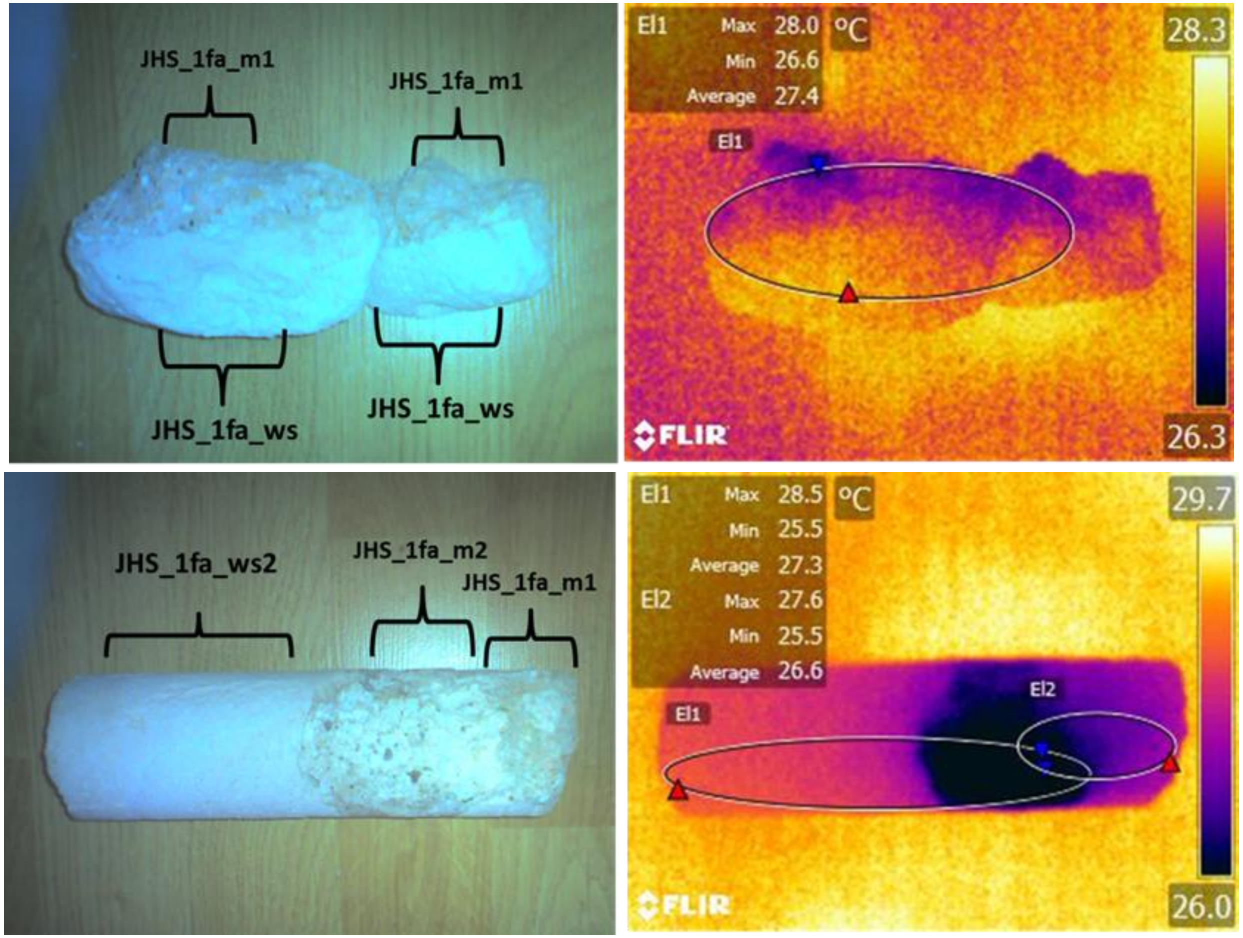


SAMPLE CORES –EXTRACTION POINTS



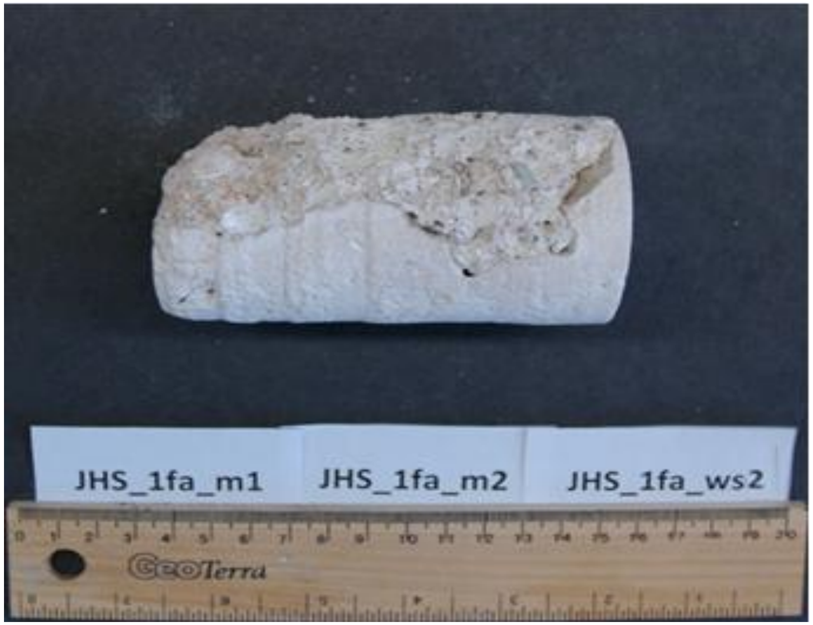
OVERALL SAMPLES PRESENTATION AND DESCRIPTION

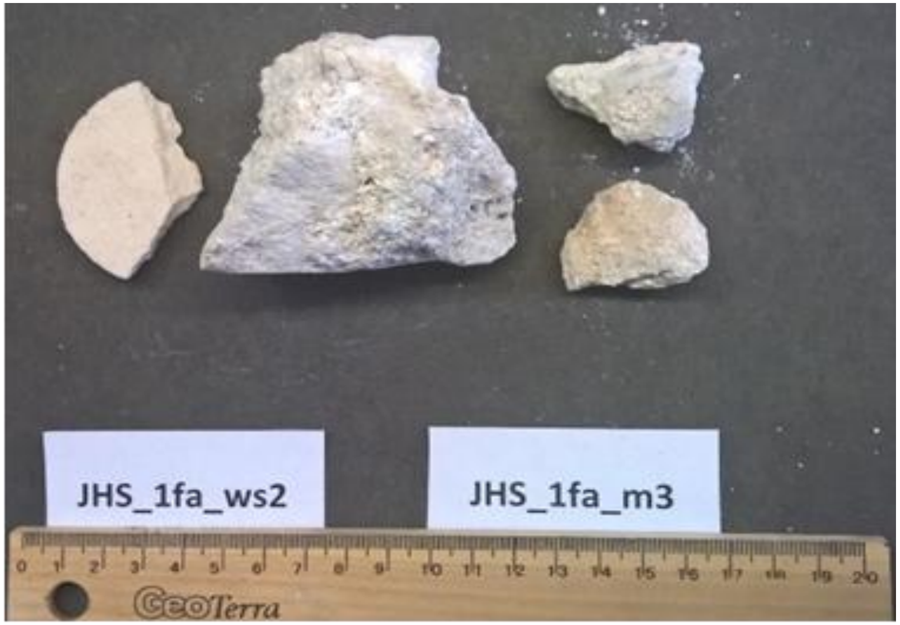
	Samples' Location	Macroscopic Sample Description	Construction Phase	Sample Code
1	Façade Core Sample	Yellow Stone – External Façade Building Stone	Komnenos Phase	JHS_1fa_ys
2	Façade Core Sample	Mortar	Komnenos Phase	JHS_1fa_m1
3	Façade Core Sample	Mortar	-	JHS_1fa_m2
4	Façade Core Sample	White Stone – Masonry Building Stone	Crusaders' Phase	JHS_1fa_ws
5	Façade Core Sample	White Stone – Masonry Building Stone	Crusaders' Phase	JHS_1fa_ws2
6	Floor Core Sample	Pink Stone – Floor Substrate Building Stone	-	JHS_2fl_ps
7	Floor Core Sample	Black Stone – Floor Building Stone	-	JHS_2fl_bs
8	Floor Core Sample	White Stone - Rock of Calvary	-	JHS_2fl_ws
9	External East Facade	Filling Mortar	Komnenos Phase	JHS_fe_m
10	Façade Core Sample	Mortar	Komnenos Phase	JHS_1fa_m3
11	Internal Staircase	Plaster	Komnenos Phase	JHS_intss_pl
12	Holy Aedicule's terrace	Mortar	Komnenos Phase	JHS_t_pl
13	Crusader Masonry behind the Chapel's internal South facade	Binding Mortar	Komnenos Phase	JHS_intsf_m1
14	Crusader Masonry behind the Chapel's internal South facade	Mortar	Komnenos Phase	JHS_intsf_m2
15	Under the plaster of the internal staircase	Binding Mortar	Komnenos Phase	JHS_intss_m
16	Under the plaster of the internal staircase	Building Stone	Komnenos Phase (possible reuse of building stone)	JHS_intss_s1
17	Crusader Masonry behind the Chapel's internal South facade	Building Stone – Soft Stone	Crusaders' Phase	JHS_intsf_s
18	Internal Staircase	Building Stone – Filling Stone	Komnenos Phase (possible reuse of building stone)	JHS_intss_s2
19	Internal Staircase	Building Stone	Komnenos Phase (possible reuse of building stone)	JHS_intss_s3
20	External South Façade	Building Stone of external facade	Komnenos Phase	JHS_extsf_s



INCOMPATIBILITY BETWEEN BUILDING MATERIALS (STONES - MORTARS)

- Mortars have lower temperature than the stone
- Maximum temperature difference 3 ^{o}C
- Indication of humidity presence





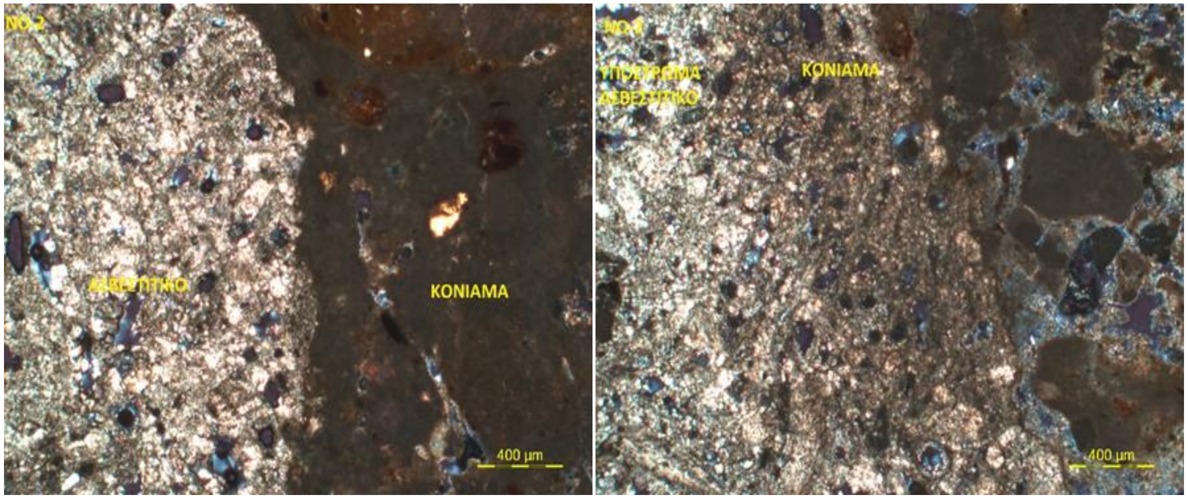
Historical Mortar Characteristics – Holy Aedicule of the Holy Sepulchre

- *Binder of calcitic nature*
- *Aggregates the combination of sands or sand and crushed brick*
- *The mortars can be characterized as slightly hydraulic (pozzolan mortars). The hydraulic character is attributed to CAH (calcium aluminate salts which develop during the setting and hardening of hydraulic lime and originated during the firing of a marly limestone. This is the main cause for their deterioration, due to the water inflow from the opening in the dome, and also due to rising damp and* condensation

MINERALOGICAL CHARACTERIZATION OF MORTARS

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

POLARIZED OPTICAL MICROSCOPY

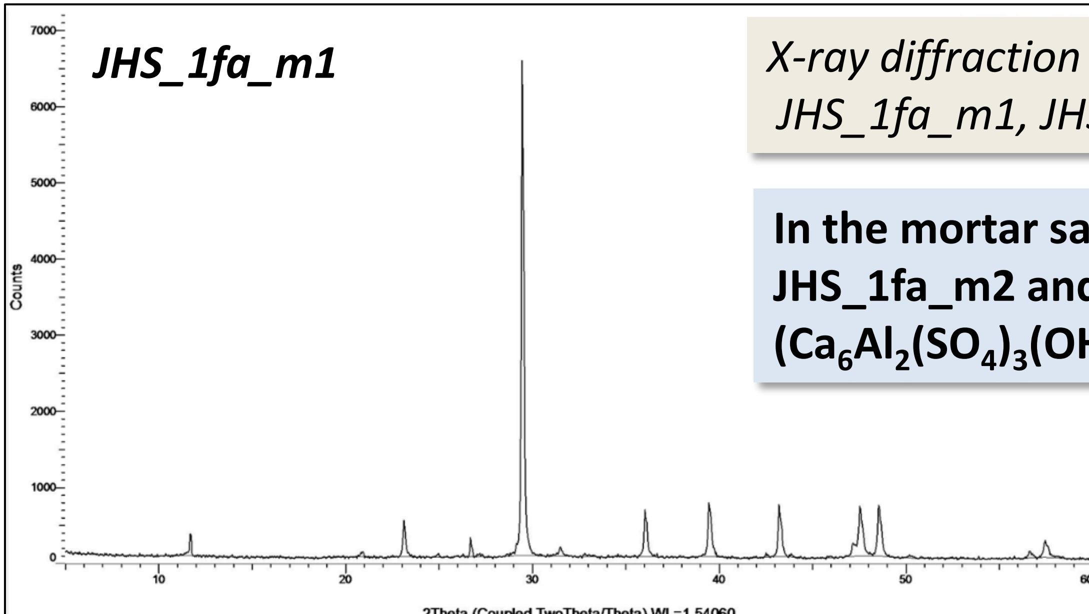


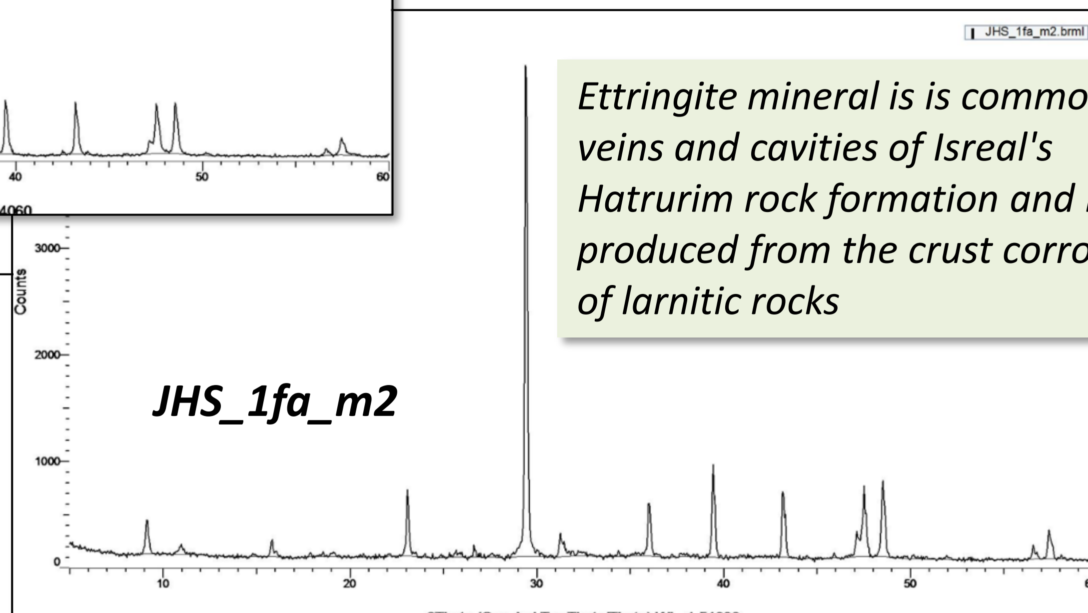
- **JHS_1fa_m1:** Lime mortar (Komnenos phase)
    - Microcystalline calcite with ferrous oxides-hydroxides in binder phase
    - Aggregates: a) crushed brick (<10% of mortar), b) recrystallized quartz (< 4%), c) fragments of limenstone composition (< 15%)
- **JHS_1fa_m2:** Lime mortar
    - Mainly of calcitic composition
    - Aggregates: a) fragments of micritic limestone consisting of calcite, b) quartz fragments (< 2%) c) serpentine fragments, d) mineral apatite syndromes (< 3%), e) chlorite and f) mica (muscovite composition)
- **JHS_1fa_m3:** Lime mortar
    - Microcystalline calcite
    - Aggregates: a) larnite minerals (< 6%), b) gypsum (~5%) and c) quartz (< 7%)

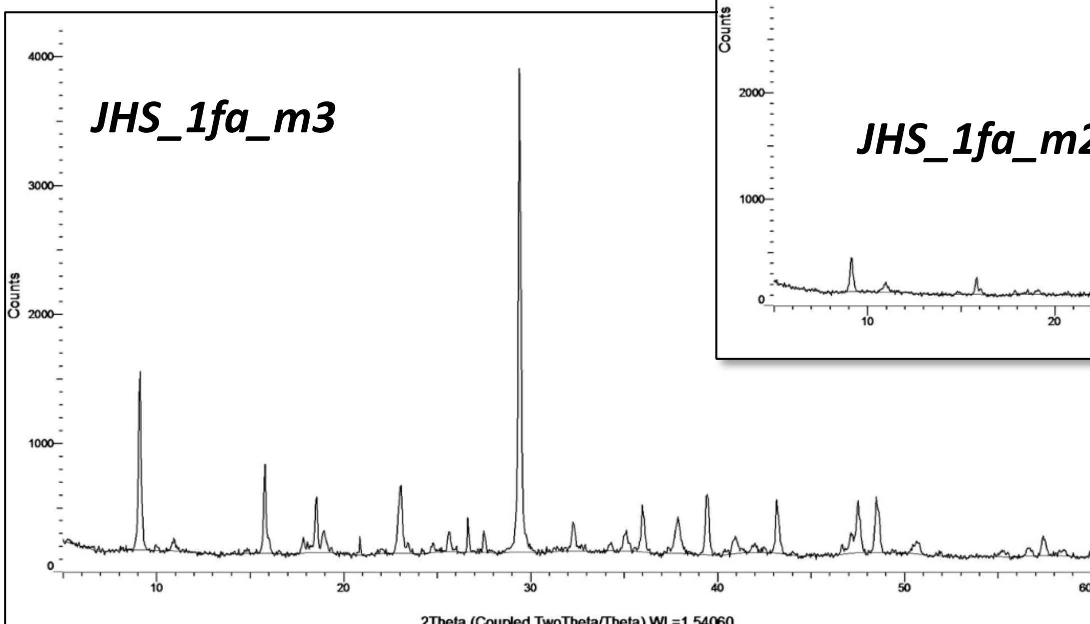
X-ray diffraction results for samples: JHS_1fa_m1, JHS_1fa_m2, JHS_1fa_m3

In the mortar samples of the masonry core sample, JHS_1fa_m2 and JHS_1fa_m3, ettringite is detected ($Ca_6Al_2(SO_4)_3(OH)_{12}\cdot 26H_2O$).

Ettringite mineral is is common in veins and cavities of Isreal's Hatrurim rock formation and it is produced from the crust corrosion of larnitic rocks

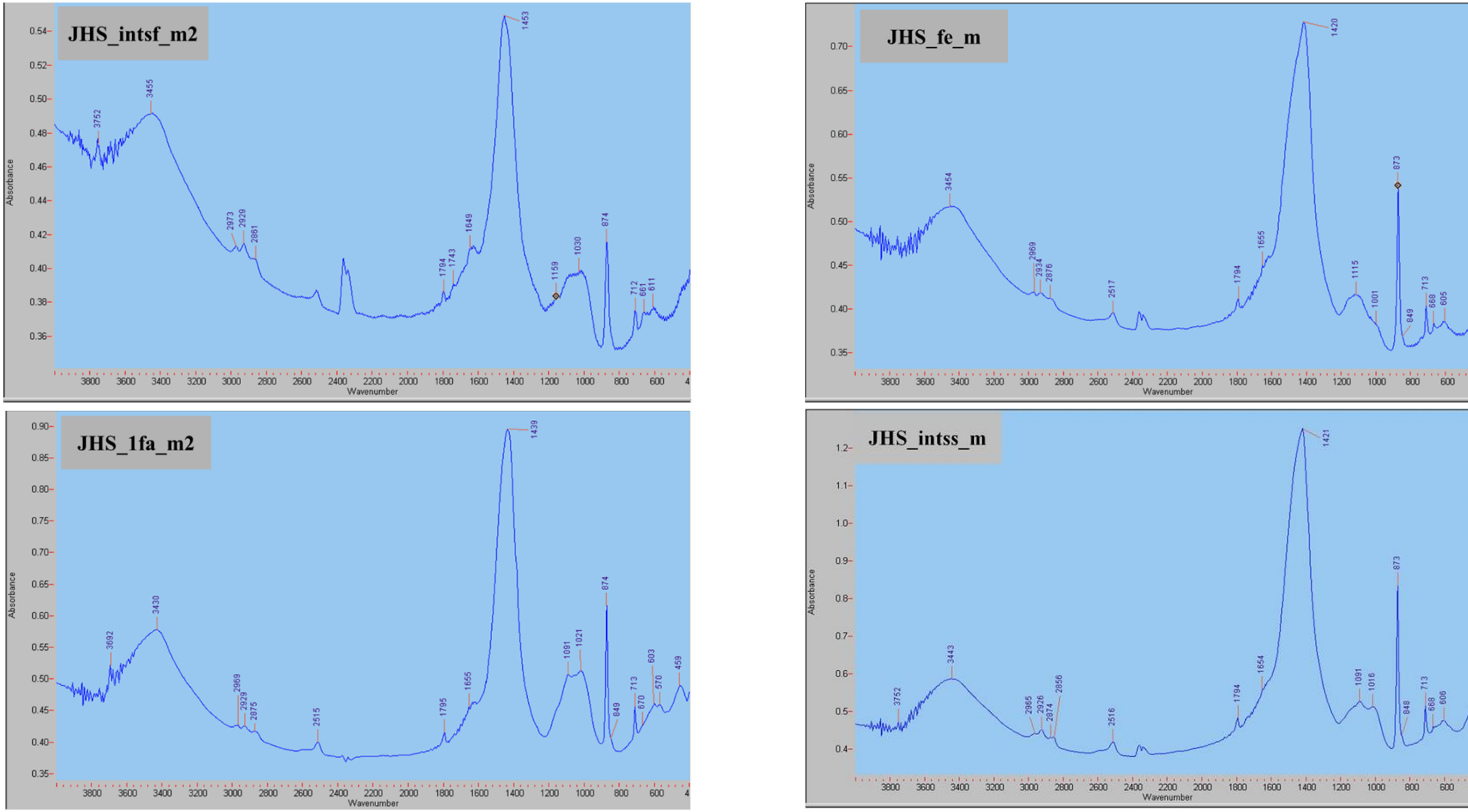






Fourier Transform Infrared Spectroscopy

QUALITATIVE DETERMINATION OF CHEMICAL COMPOSITION



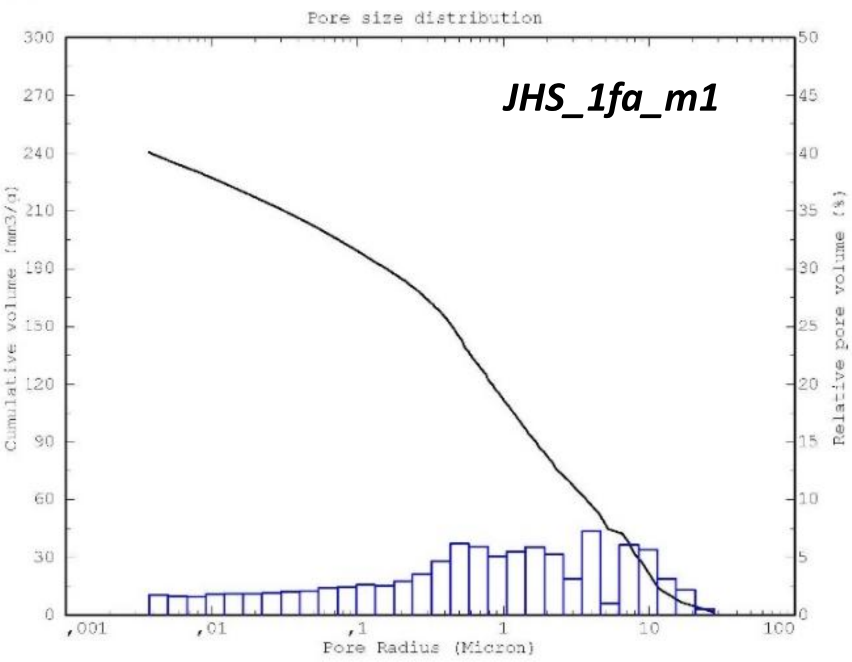
- Pronaus masonry mortar – south wall (**JHS_intsf_m2**)
- Mortar in masonry core sample (**JHS_1fa_m2**)
- Façade filler mortar (**JHS_fe_m**)
- Staircase masonry mortar (**JHS_intss_m**)

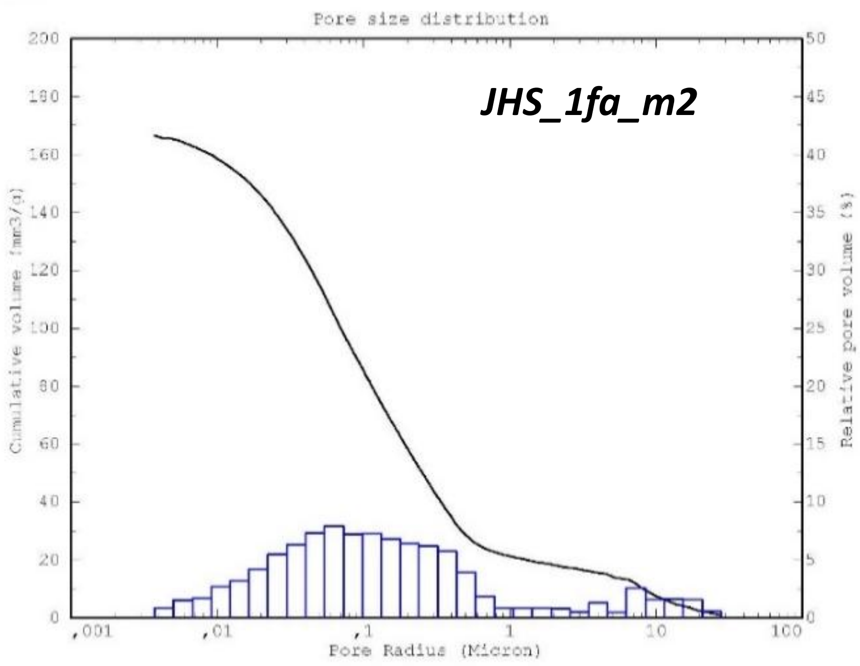
- **Calcium carbonate**
- Organic compounds
- Aluminosilicate Compounds
- Traces of calcium sulphate

