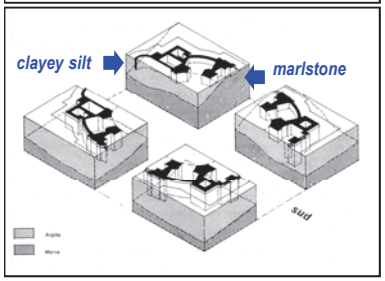
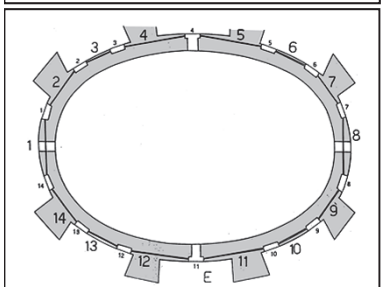




Centro Congressi del Santuario di Vicoforte 15-16 GIUGNO 2017

MONITORAGGIO PERIODICO E CONTINUO DI STRUTTURE DEL PATRIMONIO ARCHITETTONICO

COLUMBIA-POLITO Spring School on "Structural Health Monitoring of Architectural Heritage"
COLUMBIA UNIVERSITY – POLITECNICO DI TORINO

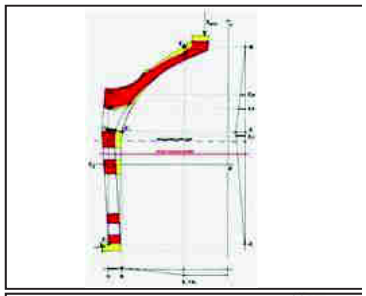
Mario Alberto Chiorino

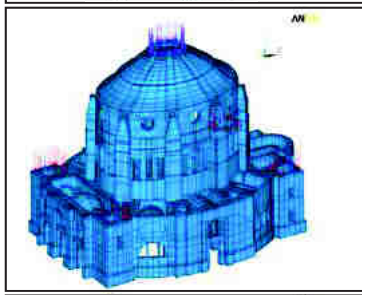
ANALISI STRUTTURALE E MONITORAGGIO DELLE GRANDI CUPOLE IN MURATURA

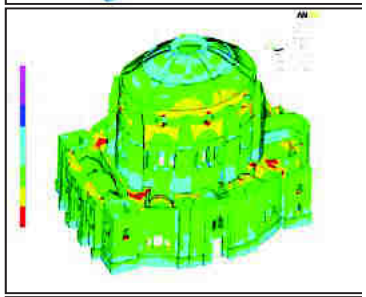
Il caso studio della Cupola di Vicoforte

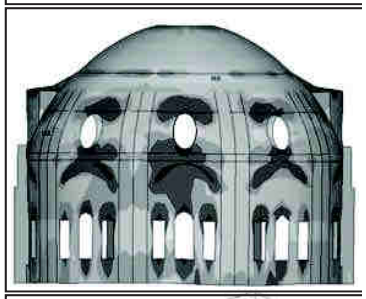
La più grande cupola ellittica al mondo

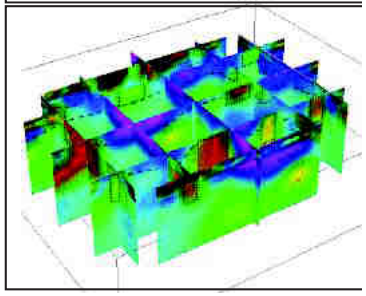
15 Giugno 2017

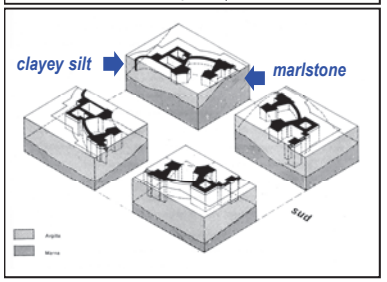


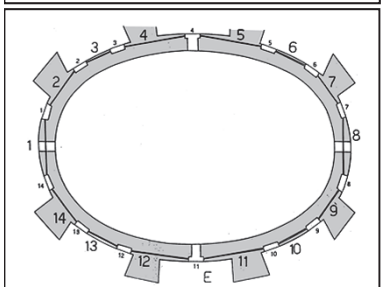












Scuola di Dottorato del
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The role of structural engineering and geotechnics in the conservation of historical monuments:

Case study of the survey and structural modeling for the reliability assessment of the world's largest elliptical masonry dome at Vicoforte, Italy

Largest Elliptical Dome at Vicoforte, Italy

Ruolo dell'area strutturale e geotecnica nella conservazione dei beni monumentali

Il caso studio del Santuario di Vicoforte con la grande cupola ellittica

The role of structural engineering and geotechnics in the conservation of historical monuments

The case study of the of the Sanctuary of Vicoforte with its large elliptical dome

Mario Chiorino,
Professore Emerito, Politecnico di Torino

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presso DISEG

European Schools in the Teaching of Restoration

The 150th Anniversary of the Foundation of School of Applied Civil Architecture at the Politecnico di Milano

The role of structural engineering and geotechnics in the conservation of historical monuments. The case study of the Sanctuary of Vicoforte with its large elliptical dome

Mario Alberto Chiorino

Introduction

The protection of architectural heritage requires the contribution of different sciences. The paper discusses the significant and progressively increasing role of structural and geotechnical disciplines in the strategies for conservation and restoration of historical constructions and monumental buildings. Attention is paid to the gradually increasing recognition of the importance of this role within international debate,[1] and corresponding reflection in principles and guidelines successively incorporated in charters and documents formulated at national and international level. A process that was accentuated in recent years, in connection in particular with the perspective of establishing scientifically based global strategies for the evaluation and mitigation of the seismic risk of some of the most relevant architectural heritage patrimonies located in seismic active areas, as e.g. Italy and India.[2] In the end, attention is focused on a relevant case study apt to demonstrate how these disciplines can contribute to the processes of reliability analyses of structur-

1. D.F. D'Ayala, M. Forsyth, *What is Conservation Engineering?*, in M. Forsyth (ed.), *Structures & Construction in Historic Building Conservation*, Wiley-Blackwell, Oxford 2007.
2. R. Cecchi, M. Calvi (coords.), S. Lagomarsino (ed.), *Linee Guida per la valutazione e riduzione del rischio sismico del patrimonio culturale con riferimento alle Norme Tecniche per le Costruzioni* (Guidelines for the evaluation and reduction of seismic risk of cultural heritage with reference to the Technical Code for Constructions, in Italian), July 2006, 1st official edition: Duett. Pres. Cons. Min. 12.10.2007, Gazzetta Ufficiale 29.01.2008 n. 24; 2nd official edition: Duett. Pres. Cons. Min. 09.02.2011, Gazzetta Ufficiale 26.02.2011, n. 47, Supplemento ordinario n. 54.
EU-India Economic Cross Cultural Programme: Improving the Seismic Resistance of Cultural Heritage Buildings, *Guidelines for the Conservation of Historical Masonry Structures in Seismic Areas*, Universidade do Minho, Universidad Politécnica de Catalunya, Central Building Research Institute (India), Università di Padova, 2006.

POLITECNICO DI MILANO

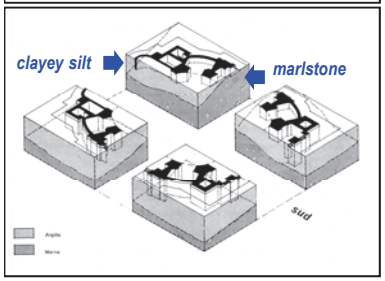
Dipartimento di Architettura e Studi Urbani

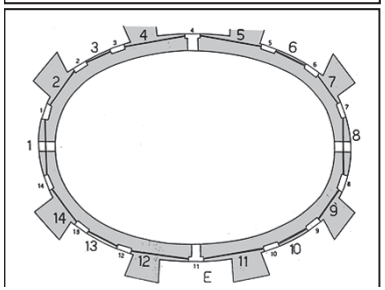
Department of Architecture and Urban Studies

L'insegnamento di restauro nelle Scuole di Architettura europee

Per i centocinquant'anni dalla fondazione della Scuola di applicazione per gli architetti civili al Politecnico di Milano

27- 28 Novembre 2014





Scuola di Dottorato del
Politecnico di Torino
Dottorato in Beni Culturali

The role of structural engineering and geotechnics in the conservation of historical monuments

- The conservation of architectural heritage requires the contribution of different sciences.

- The lecture discusses the significant and progressively increasing role of structural and geotechnical disciplines in the strategies for conservation and rehabilitation of historical constructions and monumental buildings, as recognized also by guidelines formulated at national and international level, in particular in recent years.

- Specific attention is paid to the contribution of these disciplines to the analyses in the static domain for reliability assessments under gravity loads, as well as to the analyses in the dynamic domain for both model updating processes and the evaluation of the seismic risk.

First Italian Restoration Chart, 1883

developed within the 3rd Congress of Italian Architects and Engineers in 1883

- **establishes as basic principle the respect of authenticity of monuments of architectural heritage,**
- **takes into consideration the problems arising from the need of improving their structural reliability,**
- **recommends a proper strategy based, on one side, on minimum interventions, and, on the other side, in case of necessary additions, on an easy possibility to distinguish them from the original parts**

The Athens Charter for the Restoration of Historic Monuments, 1931

Adopted at the First International Congress of Architects and Technicians of Historic Monuments, Athens 1931

- represents the main document in this domain developed in the first half of 20th century.
- establishes basic principles and guidelines.
- For the first time it clearly states the principle that "modern techniques and materials may be used in restoration work", while recommending a "judicious use of all the resources at the disposal of modern technique and more especially of reinforced concrete" (an ambiguous evidence given to this technique, whose use is expected today to be considered with caution, in particular when rehabilitation interventions are intended to reduce the seismic risk of traditional architectural heritage).
- recommends that, "before any consolidation or partial restoration is undertaken, a thorough analysis should be made of the defects and the nature of the decay of these monuments", recognising that each case needs to be treated individually: an anticipated recommendation of modern integrated approach and methodological consistency, which currently specify, as e.g. in ICOMOS Principles (2003), and especially in (EU-INDIA 2006), that "the study of an historical construction consists of four subsequent phases, namely survey, diagnosis, safety evaluation and design of the intervention".

International Charter for the Conservation and Restoration of Monuments And Sites (The Venice Charter 1964)

2nd International Congress of Architects and Technicians of Historic Monuments, Venice, 1964

Principal Authors: ***Piero Gazzola, Roberto Pane e Raymond Lemaire***

Piero Gazzola
"Proceedings of the 2nd International Congress of Architects and Technicians of Historical Monuments, 1971":

- ***Les résultats de cette rencontre à Venise sont, dans l'ensemble, de grande importance. Il suffit de rappeler la création du ICOMOS International Council on Monuments and Sites, l'Institut qui constitue l'assise suprême dans le secteur de la restauration monumentale, de la conservation des centres historiques anciens, du paysage, des localités témoins de l'art et de l'histoire en général.***
- ***Il faut par ailleurs reconnaître que le résultat le plus positif, et de loin, obtenu par cette assemblée a été la 'Charte Internationale de la Restauration': ce n'est pas un épisode culturel mais un texte de portée historique.***
- ***La Charte de Venise sera en effet désormais, dans le monde entier, le code officiel dans le secteur de la conservation des biens culturels***

International Charter for the Conservation and Restoration of Monuments And Sites (The Venice Charter 1964)

Article 2

The conservation and restoration of monuments must have recourse to all the sciences and techniques which can contribute to the study and safeguarding of the architectural heritage

Article 10

Where traditional techniques prove inadequate, the consolidation of a monument can be achieved by the use of any modern technique for conservation and construction, the efficacy of which has been shown by scientific data and proved by experience

1996

- **ISCARSAH *International Scientific Committee on the Analysis and Restoration of Structures of Architectural Heritage***

  was founded by ICOMOS as a forum and network for engineers involved in the restoration and care of building heritage

  The first meeting of the ISCARSAH took place at the Engineering University in Rome in March of 1997 and the committee has met twice a year since then in venues all over the world.

Current President : Prof. Gorun Arun (Yildiz Technical Un. Istanbul, Turkey)

Iscarsah
www.iscarsah.org

ICOMOS – ISCARSAH
International Scientific Committee for Analysis and Restoration of Structures of Architectural Heritage

2003

- **ISCARSAH authored the ICOMOS Charter "Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage, rati-fied by ICOMOS in 2003, which were followed by "Guidelines" to be used in tandem with the Principles as global recommendations in this domain.**

ICOMOS-ISCARSAH, ***Recommendations for the Analysis and Restoration of Historical Structures – Principles and Guidelines, 2003 (http://iscarsah.org/documents/),***

Iscarsah
www.iscarsah.org

ICOMOS – ISCARSAH
International Scientific Committee for Analysis and Restoration of Structures of Architectural Heritage

2003

ICOMOS
INTERNATIONAL SCIENTIFIC COMMITTEE FOR ANALYSIS AND RESTORATION OF STRUCTURES OF ARCHITECTURAL HERITAGE

RECOMMENDATIONS FOR THE ANALYSIS, CONSERVATION AND STRUCTURAL RESTORATION OF ARCHITECTURAL HERITAGE

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INTERNATIONAL SCIENTIFIC COMMITTEE FOR ANALYSIS AND RESTORATION OF STRUCTURES OF ARCHITECTURAL HERITAGE

RECOMMENDATIONS FOR THE ANALYSIS, CONSERVATION AND STRUCTURAL RESTORATION OF ARCHITECTURAL HERITAGE

2003

PRINCIPLES

1 General criteria

1.1 Conservation, reinforcement and restoration of architectural heritage requires a **multi-disciplinary approach**

…..

1.6 The peculiarity of heritage structures, with their complex history, requires the organisation of studies and analysis in **steps that are similar to those used in medicine**.

Anamnesis, diagnosis, therapy and **controls**, corresponding respectively to:

- **condition survey**,
- **identification of the causes of damage and decay,**
- **choice of the remedial measures** and
- **control of the efficiency of the interventions**.

ICOMOS
INTERNATIONAL SCIENTIFIC COMMITTEE FOR ANALYSIS AND RESTORATION OF STRUCTURES OF ARCHITECTURAL HERITAGE

2003

RECOMMENDATIONS FOR THE ANALYSIS, CONSERVATION AND STRUCTURAL RESTORATION OF ARCHITECTURAL HERITAGE

PRINCIPLES

2 Research and diagnosis

....

2.5 **Diagnosis** is based on historical information and **qualitative and quantitative approaches**.

The **qualitative** approach is based on direct observation of the structural damage and material decay as well as historical and archaeological research, while the **quantitative approach requires material and structural tests, monitoring and structural analysis**

ICOMOS
INTERNATIONAL SCIENTIFIC COMMITTEE FOR ANALYSIS AND RESTORATION OF STRUCTURES OF ARCHITECTURAL HERITAGE

2003

RECOMMENDATIONS FOR THE ANALYSIS, CONSERVATION AND STRUCTURAL RESTORATION OF ARCHITECTURAL HERITAGE

PRINCIPLES

3 Remedial measures and controls

3.1 Therapy should **address root causes** rather than symptoms.
3.2 **Adequate maintenance** can limit or postpone the need for subsequent intervention.
3.3 **Safety evaluation** and an **understanding of the historical and cultural significance of the structure** should be the basis for conservation and reinforcement measures.
3.4 No actions should be undertaken without demonstrating that they are indispensable.
3.5 Each intervention should be in proportion to the safety objectives, **keeping intervention to the minimum necessary to guarantee safety and durability** and with the least damage to heritage values
3.6 The design of any intervention should be based on a **full understanding** of the **kinds of action (forces, accelerations, deformations** etc) that have caused the damage or decay and of those that will act in the future.
3.7 The choice between **"traditional"** and **"innovative" techniques** should be determined on a case-by-case basis with preference given to those that are least invasive and most compatible with heritage values, **consistent with the need for safety and durability.**

ICOMOS
INTERNATIONAL SCIENTIFIC COMMITTEE FOR ANALYSIS AND RESTORATION OF STRUCTURES OF ARCHITECTURAL HERITAGE

2003

RECOMMENDATIONS FOR THE ANALYSIS, CONSERVATION AND STRUCTURAL RESTORATION OF ARCHITECTURAL HERITAGE

PRINCIPLES

3 Remedial measures and controls

3.8 At times the difficulty of evaluating both the safety levels and the possible benefits of interventions may suggest "an observational method", i.e. an **incremental approach, beginning with a minimum level of intervention**, with the possible adoption of subsequent supplementary or corrective measures.

3.9 Where possible, **any measures adopted should be "reversible"** so that they can be removed and replaced with more suitable measures if new knowledge is acquired. Where they are not completely reversible, interventions **should not compromise later interventions**.

3.10 The characteristics of materials used in restoration work (in particular new materials) and their **compatibility with existing materials** should be fully established. This must include long-term effects, so that undesirable side effects are avoided.

…….

ICOMOS
INTERNATIONAL SCIENTIFIC COMMITTEE FOR ANALYSIS AND RESTORATION OF STRUCTURES OF ARCHITECTURAL HERITAGE

2003

RECOMMENDATIONS FOR THE ANALYSIS, CONSERVATION AND STRUCTURAL RESTORATION OF ARCHITECTURAL HERITAGE

GUIDELINES

1 General criteria

2 Acquisition of data: Information and Investigation

2.1 Generally
2.2 Historical, structural and architectural investigations
2.3 Survey of the structure
2.4 Field research and laboratory testing
2.5 Monitoring

3 The structural behaviour

3.1 General aspects
3.2 The structural scheme and damage
3.3 Material characteristics and decay processes
3.4 Actions on the structure and the materials

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4.3 Safety evaluation
4.3.1 The problem of safety evaluation
4.3.2 Historical analysis
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4.3.4 The analytic approach
4.3.5 The experimental approach
4.4 Decisions and explanatory report

5 Structural damage, materials decay and remedial measures

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5.4 Iron and steel
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INTERNATIONAL SCIENTIFIC COMMITTEE FOR ANALYSIS AND RESTORATION OF STRUCTURES OF ARCHITECTURAL HERITAGE

2003

RECOMMENDATIONS FOR THE ANALYSIS, CONSERVATION AND STRUCTURAL RESTORATION OF ARCHITECTURAL HERITAGE

GUIDELINES

……

4.3.4 The analytic approach

This approach uses the methods of **modern structural analysis** which, on the basis of certain hypotheses (theory of elasticity, theory of plasticity, frame models, etc.), draws **conclusions based on mathematical calculations**. In philosophical terms it is a deductive procedure. However, the uncertainties that can affect the representation of the material characteristics, and the imperfect representation of the structural behaviour, together with the simplifications adopted may lead to results that are not always reliable, even very different from the real situation.

The essence of the problem is the identification of meaningful models that adequately depict both the structure and the associated phenomena with all their complexity making it possible to apply the theories at our disposal.

