Archaeoseismology in a Mediterranean City

Siena and the PROTECT Project

Andrea Arrighetti

HISTORICAL ARCHAEOLOGIES SERIES

Access Archaeology

Archaeopress Access Archaeology

About Access Archaeology

Access Archaeology offers a different publishing model for specialist academic material that might traditionally prove commercially unviable, perhaps due to its sheer extent or volume of colour content, or simply due to its relatively niche field of interest. This could apply, for example, to a PhD dissertation or a catalogue of archaeological data.

All *Access Archaeology* publications are available as a free-to-download pdf eBook and in print format. The free pdf download model supports dissemination in areas of the world where budgets are more severely limited, and also allows individual academics from all over the world the opportunity to access the material privately, rather than relying solely on their university or public library. Print copies, nevertheless, remain available to individuals and institutions who need or prefer them.

The material is refereed and/or peer reviewed. Copy-editing takes place prior to submission of the work for publication and is the responsibility of the author. Academics who are able to supply print-ready material are not charged any fee to publish (including making the material available as a free-to-download pdf). In some instances the material is type-set in-house and in these cases a small charge is passed on for layout work.

Our principal effort goes into promoting the material, both the free-to-download pdf and print edition, where *Access Archaeology* books get the same level of attention as all of our publications which are marketed through e-alerts, print catalogues, displays at academic conferences, and are supported by professional distribution worldwide.

The free pdf download allows for greater dissemination of academic work than traditional print models could ever hope to support. It is common for a free-to-download pdf to be downloaded hundreds or sometimes thousands of times when it first appears on our website. Print sales of such specialist material would take years to match this figure, if indeed they ever would.

This model may well evolve over time, but its ambition will always remain to publish archaeological material that would prove commercially unviable in traditional publishing models, without passing the expense on to the academic (author or reader).

Archaeopress Access Archaeology

Archaeoseismology in a Mediterranean City

Siena and the PROTECT Project

Andrea Arrighetti

Access Archaeology

Archaeopress Access Archaeology

Archaeopress Publishing Ltd
13–14 Market Square
Bicester
Oxfordshire
OX26 6AD
United Kingdom
www.archaeopress.com

ISBN 978-1-80583-058-0
ISBN 978-1-80583-059-7 (e-Pdf)

Cover: A view of Siena's rooftops by Marco Repole.

This book is available direct from Archaeopress or from our website www.archaeopress.com

Historical Archaeologies Series

The Historical Archaeologies Series (HAS) is a monograph series in the Archaeopress Access Archaeology imprint for studies that explore past societies, considering long-term perspectives, with a particular focus on the archaeological study of literate societies.

The collection is interested in the historical dimension of archaeological research, exploiting perspectives such as microhistory, multiscale analysis, comparative studies, multiple temporalities, deep landscapes, etc. The multiproxy analysis of historical societies is also a key concern, considering not only the extensive use of archaeological sciences, but also more ‘traditional’ sources in a critical and inclusive way. The archaeological study of written records and the documentary study of the archaeological record, overcoming the scholarly disjuncture between disciplines, are among the perspectives that will be enhanced, together with conceptually and theoretically informed approaches. There is also a keen interest in topics, geographies, and initiatives emerging in the periphery of mainstream archaeological research. The series intends also to open avenues to younger scholars and groundbreaking research, covering worldwide geographies.

The Historical Archaeologies Series will comprise:

1. Thematic studies that offer a comprehensive review of the most important current problems in archaeology in a long long-term perspective, in particular the archaeological study of medieval, modern, and contemporary periods.

2. Original research monographs between 60,000 and 200,000 words. Monographs should follow the standard format of an archaeological paper. Papers will be submitted to a double-blind peer review process.

3. Collective books centered on relevant topics related to historical archaeologies.

4. Innovative and experimental proposals aimed at overcoming the limits of current historical archaeologies.

Contents

List of Figures and Tables ii
Acknowledgements vi
Foreword 1
Introduction 3

Chapter I - The PROTECT project: archaeoseismology applied to urban areas 8
Chapter II - The city of Siena: the context of investigation and research strategy 11
2.1 Introduction to the study context 11
2.2 A seismic history of the city of Siena 15
Chapter III - Methodologies of analysis 20
3.1 Analysis of historical and seismological sources 20
3.2 Analysis of archive and documentary sources 22
3.3 Archeological surveys of built structures 22
3.4 Digital surveys 23
3.5 Archeosismological analysis of built features 26
Chapter IV - Application to study context 32
4.1 Analysis at the macro scale: Terzi and Popoli 33
4.1.1 The 1467 earthquake: new scenarios involving history and archaeology 33
4.1.2 The survey of post-seismic construction techniques in the Terzo di Città 49
4.2 Medium-scale analysis: street fronts and building aggregates 60
4.3 Micro-scale analysis: architectural complexes 74
Chapter V - First steps towards an operational protocol for historic city centres 90
5.1 The analysis protocol 90
Level 1 90
Level 2 92
Level 3 93
Results 94
5.2 Validation of the method: Siena and the 2023 earthquake 95
Chapter VI - Conclusions and prospects for research 102

References 106
Bibliography 107

List of Figures and Tables

Figure 1.1	The city of Siena inside the Italian boundaries	9
Figure 2.1	The city of Siena inside its regional boundaries	12
Figure 2.2	Drone photograph of the town centre of Siena. Image: Gianluca Fenili	13
Figure 2.3	Diagram of the earthquakes recorded in the Sienese territory between the 14th and 19th centuries (Locati et al., 2022)	14
Table 2.1	Earthquakes whose effects in Siena have been assessed in intensity VII MCS (ROVIDA et al., 2022). Legend: I = intensity; Mw = magnitude moment (Image taken from the article: Castelli 2023)	15
Figure 2.4	Distribution of the maximum intensities observed in the Tuscany Region (Locati et al., 2022)	17
Figure 2.5	Distribution of earthquakes located in or near the Province of Siena (Rovida et al., 2022). The dates shown are those of earthquakes with magnitude ≥ 5.0. Image taken from: Castelli 2023	18
Figure 2.6	Seismic history of Siena with major intensity earthquakes highlighted (Locati et al., 2022)	18
Figure 3.1	Some examples of post-seismic techniques documented during the archaeoseismological fieldwork survey: bond stones (a and d) and relieving arch (b and c)	23
Figure 3.2	Longitudinal section of the three-dimensional model of the Church of St. Augustine obtained by laser scanner and photogrammetric survey (elaboration: Marco Repole)	24
Figure 3.3	Image of a 'classic' Elevation Map with colors (elaboration: Marco Repole)	24
Figure 3.4	Images of the survey fieldwork carried out using mobile and terrestrial laser scanners	26
Figure 3.5	Detail of a moment of photographic data acquisition with a drone	27
Figure 3.6	Detail of the archaeological analysis of the architecture carried out in the field	28
Figure 3.7	The material structure worksheet realized for the documentation of road fronts, divided into three sectors: road fronts, standing buildings, post-seismic construction techniques	29
Figure 3.8	Methodological table illustrating the digitization of the archaeological analyses carried out on the street front of Via Pendola. In the centre of the image is shown a photo-plan of a portion of the street front where the stratigraphic analysis, the characterization of the cracking framework and the documentation of the post-seismic techniques were carried out. Above are shown portions of the elevation (a, b, c) with enlargements of the stratigraphic analysis (in blue) and of the cracks pattern (in red). At the bottom, the post-seismic techniques and cracks are shown (d, e, f) (Elaboration: Marco Repole)	31
Figure 4.1	The 1467 Sienese earthquake sequence in the CPTI15 catalogue (Rovida et al. 2022)	35
Figure 4.2	Sources and transmission of informations about the 1467 earthquake [round: textual sources; italics: iconographic sources; solid lines: explicit filiation; dotted lines:	

conjectural filiation]. Image elaborated by Viviana Castelli and taken from: Arrighetti et al., 2025 35

Figure 4.3 The historical centre of Siena subdivided into the Popoli of the 15th century. For each popolo, the name is reported and in brackets the number of attestations reported in the Lira of 1468. Elaboration: Andrea Arrighetti and Barbara Gelli. Image taken from: Arrighetti et al., 2025 45

Figure 4.4 The historic centre of Siena subdivided into the areas assumed to be severely (red), medium (orange), low (yellow) and unaffected (green) by the 1467 earthquake. Elaboration: Andrea Arrighetti and Barbara Gelli. Image taken from: Arrighetti et al., 2025 47

Figure 4.5 The historic city centre of Siena: framing of the urban area involved in the fieldwork (GEOscope WMS - Region of Tuscany. Re-elaboration: Valeria Razzante) 50

Figure 4.6 The GIS platform created to record the construction techniques identified in the Terzo di Città with the table with elements characterizing buttresses and scarped walls (Elaboration: Valeria Razzante) 51

Figure 4.7 Example of a wooden beam set inside wall masonry (Photo: Andrea Arrighetti) 53

Figure 4.8 Example of buttresses inserted above wall (Photo: Valeria Razzante) 54

Figure 4.9 Relieving arch inserted into the façade of a building in Via Pendola (Photo: Gianluca Fenili) 55

Figure 4.10a Examples of buttressing arches 56

Figure 4.10b Examples of buttressing arches 57

Figure 4.11 Re-elaboration in GIS of the post-seismic techniques analyzed during the survey of the Terzo di Città (GEOscopio WMS - Region of Tuscany. Re-elaboration: Valeria Razzante) 59

Figure 4.12 Aerial view of the historic centre of Siena with the two road fronts under investigation highlighted: Via Fontebranda and Via Pendola. (Map data Google, Landsat / Copernicus. Re-elaboration: Marco Repole) 61

Figure 4.13 Documentation by Standing Building (top) and by USM (bottom) of the street front of Via Pendola. The plastered portion of the street front was not considered in the analysis because the absence of stratigraphic data did not allow a clear understanding of how its façade relates to the evidence emerging from the documentation of the deformations of the surrounding buildings (Image taken from: Arrighetti and Repole 2024) 63

Figure 4.14 Stratigraphic analysis of a portion of the street front in Via Pendola containing: stratigraphy (black colour), crack pattern (red colour), post-seismic construction techniques (green colour) Elaboration: Marco Repole 63

Figure 4.15 Screenshot of the point cloud obtained from the laser scanner survey of Via Fontebranda 64

Figure 4.16 The image shows the difference in graphic rendering of the deformation data of a portion of the external road frontage related to Via Pendola. In particular, from the image, it is possible to appreciate how the deformations visible on the Elevation Map on the top (composed of a colour gradient that ranges from green corresponding to an elevation of 0 cm to a maximum displacement in red of 20 cm) provide generic information on the trend of the entire frontage, while in the Map on the bottom (composed of isohypses with a Δ variation of 2 cm) they provide not only a general view but also a precise measurement of the extent of the displacement in that given area. The use of contour lines also allows for more detailed references on the frontage, moving by individual standing building, which made it possible to identify deformations (such as those on the right of the framed frontage) that were difficult to see with the colour gradient method. In our opinion, for the colour gradient to be graphically clear, more detailed measurements on the façade plane are necessary (Image taken from: Arrighetti and Repole 2024) ... 65

Figure 4.17a Orthophoto plan (top) and stratigraphic analysis (bottom) of the west street front of Via Pendola ... 66

Figure 4.17b Orthophoto plan (top) and stratigraphic analysis (bottom) of the east street front of Via Pendola ... 67

Figure 4.18 Image of the user interface in the OPUR database updated by the PROTECT project ... 70

Figure 4.19 The ‘stratified instability map’, i.e. the integrated representation of the deformation framework (in blue), the crack framework (in red), the stratigraphy (in black) and the post-seismic construction techniques (in green). Elaboration: Andrea Arrighetti and Marco Repole ... 71

Figure 4.20 Image showing: a detail of the archaeoseismological reading (in black) and the building techniques (in green) of the outer face of a street front (8a); the same detail with the layering of stratigraphy (in black), cracks (in red) and deformations patterns made by colours (8b); the same detail with the layering of stratigraphy (in black), cracks (in red), the post-seismic building techniques (in green) and deformations patterns made by isohypses (8c) (Image taken from: Arrighetti and Repole 2024) ... 72

Figure 4.21 The image shows how it is possible to quantify and integrate the deformation data with the archaeological data. The bottom part of the image shows details of the interactions between stratigraphy (in black), deformation framework (in blue), crack framework (in red) and post-seismic building techniques (in green). In particular, it is possible to appreciate the clear deformation that the isohypses undergo when they cross the stratigraphic interfaces of the infilling of the openings (a, b) or in the connecting masonry between two buildings erected in different periods (b). Furthermore, in figures b and c some cracks are clearly cut by the construction of new masonry or new openings within the buildings (Image taken from: Arrighetti and Repole 2024) ... 73

Figure 4.22 The church of Sant’Agostino (Image: Gianluca Fenili) ... 75

Figure 4.23 The interior of the church in Baroque style ... 76

Figure 4.24 Analyses performed on the arches and columns of the inner portion of the church of Sant’Agostino (Elaboration: Marco Repole) ... 79

Figure 4.25 Elevation Map of the northern external front of the church (Elaboration: Marco Repole) ... 80

Figure 4.26 Subdivision of the architectural complex into standing buildings ... 81

Figure 4.27 Archaeological restitution by masonry stratigraphic units of the northern external front of the church ... 82

Figure 4.28 Restitution of the exterior fronts of the church by construction phases ... 85

Figure 4.29 Stratified instability map of the northern external front of the church created by superimposing: deformation framework (in blue), crack framework (in red), stratigraphy (in black) and post-seismic construction techniques (in green). Elaboration: Andrea Arrighetti and Marco Repole 87

Figure 4.30a Detail of a false vault made after the 1798 earthquake 88

Figure 4.30b Detail of a false vault made after the 1798 earthquake and subsequently brought to light during the latest restoration work on the structure 89

Figure 5.1 Flow chart illustrating the conceptual framework underpinning the Level 1.1 of the macro-analysis of the historical centre of Siena 90

Figure 5.2 Flow chart illustrating the conceptual framework underpinning the Level 1.2 of the macro-analysis of the historical centre of Siena 91

Figure 5.3 Flow chart illustrating the conceptual framework underpinning the Level 2 of the medium-analysis of the historical centre of Siena: the expeditious investigation of street fronts 92

Figure 5.4 Flow chart illustrating the conceptual framework underpinning the Level 3 of the micro-analysis of the historical centre of Siena: the architectural complexes 94

Figure 5.5 The image shows the differences between the deformation framework of the street front of Via Pendola before (top) and after (bottom) the earthquake of February 2023. (Elaboration: Marco Repole) 96

Figure 5.6a The image shows the deformation framework of the northern external elevation of Sant'Agostino's Church before the earthquake of February 2023. (Elaboration: Marco Repole) 98

Figure 5.6b The image shows the deformation framework of the northern external elevation of Sant'Agostino's Church after the earthquake of February 2023. (Elaboration: Marco Repole) 99

Figure 5.7a Restitution of the northern external elevation of the church of Sant'Agostino with the isohypses of the old (in blue) and the new (in red) deformation framework modified following the earthquake of February 2023 highlighted 100

Figure 5.7b Restitution of the archaeological analysis by Stratigraphic Units (in black) of the northern external elevation of the church of Sant'Agostino with the isohypses of the old (in blue) and the new (in red) deformation framework modified following the earthquake of February 2023 highlighted 101

Figure 6.1 The three restitutions created by the analysis of the street front: orthophoto, elevation map and the stratified instability map (Elaboration: Andrea Arrighetti and Marco Repole) 103

Figure 6.2 An example of communicating the results of the PROTECT project to the population of Siena is the exhibition organised at the Palazzo di San Galgano in September 2023 105

Acknowledgements

I would like to express my sincere gratitude to Prof. Hélène Dessales (École Normale Supérieure – Université Paris Sciences Lettres) and Prof. Giovanna Bianchi (University of Siena), respectively my supervisor at the host institution and co-supervisor during the secondment period of the PROTECT project, for their invaluable moral and professional support. I am also deeply thankful to Prof. Christophe J. Goddard, Director of UMR 8546 AOROC, and Prof. Enrico Zanini, Director of DSSBC at the University of Siena, for their willingness to support the project. Finally, I would like to extend my thanks to all those who actively contributed to the PROTECT project: Marco Repole, Raffaella Leporini, Viviana Castelli, and Barbara Gelli, whose collaboration has been essential to the success of this work.

The project 'PROTECT – Knowledge for PReventiON. TEChniques for repairing seismic damage from The Medieval period to the modern era' was funded through the European Union's Horizon 2020 Research and Innovation program together with a Marie Skłodowska-Curie Individual Fellowship (Grant Agreement n. 101018762).

Project website: www.protect.altervista.org.

Host Institution: École Normale Supérieure – Université Paris Sciences Lettres, Laboratoire Archéologie & Philologie d'Orient et d'Occident

Secondment Institution: Università degli Studi di Siena, Dipartimento di Scienze Storiche e dei Beni Culturali

Graphic: Marco Repole

Foreword

Hélène Dessales[1]

Since ancient times, Mediterranean cities have continually faced the threat of earthquakes. From Rome to Antioch, from Messina to Skopje, earthquakes have left an indelible mark on both urban landscapes and collective imaginations. But beyond the destruction, these disasters have also revealed essential aspects of the history of cities: the ability of societies to adapt in the face of the unforeseeable, the evolution of living spaces, the methods of restoration, and possible preventive strategies. It is precisely these aspects – often elusive in historical accounts –, that Andrea Arrighetti's book allows us to explore more closely, through the emblematic case of Siena. The urban stratigraphy of this medieval Tuscan city, the extent of its preserved architecture, and the wealth historical sources make it an ideal observatory for examining the interactions between humans, the city and its environment over time.

This book offers a new perspective on Siena's urban history in light of earthquake risk, combining geological context, historical sources, archaeological data and architectural studies. It effectively identifies the material traces of successive earthquakes, the first of which is recorded as occurring in 1320, and provides a detailed contextual analysis of their consequences. The book aligns perfectly with the expanding field of archaeoseismology — a specialized branch of archaeology that has seen significant growth in the past decade, and of which Andrea Arrighetti is undoubtedly the leading figure in Europe. We already owe him a highly valuable manual on the subject[2], as well as the publication of two international congresses, one in the form of a methodological assessment[3], the other focusing on the case of Siena[4]. It should be noted that the strong impetus in this field of research is closely linked to the programme that Andrea Arrighetti developed in 2022 and 2023, as part of a Marie Sklodowska-Curie fellowsship at the École Normale Supérieure, and for which I had the honour of being the supervisor: PROTECT - Knowledge for PReventiOn. Technique for reparing seismic damage from medieval period To modern era. Carried out with dynamism and passion, the scientific activity was substantial, as demonstrated by the numerous publications resulting from these two years, and it had a significant impact at the European level. The originality of the project lays in its focus on the case of Siena, explored in terms of the relationship between seismic events and urban heritage.

This book is the result of personal field research carried out within this context. It presents the history of the city of Siena from a unique and lesser-known perspective. In fact, it would be more accurate to speak of multiple histories of the city, as they are organized according to a multi-scalar approach, following a zoom effect throughout the volume: at a first contextual level, an overview of the entire city, comparing archival data on earthquake damage (in particular, the very rich 1468 Lira tax records) and archaeological observations of the buildings; at a second macro-level urban approach, a study focusing on the "Terzo di Città" area of Siena's old city centre, which combines the identification of successive damage, proposing a "stratified disruption map" of the elevations, and the typology of post-seismic repair techniques over time (96 identified features, categorized into four groups: wooden braces and tie rods, buttresses, relieving arches, and buttressing arches); finally, at a third micro-level, a case

[1] École normale supérieure, PSL, AOROC / Université de Lausanne

[2] Arrighetti 2015.

[3] Arrighetti 2018b.

[4] Arrighetti 2023.

study of the church of Sant'Agostino, whose entire architectural chronology is reconstructed by cross-referencing stratigraphic observations with sources on historical seismicity.

Such a vast amount of data and the relevance of its use are truly admirable, and the example of Siena stands out due to the wealth of contextual sources, both quantitative and qualitative. On the one hand, it is evident that the city has been affected by numerous earthquakes of medium to high intensity throughout its long history, with six of them reaching or exceeding intensity VII on the MCS scale. On the other hand, the preservation of its buildings allows for in-depth analysis, making them particularly well-suited for reconstructing post-seismic damage and subsequent rebuilding efforts. Finally, since medieval times, the city's State Archive has contained a collection of highly detailed texts recording the impact of earthquakes and the municipal measures that followed. Such documentation is undoubtedly exceptional and is a source of envy for any archaeologist interested in this field of study.

A relevant comparison could be a similar programme on Pompeii, which focused on the reconstruction of this small Roman town following the earthquake that struck seventeen years before the eruption of Mount Vesuvius. While the accounts of Seneca and Tacitus provide us with the date of the disaster and present Pompeii — particularly affected — as the epicentre of the earthquake, no textual sources exist regarding the conditions of reconstruction and the strategies adopted. It is only through archaeological and engineering observation, supported by a specific database, that we have been able to map the post-seismic repairs (nearly 260 recorded in about 15% of the excavated portion of the city) and characterise their building techniques, offering valuable insight into the socio-economic conditions of Pompeii during its final years[5].

The highly innovative method ensures that this book can also serve as a genuine handbook for archaeologists, architects, and all specialists in built heritage. In addition to the multi-scalar and multi-disciplinary approach, we must also highlight the exceptional quality of the field surveys (laser scanning, photogrammetry, stratigraphical analysis, specific database for recording repairs) and all the graphic documentation produced by Marco Repole, which includes striking and highly successful experiments that renew the renderings typically expected in the fields of architecture and archaeology of the built environment. One example is the use of elevation mapping similar to topography, with colour gradients and graphic renderings of deformation data, as illustrated by the example of Via Pendola. In this regard, the image at the end of the book, showing the effects of the 2023 earthquake and the new deformations generated by this seismic event, particularly demonstrates the full potential of this method.

In conclusion, this book — beyond the example of the Siena area — stands out for the study protocol, and it proposes and opens a new path in archaeoseismology. Through the data gathered on the evolution of Siena's city centre over time, it illuminates the complex dynamics between a rich historical heritage and the impact of natural hazards. It encourages us to view seismic risk not as an exogenous or one-off event, but as a factor that is intrinsically linked to urban history, one likely to have a lasting influence on building practices and heritage management. Understanding the impact of earthquakes on cities from a diachronic perspective not only enhances our understanding of their material history but also contributes to contemporary discourse on prevention, urban resilience, and heritage conservation. Furthermore, it raises important questions about the memory of disasters and its appropriation by local populations. In fact, the approach presented in this book is exemplary, as the data has also been made accessible to a wider audience through an exhibition organised in September 2023 at the Palazzo di San Galgano. The exhibition offered the general public a glimpse into the little-known history of Siena — an essential history that must be considered if we are to build cities more resilient in the face of earthquakes.

[5] Dessales 2022.

Introduction

In the Mediterranean context, the frequency of destructive seismic events continues to be rather high. This is in continuity with the sequence and pattern of earthquakes that took place in Antiquity, and for which we have evidence. The heritage located within this context, including both the built environment and the natural landscape, is subject to a range of different levels of seismic risk. These are determined by the seismic characteristics of each area, on the one hand, mainly linked to environmental and geological factors, and on the other hand, as regards aspects associated more with built structures, by the degree of exposure to seismic risk itself. This risk is introduced both by the recent phenomenon of over-anthropisation of spaces, and by the degree of vulnerability of the historical buildings and structures found in urban and rural centres (Mecca 2022: 30). Whereas it is hard to intervene as regards geological and environmental factors, when it comes to the degree of exposure and, above all, to the vulnerability of buildings and constructions, specific projects can be set up aimed at safeguarding and protecting the built cultural heritage, improving its response to the movements triggered by earthquakes. This is an extremely important factor, requiring specific multidisciplinary analyses aimed at a correct documentation, understanding and assessment of each individual architectural complex that makes up a rural or urban centre. Indeed, following on from this consideration, it is well known that very often ancient masonry structures have intrinsic vulnerabilities in the characteristics of their construction. These correlate to the building techniques used, but they can also include defects in their construction design, or in their execution. Moreover, over time, the constant state of exposure to environmental factors leads to a certain degree of deterioration, and thus to a direct reduction of the original properties of the materials used in their construction. With specific reference to some historical town centres, we should also not overlook the aspect involving ways in which these same buildings have been used and renovated. Indeed, these buildings continue to exist as such inasmuch as they have been constantly used and inhabited over time (Valluzzi 2016: 45), altering their original construction properties. All these factors, when combined with geological, geomorphological and seismological factors etc., may lead to differing seismic scenarios for each study context, not only today but also in the past. As confirmation of this, as regards the impact of earthquakes in history, it has been possible to see that in many scenarios from the past, investigated both by scientific methods and by means of the disciplines that make up the traditional framework of studies on earthquakes[1], also coinciding with seismic events on a moderate scale, huge degrees of damage have been caused. This is an aspect which, once again, but with older chronological horizons, highlights the great vulnerability of buildings and historical contexts in the Mediterranean area (Valluzzi 2016: 45).

Regarding the response of past populations to earthquakes, if we omit scenarios in which sites were abandoned altogether in favour of a different area, a direct comparison between archaeological and documentary sources allows an understanding of the degree of the destructive impact of individual seismic episodes on each site context. While sometimes peoples hit by earthquakes opted for a wholescale reconstruction of their infrastructure and dwellings along the lines of the previous structures[2], in other situations earthquakes helped to lead to full-scale cultural changes, encouraging the creation and spread of technical expedients and new architectural models that were carefully designed to withstand the effects of earthquakes (Stiros 2016). Two very different scenarios that can be reconstructed from an analysis of historical buildings that have survived down to the present day. Accordingly, as regards

[1] The identification and characterisation of earthquakes define archaeoseismology, as well as paleoseismology and historical seismology, which are vital for enhancing our knowledge of seismicity in the past (Galadini et al., 2006: 397).

[2] Here the well-known example is cited of the major earthquake at the ancient city of Pergamon: occurring in 1246, the quake prompted local people to intervene with a large-scale reconstruction of civic infrastructure.

archaeology, we must consider the buildings and masonry structures of which they are comprised both as evidence of the material culture and technical knowhow of the master-builders and populations, and as the final outcome of constant transformations that took place over time (Parenti 2002: 73), and that include the historical aspect and also the technical aspect, this latter aspect being linked to the formal and material characteristics of walled features. But how can this type of context be studied from the point of view of archaeology, and what is the correct operational procedure, and what level of detail might be appropriate in our analyses?