MICROSTRUCTURE CHARACTERISTICS

Characteristic curves of pore distribution

Total cumulative volume:	**166.7-570.5 (mm3/g)**
Apparent density:	**1.0 – 1.7 (g/cm3)**
Average pore radius:	**0.1 – 0.8 (μm)**
Specific surface area:	**1.9 – 8.0 (m2/g)**
Total Porosity:	**28.4 – 56.0 %**

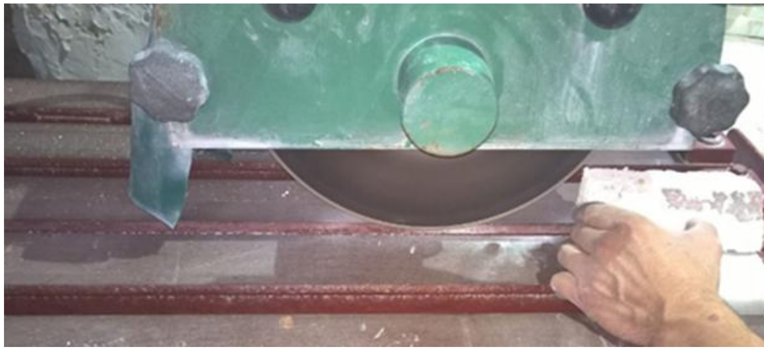
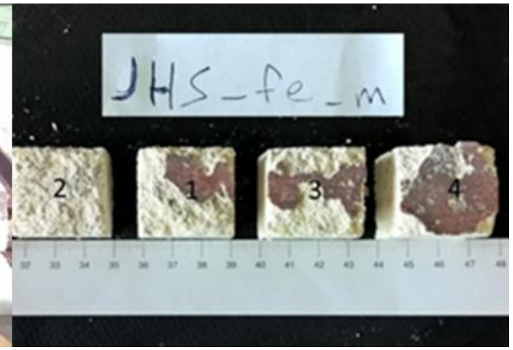




MORTAR MECHANICAL CHARACTERIZATION

Laboratory of Strength and Materials, Dept. of Mechanics, School of Applied Mathematical and Physical Sciences, NTUA,
Prof. St. Kourkoulis
PhD Cand. E. Pasiou, PhD Cand. M. Alexakis(Lab. Materials Science and Engineering, Sch. Chem. Eng)

Sample Preparation

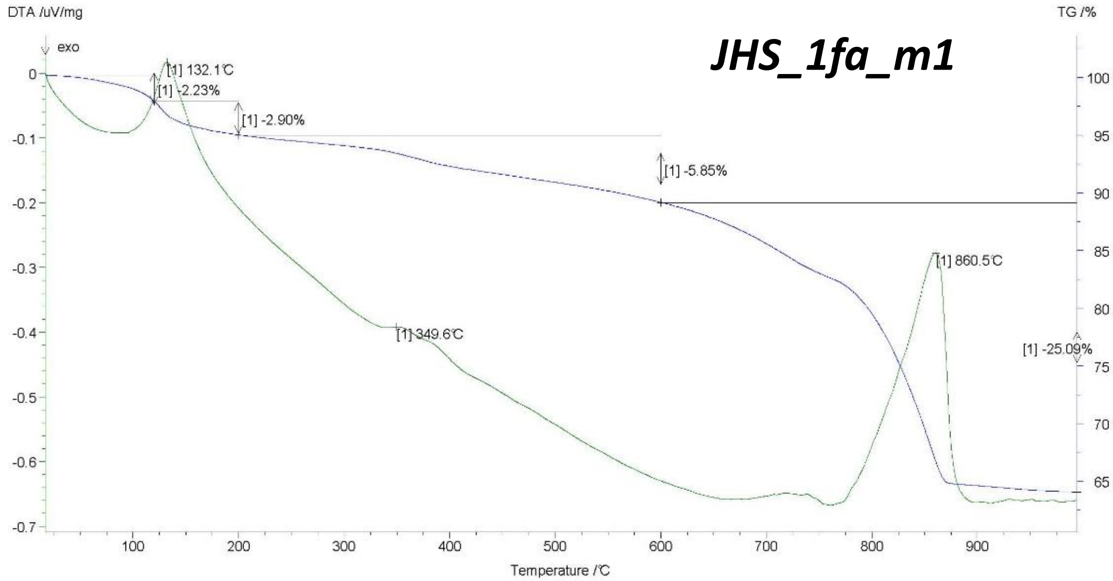
Sample Measurement

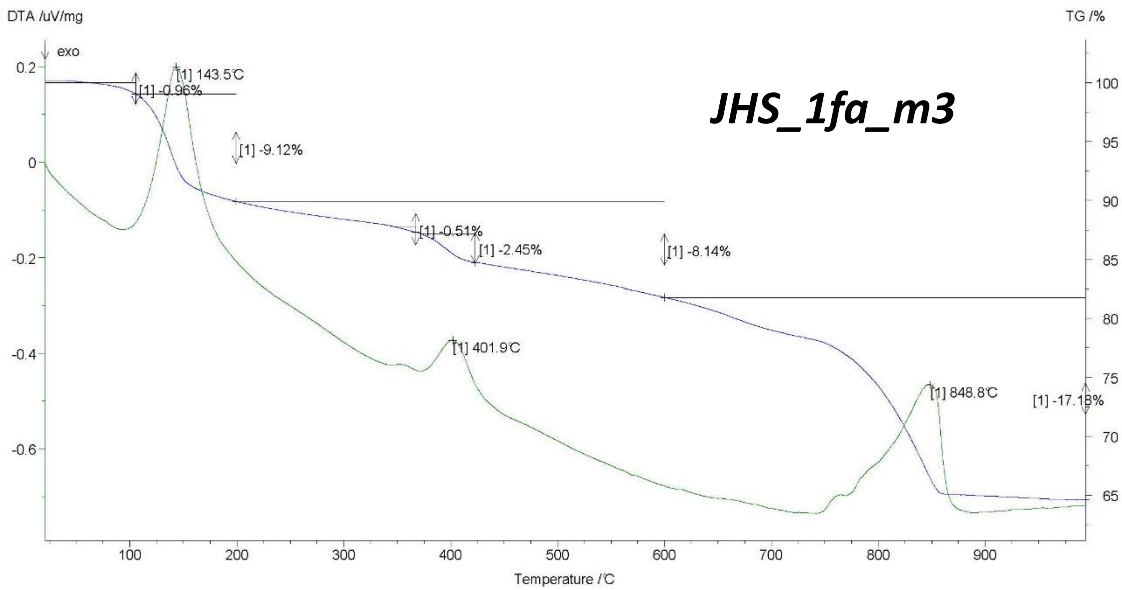

Filling Mortar
External East Façade (JHS_fe_m)
Komnenos' Phase

- Anisotropic
  - Different Material Properties depending on the load direction
  - Higher Values of Mechanical Strength when loading direction is parallel to the reddish colored layer.

	Yield strength Compression [MPa]	Young Modulus Compression [MPa]
	1.85	82.45
Loading Direction: parallel to the reddish coloured layer plain.		
	1.0	22.8
Loading Direction: perpendicular to the reddish coloured layer plain.		

CHARACTERIZATION OF THE HISTORICAL MORTARS OF THE HOLY AEDICULE OF THE HOLY SEPULCHRE

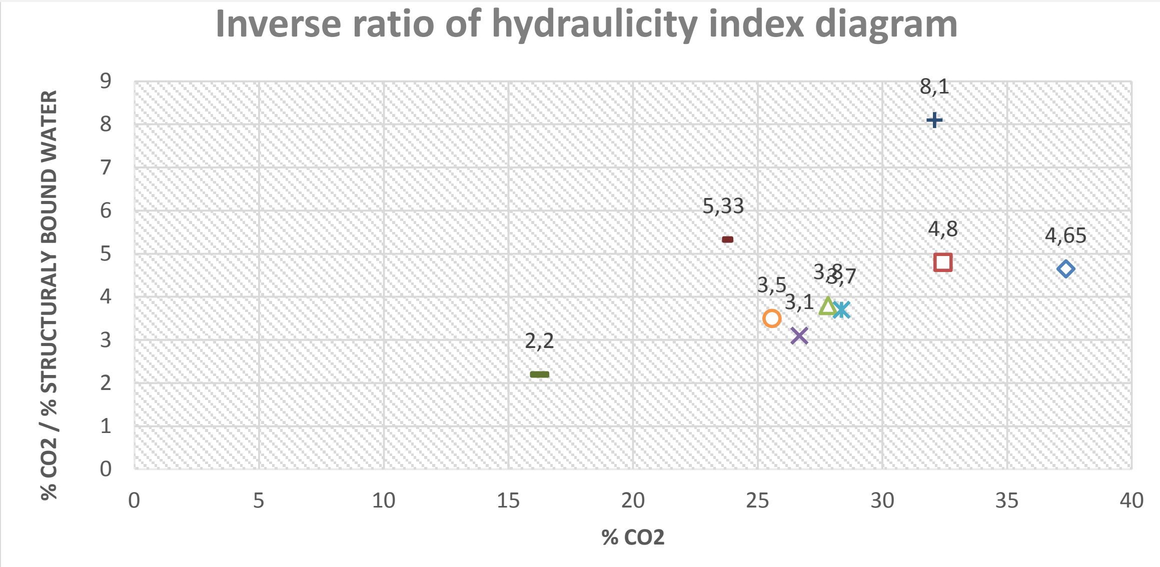




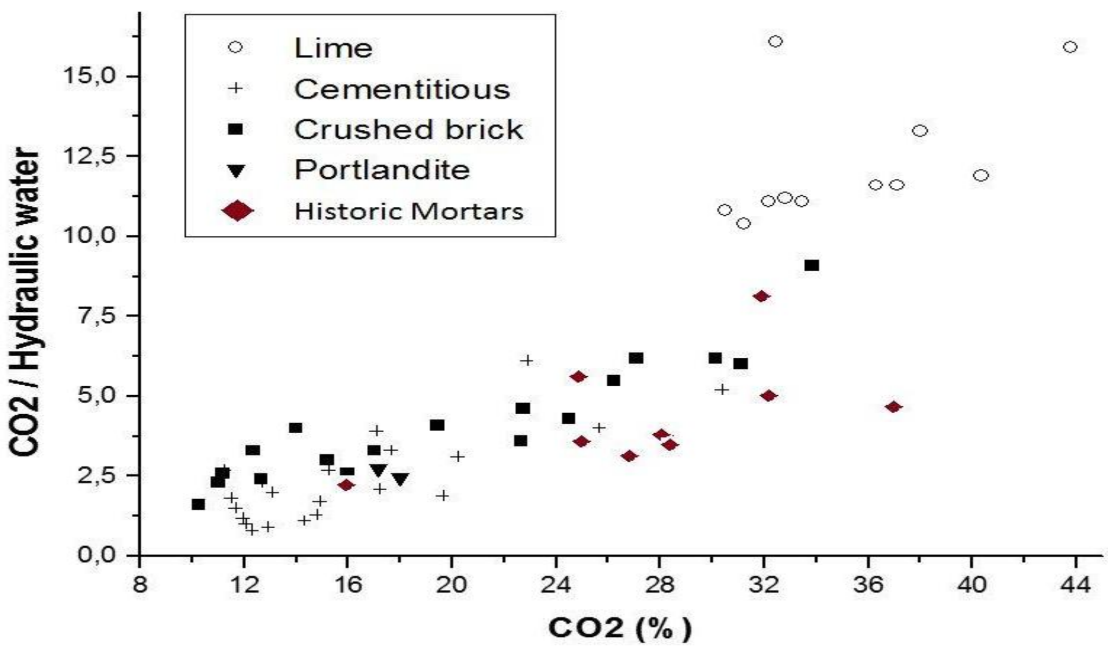
Characteristic curves of the thermal analysis on mortar samples

The mortars present a slight hydraulic nature, are calcitic (marly limestone) with the presence of ettringite

CHARACTERIZATION OF THE HISTORICAL MORTARS OF THE HOLY AEDICULE OF THE HOLY SEPULCHRE



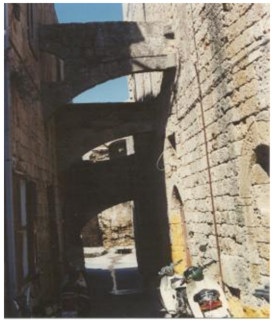
The inverse ratio of hydraulicity of the historic mortars of the Holy Aedicule and comparison with historical mortars studied at the NTUA Lab of Material Science & Engineering



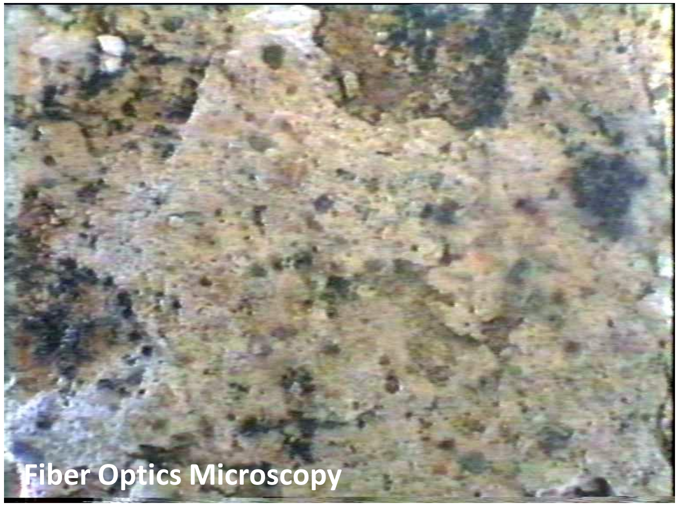
The historical authentic mortars of the Holy Aedicule, depicted with a rhombus, appear in the pozzolanic mortars group area

Typical lime mortars

Binder: lime
Aggregates : carbonate /aluminosilicate nature or mix
Binder/Aggregate proportion: 1:1-1:4

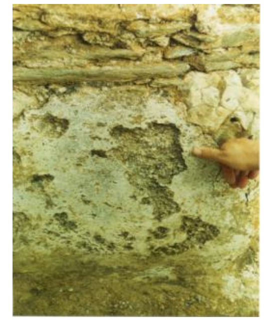


Lime mortar on masonries in the Medieval city of Rhodes

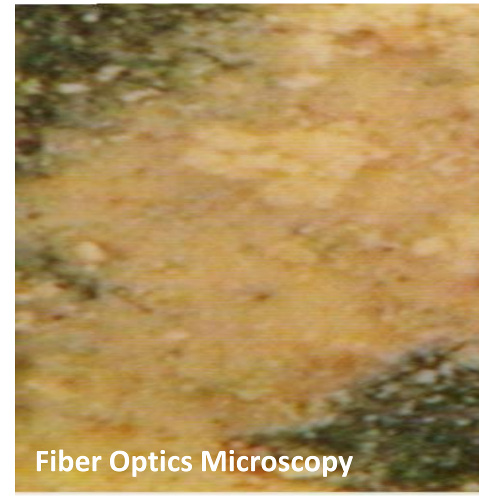


Lime – Pozzolana mortars

Binder: lime
Aggregates: carbonate /aluminosilicate nature or mix
Additives: Pozzolana
Binder/Aggregatesproportion: 1:2-1:4



Cistern in Lavrio

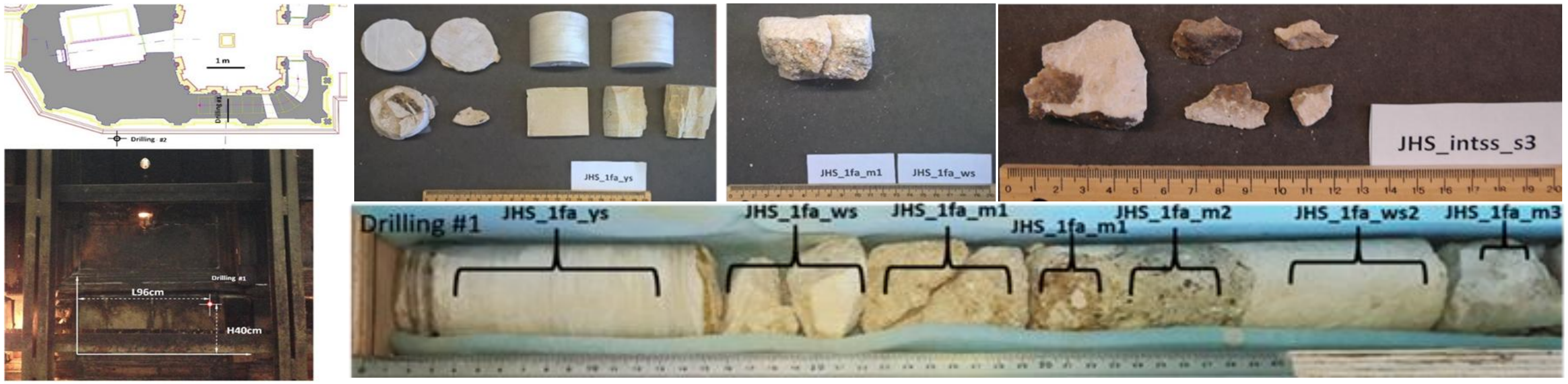


Crushed brick-lime mortars

Binder: lime
Aggregates: conventional or crushed brick
Binder/Aggregate proportion: 1:2-1:4

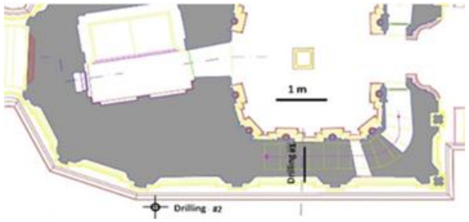
Crushed brick-lime mortar in Hagia Sophia

BUILDING STONES CHARACTERIZATION



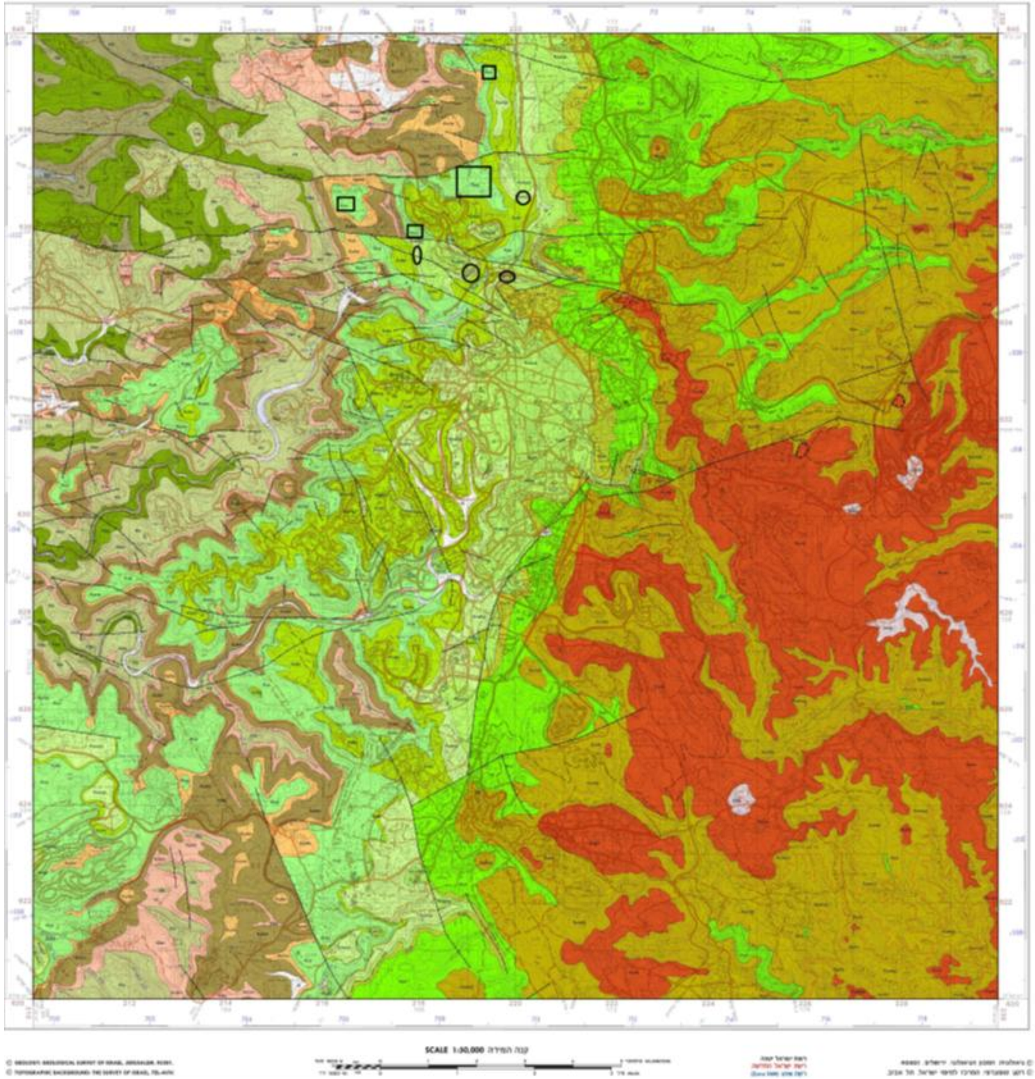
- **External Façade Building Stone - Komnenos' Phase** (JHS_1fa_ys): ***Micritic Fossiliferous Limestone***
  - Main Composition: Micritic Calcite
  - Secondary Composition: Quartz crystals, clay minerals, opaque metallic minerals and oxides and hydroxides of ferric
  - Total Porosity / Special Surface: 0.32% / 0.39 m^2/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 m^2/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 m^2/g

BUILDING STONE CHARACTERIZATION



- **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 m^2/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 m^2/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 m^2/g
  - Yield Strength / Young Modulus: 10.3 MPa / 21.7 GPa

IDENTIFICATION AND PROVENANCE INVESTIGATION OF BUILDING STONES



Sample Code	Macroscopic Sample Obsesrvation	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

Limestones: Geological Aminadav – Kua Formation

Dolomites: Geological Weradim Mizi Yahudi – Kuw (y) Formation

Indicative Areas of the Building Stones Provenance

NATIONAL TECHNICAL UNIVERSITY OF ATHENS

Interdisciplinary Research Team for the Protection of Monuments

Scientific Coordinator:
Prof. A. Moropoulou

Interdisciplinary Research Group NTUA**:**
Prof. Em. Korres, Prof. A. Georgopoulos, Prof. A. Moropoulou, Prof. C. Spyrakos

School of Civil Engineering
Laboratory for Earthquake Engineering

Structural Assessment
(Scientific Responsible: Prof. C. Spyrakos)

Επιστημονική Ομάδα :
Assistant Professor Ch. Mouzakis
Researcher: S. Asimakopoulos,
Dipl. Civil Engineer, MSc, PhD Ch. A. Maniatakis
and others

Research Aims

- ❖ Creation of a Finite Element Model

NATIONAL TECHNICAL UNIVERSITY OF ATHENS

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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)

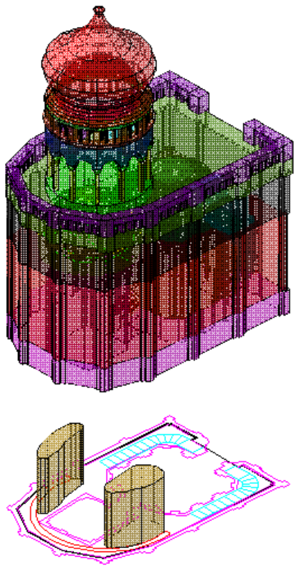
Scientific Team:
Dipl. Civil Engineer, MSc, PhD Ch. A. Maniatakis

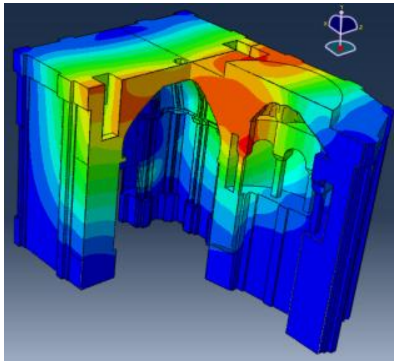
Research Aims

This presentation includes:

- Current condition **assessment under static and seismic loading**
- **Proposal** for **interventions**

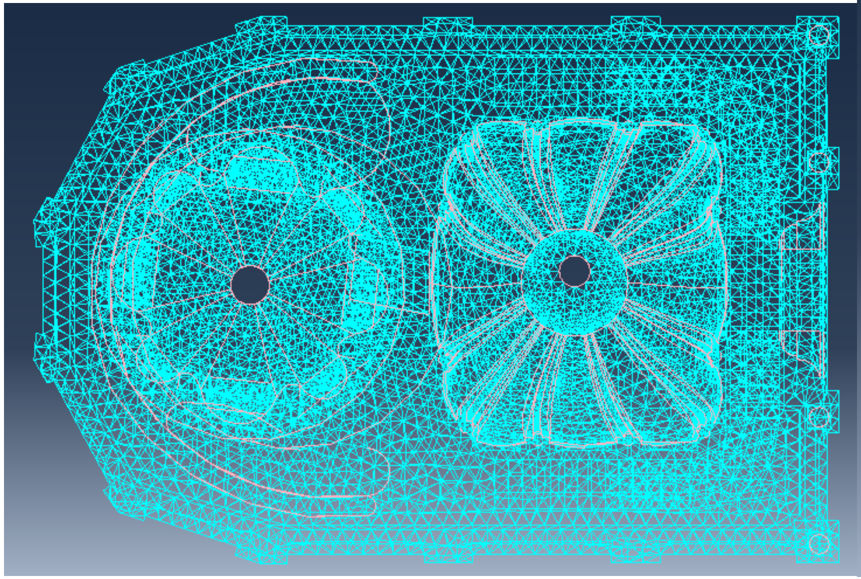
regarding the Holy Edicule of the Holy Sepulchre in the Church of the Resurrection in Jerusalem applying the Finite Element Method (ABAQUS).