2006

Title: **GUIDELINES FOR THE CONSERVATION OF HISTORICAL MASONRY STRUCTURES IN SEISMIC AREAS**

Date: August 2006

Title: **IDENTIFICATION OF STRENGTHENING STRATEGIES**

Date: October 2006

Title: **DESIGN AND VALIDATION OF MONITORING SYSTEMS AND SENSORS**

Date: August 2006

Asia-wide Programme:	EU-INDIA ECONOMIC CROSS CULTURAL PROGRAMME
Project Title:	IMPROVING THE SEISMIC RESISTANCE OF CULTURAL HERITAGE BUILDINGS
Project Contract N°:	ALA/95/23/2003/077-122
Project Beneficiary:	UNIVERSIDADE DO MINHO, PORTUGAL
Partners:	TECHNICAL UNIVERSITY OF CATALONIA, SPAIN
	CENTRAL BUILDING RESEARCH INSTITUTE, INDIA
	UNIVERSITÁ DEGLI STUDI DI PADOVA, ITALY

2008

Politecnico di Torino

Ph.D. courses on the conservation of architectural heritage

with contributions of the faculty of the Structural Engineering Department and of Architecture /Conservation Departments

2006

Italian Guidelines for the evaluation and reduction of seismic risk of cultural heritage
2006, 2008, 2011

Linee Guida per la valutazione e riduzione del rischio sismico del patrimonio culturale con riferimento alle norme tecniche per le costruzioni

Luglio 2006

GRUPPO DI LAVORO
ai sensi dell'art. 3 dell'Ordinanza P.C.M. 3431/2005, istituito con decreto interministeriale del 23 maggio 2005

Arch. Roberto CECCHI (coordinatore)
Direttore Generale per i beni architettonici e paesaggistici, Ministero per i beni e le attività culturali

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Prof. Carlo VIGGIANI
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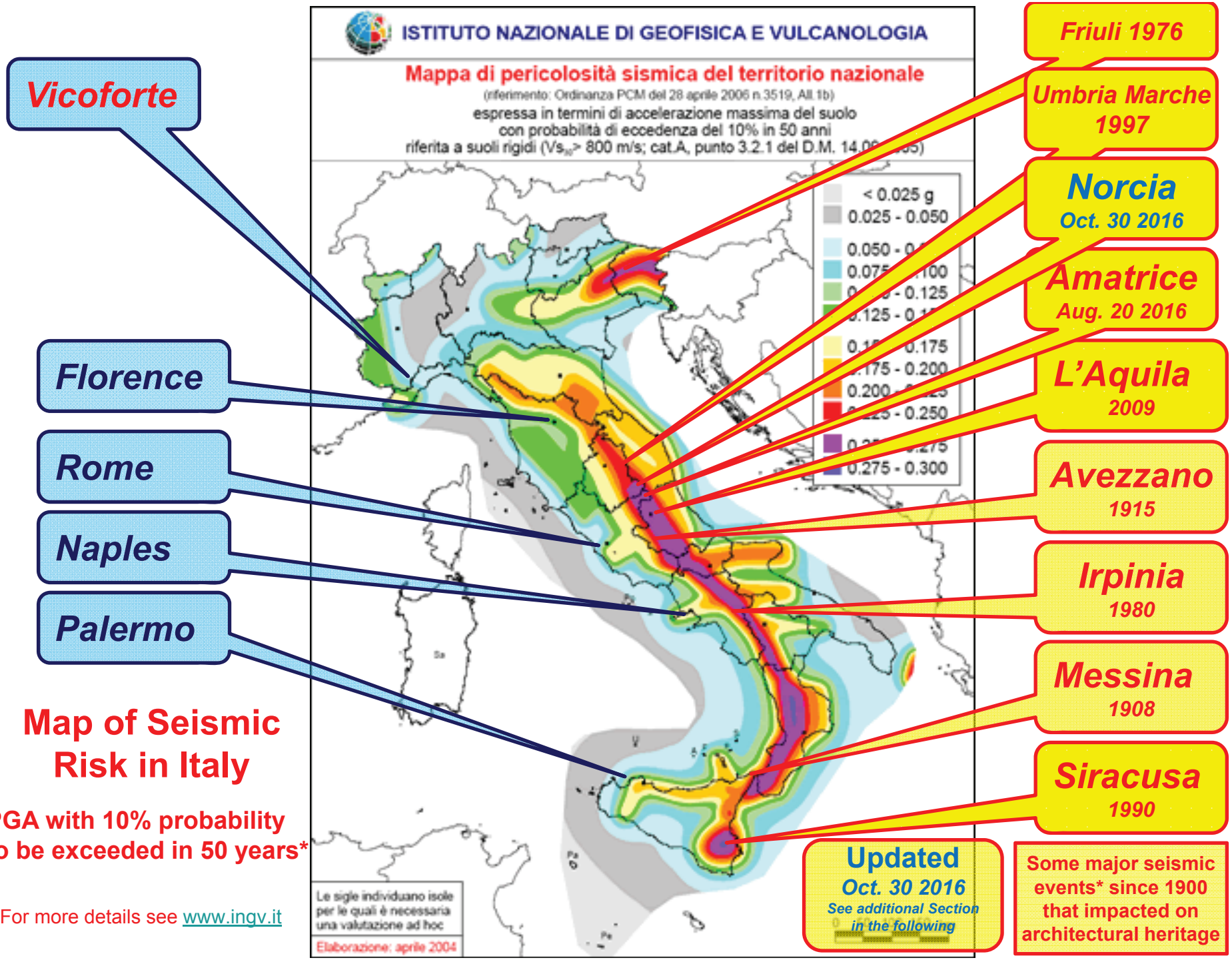

Map of Seismic Risk in Italy

PGA with 10% probability to be exceeded in 50 years*

* For more details see www.ingv.it

2011

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2011

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Allegato B. L'analisi strutturale delle costruzioni storiche in muratura

Allegato C. Modello per la valutazione della vulnerabilità sismica delle chiese

Appendix C
Models for the evaluation of the seismic vunerability of churches

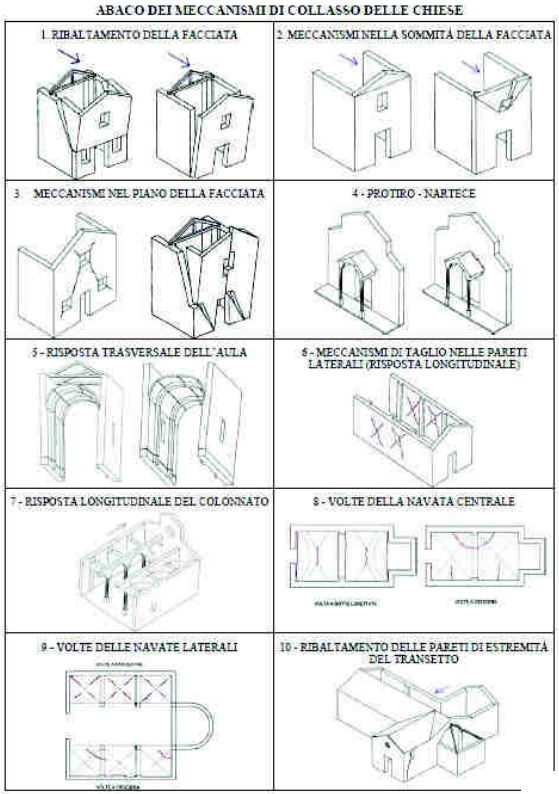
2011

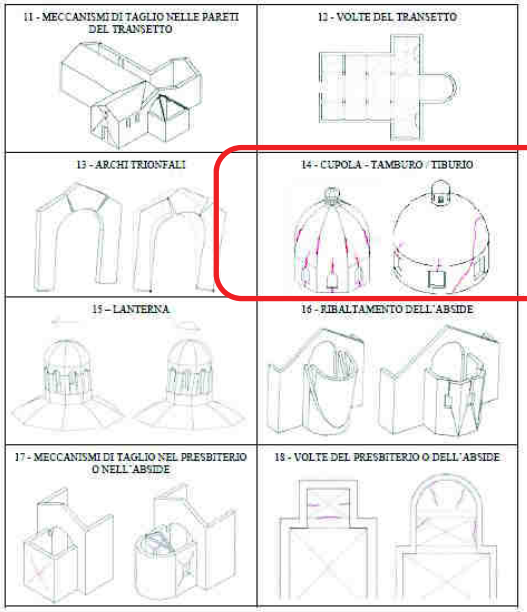
ALLEGATO C

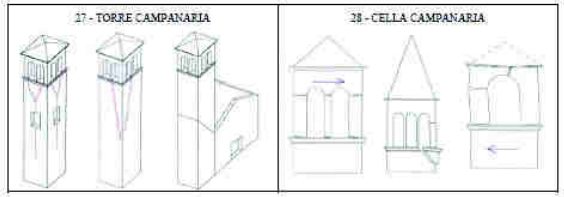
Modello per la valutazione della vulnerabilità sismica delle chiese

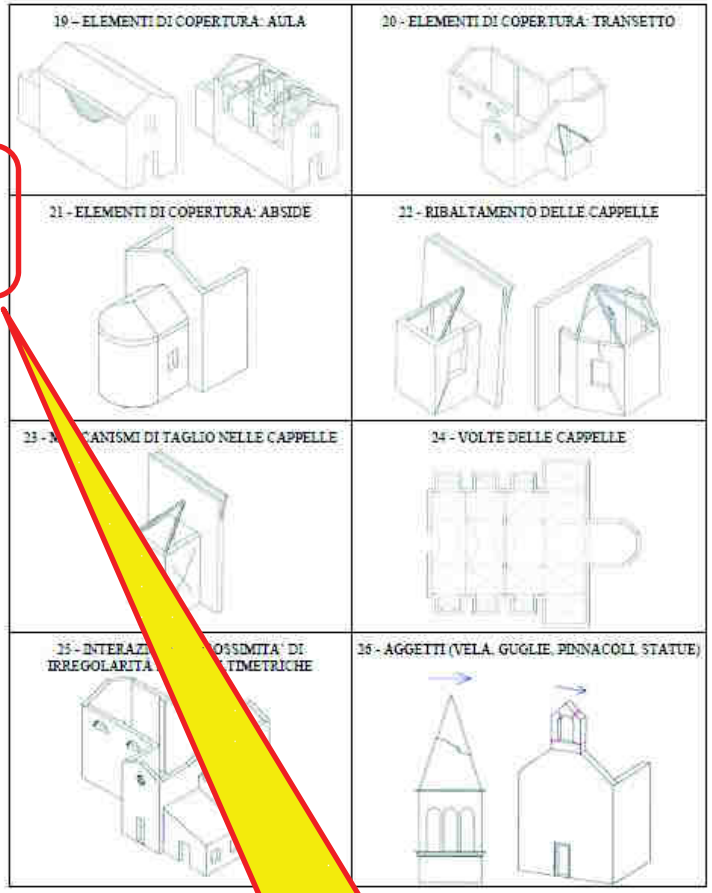
APPENDIX C

Model for the evaluation of the seismic vunerability of churches







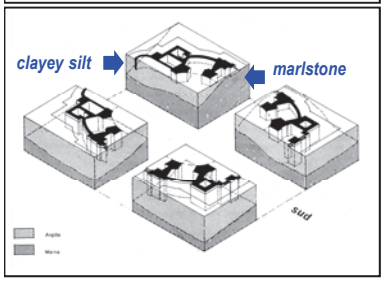


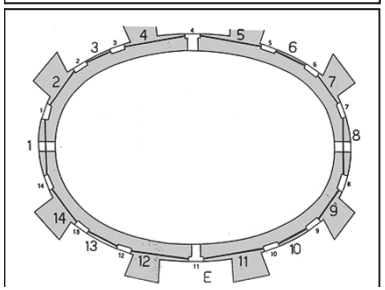
ABAQUS OF FAILURE MECHANISMS OF CHURCHES

Dome and drum architectural systems

Scuola di Dottorato del
Politecnico di Torino
Dottorato in Beni Culturali

Section added after the seismic event of Norcia, October 30, 2016





Earthquake October 30, 2016

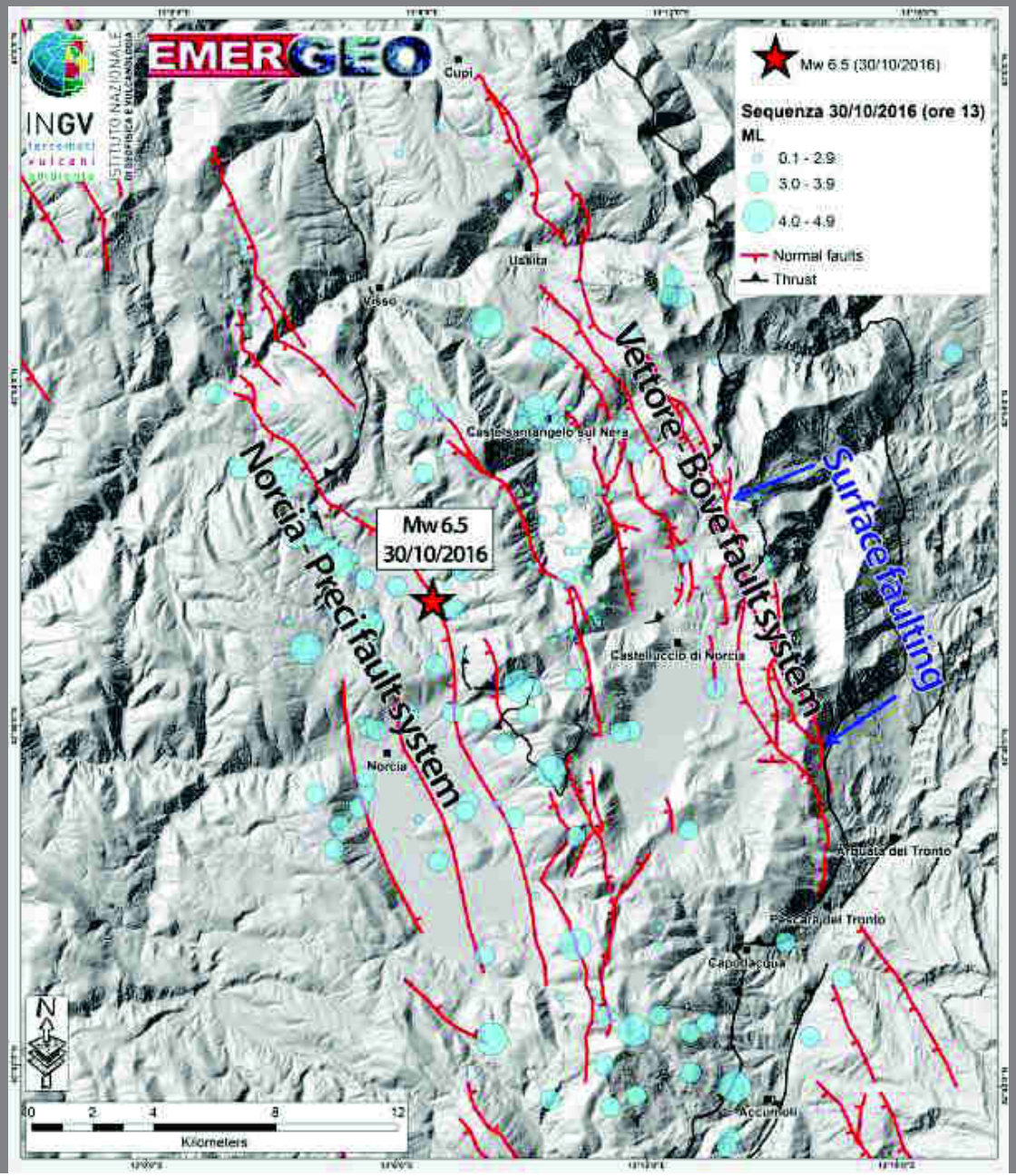
Epicenter near Norcia
Central Italy


Norcia
Distance to Epicenter 3.4 mi
Norcia Cathedral

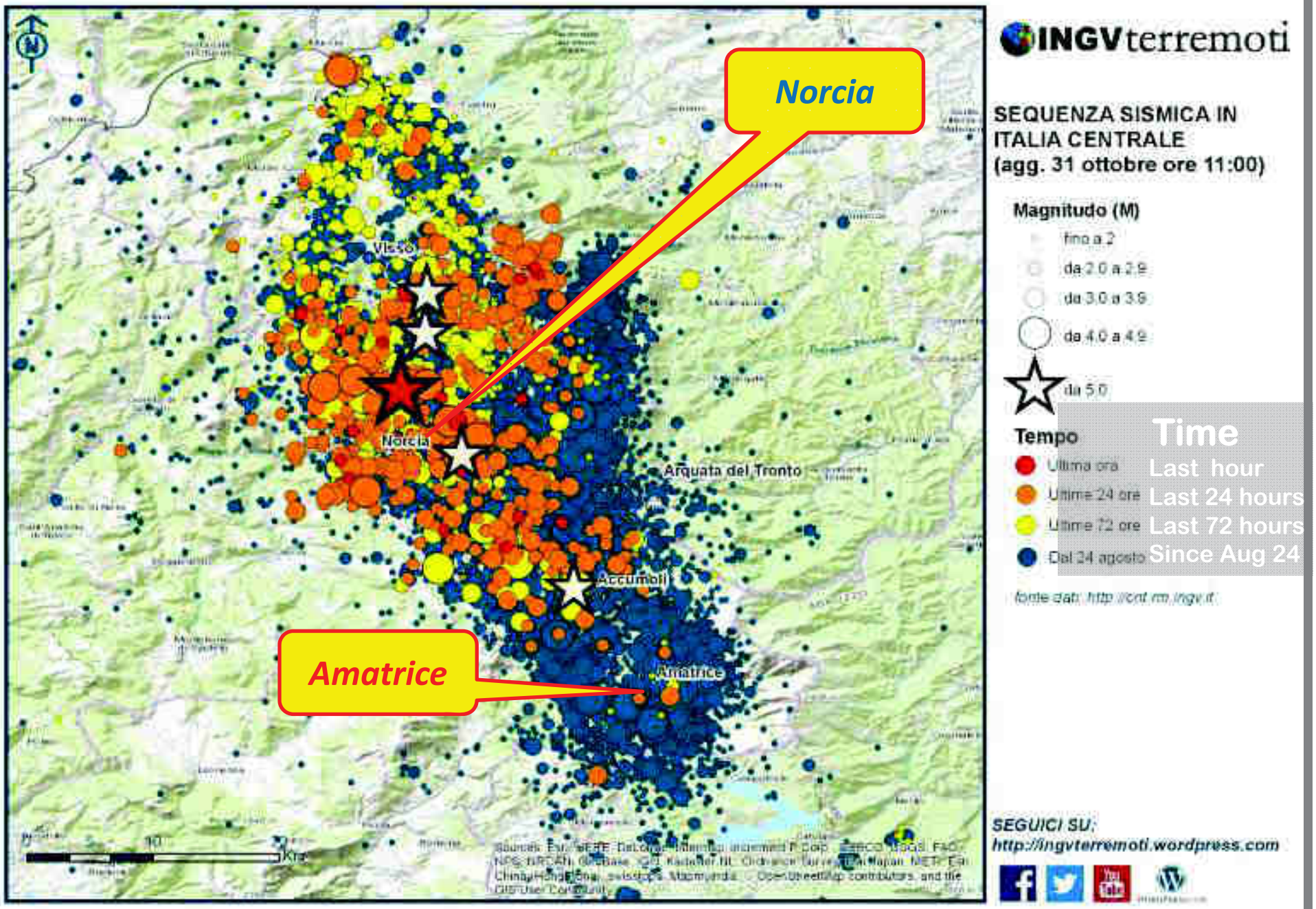
Castelluccio di Norcia

Distance to Epicenter 5.6 mi

Location of epicenter



Seismic sequence as for October 31 at 11 a.m



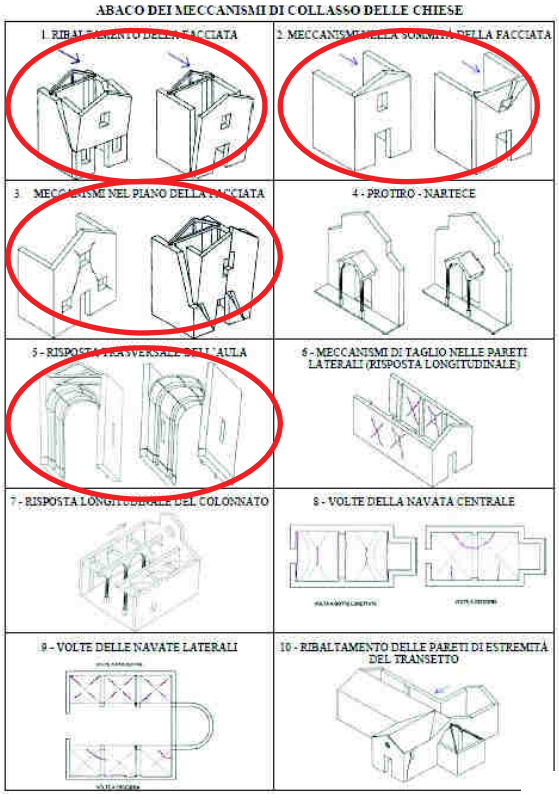
2011

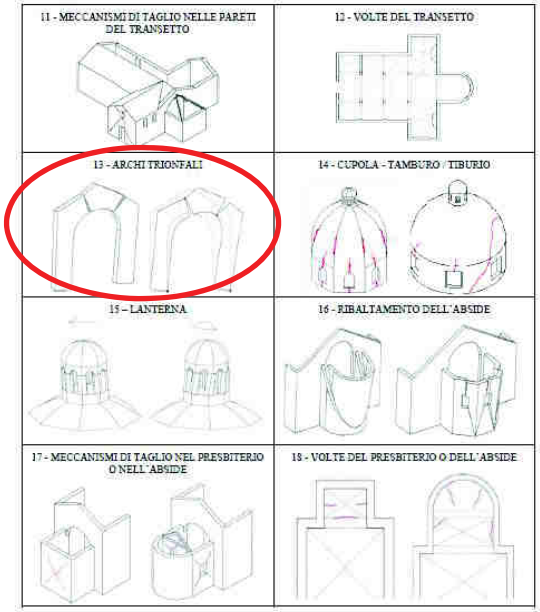
ALLEGATO C

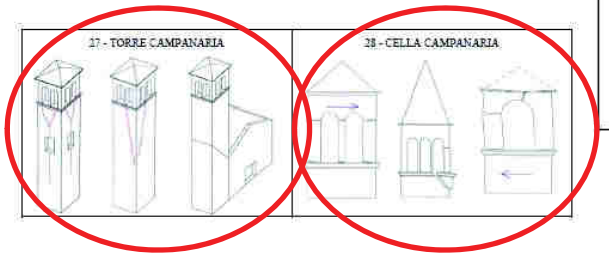
Modello per la valutazione della vulnerabilità sismica delle chiese