The answer to this question is not straightforward. The protection of the architectural cultural heritage in contexts prone to risk, both anthropic and natural, should envisage a territorial-scale form of management that includes strategic plans for specific action, and that fosters the development of predictive analyses based on a deep understanding of the fabric of every building. The studies that up until 2010 have addressed the issue of protecting architectural heritage exposed to seismic risk have seen two parallel lines of research come into being, and become established: on the one hand a large-scale, generic approach, which partially ignores any historical contextualisation, and overlooks an investigation based on stratigraphy and construction history of the complexes where interventions have been carried out, denying the possibility of comprising any understanding of seismic issues on the part of the builders of the past; and on the other hand a practice that takes a more careful and specific look at the history of buildings, and their intrinsic features, and which takes into account the existence of construction systems and expedients that were put in place at the same time as the construction of built features. Since 2010, thanks to national directives in the Italian context, and more in-depth efforts in terms of theory and data collection, the reconstruction of earthquake-damaged buildings has led to the development of concrete para-seismic norms (Dessales and Tricoche 2018: 19). As regards historical buildings, the Linee Guida per la valutazione e riduzione del rischio sismico del patrimonio culturale [Guidelines for the assessment and reduction of seismic risk to the cultural heritage] (MIBAC 2011), discussed in more detail in the following chapter, underline the fact that an understanding of an architectural feature derives from an all-encompassing analysis that is the result of the coming together of several different disciplines and approaches (from technical knowledge in the fields of architectonics and engineering, to historical and archaeological studies). Indeed, one of the optimal solutions in terms of a multidisciplinary approach sets out to enhance structural analyses by means of stratigraphic observations aimed at a diachronic interpretation of the phases of life of a particular building that is under investigation (Arrighetti 2015; Brogiolo and Cagnana 2012: 14-15). From a purely documentary point of view, when we turn our attention to the past, both in Antiquity and for the Middle Ages, there do not seem to be any surviving written records of regulations drawn up in a post-seismic context. For this reason, as well as being tools for preferential information regarding the empirical knowledge acquired by the builders that may in some cases be influenced by the recurrence of earthquakes, or that may possibly be associated with seismic events (Dessales and Tricoche 2018: 19), archaeology and archeoseismology make a full contribution, along with other disciplines, to efforts to protect and conserve old town centres where the daily life of local communities routinely takes place within residential spaces and workplaces that are incorporated within buildings founded in the historical past.

Thus these multidisciplinary approaches give rise to a correct approach to the subject of vernacular architecture, the conceptual and etymological origin of which can be suitably rendered by considering the meaning of the Latin term vernaculus, corresponding to the terms “indigenous” or “domestic”. By extension, in the context of architecture the use of the term “vernacular” refers to a kind of building technique in a given geographical area, in connection with an ethnic group that populates that same territory. Around the middle of the last century the definition that is now generally accepted and used of vernacular architecture came into common use, in conceptual and ideological opposition to an academically formulated type of architecture. As regards the Italian context, a systematic approach to the subject of vernacular architecture dates back to the 1970s. The earliest studies addressed the overall structure of buildings and an analysis of their façades (and thus the number of floors, and the positions of doors and windows). Later on, an approach became established that was more based on the conservation and restoration of monuments, with special attention to the materials and building techniques used in historical times, also in relation to areas at risk from earthquakes. Research activities received a considerable new boost in particular from the unfortunate seismic events that have taken place in central Italy in recent years. These have prompted notable insights that have given rise to new approaches and research methods in the field of earthquakes and the conservation of historical buildings[3]. Interesting projects and research groups are also active in the international sphere. Most often these involve teams drawn from a range of disciplines and specialities. Depending on the area of interest concerned, research studies range between studies looking at masonry structures (especially in the European context) and studies focusing on buildings made from perishable materials (in which case the prime contexts in question are from south-east Asia and the Middle East).

Hand-in-hand with the development of this type of investigation, the concept of "local seismic culture" has come into being, and is taking root. This can be called a veritable cultural response by quake-hit local people, by means of specific building practices which vary from one area to another, in accordance with differences in available materials, construction knowhow, and direct observation of the effects of earthquakes on buildings (Arrighetti 2015: 72-81; Ferrigni et al., 2005; Helly 1995; Pierotti and Ulivieri 2001). The development of these cultures over time was heterogeneous, being mainly linked to advances in scientific disciplines. Indeed, the earliest theoretical discussions of seismic cultures compiled in treatises date to the 16th century, while for a direct application of these practices in the field in a purely empirical and experimental form, through the implementation of solutions that can be described as such, we find numerous examples dating as far back as thousands of years earlier (Ferrigni et al., 2005: 199). Thus here we are dealing with pre- and post-seismic building practices that are not formalised and theorised, but that can be perceived in practical terms within specific construction features or characteristics involving the choice of site, or within a larger territorial reorganisation (Ferrigni et al., 2005: 91-92). The necessary condition for the existence of these seismic cultures is given by the frequency and intensity of seismic phenomena: the more frequent and destructive the event (from level VII to level X on the MCS scale), the more the local population affected by the damage will tend to develop a "culture of seismic prevention" over time; the more the earthquake is of moderate intensity (from level VI to level VIII on the MCS scale), the more the collective response will tend to be geared towards a "culture of seismic repair" (Arrighetti 2015: 73-74). Thus we may take the view that when a seismic culture is found to be well rooted locally in each individual within a given community, this has such an influence that it stimulates the systematic creation of measures designed to safeguard buildings in advance, by seeking to reduce their vulnerability, or else with a view to reconstruction, when they are restored (Ferrigni et al., 2005: 193-194).

These, then, are the factors that allow us to understand the extent to which the role of archaeology applied to contexts exposed to seismic risk, albeit with different concepts and methods, should be regarded as a fundamental operation in analyses of contexts faced with seismic risk. This role includes both the world of research and the professional sphere, and brings tangible material benefits as part of interventions involving historical buildings and the broader planning of urban and rural areas. The PROTECT project, the research aspects of which are described in the present volume, follows these prerogatives: implementing archaeoseismological analyses, previously used in rural areas, in an experimental way in a historic urban centre, Siena, and also covering potential developments and

[3] Among the most recent and disastrous were the earthquakes that mainly struck Abruzzo, Le Marche and Umbria: 06/04/2009 (L'Aquila), 24/08/2016 (Amatrice), and 30/10/2016 (Norcia).

problematic factors in every phase of its application. The results discussed here clearly show that this type of approach brings essential benefits to knowledge of the study context as regards seismology, history and architectural history, introducing innovations and new data to explore seismic scenarios in more detail. Scenarios which have been little understood up until now, producing technical material with a view to protecting and safeguarding the architectural heritage, and providing notable improvements and a greater awareness of the risks affecting people's lives.

CHAPTER I

The PROTECT project: archaeoseismology applied to urban areas

The natural repetition of seismic events, and the widespread presence of historical buildings located in areas at seismic risk, are features of much of Italy's national territory. Apart from the Civil Protection Department itself, the strategic problem of protecting the Cultural Heritage also involves the spheres of research and conservation. The dialogue established between institutions, professionals and Universities has led Italy's Ministry for Cultural Assets and Activities to issue the aforementioned Guidelines for the assessment and reduction of seismic risk to the cultural heritage (MIBAC 2011), a decree law with later amendments. This is founded on a synergy between knowhow in the fields of science and the humanities, and is designed with a view to standardising, as far as possible, the forms of intervention regarding heritage assets in areas subject to seismic phenomena. It seems abundantly clear from a critical reading of this document that an understanding of historical seismic activity, and its effects on given areas, can also be reconstructed thanks to a series of traces present on the actual ground and in the built cultural heritage, with the latter being described as a "container" of the effects caused by historical earthquakes on a specific study context. Accordingly, architecture constitutes a priority, and an analysis of it allows us to suggest forms of intervention and types of restoration, and maintenance, with a view to preventing damage from future earthquakes, by means of pre- and post-seismic interventions put in place by local communities over the centuries. This process is effected using a series of methods, both traditional and innovative, drawn from the humanities-related sciences, with the support of scientific and technological tools.

This consideration appears even more interesting when we move away from buildings to consider much more complex and interconnected organisms as regards construction, urban planning, and the social dimension, namely entire old town centres. Indeed, the study of these, in cases where they are situated in seismic areas, allows an understanding that is not restricted to an individual architectural complex, but that makes such a complex one of the case studies featuring in a more general and heterogeneous mechanism. Thus, studying the seismic history of old town centres and, more particularly, the effects of certain specific earthquakes on the documentary and material components that make up its basic structure, becomes a highly useful element in several respects (social, economic, political etc.). Unfortunately, very often we lose sight of these processes, as they are not reported or recorded for posterity, due to a highly subjective element within written sources. However, they do leave a trace in architectural complexes, which often become the only objective witnesses to a seismic past, an understanding and knowledge of which is still constantly evolving down to the present day. To get such information, we make use of the collaboration of numerous disciplines drawn from both the humanities and sciences. Archaeoseismological analyses, seismological and archive research, surveys and structural analyses are combined and transformed into a complex set of information that is extremely useful. It can be used, for example, to get an understanding of the study context from the historical point of view, as well as in reference to future analyses of the vulnerability of buildings, and with a view to the planning of restoration interventions or, as regards seismology, for a better understanding of seismic history, and its concrete effects on buildings and on the urban fabric generally.

It is in this field of research that the *PROTECT - Knowledge for PReventiOn. Technique for repairing seismic damage from medieval period To modern era* project has its place. This is a two-year research project funded by the European Union's Horizon 2020 research and innovation programme, with a Marie Skłodowska-Curie Individual Fellowship held at the École Normale Supérieure - Université PSL in Paris. The aim of the research has been to apply, on a wholly experimental basis, methods of archaeoseismological analysis to Siena's old city centre (fig.1.1), in Tuscany, with a view to an in-depth documentation of the study context for the purposes of fact-finding and, as a result, the prevention of seismic damage. The project has taken its first steps in a scientific field of huge interest, but it has also so far been extremely innovative. Indeed, it is useful to underline that, up until now, no archaeoseismological investigation has ever been proposed in a historical urban centre that is still "alive" and inhabited, despite the fact that such contexts are a recurrent and distinctive feature of Italy and much of Europe. The research under way, undertaken in Siena, aims to bridge this gap, using findings from disciplines drawn from the humanities and sciences, linking this information together so as to apply it directly in the future in other research contexts.

In operational terms, the PROTECT project is based on the application and testing of archaeological analyses of the effects of earthquakes on historical buildings in Siena, in line with a vision that adopts differing scales of investigation in the study of built features. An initial, more general level relates to the analysis of the context in all its complexity. This research process is addressed by means of a historical and seismological investigation geared to individual seismic events, transposing the results to tools that allow a characterisation and a large-scale view. The second step, which is more in-depth than the previous step but which is closely linked to it, relates to the process of analysis of a number of sectors of the city centre so as to understand the historical dynamics of their construction, and the presence

Figure 1.1 - The city of Siena inside the Italian boundaries.

of possible specific construction features designed to withstand the effect of earthquakes. This stage in the investigation deals with earthquakes over long periods of time, and thus not individual events, and features a cursory, mid-scale archaeoseismological investigation, by detailed analysis that can vary from a neighbourhood to an individual street-front. A third, final level of investigation involves an individual architectural complex, analysed archaeologically and documented three-dimensionally, with a detailed, specific research methodology aimed at assessing the effects of certain specific earthquakes on the building, and the pre- and post-seismic construction techniques used in its construction features. The archaeoseismological analysis, the historical-archival study, and the survey and structural analyses were therefore integrated to form an extremely useful dataset. This will be used both for acquiring knowledge, from a historical perspective, of the context of study, and also for future analyses of the vulnerability of built structures, for planning restoration activities or, from a seismological point of view, for a better understanding of seismic history and its actual effects on the fabric of the city. The reworking of the acquired data will therefore allow us to answer historical and technical questions that are tied in with individual architectural complexes, or entire reference areas.

The project's final objective was to create an operational protocol for the archaeoseismological analysis of the historical centre of Siena, or at least a part of it, and to export this model to other Italian or European sites, with a view to understanding, safeguarding and preserving the historical heritage from seismic risk.

CHAPTER II

The city of Siena: the context of investigation and research strategy

The case study identified for the application of the PROTECT project is the city of Siena, an urban centre in southern Tuscany that has been on the UNESCO World Heritage list since 1995 (fig.2.1). Siena is an exceptional context for propounding an archaeoseismological research study. Indeed, the city displays essential characteristics for proposing a study of this sort, such as: it has been affected by numerous seismic events throughout its history, some of which were of medium to high intensity; the architecture is well-preserved in its original features, and is therefore also easily readable from an archaeological point of view (fig.2.2); the city's State Archive holds an incredibly large and detailed collection of texts covering the period from the Middle Ages to the present day; and several studies in the field of historical seismology and archaeology have already been published, and can be used as a starting point for the investigation.

These, then, are the considerations that led to Siena being proposed as a perfect case study for trying out and applying a large-scale archaeoseismological working methodology, one that comprises, as will be explained in the following chapters, a focus ranging from individual structures to the entire historical centre, pursuing multiple and different levels of detail. Before moving on to a discussion of the various operational phases executed during the project, it is worth emphasising the complex events associated with the history of the urban context, and the historical earthquakes that have affected the city over time.

2.1 Introduction to the study context

The city of Siena boasts a long-standing history consisting of a great number of events that are known about, thanks to a large amount of documentary and iconographic sources, accompanied by numerous archaeological excavations conducted in the urban area by the Medieval Archaeology faculty at Siena University. According to current research, the history of Siena seems to begin in the Etruscan era. The earliest nucleus of Siena that was inhabited, as far back as the pre-Roman period, was the hill known as Castelvecchio, situated in the south-western area of what is now the historical centre. Its growth and development dates to between the 4th and 2nd centuries BC (Cantini 2011). Unfortunately, there is only scant evidence of this phase of occupation of the area, and this is limited to the discovery of a number of grave goods from burial areas. In the following period, the shape and appearance of the Roman settlement, which developed on top of the previous Etruscan site, was probably of the "castle" type, surrounded by a wall and having at least three gateways (Leoncini 1998). The development of the Roman city seems to undergo an early interruption between the late 2nd and the 3rd centuries AD, later reappearing on the hill of the Cathedral, between the late 4th and the 5th century, where it seems to take the shape of the new nucleus of the Christian Saena Iulia (Cantini 2011). The presence in Siena of a bishop, Eusebio, is first documented as of 465 AD. A clear break with the previous centuries occurs in the mid-6th century. The Greek-Gothic wars (535-553 AD) usher in a period of crisis, during which we see considerable urban decline within the area of the hill of Santa Maria, which is manifested in the form of stone-robbing, reuse, abandonment and alluvial deposits (dark layers). Thus, with the onset of the Early Middle Ages, there seems to be a contraction of the urbanised areas in Siena compared to the Imperial and Late Antique periods, akin to what we find in other cities. The city then goes on to see a later flourishing period under Lombard dominion when, after the Val di Chiana becomes marshy, and the former Via Cassia becomes impassable as a result, direct routes to Rome undergo changes, and Siena becomes a necessary transit point for pilgrims, imperial officials and prelates bound for the Holy City. This factor, together with its militarily important position, would make Siena an increasingly significant urban reality within the Lombard kingdom (Ascheri 2013).

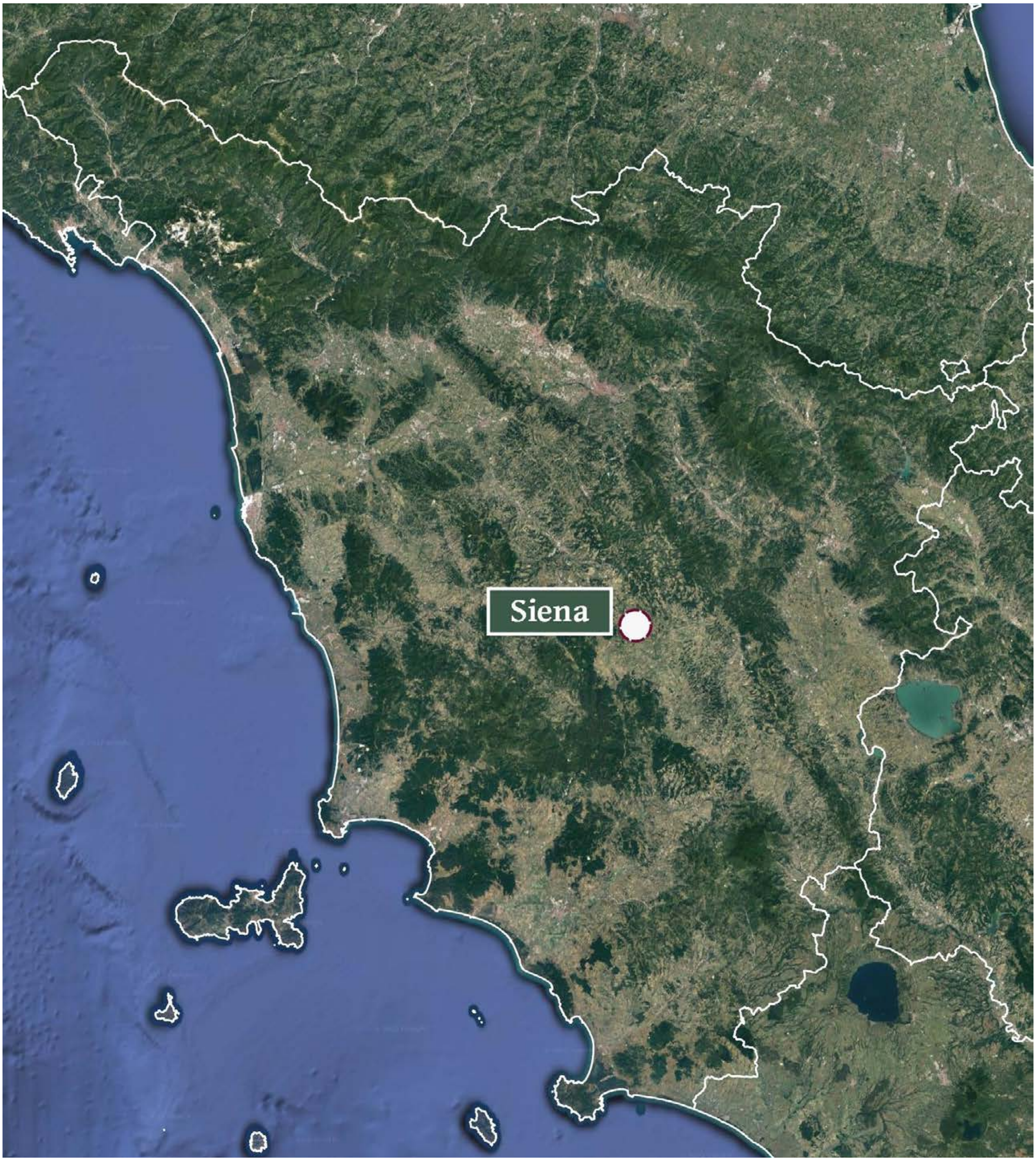

Figure 2.1 - The city of Siena inside its regional boundaries.

During the second half of the 7th century, the sources attest to the presence of a gastald (Lombard official), as well as a period when the post of bishop was left vacant. This comes to an end at the start of the 8th century, when the urban layout appears to become stabilised. In the early decades of the 9th century, Siena becomes a Carolingian possession headed up by Counts. In archaeological terms, we see the reappearance of buildings made from stone and lime, as well as imported pottery wares, bearing witness to the fact the episcopal area was quite well-off. As of the 11th century we see an increase in urban features on and around the Cathedral hill. During that same century, along the route of the Via Francigena, a series of suburban nuclei begin to appear, often close to churches or places offering hospitality (Cantini 2011). Indeed, this pilgrims' route represents the main thoroughfare along which urban expansion takes place outside the old city walls, extending northwards. As traffic along the Via Romea intensified, so too, between the 10th and the 12th centuries, was growth seen in one zone in particular. This area, the burgus de Camullia, was separate from Castelvecchio, but had already been established in a structured form for some time, standing to the north of what is now the old city centre. Between Camollia and the "old" city, in this same space of time, further burgi grew up, grouped around the main ecclesiastical institutions. Around the mid-12th century this collection of urban nuclei appears to have been enclosed within a new circuit of outer defensive walls. In the course of the second half of this century the great flowering and growth of Siena, in political and economic terms, and in terms of urban development, led to considerable changes in its urban structure, in the early decades of the 13th century. The towers of the consortium families that were such distinctive features of the cityscape, both as defensive features and as symbols of family prestige, at one and the same time, gradually lost their defensive purpose and took on a more residential function, with larger internal spaces and more doors

Figure 2.2 - Drone photograph of the town centre of Siena. Image: Gianluca Fenili.

and windows, allowing the addition of external supporting brackets and balconies (Gabbrielli 2010). The tendency towards vertical development, which is hard to perceive nowadays owing to the reduced size of surviving tower-shaped residential structures, was to remain a dominant feature of the urban centre for a long time thereafter. In archaeological terms we find that the use of stone in tower-houses still constitutes the main construction material, typifying such buildings.

However, already as of this date brick starts to appear as the chief building material in medieval Sienese buildings, becoming established once and for all as of the second half of the century, when it was used almost exclusively. However, in the 14th century, at a time when Siena had apparently been "relegated" to a lower status, the city saw its heyday in terms of art and architecture: from the city's outer walls to the palazzi, from the city gates to its streets, there emerges a great attention on the part of the city's governing authorities (as well as its people) towards aesthetic aspects. Grandiose public works projects were inaugurated, starting with the time the new government took office: the decision was made to construct a palazzo dedicated exclusively to the Communal magistrates and to the Podestà, the building now known as the Palazzo Pubblico. In the early decades of the 14th century, Siena must have had a population numbering approximately 47,000-50,000 people (Gabbrielli 2010), a figure that was set to rise continually. Another project designed to regulate urban expansion was the large-scale scheme to expand the city's outer walls. Dating to 1326, the plan was designed to include the southern suburbs within the city itself (Balestracci and Piccinni 1977). Unlike previous expansion schemes, built after the growth of the borghi, in order to ensure protection for the new additions to the urban layout, this latest expansion was aimed at allowing in advance for future demographic growth and new buildings, by also including extensive green spaces that had not yet been urbanised. These expansions and reconstructions of the outer walls would continue until the second half of the 15th century, and would also comprise a residential nucleus that was continually expanding in size, and in its urban structure, with new built-up areas that would occupy the empty spaces that characterised the outermost areas. The buildings and structures located within it would also tend to become constantly modified following reconstructions or restorations which could be either voluntary or determined by natural or anthropic phenomena that could lead to destruction on a larger or smaller scale. The evolution of buildings would not be homogeneous, and in most cases, especially in the case of prestigious buildings, it later followed the styles and tastes of the various different historical periods, from the Renaissance down to the present day.

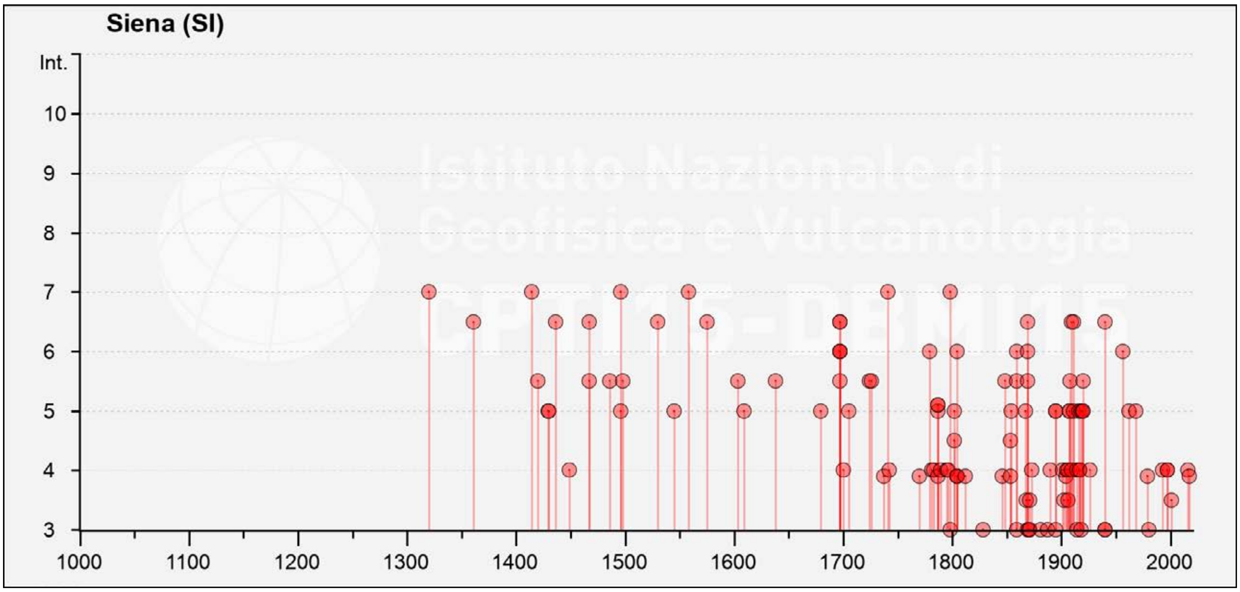

Figure 2.3 - Diagram of the earthquakes recorded in the Sienese territory between the 14th and 19th centuries (Locati et al., 2022).

Data	Area epicentrale	I epicentrale	Mw	Studio di riferimento
1320-12-16	Siena	VII	5.1	Castelli et al. 1996
1414-08-07	Colline Metallifere	VII-VII	5.7	Castelli et al. 1996
1496-06-04	Siena	VII	5.1	Camassi et al. 2011
1558-04-13	Valdarno superiore	IX	5.97	Camassi et al. 2011
1741-10-01	Siena	VII	5.1	Castelli et al. 1996
1798-05-26	Senese	VI-VII	4.85	Castelli et al. 1996

Table 2.1 - Earthquakes whose effects in Siena have been assessed in intensity VII MCS (ROVIDA et al., 2022). Legend: I = intensity; Mw = magnitude moment (Image taken from the article: Castelli 2023).

2.2 A seismic history of the city of Siena[1]

Observations of macroseismic effects in Siena began in 1320, and become relatively frequent from the 15th century to the mid-20th century, although without ever becoming particularly intensive (fig. 2.3).

From the seismic point of view, the situation of Siena is significantly less serious than other cities in central and southern Italy, which suffered serious destruction, occasionally on a repeated basis, in the period in question (fig.2.4). Similarly, other sites in Tuscany, which in the past recorded macroseismic effects on a scale corresponding to degrees IX and X on the MCS scale, show a frequency of events greater than for Siena. In the case of Siena, included among the 147 events of a certain intensity in its seismic history are the effects of earthquakes having their epicentre outside Tuscany. However, the earthquakes which, according to the current state of our knowledge, had the most significant effects on the city are located in the territory of the modern-day province, or in its immediate surroundings (fig.2.5).

As stated previously, in approximately the last millennium seismic activity in Siena and its surrounding province has been relatively frequent, albeit with an intensity well below that of the central-northern Apennines, where events with an Mw (moment magnitude) above 6.0 have been observed several times in the same period. The most recent earthquake listed in the catalogue dates to 22 February 1956, if we exclude the seismic sequence of February 2023.

Regarding neighbouring areas, south-east of Siena, in the Val d'Orcia and in the Crete Senesi area, we see a concentration of historical epicentres, with some significant events in the 16th-18th centuries, and the earthquake of 25 August 1909 (Mw 5.3), which caused damage in the municipalities of Buonconvento, Murlo and Monticiano, with effects in Siena assessed as corresponding to degree VI-VII MCS. Finally, on the southern border of the province of Siena, the Monte Amiata area displays recurrent seismic activity, with significant events in 1919 and in 1940.