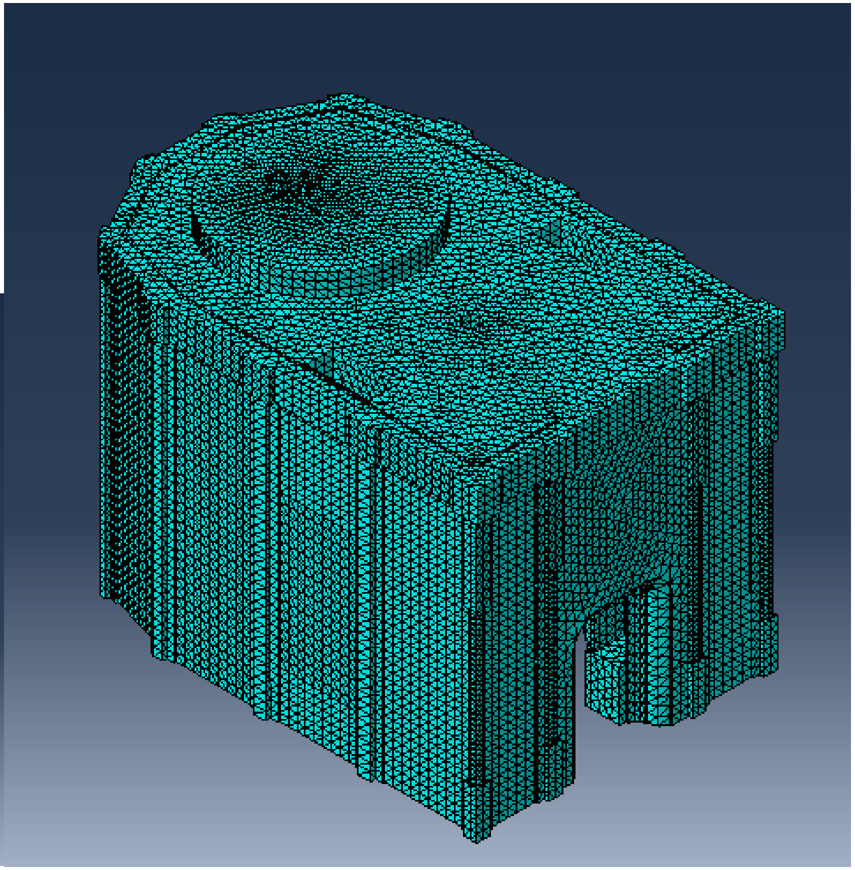


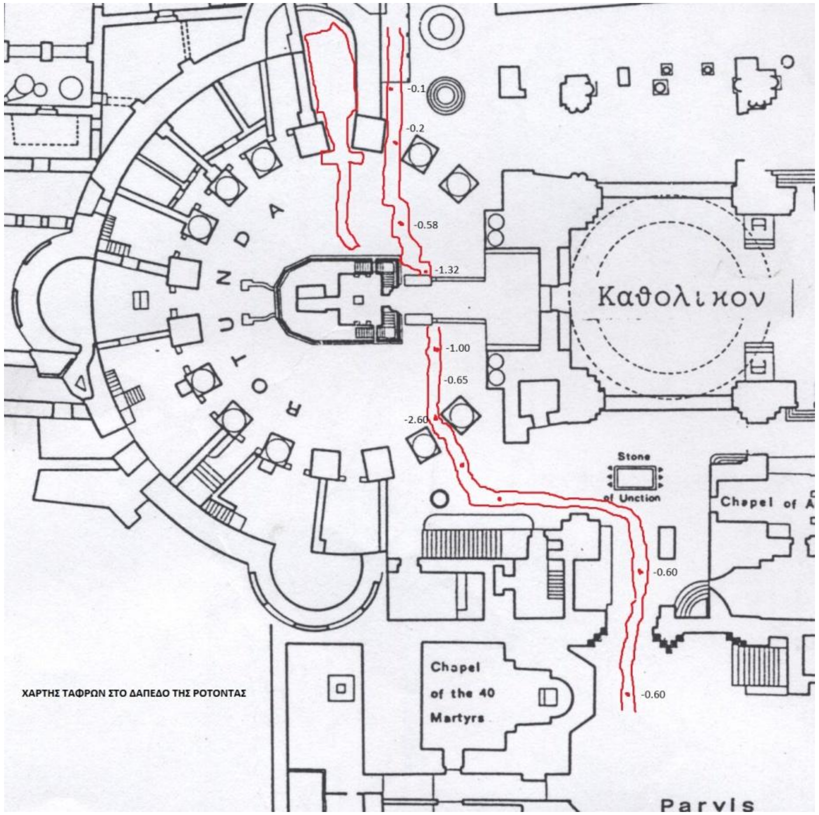


Main Bearing Structure
Finite Element Model

The model consists of 426674 tetrahedral solid elements and 623586 nodes







Map of trenches
© Theo Mitropoulos

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Scientific Coordinator:
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Interdisciplinary Research Group NTUA**:**
Prof. Em. Korres, Prof. A. Georgopoulos, Prof. A. Moropoulou, Prof. C. Spyrakos

Diagnosis

1. **Accurate Geodetic Measurements for determining eventual deviations and deformations of the Holy Aedicule**
2. **Structural Damage of the Holy Aedicule**
3. **Documentation of the construction phases and decay diagnosis and pathology**
4. **Dynamic characteristics of the Holy Aedicule**
5. **Assessment of Current Condition under Static and Seismic Loading for the Holy Aedicule of the Holy Sepulchre**

NATIONAL TECHNICAL UNIVERSITY OF ATHENS
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Interdisciplinary Research Group NTUA:
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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 Panatzis, *Assoc. Professor NTUA*
Panagiotis Agrafiotis, *Rural and Surveyor Engineer, MSc*
Lydia Kotoula, *Rural and Surveyor Engineer*
Alexandra Papadaki, *Rural and Surveyor Engineer*

Research Aims

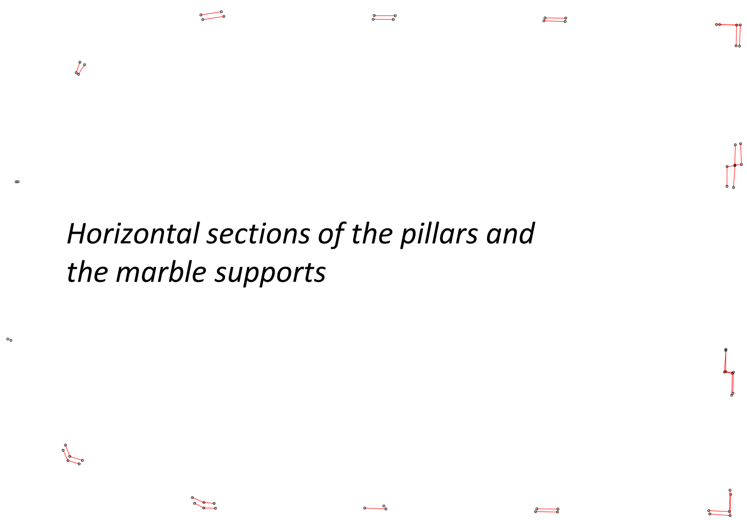
Measurements for determining eventual deviations and deformations of the Holy Aedicule:

- A longitudinal section of the Holy Aedicule
- Four horizontal sections of the dome of the Holy Aedicule at elevations of 6.00m, 8.00m, 8.80m and 12.00m, from the interior floor of the Holy Aedicule.
- Two horizontal sections of the pillars and the marble supports of the Holy Aedicule, which present obvious deformations, at heights 0.70m and 4.40m respectively, from the interior floor of the Holy Aedicule
- On the metal supportive beams which are outside of the Holy Aedicule

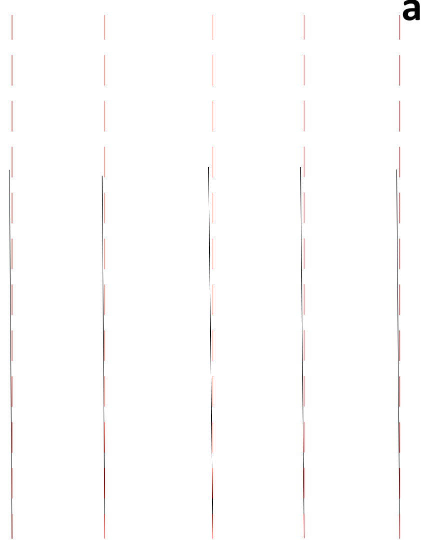
Horizontal sections of the dome of the Holy Aedicule with the positions of their centers

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

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



Horizontal sections of the pillars and the marble supports



Deformations of the metal supportive beams

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

NATIONAL TECHNICAL UNIVERSITY OF ATHENS

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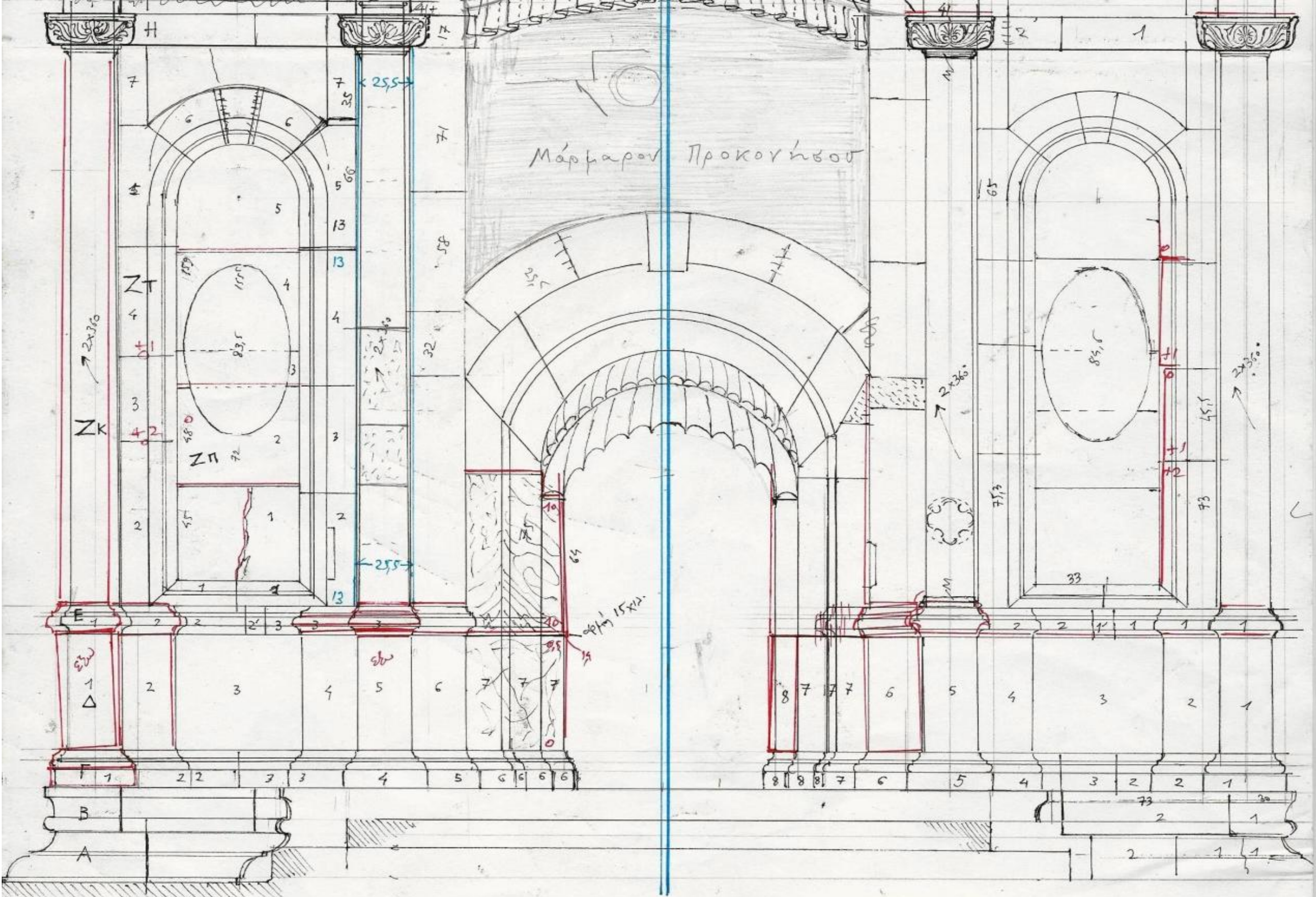
Interdisciplinary Research Group NTUA**:**
Prof. Em. Korres, Prof. A. Georgopoulos, Prof. A. Moropoulou, Prof. C. Spyrakos

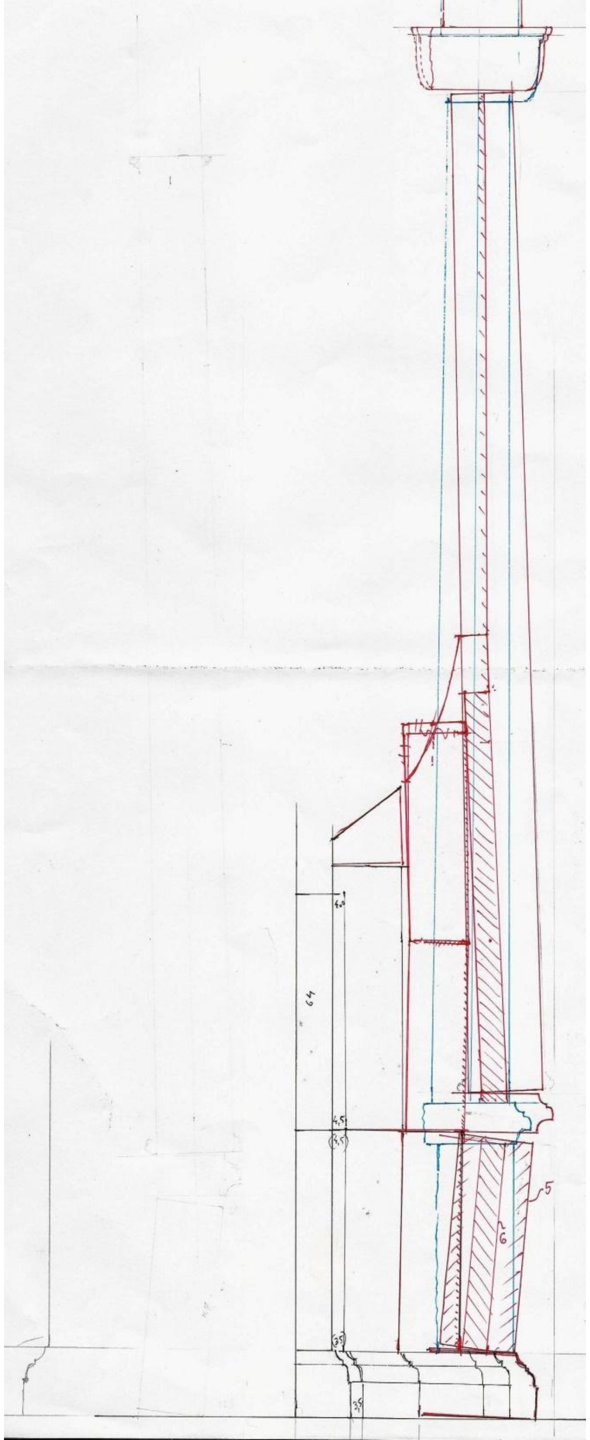
School of Architecture
Department of Architectural Design

Structural Damage of the Holy Aedicule
(Scientific Responsible: Prof. Emm. Korres)



Dr. T2 Holy Aedicule, drawing of the façade that describes the boundaries and the movement of each stone, vertical and horizontal design sections (Em. Korres, 2015).

dr.T3
vertical axial section at the location of the main entrance with view to the right of this column. Red color denotes the current state (significant deformation and lifting mechanism of columns and superstructure). Blue color indicates the canonical form and the intended reconfiguring.



NATIONAL TECHNICAL UNIVERSITY OF ATHENS

Interdisciplinary Research Team for the Protection of Monuments

Scientific Coordinator: **Prof. A. Moropoulou**

Interdisciplinary Research Group NTUA: **Prof. Em. Korres, Prof. A. Georgopoulos, Prof. A. Moropoulou, Prof. C. Spyrakos**

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)

Research Aims

- ❖ Documentation of the construction phases of the structure of the Aedicule
- ❖ Diagnosis of decay and pathology

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

Scientific Responsible:	*Prof. Antonia Moropoulou*
Research Team members:	*Researcher, Dr. Kyriakos Labropoulos*

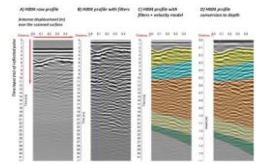
❖ **Diagnosis of decay and pathology**

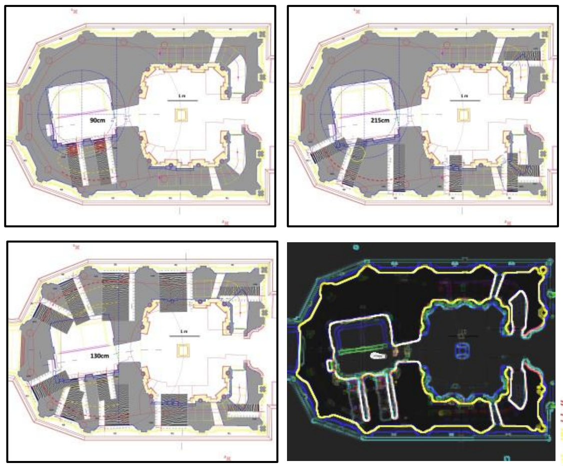
- In-situ macroscopic observations
- In-situ non-destructive testing (infrared thermography, ground penetrating radar. Ultrasounds, etc.)
- Decay diagnosis and pathology

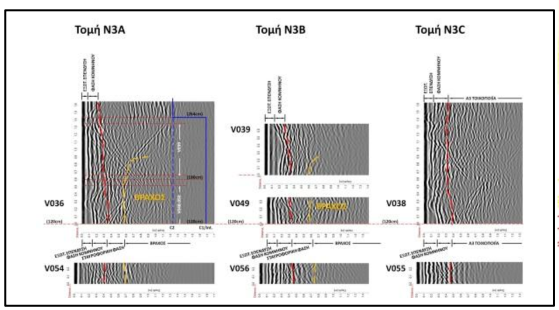
Scientific Responsible:	*Prof. Antonia Moropoulou*
Research Team members:	*Assist. Prof. Asterios Bakolas,* *Researchers: Dr. Ekaterini Delegou, Dr. Petros Moundoulas†,* *PhD Candidate Emmanuel Alexakis,* *Grad. Student Lamprini Sioula*

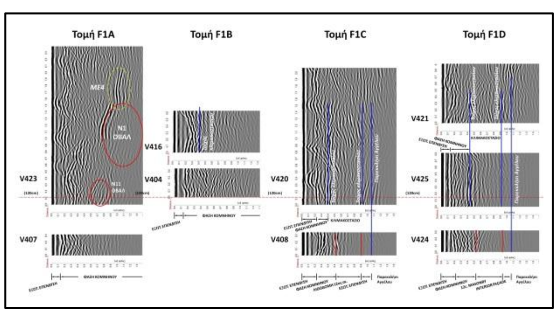
Non-destructive prospection / Rendering of the interior structure of the Aedicule of the Holy Sepulchre by use of ground penetrating radar

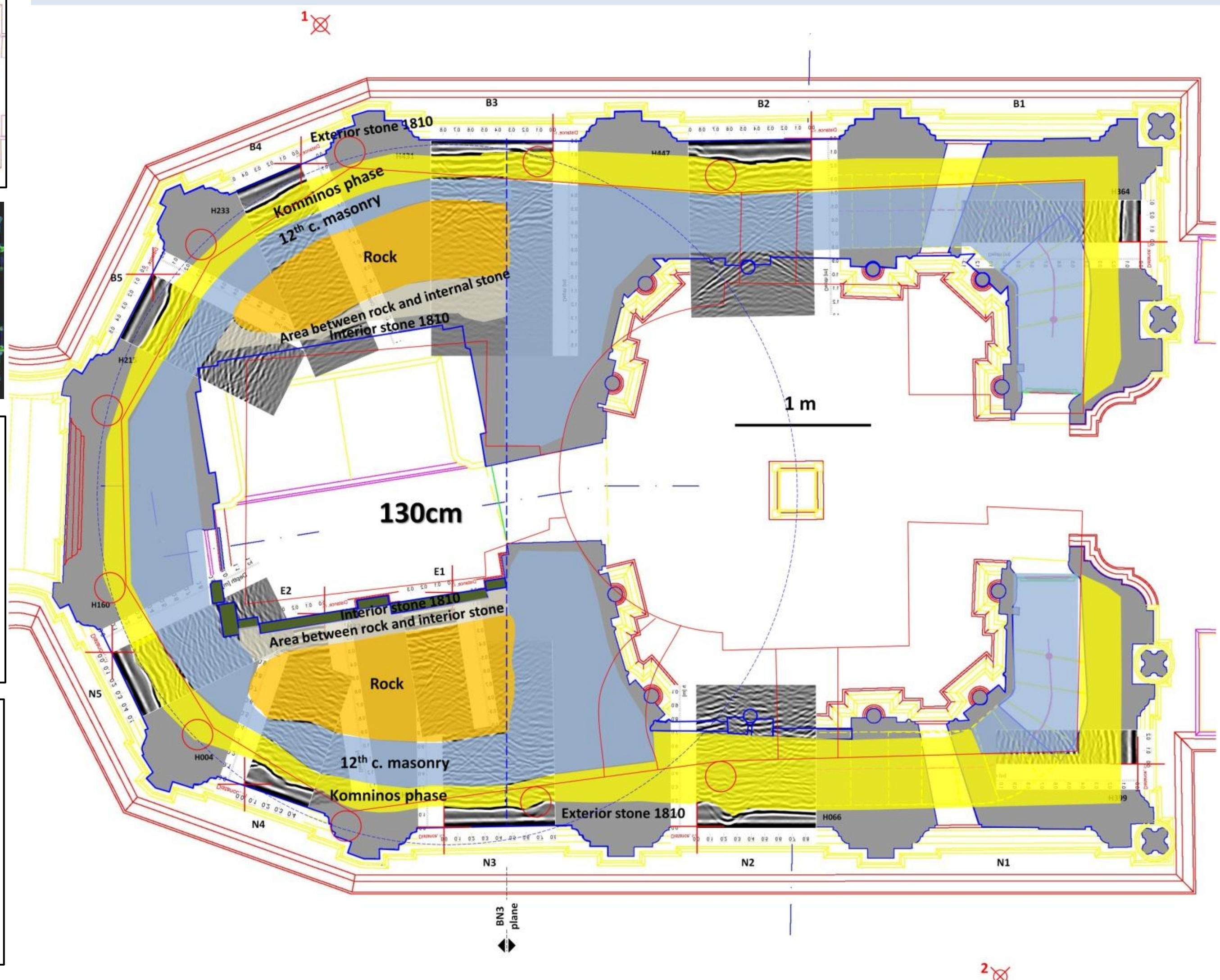
- ***Prospection of the internal structure of the Holy Aedicule:*** *Holy Rock, Crusaders' construction phase, Komninos phase*
- ***Documentation of the construction phases***

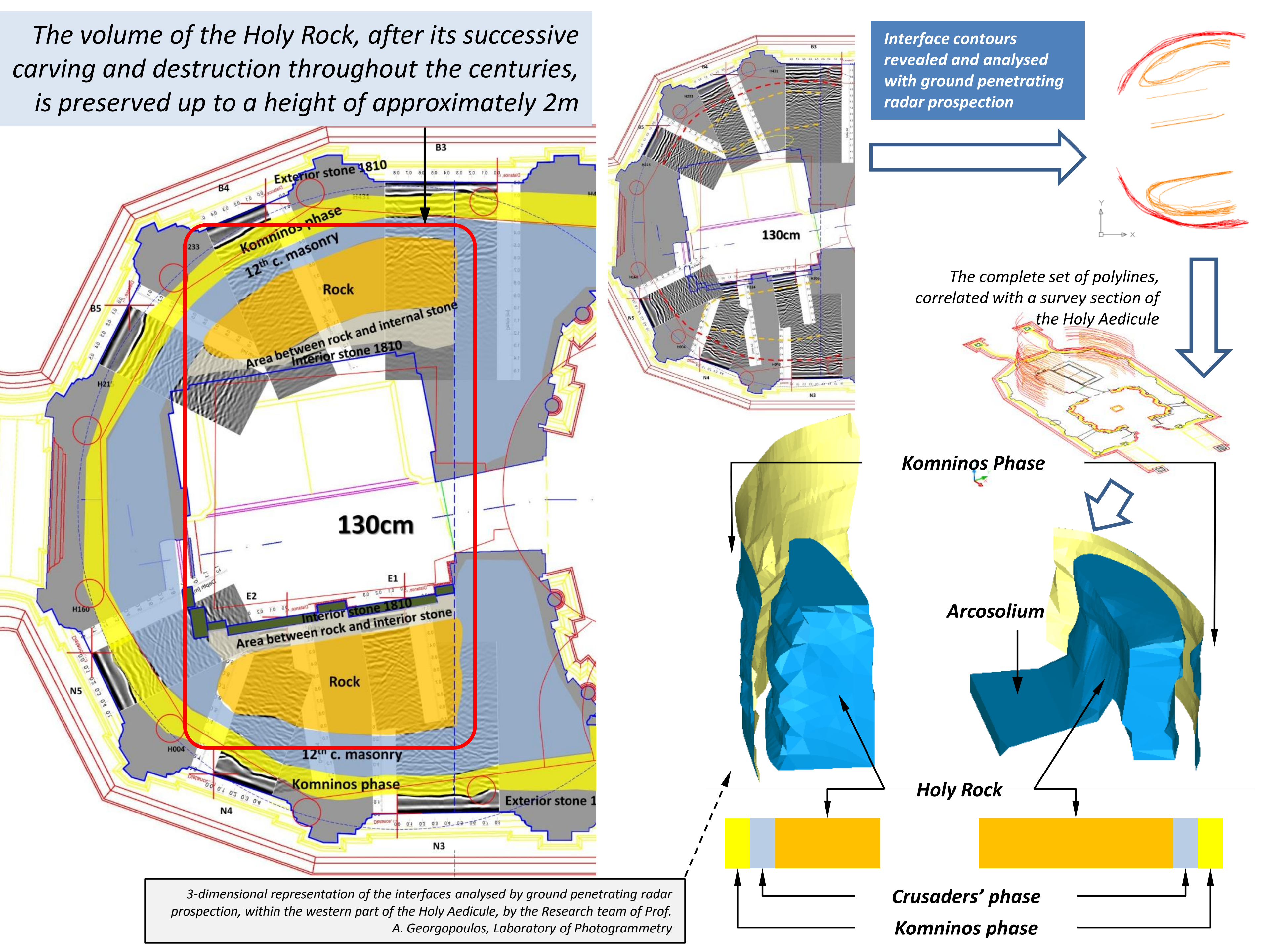








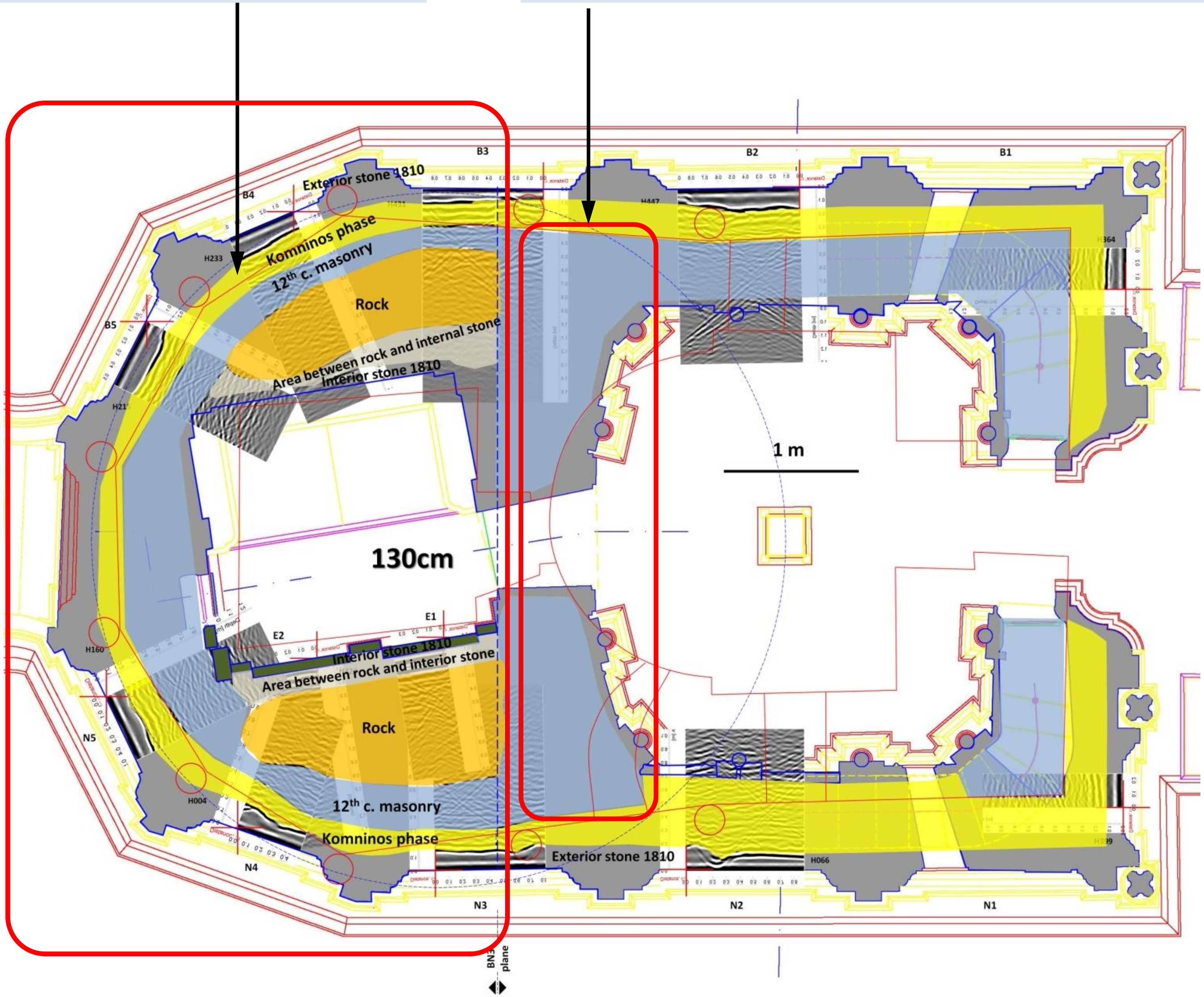




3-dimensional representation of the interfaces analysed by ground penetrating radar prospection, within the western part of the Holy Aedicule, by the Research team of Prof. A. Georgopoulos, Laboratory of Photogrammetry