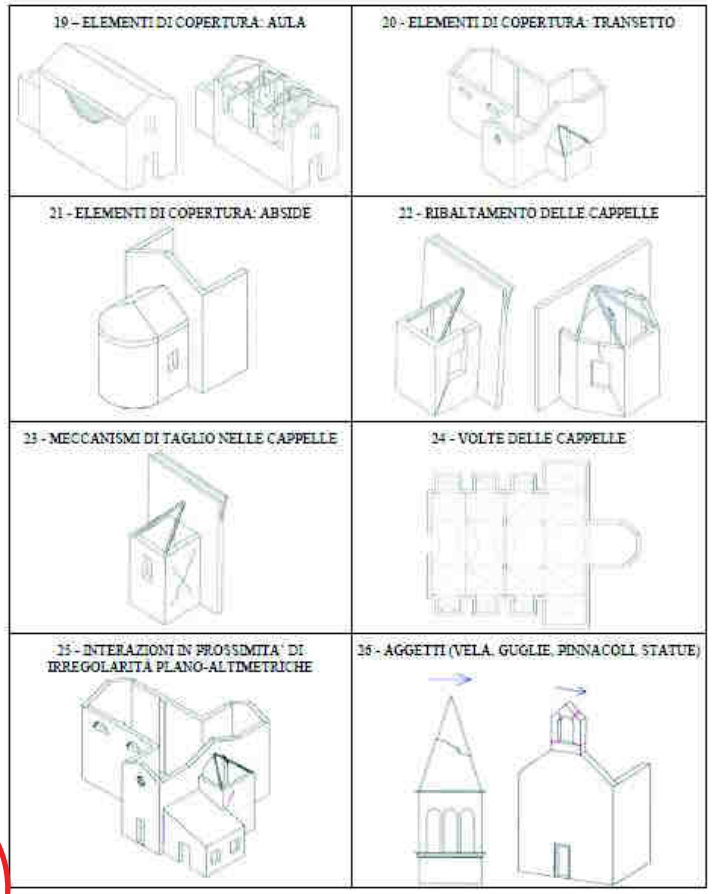
APPENDIX C

Model for the evaluation of the seismic vunerability of churches









79

ABAQUS OF FAILURE MECHANISMS OF CHURCHES


Basilica di San Benedetto - Norcia


Basilica di San Benedetto - Norcia


STV
Basilica di San Benedetto - Norcia


STV
Basilica di San Benedetto - Norcia


Basilica di San Benedetto - Norcia


STV
Concattedrale di Santa Maria Argentea - Norcia


STV
Concattedrale di Santa Maria Argentea - Norcia

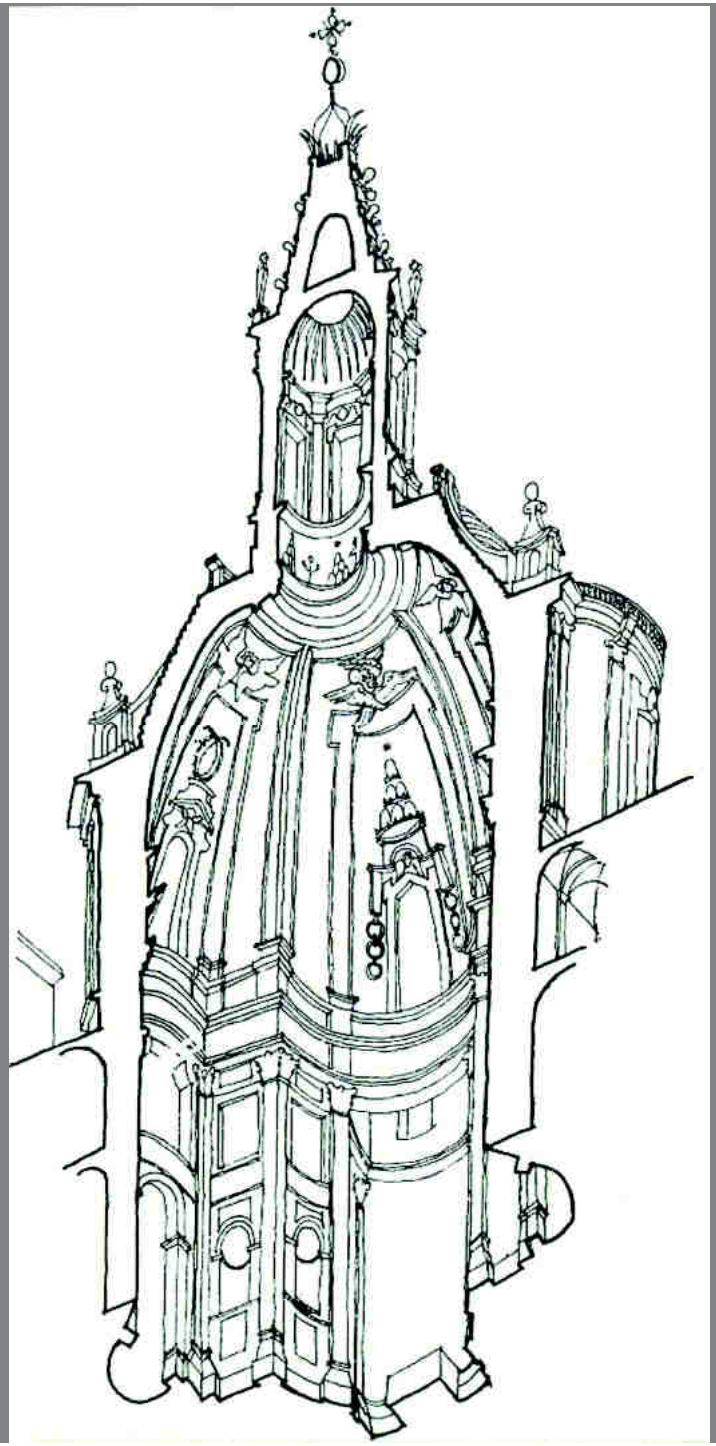

STV
Chiesa della Misericordia - Norcia


Chiesa della Misericordia - Norcia


Chiesa di Santa Maria delle Vergini
1562
Macerata
Distance from epicentre 40 miles
Damages to the dome


San Ivo alla Sapienza
Borromini , 1660
Rome
Distance from epicentre 70 miles
Cracks (re)appeared in the dome


San Ivo alla Sapienza
Borromini , 1660
Rome
Distance from epicentre 70 miles
Cracks (re)appeared in the dome



San Ivo alla Sapienza

Borromini , 1660

Rome

Distance from epicentre 70 miles

Cracks (re)appeared in the dome

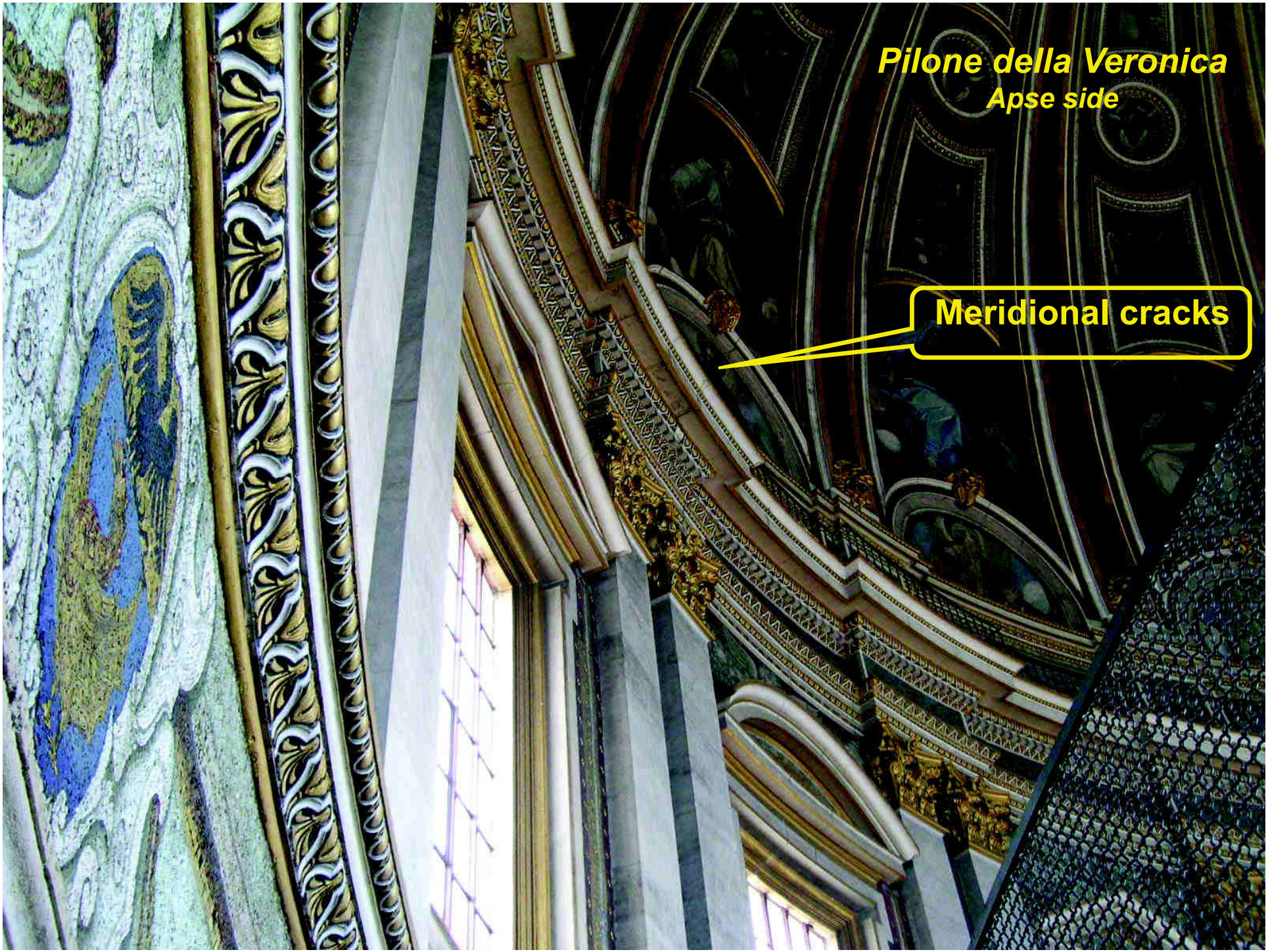
San Peter dome
Rome

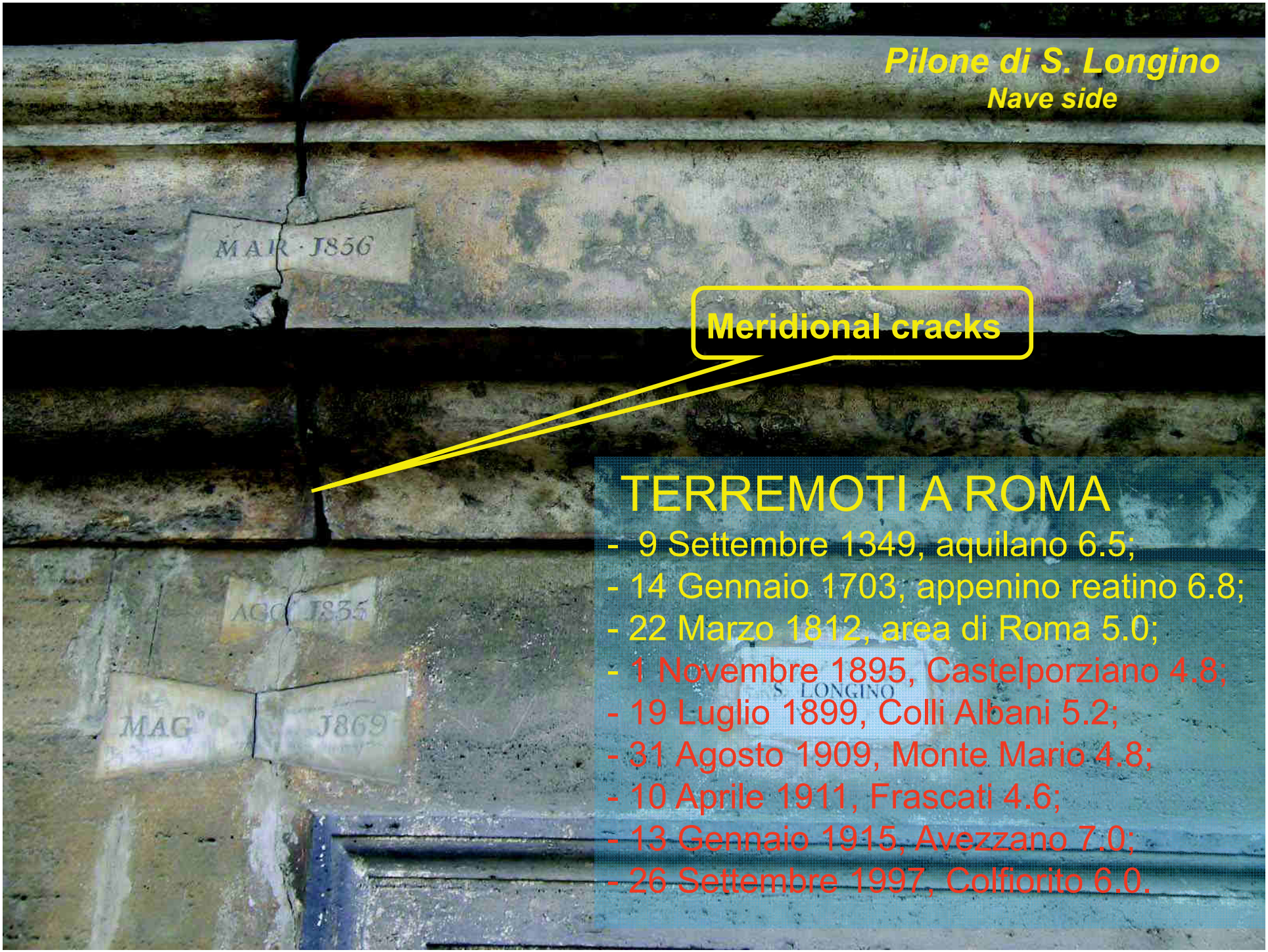
J. Dalla Porta, 1590

Insertions of new iron rings
G. Poleni e L. Vanvitelli,1743-48

Distance from epicentre 70 miles

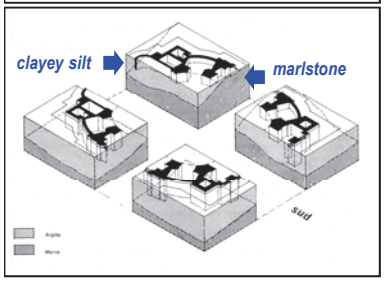
It would be interesting to know if any variation happened in the crack widths after the Norcia earthquake
No information available at the moment

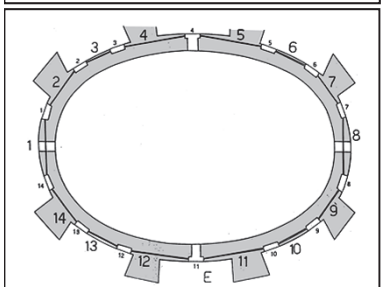

Pilone della Veronica
Apse side
Meridional cracks



TERREMOTI A ROMA

- 9 Settembre 1349, aquilano 6.5;
- 14 Gennaio 1703, appenino reatino 6.8;
- 22 Marzo 1812, area di Roma 5.0;
- 1 Novembre 1895, Castelporziano 4.8;
- 19 Luglio 1899, Colli Albani 5.2;
- 31 Agosto 1909, Monte Mario 4.8;
- 10 Aprile 1911, Frascati 4.6;
- 13 Gennaio 1915, Avezzano 7.0;
- 26 Settembre 1997, Colfiorito 6.0.





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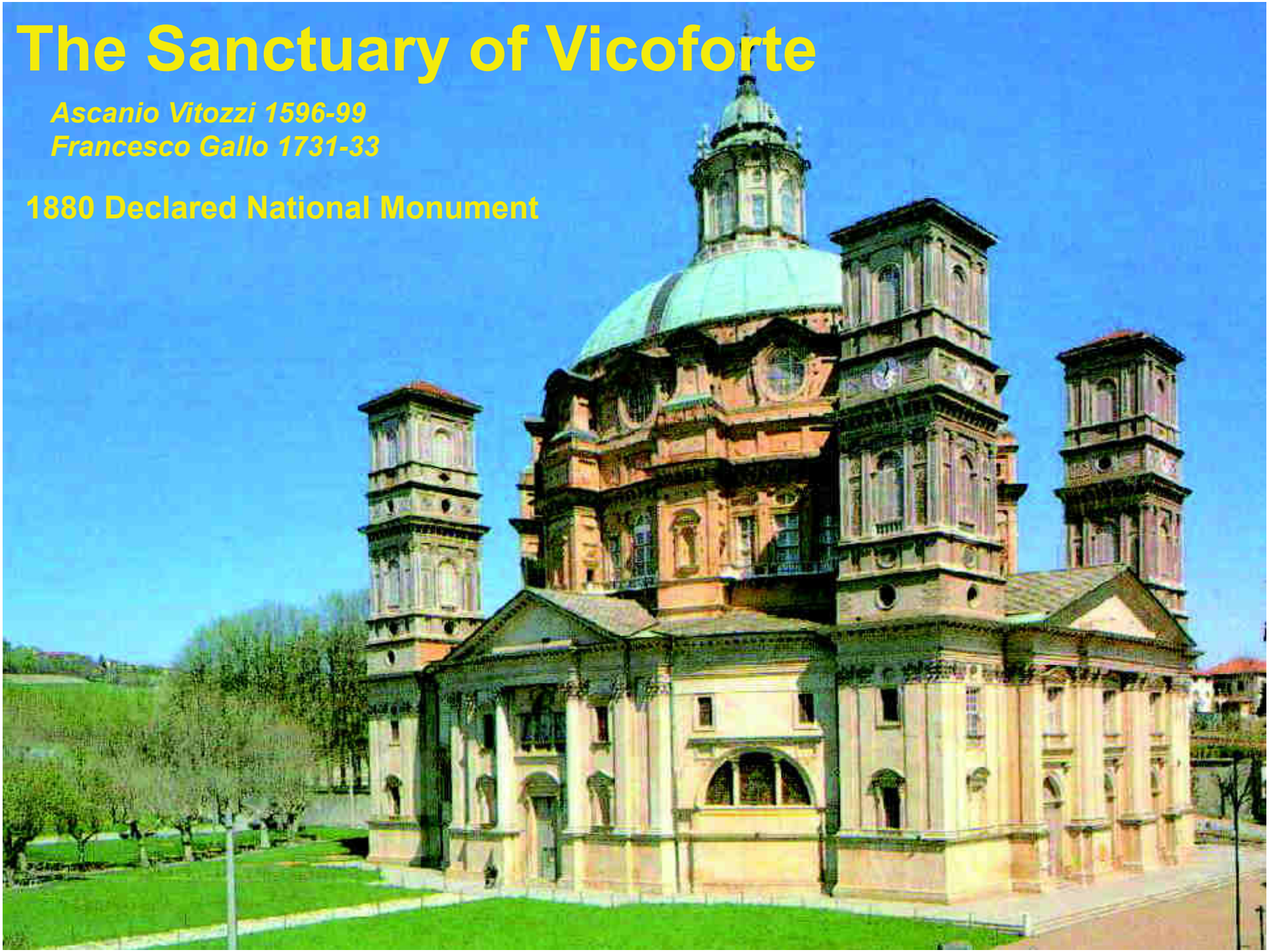
Case study of the survey and structural modeling for the reliability assessment of the world's largest elliptical masonry dome at Vicoforte, Italy

The Sanctuary of Vicoforte

Ascanio Vitozzi 1596-99
Francesco Gallo 1731-33

1880 Declared National Monument



The frescoes, a kind of artistic poem covering a surface of more than 65,000 sq feet, are the work of Mattia Bortoloni and Felice Biella (1752)


COMPARISON WITH OTHER
DOMES


The elliptical masonry dome of the
Sanctuary of Vicoforte
is the largest dome of this kind
in the world
•major internal axis 37.15 m
•minor internal axis 24.80 m
•maximum height of the monument 84 m

Comparison with other domes

(internal diameters)

Circular domes

- Pantheon 43.30 m
- San Pietro 42.84 m
- S. Maria del F. 42.0 m*

*diameter of the inscribed inner circle

- Gol Gumbaz 38.00 m
- Hagia Sophia 33 m
- St. Paul 33 m

Elliptical domes

Vicoforte 37.15x24.80 m

S. Andrea Quir. 25.80x16.25 m

S. Carlo Q. F.

S. Giacomo 23 ÷ 25 m x

S. Hermenegildo 16 ÷19 m

Conv. Bernarda

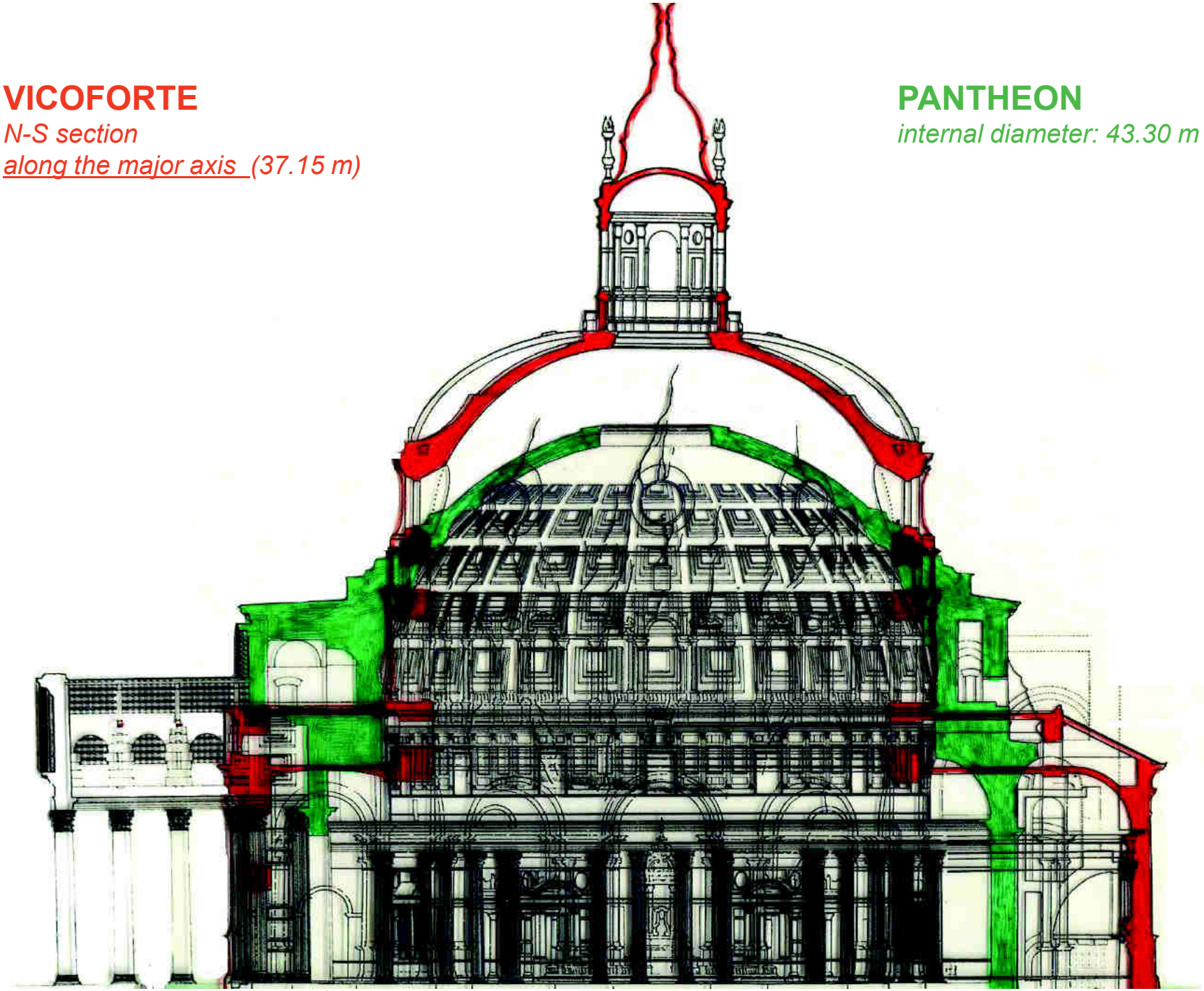
VICOFORTE

N-S section

along the major axis (37.15 m)