As for Siena itself, the seismic repercussions having an intensity equal to or greater than degree VI MCS (threshold of damage) number 25. The highest intensity in recorded history, equivalent to degree VII MCS, was attributed to the earthquakes shown in table 2.1. According to the interpretative scheme of Molin et al. (2008), degree VII MCS denotes: slight damage to half of all buildings; damage causing temporary unusability of around 25% of all buildings; and serious damage and partial collapse for no more than 5% of all buildings. Degree VI MCS presupposes: slight damage to around half of all buildings; moderate damage to a further 25% of buildings; and serious damage to less than 5% of buildings.

[1] The information in this section is taken from a paper presented by Dott.ssa Viviana Castelli from the Istituto Nazionale di Geofisica e Vulcanologia at the conference entitled "Siena e i terremoti. Punti di vista multidisciplinari per una lettura archeosismologica del centro storico", held as part of the cycle of events entitled "Economia e tecniche della costruzione. Antichità, Medioevo, Età Moderna" at the Department of History and Cultural Heritage at Siena University. The event was followed by an open-access publication, curated by myself: Arrighetti 2023. For more details, as well as the aforementioned paper, readers are referred to the following publications: Castelli et al., 1996; Castelli 2004; 2009; 2016.

In Siena, degree VI MCS has been attributed to earthquakes having their epicentre within a radius of a few kilometres from the historical centre. There are events with effects in Siena assessed at between degrees VI and VII MCS, generally when the scenario of effects displays requisites of both degrees. This is the case with earthquakes having their epicentre close to the city (1467, 1575, 1697, 1779, 1859, 1869, 1940, and 1956), and those located further away (1545, 1726, 1909, 1724, and 1804) (fig.2.6).

Insofar as one may refer to 'typical' earthquakes in Siena, two recurrent categories seem to emerge:

- Sequences of Perceptible Tremors: Comprising numerous perceptible tremors without a clearly defined main event, such as those of August/September 1467[2] and September/December 1697, which can lead to panic and the temporary abandonment of dwellings[3].
- Sequences with a Main Event: These begin with a main event of greater energy followed by a small number of after-shocks in a short space of time, such as the earthquakes of 13 April 1558 and 26 May 1798. The 1558 earthquake, with its epicentre close to the north-eastern border of the province of Siena (Valdarno Superiore), caused serious damage in Caposelvi and in Siena, aggravated by the existing state of disrepair of the buildings, following the siege of 1554-1555. The 1798 earthquake caused significant damage in Siena, predominantly to buildings that were already run-down, with greater, widespread damage compared to the surrounding areas.

According to the facts reported by Viviana Castelli (Castelli 2023), the seismic damage most frequently reported in contemporary accounts is the partial or total collapse of chimneys, which can cause further damage to surrounding rooves and structures.

This type of damage, although not extremely serious, can have significant effects, and documented accounts are not always complete, as in the case of the earthquake of June 1575, for which contemporary sources are few and far between, and not always indicative of the real effects. Basically, although seismic activity in Siena displays effects that are less serious than in other areas, a detailed analysis of historical accounts and damage can provide a more in-depth understanding of regional seismic activity, and the way this developed.

Analysing the current data in the seismic catalogue, earthquakes belonging to the "sequences of perceptible tremors" type (ie. the 1467 and 1697 earthquakes) led to damage on varying scales in Siena, being mainly slight and sporadic. This damage may derive more from the accumulation of stresses due to the frequency of the tremors, rather than to the actual intensity of each single event. It is important to underline that the investigations conducted thus far are preliminary and cursory; accordingly, we cannot rule out the possibility that future, more detailed studies may revise and further refine our interpretation of seismic effects. The most well-documented earthquakes that reached the maximum level of seismic intensity attested in Siena (degree VII MCS) seem instead to belong to the "sequences with a main event" type, the main examples of which are those of 13 April 1558, and 26 May 1798.

---

[2] As we will see later on, for this earthquake, the subject of specific analysis in the PROTECT project, the discovery of new historical and archaeological information has led to a reassessment of the earthquake's impact on Siena's old city centre.

[3] This is the situation recorded in the famous Biccherna book-panel for 1467 (ASSI, 15th cent.), described thus by a contemporary: "Tremuoti: cioè adì 22 d'agosto 1467 a ore due di notte fu un grandissimo tremuoto, e seguitorno degli altri più comunali, di modo che ognuno s'uscì di casa, ed andavano per le piazze e per gli orti per lo meglio potevano; e féssi molte trabacche, e padiglioni, e case di legname; e spesso ne traeva de' grandi e piccoli. E adì 3 di settembre ne trasse uno sì grande, che fe' sbalordire ognuno; e cadde due armi de' merli degli Uffiziali della Mercanzia verso il Campo, e per la Dio grazia non si è mai fatto male a nessuno" (Allegretti 15th cent.).

The 1558 event, with its epicentre just outside the north-eastern boundary of the province of Siena, was distinguished by a small number of perceptible after-shocks, including one main after-shock on the afternoon of 13 April, and a few minor ones on the morning of 14 April. The earthquake caused significant damage in the Valdambra, with the greatest destruction in Caposelvi. In Siena, serious damage was caused to the Cathedral, the church of Sant'Agostino and Palazzo Cerretani (now Pannocchieschi d'Elci) in Piazza del Campo. Most buildings suffered some physical damage, and there was a generalised collapse of chimneys. It is quite possible that the effect of this earthquake on Siena was magnified by the structural deterioration of buildings in the aftermath of the 1554-1555 siege.

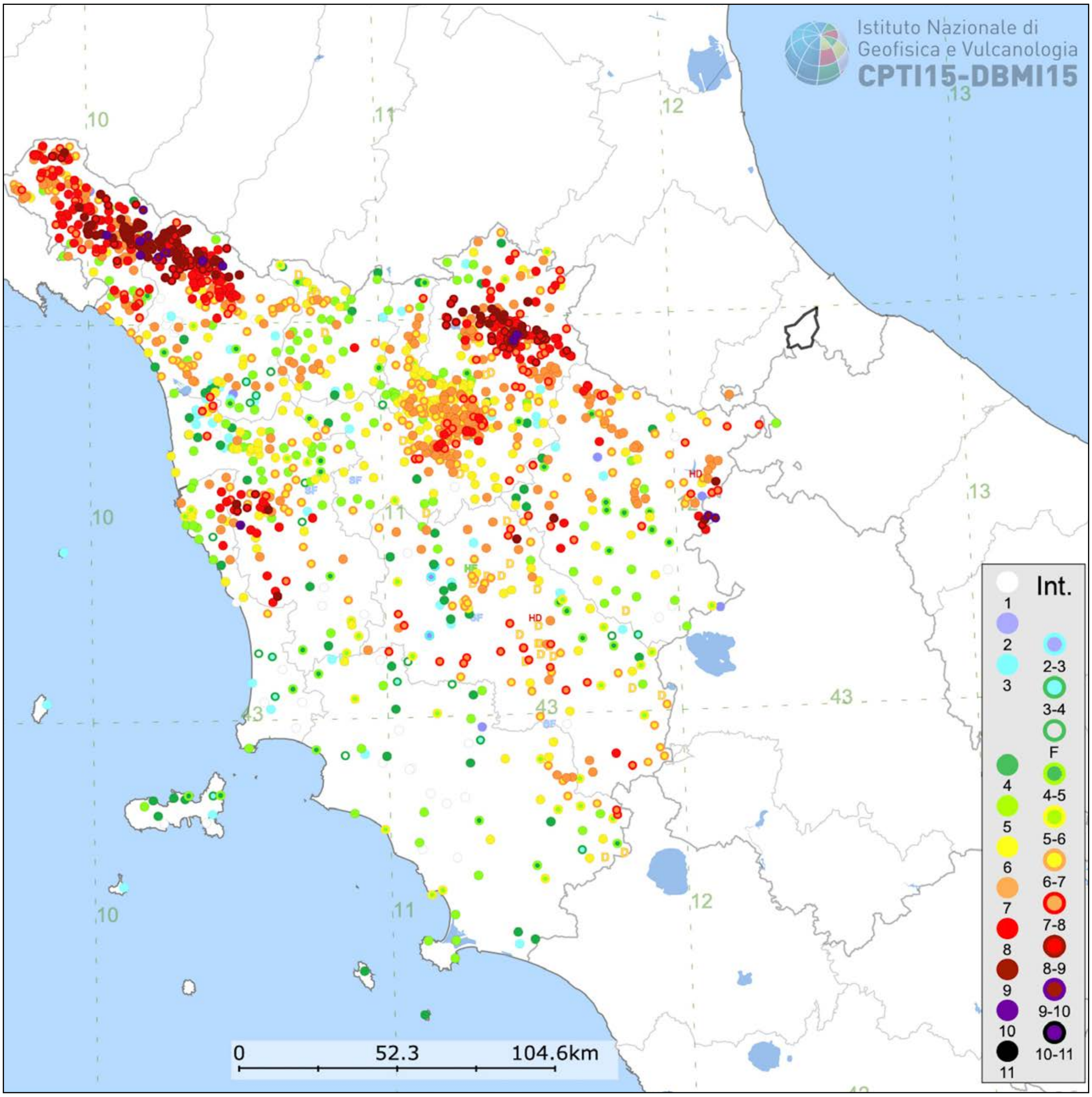

Figure 2.4 - Distribution of the maximum intensities observed in the Tuscany Region (Locati et al., 2022). Image taken from: Castelli 2023.

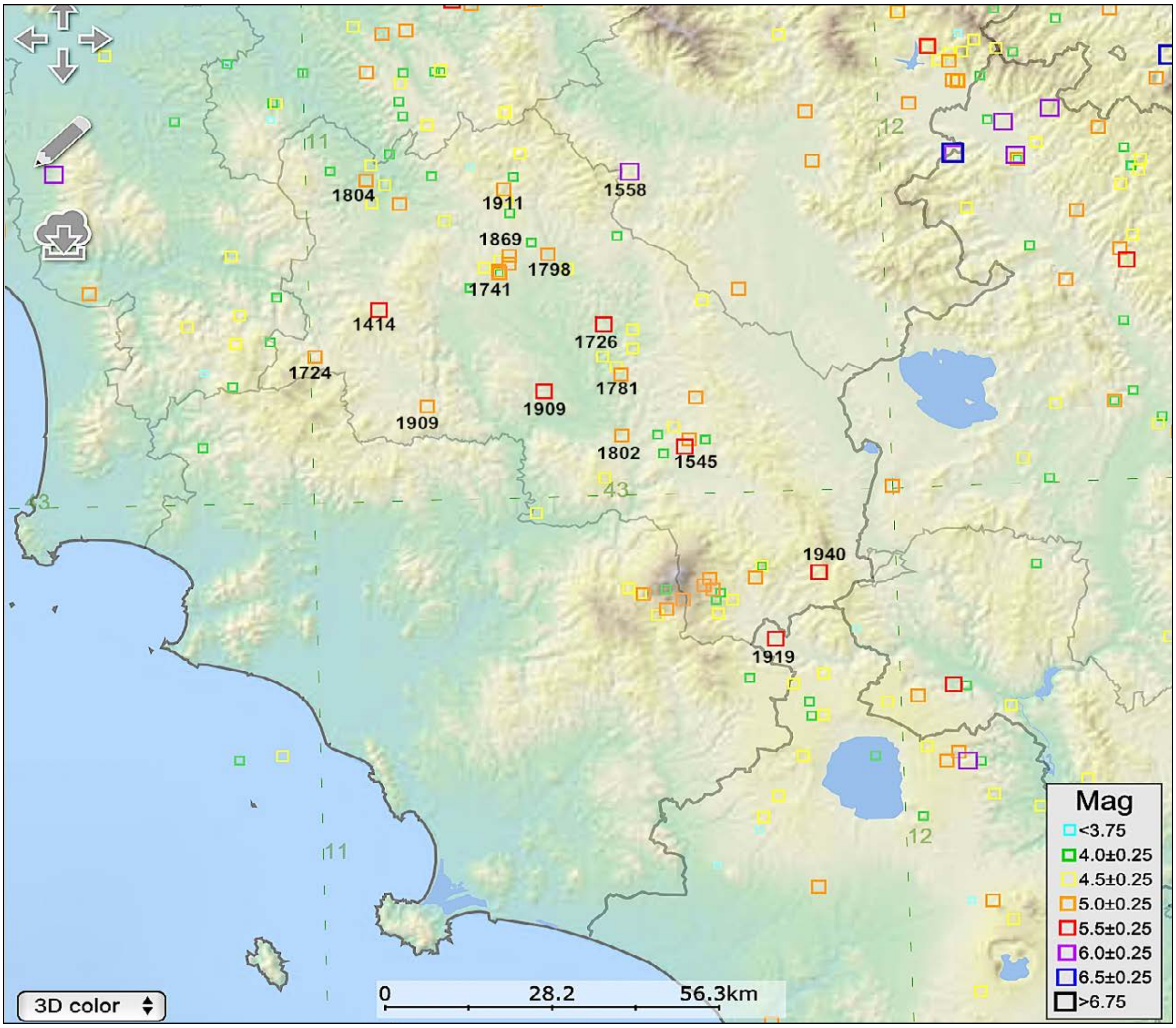

Figure 2.5 - Distribution of earthquakes located in or near the Province of Siena (Rovida et al., 2022). The dates shown are those of earthquakes with magnitude ≥ 5.0. Image taken from: Castelli 2023.

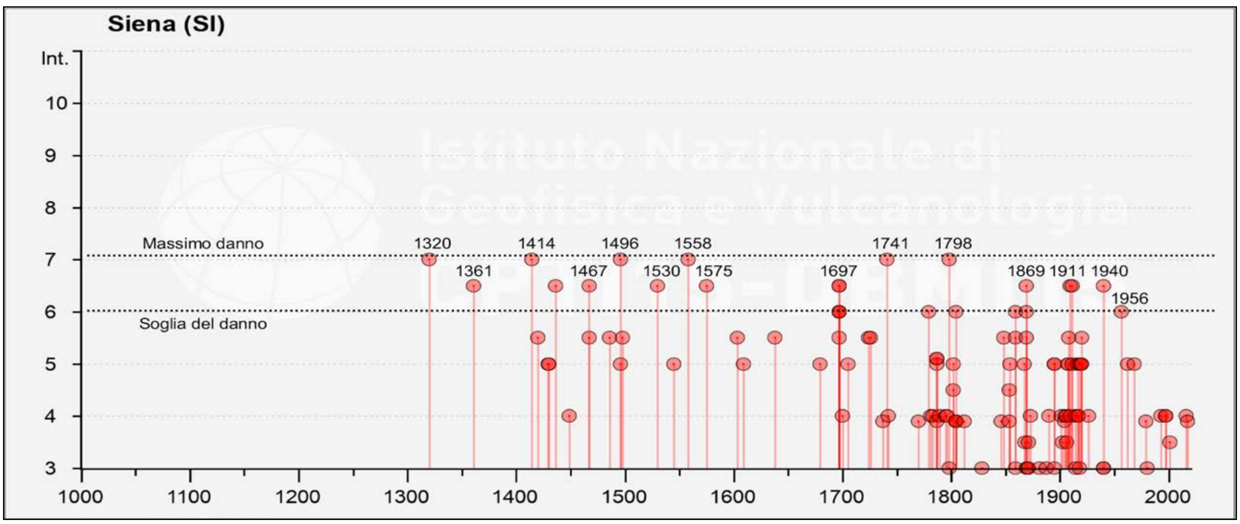

Figure 2.6 - Seismic history of Siena with major intensity earthquakes highlighted (Locati et al., 2022). Image taken from: Castelli 2023.

The earthquake of 26 May 1798, of local origin, was followed by lesser tremors that "tended to noticeably diminish until 30 May [...] after which no more effects were noted", as we are told by a contemporary witness[4].

The event, outside the city, caused minimal, isolated damage that was limited to the area between Siena and Castelnuovo Berardenga, an area featuring small, scattered habitation nuclei. In Siena the damage was more serious and internal, including the collapse of vaulted ceilings and large cracks, and it affected both monumental buildings, such as the Cathedral[5], and many residential buildings, especially buildings that were already in poor condition[6]. There were no total collapses during the main quake or the subsequent after-shocks. The main, actual collapses occurred in June, days after the end of the tremors[7]. Nevertheless, occasional structural collapses were frequent in Siena even without earthquakes[8]. Contemporary figures agree on the fact that the 1798 damage was aggravated by the existing precarious state of the buildings[9]. Restoration work took years, but the urban fabric of Siena recovered over time. Currently, more than 200 years after the last major quake, traces of the damage are faint, and mainly consist in structural reinforcements, façade supports, the filling-in of loggias and arches, and occasional commemorative inscriptions in the old city centre.

In conclusion, it is possible to say that, if we exclude the 1558 and 1798 earthquakes, for which detailed information is available thanks to extensive research involving consultation of public and private archives in Siena and Florence, and contemporary narrative sources, most of the information on the other earthquakes that caused damage in Siena is less complete. Indeed, information relating to these latter events comes largely from more general or preliminary seismological studies (Castelli et al., 1996). These gaps in our knowledge have thus stimulated a desire to fill the void, and this was one of the chief reasons why the PROTECT project has decided to focus part of its investigations on one of the most oft-debated and, at least apparently, non-destructive seismic events in the history of Siena, namely the 1467 earthquake.

---

[4] "[...] per quanto ho potuto scuoprire interrogando varie persone meno timide e più veridiche, posso con sicurezza affermare, essere stati non più di nove o dieci i terremoti sensibili della terra. Io suppongo però con tutta verisimiglianza, che vi saranno state delle scossette insensibili, che avranno preceduta la grande; ed altre egualmente piccole son d'avviso che abbiano seguitato anche dopo il dì 30. Ma comunque siasi, certo è, che dal dì 26 sono andati i terremoti sensibilmente diminuendosi fino al dì 30, in cui io sentii la scossa surriferita, dopo la quale di null' altro ho potuto accorgermi" (Soldani 1798: 8).

[5] It remained unusable for several months, and was partially reopened for worship only in 1799 (Sembranti 1995).

[6] "[...] le Case sono in buona parte inabitabili [ma] vi sono molti Rioni, che hanno poco sofferto, parlando generalmente, perché ancora in quelli qualche Casaccia ha dei patimenti notabili" noted one expert eye-witness, the engineer of the Regie Fabbriche di Siena, on 10 June 1798 (ASS 1798).

[7] "[12 June 1798] Domenica caddero due case, cioè i tetti [e] palconi del Gonzi, ed altre vicino ad esso apresso le Due Porte. Jeri cadde al Bruco la casa del Mariottini, ed in quest'ultima vi erano stati gli famosi ingegnieri fiorentini Giuseppe Del Rosso, Bernardino della Porta, Giuseppe Fontebuoni, i quali aveano giudicato per ora non esservi pericolo, non erano sortiti dalla contrada del Bruco, che la casa era caduta, onde sono venuti a pappare i fiorentini" (Bandini 18th-19th cents. ms. D.III.14, c. 91v).

[8] Ibidem, ms. D.III.13, c. 53r (3 May 1797) "Caduta di fabbrica al mercato | Al mercato in questa mattina è caduta una casa che ha fatto assai chiasso, la medesima spetta al cappellajo Zocchi, vi sono restati due manovali, che la famosa [parola illeggibile] tedesca, ed altro uomo".

[9] The governor of Siena wrote, on 1 June 1798: "Per quanto le Fabbriche non presentino all'esterno molti danni, alla riserva di poche, hanno nell'interno infinitamente sofferto, maggiormente per altro nell'alto che nel basso, forse proprio per la loro evidente elevazione, per la cattiva costruzione, e perl'aggregazione di diverse vecchie Case per formarne una" (ASS 1798).

CHAPTER III

Methodologies of analysis

Before embarking on a detailed analysis of the operational procedure applied experimentally to Siena's historical centre, it will be useful to discuss the main methods of analysis adopted during the PROTECT project, setting out from an examination of their general characteristics, and specifying how they were adapted to the specific analysis of the study context. This operation, which helps to refine the archaeoseismological method of analysis, created the foundations for the construction of a specific operational protocol, presented and discussed in chapter 5.

It also seems useful to underline the fact that most of the methodologies briefly described in the following sections require the presence, within the project, of specific professionals who must work side-by-side with archaeologists. Indeed, the archaeoseismological analysis of a context envisages a highly multidisciplinary investigative protocol in which archaeologists, historians, seismologists, architects, engineers, and geologists work closely together in the various phases of analysis.

3.1 Analysis of historical and seismological sources

The first step in the archaeoseismological investigation of a context prone to seismic risk is to gather specific, detailed information regarding historical earthquakes and their effects on the anthropic and material fabric. Specifically, this phase of the analysis places attention on the following aspects:

- the number and characteristics of telluric events that have affected the research context, seeking to understand how strong they were and, whenever possible, what types of damage they caused to the urban fabric and to built structures;
- the area of diffusion of each single event, i.e. its real extent;
- the measures adopted to deal with seismic scenarios, namely the technical and practical provisions (the criteria of intervention, and any pre- and post- seismic protective features used in buildings) and political and economic provisions (in terms of regulations, laws, best practices etc.);
- the repercussions in political, economic and social terms caused by the event, namely how the research context reacted to the event in the short and long term, ranging from resilience to abandonment.

In order to obtain this kind of information, in most cases one makes use of studies produced and published by historical seismologists. As a brief introduction to the subject, for which we refer readers to a special bibliography[1], we could say that the assessment and interpretation of the effects of past earthquakes in an anthropised territory, be it rural or urban, are carried out by historians of seismology, and are essentially based on a critical interpretation of the information contained within documentary sources. In other words, historical seismology recovers information on the macroseismic effects of a given earthquake as reported by the aforementioned sources, and on the basis of these it reconstructs the scenario and the distribution of these effects in the local area, assigning a degree of intensity to each locality for that particular earthquake. Using special algorithms, these values can then be converted into estimates of the location of the epicentre, and the magnitude of the earthquake, that are equivalent in every respect to modern parameters of measurement. In Italy, for example, this process allows us to obtain information for every historical earthquake that can be added to the Italian Parametric Earthquake Catalogue (CPTI15) and the associated macroseismic database (DBMI15) (Rovida et al., 2022). Finally, a comparison between modern-day and historical seismic activity helps to outline the seismic characteristics of the local area, and represent a very important part of studies aimed at modern estimates of seismic dangerousness.

These kinds of data are absolutely essential for archaeoseismologic analyses, since they make it possible to:

- determine the boundaries of the investigative context;
- set strategic objectives in research on the basis of the evidence reported in the sources;
- obtain specific chronologies in the phase involving the archaeological analysis of masonry palimpsests both as regards damage and structural collapse caused by earthquakes, and also with reference to the restoration and reconstruction of individual architectural complexes;
- obtain more data with a view to putting forward suggested historical reconstructions that are as faithful as possible of the pre- and post-seismic scenarios.

In the PROTECT project, scrutiny of seismological sources, which took place in direct contact with some of the leading experts in the field of seismology in the area of Siena[2], as we shall see in section 4.1.1, has enabled us to identify the most representative earthquakes to be analysed, the parts of the old city centre struck by such events, and the damage and/or collapses in the case of individual building complexes.

[1] The treatise De Terraemotu (Manetti 15th cent.) can be regarded as the first example of an Italian study in the field of historical seismology. This includes a list of the most powerful earthquakes to have taken place in Italy, Europe and the Mediterranean area since the creation of the world, and up until 1456. Between the 16th and 19th centuries a great number of Italian and European scholars devoted themselves to studying ancient and recent earthquakes, and to compiling chronological lists of earthquakes at the local, national or even global level: the treatise entitled Terra Tremante (Bonito 1601) refers to earthquakes in China, Japan and the eastern and western "Indies". This long period of studies culminated in the late 19th century with I Terremoti d'Italia (Baratta 1901) which provides a documented chrono-history of 1,336 Italian earthquakes from the year 0 AD up to the year 1898. For the period prior to the 20th century BARATTA 1901 is the main source for the first Italian parametric seismic catalogue designed for public consultation (Postpischl 1985), and it continues to be responsible for helping to identify most earthquakes occurring before the 1900s present in the current catalogue (Rovida et al., 2022). To identify earthquakes not mentioned by Baratta 1901 or in the parametric catalogues, see: Camassi et al., 2011. For other information on matters relating to ancient and recent historical seismology, readers may refer to: Guidoboni 1989; Guidoboni and Comastri 2005; Guidoboni and Stucchi 1993; Guidoboni et al., 2019; Camassi et al., 2011.

[2] I wish to thank Dott. Romano Camassi and Dott.ssa Viviana Castelli of the Istituto Nazionale di Geofisica e Vulcanologia for their valuable collaboration.

3.2 Analysis of archive and documentary sources

The preliminary seismological analyses of the investigative contexts described earlier, especially for some historical periods not explored in macroseismic databases, do not display a sufficient amount of information for carrying out an archaeoseismologic analysis. For this reason, whenever possible, as well as examining the sources contained in seismological catalogues, it is also useful to conduct a specific analysis of public and private archives of the individual research context, or sites close to the context in question. This step, although often underestimated, is shown to be absolutely vital, since it allows us to fill in any historical and chronological gaps for little-known earthquakes and, when the archives feature an exceptional wealth of documents, to advance completely new scenarios for earthquakes that have not been explored in detail by seismologists, or which are even wholly unknown. In addition, an analysis of archive documents offers us the chance to get hold of information that is crucial for dating and interpretation, as supplementary evidence when it comes to an analysis of masonry. This helps the archaeologist in understanding certain dynamics involved in construction and/or destruction, and in relative dating, or sometimes absolute dating, of particular Stratigraphic Units (Unità Stratigrafiche) at the analysis stage.

Within the PROTECT project the archive research was conducted in collaboration with a researcher in the field of medieval and modern history[3], and it involved an analysis of the documentary sources held at the State Archive of Siena for 14th and 15th century earthquakes. This research work, as shown in section 4.1.1, took around six months, and revealed the total absence of information for 14th century earthquakes (at least for the sources we analysed). By way of compensation, an exceptional document was discovered, a Lira tax record, described in the next chapter, which offered a very detailed description of the effects of the 1467 earthquake on the entire old city centre of Siena.

3.3 Archeological surveys of built structures

A vital operation for area-wide archaeoseismological fieldwork, whether it be in a rural or urban setting, is an archaeological survey of the study context, so as to determine the samples to be analysed. This operation is closely connected to the analyses described in the previous sections, since in order to be formulated it requires detailed preliminary knowledge of the study context, and of the dynamics of individual seismic areas. In operational terms, the survey involves a macroscopic survey conducted using specially designed record sheets, backed up by supporting graphic documentation (drawings, photographs, rapidly executed measured drawings etc.), of the samples of interest, with a view to classifying these features in qualitative and quantitative terms. This process thus allows us to find out how many samples of the research context can be studied, since they have features that match the research goals, and that are suited for being classified on the basis of the kind of information they contain. Indeed, setting out from the belief that, within the time limits of a project, it is impossible to study a whole research context as large as an old town centre, a selection needs to be made of the sample that has been judged to be suitable. For the archaeoseismological analyses of built features, this is later selected and divided into two groups: buildings whose features give us specific information about individual seismic events; and buildings that have features that are compatible with the aims of the project, but which provide less reliable and clear findings. Accordingly, whereas in the first case the analysis of the evidence will be addressed in a detailed way so as to get data that may be used as a basis for the construction of the main samples on which to formulate the detailed analyses, in the second

[3] In this connection I thank Dott.ssa Barbara Gelli of Siena University for her valuable collaboration.