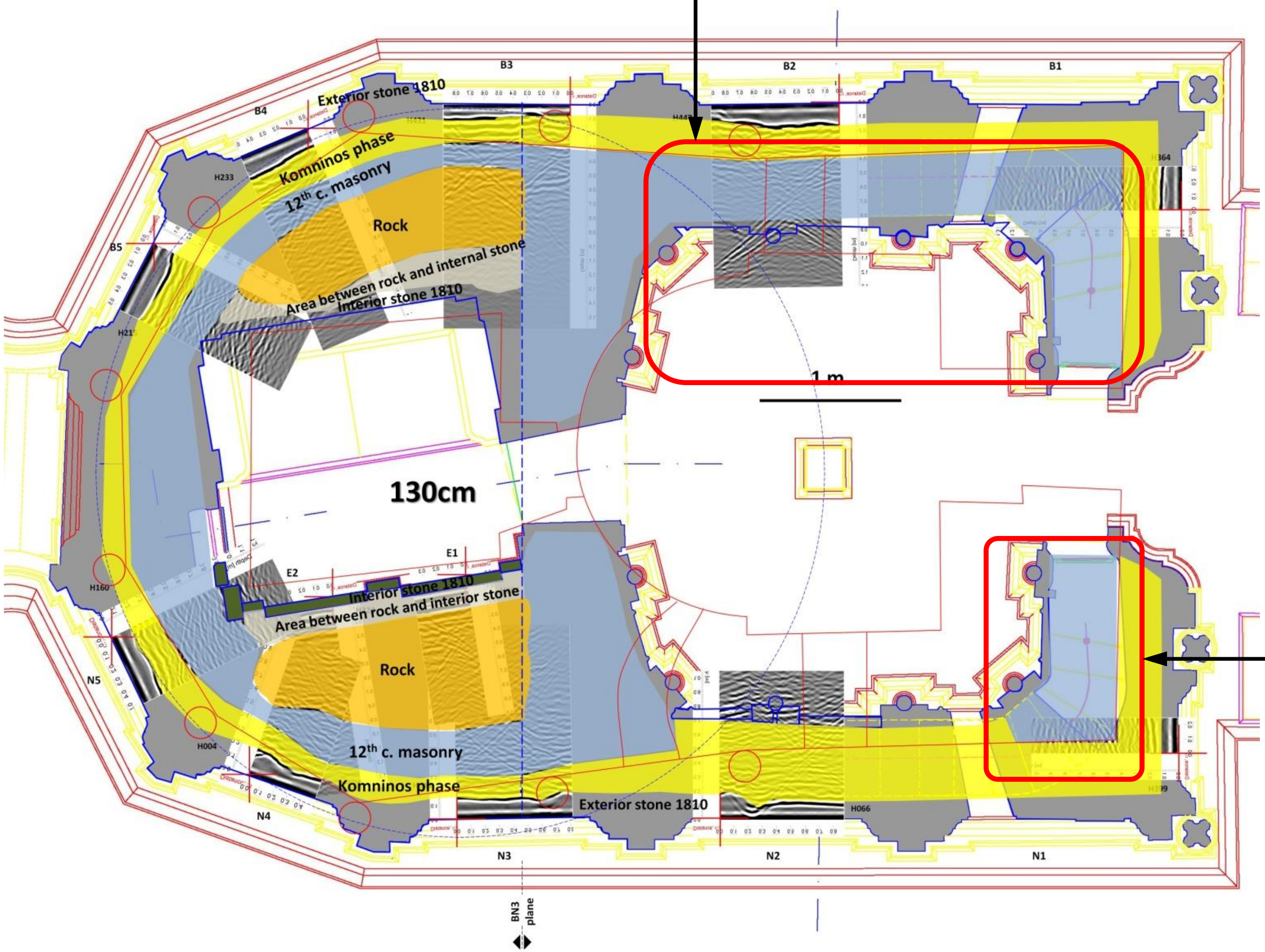
At the western part of the Holy Aedicule, the Komninos construction phase (1810) has been added externally to the 12th century masonry

Eastern to the vertical plane BN3, i.e. at the area of the entrance to the Holy Sepulchre, there exists masonry that is a combination of 12th cent. masonry (at the lower parts) and newer masonry of 1810 (upper parts)

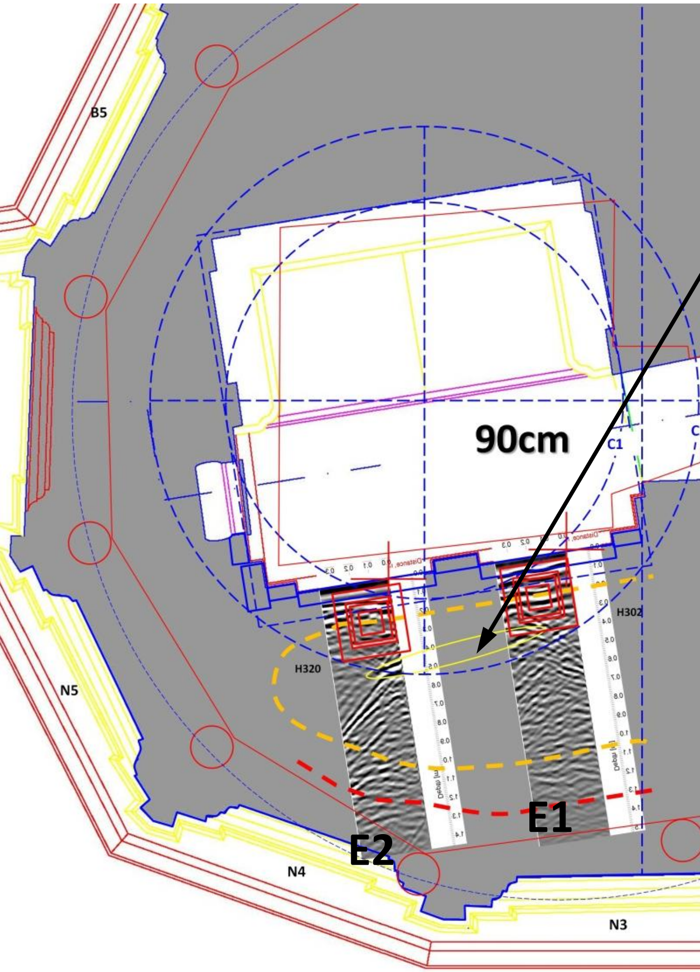


The north masonry of the Crusaders phase at the Chapel of the Angel has been preserved, at its lower parts, and embedded within the structure of 1810.

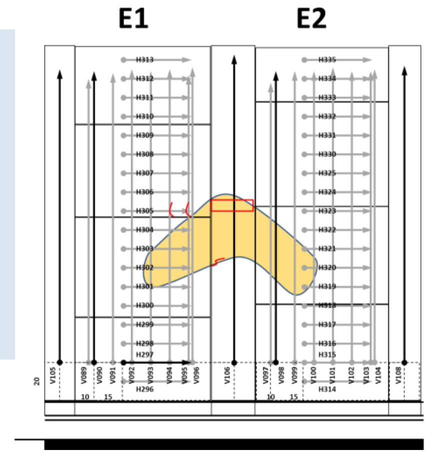
At the corresponding southern part, only the part of the masonry that is below the south staircase has been preserved.



• *Damage diagnosis at areas within the structure of the Holy Aedicule*

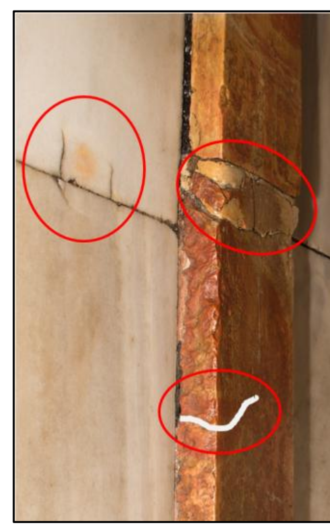


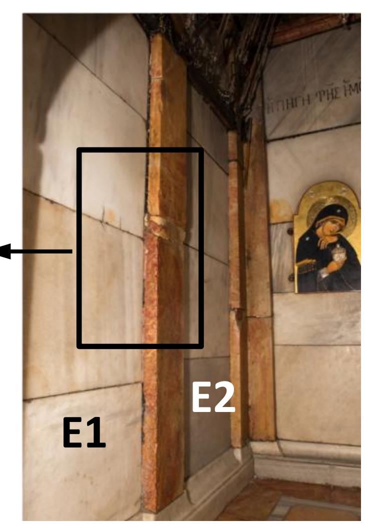
*Presence of a inhomogeneity, which it is theorized to correspond to an **internal fracture within the Holy Rock** at areas E1 and E2, between the height levels 80-120cm and with a form of an inverted "v"*



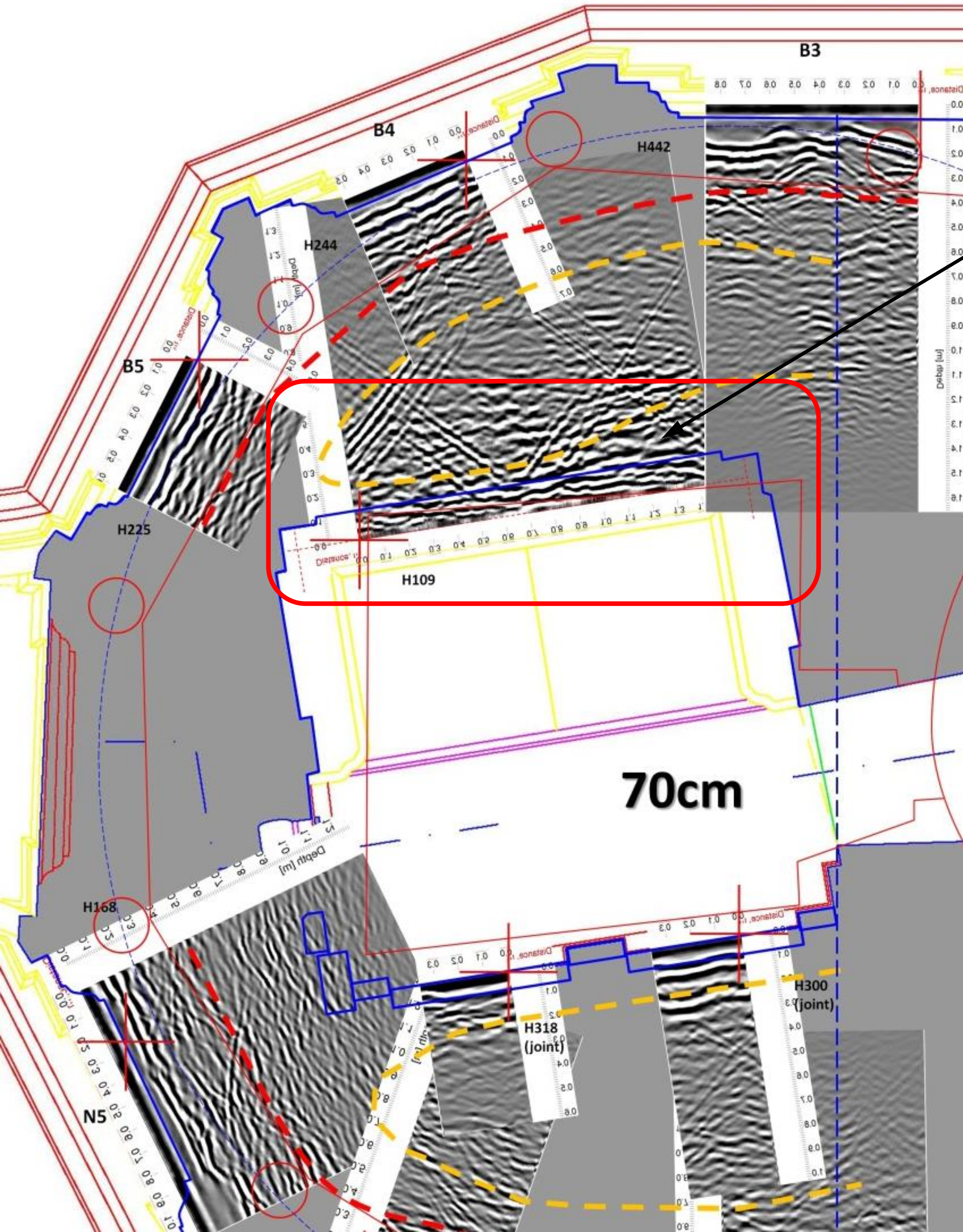
A possible interpretation of the mechanism of formation of this internal fracture is that **since these pillars are half-founded on the rock and half-found on the masonry between the rock and the interior panel, during dynamic loading, the intensity of the applied stresses at this area, possibly led to the "internal detachment" of part of the rock**.

*At the boundaries of this area, there are **macroscopically observed – at the surface of the panel – cracks and displacements, the location of which corresponds satisfactorily with the boundaries of the theorized internal fracture**.*





Necessitate the **design of strengthening interventions within the Holy Tomb too and in particular at its southern part**, i.e. areas E1 and E2, so as to avoid possible static problems of the roof structure above the Holy Tomb



The reflections possibly correspond to the ***loss of cohesion with the masonry behind and above the arcosolium****, between the interior marbles and the rock.*

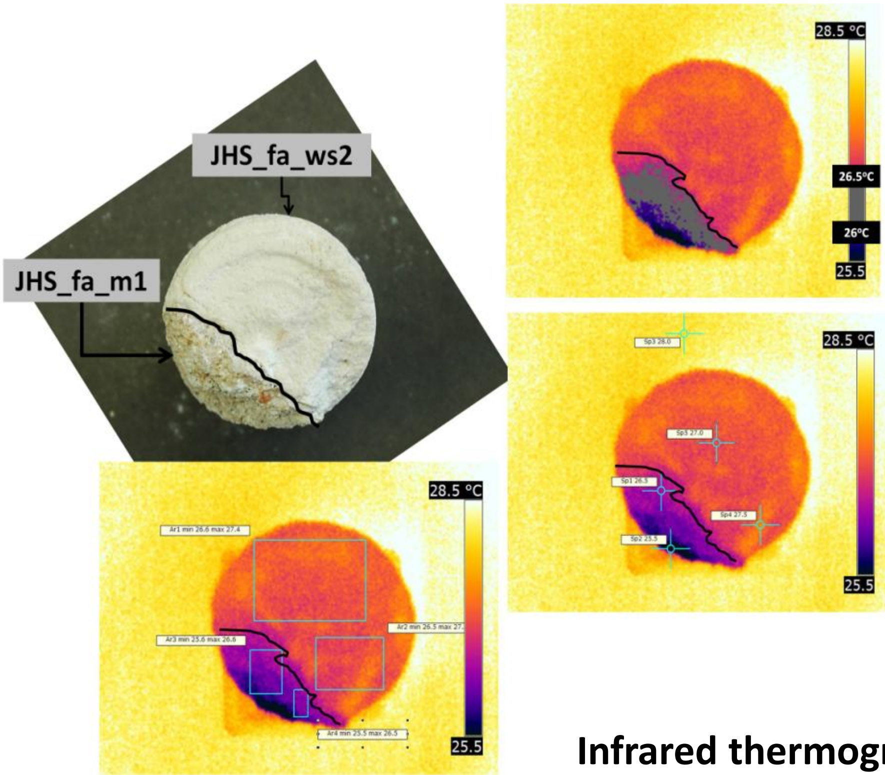
It should be noted that these areas occur below corresponding pillars such as those of areas E1 and E2, although, due to the lack of sufficient horizontal scans from the northern interior, no safe correlation could be performed.

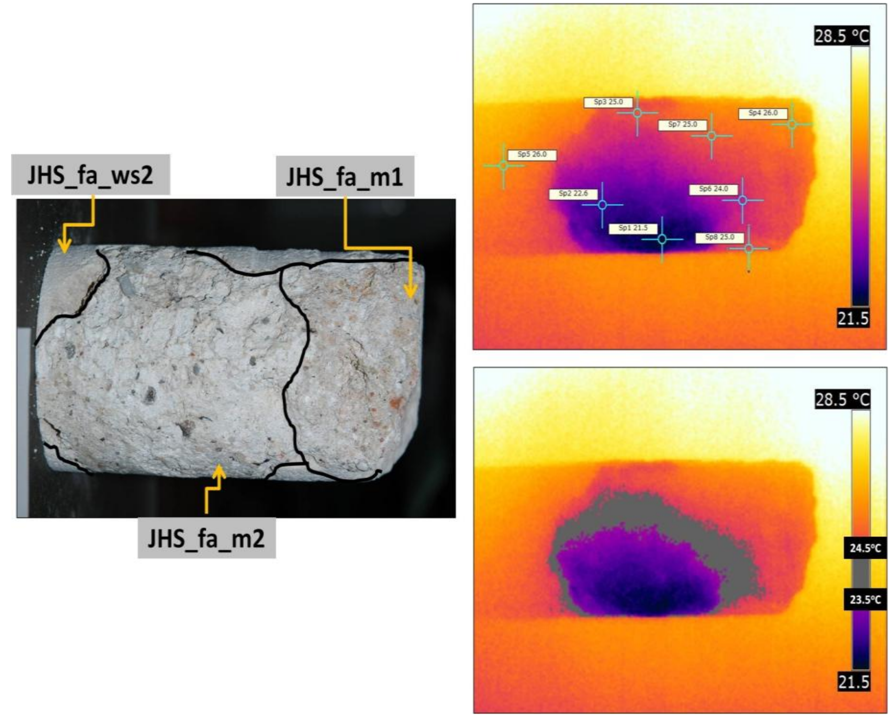
The area behind and above Jesus tomb is in need of further attention and possibly requires strengthening interventions*, as in areas E1 and E2, although, due to accessibility limitations, any such work will be difficult to implement*

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.

The cause of the deformation is the deterioration of the mortars. Their hydraulic character is attributed to CAH (aluminates salts of calcium), that develop during the setting and the hardening of the hydraulic lime that is produced by the burning of the marl limestones. This is the main reason of their deterioration, from the infiltration of drainwater from the opening of the dome, but also from rising damp and the condensation and respiration of the pilgrims

Results of non-destructive testing of architectural surfaces with infrared thermography





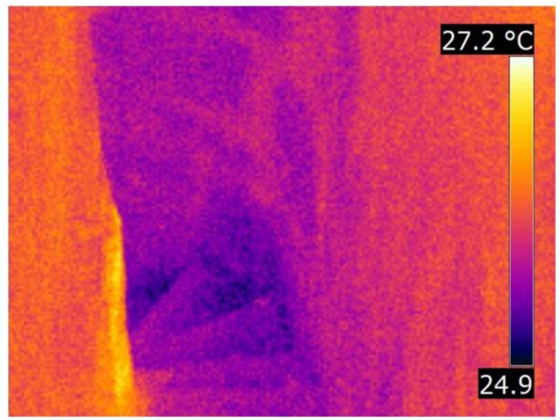
Infrared thermography of part of the drilling samples of the masonry

Physicochemical incompatibility between the joint mortars and the stone

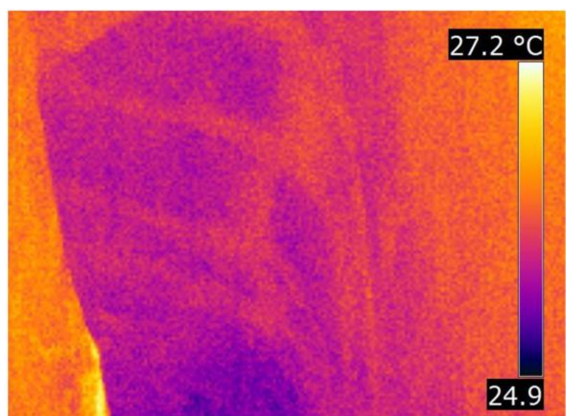
From the above infrared thermography image, coming from a part of the façade core sample, the physicochemical incompatibility between the historic grouting mortar and the building stone is found. Due to its erosion, mortar performativity has been lost attributing lower temperatures than the building stone within a temperature range of 3 °C, whereas the 1 °C temperature range area indicates the moisture transportation procedure from the rich ettringite lime mortar JHS_fa_m2 to the building stone JHS_1fa_ws and lime mortar JHS_fa_m1.

Infrared thermography of the internal sidewall of the masonry of the eastern and southern side the staircase leading to the terrace

The metallic elements have been oxidized and subsequently have swelled. Due to this, plaster cracking has been occurred causing, in turn, partial material detachment.

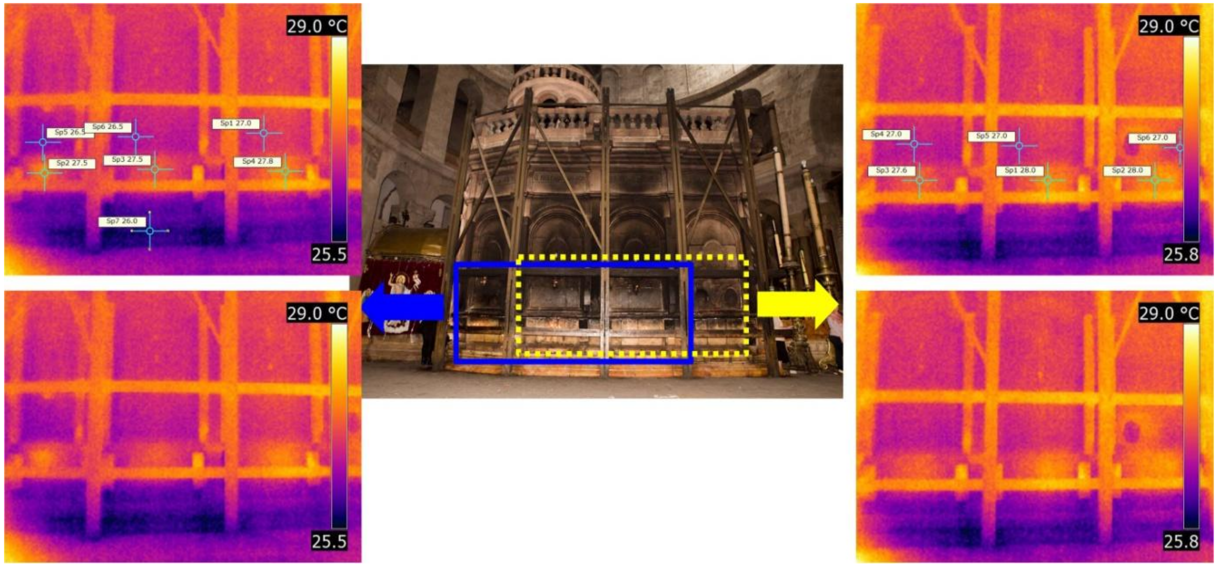


During the IR-Thermal inspection of the area (Figure 31) along the cracks and around the areas where material detachment has taken place, higher temperature, following the decay and a metallic mesh patterns, is observed.



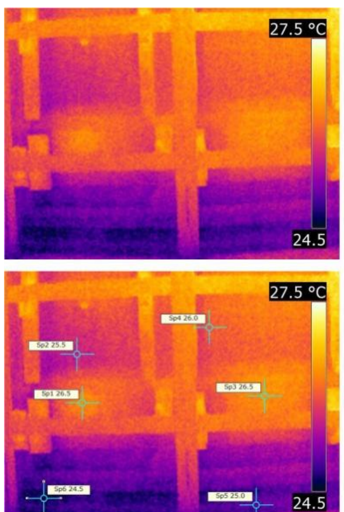
This makes possible the existence of metallic elements invisible macroscopically under the plaster

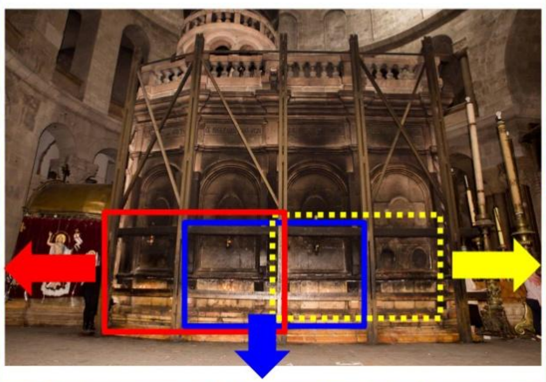
Infrared thermography of the southern façade of the Holy Aedicule

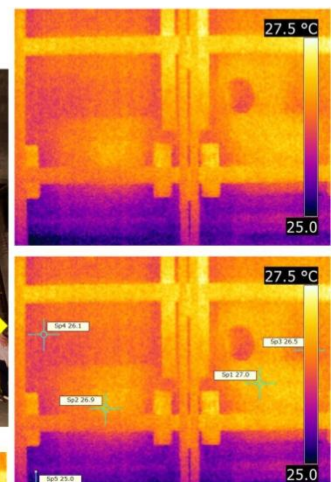


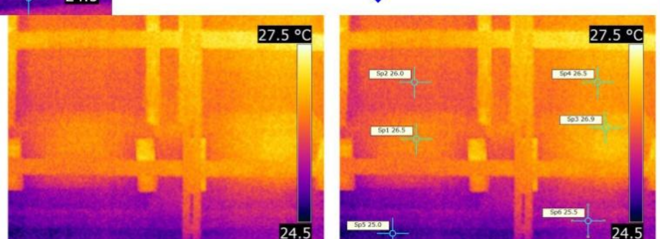
The thermographic examination of the north façade of the Holy Aedicule revealed that the temperature distribution differentiates according to the various building stones of the façade combined with the distribution and the concentration of black deposits from dust and smoke particles of burning candles and oil-lamps.