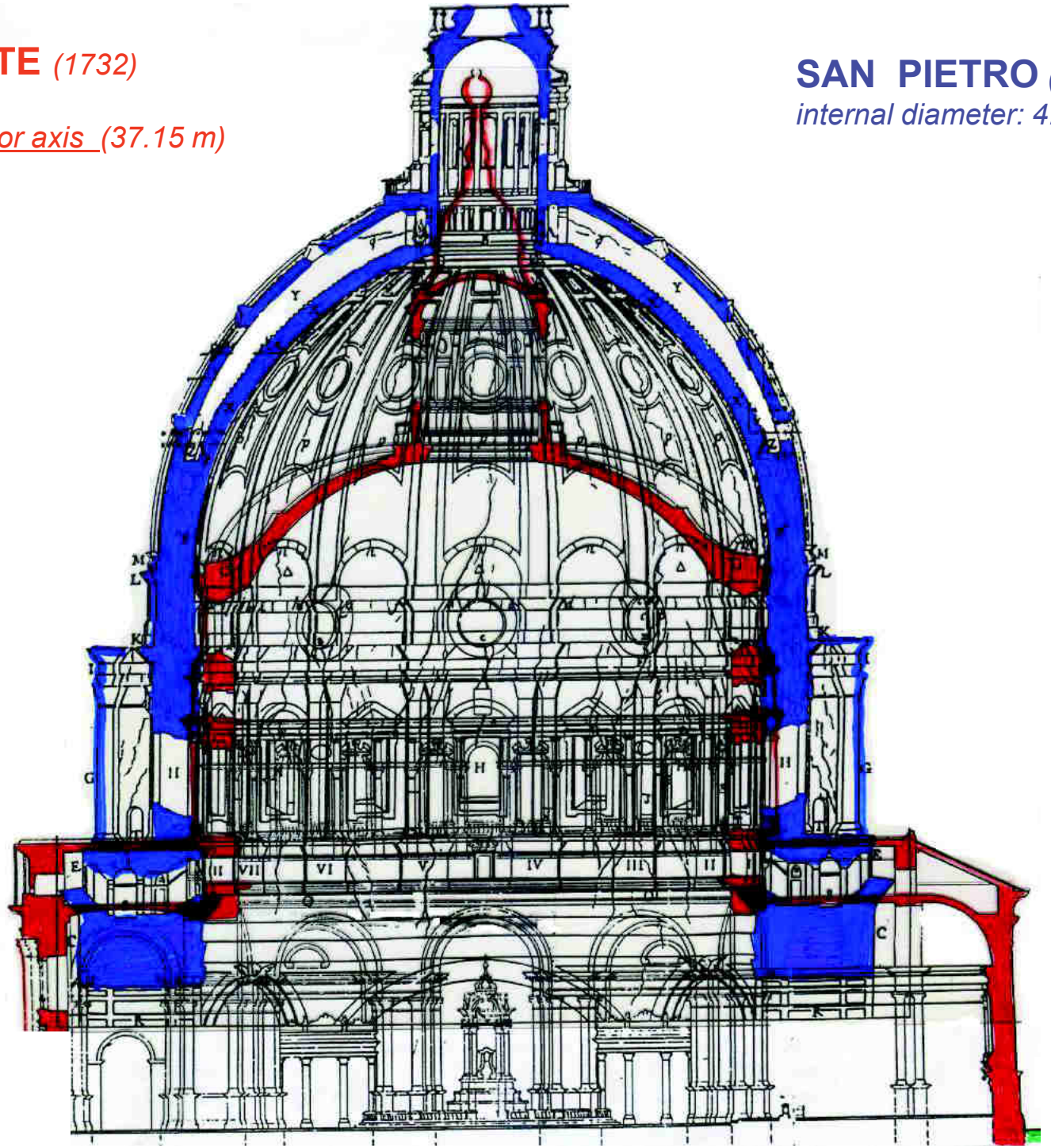
PANTHEON

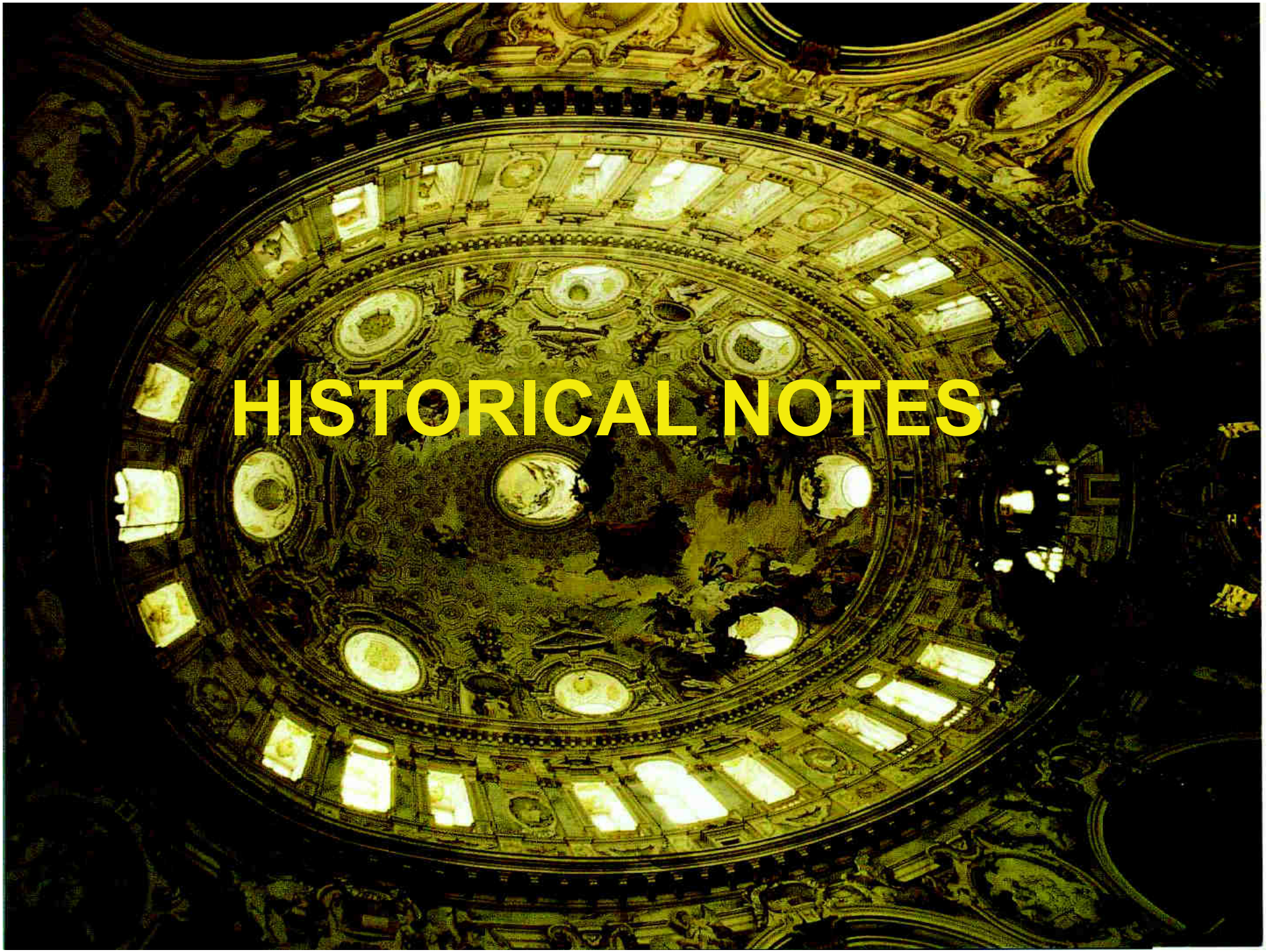
internal diameter: 43.30 m



VICOFORTE *(1732)*
N-S section
along the major axis (37.15 m)

SAN PIETRO *(1590)*
internal diameter: 42.84 m




HISTORICAL NOTES

Filippo II d'Asburgo (*Felipe II de España*)
(1527 – 1598)

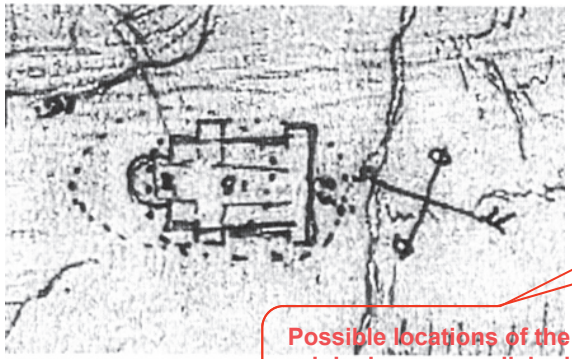
Caterina di Spagna
(1567-1597)

Carlo Emanuele I di Savoia
(1562-1630)

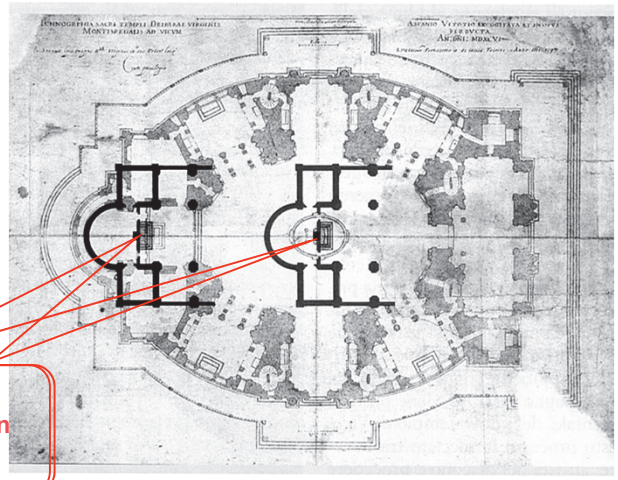
The Sanctuary in Vicoforte

as a Mausoleum for the dynasty of the Dukes of Savoia

[Kings of Savoia (1713) , Kings of Italy (1861)]



Possible locations of the original unaccomplished latin cross churh

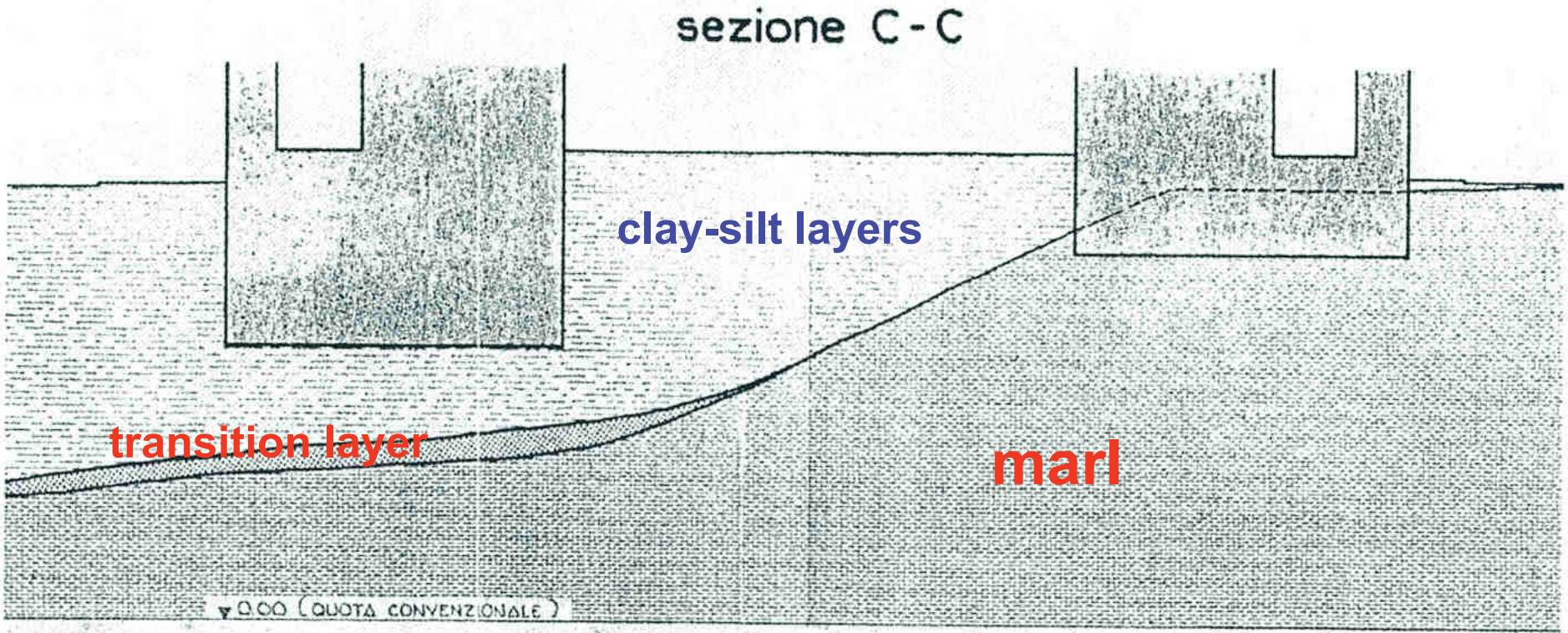


Preliminary sketch

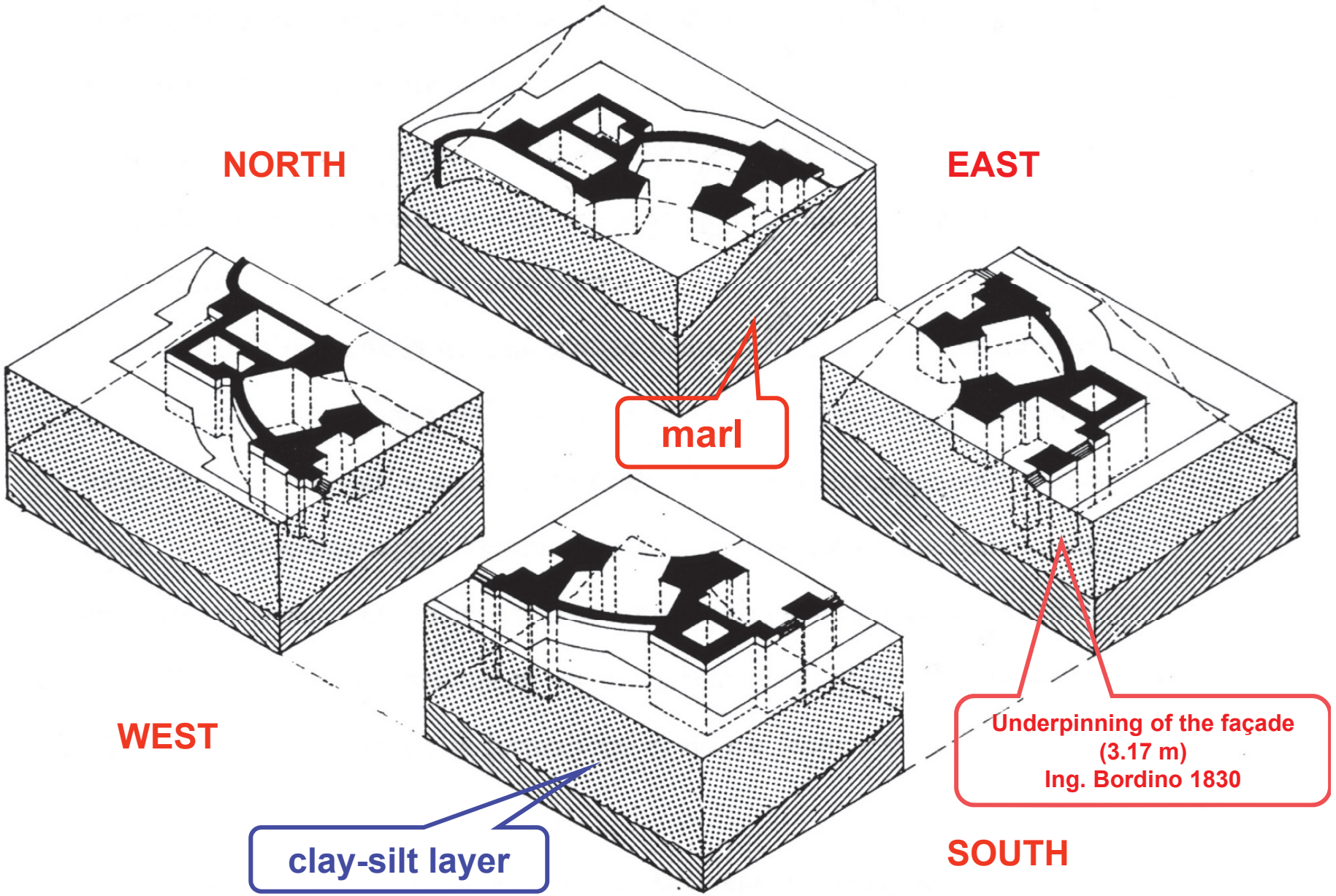
Final drawings by Ascanio Vitozzi (1596)

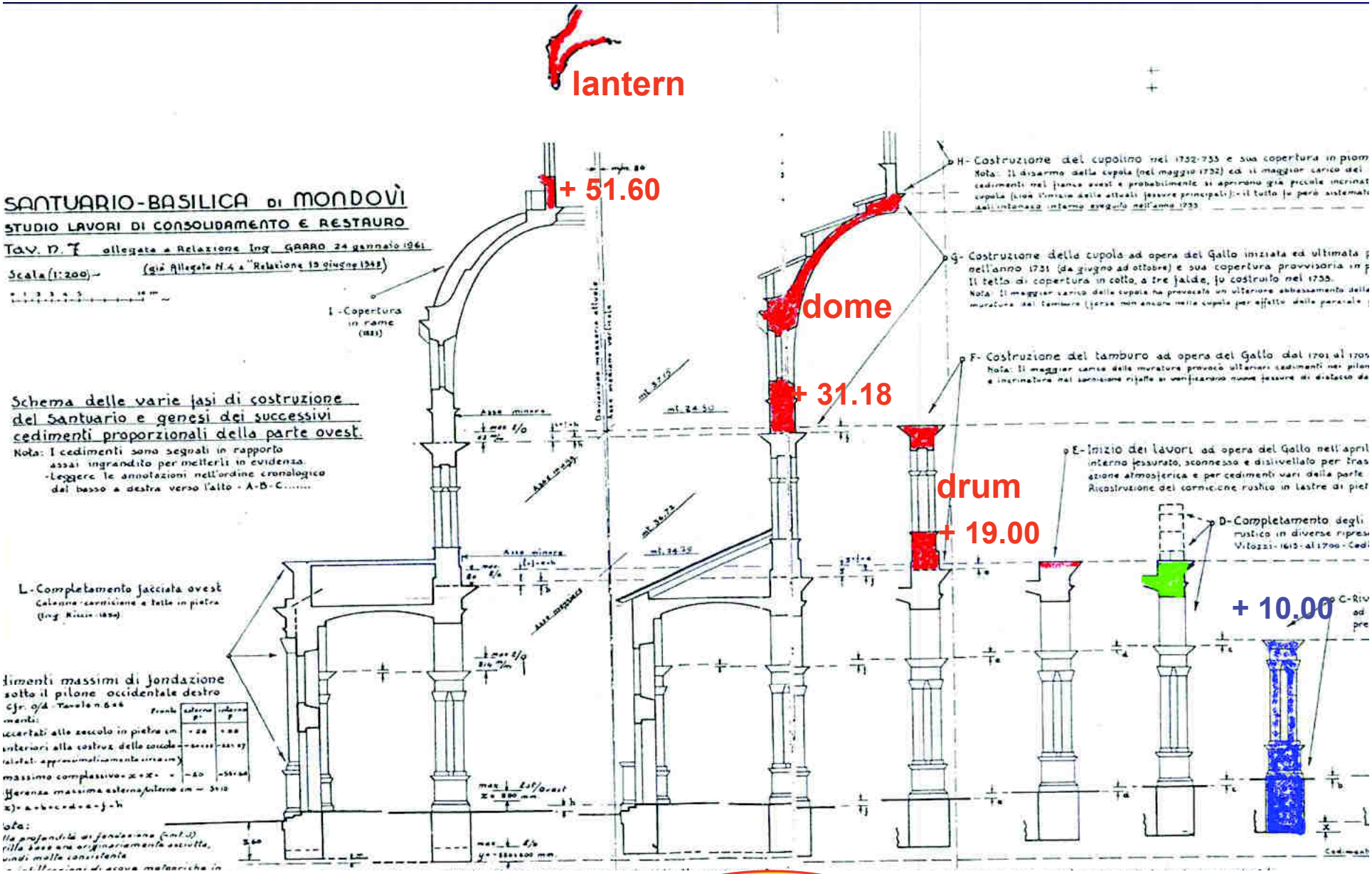
Carlo Emanuele I di Savoia
(1562-1630)