Figure 3.1 - Some examples of post-seismic techniques documented during the archaeoseismological fieldwork survey: bond stones (a and d) and relieving arch (b and c).

case the evidence will prove to be excellent material for carrying out specific typological comparisons with the samples in the first group, with a view to determining types of construction or destruction operations that are chronologically similar.

In the PROTECT project this process proved to be a totally vital step for abiding by the timeframe set in place by the research programme, lasting a total of two years, and for trying to analyse a context that is packed with rich evidence, the choice of which initially appeared to be extremely complex. Thus, in operational terms, as we shall see in the next chapter, we proceeded by identifying the investigative context to be analysed by means of the archaeological analysis of built structures, namely the Terzo di Città (one of the three main quarters of the city), and later on by conducting a specific survey of the area, and documentation of the samples of interest, by means of specially designed site record sheets, an open source database, and compiling a photographic database of details of interest (fig.3.1).

3.4 Digital surveys

Surveys have long been an exceptionally valuable tool for archaeology. The technologies now available record a great amount of data, offering an opportunity to work on models that are perfectly compatible with the real object. Working on a digital model of a built feature, while not excluding necessary fieldwork, which every operator is required to carry out, makes it possible not only to document and record thoughts and observations made when in direct contact with the object being examined, but also to provide suggestions that may be useful for interpreting, and thus understanding, historical and archaeological information.

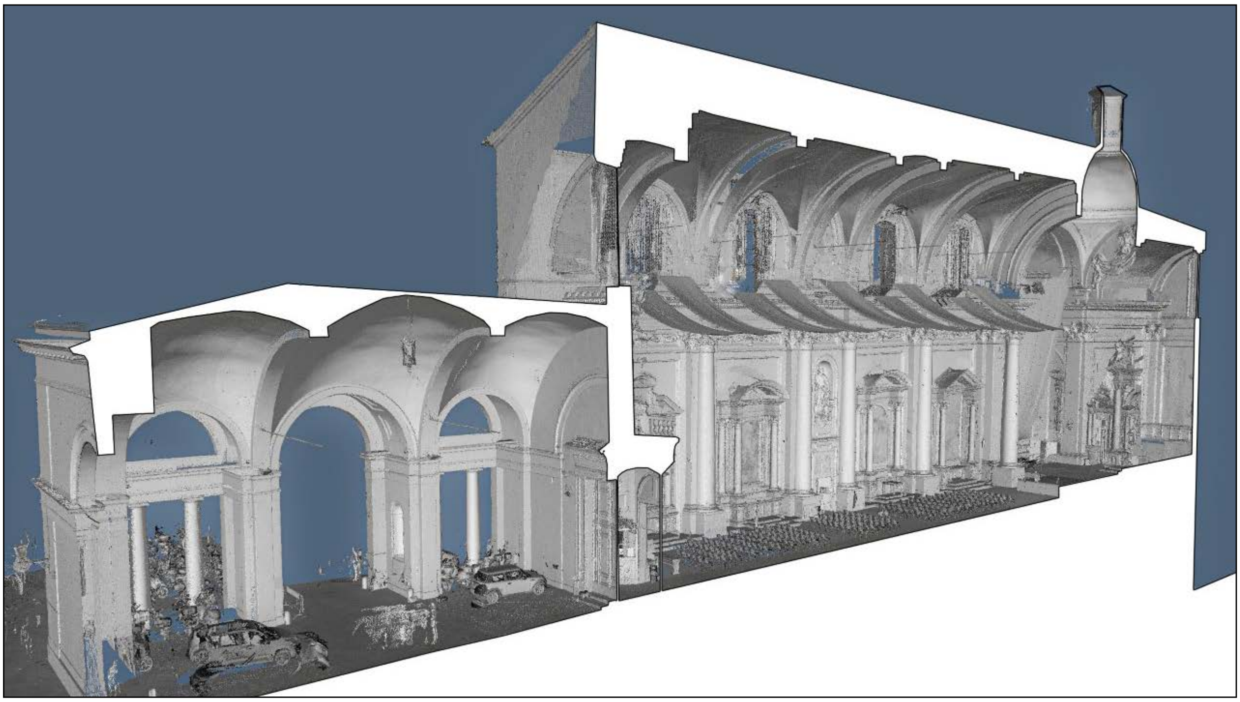

Figure 3.2 - Longitudinal section of the three-dimensional model of the Church of St. Augustine obtained by laser scanner and photogrammetric survey (elaboration: Marco Repole).

Figure 3.3 - Image of a 'classic' Elevation Map with colors (elaboration: Marco Repole).

This reflection becomes an even more fascinating concept if we consider historical buildings, features that encapsulate a rich complexity of organisation, function, construction, and symbols, and that are the fruit of experiences, skills, and empirical and scientific knowhow that is passed on, but which is instrinsically bound up with man and human societies. And it is in just such contexts that surveys become a vital tool in support of archaeology in every working phase. In this connection we might cite the example of the countless transformations that the internal parts of a building undergo over time, with an alteration, or more often several alterations, affecting the height of floors and ceilings, and thus the relationships between the various rooms (fig.3.2). Often what remains of the initial phases of life of a building are "sealed" within spaces that are physically hard to access, topographically far apart, and often separated from each other. Managing to place such data points in relation to each other is an absolutely vital operation for gaining a full understanding of the evolution of a building, and the building design decisions made by the patrons concerned, and by the master-builders who helped to build it and to alter it over time.

Although anthropic alterations are found to be understandable in many ways, and often logical or at any rate linked to a clear aim on the part of the people who ordered the construction, the scenario seems very different when a structure is transformed by natural events. In this case there are several factors that help to define a diverse range of factors involving alterations to buildings during pre- and post-seismic scenarios. However, in this case too buildings record all these dynamics, and seal them within their physical structure. It is down to archaeologists to document these traces, and to turn them into negative and positive actions, and finally to interpret them. In this event, too, surveys become truly essential tools both when it comes to the recording phase, and in the delicate moment of interpretation. The most striking example lies in the use of Elevation Maps (fig. 3.3), i.e. two-dimensional representations of what are initially three-dimensional data, namely deformations. These not only allow us to assess the state of conservation and the problematics involving an architectural artefact at the time when we carry out the survey, and also to provide assessments regarding the dynamics associated with seismic events that have affected the building over time. In that sense, the detailed recording of deformations, as well as of cracks, becomes vitally important for understanding the evolution of the structure itself, its transformations and its signs of disrepair, and consequently the dynamics underlying decisions to intervene and transform an architectural complex.

This type of consideration has an even more hard and fast legitimation in areas that are periodically affected by seismic events on a medium to large scale. In these cases it is absolutely indispensable to understand the effects of earthquakes on the buildings present at that historical time, together with the characteristics and state of conservation of the individual buildings. When possible, this type of information allows us to produce historical data relating to seismic activity that has affected an area, and the societies that have contributed to the transformation of landscapes over time. At the same time, archaeoseismological analysis provides numerous items of technical information, relating to the mechanical history of a building, that are vital for the purposes of possible future planning of restoration or maintenance work.

In the PROTECT project, as shown in section 4.2, trying out a range of different survey systems offered highly interesting discussion points as regards the dynamics of use of techniques and technology in the various phases of the project's development. Indeed, in operational terms steps were taken to include various different types of survey (mobile and land-based laser scanner, fig.3.4, close-range and drone-based photogrammetry, fig.3.5) in specific moments during the progress of the investigations, from surveying to documentation. Moreover, the documentation may be conducted either cursorily or in a highly detailed way, assessing, as and when, the negative and positive aspects of the tools and instrumentation that are used, as well as the timing and results achieved.

Figure 3.4 - Images of the survey fieldwork carried out using mobile and terrestrial laser scanners.

3.5 Archeosismological analysis of built features

Archaeoseismology, namely the suite of archaeological analyses applied to the study of contexts situated in zones at seismic risk, is a widely-used discipline, and has been for decades now, in many parts of the world. There are several reasons why it is so widespread, given that, thanks to this fact, it becomes possible to glean information regarding earthquakes from past times that is hard to infer by means of a more traditional form of analysis. Although the application of archaeoseismology to subsoil sequences, and to remains of built structures now in ruins, in the form of archaeological remains, is nowadays very common internationally, the use of methods that are part and parcel of the archaeology of architecture for an analysis of historical buildings in contexts such as old urban centres located in areas at seismic risk is, thus far, a geographically limited field, and one that has been approached in a variety of differing ways (Arrighetti 2015). At the European scale, the archaeology of historical buildings has only dealt fairly sporadically with analyses of whole agglomerations from the seismological viewpoint, with projects aimed at reconstructing the seismic history of contexts, with a view to prevention. An exception to this panorama seems to be Italy where, due in part to a seismic activity on a fairly large scale, in recent years we have seen a renewed interest in the discipline of archaeoseismology applied to excavation contexts and, albeit on a more sporadic basis, to historical buildings. This is borne witness to by the fact that specific projects have been set up developed in several parts of Tuscany[4], and by the proliferation of debates that have featured at national and international conferences and conventions on specific historical and archaeological subjects, held following the 2009 earthquake in Abruzzo, the 2012 earthquake in northern Italy, and the 2016 earthquake in central Italy[5].

---

[4] With special reference to the Mugello, Casentino and city of Florence areas. The projects were developed in collaboration between Siena University's DSSBC department, and Florence University's DIDA – Department of Architecture.

[5] To cite some of the most significant examples: the SAMI conference held at L'Aquila in 2012 (Redi and Forgione 2012); the Italo-French conference of Cascia and Le Mans, held on two occasions between 2019 and 2020 (Soussignan et al., 2022); the Mantua conference on the 1117 earthquake (Calzona et al., 2018); the seminar at Rome's Istituto Storico Italiano per il Medio Evo, the proceedings of which appeared in number 122 of the bulletin published in 2020; the Construction Economies and

Figure 3.5 - Detail of a moment of photographic data acquisition with a drone.

Within this panorama special importance attaches to the debate over the criteria governing the appearance, development and spread of techniques of post-seismic repair in the medieval period and in the modern era. Although the literature focusing on built features in the Classical and pre-Classical period gives us a fairly rich picture of research into the effects of earthquakes and forms of intervention prior to and in the wake of a seismic event, by means of expedients mostly correlating to the skills and beliefs that permeated societies of the past[6], in the European field, for the medieval period, there are few in-depth archaeoseismological studies that look at a particular local area[7]. Publications become more extensive, with considerably interesting in-depth discussion, shifting their attention to modern and contemporary structures, where the subject is addressed especially by architects and engineers with reference to the major restoration projects that have involved the numerous areas in Europe, and outside it, affected by earthquakes having medium and high macroseismic intensity[8].

Techniques research conference, held in Siena in 2018, the proceedings of which appeared in number XXIII of the journal Archeologia dell'Architettura (Arrighetti 2018b); and the 2017 conference in Foggia on the heritage of the Capitanata district (Zullo 2018).

[6] Of the most important examples in Italy currently under way, we might mention a number of recent publications referring to projects involving the archaeological sites of Pompeii (Dessales 2022) and Ostia (Marra et al., 2020; Pecchioli et al., 2018; Pecchioli 2022) and a selection of broad-ranging conference proceedings on this topic (Broek-Parant and Ismaelli 2021; Alberti et al., 2019; Correia et al., 2015)

[7] The most well-known include: the "Archeologia dell'architettura e rischio sismico in Mugello" project, which takes a local geographical and methodological approach (Arrighetti 2015); the "ArMedEa - Archaeology of Medieval Earthquakes in Europe (1000-1550 AD)" project, developed by Durham University's Department of Archaeology, which has characteristics more directed to the political, economic and social effects of seismic events (Forlin et al., 2015; Forlin and Gerrard 2017; Gerrard et al., 2021); and the Italo-French "ACROSS - "ArChaeology, inventory of RecOnstruction, Seismology and Structural engineering" project, developed in the Mugello area, with special attention to post-seismic intervention dynamics of a historical nature involving belltowers (Montabert et al., 2020; 2022).

[8] One example worth mentioning are the numerous publications dealing with the effects of the powerful Lisbon earthquake of 1755.

For pre-modern periods these techniques seem to have been probably used as forms of empirical experimentation, with reference to the formation of particular and frequent forms of structural damage caused by earthquakes to buildings, although their real spread and development within larger or smaller geographical contexts is still not clear today. If we take the planning of the anti-seismic home of Pirro Ligorio (Guidoboni 1987), dated 1570, as our point of departure in our critical and conscious considerations regarding the design and implementation of repair or prevention techniques for buildings in reference to earthquakes, what happens in chronologically earlier periods, in the absence of historical sources that testify to it in a detailed way, can only be reconstructed by analysis of the buildings of the past. In this case the building, once the phases of construction and destruction have been understood, and stratigraphical information correlated to the structural damage of seismic origin, becomes the main source for our understanding of construction phenomena linked to the intention

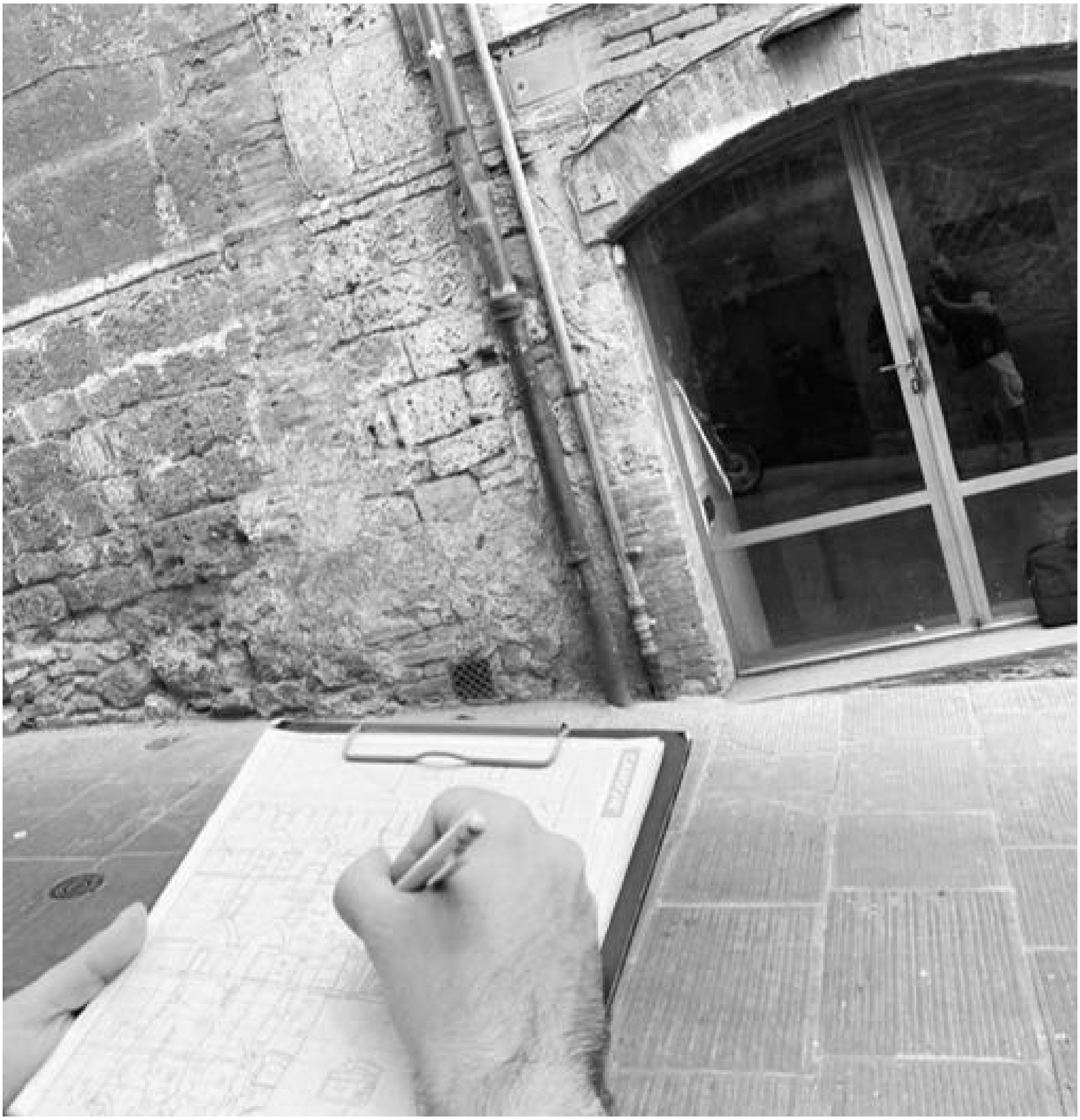

Figure 3.6 - Detail of the archaeological analysis of the architecture carried out in the field.

STREET FRONT			
Name: Via Pendola	Num. CF: 7 + n.d.	Num. UUSS: 1391	No. TC: 30 traditional + 37 post-seismic
Description: Street front of about 100 linear meters, characterized by numerous buildings of which one plastered and therefore unreadable from the stratigraphic point of view. The readable street front has extensive stratification with cracks and post-seismic techniques clearly visible. There are also numerous openings, most of them related to modern or contemporary reconstruction operations. It is noteworthy the presence of a stone face in the eastern part, related to the presence of the previous walls of the town of Siena, later incorporated into the street front. On the intersection with Via San Pietro, there is also a building similar to a tower.			

BUILDING				
ID: CF5	Num. CF: 5	No. of construction periods: -	No. of the phases: -	Type: Civil construction - road front
Description: Building built in bricks, of which the only street front is readable. The building is preserved only up to half (?) of its original overall height. The cut involved the installation of three other buildings above. It has numerous openings modified or made from scratch in modern and contemporary times. It also has numerous post-seismic techniques, probably linked to earthquakes, to counteract overturning processes (buttresses and iron chains) and to strengthen the masonry from the structural point of view (infill of openings, drain arches).				

PRELIMINARY ANALYSIS	**STATE OF CONSERVATION**
Visibility: Excellent	Structural degradation: cracks and deformations
Readability: Very good	Degradation of surfaces: -
Synthesis of phases: -	Structural elements: iron chains, discharge arches, buttresses
Activity: -	Elevation of ref.: -

PHYSICAL RELATIONSHIP	
	Front to: CF4, CF5.A, CF5.B, CF5.C
	Back to: CF6

POST-SEISMIC TECHNIQUES				
ID: P1	Typology of Element: Buttress	Building: CF5	Elevation: Sud	UUSS: 675
Material for construction: Bricks		Processing: -	Finishing: -	

CHRONOLOGY	Relative		
	Anterior *735, 547, 1390, 1391*	*Posterior* -	*Contemporary* -
	Absolute: 1798 (?)		

Description:	Interpretation:
Buttress size (1.45 x 9 m) made of bricks with an irregular brickwork.	Buttress built probably as a result of the instability (overturning of the CF5 street front) caused by the earthquake of 1798. The post-seismic technique was built over another previous buttress, also made of bricks but larger.

Figure 3.7 - The material structure worksheet realized for the documentation of road fronts, divided into three sectors: road fronts, standing buildings, post-seismic construction techniques.

to achieve protection against the effects of earthquakes. The phenomenon is of great interest, and it acquires a historical profile if associated with the political, economic and social dynamics that affected the study context in a given historical period, and at the same time a technical and scientific profile, deriving from the documentation, description and evaluation of these elements with a view to future restoration projects or interventions compatible with ancient structures.

For the PROTECT project, the phase of archaeoseismological interpretation of standing remains was conducted by means of a first-hand observation and examination of study contexts. For every masonry part of interest, on-site sketches were made of the elevations, showing the respective Stratigraphic Units (Unità Stratigrafiche) identified in the course of the archaeological analysis (fig.3.6). In addition, site record sheets, specially designed for the various situations encountered in the course of investigations, were filled out. These adopt differing criteria of analysis depending on the various different objectives set for each study context (fig.3.7). These data were later transferred to renderings produced by digital survey, where all the features of interest found by fieldwork were documented and recorded (fig.3.8).

Figure 3.8 - Methodological table illustrating the digitization of the archaeological analyses carried out on the street front of Via Pendola. In the centre of the image is shown a photo-plan of a portion of the street front where the stratigraphic analysis, the characterization of the cracking framework and the documentation of the post-seismic techniques were carried out. Above are shown portions of the elevation (a, b, c) with enlargements of the stratigraphic analysis (in blue) and of the cracks pattern (in red). At the bottom, the post-seismic techniques and cracks are shown (d, e, f) (Elaboration: Marco Repole).

CHAPTER IV

Application to study context

In terms of its operation, the PROTECT project is based on applying and testing the archaeological interpretation of the effects of earthquakes on historical buildings in Siena, in line with a vision with differing scales of analysis in studying built features. An initial, general level involves the analysis of the context overall. This research process is addressed by means of an investigation of a historical and seismological nature geared to individual seismic events, and a transposition of the findings to tools that allow them to be typologised, and that allow a large-scale vision.

A second step, more in-depth than the previous one but closely linked to it, involves the process of analysis of a number of sections of the city centre so as to understand the dynamics of its construction, from a historical perspective, and the presence of any specific architectural elements designed to counter the effect of earthquakes. This phase of the investigation relates to earthquakes over long periods of time, and thus not individual events, and involves a cursory, medium-scale archaeoseismological investigation, by means of a level of analysis ranging from an entire neighbourhood to an individual street front. A third and final level of analysis involves an individual architectural complex, analysed archaeologically, and documented in its three-dimensional aspect, with an attentive and specific investigative method, aimed at assessing the effects of certain specific earthquakes on the building, and the pre- and post-seismic construction techniques used in its various parts.

Later this approach acquired a common element: the 1467 earthquake. Indeed, this event, documented in exceptional detail in a document, a Lira (property tax record), present in Siena's State Archive, was the basis with which a large-scale analysis was put forward of the entire old city centre by means of a survey, and the subsequent creation of a GIS. In addition, this document, given the discrepancy concerning the effects reported in the sources previously known to us and those found in the Lira, acted as the spur behind the decision to increase our knowledge of the 1467 quake by means of archaeological analysis of masonry structures.

This absolutely important step on the one hand made it possible to structure the subsequent technical, operational and methodological steps for an analysis of tangible features at different scales of examination (whole Terzi, sections of street fronts, and individual architectural complexes) while, on the other hand, also enabling the findings from archaeological analyses to be integrated with documentary analyses. Moreover, given the limited time available, an attempt was made to put together specific operational procedures for each individual context under investigation, deciding on a case-by-case basis which tools and techniques to use, at what level of detail, and with what final results. These activities are shown below, subdivided into the three different scales of detail that make up the project, describing the operations that were carried out, and the results achieved both in terms of methodology and in terms of the complex historical and seismological events surrounding the 1467 earthquake.

4.1 Analysis at the macro scale: Terzi and Popoli

An initial model of analysis proposed by the project is by urban macro-sectors. This type of study is to be applied to the characteristics of each individual context, and it is therefore paramount that it is adapted to the dynamics imposed by the urban historical layout that distinguishes it. In the case of Siena, the subdivision into Terzi (city quarters) and Popoli (neighbourhoods) has enabled a sufficiently sector-based interpretation of information that could not be distinguished by analyses that were either too detailed or too general. This initial subdivision was used to get an understanding of the forms of settlements, and their construction models, with special reference to the state of preservation and conservation of built features, and the amount and quality of information on seismic activity in the area as known up until now. Setting out from this prior information, we pursued a dual path in terms of intervention: on the one hand we tried to expand our knowledge of seismic events affecting the sites via archive research focusing on the 14th and 15th centuries; on the other hand a survey was conducted of buildings of interest, and of the architectural characteristics that might suggest effects or restorations associated with seismic events. This survey was conducted in the Terzo di Città, and allowed us to assess, specifically, the presence of slight or structural damage caused by earthquakes, and post-seismic operations correlating with seismic or other events.

4.1.1 The 1467 earthquake: new scenarios involving history and archaeology [1]

1. State of our knowledge prior to PROTECT project[2]

In the current version 4.0 of the Parametric Catalogue of Italian Earthquakes CPTI15 (Rovida et al., 2022, updated as far as February 2022), the seismic sequence of 1467 is represented by two strings that sum up the epicentre parameters identifying the only two events that the narrative sources available allow to be dated with precision (fig.4.1). The main event in the sequence (3 September 1467) is given a macroseismic intensity, observed in Siena, corresponding to degree VI-VII on the MCS (Mercalli-Cancani-Sieberg) scale.

The estimate of macroseismic intensity, i.e. the classification of the effects of an earthquake in a given area, is arrived at by comparing the available information with the standard descriptive scenarios (degrees) on a macroseismic scale, and is a crucial phase in investigations into historical seismology. To clarify broadly what the intensities attributed to Siena on the occasion of the 1467 events correspond to, we will adopt the interpretative model drawn up by Molin et al. (2008) for the application of the MCS scale[3]. Under this model, degree VI is attributed when the overall set of effects by and large comprises the following: slight damage (e.g. cracks in plaster, a few tiles fall) to 50% of the buildings at a given location; moderate damage (cracks in walls, many tiles fall and/or chimneys collapse, causing damage to rooves or ceilings below, poorly attached decorations become detached) to 25% of buildings; and damage such as to cause the temporary unusability of a further 5% of buildings. In cases when the overall picture of observed effects includes not only the indicators envisaged for a particular degree but also one or more of the indicators envisaged by the degree immediately above, a double degree is

[1] The work of analysis of the documentary sources and archaeological evidence described in this section was carried out in collaboration with Dott.ssa Barbara Gelli from Siena University, and with Dott.ssa Viviana Castelli from the Istituto Nazionale di Geofisica e Vulcanologia, and is currently edited in the journal "Mélanges de l'École Française de Rome - Moyen Âge" (Arrighetti et al., 2025).

[2] This section was curated by Dott.ssa Viviana Castelli of the INGV.

[3] See section 2, "Assegnazione dell'intensità macrosismica" (Molin et al., 2008: 20-22).

attributed to the location, indicating a certain inconsistency. In the case of the event of 22 August 1467, degree V-VI corresponds to a scenario of effects that includes reports of a warning with fear and people fleeing their homes (V), with evidence that means we cannot exclude the possibility of slight or isolated damage occurring in poorly built or old homes (VI).

The data compiled in the Parametric Catalogue of Italian Earthquakes CPTI15 and in the corresponding Italian Macroseismic Database DBMI15 (Locati et al., 2022) sum up the state of our knowledge concerning earthquakes that struck parts of Italy, or that may have taken place on Italian soil, with damaging effects between the year 1000 AD and 2020, making reference, for each of these, to one study in particular, among the many that are listed and found in the database of the Italian Historical Macroseismic Archive ASMI[4] (Rovida et al., 2017).

The 1467 earthquake in Siena has been the subject of two studies of historical seismology (Castelli et al., 1996; Guidoboni et al., 2007), both based on a set of contemporary and non-contemporary narrative sources, which – it is interesting to note – are largely already known to the so-called "seismological tradition", the set of studies and descriptive compilations of earthquakes that became established in Italy between the 15th and 19th centuries, and which still constitutes an important landmark for the start of studies into historical seismology. Only one of the two studies (Castelli et al., 1996) attempted an analysis, one that is moreover cursory and summary, of archive sources (ASS 1467a-b). Apart from a couple of references in the minutes of sessions of the Concistory (Siena's highest governmental body) in September 1467[5], the set of information reconstructed by historical studies is composed exclusively of notations in chronicles (fig.4.2). The most detailed account is the one provided by Allegretto Allegretti (15th century), a member of the city's oligarchy at the time who was just under the age of 40, and who may have experienced the earthquake at first hand[6].