3 hours after burning the candles out



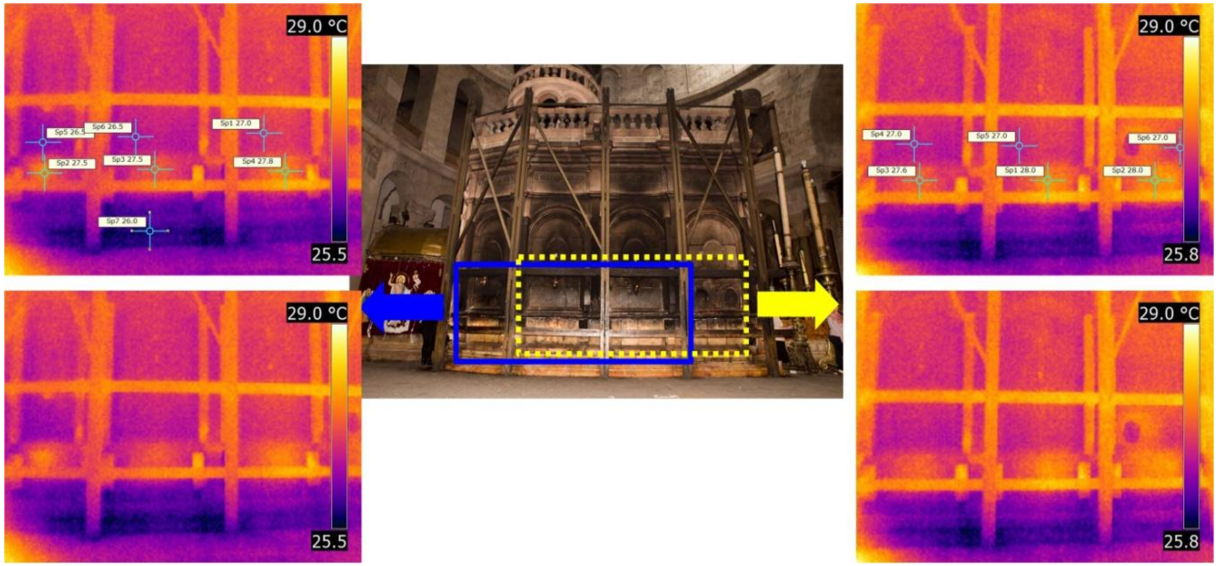




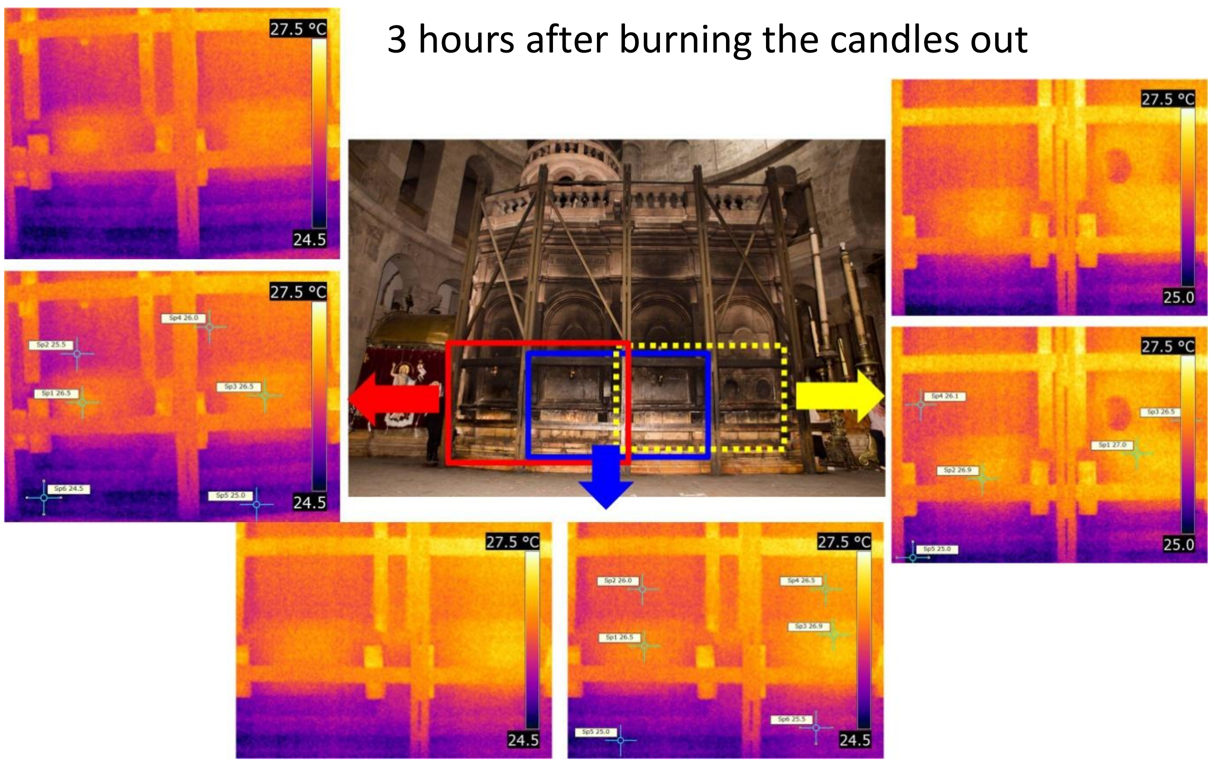


Higher temperature by 1.5°C of the building stones neighbouring the flame of the candle. The anisotropic heat distribution over the surface of the building stone and subsequently in the deeper layers of the wall via the mechanism of heat induction and the maintenance of that temperature difference at least by 0.5 °C 3 hours after burning the candles out, proves the topical thermal heterogeneity

Infrared thermography of the southern façade of the Holy Aedicule



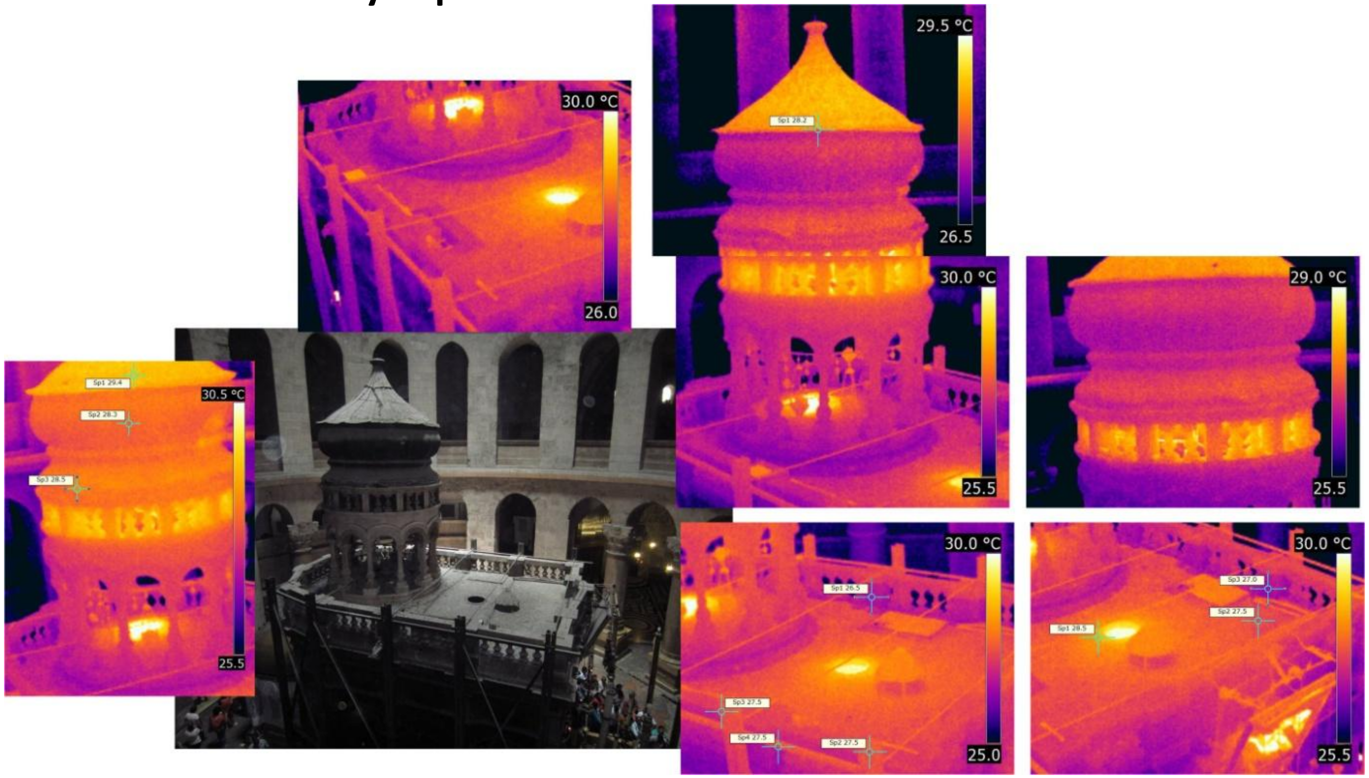
3 hours after burning the candles out



The aforementioned action, taking place in a daily basis causes corresponding changes in the thermo-hygrometric behaviour of the building materials of the masonry, accelerating their deterioration.

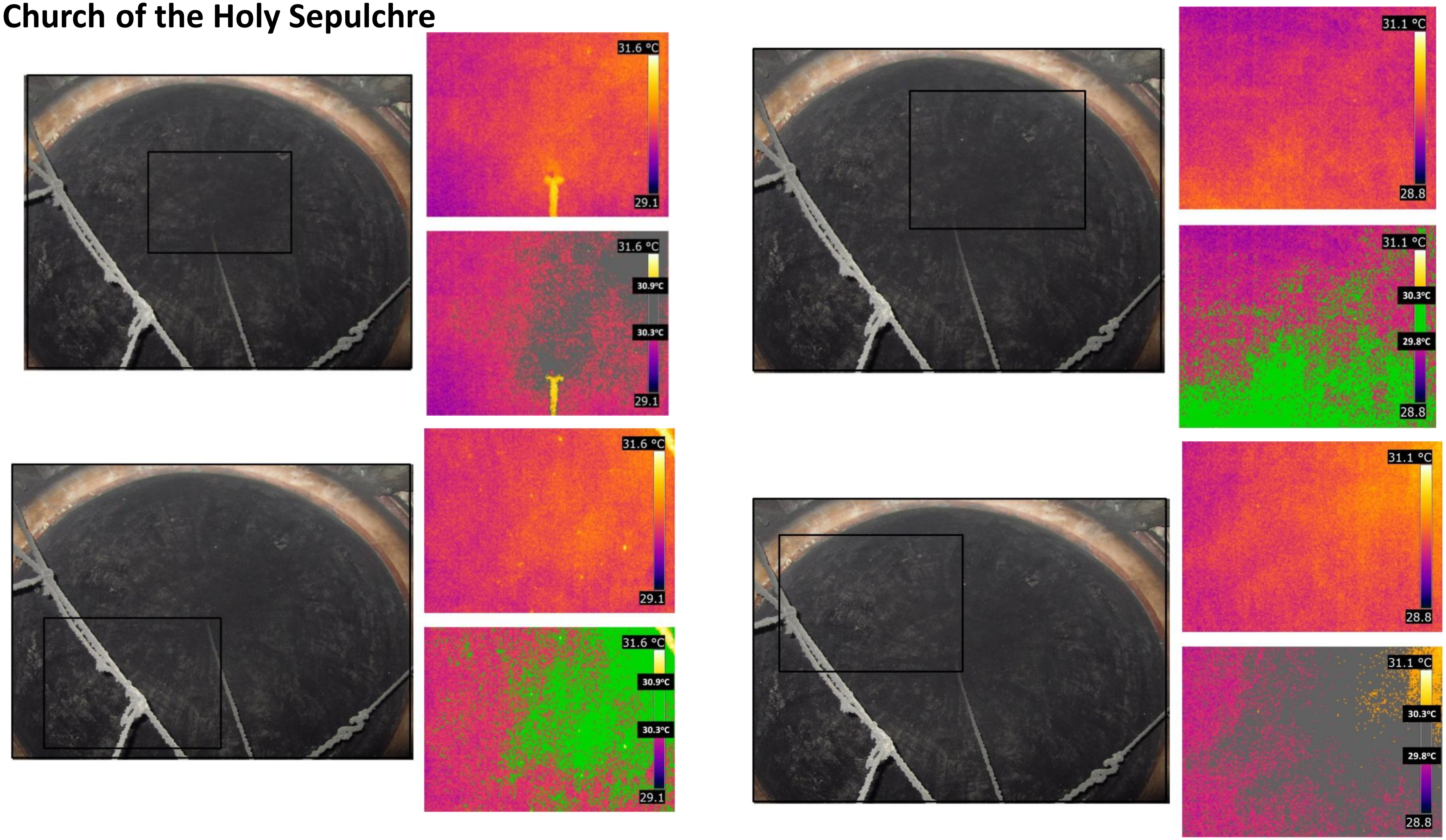
It is clear that the burning candles or/and the oil-lamps being in contact or having close proximity to the architectural surfaces of the Holy Aedicule is prohibitive and is suggested the particular action to take place at a sufficient distance from it.

IR-Thermal inspection of the dome and the terrace of the Holy Aedicule of the Church of the Holy Sepulchre



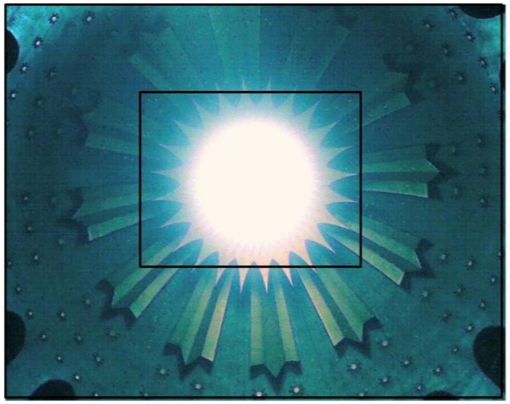
Respective thermal stress due to the burning oil-lamps in the interior of the Holy Aedicule was found from the examination of the terrace. The areas around the terrace holes are have at least 1 ° C higher temperature than the areas of the roof edges.

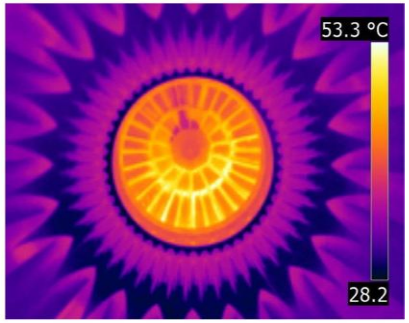
IR-Thermal inspection of the dome and the terrace of the Holy Aedicule of the Church of the Holy Sepulchre

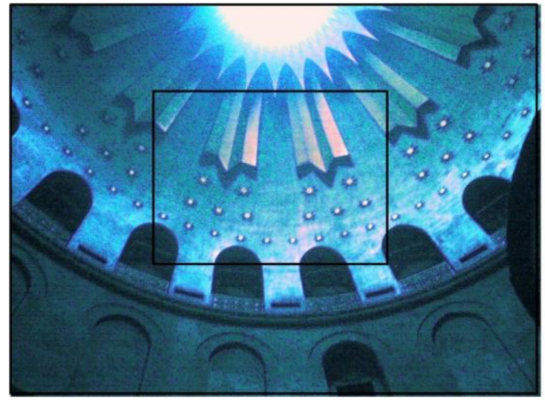


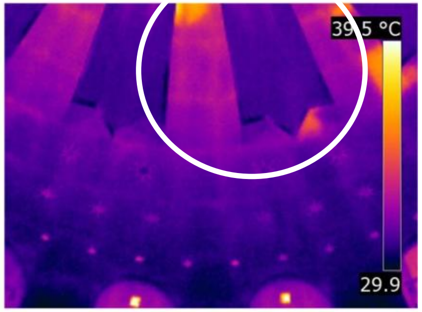
As seen from the Thermographs of the isotherms, there is observed heat accumulation in the centre of the dome above the Tomb’s chamber, resulting in approximately 1 °C higher temperature in the area around the centre.

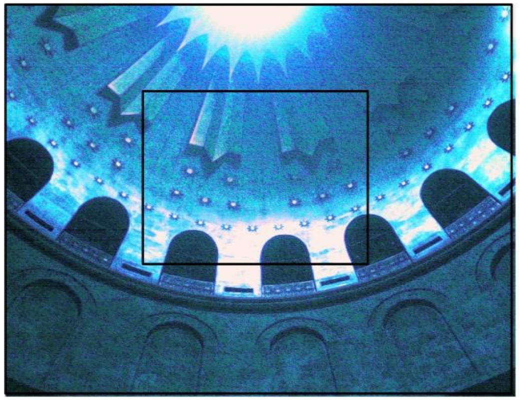
IR-Thermal inspection of the Rotunda dome

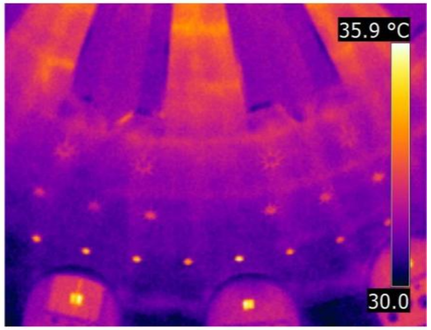


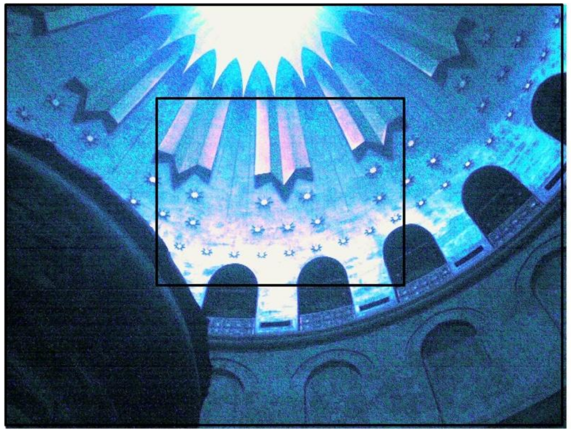


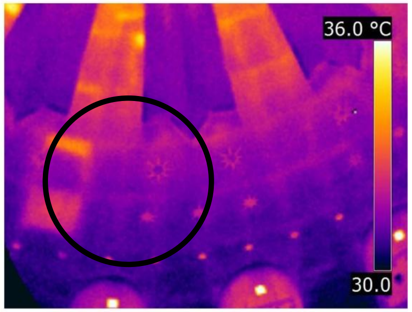












The IR-Thermal analysis managed to map the metal skeleton of the concrete dome of the Rotunda, as well as structural elements, not visible macroscopically, some of which might need further investigation with respect their preservation state

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Interdisciplinary Research Group NTUA**:**
Prof. Em. Korres, Prof. A. Georgopoulos, Prof. A. Moropoulou, Prof. C. Spyrakos

School of Civil Engineering
Laboratory for Earthquake Engineering

Dynamic characteristics of the Holy Aedicule
(Scientific Responsible: *Assist. Prof. Ch. Mouzakis*)

Επιστημονική Ομάδα :
S. Asimakopoulos, *Researcher NTUA*
Dr. L. Karapitta, *Researcher NTUA*

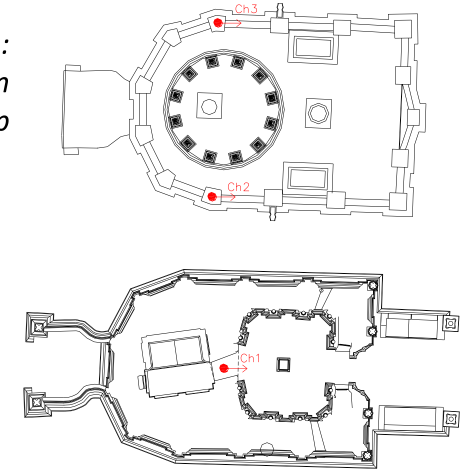
Research Aims

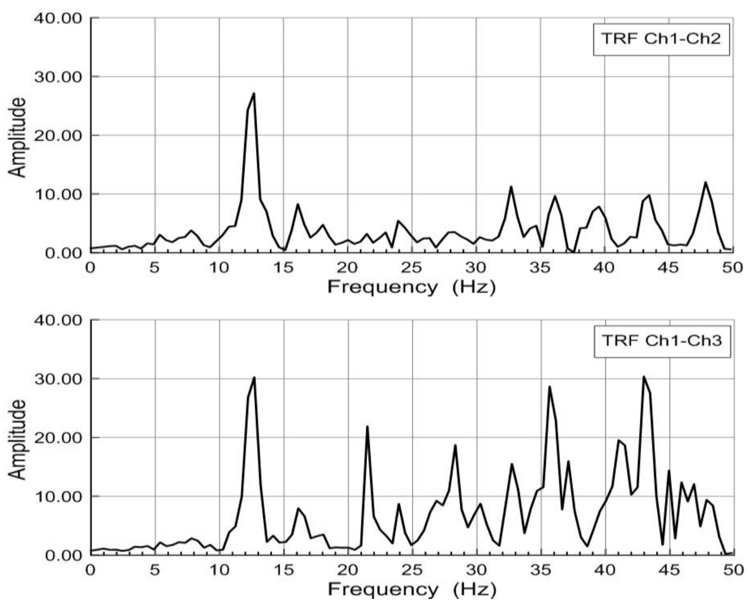
Measurement of the dynamic characteristics of the Holy Aedicule and the examination of the degree to which the different constituent parts of the Holy Edicule interact among them and whether the structure behaves as a whole. In addition, measurements to determine the internal tension forces of the ties of the steel structure of the Holy Edicule were performed

During these measurements the instruments were positioned in the locations shown in Figure 4 along the W-E direction. Table 2 presents the information relevant to their calibration. The channel 1 instrument was placed on the ground, while the instruments for channel 2 and 3 on the enclosure balustrade of the slab of the Holy Edicule.

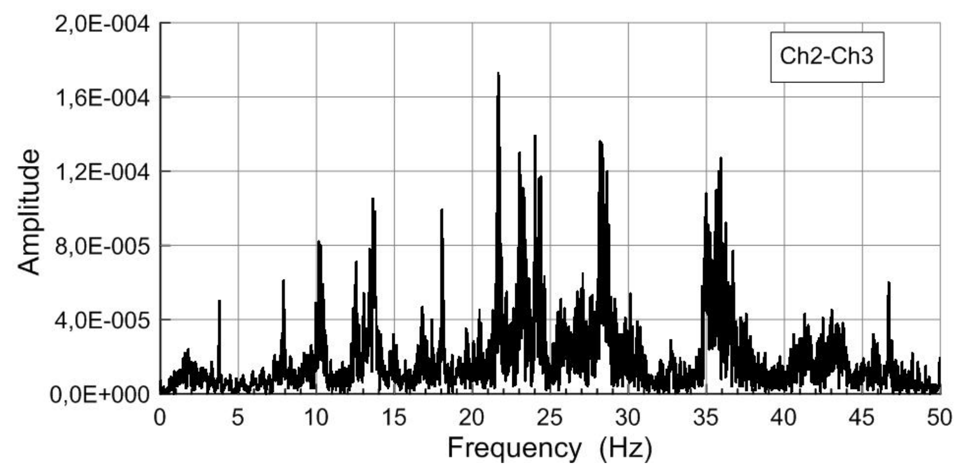
Channel Ch	Instrument Position	Instrument Number	Lowpass Filter (Hz)	Gain (dB)
Ch1	Ground	232	30	48
Ch2	Slab-Balustrade-South side	292	30	54
Ch3	Slab-Balustrade-North side	235	30	54

Measurement 1: Instrumentation Setup





Measurement 1- transfer functions: a): Ch1-Ch2, b): Ch1-Ch3.



Measurement 1- Fourier spectrum of Ch2-Ch3 subtraction.

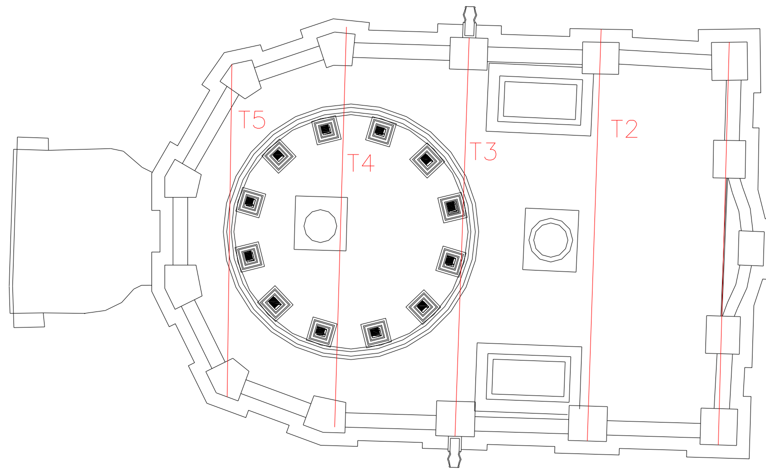
Result	Direction	Frequency (Hz)
Ch1-Ch2 (transfer function)	W-E	5.37, 7.81, 12.69, 16.11, 18.07
Ch1-Ch3 (transfer function)		5.37, 7.81, 12.69, 16.11, 21.48
Ch2-Ch3 (Fourier spectrum)		3.78, 7.9, 10.16, 12.56, 13.62

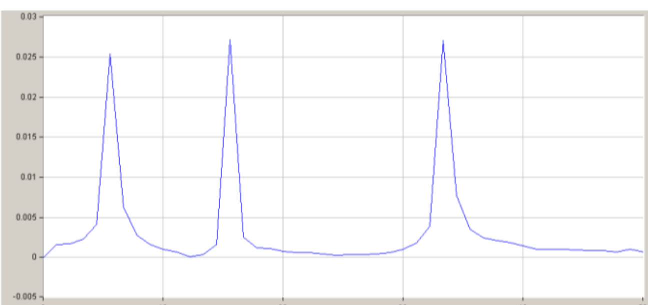
After the elaboration of the measurement results, the following conclusions can be drawn:

1. *The natural frequency along the E-W direction is 12.96 Hz. This mode is both translatory and rotational.*
2. *The natural frequency along the N-S direction is 10.25 Hz. This mode is both translatory and rotational.*
3. ***The values of the frequencies indicate that the structure is stiff, resulting in the development of small displacements during an earthquake. Therefore the drifts will too be small, so the cracks will not appear during an earthquake**. This also applies to the marble cladding, when it is attached to the load-bearing system of the Edicule. In case of total or partial detachment of the marble cladding from the load-bearing system, overturning of the marbles is possible.*
4. ***The structure behaves as a whole.***
5. ***In cases where a numerical model will be implemented for the evaluation of the seismic behaviour, the use of half values of the moduli of elasticity is recommended after the convergence of the analytical eigenvalues with the measured ones**.*

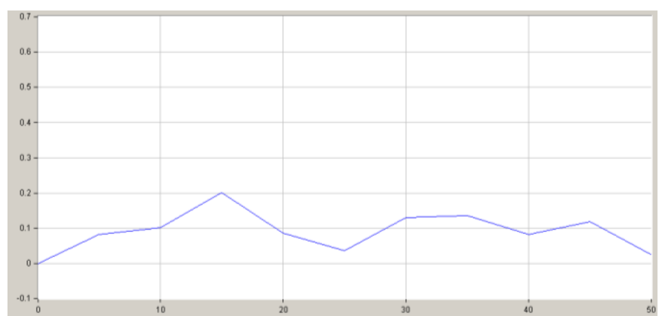
In order to determine the internal tension forces of the ties of the steel structure of the Holy Aedicule, five measurements were conducted.