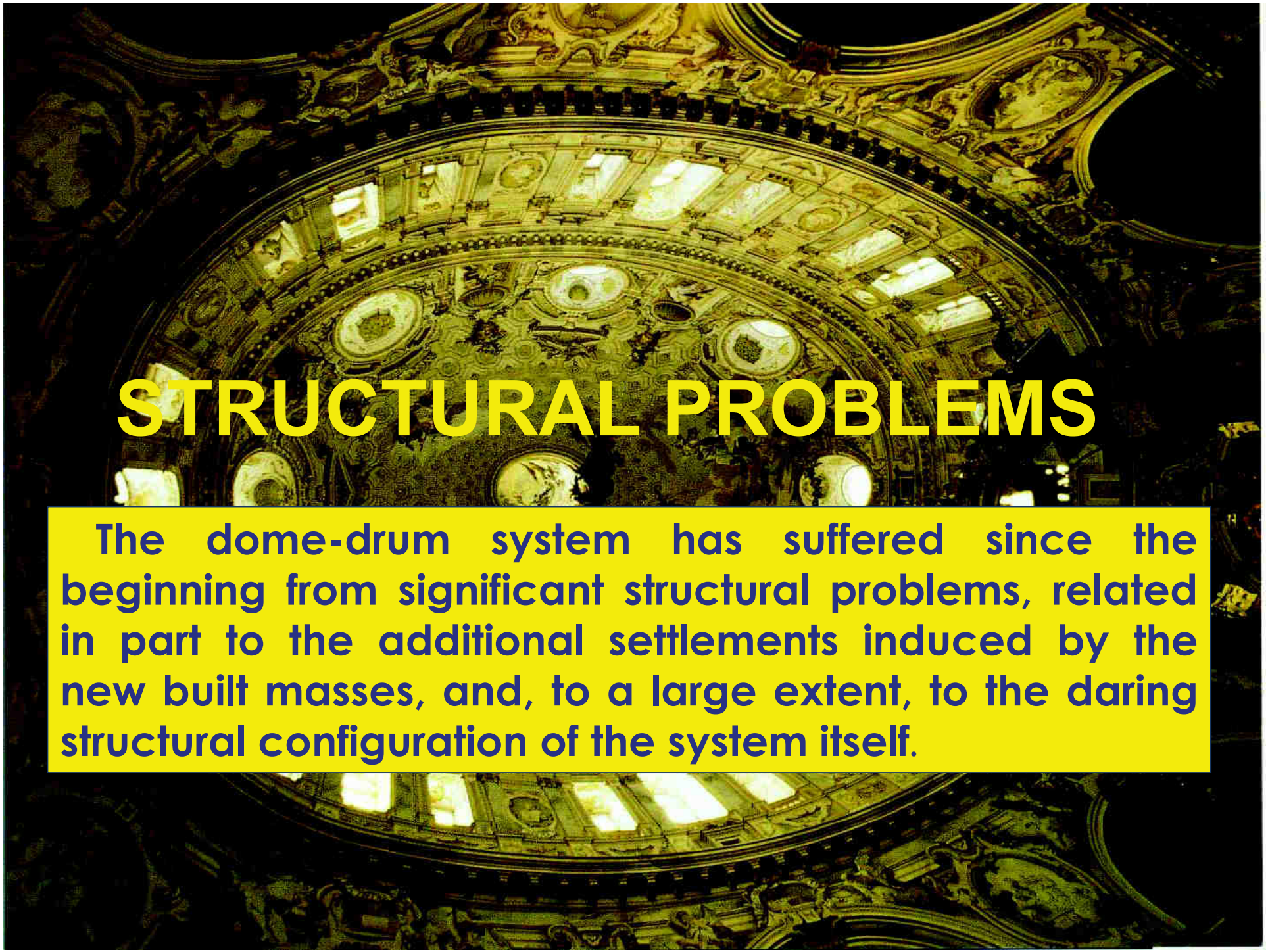
- **Inadequate choice of site:**
  - 1/3rd on consistent marl in the N.E. side
  - 2/3rd on clay-silt layers of thickness up to 3.5 m



SCHEMATIC VERTICAL SECTION OF FOUNDATIONS AND FOUNDATION LAYERS


NORTH
EAST
marl
WEST
Underpinning of the façade
(3.17 m)
Ing. Bordino 1830
clay-silt layer
SOUTH


lantern
+ 51.60
dome
+ 31.18
drum
+ 19.00
+ 10.00
SANTUARIO-BASILICA di MONDOVÌ
STUDIO LAVORI DI CONSOLIDAMENTO E RESTAURO
Tav. D. 7 allegata a Relazione Ing. GARRO 24 gennaio 1961
Scala (1:200)
(già Allegato N.4 a "Relazione 19 giugno 1948)
Schema delle varie fasi di costruzione del Santuario e genesi dei successivi cedimenti proporzionali della parte ovest.
Nota: I cedimenti sono segnati in rapporto assai ingrandito per metterli in evidenza.
-Leggere le annotazioni nell'ordine cronologico dal basso a destra verso l'alto - A-B-C.....
1732-33
1731
1705-30
1701
1615-92
1596-99
Francesco Gallo
A. Vitozzi
Construction of the dome
Time line



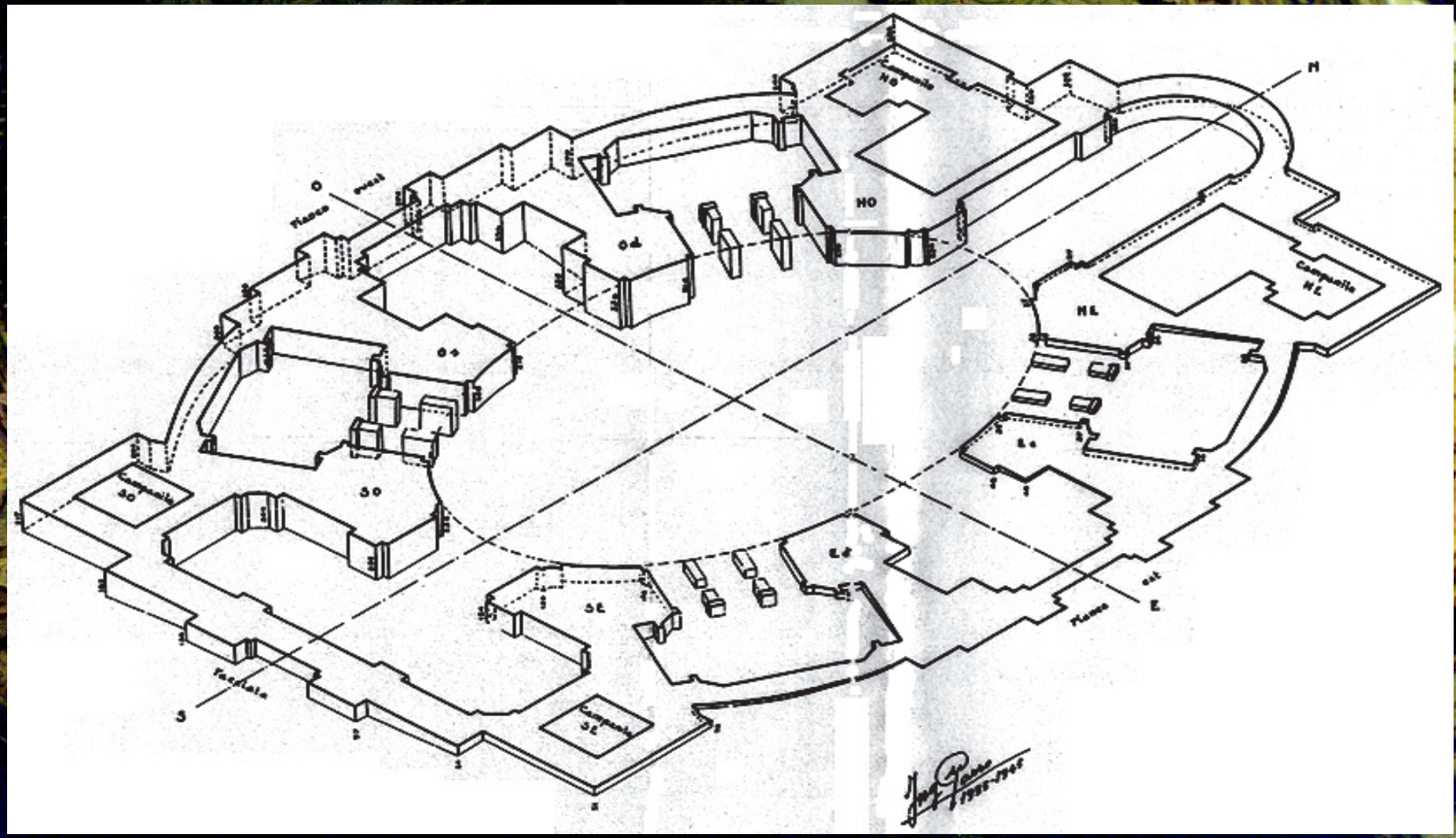
STRUCTURAL PROBLEMS

The dome-drum system has suffered since the beginning from significant structural problems, related in part to the additional settlements induced by the new built masses, and, to a large extent, to the daring structural configuration of the system itself.

Foundation settlements

(Assonometria, Garro 1962)

Maximum differential settlements WEST vs NORTH-EAST : 33 cm



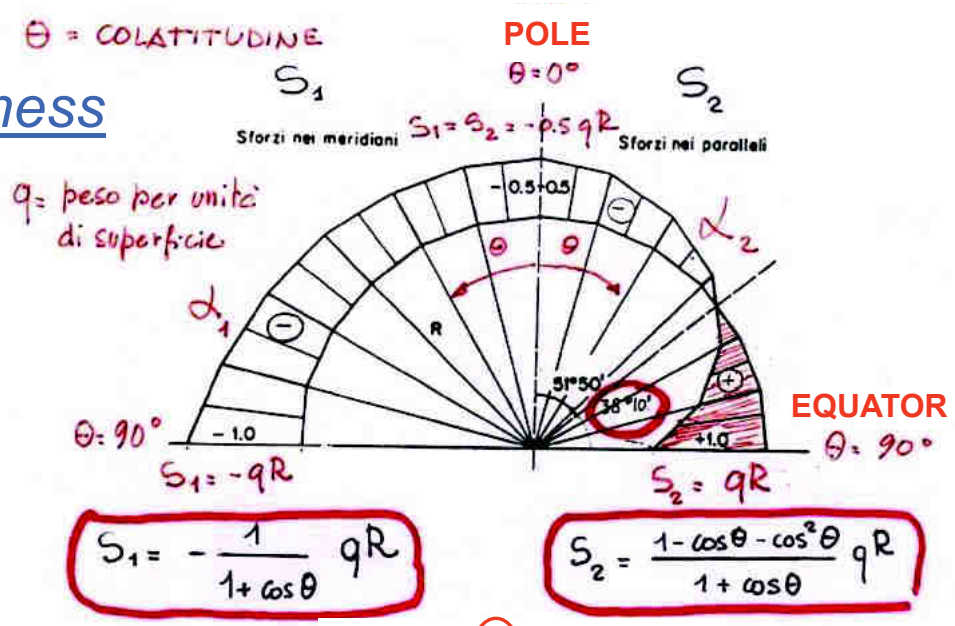

Cracks in the dome

Spherical dome of uniform thickness

- ✓ *Membrane solution*
- ✓ *Self weight "q"*

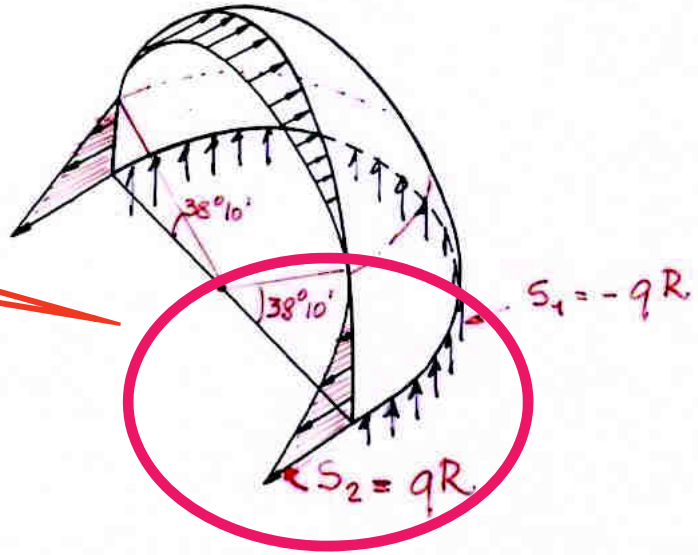
S_1 = meridional force

S_2 = hoop force

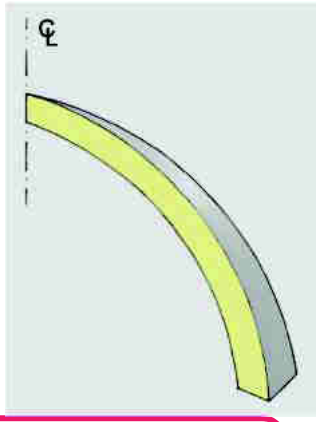


$S_{1,2} = \alpha\ qr$

Field of tension hoop forces S_2 between equator and latitude 38° 10'



Schematic behaviour of masonry domes



Compressed cap

Compression stresses S_1 along the meridians

Cracks along the meridians

Dome

Lack of hoop (circumferential) stresses S_2

Need of tension:
- *tension ring and/or*
- *masonry buttresses*

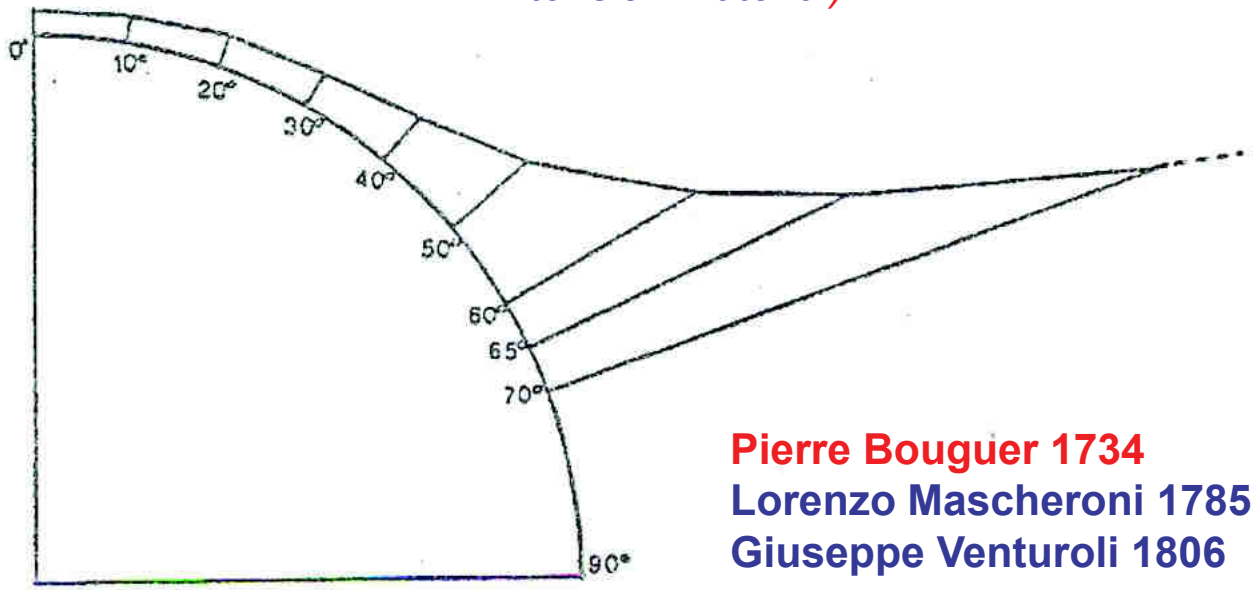
Lunes **(dome and drum slices)**
System of converging arches

Drum

Geometry of the dome (1731)

Gradi	Spessori
0°	1
10°	1,046
20°	1,205
30°	1,539
40°	2,224
50°	3,765
60°	8,000
65°	13,248
70°	24,994
80°	190,977
89°	171467,8
90°	indet.

Theoretical determination of the thickness of a semi-spherical dome without tension stresses along the parallels *(i.e. for a rigid no-tension material)*



Pierre Bouguer 1734
Lorenzo Mascheroni 1785
Giuseppe Venturoli 1806

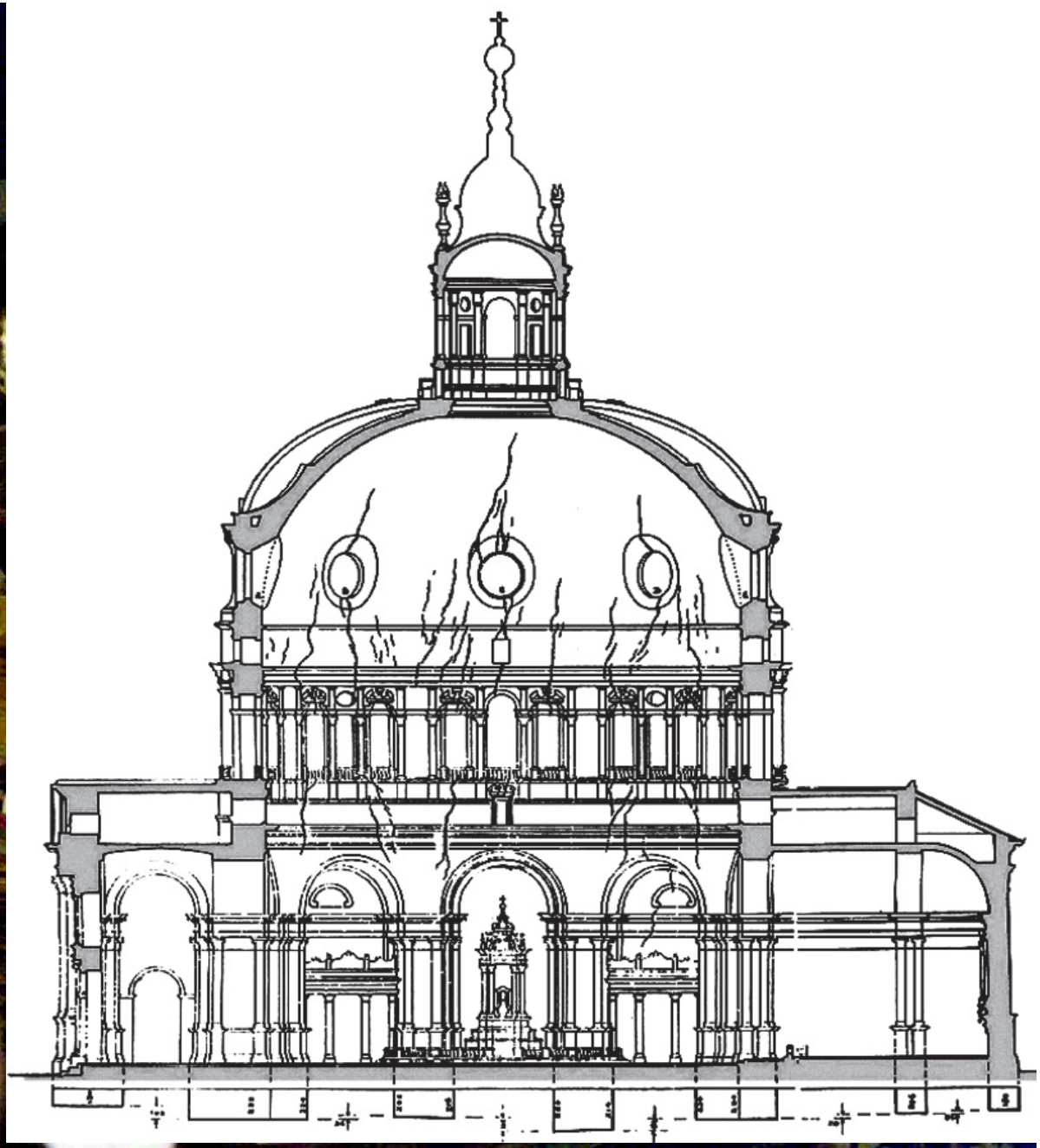
Pierre Bouguer, *Sur les lignes courbes qui sont propres à former les voû tes en* dôme, Académie Royale de France, 1734
Lorenzo Mascheroni, *Nuove ricerche sull'equilibrio delle volte*, Bergamo 1785
Giuseppe Venturoli, *Elemenrti di Meccanica e d'Idraulica*, 1806