"Tremuoti: cioè adì 22 d'agosto 1467 a ore due di notte fu un grandissimo tremuoto, e seguitoro degli altri più comunali, di modo che ognuno s'uscì di casa, ed andavano per le dell'assegnazione piazze e per gli orti per lo meglio potevano; e fessi molte trabacche, e padiglioni, e case di legname; e spesso ne traeva de' grandi e piccoli. E adì 3 di settembre ne trasse uno sì grande, che fe' sbalordire ognuno; e cadde due armi de' merli degli Uffiziali della Mercanzia verso il Campo, e per la Dio grazia non si è mai fatto male

[4] ASMI includes studies on all the earthquakes covered by CPTI15 and DBMI15, on earthquakes below the intensity/magnitude thresholds adopted by CPTI15 and DBMI15 (intensity 5 and/or magnitude 4), on earthquakes recognised as false, and on earthquakes that occurred prior to the year 1000. For each event taken into consideration, ASMI contains and makes available one or more studies, providing an overview of the multiplicity of existing information, while DBMI15 and CPTI15 contain the fruit of the analysis, selection, and compiling of this multiplicity by means of a single record for each earthquake. Another fundamental difference is that CPTI15 and DBMI15 are updated every several years, whereas ASMI is updated continuously, every time a new study is published.

[5] Only the former refers explicitly to the earthquake: "Die secunda Septembris [...] Magnifici et potentes dominj et capitaneus populi ad consistorium congregati in numero completo ad reverentiam Dei fiat processio religiosorum per civitatem et usque ad suam reversionem non aperantur apotece et mandetur societatibus disciplinatorum quod intersint et hoc propter occurrentes terremotus. [...] Die Jovis iij Septembris. [...] Magnifici domini in mane presentis die iverunt ad processionem" (ASSb, 1467, cc. 2v-3r). Ten days later, on September 12 (ivi, c. 8v), the Concistory orders "quod operarius camerarius Communis expensis communis et camere murari et reaptari faciat merlos palatii qui habent oportunitatem reparari et arcale tecti anditus carcerum", in this case without indicating the cause of the disrepair, although it may be imagined that the earthquake could have been connected to it.

[6] Tommaso Fecini (15th century), who was not in Siena in 1467, noted simply that "A di 15 d'agosto comincioro e' tremuoti in Siena e seguitando, ogni uno facieva gli alogiamenti per le piaze. In detti dì si fe' una bella procissione diciendo : "Qui abitat in aiutorium Altissimi". E duroro[no] tanto li deti trimuoti che per li disagi si colse molte infermità e moriro molte persone dabene». Bartolomei et al. (15th century) echoed him, reporting the "Terraemotus ingentes [...] qui circa Augusti mensis finem incipientes, per dies viginti perduravere, tanto mortalium terrore, ut in plateas plurimi dormitum exirent, ita ut pro incommodo multi languoribus afficerentur".

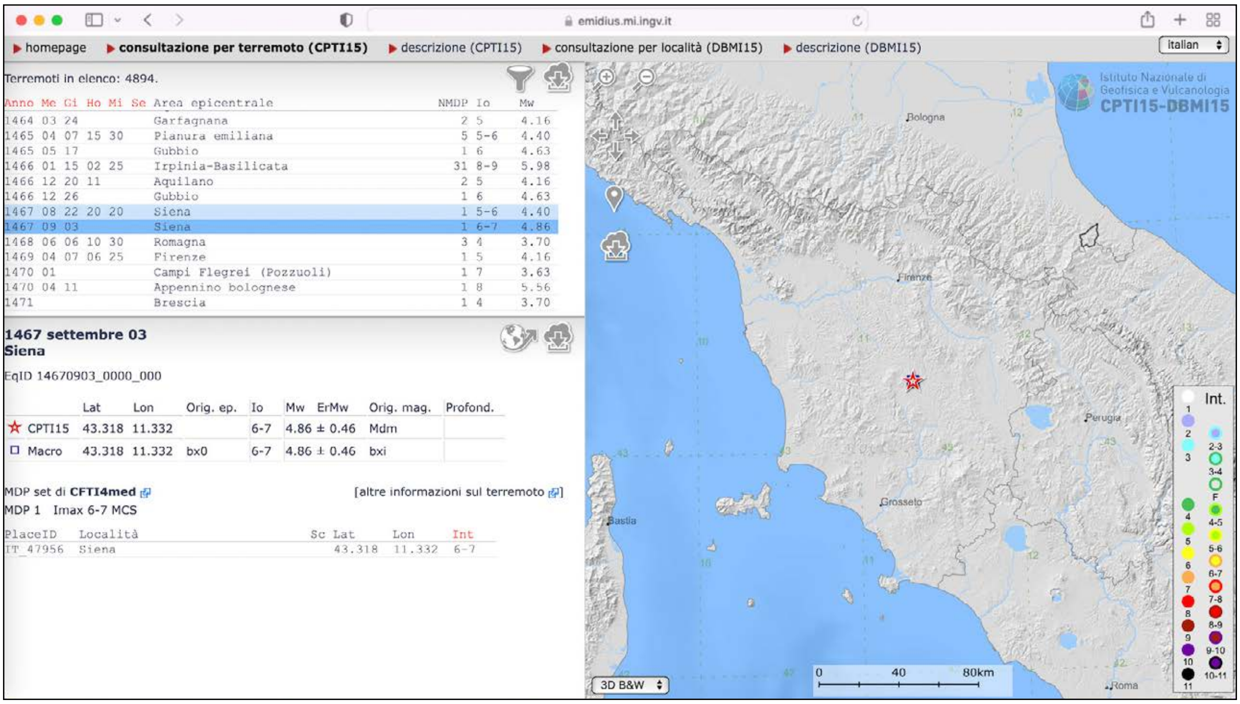

Figure 4.1 - The 1467 Sienese earthquake sequence in the CPTI15 catalogue (Rovida et al. 2022). Image taken from: Arrighetti et al., 2025.

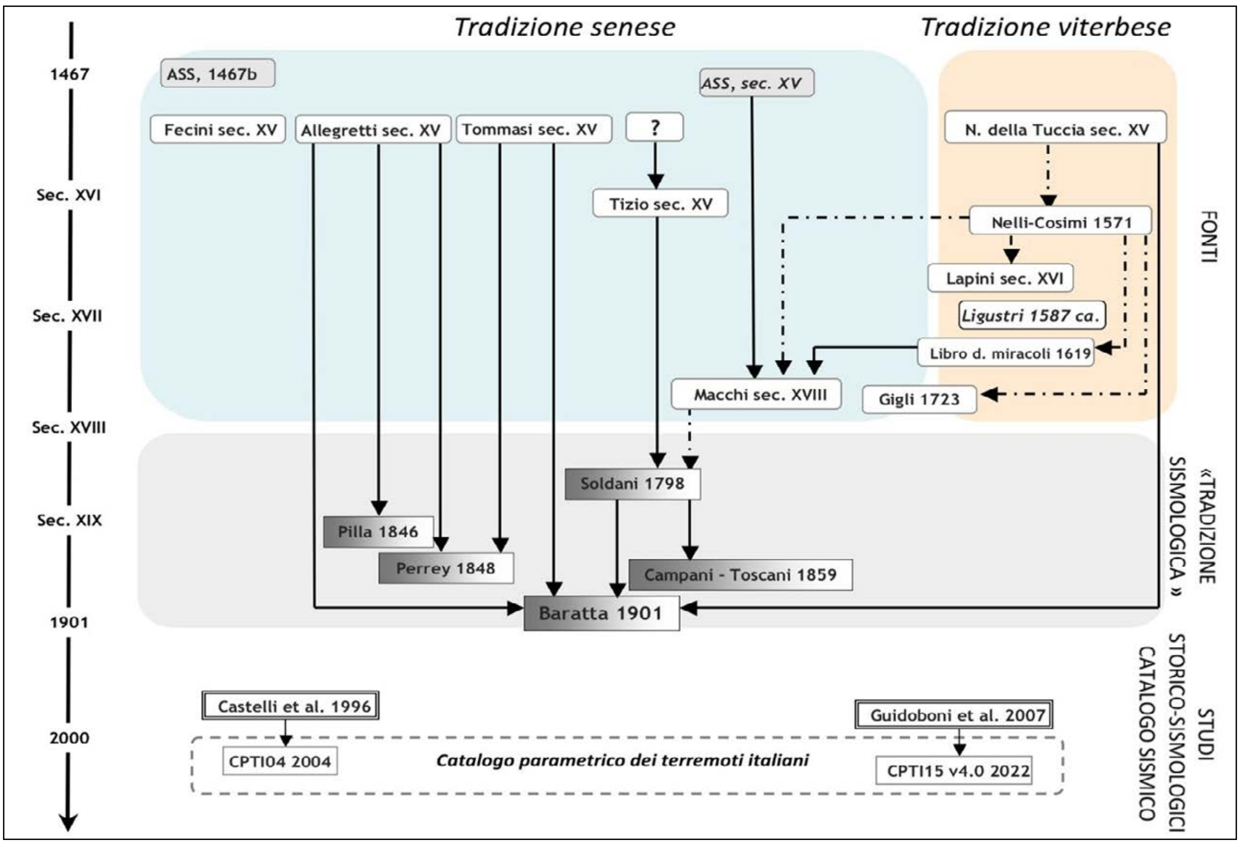

Figure 4.2 - Sources and transmission of informations about the 1467 earthquake [round: textual sources; italics: iconographic sources; solid lines: explicit filiation; dotted lines: conjectural filiation]. Image elaborated by Viviana Castelli and taken from: Arrighetti et al., 2025.

a nessuno. Stimano molti per lo gran caldo, che è stato già più mesi, e per lo gran seccareccio, che mai è piovuto, sieno proceduti questi tremuoti; e alcuni dicono per li nostri peccati, che è più da credere".

The unpublished Historiae Senenses by Sigismondo Tizio[7] add a number of second-hand reports to this overall picture, but they contain original content, which the author, who was Sienese by adoption, and who was connected to two of Siena's leading families, the Borghesi and the highly influential Piccolomini Todeschini (relatives of the two 15th century Popes from Siena, Pius II and Pius III), may have derived from the recollections of someone who had lived through it themself:

"Terremotus interea ingentes, atque pervalidi, qui et tremere faciebant Senam urbem, et concussione, ac strepitu mortales terrebant, die Augusti secunda, atque vigesima incepere, ita ut pro maiori parte relinquere domos oporteret, atque in areis partim sub papilionibus, partim vero sub divo degere, atque pernoctare. Primus namque eiusdem diei, que Sabbatum fuit, circiter secundam noctis horam improvisus, atque inopinatus accessit, tum ingeminante malo surgere e stratis mortales compulsi sunt nutante domo tuguria quoque in hortis, et caeteris in locis procul a domibus, ut fas erat, compacta incolere, multa quoque in prato Camollie, estate, atque estu alliciente, tentoria erecta sunt, in que cives cum universa familia sese recepere tutiores. Ut autem cives metu perculsi, ac pavide matres exitiale malum, atque funestum, quo nullum horridius avertere valerent, supplicationes ad Deum porrigere ad avertendam ejus iram saluberrimum censuere. Itaque urbem religiosis processionibus devotissime lustravere cum Marie vel Christi auxilio invocato. Verum ad diem fere quintam atque vigesimam terremotus et die, noctuque protensi sunt. Quapropter aestu iam declinante, et aëre tum frigidiore, tellurisque humiditate prodeunte, et tussis, et variae in hominibus egritudines causate sunt, ita ut in autumno supernam evadentem cladem inferiorem non evaderent, igitur non exigua hominum portio, civium maximae clarissimorum non assueta huiusmodi stationibus in morbos prolapsa extremum diem clausit. Quos inter Marianus Sozzinus juris consultus eminentissimus fuit [...][8]"

Thus, a picture takes shape of a seismic sequence that began at around 22.00 hrs local time (in accordance with the modern timekeeping system) on 21 August 1467[9], with an initial, major quake that was apparently followed by many after-shocks lasting around a month (Bartolomei et al., 15th cent.; Tizio 16th cent.). Many people in Siena fled their homes to camp outside in the open air (Allegretti 15th cent.; Tizio, 16th cent.), performing acts of devotion aimed at beseeching the end of the tremors. However, the written accounts of the deliberations of the Consistory (ASS 1467a-b) indicate that the members of the city's supreme magistracy remained in their residence at Palazzo Pubblico, as they were duty-bound to do, without interrupting their normal government activities. They only left the building, on an exceptional basis, on 3 September in order to take part in a solemn procession "propter occurrentes terremotus" (ASS 1467b). Indeed, eye-witnesses at the time focus mainly on a description

---

[7] Born in Castiglion Fiorentino in 1458 but Sienese by adoption, he only arrived in the city in 1482, and began to write his Historiae in around 1506.

[8] The Viterbo tradition regarding the 1467 earthquake began with the chronicle by Nicola della Tuccia (15th century), who in 1467 was one of the Priori of Viterbo, and who reports independent (but not conflicting) information compared to Sienese tradition. These details shift attention away from Siena to Viterbo, which plays host to a Marian image, the Madonna della Quercia, to which is ascribed a miraculous intervention in defence of the Tuscan city: "In quel tempo, 22 d'agosto [1467], furno nella città di Siena di notte 170 terremoti, e tuttavia multiplicavano. Il popolo di Siena fece voto alla gloriosa Vergine Maria, che se cessava quel pericolo volevano portare alla Madonna della Cerqua di Viterbo una cittadella d'argento fatta a sembianza di Siena, e subito la città fu liberata da terremoti: non cascò nessun edifizio, né ci morse che sole tre persone". This version of events, also reported by Florentine sources [Lapini 16th cent.] and depicted in the cycle of miracles of the Madonna della Quercia, the fresco painted in the late 16th century by Tarquinio Ligustri in the eponymous chamber in Viterbo's Palazzo Pubblico (Ligustri ca. 1587), would later be ascribed to the Sienese tradition by 18th century scholars (Macchi 18th cent.; Gigli 1723).

[9] Allegretti (15th cent.) and Tizio (16th cent.) refer to the second hour at night on August 22, in accordance with the Italian system of timekeeping (with the day being divided into 24 hours, as of 1 hour after sunset).

of the stresses and strains engendered by having to bivouac outdoors, which led "many respectable folk" to fall ill (Fecini, 15th cent.), with some dying[10]. The only actual damage mentioned explicitly by chroniclers was the collapse of "due armi de' merli degli Uffiziali della Mercanzia verso il Campo", on 3 September[11]. As for institutional initiatives, we only know that on 12 September 1467 the Consistory appointed the Commune's Clerk of Works to see to the repair of the crenellations of the palazzo, and the roof arch at the entrance to the prison (ASS 1467b), although without mentioning the earthquake as the cause of the damage: was this perhaps because it was taken as read?

There is a reference to another possible official initiative resulting from the earthquake in a Viterbo chronicle. According to this report, the custodian of the local Madonna della Quercia sanctuary (a man from Siena[12]) urged his fellow citizens to invoke that specific Marian icon to implore an end to the tremors, and after this had come about the authorities in Siena were to donate to the sanctuary a precious ex voto, and were to arrange a pilgrimage to Viterbo. There is no reason to doubt the report in itself, but no trace has yet been found in Sienese institutional sources of any initiative to this end, and similarly no evidence has come to light of particularly extensive or serious damage caused by the tremors in August and September 1467[13].

2. A possible new interpretation[14]?

Compared to the silence or omissions in chronicles and documentary sources referring to the many local earthquakes, the 1467 quake was the only one to be included in that unique "Sienese chronological history in paintings" known as the Biccherna and Gabella series of plates, produced between the 13th and 18th centuries. An 'iconographical collection' based on the depiction, every six months, of the main events in the city, with Sienese symbols or characters on the wooden covers of the state tax magistracies [15](called Biccherna and Gabella). The panel in question – painted by the celebrated artist and architect Francesco di Giorgio Martini – refers to the year 1467, and bears the caption "Siena in the time of earthquakes". It very powerfully documents the dismay and terror of the population by depicting a deserted city surrounded by the tents of the evacuees, pitched outside the city walls[16]. This image is iconographically consistent with reports given by the local chroniclers Allegretti (Allegretti 15th cent., col. 772), Fecini (Fecini 15th cent.: 870), Tommasi (Bartolomei et al., 15th cent., col. 63d) and Tizio (Tizio 16th cent.: 59), who report that, starting in August 1467, the city was hit by a string of tremors that was not only long but also on a significant scale. These led the inhabitants to set up makeshift shelters in open areas, abandoning their unsafe homes and dwellings. Similarly, the event was viewed as being significant enough to lead the Civic Regiment to organize not only a procession through the city streets (Fecini cent. XV: 870) but also (for the first time in Siena's history) an expedition to what was believed to be the most appropriate place of worship for averting the effects of an earthquake: the Madonna del

[10] According to Tizio (16th cent.), the most illustrious victim was the jurist Mariano Sozzini senior.

[11] Allegretti 15th cent. La Loggia della Mercanzia, now the Casino dei Nobili, looks on to the north side of Piazza del Campo.

[12] Indeed, at the time the running of the sanctuary was in the hands of the Jesuati religious order, of Sienese origin (Biggi 2020).

[13] The archives of the Consiglio Generale and the Biccherna (Siena State Archive) were consulted, as well as the documents of the Opera del Duomo. The Magistrato di Balìa archive (special committees tasked with attending to particular questions in place of the Concistory) is missing its entries for 1467. No reference to the earthquake was found in the Sforza family and Borgia family diplomatic correspondence of interest to Siena (Senatore 2009).

[14] This and the following two sections were curated by Dott.ssa Barbara Gelli of Siena University. Special thanks go to Dottor Fabrizio Fontani for his help with Sienese place-names.

[15] For this, see: Ceppari et al., 2008; Tomei 2002.

[16] This is the Gabella panel no. 34, on display at the Biccherne Museum at the Siena State Archive (Tomei 2002: 198-199).

Quercia sanctuary in Viterbo. To this end, the Commune commissioned a valuable silver image depicting the city of Siena, and this was offered to the Virgin at a solemn ceremony that did not fail to attract the attention of local chroniclers, such as Niccolò della Tuccia, of Viterbo (Della Tuccia 15th cent.: 92).

To date, the 'silence' of Sienese decision-making bodies has helped to support the idea that this earthquake simply caused much panic, while producing only slight damage to the city's structures. However, the new information offered by study of the 1468 "Lira", together with a number of preliminary considerations regarding certain building interventions dating to the mid-15th century seem to give rise to a completely different interpretation.

3. An additional fact: the campaign to abolish wooden balconies in Siena

Starting in the 1440s, the city of Siena, in common with other prominent towns and cities in Italy, also decided to embark on an important process of urban renewal, in line with the changed architectural sensibilities of the time. Indeed, according to the new aesthetic canons of the Renaissance, any local rulers who wanted to undertake an effective campaign of redesigning their urban space were to support a new 'horizontal' layout of dwellings, in accordance with the implementation of greater symmetrical and proportional qualities (with a conceptual transition from the prototype of the tower house to the prototype of the palazzo), and promote a wholesale, unified reorganisation of the street system (Romby and Rovida 2012) (making them wider and more uniform).

In Siena the government transferred all functions regarding the promotion of urban improvements to a special magistracy, the so-called "Ufficio dell'Ornato", which proved to be highly active in promoting new palazzi created by incorporating more than one adjacent dwelling together, in an overall review of the pre-existing urban building scheme[17], and in the removal of those features attached to the outside of buildings which, by protruding, covered the façades, obscured the city's streets and alleys, which were already narrow, and clashed with any principle of regular urban planning: external wooden balconies[18].

Throughout the middle decades of the 15th century the campaign by the Ufficio dell'Ornato against wooden balconies was strongly opposed by private individuals, owing to the very high costs involved, until, with the advent of Siena's own Enea Silvio Piccolomini to the papacy, Siena's government decided to insist on the issue once and for all, taking on board, wholesale, the similar, related building renewal plans sponsored by its illustrious native son, and by his humanistic circle (Nevola 2009). Thus, one year from the emblematic campaign to demolish the wooden balconies of Viterbo, promoted and financed by Pius II (Nevola 2009: 188-189; Rubinstein 1968: 235-239; Valtieri 1980: 19-30), on June 30 1463 the officials of the Ufficio dell'Ornato also decided to issue a similar regulation aimed at abolishing Siena's own wooden balconies, and imposing a fine for failing to do so[19]. Unlike in the past, anyone who subscribed to the initiative was able to benefit from financial aid to carry out the necessary work, thanks to the awarding of a number of public posts in the contado (rural area). In terms of the local government, the initiative proved to be a success. Indeed, in the space of a few short years, many of the city's streets (especially those nearer the city centre, populated by wealthier citizens who were able to subscribe to the scheme thanks to their own large financial resources, as well as funds from the public offices that

[17] On the policies of the Ufficio dell'Ornato: Pertici 1995; Turrini 1997; Nevola 2000.

[18] On the wooden balconies of Siena: Balestracci and Piccinni 1977: 91-93; Nevola 2000.

[19] ASS, Consiglio Generale 230, cc. 51v-52r cited in Pertici 1995: 78.

were awarded to them) were cleared of these balconies and wooden extensions[20]. Despite this, in the eyes of the general public, the Ornato project was seen as a burdensome imposition by the state that was only partly made up for by the economic aid that was handed out. It is no surprise, therefore, that the people of Siena sent petitions to the Ornato officials documenting a widespread malcontent over the initiative, hastily brought in by force, that led to a total drastic redesigning of buildings (both externally and internally), with resultant repercussions on the size, layout, and, later on, the very stability of these palazzi. As witnessed by the correspondence between ordinary citizens and the officials, the balconies were mainly found to be extensions of formal rooms and bedrooms, and their size was significant enough that in many cases they added around one third to the size of the property itself[21]. Thus it is clear that, for the owners of these properties, demolishing them meant a considerable loss of residential space, which was inevitably associated with a wholescale redefinition of the internal spaces and façades[22].

In some cases, given the impossibility of achieving a coherent or at least satisfactory reorganisation of home interiors, some wealthier Sienese informed the Ornato officials of their decision to demolish and rebuild their homes right from the foundations[23]. However, in most cases we see a more or less improvised alteration of private dwellings that was more or less harmonised, with consequent repercussions also with regard to the stability of adjacent buildings, which was only partly offset by the construction of sporadic connecting walls, vaults and bridging arches between one building and another[24].

In the following years, the Sienese continued to complain to the government over the inconvenience connected to this initiative, forcefully stressing the extreme fragility of their buildings after the alterations made to them. A typical example is the complaint by two brothers, Bartolomeo and Francesco di Cristofano, residing in the compagnia del Casato di Sopra, who pointed out that “chassa de la [loro] abitazione [...] tuta chade, cioè diettro e di fuore, senza balatoi[25]”.

Accordingly, when the earth shook several times in the summer of 1467 (perhaps as many as 160 times), the tremors, although not particularly strong if considered individually, impacted on an urban context that were already compromised in a major way by pre-existing structural problems. We may therefore tentatively surmise that the effects of the quake were somehow amplified by the exceptional vulnerability of many of the city’s buildings, leading to an unprecedented, significant sequence of damage to the buildings themselves, for reasons very much related to this particular time.

4. The city of Siena in the 1468 Lira

The first and strongest earthquake tremor occurred on 22 August 1467, and was followed by a sequence of lesser tremors that continued for the following months. The chronicles, always concerned with proposing a predominantly ‘public’ narration of events, report that “due armi de’ merli [present in the palazzo] degli Uffiziali della Mercanzia[26]” became detached, omitting to describe the effects of the quake on privately-owned dwellings. The absence of any archive information relating to the public handling

[20] For example: ASS, Consiglio Generale 230, c. 100r, 24 February 1464, cited in Pertici 1995, p. 78, or ASS, Consiglio Generale 232, c. 288r, [perhaps 1466] cited in Pertici 1995, p. 102.

[21] On this: Pertici 1995: 84, 29 October 1464.

[22] For example: Pertici 1995: 94, 1465.

[23] For example: ASS, Lira 155, c. 512, 1467.

[24] For example: Pertici 1995: 106, 27 October 1467.

[25] ASS, Lira 159, c. 341, 1468.

[26] Allegretti 15th cent., col. 772.

of the earthquake could be explained in two ways: either owing to the loss of the documentation produced by possible special magistrates or commissions to whom the government may have delegated the management of the earthquake, or the absence of public initiatives of this sort. Alternatively, as regards the understanding of the damage caused by the quake to private dwellings, it is possible to get some kind of idea from the information contained in the so-called "Lira" of 1468: a highly detailed fiscal source that was sponsored by the government across the entire urban area just one year after the quake itself[27].

Like the more famous contemporary Land Register (Catasto) of Florence (Herlihy and Klapisch Zuber 1988), the Sienese Lira was also based on a system of self-reporting of property, compiled by all the heads of households living in the city. The statements were drawn up in accordance with a more or less fixed model that included the name of the head of the household himself, the district he lived in, his profession, a list of his property and possessions, his credits and debts, and a list of his other family members, if he had any. These written documents were collected and analysed by the so-called tax inspectors, citizens of Siena who were able to check the truthfulness of the statements made, since they were recruited uniformly from every city district, and knew the other people who filed such statements. These were responsible for drawing up a list of taxable assets, based on the varying resources of each individual[28].

Siena's government usually brought in a property tax assessment every ten years. Until such a time as a new Lira was introduced, taxation continued to be calculated on the basis of the last statement of taxable property, but in the case of exceptional events the government could set in place a new fiscal reckoning initiative in order to take into account necessary variations. This was clearly the case with the 1468 Lira, as it was brought in just three years after the previous one, and one year after the earthquake, so as to devise a level of taxation that was in line with the altered appearance of the city.

The statements filed by the citizens of Siena cover the entire urban area, and were drawn up in such a way as to refer to the location of their dwellings, in accordance with the long-standing division of the city into "Terzi" (a subdivision of the city into three macro-areas: Città, San Martino, and Camollia), and into "Popoli" (a sort of neighbourhood based on the ancient military sectors of the city).

Unlike the picture we glean from the other sources investigated thus far, the Lira records an overall view of privately-owned buildings in the city, in the aftermath of the quake, that accords with a style of narration that is 'naturally' designed to underscore the damage caused (presumably by the earthquake) to the various dwellings. Indeed, in describing their property to the tax office, the people of Siena had every interest in highlighting the structural problems of their property, in order to persuade the tax inspectors to give some form of tax discount. In this way it is possible to document the presence within the city walls of a great many buildings that displayed serious structural problems, and to outline an approximate but nevertheless indicative picture of the zones that we can suggest were more or less affected by the quake. Obviously the somewhat arbitrary 'narrative' with which the people of Siena compiled their statements prevents us from drawing up an objective, detailed picture of the damage, all the more so given that the presence of local inspectors, who were well aware of the real state and condition of property in the city, discouraged people from going into too much detail in their descriptions. Indeed, in this connection, many Sienese informed the fiscal office of the parlous state of their dwelling, without offering more specific information, not to mention all those who simply forwarded to the Commune's officials a reduced estimate of the value of their home. For this reason, although aware that the number of damaged buildings must be considered as being considerably higher than the figure recorded at the

[27] ASS, Lira 155, 157, 159, 166, 168, 172-173.