Each tie was excited impulsively and its response was recorded. From each measurement the Fourier spectrum of the response was calculated, through which the natural frequency was identified.





Tie 1- Fourier response spectrum



Tie 2- Fourier response spectrum

Tie	Natural Frequency, f (Hz)
T1	5.55
T2	15
T3	10
T4	10
T5	6

Ties T1, T3, T4 and T5 are loose and only T2 is stressed

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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)

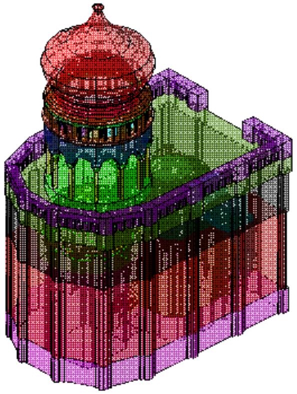
Scientific Team:
Dipl. Civil Engineer, MSc, PhD Ch. A. Maniatakis

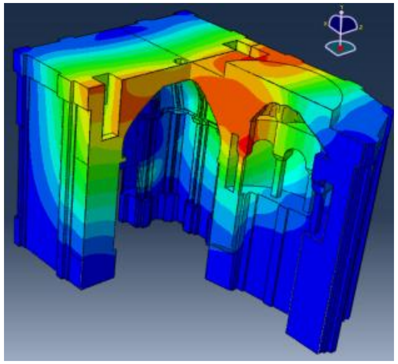
Research Aims

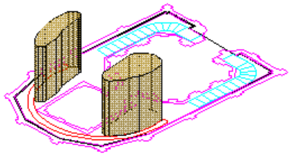
This presentation includes:

- Current condition **assessment under static and seismic loading**
- **Proposal** for **interventions**

regarding the Holy Edicule of the Holy Sepulchre in the Church of the Resurrection in Jerusalem applying the Finite Element Method (ABAQUS).



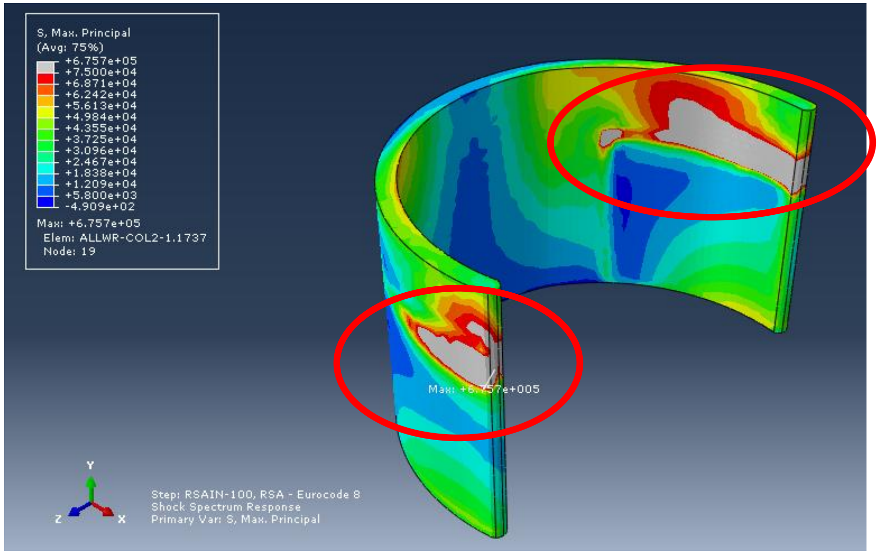




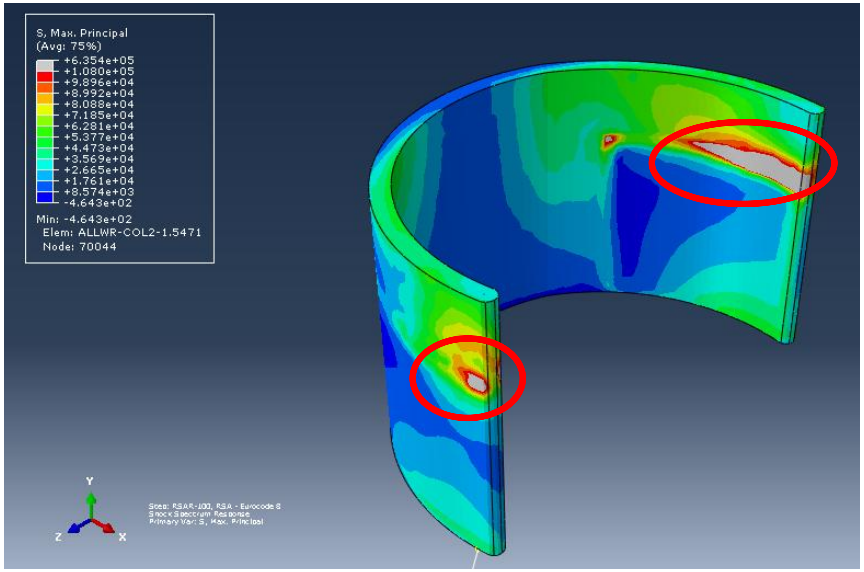
Main Bearing Structure

Masonry of the Crusaders' structural phase

Seismic Loading



Current state

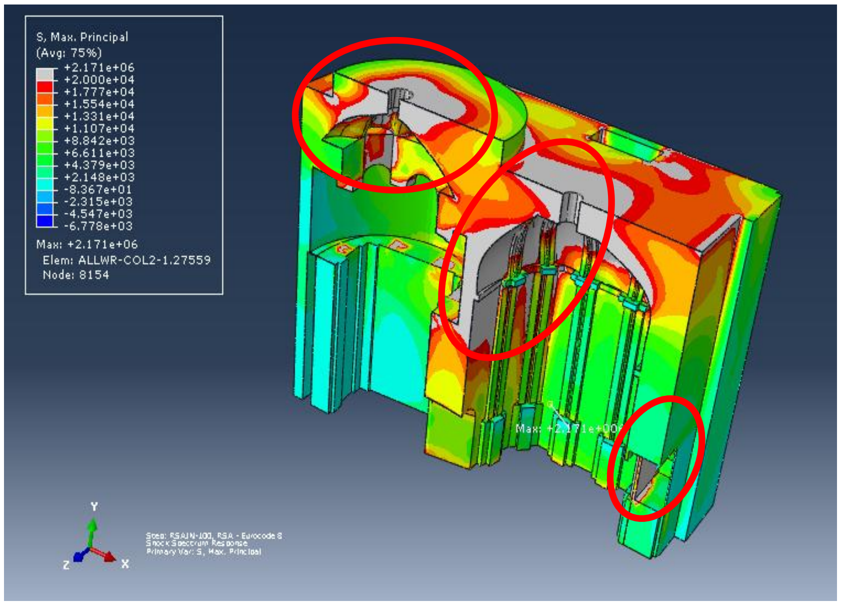


Strengthened

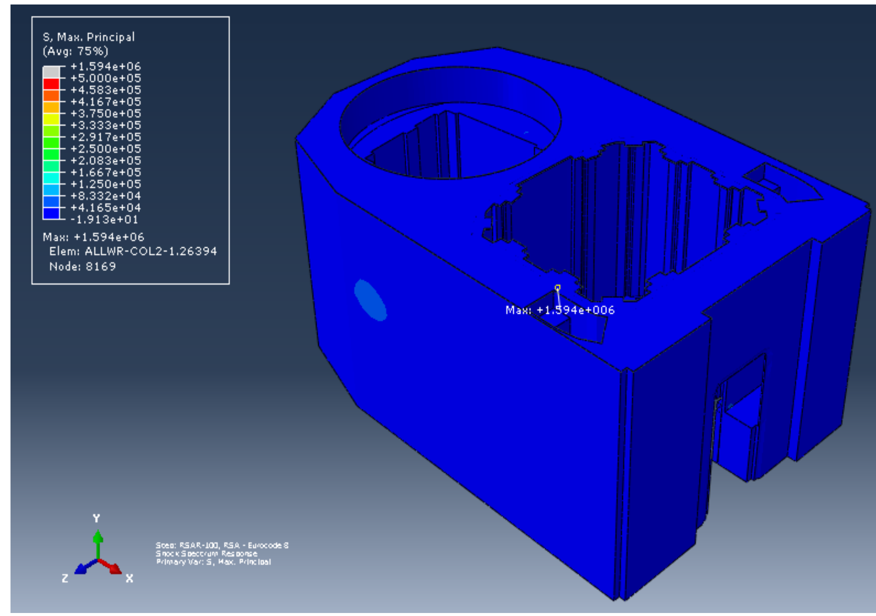
Maximum principal stresses

Strain stress beyond limits (**in red circle**)

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



Current state



Strengthened

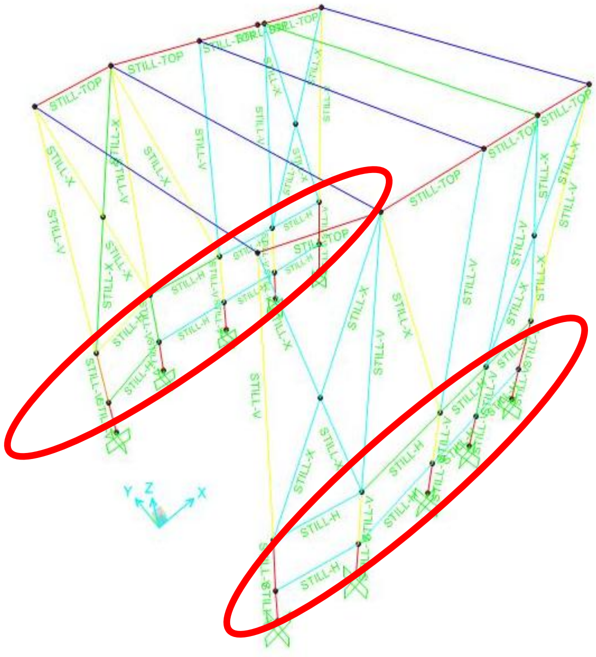
Maximum principal stresses
Strain stress beyond limits (**in red circle**)

External Metal Structure
Finite Element Model
Seismic Loading

Beam Elements.

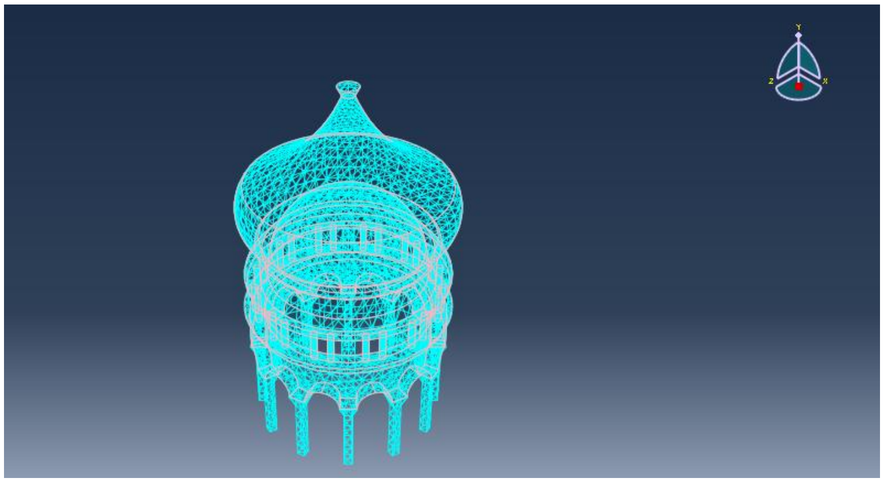
The inertial loads corresponding to the masses of marble panels are transferred at the wedging positions.

The wedging and the tendon forces are applied.

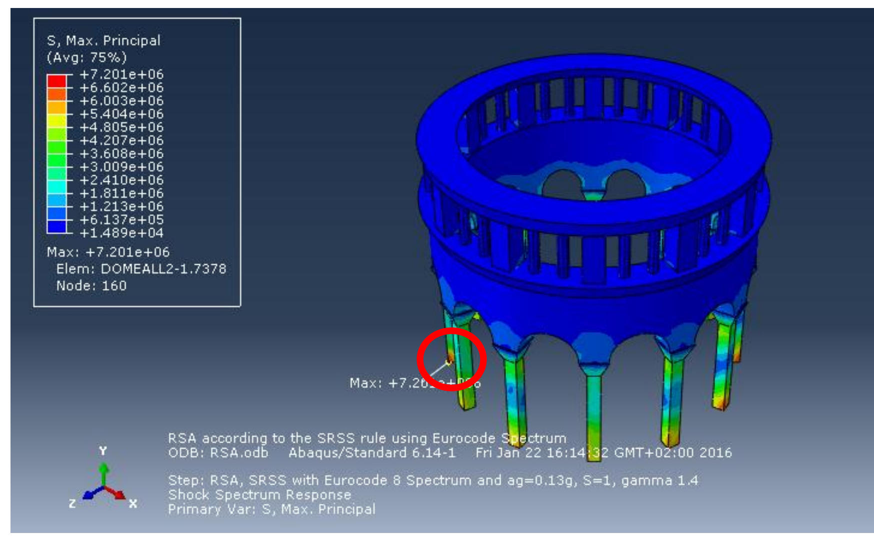


Failure of members (in red cycle)

Outer Dome
Finite Element Model
Seismic Loading



The model consists of 37395 solid tetrahedral elements



Exceedance of tensile strength at column base (**in red cycle**)

CONCLUSIONS
Failures prior interventions

(i) Under tension at the **base of the columns** of the outer **dome**.

(ii) Under tension at: (a) the **masonry** of the **Crusaders**' phase; (b) the **internal stairwells** at the **Angel's Chapel**; (c) the **base of internal bearing columns** at the **Burial Chamber**; (d) the **wall that separates the two chambers** of Holy Edicule; and (e) the **internal vaults**.

(iii) Under combined axial force and bi-directional bending **of the columns** of the **metal supporting structure**.

(iv) Formation of **mechanism** for the **marble panels**.

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PROPOSAL

1. **Conservation reinforcement and rehabilitation materials and interventions**
2. **Design of reinforcement and rehabilitation interventions**
3. **Organization management of construction site**

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School of Chemical Engineering
Laboratory of Material Science and Engineering

Conservation reinforcement and rehabilitation materials and interventions
(Scientific Coordinator: Prof. A. Moropoulou)

Scientific Team:
Assistant Prof. Asterios Mpakolas,
Dr. Ekaterini Delegou, Dr. Petros Moundoulas†,
PhD Cand. Emmanouil Alexakis,

Research Aims

- Restoration mortars
- Grouts
- Titanium bolts, anchors and lamella
- Planning & Application of Cleaning Interventions on the Facings of the Holy Sepulchre Architectural Surfaces

METHODOLOGY OF DESIGN OF COMPATIBLE RESTORATION MORTARS [REVERSE ENGINEERING]: (A. MOROPOULOU)

1. *Characterization and evaluation of historic mortars – selection of raw materials – Restoration mortar synthesis directives*
2. *Preparation of restoration mortars. Maintenance in controlled environment during setting and hardening*
3. *Evaluation of restoration mortars properties*
4. *Optimization – Standardization based on characteristics*
5. *Pilot application for the evaluation of restoration mortars on masonry scale*

2. PREPERATION OF RESTORATION MORTARS

SELECTION OF RAW MATERIALS

The raw materials used in the mortar mixes must fulfill specific criteria. The criteria derive from the examination of historic mortars (lab experience) as well as information obtained from literature

Binders

lime,

Natural hydraulic lime

Additives

Conferring hydraulicity to the binder: metakaolin (artificial pozzolan)

Aggregates

silicate sand and crushed brick

SELECTION CRITERIA

BINDERS:

Lime:

α) Low baking temperature of the original limestone (~900 ^{0}C)

β) Appropriate slaking process of the quick lime for the production of lime powder

γ) Purity of the original limestone in calcium carbonate (>95%) ENV459/1

Natural Hydraulic Lime:

α) Low baking temperature (~ 950 ^{0}C)

β) Free $Ca(OH)_2$ < 8%

ADDITIVES CONFERRING HYDRAULICITY TO THE BINDER

Metakaolin (Artificial Pozzolan):

1. High specific surface area
2. High fineness <63 μm
3. Pozzolanic properties (compressive strength value >5 MPa in the pozzolanicity test and percentage of active silica >20%)
4. Baking temperature of the original ceramic, as well the ceramics raw materials <900 ^{0}C

AGGREGATES

Sand:

1. High purity
2. Absence of soluble salts and extraneous compounds (<1%)
3. Desirable gradation, based on acceptability limits
4. Natural origin

Crushed brick:

1. Absence of extraneous compounds (bio-products, salts <1%), as well as the requirements placed for the artificial pozzolan

RESTORATION MORTARS & CONCRETES MIX SYNTHESIS

Mortars

a) Lime (27.5%) - Metakaolin (2,5%) – Sand (70%) LM1

b) Lime (25%) - Metakaolin (5%) – Sand (70%) LM5

c) Natural Hydraulic Lime (25%) – Sand (75%) NHL

Concretes

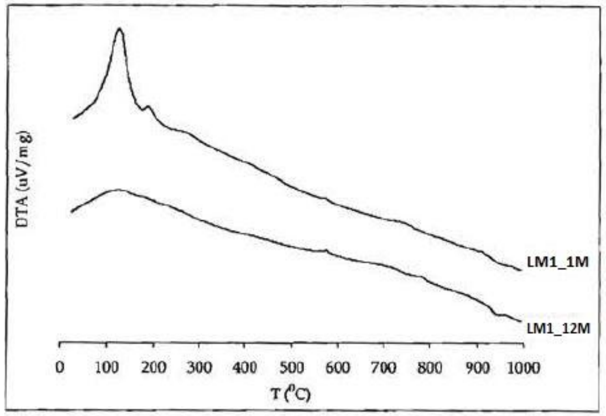
a) Lime (27.5%) – Metakaolin (2.5%) - Sand (35%) – Crushed Brick (35%)

b) Lime (20%) – Metakaolin (10%) - Sand (35%) – Crushed Brick (35%)

c) Natural Hydraulic Lime (30%) – Crushed Brick (35%)- Sand (35%)

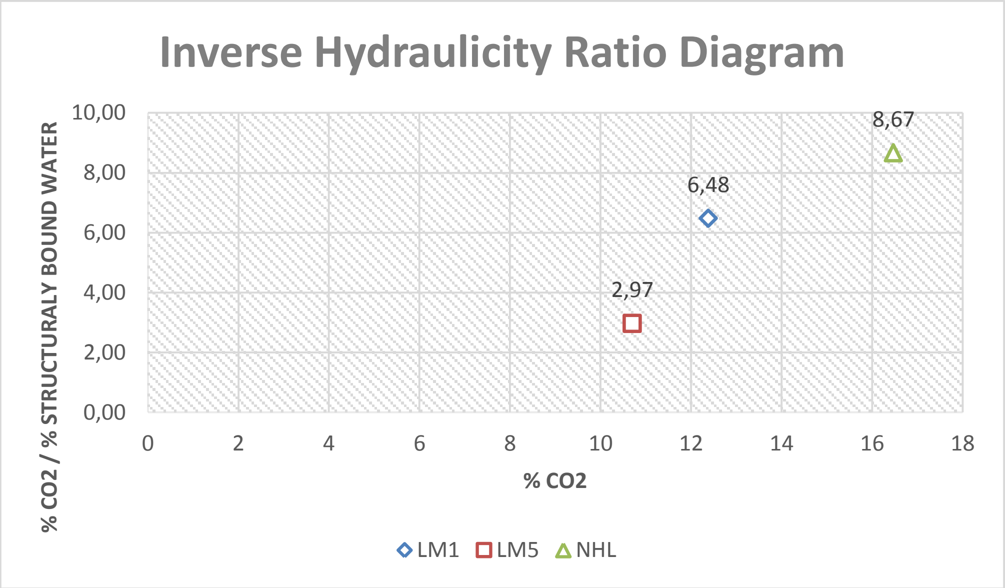
3. EVALUATION OF RESTORATION MORTAR CHARACTERISTICS DURING SETTING AND HARDENING

ACCEPTABILITY CRITERIA 1. Differential Thermal Analysis – Θερμοβαρυμετρία (DTA-TG), carbonation / development of hydraulic phases



Evolution of chemical reactions through the use of thermal analysis on restoration mortar LM1 at one month (LM1_1M) and twelve month of curing (LM1_12M) Complete carbonation

Inverse Hydraulicity Ratio Diagram
For pozzolanic restoration mortars



Hydraulic Lime Mortar

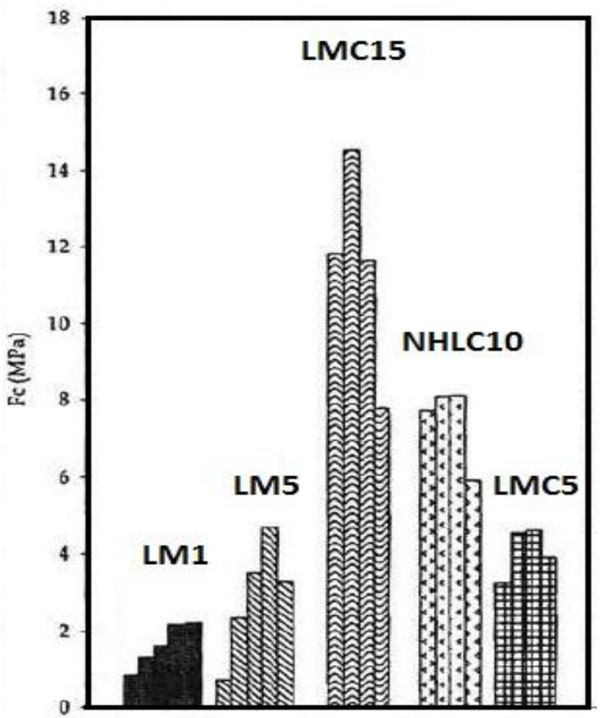
Chemically bound water after 15 days of hardening. Presence of hydraulic phases

Pozzolanic mortars and concretes (Metakaolin)

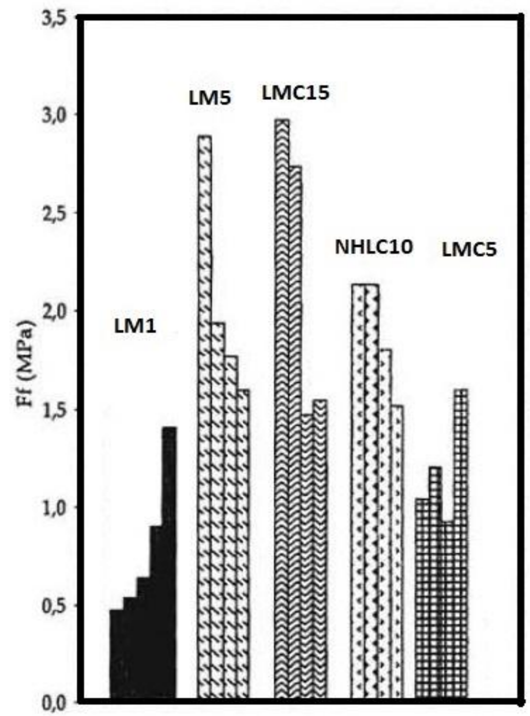
High carbonation rate. High percentages of chemically bound water already after one month of curing. Metakaolin assist in the development of hydraulic phsaes (chemically bound water)

3. EVALUATION OF RESTORATION MORTAR CHARACTERISTICS DURING SETTING AND HARDENING

ACCEPTABILITY CRITERIA 2. Mechanical strength properties, for the evaluation of serveacibily



Development of compressive strength (left) and flexural strength (right) for the examined mortars and concretes (large range of compressive strength values between 2 – 15 MPa – an asset in the decision making process



Hydraulic Lime Concrete

Quick development of mechanical strenght (compressive and flexural) from the first month of curing

Tensile to compressive strength values ratio within limits

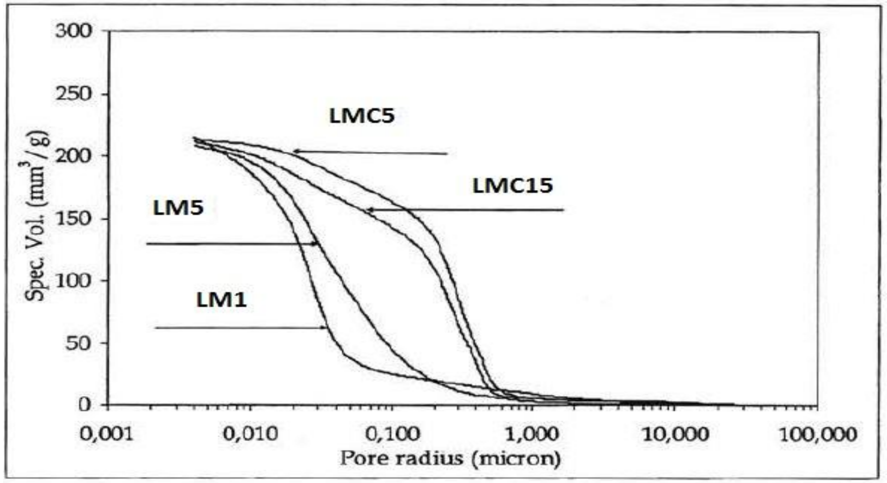
Mortars and concretes with pozzolanic additions

Satisfactory development of mechanical strength, which can achieve values up to 15 MPa in accordance to the percentage of added metakaolin

Tensile to compressive strength values ratio within limits

3. EVALUATION OF RESTORATION MORTAR CHARACTERISTICS DURING SETTING AND HARDENING

ACCEPTABILITY CRITERIA 3. Examination of miscrostructure through the use of mercury intrusion porosimetry, for the assessment of compatibility



Microstructure characteristics (total cumulative volume in relation to average pore radius) for different categories of mortars and concretes

LIME-POZZOLAN MORTARS

	Cumulative Volume (mm^3/g)	Apparent density (g/cm^3)	Total Porosity (%)	Specific Surface Area (m^2/g)	Average pore radius (µm)
LM1	198.8	1.73	34.3	4.15	0.32
LM5	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

The examined restoration mortars fulfill the established acceptability criteria. Even the hydraulic lime mortar is within the ranges established for lime-pozzolan restoration mortars.

The examined concretes were utilized in the construction of traditional structured pilot masonries and were tested on the vibration table in order to assess their behavior in earthquake stresses. The masonry was subjected to uniaxial compressive stress in the X axis in a range of maximum acceleration values of the seismic simulator 0.08 – 0.85 G, which is equivalent of a 7 Richter magnitude earthquake and exhibited excellent behavior

PhD Th. E. Aggelakopoulou, Supervisor Prof. A. Moropoulou
Lab for Earthquake Engineering, Prof. P. Karydis, Ass. Prof. Ch. Mouzakis

RESTORATION MORTAR PROPOSAL

Lime-pozzolan mortar (High reactivity metakaolin),
With river quartz origin aggregates of 2 mm maximum gradation and inorganic mineral fibers.