Cracks in dome and drum

N-S cross section

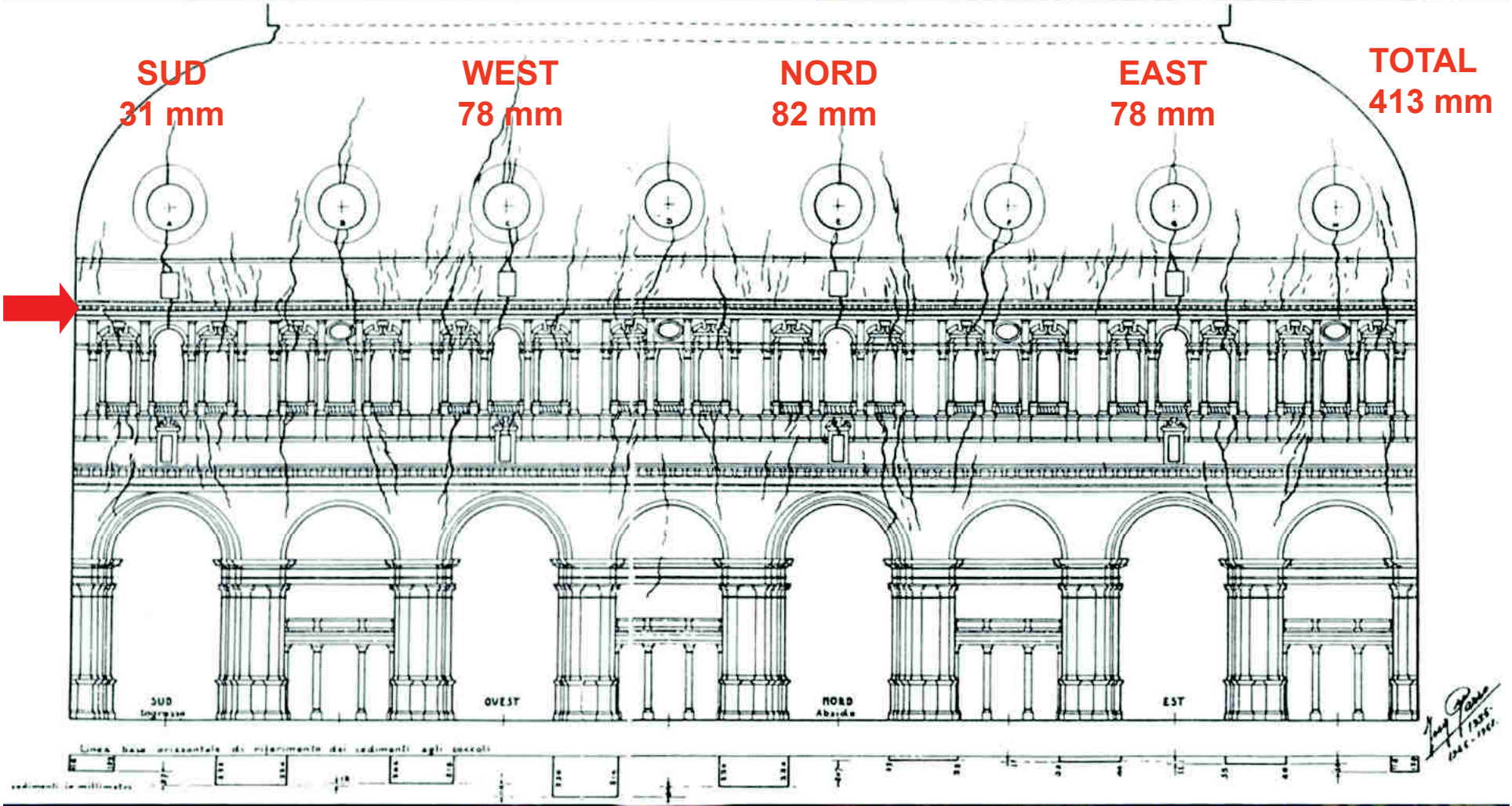
WEST view

(Garro 1962)



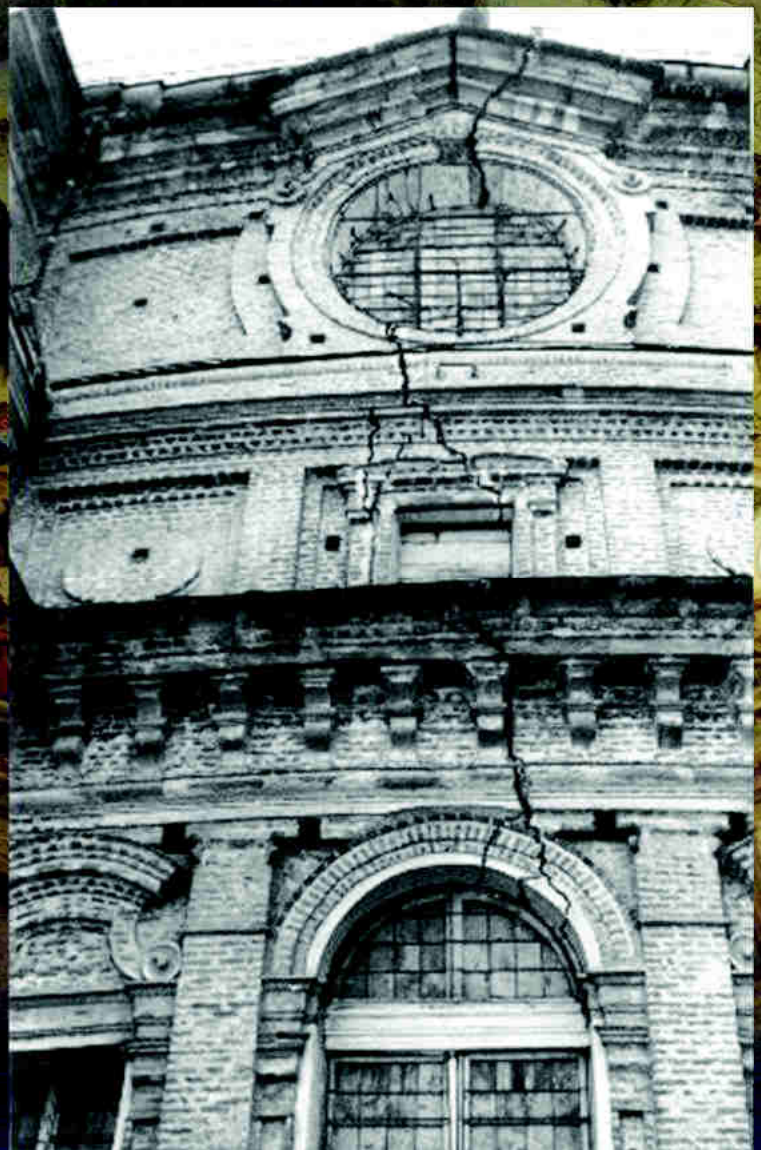
Cracks in dome and drum

Developed prospect (Garro 1962)

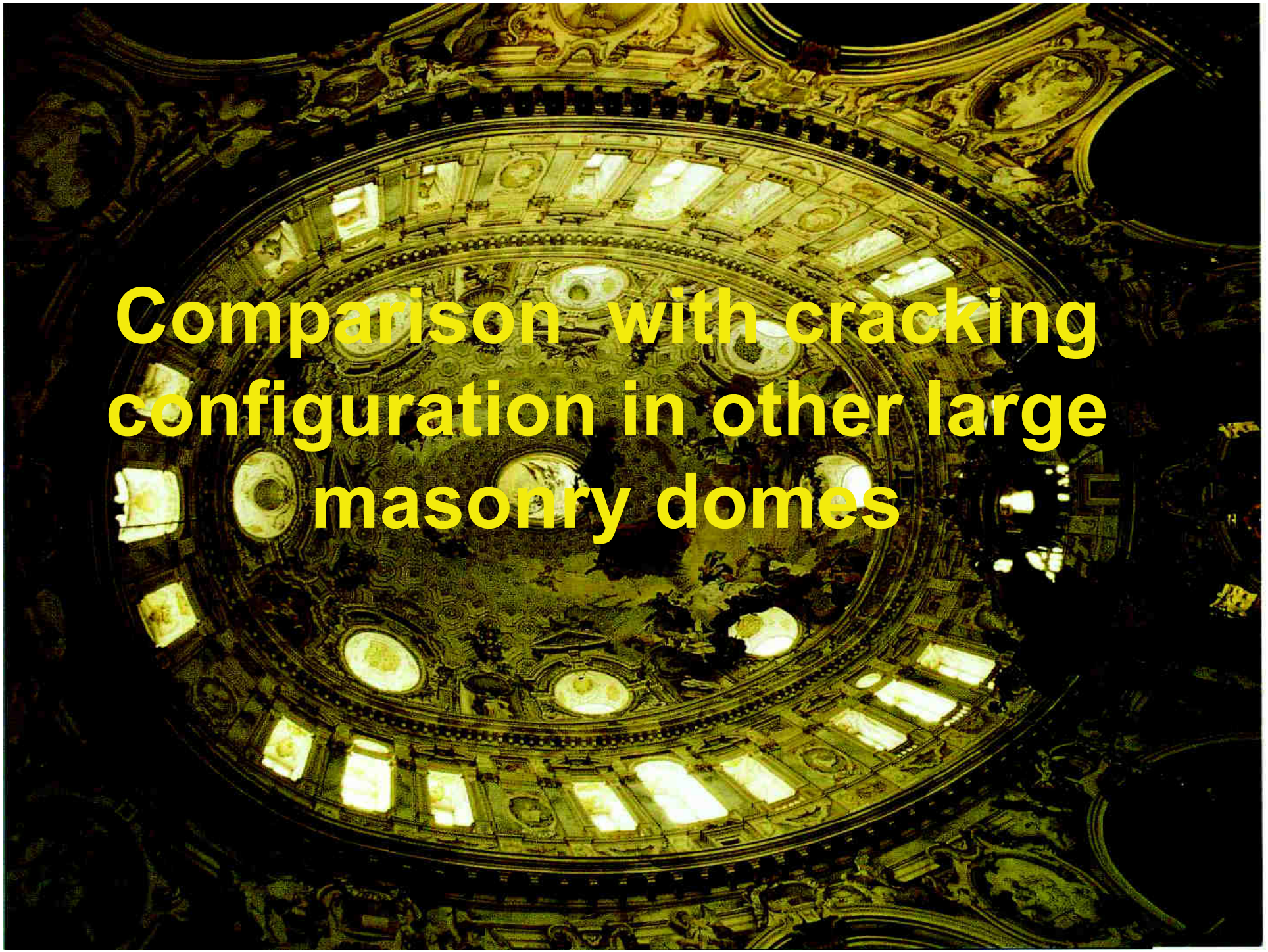


Cracks in dome and drum

External view of the large meriodional crack on WEST side before repair and strengthening works



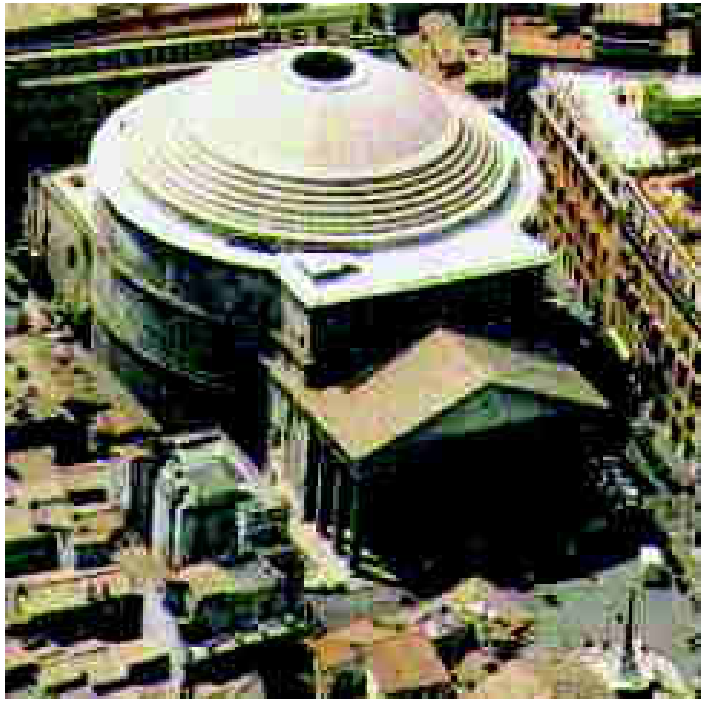
Development of diagonal cracks in the buttresses


Comparison with cracking configuration in other large masonry domes

Pantheon

Rome 118 to 128 A.D.

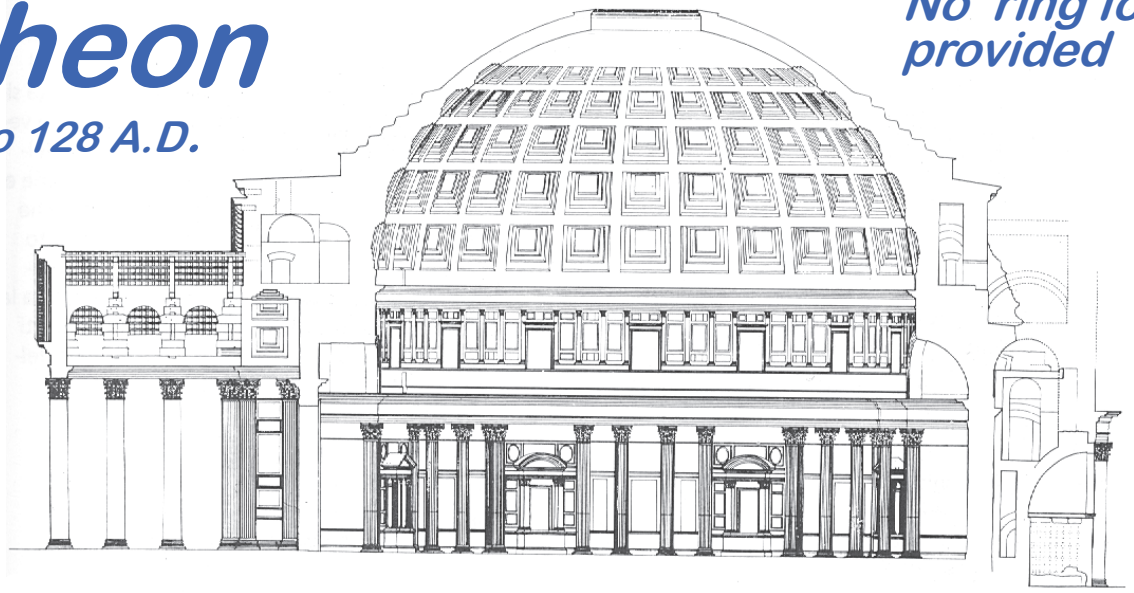
Φ_i 43.30 m



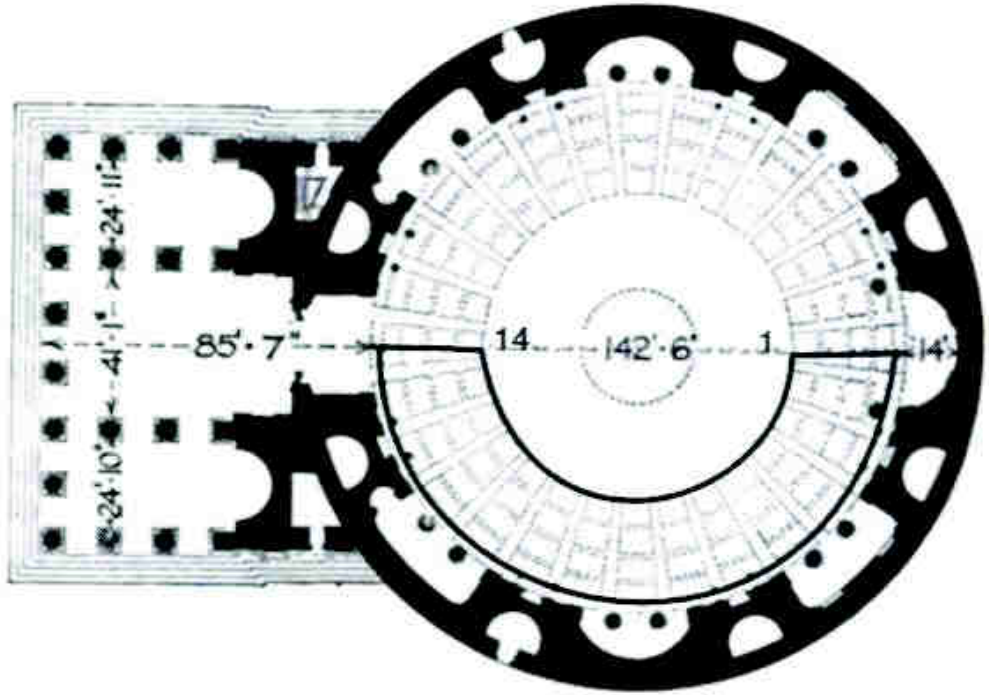
Pantheon

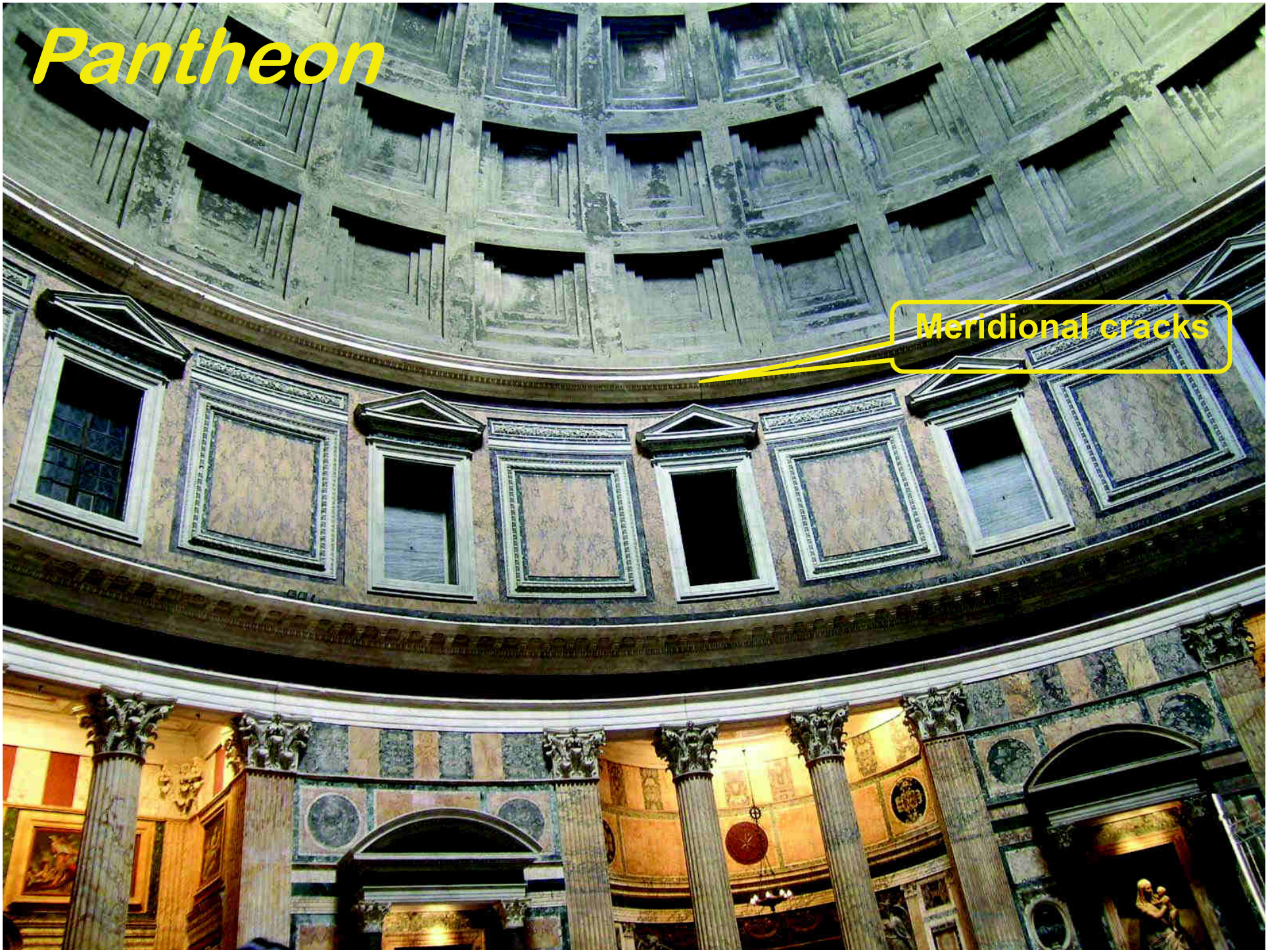
Rome 118 to 128 A.D.