[28] Regarding the Sienese Lira, see: Banchi 1868; Catoni and Piccinni 1984; Catoni and Piccinni 1987; Isaacs 1970.

time, the project has chosen to only consider statements in which the description of the damage is more explicit, detailed and consistent with earthquake damage: homes which, compared to the previous tax assessment[29], seemed to display new problems of stability, and which were depicted as being "shored up", "collapsed", or about to collapse. In this way the survey focused on a documentary sample that is definitely very limited (81 out of around 3,500 filed statements[30]), but reliable, and able to produce information that can be applied to the whole of the urban area: indeed, in listing the characteristics of their property, scattered across the various Popoli, many taxpayers were also careful to provide details regarding the state of adjacent dwellings, or of the whole neighborhood.

Thanks to the information provided by the Lira, it has thus been possible to plot the phenomenon in spatial terms, and trace a map of Siena's Popoli that were struck to a greater or lesser extent, documenting the presence of the urban areas that were most affected by the quake: the area around the church of Sant'Agostino[31] (where many buildings were declared to be hazardous), the Pantaneto area[32] (with damage more or less throughout), the two Popoli known as Ovile di Sopra and Ovile di Sotto[33] (where the situation was so compromised that the few houses that had not been shored up were regarded as being in good condition[34]), and the Popolo di San Cristoforo[35] (highly hazardous, and therefore evacuated by government decree).

Assuming that the 1467 earthquake was the cause of the damage, our research found that the damaged buildings had very differing stylistic features, as properties belonging to every social level (from humble dwellings in the Ovile zone, to the tower-houses and prominent homes of merchants and leading, wealthy business families giving on to the main streets). Homes which were already subject to various degrees and types of structural fragility, which the quake may have helped to bring out, and, in many cases, to accentuate. One need only mention the wide range of tower buildings, or, as they are referred to in the sources, "old-style" buildings[36]. For these, their height became a source of great instability. Then there were also a great number of homes of poor or very poor construction quality which, as in the aforementioned Ovile zone, were built one against another, in very steep areas, which led to dangerous domino effects in the transmission of physical pressures and strains. Finally, and generally, the quake apparently struck tenement buildings or tower houses whose stability, in other contexts, would not have been in question, but which had recently been subjected to the aforementioned campaign to eliminate wooden balconies in the city. Accordingly, these houses had been subjected to major structural alterations that in some cases had not been completed, or that had not been carried out properly.

House descriptions are generally very brief, but there are exceptions. Indeed, as well as the respective Popolo indicating the location of each dwelling, it is sometimes possible to note references to a few local toponyms[37], or to well-known families on the urban scene. This additional information can sometimes enable a precise identification of the buildings. Thus, among damaged homes it is possible to recognise

[29] ASS, Lira 151-154, 156, 158, 160-165, 169-171.

[30] Some statements fail to give the year they were compiled, and so there is no certainty that they are to be ascribed to this round of assessments.

[31] For example: ASS, Lira 155, c. 497.

[32] For this zone, see for example ad ASS, Lira 166, cc. 12r, 66r-v, 83r.

[33] For example: ASS, Lira 172, c. 160.

[34] ASS, Lira 172, c. 160, statement by Iachomo di maestro Martino lanaiolo: "una chasa della sua abitatione, terzo di kamollia e populo di Sancto Pietro a Uvile di Sopra : buona e non è apontellata". For the Ovile zone, see ASS, Lira 172, cc. 160, 247, 342, 384, 394, 438, 495, 511, 516, 548, 565, 572, 593, 594, 595 and ASS, Lira 157, c. 114.

[35] ASS, Lira 172, c. 515.

[36] For example, ASS, Lira 172, c. 144r.

[37] For example, ASS, Lira 159, c. 36.

what is now Palazzo Cerretani[38] (overlooking Piazza del Campo), Palazzo Ciani[39] (near the Baptistery), and the area corresponding to Palazzo Piccolomini[40] (at the entrance to the Popolo di Pantaneto).

In the case of many buildings, the fact they were adjacent, and shared beams or damaged walls, created a common structural fragility that was set to generate much panic:

"una chassa posta in su la porta all'arco de la nostra abitazione male in ordine ed à le travi rotte del tetto che sono apontellatte. Ed [h]a una chasela da latto de' frati di Santo Aghustino la quale chade ed [h]a tutte le travi rotte da una in fuore. Ed è pocho tenpo che ne chad[d]e una che fecie pelare la nostra chassa e stiamo in grande pericolo. Che Idio e la vergine Maria ci schampi di questa ruina![41]".

In this situation, some people moved out of their homes to live with relatives[42], and others decided to move into rented apartments[43], while a large number were forced to stay in their own homes[44], living with the constant fear of further collapse. In any event, for everyone in the city, the earthquake represented a source of serious financial loss, since it forced the owners of the buildings to plan necessary rebuilding and refurbishment that was highly costly and unforeseen[45]. The Lira statements reveal the dismay of the lower classes over the fact it was impossible for them not only to complete the work necessary for reconstruction[46] but in some cases even to get such work under way[47]. This was even more true given the fact that, as mentioned, many buildings stood next to each other, necessitating joint building work by several different owners. In these circumstances, we may well imagine that the Sienese government probably intervened with special decrees, the contents of which are unfortunately unknown to us. However, whatever the solutions that were mooted, they cannot have proved to be particularly effective, in the face of the huge financial disparities between the various different home-owners. One example of this is what happened in the Popolo di Sant'Agata, where the serious earthquake damage inflicted on the buildings persuaded the monks of Sant'Agostino to plan the total demolition and reconstruction of their many properties, creating serious difficulties for those few small home-owners who opposed the destruction of their own homes: "una chassa posta nel terzo di città e compagnia di Santa Aghata [...] e ne la cassa no vi stà persona e però che cade. E' frate [di Sant'Agostino] cercano di farla chaschare [...] chome [h]anno fatte l'a[l]tre casse che v'erano da torno[48]".

In such circumstances the huge resources of Siena's leading families, and its most important secular and ecclesiastical institutions, made them the true protagonists of the subsequent process of reconstruction and/or refurbishment in the aftermath of the quake. Indeed, drawing on their capital, and their considerable assets at the neighbourhood level, they were able to make forceful interventions in the sphere of privately-owned buildings that made a truly significant impact on urban planning. However, while the biggest institutions restricted themselves to rebuilding in order to preserve the size and value of their properties, without adding anything in stylistic terms, Siena's elite families seized this

---

38 ASS, Lira 159, c. 128.

39 ASS, Lira 159, c. 108.

40 ASS, Lira 166, cc. 12r-v.

41 For example, ASS, Lira 155, c. 518.

42 ASS, Lira 172, c. 565.

43 ASS, Lira 172, c. 516.

44 ASS, Lira 155, c. 518.

45 ASS, Lira 167, c. 95.

46 ASS, Lira 166, c. 66.

47 ASS, Lira 172, c. 201; ASS, Lira 172, c. 384; ASS, Lira 172, c. 275, 1467; ASS, Lira 166, c. 319.

48 ASS, Lira 155, c. 497.

opportunity to also create new, modern palazzi that were more in line with the new aesthetic canons of the Renaissance. One need only mention one of the finest constructions in Siena of the day, Palazzo Piccolomini, designed by the architect Rossellini by amalgamating together several rather run-down tenement buildings, one year on from the aforementioned Lira tax declarations when, in the grip of not a little consternation, the brothers Giacomo, Andrea, Nanni and Laudomia Piccolomini drew up the following statement for the fiscal office:

"li casamenti nostri con le massaritie posti in nel Popolo di Sancto Martino et Compagnia di Pantaneto de' quali affadiga ne sono tanti in piè che habilmente ci possiamo tutti habitare. Et una parte sono in terra et quasi ruinati et l'altra parte stanno per ruinare come apertamente si vede. Et per la spesa grande che vi sarà per lo edificare che ci mettono assai pensieri le vostre spetialità le ragionaranno in quello modo lo parrà convenevole". [In] "più ci pesa [avere] il casamento per terra, come si vede, che per honore de la città et nostro cognosciamo essere mancamento grandissimo[49]".

Ultimately, in many parts of the city, reconstruction work undertaken in the years after 1467 was used as an important opportunity to redesign and transform the urban space, in the interests of indirectly adapting buildings to the new architectural styles. All this abided fully by the principles long championed by the Ornato officials: improving the quality of existing residences, and ensuring the city's neat and tidy appearance by creating "bellissimi casamenti" (Pertici 1995; Romby and Rovida 2012).

5. A platform to record the possible effects of the 1467 earthquake

The details derived from bibliographic and archive analyses, described in the sections above, offer a panorama rich in information, to a greater or lesser extent, regarding the characteristics of past earthquakes that have affected the city of Siena, and also regarding the damage involved, and the subsequent measures adopted. However, they can also be used as an key for understanding and interpreting the alterations made to the city's appearance and layout, and to individual architectural nuclei, over time. Translating documentary sources into hard facts relating to actual buildings, or to a given geographical location or area, is never a straightforward task, especially when the work is concentrated on earlier phases for which details and information are inevitably more scant. In this connection, the operation that requires a greater interpretative effort lies in assembling, in a concrete and systematic form, an initial dataset that lacks clear reference details in terms of places and facts which, at the time when the document was compiled, were not necessary, or were taken for granted, but which today constitute some of the vital fundamental information whereby we may devise a reliable, broad-ranging research task. In the case presented here, a decision was made to proceed by ordering, in a systematic form that is as reliable as possible, historical details within the context of 15th century Siena, before then integrating detailed archaeological information, obtained by means of a survey of the buildings found in the most-damaged areas, along with a scansion and interpretation of the stratification of the seismic events visible in their walled parts. The information derived from the historical analysis and the archaeological interpretation were then integrated to create a thematic map of Siena's old city centre in 1468, showing its state of earthquake damage, divided by each Popolo. Lastly, the map functioned as the basis for the creation of a GIS, currently in experimental form, to record damage and disrepair in the centre of Siena over time.

[49] ASS, Lira 166, cc. 12r-v.

6. Plotting historical details on a cartographic base

For the documents that comprise the 1468 Lira, and which, as explained in the previous section, our working hypothesis suggested could reflect damage ascribable to the 1467 quake, the first major challenge was to create a cartographic basis that depicted the city of Siena in the mid-15th century. Accordingly, our work sought to create a subdivision that was more in line with the state of the city in the 15th century, by evaluating which Popoli might be regarded as being topographically unchanged, and which ones had seen subdivisions or incorporations. To carry out this task, historical information about buildings was integrated and plotted on a map, and an evaluation was conducted of all the possible interactions between previous knowledge and targeted surveys of some parts of the city centre. These considerations proved vital for understanding how modern and contemporary transformations have altered the late medieval street plan and urban layout. The map compiled by means of this investigation shows Siena as a highly fragmented city, consisting in some Popoli with large neighbourhoods in which building complexes have much space between them, with others comprising just a few dwellings packed close together, sometimes built up against each other along a single street (fig.4.3).

While the aforementioned operation partially solved the cartographic problem, at the same time it nevertheless outlined another set of factors that needed to be taken into consideration, so as to offer up a correct picture of the city of Siena during the period after the 1467 earthquake. Indeed, the aforementioned findings have a considerable impact on the characteristics of the damage and disrepair recorded in the documents. To cite one example, if we wanted to establish a reference parameter, one that is a totally arbitrary but based on documentary information, to look at the extent of damage to buildings in the individual Popoli, the situation would be very different in the centre compared to peripheral areas. In the sector near Piazza del Campo, with an abundance of smaller Popoli that accordingly have a smaller number of homes, the possibility of coming across even a small number of documentary references to damage or disrepair is a hugely valuable find. By contrast, if we find a similar number of documentary references in a large Popolo containing many buildings within it, located in areas closer to the city walls, while this finding is certainly worth taking into account, this should be done on a much more contained scale. At the same time, it is important to bear in mind numerous other variables which are unfortunately sometimes impossible to imagine, but which are to be taken into account for a projection that is as solid as possible of the effects of earthquakes on contexts that are as complex as historic city centres[50]. Thus, we are dealing with information that definitely merits specific reflection, and which, for the context of Siena, is fortunately based on an extensive tradition of studies in the fields of history and archaeology, and in the field of architecture and buildings. This allows us to build a foundation that we can use to produce a series of considerations which, while betraying a certain degree of uncertainty, nevertheless represent a first step for broad-ranging studies such as those proposed here.

The analysis of the 1468 Lira, selectively considering the damage and disrepair stemming from the 1467 earthquake that affected the individual Popoli, and so excluding possible property declarations regarding collapses or problems not correlating to the effects of an earthquake, led to the following preliminary subdivision into basic, main groups:

[50] To mention some: the state of preservation of the buildings in the year of the earthquake, the architectural features and internal and external distribution of the individual building units, the characteristics of the urban layout (isolated houses, or houses belonging to aggregated dwellings or street fronts), the characteristics of the subsoil, the morphology of the terrain, and the position of the buildings in terms of slopes etc.

- zones not struck by the earthquake (0 REPORTS): the Popoli of San Vincenzo, Sant'Egidio, San Pellegrino, Vallepiatta, Aldobrandino del Mancino, San Pietro alle Scale, San Vigilio, Abbadia Nuova di Sopra, San Giusto, Borgo di Santa Maria, Abbadia all'Arco, San Marco, Stalloreggi di Dentro;
- zones only slightly affected by the earthquake (1 – 3 REPORTS): the Popoli of Casato di sotto (1), San Quirico in Castelvecchio (1), Compagnia di Stalloreggi di Fuori (1), Casato di Sopra (3), San Pietro in Castelvecchio (3), San Quirico in Castelvecchio (1), San Salvatore (3), Popolo della Magione (2), San Donato in Montanini (1), Santo Stefano (1), San Donato al lato della chiesa (3), San Giorgio (2), Spadaforte (2), Abbadia Nuova di sotto (2), San Maurizio (2), Salicotto (1), Sant'Angelo a Montone (1), Rialto (1), Pian dei Mantellini (1), Pian del Moro (1), Poggio Malavolti (1), San Giulio in Camporegi (1), Arco dei Rossi (1), Provenzano (1), Fontebranda (1);
- zones hit by the earthquake to an average extent (4 – 5 REPORTS): the Popoli of Porta all'Arco (4), Porta Salaria (4);
- zones severely hit by the earthquake (MORE THAN 6 REPORTS, OR WHOLE AREAS INVOLVED): the Popoli of Sant'Agata (widespread damage and disrepair throughout the area), San Cristoforo (evacuated neighborhood), San Pietro a Ovile (widespread damage and disrepair throughout the area), Pantaneto (widespread damage and disrepair throughout the area).

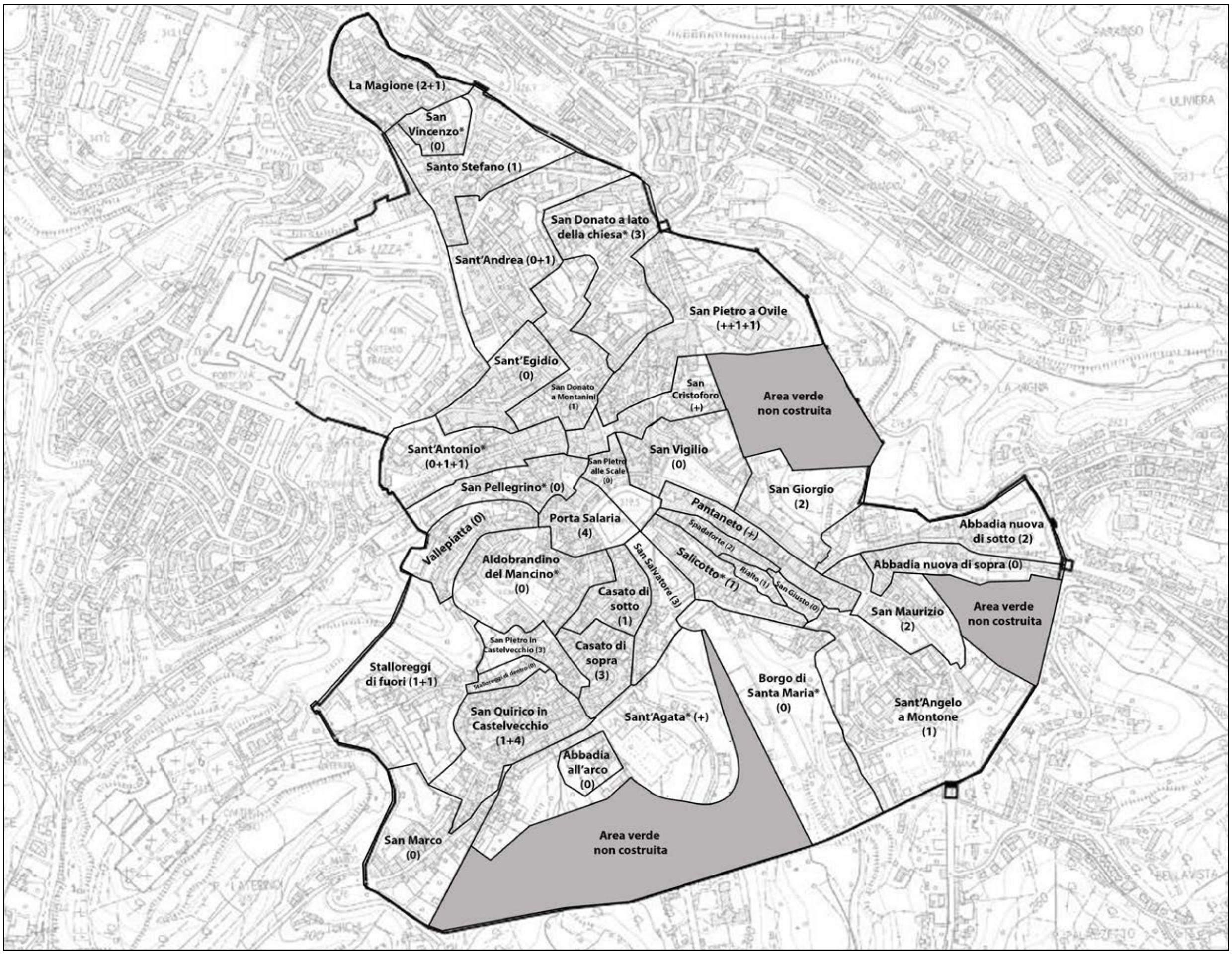

Figure 4.3 - The historical centre of Siena subdivided into the Popoli of the 15th century. For each popolo, the name is reported and in brackets the number of attestations reported in the Lira of 1468. Elaboration: Andrea Arrighetti and Barbara Gelli. Image taken from: Arrighetti et al., 2025.

In order to back up this hypothesis, namely the suggestion of a correlation between the seismic event and damage to buildings, the research made it necessary to contextualise the findings made with the information that can be derived from an analysis of the characteristics of buildings in the city centre, by means of archaeological analysis of the palimpsests of wall faces. Owing to the obvious constraints of time and resources, it was not possible to analyse the whole historical centre of the city, and thus a decision was made to carry out a targeted reading of some parts of the city centre. Accordingly, we opted to conduct a survey of the Popoli that were worst affected by disrepair and damage in 1468, and to identify a number of specific, representative street fronts on which to carry out a cursory (i.e. expeditious) archaeological examination of the buildings. The method used, and the results, are described in section 4.2.

7. The creation of the thematic map and GIS database

The data obtained from the documentary analyses enabled a thematic map to be drawn up, with the objective of showing the areas that displayed varying degrees of critical status in 1468. In operational terms, taking the above as a reference, and integrating previous written documentation with the findings that emerged from examination of the Lira records, the work sought to propose a colour-coded subdivision of the Popoli present in the city centre, a partition that was made on the basis of the numerical prevalence and degree of damage that the buildings within them had suffered. This process accordingly led to the creation of a thematic map (fig. 4.4) which described the individual Popoli by means of the following colours:

- green: absence of references to the earthquake
- yellow: 1 – 3 references to the earthquake
- orange: 4 – 5 references to the earthquake
- red: more than 5 reports referring to the earthquake

Subsequently, setting out from this initial data, the information was placed in its context, associating it with features of the plan of each respective Popolo. This enabled us to calibrate the result by correlating it to the number of homes present, and to the characteristics of the urban layout, which is crucial in any analysis of the vulnerability of clusters of dwellings. Lastly, the information reported in individual accounts preserved in the tax records was evaluated, to understand where damage was slight, and where, as in the case of the Ovile area, whole districts were evacuated. The map that is the end result of this work describes a large central band of the city centre, coloured red and orange, found to be considerably affected by damage and disrepair, while more marginal zones, coloured green and yellow, are found to be less affected by the possible effects of the 1467 earthquake.

Obviously, as stated earlier, the characteristics of the various dwellings, and of the distribution of buildings, played a vital role in this type of consideration, but the areas most affected, and where the quake propagated most, are very clear. Indeed, an examination of the map leads us to clearly identify the zones of Ovile-San Cristoforo to the east, Sant'Agata to the south, and Salicotto in the centre as the areas featuring a higher incidence of buildings damaged in 1468. These are followed, with impact levels that are less pronounced, but still of considerable importance, by the Popoli adjacent to the aforementioned districts, which thus display numerically high levels of damage and disrepair, with

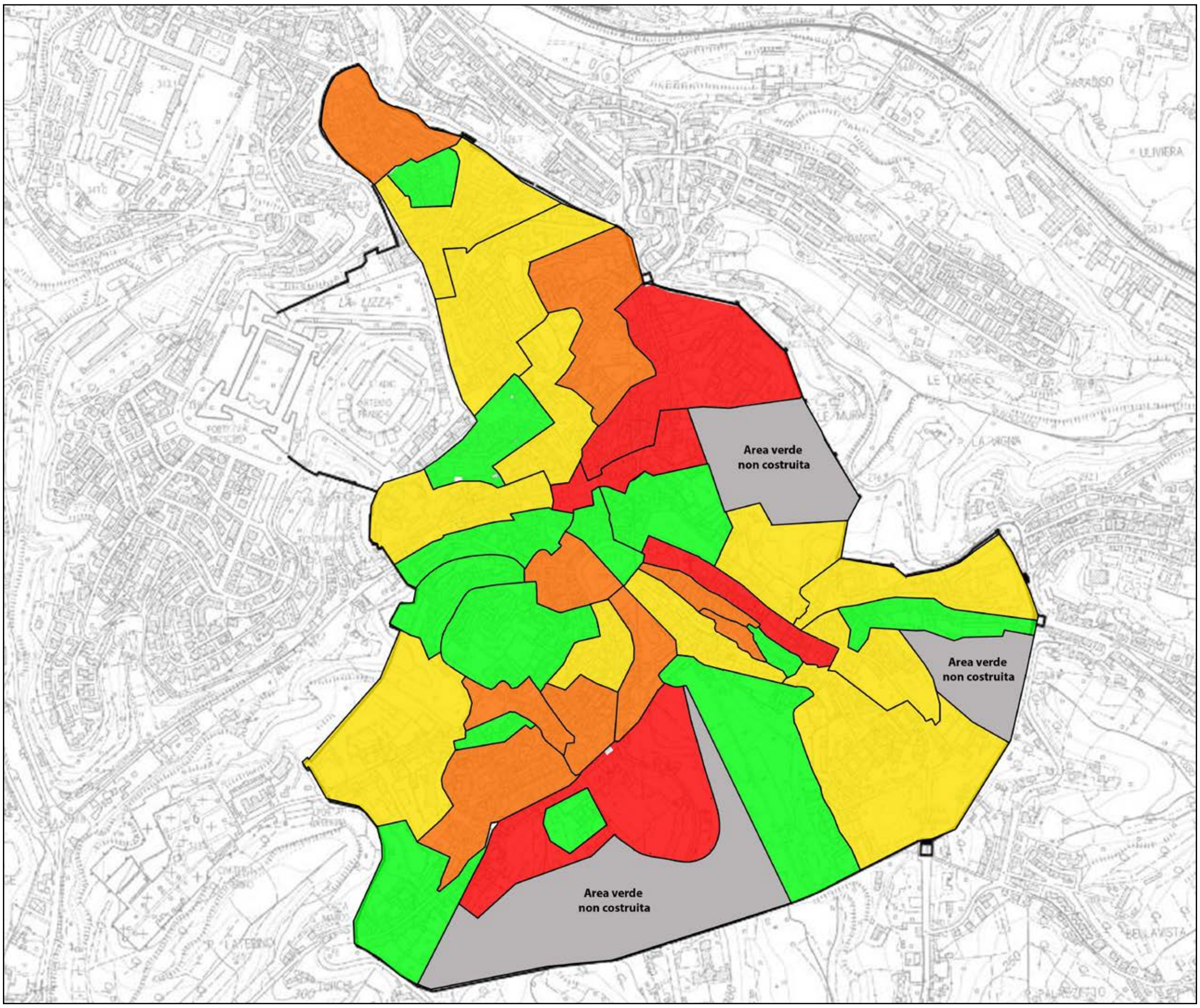

Figure 4.4 - The historic centre of Siena subdivided into the areas assumed to be severely (red), medium (orange), low (yellow) and unaffected (green) by the 1467 earthquake. Elaboration: Andrea Arrighetti and Barbara Gelli. Image taken from: Arrighetti et al., 2025.

fairly major characteristics. By contrast, the central portion of Siena's city centre, where the details of the buildings and features of the distribution of dwellings would both lead us to imagine the building units as being highly vulnerable, seems to have suffered little or no damage from the earthquake. This is probably because, despite the fact that the city centre of Siena appears as a context consisting of buildings with architectural characteristics deriving from the medieval period, and thus without anti-seismic features, some elements set in place in former times, along narrower streets in the centre, designed to prevent buckling or other forms of damage (supporting arches, relieving arches, wooden wall braces (or stays), bonding stones, stone reinforcements and buttresses), served a preventive function that was not insignificant in combating the effects of quakes[51].

Once all the data relating to damage that can probably be ascribed to the 1467 earthquake, necessary for analysis of the study context, was collected and organised scientifically, it was decided that the information would be systematically ordered on a GIS platform for Siena's city centre. This tool, up and

[51] The analysis of post-seismic construction systems is presented in section 4.1.2, and was published in more detailed form in the journal Restauro Archeologico (Arrighetti et al., 2022)

running ever since 2020, and used to enter the findings from the survey of post-seismic architectural features found in the city centre, described in the following section, formed an invaluable foundation both for ordering the information acquired and for correlating these data with geomorphological aspects, and the seismic microzonation conducted on the city (Albarello et al., 2007). The process of entering data from the work described here in this volume was organized by Terzi (general urban district), creating a single layer such as to contain within it all the Popoli, each characterised by a polygon delimited within its confines. In turn, each Popolo was associated with a database designed to show all the historical information, and archaeological information (if any), relating to the buildings found within it. The database was structured with a view to it being used over time. In order to achieve this, the fields were designed so as to store information deriving not only from the analysis of the 1468 property tax records, but also further data that might emerge from future history-related explorations of the city of Siena. Below, we list the fields used in the database for the individual Popoli, subdivided into their respective macro-fields:

- Identifying information: city, Terzo, Popolo, building
- Archive: location, name of archive, type (public, private etc.), chronology
- Document: type, chronology, description
- Mentions: number, reliability
- Seismic aspects: individual earthquake, location and description of damage
- Corresponding details from other sources
- Observations

By means of this database, clearly designed for archaeoseismological purposes since it is structured with a view to recording earthquake-related information, and the resultant georeferencing of each alphanumeric, vectorial and raster datum point within the GIS platform, it is thus possible to select for Popoli or Terzi, and find out about the characteristics and impact of the seismic events that have affected them. This is a highly interesting feature in studies characterising the city centre since, once the information connected to known events, for example the 1798 earthquake (Gennari 2005), has also been entered, and after the addition of new data from the ongoing examination of documents that are analysed in the course of new projects or research, the platform can become a useful tool not only for research, but also in prevention and planning connected to seismic risk.