Guarantees compressive strength >15 MPa
is 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).

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).

Titanium is one of the materials that are used mainly in the restoration of restoration works*, mainly because of its high resistance to all types of corrosion. Also commercially pure titanium (Grade 2 ASTM B265 and B348) used in restoration works is compatible material with marble in terms of physical and mechanical properties.*

Titanium presents an excellent behavior to corrosion; its specific weight is half the specific weight of steel; the same applies for its elasticity; furthermore it presents adequate tensile strength values and a very high fracture elongation. ***The low thermal expansion coefficient that titanium presents is closer to marble than any other metal****, such as brass, stainless steel, whereas it presents adequate plasticity*

Connecting broken stone blocks with titanium bolts and anchors and compatible mortars, is a solution adopted frequently in restoration works and aims to restore the monolithic character and behavior of the broken architectural elements

- ***In stones that have failed generally due to exceeding their tensile strength, the reinforcing bolts that are positioned in a direction perpendicular to the fracture surface, are intended to receive tensile loads.***

- ***ενώ το βασικό κριτήριο αστοχίας του οπλισμού και όχι των μαρμάρινων στοιχείων εξακολουθεί να ισχύει. In cases where the titanium bars are expected to be exposed to shear loads, as in connectors where the interface is parallel to the direction of the seismic load, the bars will act as bolts, whereas the main criterion of the failure of reinforcement and not of the marble elements remains valid.***

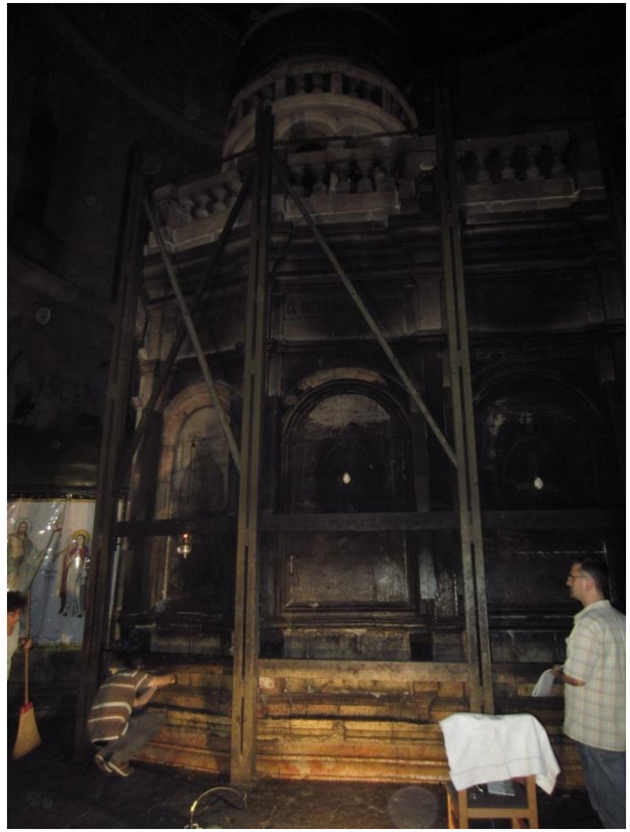
Titanium rods ASTM B348 GRADE 2 in diameter 2mm – 35mm, suitable for restoration and reconstruction works in monuments, sculptures, etc.

Properties of Titanium ASTM B348 Grade 2:
Density (gr/dm^3) : 4510
Modulus of Elasticity (MPa): 105000
Tensile Strength (MPa) : 420
Yield Strength(MPa): 300
Thermal Expansion Coefficient: $9\times10^{-6}/^{o}C$

Planning & Application of Cleaning Interventions on the Facings of the Holy Sepulchre Architectural Surfaces

The architectural surfaces of the Holy Selpuchre façades are consisted of the following four different stone types:

- *the off-beige, compact micrite fossiliferous limestone which presents high mechanical strength and rough surface texture,*
- *the slightly reddish porous microcrystalline – microsparitic dolomite, of smooth and shiny surface texture which can be classified as "slayeb" stone type,*
- *the black compact biomicritic fossiliferous limestone, and*
- *the marble of Prokonisos (Marmara Adasi) from Constantinople.*

The main decay patterns presenting in all the above mentioned architectural surfaces are **<u>oily depositions</u>** and extended **<u>black depositions</u>** which are primarily consisted of soot particles. Candles' burning close to or even in contact to the architectural surfaces is the major factor for the presence of these decay patterns.
<u>However, the sulphation of stones surface cannot be excluded</u>.

Black depositions and oily depositions should be removed by the application of **compatible cleaning interventions.**
Cleaning is a mandatory conservation intervention for both aesthetic and physic-chemical reasons.

The removal of black depositions and oily depositions will **further reveal and preserve the artistic value of the Holy Selpuchre**, upgrading Its aesthetics.

Black and oily depositions not only alter the visual appearance of the stonework due to the discoloration development, but also lead to further decay.

The accumulation of black depositions on stone facings acts as catalyst for degradation processes, accelerating further decay.

Therefore, the employment of **cleaning** becomes essential not only for the present conservation of deteriorated areas, but also for **preventing further erosion phenomena**.

The term "black depositions" describes shortly the suspended atmospheric particles that are adsorbed or/and deposited on architectural surfaces and are mainly consisted of soot, dust fall (particles of aluminum-silicate composition), saturated and unsaturated hydrocarbons, as well as metal oxides or/and metals like Fe, Pb, Zn, Ni, Vn, etc.

The following cleaning methods are selected for the conservation of the architectural surfaces of the Holy Selpuchre, based on the stone facings' preservation state (building material and decay), the international common practice, as well as the former experience of NTUA:

- application **of AB57 poultice with triethanolamine and ammonia**,
- application of **poultice of ion exchange resin and/or sepiolite with water solution of ammonium bicarbonate**,
- application of a **soap-water emulsion** and then spraying **oxalic acid solution** of low concentration. The application of the **oxalic acid solution protects** the architectural surfaces from further decay, because of **its hydrophobic action**.
- application of a **wet micro-blasting method**, where spherical particles of $CaCO_3$ (diameter <80μm), are springing with a maximum function pressure of 0.5bar The proportion of water to spherical particles of $CaCO_3$ in the device's commixture barrel should be 3:1.

The exact technical characteristics of the finally applied cleaning treatment(s) like application time, solution concentrations, etc, or possible combination of them, will be clarified after the in situ pilot application and performance assessment of the above mentioned cleaning interventions.

Many parts of the stone facings will be treated in the conservation lab that is setting up inside the Holy Church of Resurrection, for the better management and organization of the worksite. The rest of the stone facings will be treated on site since scaffolding is to be risen.

Furthermore, mortar residues on the internal side of the stone facings will be cleaned by soft brushes and/or a dry micro-blasting method of low pressure.

NATIONAL TECHNICAL UNIVERSITY OF ATHENS

Interdisciplinary Research Team for the Protection of Monuments

Scientific Coordinator:
Prof. A. Moropoulou

Interdisciplinary Research Group NTUA**:**
Prof. Em. Korres, Prof. A. Georgopoulos, Prof. A. Moropoulou, Prof. C. Spyrakos

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)

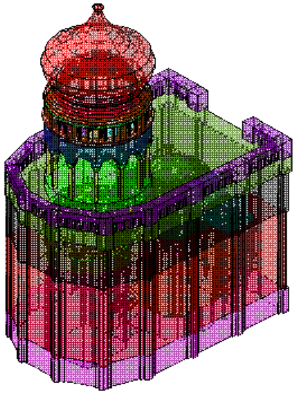
Scientific Team:
Dipl. Civil Engineer, MSc, PhD Ch. A. Maniatakis

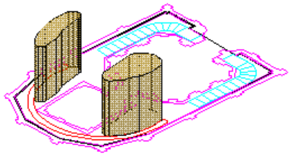
Research Aims

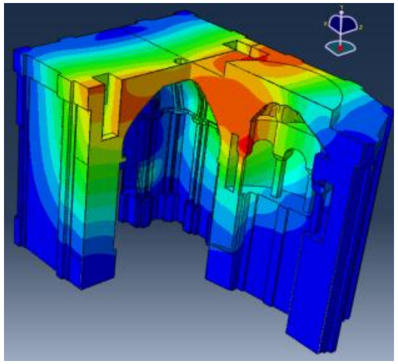
This presentation includes:

- Current condition **assessment under static and seismic loading**
- **Proposal** for **interventions**

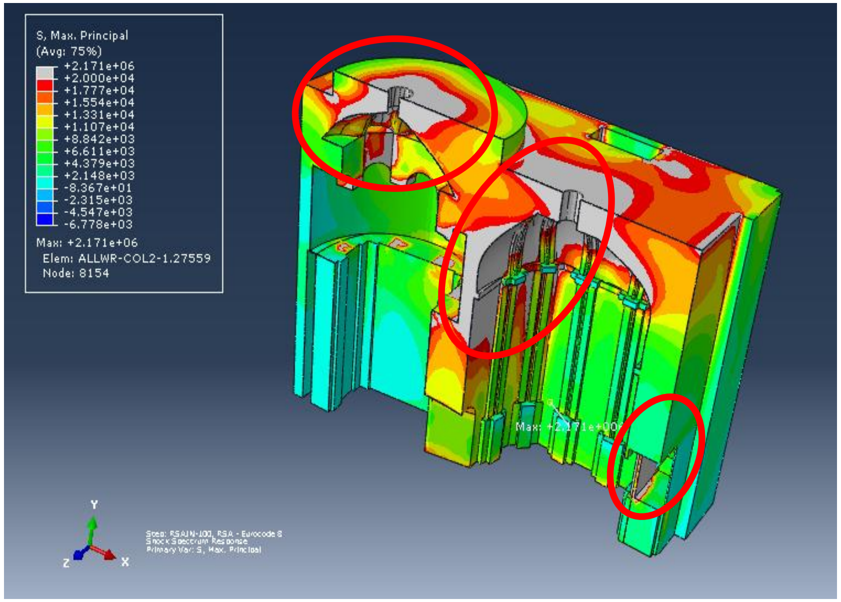
regarding the Holy Edicule of the Holy Sepulchre in the Church of the Resurrection in Jerusalem applying the Finite Element Method (ABAQUS).



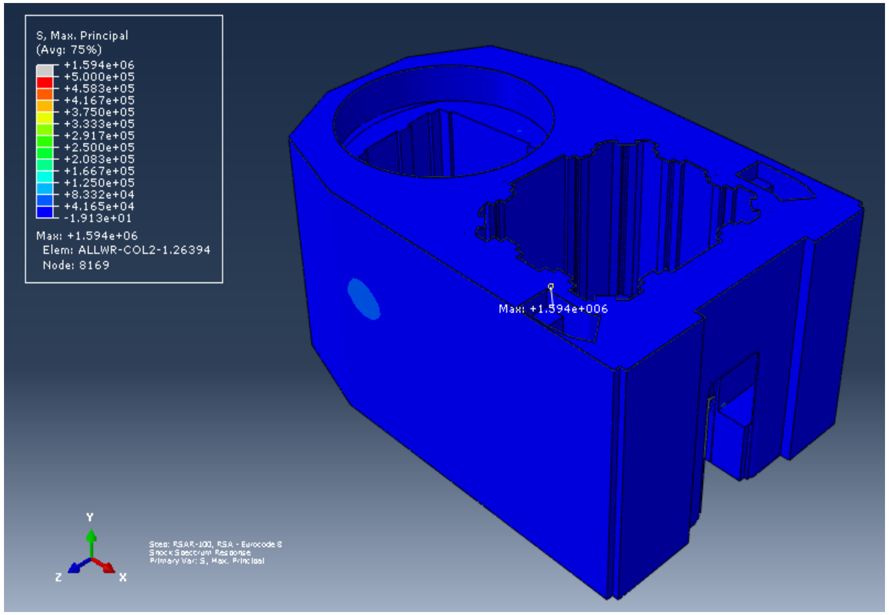




Main Bearing Structure
Mortar of the Crusaders' structural phase
Seismic Loading



Current state



Strengthened

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

CONCLUSIONS
Intervention Scheme

1. **Removal** of the **metal supporting structure.**
2. **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**.

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School of Architecture
Department of Architectural Design

Design of reinforcement and rehabilitation interventions

(Scientific Responsible: Prof. Em. Korres)

C. Interventions

C1. Metal cage
C2. Effectiveness of existing measures
C3. Necessity of a new intervention
C4. Step by step execution
C5. The step by step execution is conceivable as follows (see next slide):
C6. Extent of intervention on the external masonry
C7. Loads to be moved and the scaffold’s bearing capacity
C8. Functionality of the scaffold
C9. Intervention on the external masonry combining scaffold and fork-lift operation.
C10. Least sufficient number of scaffolds (platforms)
C11. Intervention on the dado blocks with combined use of the forklift and a metal bench
C12. Auxiliary devices for the intervention on the façade
C13. Work in the highest zone of the external masonry
C14. Scaffold for lighter work in the highest zone
C15. Electrical power supply and compressed air at the points of the operation
C16. Dust-abduction
C17. Electrical power supply and compressed air in the laboratory
C18. Dust-abduction from the laboratory and workshop
C19. Maintenance of stones in the laboratory and workshop
C20. Laboratory / workshop
C21. Diagram of the work’s progress
Annex I. Approach of a possible intervention to the interior

C5. The step by step execution is conceivable as follows:

The step by step execution is conceivable as follows:

(α) removal of marble slabs standing within the first three from East bays of the south side, from the top downwards, together with the mortar behind them.

(β) removal of the lower stone of each arched frame and of plasters behind.

(γ) removal of non-bearing stones of the string course

(δ) removal of the respective orthostates –between the postaments- (first three from East etc)

(ε) removal of the mortar behind the above, using special hooks and electric implements.

These tools will intrude in the narrow space behind the postament and string course stones remaining in place without difficulty, because with the removal of the above (c) and (d), working space would be quite sufficient.

(ζ) with screw jacks acting horizontally pushing in the corresponding string course stones until they are fully restored in correct position.

(η) Stabilization of each stone restored in position, with stainless steel hooks anchored in holes of the marbles proper and the internal masonry.

(θ) after thorough cleaning, resetting the marble slabs in the second arched frame.

(ι) removal of marbles of the arched frames 4th and 5th , and performing tasks as above (α) to (θ)

κ) repetition of the same work along the north side.

in left port arched framework implementation of the above operations a to h. M) at first by a arc of south side repeating the above work i. n) at right of port arched framework duplication of work a to h. (o) at first by a quadrant of the north side repeating the above work i.

(λ) in the arched frame of the façade to the left of the entrance implementation of the above operations (a) to (θ).

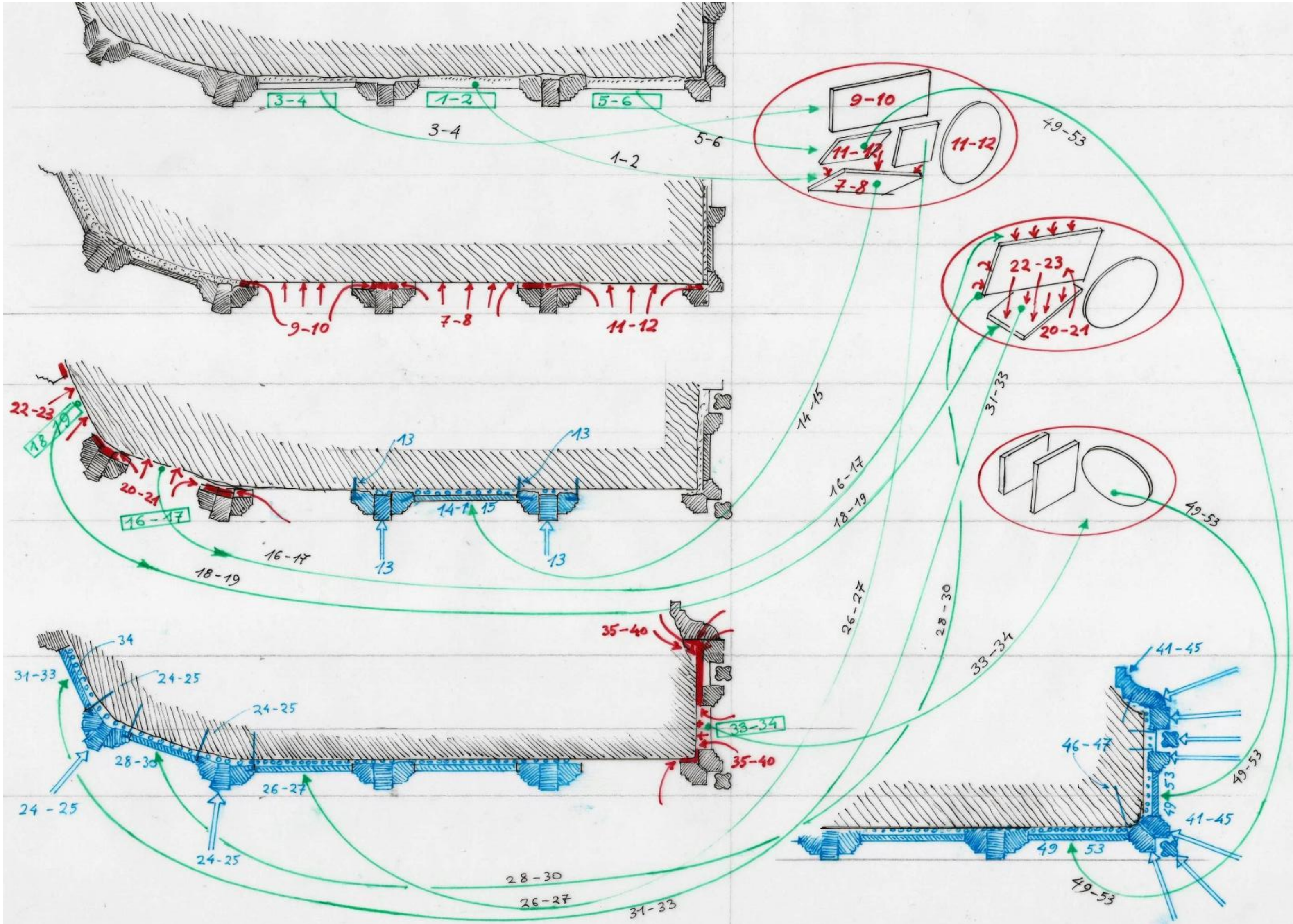
(μ) in the first from East arched frame of the south side repeating the above work (θ)

(ν) in the arched frame of the façade to the right of the entrance implementation of the above operations (a) to (θ).

ξ) in the first from East arched frame of the North side repeating the above work (θ)

ο) on both sides of the door cleaning of the joints of the postaments and columns, removing all solid impeding particles from the joints and correcting the position of the stones.

(π) dismantling and removal of the elements of the metal cage.

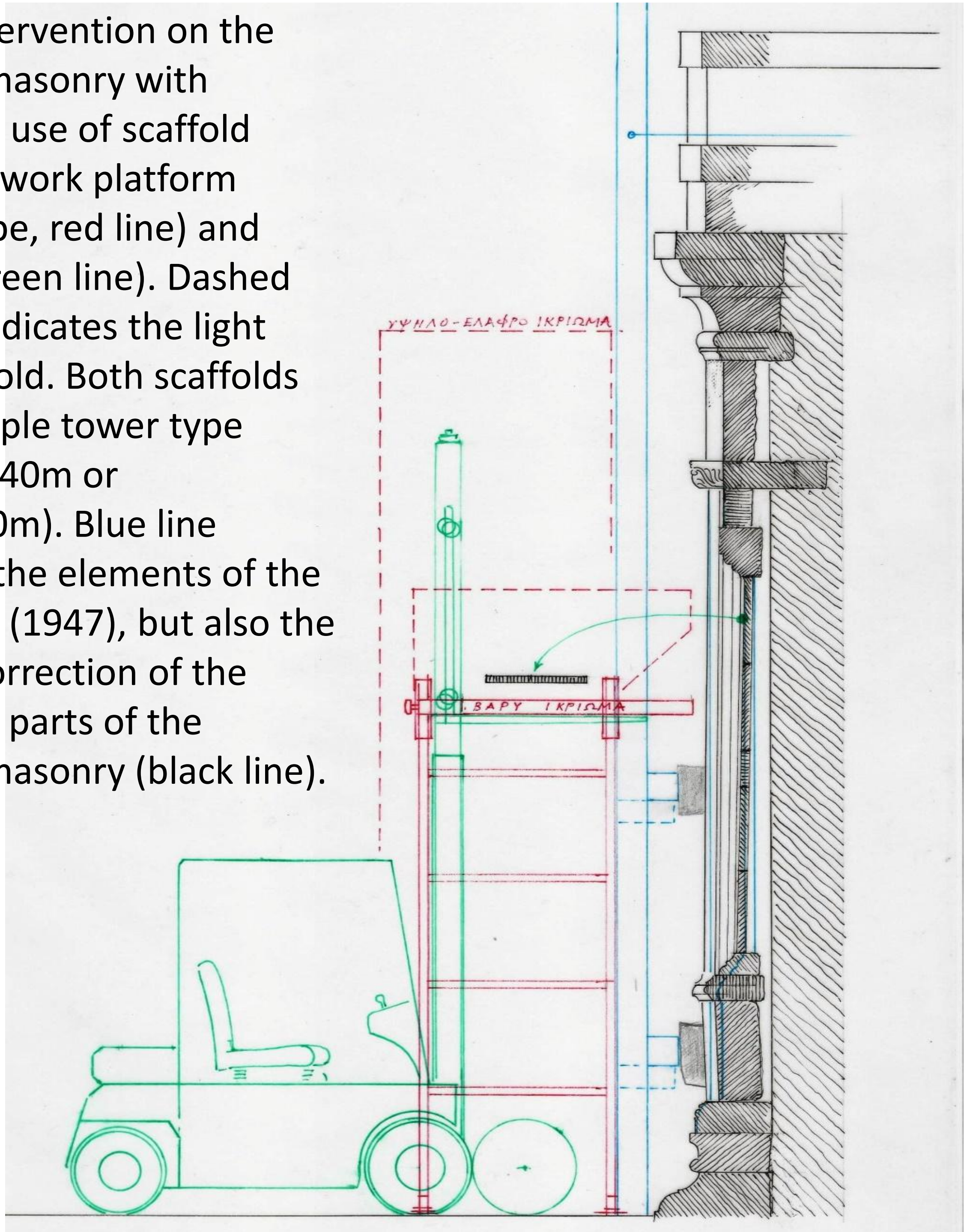


C21. Diagram of the work's progress
(The time required is indicative)

C9. Scenario A.
Intervention on the external masonry combining scaffold and fork-lift operation.

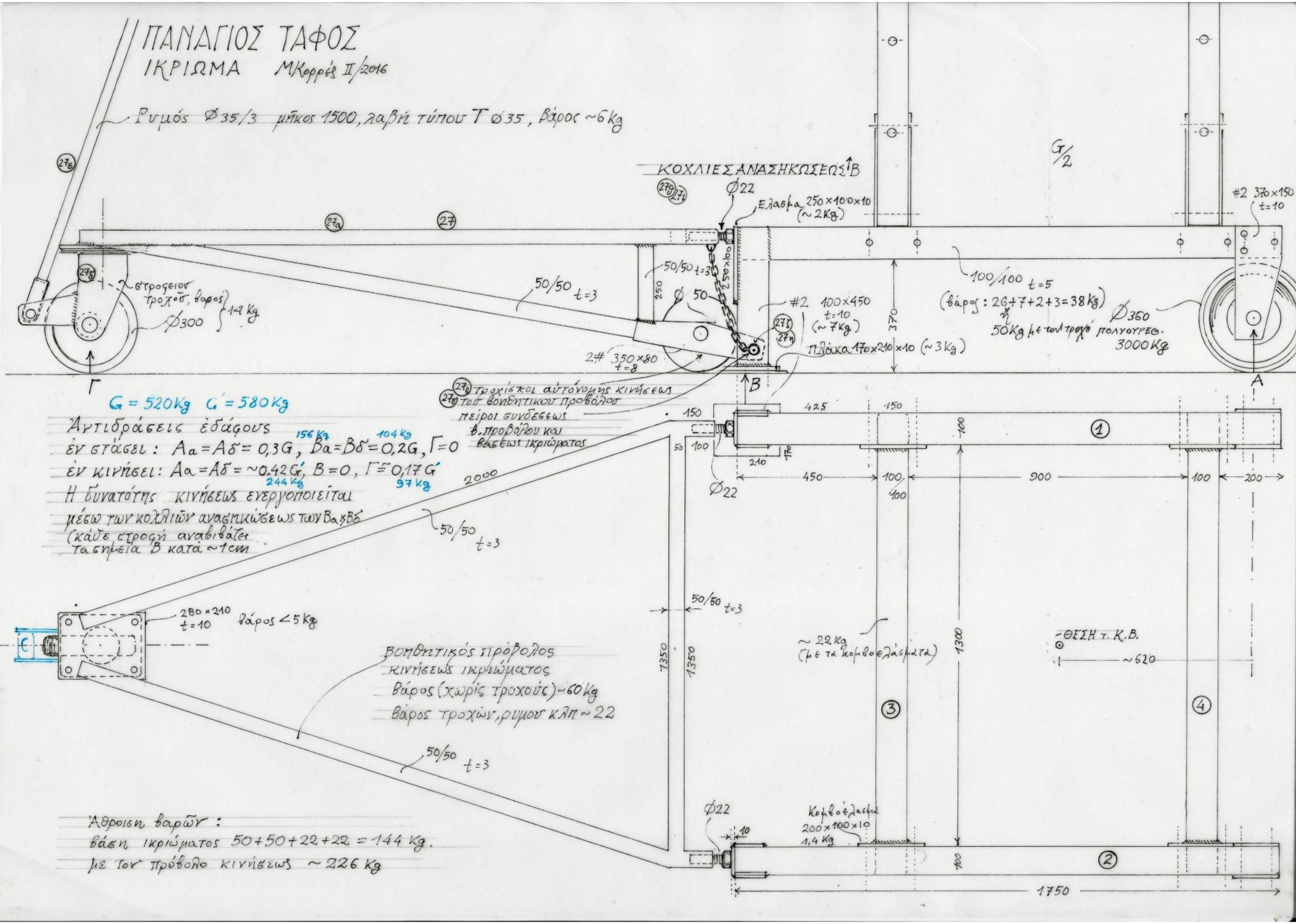
1) Cleaning free the surrounding joints from obstacles (see previous),
2)*if necessary preparation of small notches for extraction hooks (see previous),
3)*highly accurate pulling out until the slab is completely free
4) precise transfer of the slab in the middle of the platform and positioning on two wooden blocks (ca 10/10cm in section), which would leave free space on both sides, or between them, if the slab is longer than 90 cm
5)retract the outriggers
6)driving the forklift some 80 cm backwards
7)lowering and leave the platform standing to the ground,
8)further backward moving of the forklift to exit the forks from the relevant slots in the platform,
9)raise the forks in the level of the floor of the platform
10)moving the forklift forward until the forks pass sufficiently under the slab
11) lifting up the slab, and after the predicted path disposed of in the laboratory on job bank or in storage position.
12) return of the forklift, taking up the scaffold and placing it at the next position of operation, new adjustment of theoutriggers sufficient to allow the departure of the forklift to serve other work until again called for the resumption of the routine as above (No. 5 to 11)

dr. C9. Intervention on the external masonry with combined use of scaffold bearing a work platform (heavy type, red line) and forklift (green line). Dashed red line indicates the light high scaffold. Both scaffolds are of simple tower type (~1.80 x1.40m or .~200x150m). Blue line indicates the elements of the steel cage (1947), but also the desired correction of the deformed parts of the external masonry (black line).