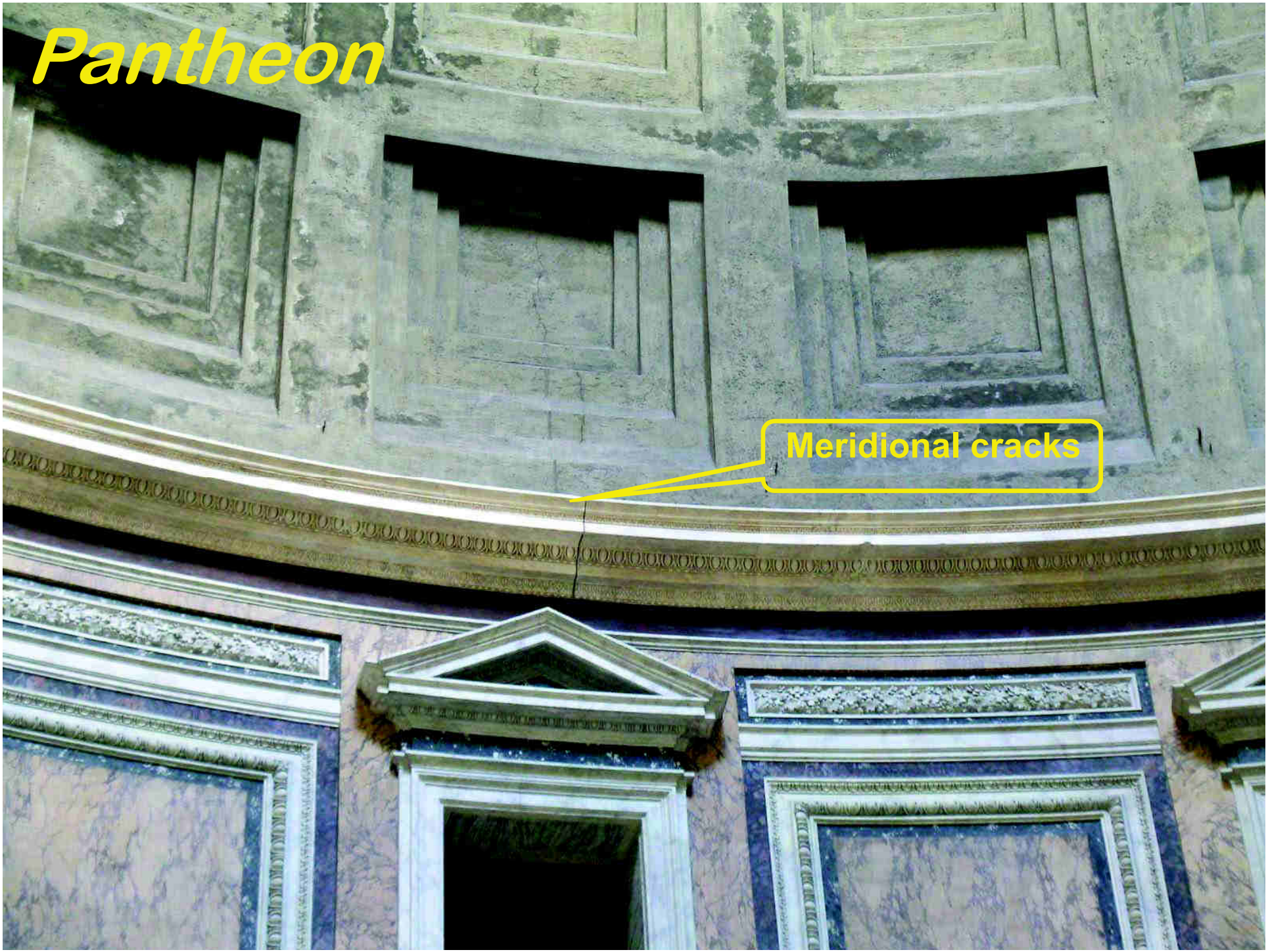
Φ_i 43.30 m



No ring for hoop tension is provided




Pantheon
Meridional cracks

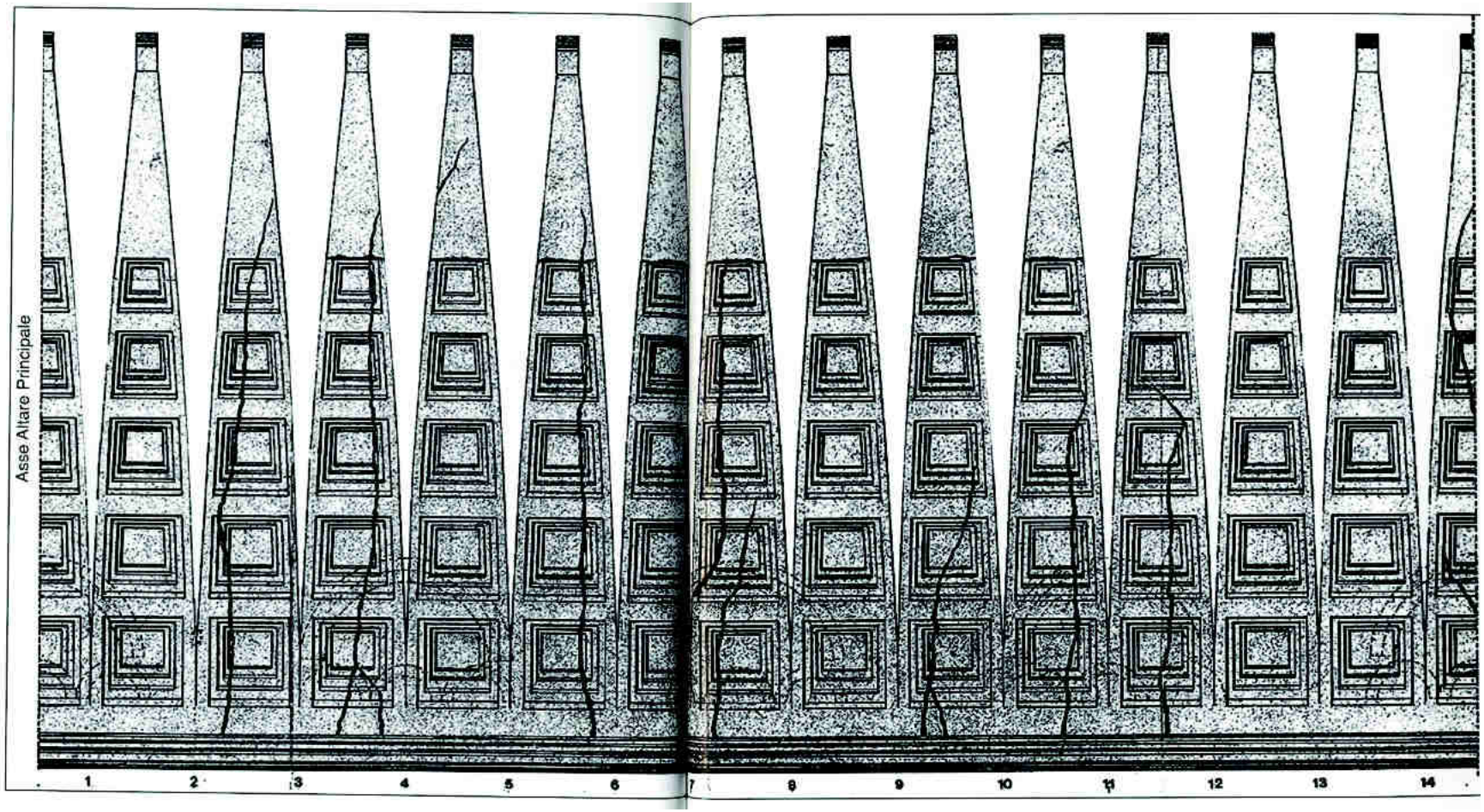

Pantheon
Meridional cracks

Pantheon

Rome 118 to 128 A.D.

Φ_i 43.30 m

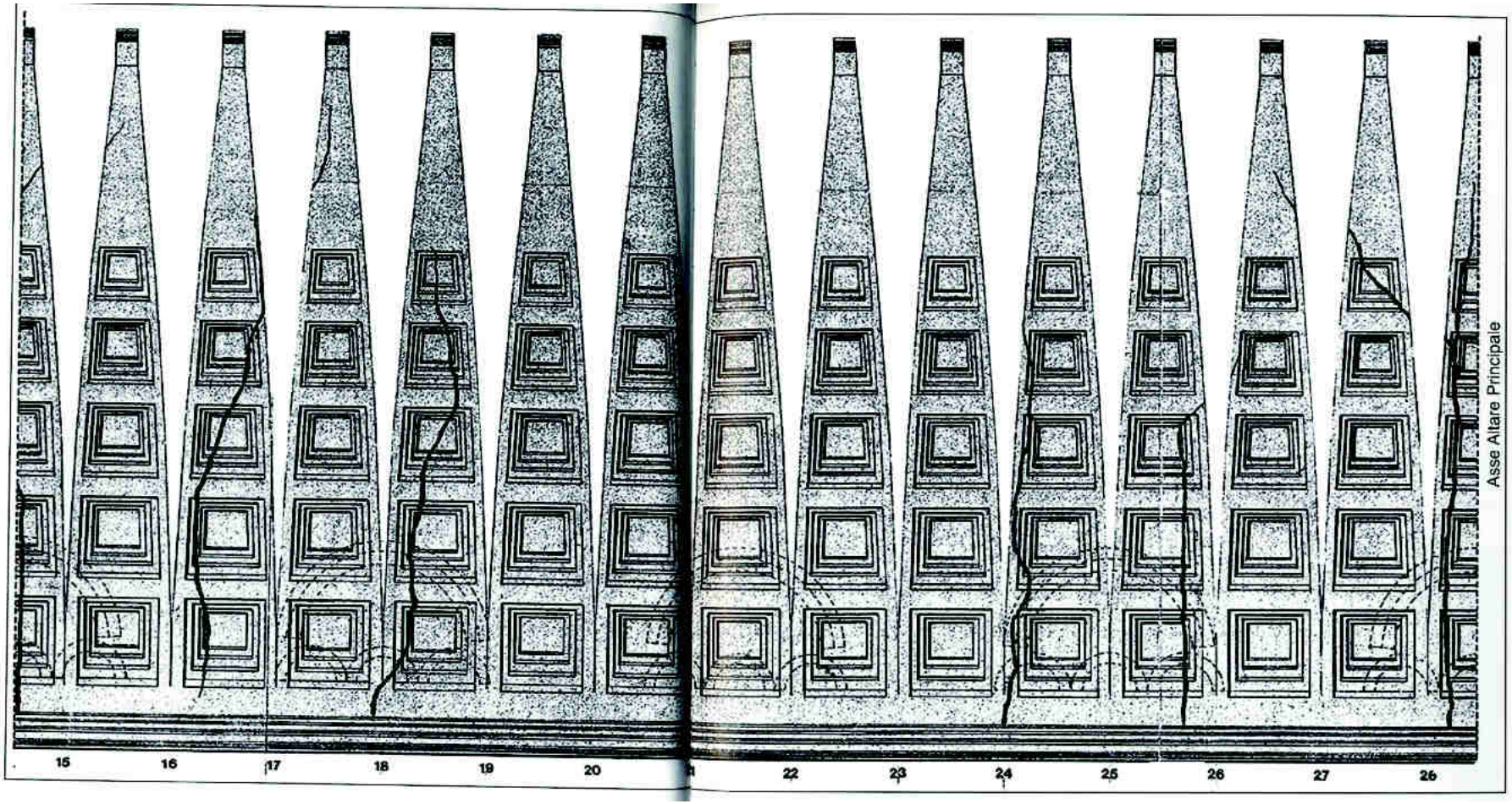
fig. 4a - Quadro fessurativo rilevato da Terenzio a partire dall'asse dell'altare principale e numerando da 1 a 28 i costoloni
Parti 1 - 14



Pantheon

Rome 118 to 128 A.D.

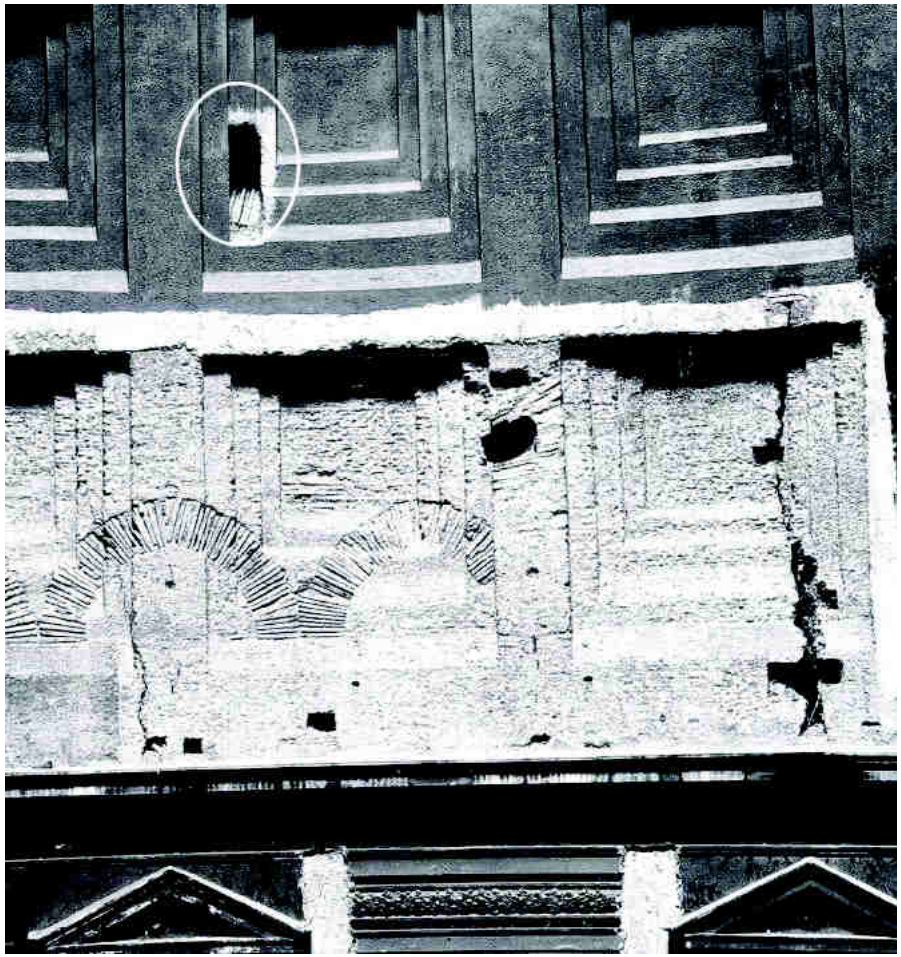
Φ_i 43.30 m

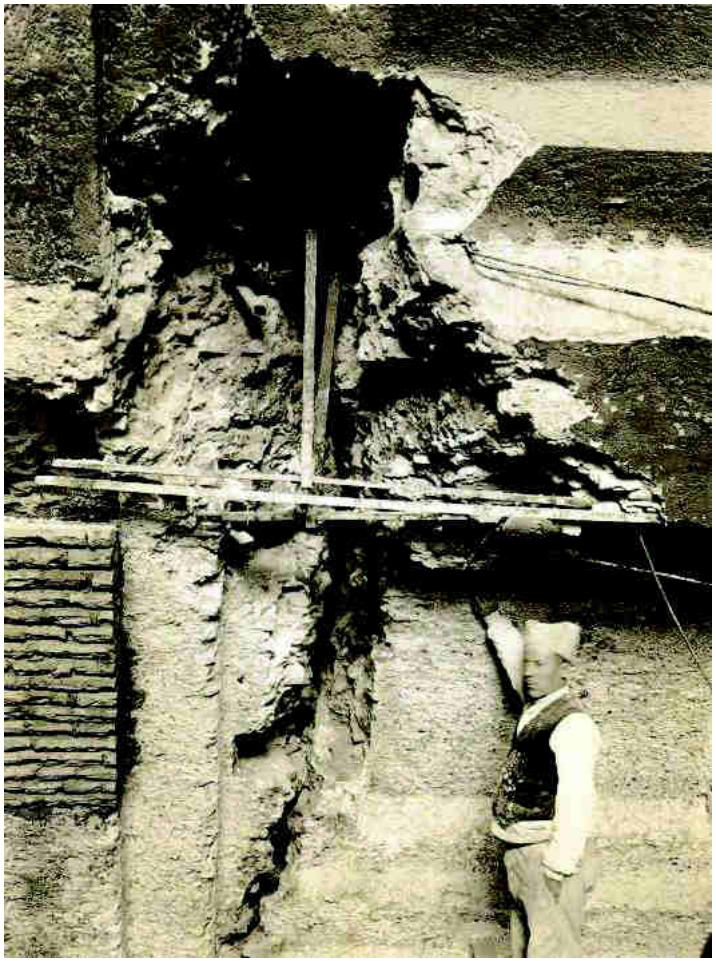


Pantheon

Rome 118 to 128 A.D.

Φ_i 43.30 m

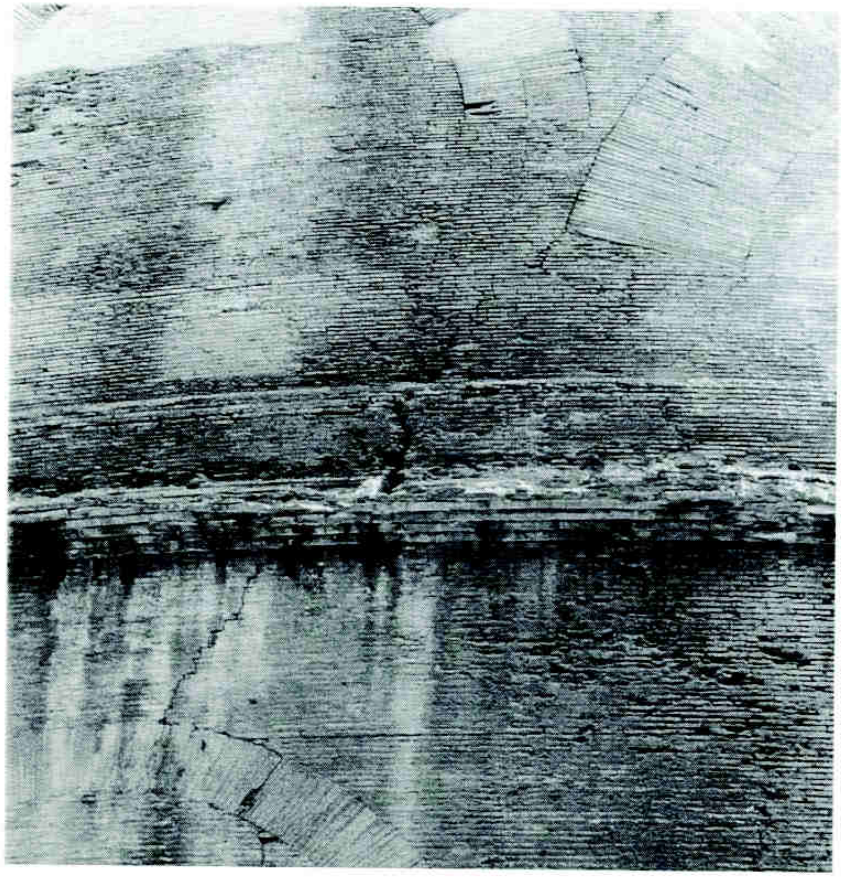


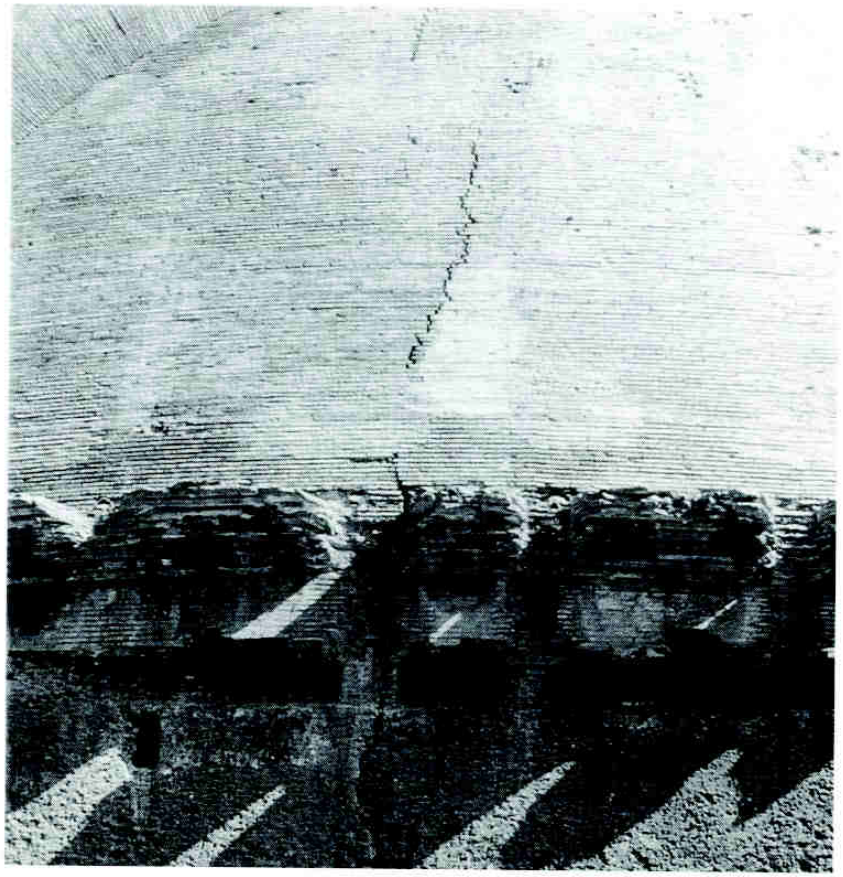


Pantheon

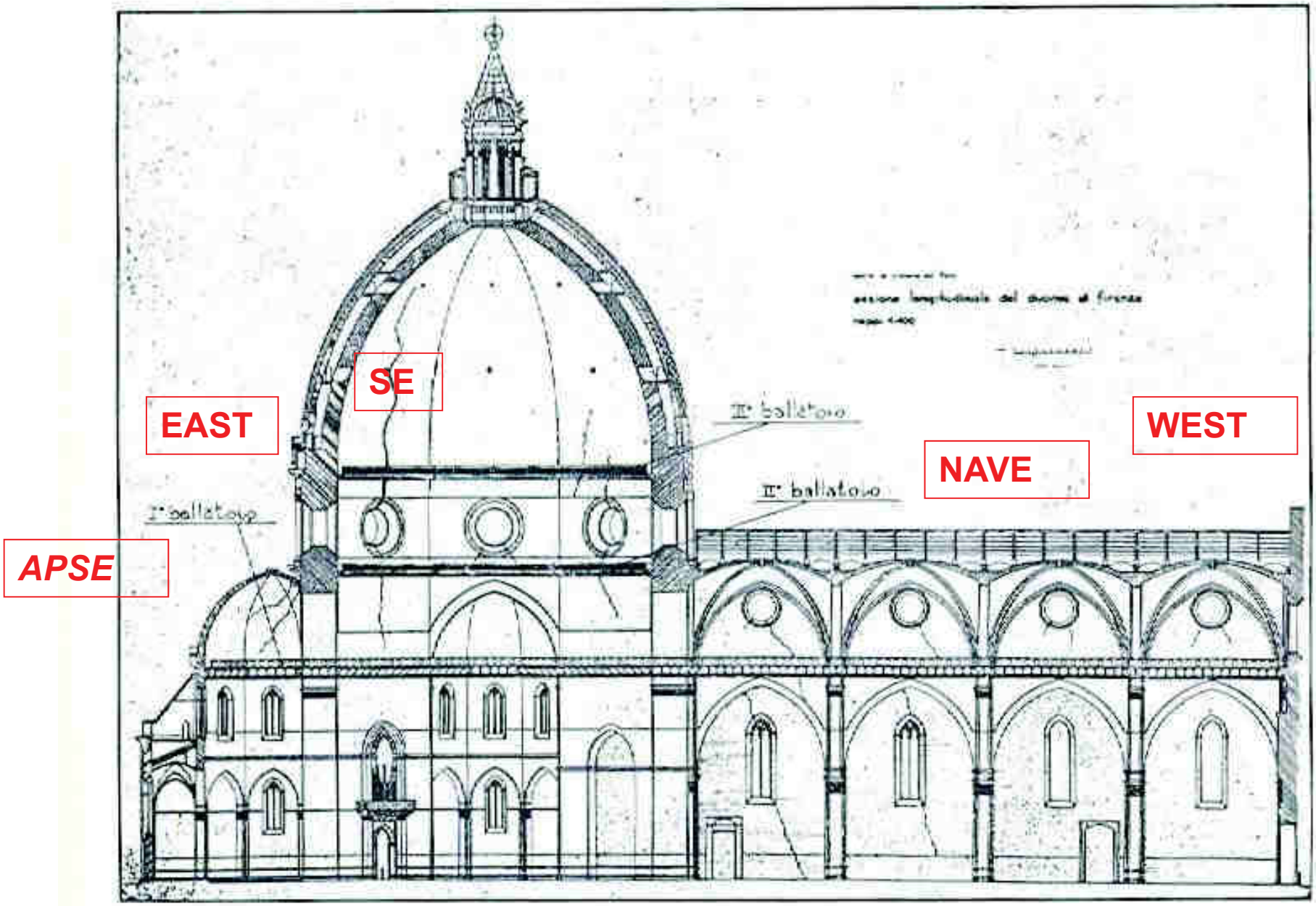
Rome 118 to 128 A.D.