8. Results and possible interpretations relating to the 1467 earthquake

The analysis of Siena’s old city centre has revealed vitally important aspects from the point of view of history and seismology regarding the possible effects of the 1467 earthquake. First and foremost, it is highly interesting to note the difference in the description of the structural problems affecting buildings, as reported by the various sources analysed. Whereas on the one hand the Lira records report clear damage to the buildings that made up the fabric of the city, sometimes also with the evacuation of neighbourhoods that we might today describe as the "red zone", on the other hand the numerous written sources held on the INGV's seismological databases lead us to reconstruct a very different scenario. Indeed, in this latter case the information recorded by seismological databases enable us to reconstruct fairly mild effects of the quake, or rather of the earthquake swarm, which characterised the context of Siena in the course of the 15th century. In addition to this information, there are the numerous written sources concerning religious buildings in Siena, reported in the publications Die Kirchen von Siena curated by the Kunsthistorisches Institut in Florenz[52], which record the same non-catastrophic panorama. Thus, a dual scenario seems to distinguish this event: on the one hand the Lira, in which the documents record significant damage to private buildings, whether belonging to important Sienese families or to the less well-off population; on the other hand, religious buildings and buildings serving a public function, which do not seem to testify to damage or disrepair relating to the seismic event. Why, then, should there be this marked difference? In our view, this discrepancy can be ascribed to one essential factor, namely the excessive vulnerability of some specific buildings in that particular historical period. Indeed, in the mid-14th century private buildings, whether aristocratic or not, were in a state of extreme vulnerability. This is because buildings were distinguished by variable states of conservation in the various zones of the city, aggravated by seismic shocks which occurred frequently in this period, and, more specifically, by the measures concerning the removal of wooden balconies, as discussed in previous sections. Since, in the case of many buildings, these balconies were elements that had a marked static function, once eliminated they had a highly negative impact on the buildings' response to seismic stresses, thereby leading to an amplification of the real effects of an earthquake the effects of which, in normal conditions, would probably only have been slight or non-existent. This is shown by religious and public buildings, where the new regulation on balconies had no effect on these buildings' vulnerability, since they were not features of these types of buildings. Indeed, there is no trace in architectural form, or in written sources, of effects connected to the 1467 earthquake. Thus what we see today is a highly unusual scenario that is profoundly marked by the decisions made by the central authorities, decisions which today, on the basis of their outcomes, we would describe as mistaken.

4.1.2 The survey of post-seismic construction techniques in the Terzo di Città[53]

Focusing again on the macro-scale of analysis of the study context, a further stage of research in the old city centre, specifically the Terzo di Città, was to document post-seismic building features. This operation involved a survey of the entire area, the cataloguing of features of interest, entering this information on a GIS platform (described in the section above), and lastly studying them by chronotype.

1. Methodology of analysis

The bibliographic information compiled during the first steps of the research proved essential in the fieldwork planning phase, to identify areas of the city struck most frequently by earthquakes, as

---

[52] This is a series of volumes, published from 1985 to 2006, which report the findings of the project entitled Die Kirchen von Siena. Undertaken by the Kunsthistorisches Institut in Florenz, it was aimed at a historical and artistic study of Siena's churches (Riedl and Seidel 1985-2006). What is of interest to the PROTECT project is the possibility of making use, for each building, of specific chrono-histories of events that have affected these structures, from their construction down to the present day, including events that took place before, during and after the earthquakes that they have experienced. Specifically, for the 1467 earthquake no information of interest is given in any of the buildings analysed.

[53] The archaeological survey of the Terzo di Città, identifying and recording building features probably associated with the effects of historical earthquakes on buildings, using a GIS support, was conducted with the collaboration of Dott.ssa Valeria Razzante of the University of Padua. The results of the investigation, with in-depth discussion of specific details, were the subject of a scientific article published in an international journal (Arrighetti et al., 2022).

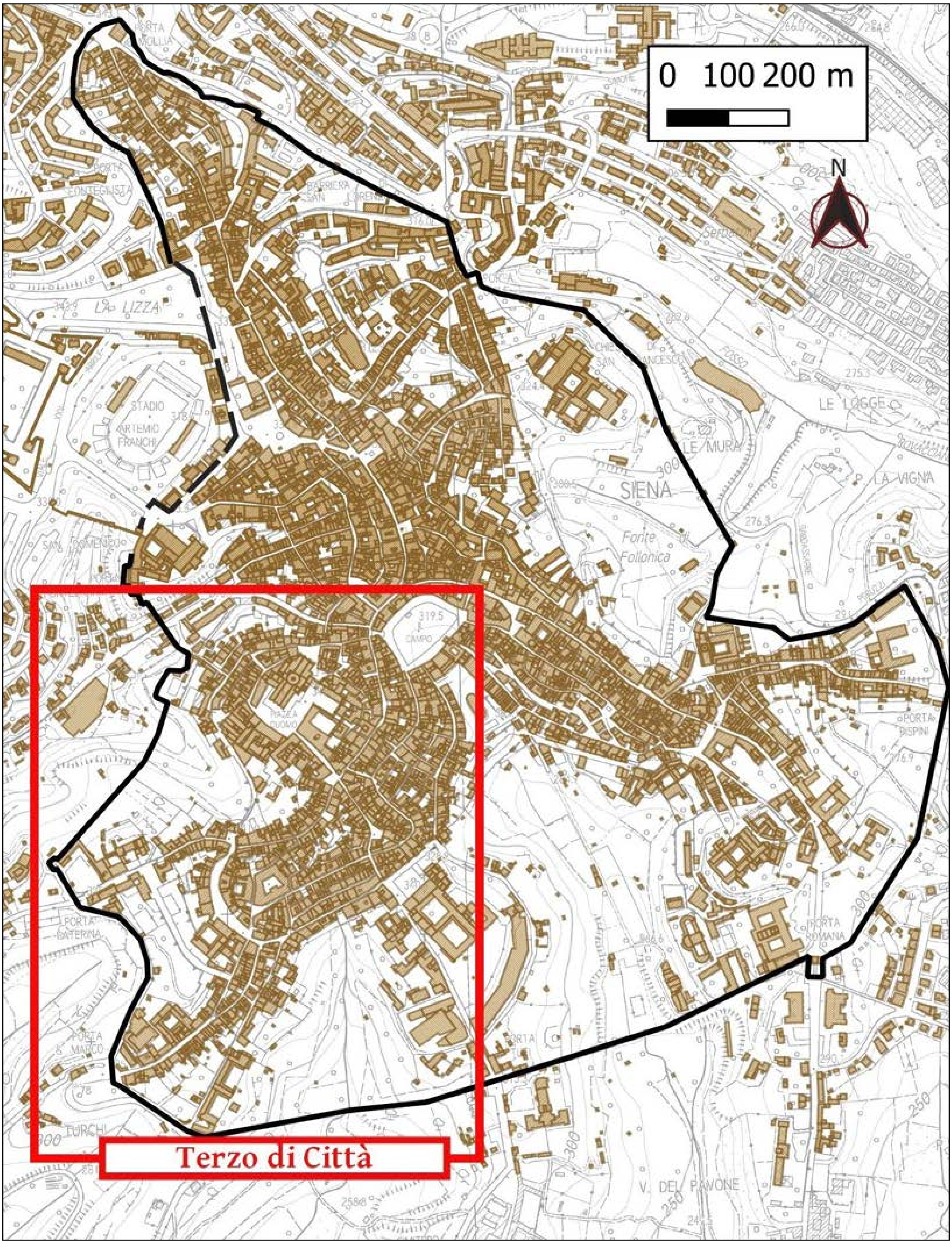

Figure 4.5 - The historic city centre of Siena: framing of the urban area involved in the fieldwork (GEOscope WMS - Region of Tuscany. Re-elaboration: Valeria Razzante).

well as drawing up a picture of buildings most subject to damage. A useful exemplification of this is documentation referring to the 1798 earthquake, which testifies to the huge post-quake damage that occurred in the poorest neighbourhoods, such as Fontebranda and Porta Ovile: here, owing to the presence of thin walls made with poor-quality mortar, and the problems connected to the kind of terrain they were built on, civil buildings suffered more from the impact of the quake.

Accordingly, a rereading of this information led to a clarification of the methods to be applied, and of the urban area to be investigated: the decision to focus the analysis on the Terzo di Città (fig.4.5) stemmed from the peculiar features of the subsoil and the characteristics of the earthquakes, and from the type of buildings found in that part of Siena's old city centre, and their state of preservation. More specifically, a decision was taken to analyse a number of post-seismic repair features excluding, a priori, systems used within the body of walls, detectable only with specific studies of individual built units, and solutions such as anchor plates or bonding stones that were added as wall reinforcements, which are less significant in terms of containing major mechanisms of disrepair, and which are thus hard to ascribe to particular periods. After cross-referencing the data collected thus far, four categories of intervention were chosen as being most appropriate for the type of analysis scheduled: wooden stays and anchor plates, counterforts and buttressed walls, relieving arches, and buttressing arches. For each category, a dedicated set of site record forms was drawn up, the models for which were drawn from technical records of anti-seismic devices (Arrighetti 2018a), as proposed by Siena University's Archeology of Architecture Lab. This process then led us to devise site record forms designed for transposing data to a GIS format (fig.4.6), containing the following descriptive fields: basic details to identify the chronology and site (eg. ID, exact address, chronology); a section to describe the structural properties, and the properties of the building materials used; sections allowing a description of aspects to do with size (for height, reference is made to joisted floors, while for length reference is made to the degree to which a feature protrudes from the exterior elevation of the building, and to the maximum length in relation to the linear extension of the individual building).

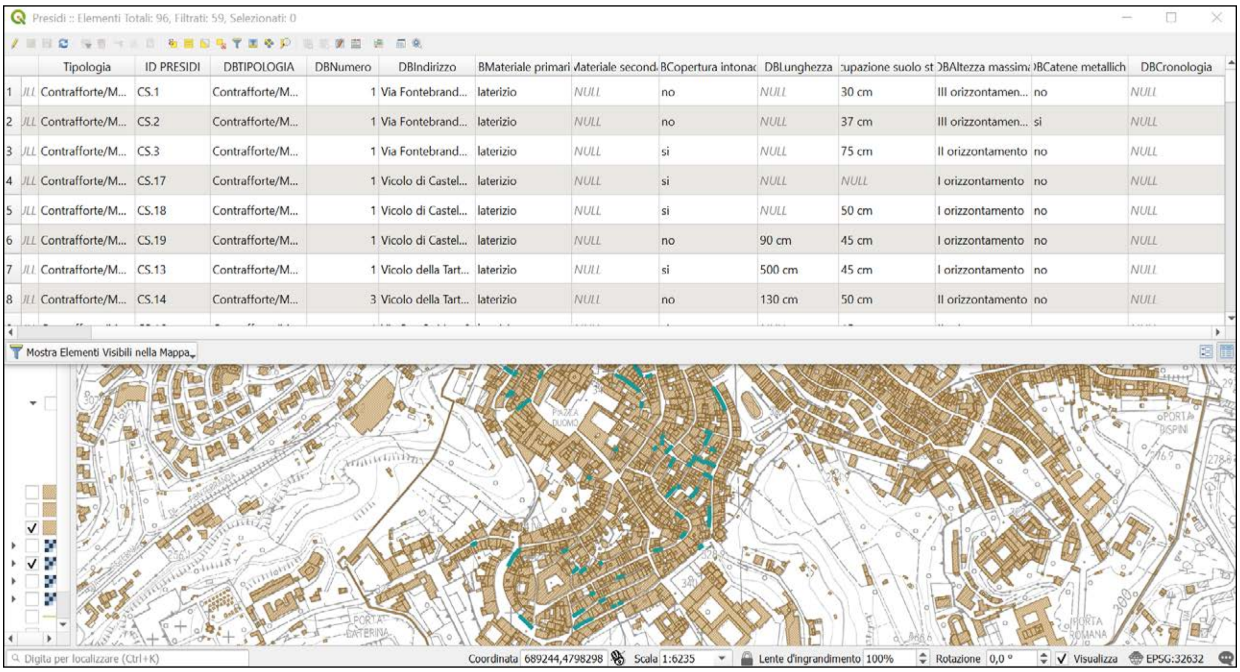

Figure 4.6 - The GIS platform created to record the construction techniques identified in the Terzo di Città with the table with elements characterizing buttresses and scarped walls (Elaboration: Valeria Razzante)

2. Urban survey of the Terzo di Città: analysis of post-seismic repair techniques

As regards methodology, the strategies implemented in the field were in line with the light archaeology model (Nucciotti and Vannini 2020), in the sense of the exploration of a local geographical area by means of non-invasive archaeological approaches, commonly used in the fields of landscape archaeology and architecture, together with stratigraphic observations carried out only on a selection of sites or areas of interest. By applying an extensive, district-wide analystical approach implemented in the Terzo di Città, the urban surveying activities led to the documentation of a total of 96 features, subdivided into the four categories of intervention serving a remedial structural purpose: wooden braces and tie rods, counterforts and buttressed walls, relieving arches, and buttressing arches.

- Tie rods and wooden braces

Evidence of the use of tie rods and wooden braces is found as far back as Roman buildings. Their introduction within masonry constructions was in contrast to the forces active in archivolt systems, serving to offset any tendency to buckle. During survey work, 4 interventions were identified that would fit this group, which it was decided to document using a more elementary form of on-site documentation, also chosen on the basis of the smaller number of features distributed across the general area of interest. Regarding their date, it has been possible to put forward a few suggestions for a relative chronology: the first case involves the metal tie rods and wooden braces in Via Fusari (fig.4.7), which are thought to have been put in place after 1408; indeed, this is the date when the brick-built bridging arch over this part of the street was built, on the orders of the Opera del Duomo. The second clearly dated feature is the parallel structure of wooden braces and buttressing arches in Vicolo di Vallepiatta: in the Statute of Thoroughfares there is a reference to building works between 1290 and 1298 involving Via del Costone, Via di Vallepiatta and Vicolo di Vallepiatta, and Via del Pozzo.

- Buttresses and buttressed walls

In ordinary construction, a seismic response is sought by building buttresses and counterforts which in practice reproduce the geometric principles of a truncated pyramid, which is more efficient in absorbing horizontal seismic actions. By opposing these forces, these devices not only ensure that walled elevations are more stable, they are also simple to construct owing to both the ease with which the materials could be got hold of, and the technological level required. In many old city centres this is the approach that was usually chosen to consolidate masonry structures in the pre-modern era. The support mechanism implemented by means of buttressed walls can be applied not only to a single building but also to a plurality of buildings built in a row. In every built feature, seismic action generates a spontaneous resistance which is manifested with compression or traction forces. With its system of alternating, natural slopes, the city of Siena can be seen as a notable example of these dynamics: Piazza del Campo, with its concave design, is prone to a “dyke effect”; under seismic action, the buildings in Piazza Mercato, with its convex layout, are subject to damage that is transferred to the upper sections of standing walls; for this reason recourse is made to the installation of buttressed walls and counterforts (fig.4.8), or alternatively new constructions, arranged in rows, are built. Thus, in these terms buttresses were used as a new curtain wall for ruined buildings, and could be put in place in the wake of fires, military destruction, or earthquakes. Also in the Sienese context, in relation to the earthquake of May 1798 there are numerous reports of the widespread creation of these expedients, both in humble civil buildings and in the most important urban projects. The Cathedral may be seen as an example of the

Figure 4.7 - Example of a wooden beam set inside wall masonry (Photo: Andrea Arrighetti)

Figure 4.8 - Example of buttresses inserted above wall (Photo: Valeria Razzante)

latter type of context: in the months that followed the 1798 earthquake, it was decided to intervene with the systematic construction of brick-built counterforts situated on both sides of the choir. Later on, two side reinforcing buttresses were added to the upper portion of the baptistery façade.

In the context of survey work in the Terzo di Città, 67 buildings were recorded as belonging to this group; their description followed a more detailed line of research that paid more attention to describing the materials used, and focused on aspects having to do more with size and structure. Regarding this latter aspect, in some cases, from direct observation of the buildings, the recurrent presence was noted of stays, such as tie rods, situated in vertical walls.

- Relieving arches

In recent years the action of arches and systems of vaults subject to seismic stress has been the subject of numerous research studies: their behaviour, in the presence of stresses of this kind, is directly influenced by the kind of structure, by the type of support (whether they be walled features, columns or pilasters), by the thickness of the wall itself, by the conditions involving load, and by the characteristics of the materials used. Specifically, it is noted that these structures have more flexibility than architrave-based systems, such as to allow a reduction of loads and a redistribution of the stresses. The architectural expedients that serve this purpose of redistributing weights above, and lightening the weight as regards lower structures, are called relieving arches. In many urban centres we find that a narrow passageway inside a building can interrupt its linear continuity, but in these circumstances, with the suitable positioning of one or more relieving arches, it is possible to sufficiently redistribute the forces acting on the overall stability of the structures involved. The survey work in the Terzo di Città led to the identification of at least 8 interventions of this sort (fig.4.9). During the phase of research conducted in situ, a number of peculiarities were highlighted: first, the recurrent building technique that uses only bricks laid radially and bonded with thick beds of mortar; second, the distribution of anchor plates together with relieving arches, to be interpreted once again, as in the case of the counterforts, as additional elements designed to restrain and stabilise the masonry parts.

Figure 4.9 - Relieving arch inserted into the façade of a building in Via Pendola (Photo: Gianluca Fenili).

- Buttressing arches

Structural elements used to combat buckling; built in stone or brick, they are positioned at the level of the joisted floors of two buildings that face each other, acting as key elements and repair features. The practice of constructing these interstitial arches between external walls was already very frequent in Roman constructions (see the Basilica of Maxentius, the Temple of Peace, or the Temple of Venus in Rome), but reports of their construction continue into the pre-modern era. Sometimes a whole bridging arch took shape from what was initially a single arch, thereby creating a continuous volumetric connection between two buildings that were originally independent from each other; in such cases the need to reinforce the walls to effectively counter horizontal pressure stemming from an earthquake was later combined with the additional advantage of creating more habitable spaces. Closely identified with the city of Siena, buttressing arches are the second most widely found category of solutions after counterforts, and indeed the quantitative relationship between the two is confirmed in the case of the Terzo di Città. In the course of the urban survey, information was gathered relating to a total of 17 such features (fig.4.10a-b). Of the recorded examples, in only two cases was it possible to propose a tentative relative chronology: for the aforementioned case of Vicolo di Vallepiatta, associated with wooden braces and datable to some time after 1290; and for the bridging arch in Chiasso del Bargello, a work which can be dated to a period after the expansion of that section of the street, which occurred in 1328.

Figure 4.10a - Examples of buttressing arches

Figure 4.10b - Examples of buttressing arches.

3. Results of the analysis

The possibility of mapping the features that emerged from the survey, and displaying them in cartographic form, enabled several considerations to be made. Some of these were specifically associated with historical and architectural aspects, while others had to do with the local subsoil characteristics, and the terrain of the city centre (fig.4.11). At first glance it is clear that there are specific areas in which these devices are used. These are probably connected in some way to the zones where the effects of earthquakes, or of other structural problematics, are particularly amplified, as for example in the area behind the Cathedral, or in the Castelvecchio zone. Another point we have to bear in mind with reference to the features that emerged in the course of the investigations is the probable precarious state of conservation of some buildings. This certainly influenced the formation of disrepair (of both natural and anthropic origin), which led to the decision to use particular protective expedients for the structures involved. Moreover, it seems interesting that the fact that some expedients were used rather than others allows us to understand the likely correspondence between an intervention and an earthquake, thereby allowing us to formulate certain hypotheses regarding the use of specific expedients for the respective chronologies. To that end, a macro-district analysis of the findings seems to reveal an integrated use of buttressing arches and wooden braces in the areas near the Cathedral, whereas the use of wood is almost totally absent in external elevations for all the other zones of the Terzo di Città. Meanwhile counterforts display a practically homogeneous scale of use throughout the whole area, and in our research they represent an element which has scant use for the purposes of a chronological characterisation. By contrast, a feature of very great interest is the extensive use of buttressing arches. These are employed more frequently in areas close to the centre and, on the basis of the characteristics of their construction, they can be grouped into two macro-types: simple arches, consisting of a semi-circular arch or pointed (ogival) arch, built using diagonal bricks and masonry above 10-15 brick courses, without further decorative details; and complex arches, built with semi-circular arches or pointed arches, and a very clearly defined decorative scheme, sometimes with a small roofed section on the upper edge. In both cases there are sub-variants based on the size of the arch section, which in some instances could have a passageway above, serving to connect two rooms in two different homes, or on the curve of the intrados, if ogival or semi-circular. In terms of chronology there is not much information that might allow us to sort the features identified into different periods. Only for buttressing arches do we have any dates, which derive from documents drawn up following the 1798 earthquake, and these allow us to identify the complex arch type as contemporaneous with the reconstructions that took place following the late 18th century earthquake. Meanwhile it seems that the use of the simple form in this kind of architectural feature can be backdated.

The study undertaken by urban surveying and rapid analysis of the Terzo di Città, integrated with the information compiled through archaeoseismological research currently under way in Siena's urban centre, has led to the definition of a number of lines of research that merit further exploration in the near future. Specifically, the following considerations appear to be of particular interest:

- The presence of specific building features in certain parts of the city, with special reference to the area surrounding the Cathedral and Castelvecchio, could be ascribed to the need to protect the buildings in areas where the effects of earthquakes and/or the high vulnerability of buildings represent an especially indicative element in the repertoire of construction techniques;

- The introduction and preferential use over time of specific repair techniques (in particular counterforts, buttressing arches, relieving arches and anchor plates), as opposed to other construction solutions, is probably a choice determined by the need to respond to problematics that frequently characterise seismic and post-seismic scenarios;

- Reflections on specific construction characteristics of the reinforcement devices analysed, with the identification of possible variants and sub-variants, lead us to compile initial typologies that enable us, albeit in a fairly generic way thus far, to put forward suggested dates regarding when they were used.

Thus, on the basis of the preliminary, initial answers obtained by means of this research, it has been possible to expand our knowledge of the seismological and archaeoseismological features of the city of Siena. On the basis of analytical observation, we carried out an initial complete survey of post-seismic repair techniques present in the Terzo di Città. Subsequently, all the information was reorganised and transposed to a GIS support: after an initial, content-based response from site documentation forms, we produced a graphic and geographical presentation of the information. The decision to document and geolocate these data made it possible to make preliminary statements regarding the characteristics of the buildings present. Thus, by pursuing this research approach for each type of architectural device, dated wherever possible, but at the same time centred on local strategies backed up by a GIS analysis of the data, there is the prospect of assembling complete catalogues of the repair techniques found in Siena's old city centre.

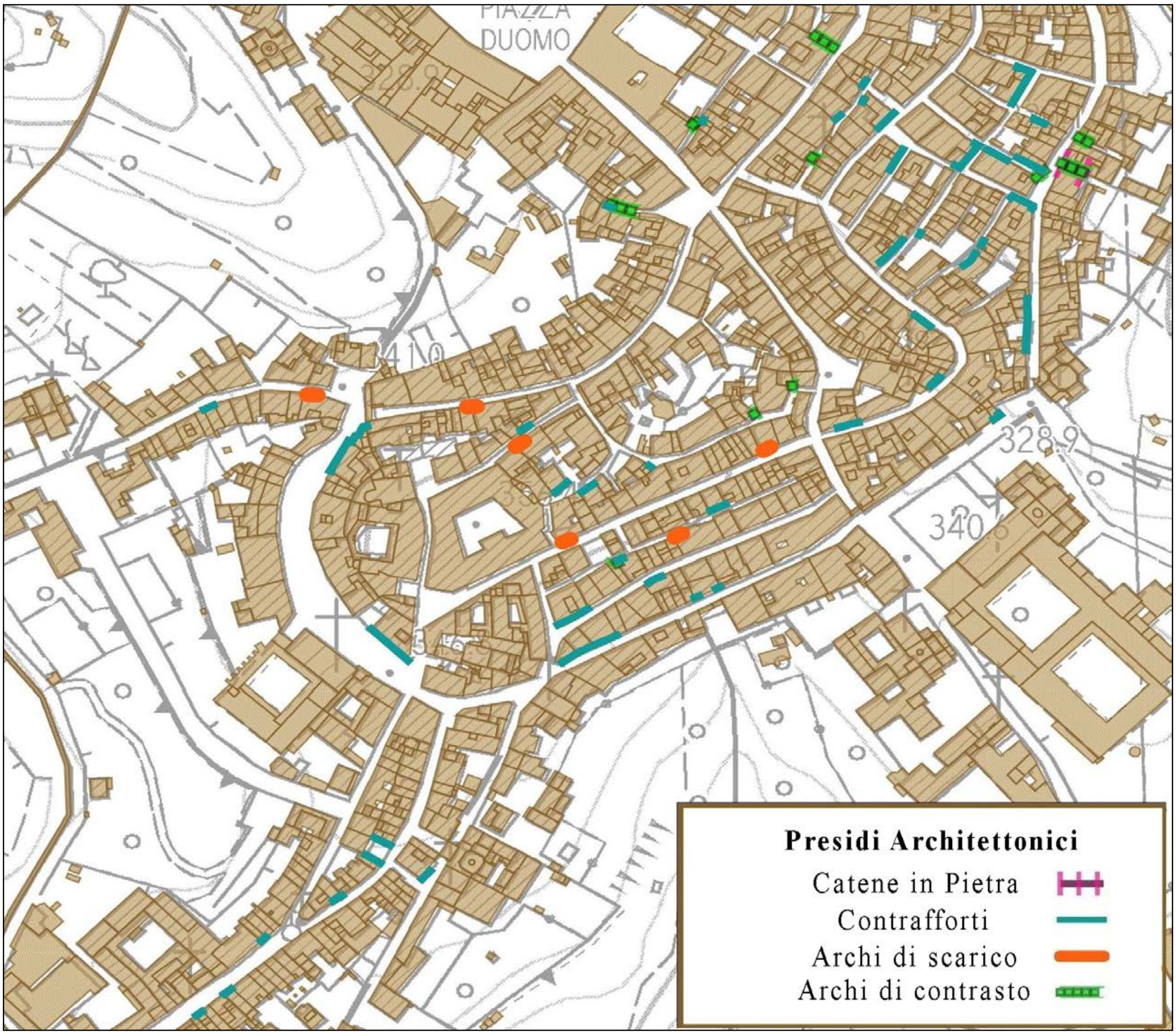

Figure 4.11 - Re-elaboration in GIS of the post-seismic techniques analyzed during the survey of the Terzo di Città (GEOscopio WMS - Region of Tuscany. Re-elaboration: Valeria Razzante).