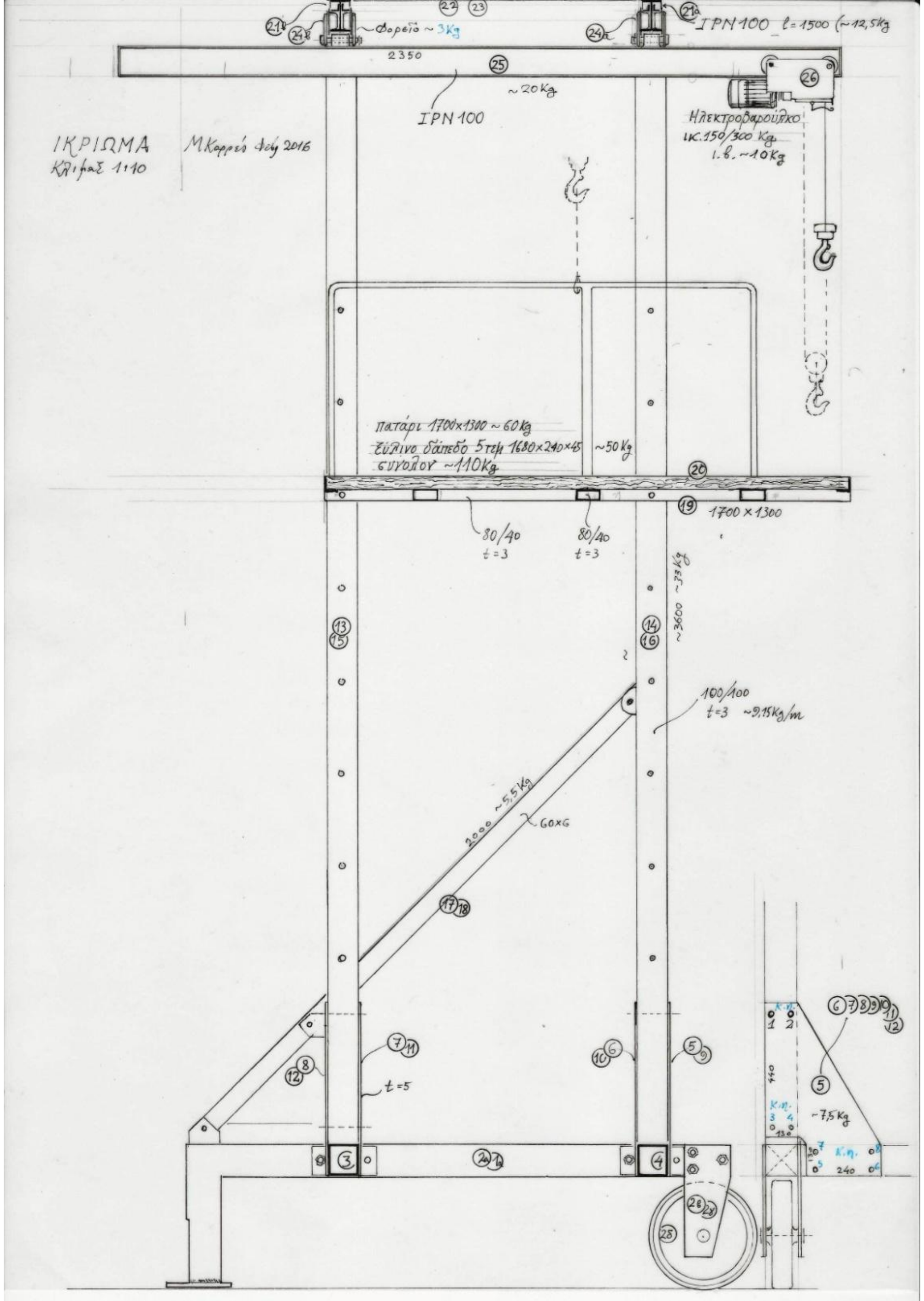


C9. Scenario B.
Intervention on the external masonry by using a height-adjastable platform on mobile scaffold.

1) Cleaning free the surrounding joints from obstacles (see previous),
2)*if necessary preparation of small notches for extraction hooks (see previous), 3)*highly accurate pulling out until the slab is completely free
4) precise transfer of the slab in the middle of the platform and positioning on two wooden blocks (ca 10/10cm in section), which would leave free space on both sides, or between them, if the slab is longer than 90 cm
5) Using the lifting system of the scaffold the slab is slightly lifted and subsequently displaced outside until the winch slides along the path and reaches its end.
6) Lowering the slab and laying it on the cart, that is stationed below the winch
7) after the predicted path disposed of in the laboratory on job bank or in storage position.



ΠΑΝΑΓΙΟΣ ΤΑΦΟΣ
ΙΚΡΙΩΜΑ ΜΚορρές ΙΙ/2016
Ρυμός Ø35/3 μήκος 1500, λαβή τύπου T Ø35, βάρος ~6 Kg
ΚΟΧΛΙΕΣ ΑΝΑΣΗΚΩΣΕΩΣ B
Ø22
Έλασμα 250×100×10 (~2Kg)
#2 370×150 t=10
G/2
50/50 t=3
250
Ø 50
250×100
#2 100×450 t=10 (~7Kg)
370
100/100 t=5
(βάρος: 26+7+2+3=38 Kg) ή 50Kg με τον τροχό πολυουρεθ.
Ø360
3000 Kg
στροφείον τροχού, βάρος 14 Kg
Ø300
2# 350×80 t=8
Πλάκα 170×210×10 (~3Kg)
Γ
B
A
Τροχίσκοι αυτόνομης κινήσεως του βοηθητικού προβόλου
πείροι συνδέσεως β. προβόλου και βάσεως ικριώματος
G = 520Kg G′ = 580Kg
Αντιδράσεις εδάφους
εν στάσει: Aα=Aδ= 0,3G, Bα=Bδ=0,2G, Γ=0
156 Kg
104 Kg
εν κινήσει: Aα=Aδ= ~0,42G′, B=0, Γ= 0,17G′
244 Kg
97 Kg
Η δυνατότης κινήσεως ενεργοποιείται μέσω των κοχλιών ανασηκώσεως των Bα και Bδ (κάθε στροφή αναβιβάζει τα σημεία B κατά ~1cm)
150
425
150
100
1
50
100
170
210
Ø22
450
100
900
100
200
2000
50/50 t=3
280×210 t=10 βάρος < 5 Kg
C
50/50 t=3
1350
1350
~22 Kg (με τα κομβοελάσματα)
1300
ΘΕΣΗ τ. Κ.Β.
~620
βοηθητικός πρόβολος κινήσεως ικριώματος
βάρος (χωρίς τροχούς) ~60 Kg
βάρος τροχών, ρυμού κλπ ~22
3
4
50/50 t=3
Άθροιση βαρών:
βάση ικριώματος 50+50+22+22 = 144 Kg.
με τον πρόβολο κινήσεως ~226 Kg
Ø22
10
Κομβοέλασμα 200×100×10 1,4 Kg
100
2
1750


ΙΚΡΙΩΜΑ
Κλίμαξ 1:10
Μ.Κορρές Φεβ 2016
~Φορείο ~3Kg
IPN100 ℓ=1500 (~12,5Kg
2350
~20Kg
IPN 100
Ηλεκτροβαρούλκο
ικ.150/300 Kg
ι.β. ~10Kg
πατάρι 1700×1300 ~60Kg
ξύλινο δάπεδο 5 τεμ 1680×240×45 ~50Kg
σύνολον ~110Kg
1700×1300
80/40
t=3
~3600 ~33Kg
100/100
t=3 ~9,15Kg/m
2000 ~5,5Kg
60×6
t=5
~7,5Kg
240

NATIONAL TECHNICAL UNIVERSITY OF ATHENS
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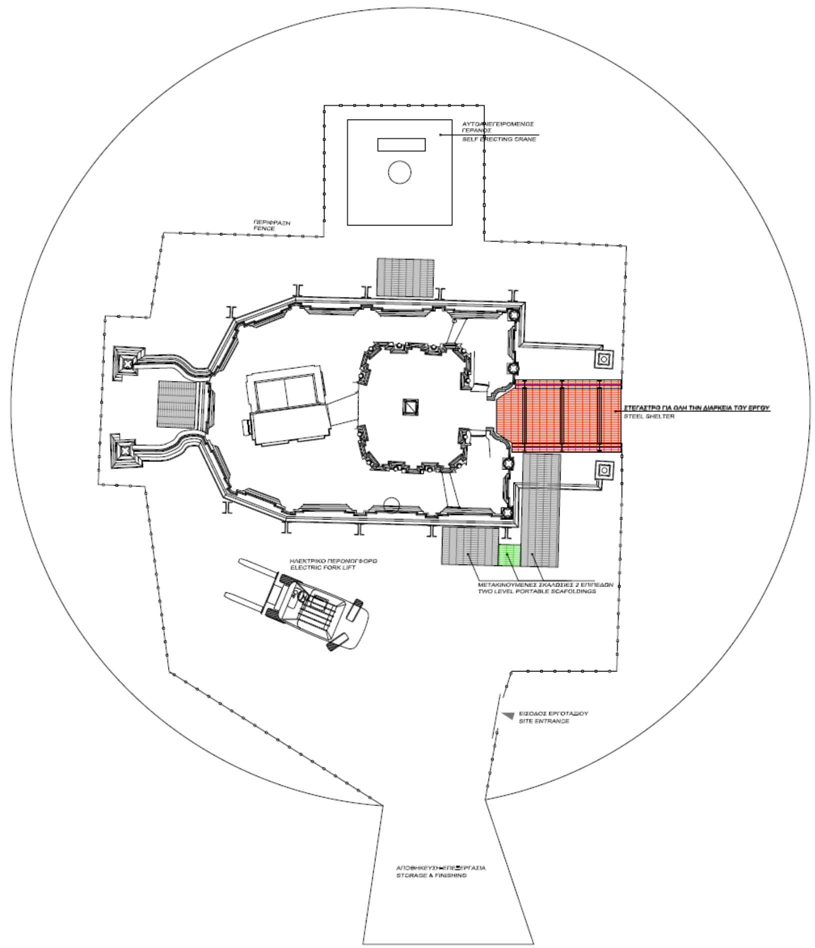
<u>Interdisciplinary Research Group NTUA</u>**:**
Prof. Em. Korres, Prof. A. Georgopoulos, Prof. A. Moropoulou, Prof. C. Spyrakos

School of Civil Engineering
Laboratory for Earthquake Engineering

Organization management of construction site
(Scientific Responsible: Assist. Prof. Ch. Mouzakis)



PRINCIPLES FOR THE ORGANIZATION MANAGEMENT OF CONSTRUCTION SITE

1 The Holy Tomb must be accessible throughout the works. therefore it is proposed that a protective cover is raised
2 Safety of the visitors
3 All spaces around the perimeter of the rotunda must be accessible
4 No entrance to the construction site is allowed to those that do not have permit
5 During the works at the interior of the structure, the pilgrimage should not be obstructed, which therefore requires that this work is performed during the night shift.
6 Presence of a permanent fence throughout the duration of the works.
7 The construction site should conform to the health and safety rules for the staff an all appropriate signs should be placed.

WORKSITE ORGANIZATION

1. DISASSEMBLY OF MARBLE STONES WILL BE EXECUTED IN VERTICAL ZONES
 A PORTABLE SCAFFOLDING WILL BE USED

2. BRACINGS OF THE STEEL SUPPORTING FRAME WILL BE REMOVED IN ZONES

3. OPERATIONS WILL START FROM THE SOUTH EAST CORNER OF THE MONUMENT

4. A SELF ERECTED ELECTRIC CRANE WILL BE INSTALLED
THE OPERATOR HAS TO BE APPROPRIATELY TRAINED AND CERTIFIED BELTS HAVE TO BE USED

5.AN ELECTRIC FORKLIFT WILL BE USED

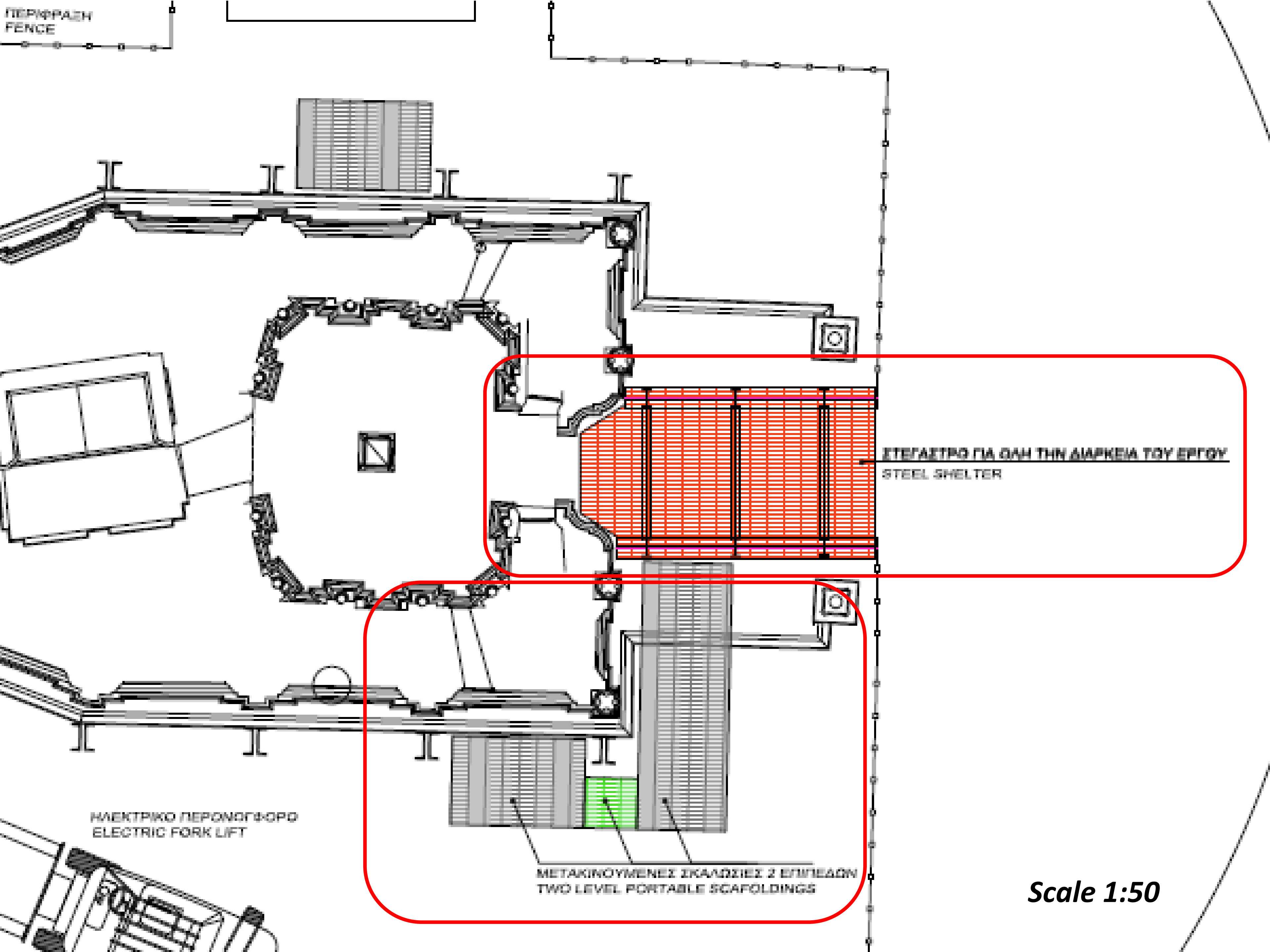
6.THE BUILDING MATERIALS WILL BE STORED IN SPECIAL BOXES OR BAGS

WORKSITE ORGANIZATION

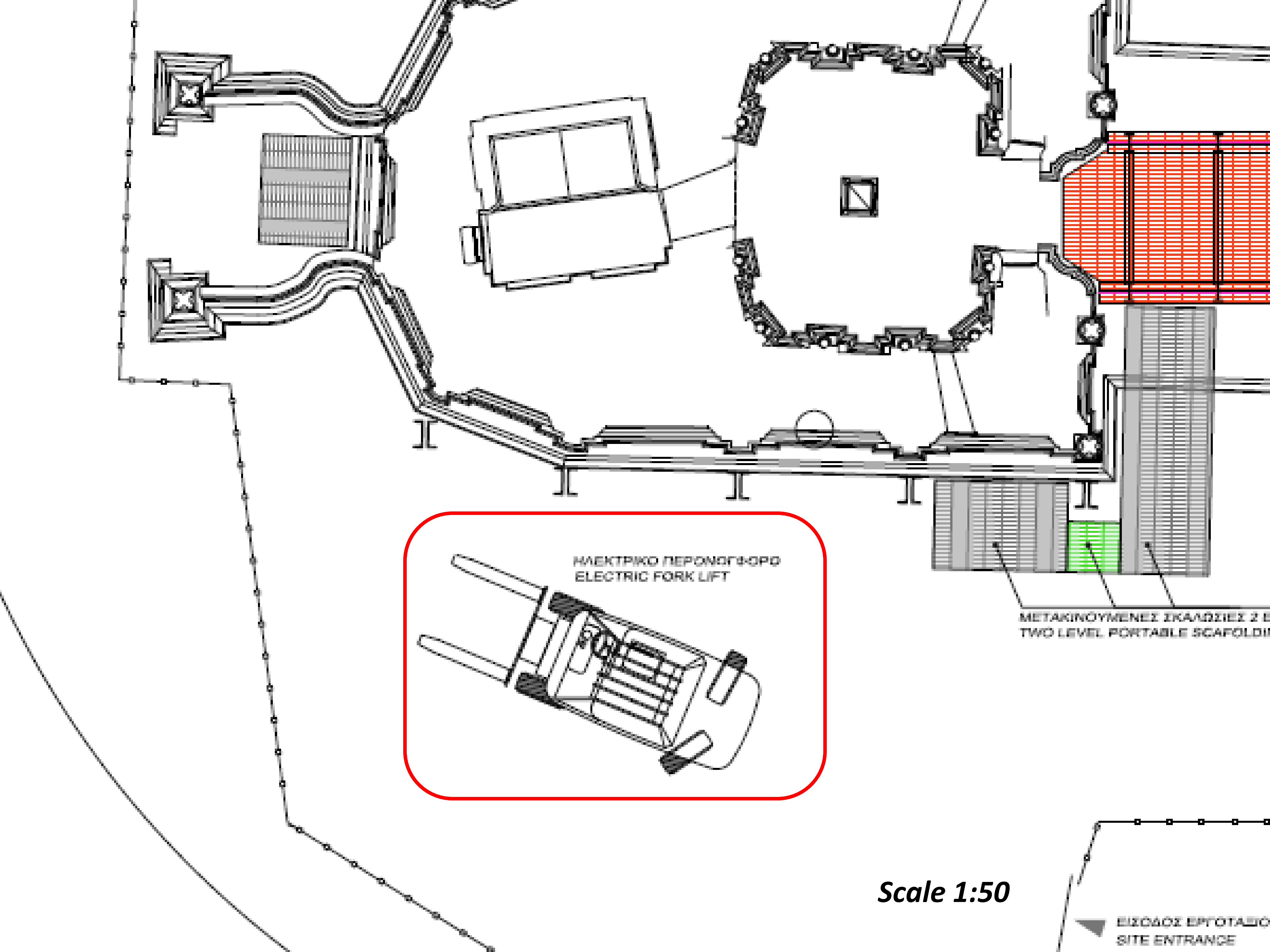
7. GROUTING EQUIPMENT WILL BE PLACED INSIDE THE FENCE
8. SUITABLE WATER HAS TO BE PROVIDED FOR THE GROUTS
9. MARBLES HAVE TO BE CLEANED IN SITU WITH THE PROPOSED CLEANING MATERIALS AND PROCEDURES
10. THE DISASSEMBLED MARBLES WILL BE TREATED AND STORED IN A PROPERLY VENTILATED SPACE WHICH WILL BE CONFIGURED AS A CONSERVATION LABORATORY INSIDE THE ROTUNDA

MULTIDISCIPLINARY TESTING LABORATORY
UNDER NTUA SUPERVISION WILL BE SET UP

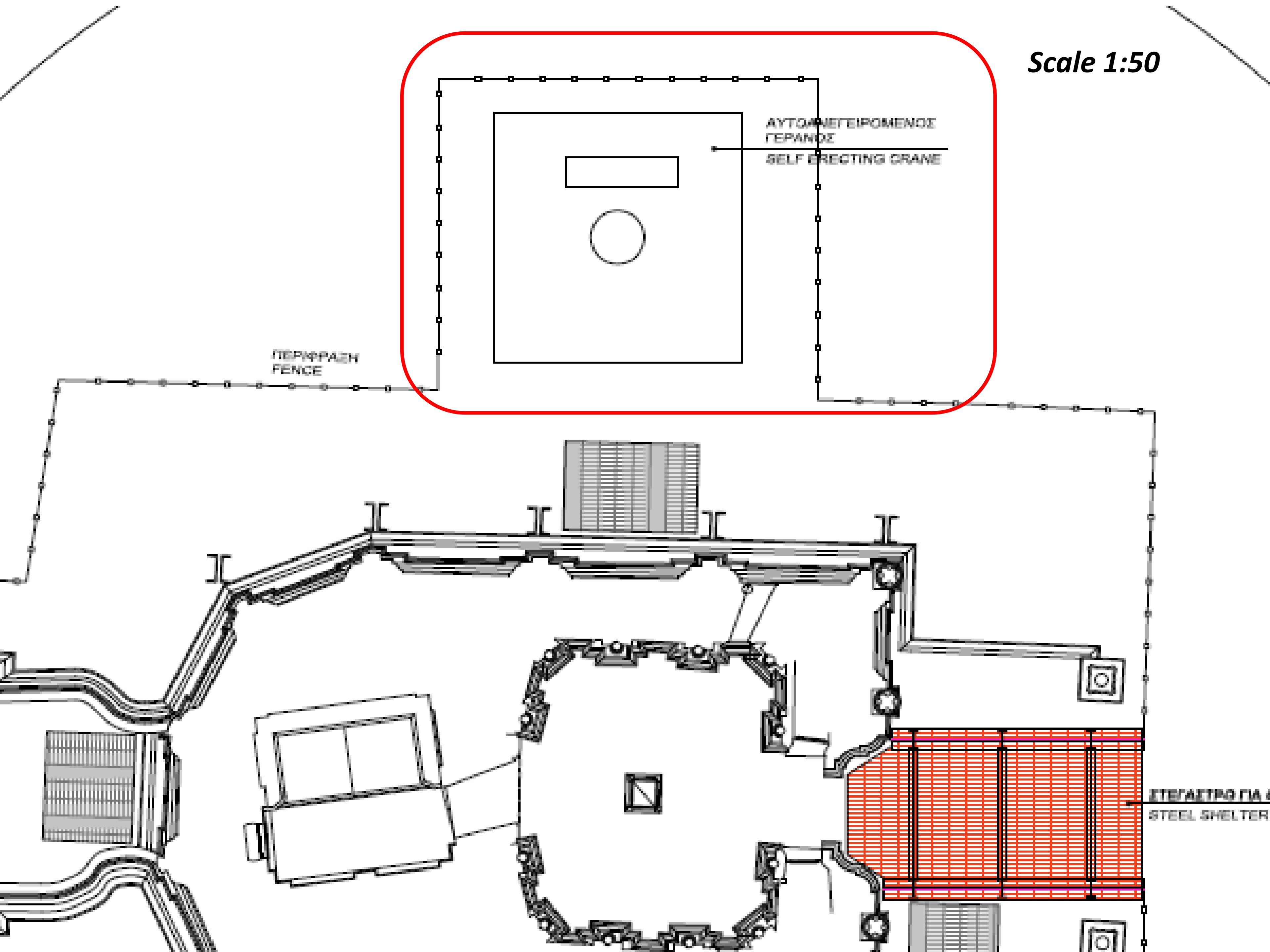
11. THE MEASURING EQUIPMENT WILL BE INSTALLED IN A DEDICATED SECURED AREA INSIDE THE ROTUNDA FOR IN REAL TIME ON SITE AND ON LINE MONITORING DOCUMENTATION AND ADJUSTMENT OF NTUA STUDY BASED ON THE FINDINGS AFTER THE DISASSEMBLY OF MARBLES. A CAMERA NETWORK WILL BE INSTALLED ALL AROUND THE WORKSITE
12. AROUND AND ABOVE THE HOLY AEDICULE, A CAMERA NETWORK WILL BE INSTALLED FOR THE CONTINUOUS DOCUMENTATION OF THE WORKS AND THE FINDINGS


ΠΕΡΙΦΡΑΞΗ
FENCE
ΣΤΕΓΑΣΤΡΟ ΓΙΑ ΟΛΗ ΤΗΝ ΔΙΑΡΚΕΙΑ ΤΟΥ ΕΡΓΟΥ
STEEL SHELTER
ΗΛΕΚΤΡΙΚΟ ΠΕΡΟΝΟΦΟΡΟ
ELECTRIC FORK LIFT
ΜΕΤΑΚΙΝΟΥΜΕΝΕΣ ΣΚΑΛΩΣΙΕΣ 2 ΕΠΙΠΕΔΩΝ
TWO LEVEL PORTABLE SCAFOLDINGS

Scale 1:50


ΗΛΕΚΤΡΙΚΟ ΠΕΡΟΝΟΦΟΡΟ
ELECTRIC FORK LIFT
ΜΕΤΑΚΙΝΟΥΜΕΝΕΣ ΣΚΑΛΩΣΙΕΣ 2 Ε
TWO LEVEL PORTABLE SCAFOLDI
ΕΙΣΟΔΟΣ ΕΡΓΟΤΑΞΙΟ
SITE ENTRANCE

Scale 1:50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ΑΥΤΟΑΝΕΓΕΙΡΟΜΕΝΟΣ
ΓΕΡΑΝΟΣ
SELF ERECTING CRANE
ΠΕΡΙΦΡΑΞΗ
FENCE
ΣΤΕΓΑΣΤΡΟ ΓΙΑ
STEEL SHELTER

NATIONAL TECHNICAL UNIVERSITY OF ATHENS
Interdisciplinary Research Team for the Protection of Monuments
Scientific Coordinator:
Prof. A. Moropoulou
Interdisciplinary Research Group NTUA**:**
Prof. Em. Korres, Prof. A. Georgopoulos, Prof. A. Moropoulou, Prof. C. Spyrakos

PROSPECTS

The interdisciplinary Research Team continues the dissemination, information, training in the innovative research project *"Integrated Diagnostic Research Project and Strategic Planning for Materials, Interventions Conservation and Rehabilitation of the Holy Edicule of the Holy Sepulchre in the Holy Church of the Resurrection in Jerusalem",* as well as the execution of in-situ pilot tests for its implementation and the training of technical staff

During works, high supervision with continual documentation, diagnosis, pilot applications and update of the study is performed by the NTUA interdisciplinary Research Group, based on real-time data