Φ_i 43.30 m

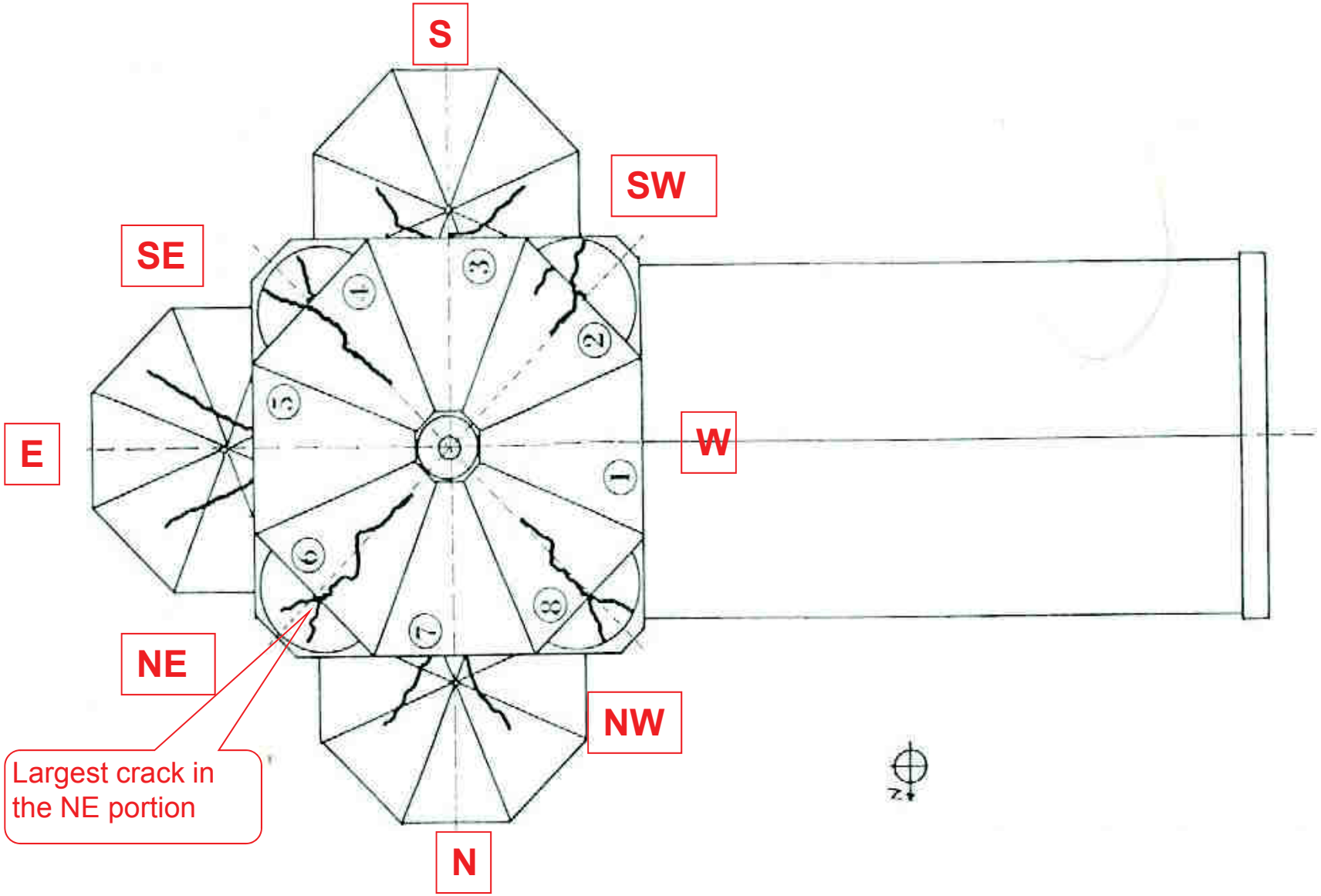




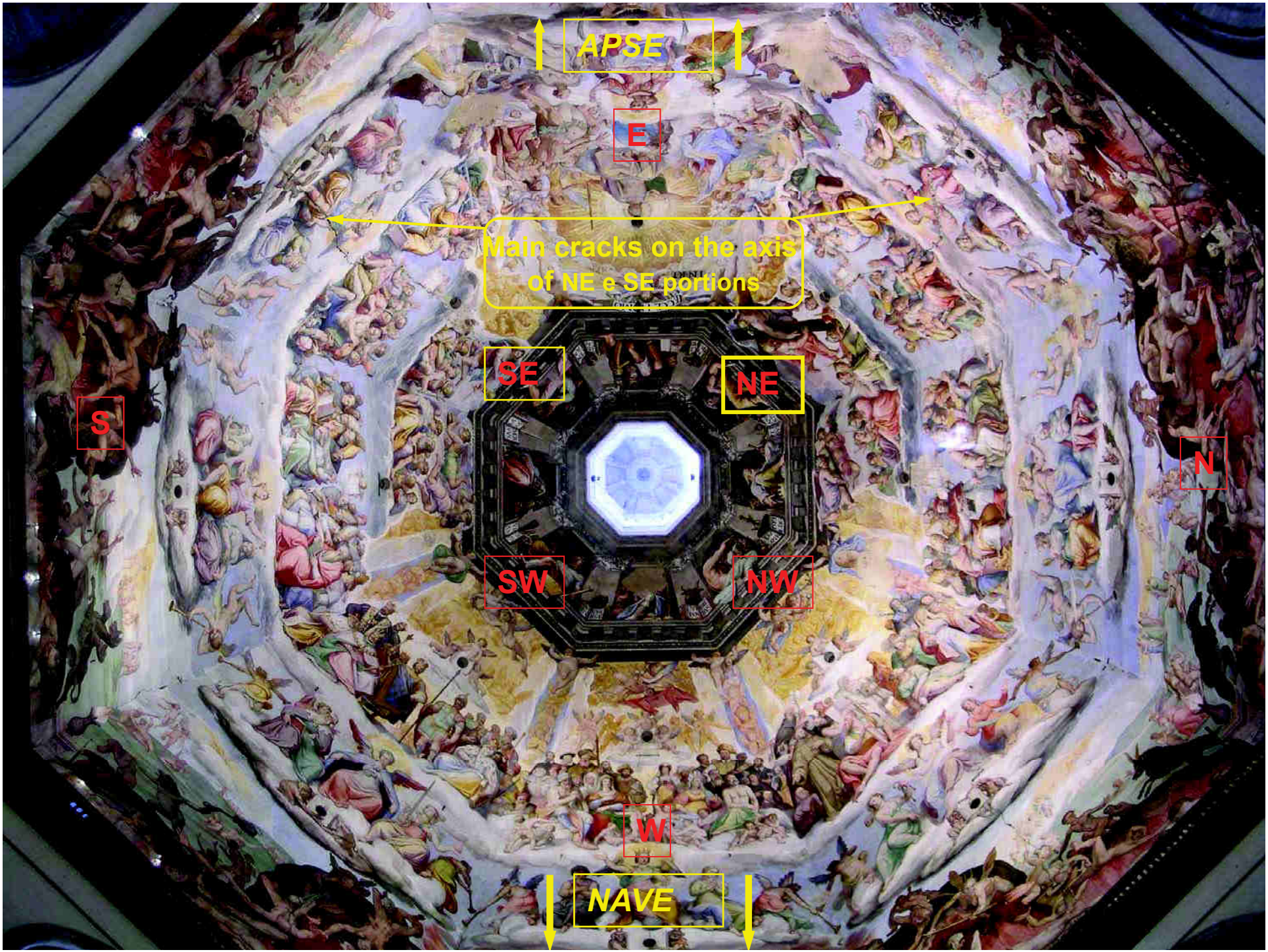

S. Maria del F.
F. Brunelleschi 1436
Φ¡ 40.93 m *
*diametro del cerchio inscritto
No iron ring for hoop
tension is provided

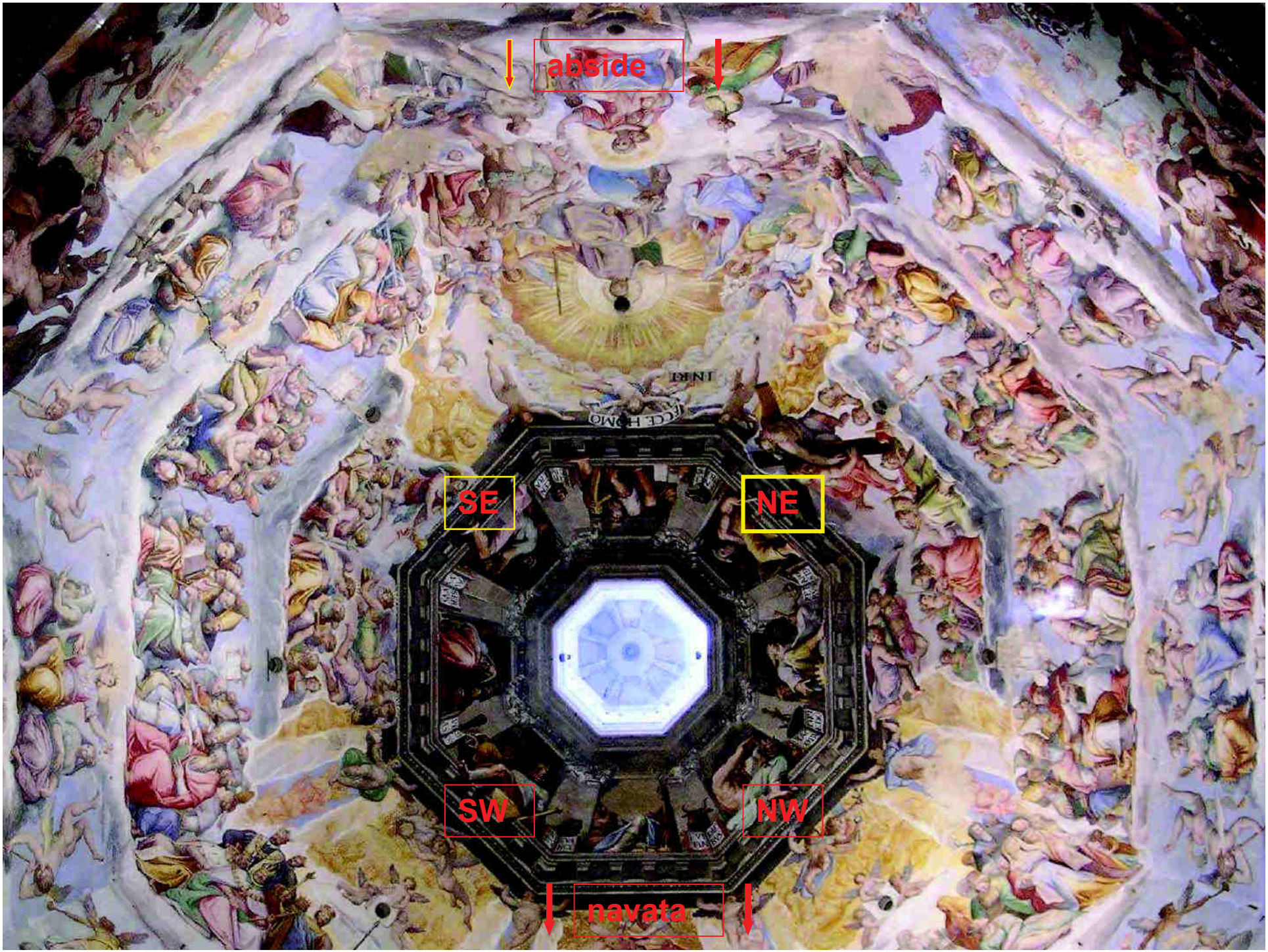


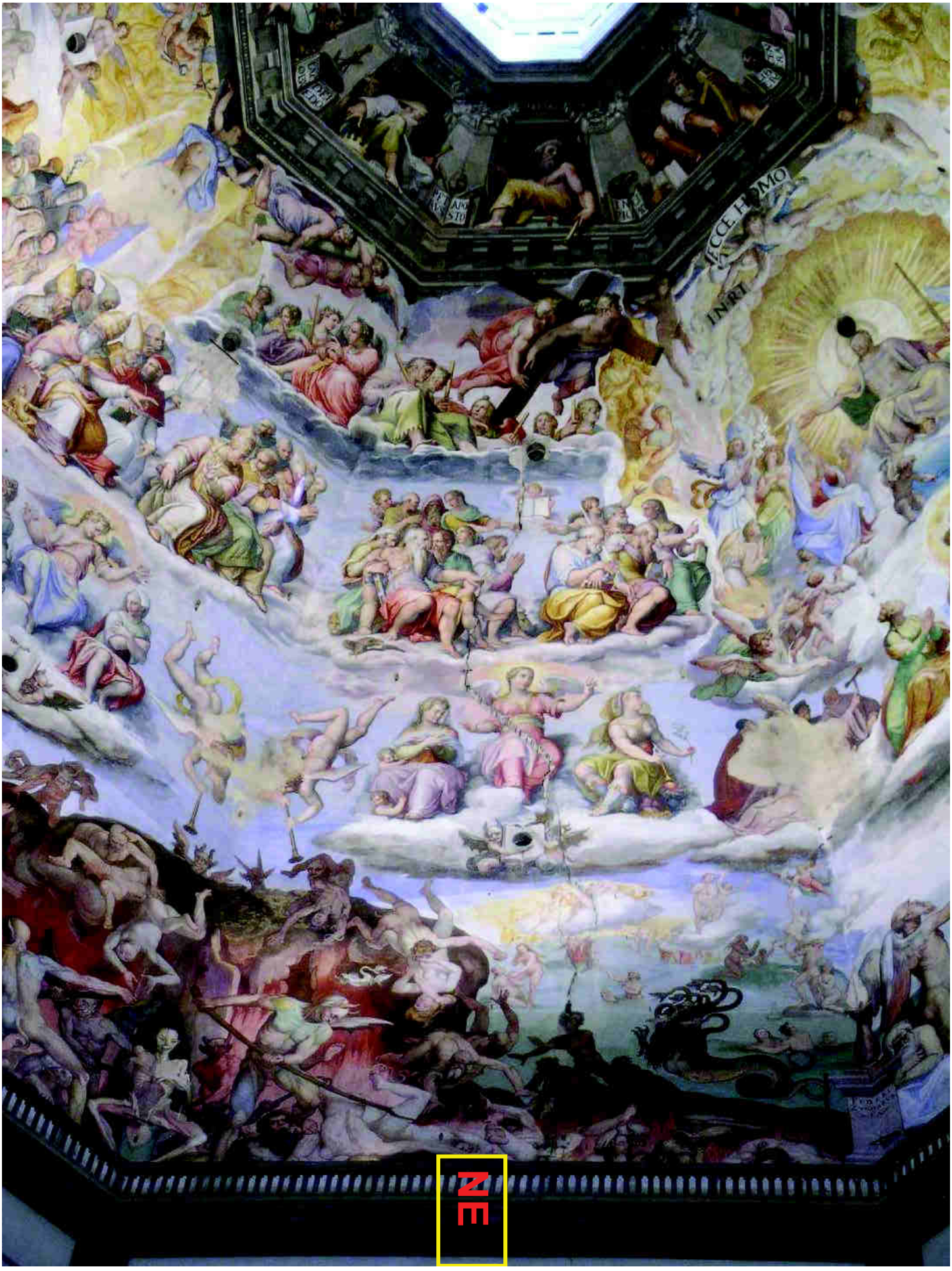
Localizzazione in elevazione delle fessure principali



DISTRIBUTION OF MAIN CRACKS

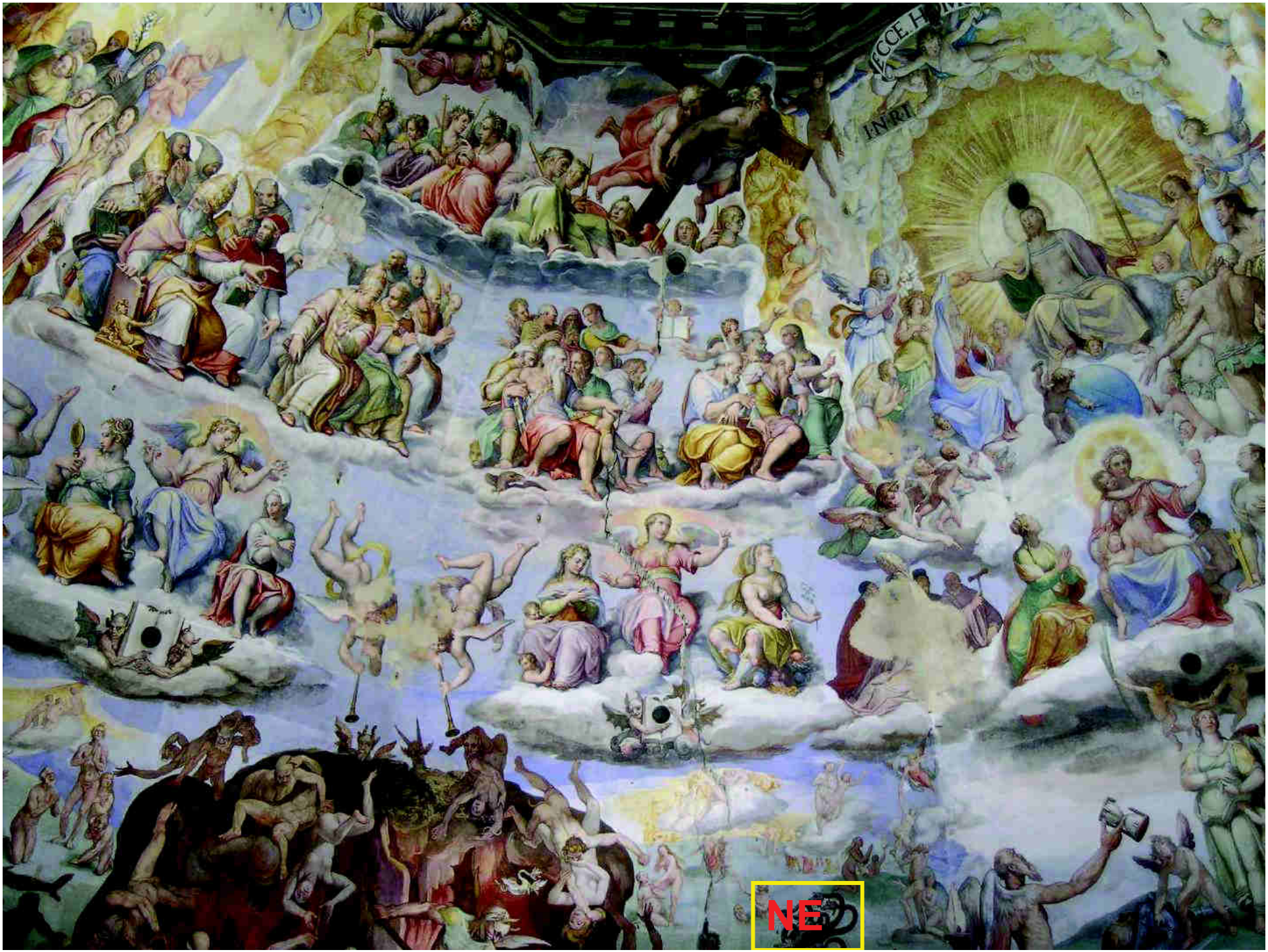

APSE
E
Main cracks on the axis
of NE e SE portions
SE
NE
S
N
SW
NW
W
NAVE


abside
SE
NE
SW
NW
navata


ECCE HOMO
INRI
NE


NE


NE


ECCE H
I.N.R.I.
NE


NE


NE