4.2 Medium-scale analysis: street fronts and building aggregates

A second type of archaeoseismological analysis conducted as part of the PROTECT project, but with a degree of examination that could be described as medium-scale, since it is based on unitary assemblages composed of more than one actual building, consists in the analysis of street fronts and aggregates of buildings[54]. In this case, one of the main planks of the research involved choosing study contexts of interest, which fell within parts of the city for which there was written, iconographic or cartographic documentation relating to the effects of one or more earthquakes, and which displayed a material component that was very visible and easy to read in archaeological terms. In addition, it was vitally important that these areas may have fallen within those classified as the "red zone" by the study of the Lira tax records. This point was essential for being able to check the data entered on to the document, and thus capable of proposing a seismic scenario that was or was not compatible with the scenario suggested by the analysis of the tax records themselves. In accordance with these priorities, two specific areas of the city were chosen: Via Pendola in the Terzo di Città, and Via Fontebranda, confined to the section between Via di Città and Via Diacceto, in the Terzo di San Martino (fig.4.12). These sections of street fronts are around 100 mt in length, and several different methods of data acquisition and interpretation of palimpsests were tried out. As for recording the information, use was made of a wide range of technologies to find out which was the most suitable, with a view to the objectives imposed by this phase of the project[55]. Thus, terrestrial laser scanners were used, both mobile and traditional, accompanied by a photogrammetry survey, the images being captured both from the ground and by drone. It was fairly clear from the first graphic representations of the point clouds obtained by laser scanner that the mobile instrument, although very quick in data acquisition, did not offer sufficiently accurate data to carry out archaeological analysis, however cursory. The excessive noise of the model, and the fact that some parts were not acquired as they were too far away, or too inclined, did not offer an adequate morphometric basis for the purposes of documenting the street front. Accordingly a decision was made to use the terrestrial laser scanner, the data from which, once processed and expressed in graphic form, was used as a basis to produce high-resolution orthophoto plans, and to determine the characteristics of the deformation features on the outer walls[56]. Archaeological analyses of walls and masonry structures, conducted in the field, were subsequently overlaid on top of these graphic renderings. These constituted an extension of the analysis by Masonry Stratigraphic Unit. The documentation compiled by means of this kind of work also enabled us to identify and sometimes to interpret signs of disrepair and restorations, both ancient and modern. This information affords a dual opportunity: in terms of acquiring raw information, it enables us to correlate stratigraphy to specific damage and disrepair, and thus to provide an initial identification of the effects of earthquakes on buildings, helping towards an understanding of these phenomena, or supplying preliminary data on which it could be worthwhile to conduct a specific, further examination in order to correlate them to the information found in written sources. On the other hand, it also allows an understanding of the state of conservation of the buildings covered by the analysis, and thus enables suitable interventions to be scheduled, with a scale of differing priorities for each individual building unit.

[54] The Italian landscape is dotted with historical building aggregates. Representing a great majority of the buildings located in the historical centres, they can be identified as agglomerates of masonry structures interacting together both during static and dynamic action.

[55] For the survey and data representation phase, involving laser scanners and photogrammetry, I wish to thank Prof. Giovanni Pancani and Prof. Giovanni Minutoli of the Department of Architecture at Florence University, and Marco Repole and Gianluca Fenili.

[56] Regarding application of the laser scanner for the analysis of deformations on the buildings' exteriors, and the way these are interconnected with the stratigraphy of the monuments, readers are referred to the following publications: Arrighetti 2022; Arrighetti 2019; Arrighetti 2018a.

1. Data acquisition

As far as recording information was concerned, different technologies were applied to assess which was the most suitable for the objective required by this phase of the project. After the initial processing of the point clouds generated by the mobile scanner with SLAM technology (Simultaneous Localisation and Mapping), it became apparent that, although very fast in acquisition, this instrument did not produce data accurate enough to be used for archaeological evaluation. This is probably due to the fact that this type of scanner uses proximity sensors, which are simpler and less accurate than those used by terrestrial scanner models, and also to what is normally called “drift”, which is the tendency of scanners to accumulate errors during acquisition in the field. The excessive noise of the model and the failure to acquire certain parts of the façades because they were too distant or too inclined, did not offer the accurate morphometric basis needed for the archaeological documentation of the street front. Therefore the choice fell on the phase-shift laser scanner, by virtue of its very high accuracy, with measurement errors of below 0.1 mm. From an operational point of view, the plan to acquire the data of the façades in Via Pendola by means of a 3D laser scanner was developed with a view to capturing all the data necessary to read the surfaces of the street fronts while minimising the number of scans (approximately 20). This method of “expeditious” surveying, already tested in other urban contexts both in Italy and internationally, reduced the amount of time required for the field survey and the data processing and recording, thus streamlining the entire workflow.

The archaeological analyses of the masonry carried out in the field were characterised by an initial division of the street fronts into Standing Buildings, followed by a detailed study by means of Masonry Stratigraphic Units (abbreviated to USM, from the Italian ‘Unità Stratigrafiche Murarie’). For example, in Via Pendola, the façades were divided into 7 Standing Buildings, one of which could be further subdivided into three elements (fig.4.13). Additionally, a considerable portion of the street front had to be excluded from the investigation because the walls were completely covered in plaster and, therefore,

Figure 4.12 - Aerial view of the historic centre of Siena with the two road fronts under investigation highlighted: Via Fontebranda and Via Pendola. (Map data Google, Landsat / Copernicus. Re-elaboration: Marco Repole).

unreadable from an archaeological point of view[57]. Following this initial selection and the assessment of the stratigraphic relationships between the various buildings, the analysis became more detailed, and analysis by masonry stratigraphic unit (USM) was implemented: this identified 1,400 remnants of damage and/or repair, highlighting the multi-layered nature of the façades. The archaeological analysis documented a construction history teeming with events, both anthropic and natural, involving collapse, rebuilding, rearrangements, and modifications of pre-existing settings (fig.4.14). For example, the frequent filling-in of windows and the subsequent installations of new openings characterise many façades, and highlight the frequent transformations that affected each building. The observed building activities must also be related to the damage and instabilities that compromised the architectural structures, to the extent that it was necessary, among other repairs, to introduce 38 safeguarding measures, still visible today, to consolidate the masonry. Among these recorded techniques, in many cases ascribable to a desire to repair the damage caused by the effects of a specific earthquake[58], we can include: bond stones, iron anchor plates, buttresses, relieving arches and infill operations that involve the blocking of openings throughout the architectural complex. Moreover, on the basis of the stratigraphic readings, 29 traditional masonry building techniques were identified: these were analysed using dedicated filing systems, which systematised the countless information useful for framing the technological dimension within which the masons operated through the ages. In addition, data obtained from field analysis was recorded directly on site by means of rapid documentation forms specially designed for this project, based on a 3-tier documentation of the structures: road front, standing building, and construction technique.

2. Digital restitution of deformations

Following the data acquisition phase, a 3D model of the street façade was produced (fig.4.15), which clearly showed how the morphology of the street front was strongly characterised by a diverse and complex geometry (elevation, width of each structure), as well as by varying levels of preservation of its buildings[59].

The documentation of the damage to buildings by Elevation Maps[60] is a technique that has been used by our research team for many years to analyse the structural instabilities caused by natural events such as earthquakes or other natural or man-made causes (Arrighetti 2019; Minutoli 2019; Pancani 2017). To create an elevation map of the building, different types of surveying instruments such as LiDAR (Light Detection and Ranging), GPS (Global Positioning System), photogrammetry, or 3D Laser Scanner are used. These instruments, although characterised by different specifications and degrees of accuracy, make it possible to detect variations in elevation between the points that constitute the surfaces of an object.

---

[57] In this specific case, given the experimental nature of the proposed analyses, which aimed at the creation of an expeditious protocol that would relate deformations and stratigraphy, and since the latter element was missing from the plastered portion of the street front in question, it was decided to exclude the part covered by plaster from the archaeological reading of the façades. Instead, the latter was considered in the restitution phase of the survey because some evidence of damage was still visible despite the plastering, and affected and related to the damage present on the unplastered walls.

[58] On the possible link between the techniques defined as 'post-seismic' and the historical seismic events that occurred in Siena, refer to the considerations set out in: Arrighetti et al., 2022.

[59] An example of the latter is the clear degradation levels of the wall faces, characterised by the disintegration of the bricks used for their construction. All these considerations, already observed and recorded during the field analysis, are even more apparent in the generated models.

[60] An Elevation Map is, in this context, a graphic representation of the differences in elevation between points on a terrain or surface.

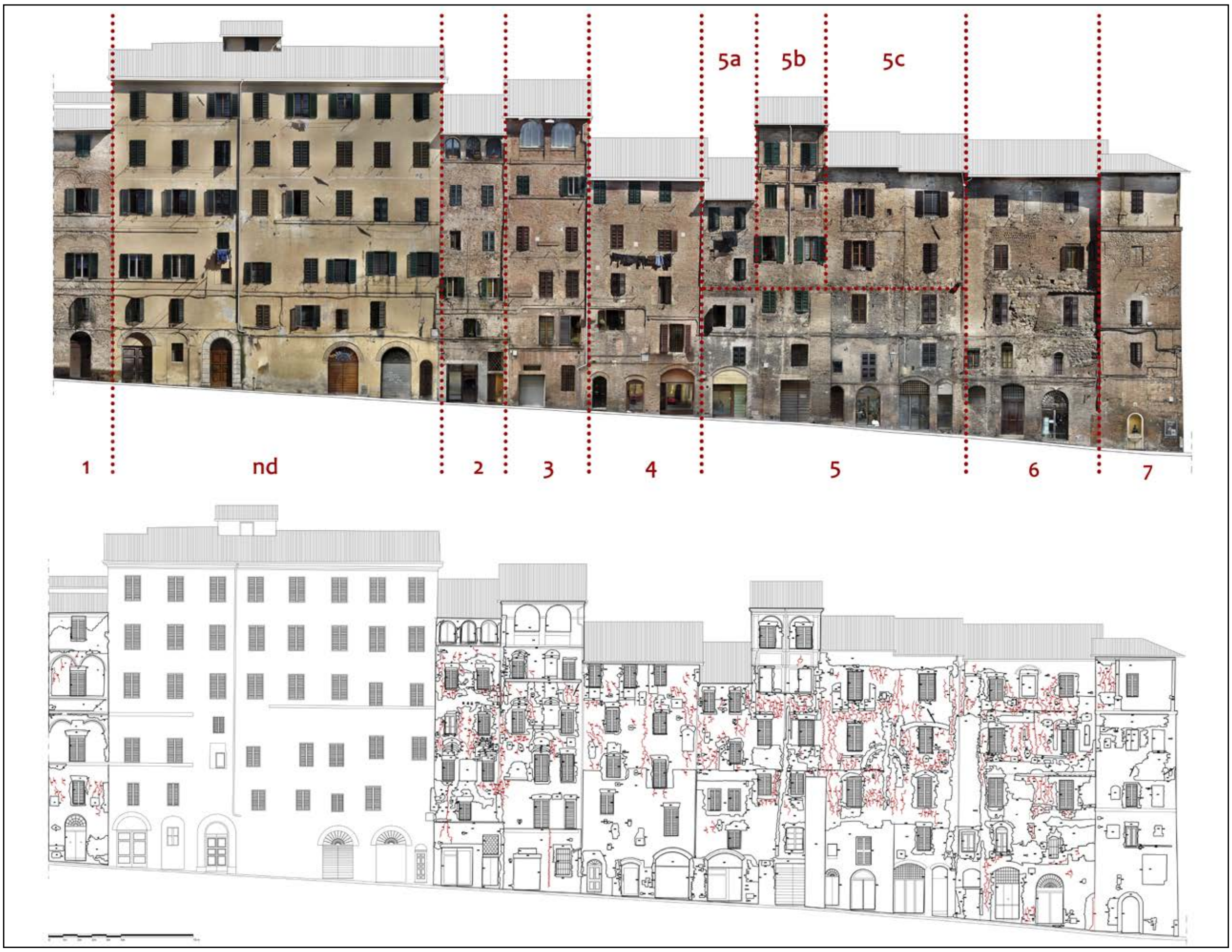

Figure 4.13 - Documentation by Standing Building (top) and by USM (bottom) of the street front of Via Pendola. The plastered portion of the street front was not considered in the analysis because the absence of stratigraphic data did not allow a clear understanding of how its façade relates to the evidence emerging from the documentation of the deformations of the surrounding buildings (Image taken from: Arrighetti and Repole 2024)

Figure 4.14 - Stratigraphic analysis of a portion of the street front in Via Pendola containing: stratigraphy (black colour), crack pattern (red colour), post-seismic construction techniques (green colour) Elaboration: Marco Repole.

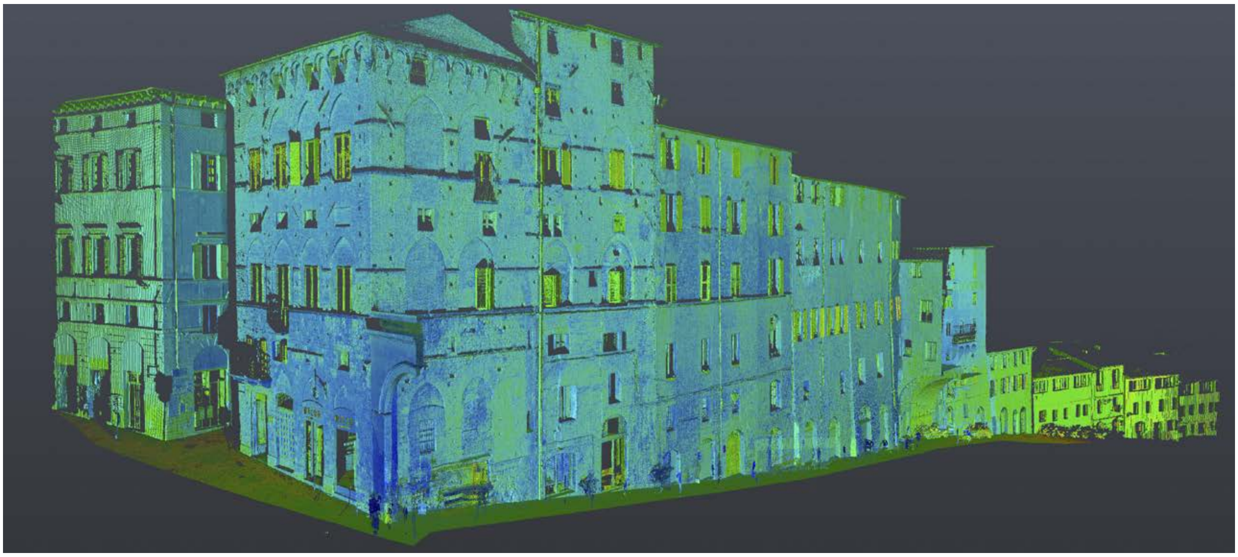

Figure 4.15 - Screenshot of the point cloud obtained from the laser scanner survey of Via Fontebranda (Image taken from: Arrighetti and Repole 2024).

The theory behind this technique consists in identifying an ideal reference plane on the surface to be analysed, which is then used as the basis for the measurement that will create the elevation map. The measurements start from a classical Cartesian system composed of a Z coefficient indicating height, an X coefficient indicating width, and a Y coefficient indicating depth. In this space, we find the surveyed model to be analysed. Since this ideal plane is composed only of X and Z coordinates, it is possible to measure all the variations of the points in their Y component, associating their size (Delta) with a given colour on a predetermined chromatic scale. Typically, the portion of the gradient leaning towards red identifies the positive deformations, while that leaning toward blue indicates the negative ones; green denotes the points closest to the reference plane, which is therefore deformation-free. Three-dimensional visualizations of data at this degree of accuracy enable the identification and analysis of the deformations on surfaces, which not only allow for the evaluation of the different issues affecting an architectural structure at the time of the survey, but also provides an assessment of the dynamics linked to the seismic events that have affected the building over time. In this regard, the precise recording of deformations, as well as of cracks, becomes essential to an understanding of the evolution of the built feature, its alterations and instabilities and, consequently, the dynamics underlying the choices of intervention and transformation of the architectural complex.

In contrast to the 'classic' elevation map described above, which features colour gradients, the PROTECT project experimented with the use of a map based on a representation system similar to the one used in terrestrial topography, namely "isohypses"[61] (fig.4.16). This type of documentation enables the identification and schematisation of all points on the analysed surface, correlating them with a given Delta. The main difference between this kind of representation applied to standing buildings rather than terrains is the scale of application: in the latter, the lines are set to a one-metre interval, while in the former the interval is one centimetre. When applied to the smaller scale of representation, this method enables the filling and demarcation of each area of a building front that is characterised by the same displacement, thus generating a digital elevation model capable of describing the deformations in detail. The advantage of using this specific type of elevation map lies in the precise identification of the size of each isostatic anomaly that describes the precise dimension of each deformation of the surface, thus documenting the direction and extent of each alteration visible in the analysed masonry.

[61] In cartography or geography, the term 'isohypses' refers to a system of representation based on contour lines that show in detail the elevation profile of a surface and its relative altitudes.

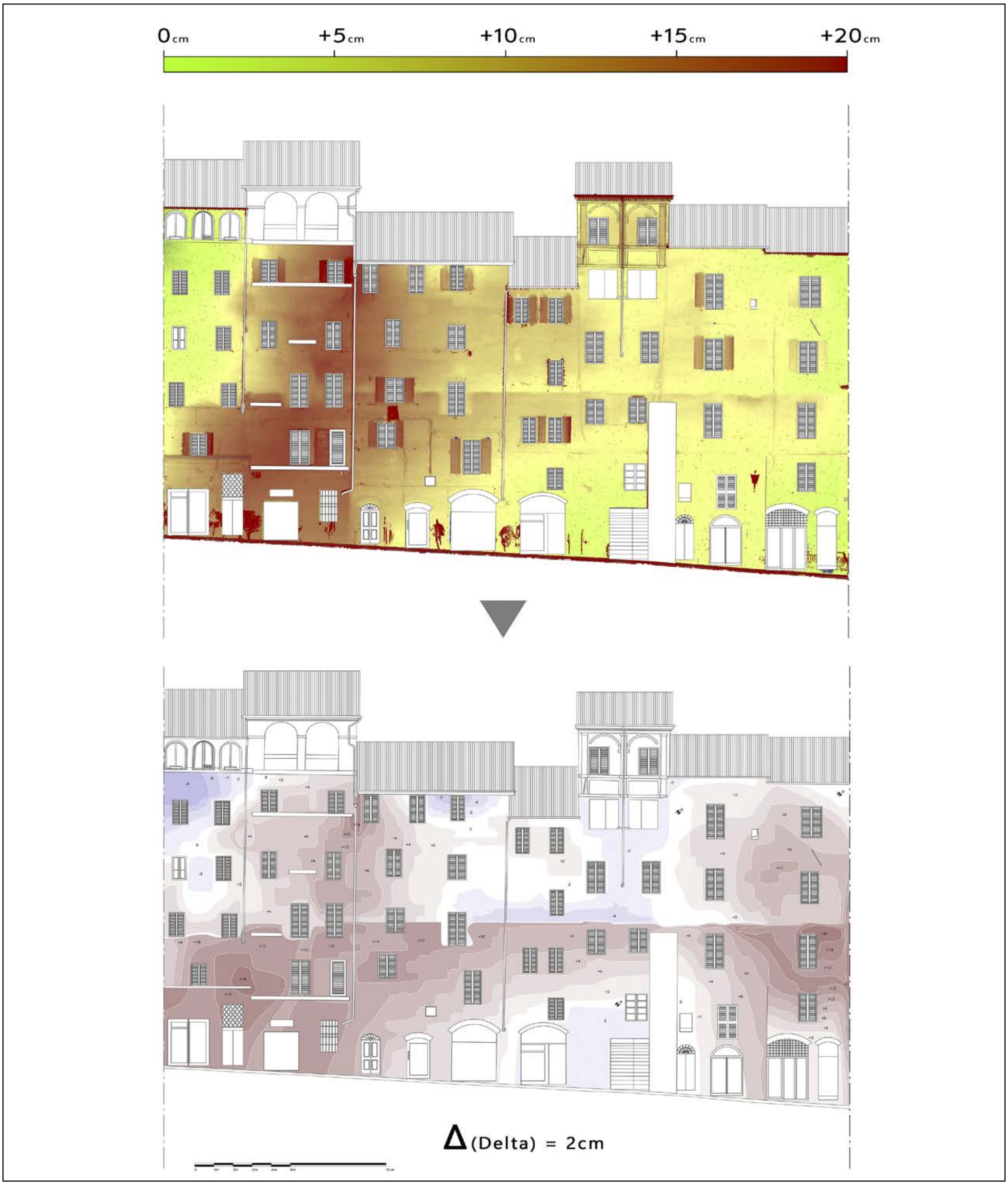

Figure 4.16 - The image shows the difference in graphic rendering of the deformation data of a portion of the external road frontage related to Via Pendola. In particular, from the image, it is possible to appreciate how the deformations visible on the Elevation Map on the top (composed of a colour gradient that ranges from green corresponding to an elevation of 0 cm to a maximum displacement in red of 20 cm) provide generic information on the trend of the entire frontage, while in the Map on the bottom (composed of isohypses with a Δ variation of 2 cm) they provide not only a general view but also a precise measurement of the extent of the displacement in that given area. The use of contour lines also allows for more detailed references on the frontage, moving by individual standing building, which made it possible to identify deformations (such as those on the right of the framed frontage) that were difficult to see with the colour gradient method. In our opinion, for the colour gradient to be graphically clear, more detailed measurements on the façade plane are necessary (Image taken from: Arrighetti and Repole 2024)

Figure 4.17a - Orthophoto plan (top) and stratigraphic analysis (bottom) of the west street front of Via Pendola.

Figure 4.17b - Orthophoto plan (top) and stratigraphic analysis (bottom) of the east street front of Via Pendola.

3. Archaeoseismological analysis

Archaeoseismological analysis applied to historical buildings deploys tools that have been progressively refined by the archaeology of architecture over the last few decades and have, therefore, become integral to this disciplinary field (Brogiolo and Cagnana 2012). However, these traditional methodologies have been modified to determine which operational practices are best suited to the context and purpose of the investigation (Arrighetti 2015). Different neighbourhoods of historical town centres comprise buildings that are inevitably complex and composite. Through fieldwork, it was necessary to 'simplify' and progressively organise the immense amount of data that characterises an architectural complex. The study, therefore, envisages a division into the different standing buildings that constitute the complex, to determine the relationship between the different structures, and reveal their chronological sequence. The analysis then proceeds towards a greater degree of detail through a stratigraphic reading by masonry stratigraphic units (USM). In this way, the individual building operations that characterise the multi-layered stratification of the elevation are identified. This makes it possible to relate the cracks framework and the interventions made by workers through the centuries with the operations that lead to the progressive transformation of the building and to the damage and disruption that altered their features and structures (fig.4.17a-b). Therefore, the historical evolution of the street fronts is charted through the reconstruction of a relative chronology.

4. Characterisation of traditional and post-seismic building techniques

The documentation of building techniques enables the recording of the specific characteristics of each wall, both in terms of understanding their material, construction and mechanical characteristics, as well as their historical and archaeological profile. This analysis, therefore, recommends a developmental approach connected to the chronological and typological analysis of masonry within a given territory, which on the one hand allows us to connect specific types of building techniques to historical periods of reference and, on the other, offers the opportunity to compare these changes with the social, political, and economic context in which they occur. This approach, if used in earthquake-prone areas, requires important reflections on the evolution of the technological aspect in relation to the technical capabilities and specificity of the patrons and craftsmen who operated in that area, linking the use of specific materials and technical-operational choices to the needs imposed by the dynamics of the emergency or the reconstruction phases (Alberti et al., 2019; Arrighetti 2016; Correia et al., 2015). In the latter case, there is often the desire to empirically experiment with new solutions, and modifications of varying complexity of traditional techniques of autochthonous or allochthonous derivation, leading to the creation of building cultures aimed at counteracting or mitigating the effects of new seismic events. These are building systems that remain unchanged in specific areas in the short or long term, sometimes losing the function for which they were initially conceived (Arrighetti and Minutoli 2019).

At an operational level, the documentation of construction techniques takes place on the margins of the archaeological reading of the masonry, an operation that enables their stratigraphic and chronological characterisation, together with documentation of the damage and disrepair visible on the building, and of the interventions carried out to repair or counteract these problems. The recording of the techniques, damage/disrepair and repairs is carried out by means of a special system of on-site record forms[62], which enables a precise qualitative and quantitative recording of these elements within the framework of the stratigraphic investigation of the building. The aim, therefore, is to link these interventions to

[62] With regard to the forms used for recording damage/disrepair and subsequent repairs, see the publication of a project carried out in Florence (Arrighetti 2019).

the historical and construction-related development of the building, and to interpret them from an archaeoseismological point of view.

Once identified, the post-seismic techniques are catalogued on a digital database called OPUR (Outil Pour Unité de Réparation / Repair Units Tool), developed as part of the RECAP programme (Reconstruire après un tremblement de terre. Expériences antiques et innovations à Pompéi / Rebuilding after an earthquake: ancient experiments and innovations in Pompeii)[63] by a team of researchers from the École Normale Supérieure - Université PSL, Paris[64]. The database, originally set up for the documentation of post-earthquake repair techniques identified at the archaeological site of Pompeii (Dessales and Tricoche 2018; Dessales 2022), was later tested and is now being updated by the PROTECT project (fig.4.18).

5. Integration of the analyses: the "stratified instability maps"

As seen above, the application of point cloud surveys enables an accurate three-dimensional recording of structures, by providing a characterisation and documentation of certain types of disrepair and monitoring the structural problems present in the material structure of the buildings. When this type of data is integrated with the vast amount of information obtained from archaeoseismological readings, a process is set in motion that leads to a profound knowledge of the structure under examination. The result is the characterisation of the construction and mechanical history of the building, and also of its seismic history. But how can all this information be summarised in visual form? The objective should be not only to periodise the construction and destruction phases visible on the buildings and to develop their structural analysis, but also to integrate these data in order to suggest a periodised characterisation of the disrepair that has occurred over time, and is still occurring, by relating the results obtained to the historical and seismological documentation of a certain area. Using the data in our possession and the documentation produced by different types of analyses, this process resulted in the generation of "stratified instability maps", i.e. images that combine the archaeological reading of the building with its main instabilities, represented by the cracking and deformation pattern (fig.4.19). Unlike classical archaeological or structural readings, however, in these representations attention is also paid to "when" the instability occurred, and its relationship with the stratigraphy present on the monument. To achieve this, the deformation pattern obtained through the Elevation Maps was represented by lines with elevation differences of 2 cm[65] and superimposed onto the archaeological reading by Masonry Stratigraphic Units (USM). In this way, some of the deformation curves were clearly interwoven with the building's stratigraphy and stratigraphic interfaces, highlighting the relationship between these two key readings of the monument (fig.4.20). The result is, therefore, a periodised reading of the material components of the architecture, which provides essential data for technicians, both in terms of the chronological aspect (when the instability was triggered or transformed), the interpretative aspect (what caused the instability to form), and the operational aspect (the instability is still occurring, or some elements have established a new static equilibrium). Therefore, the "stratified instability

[63] Project ANR-14-CE31-0005, 2015-2019, coordinated by the AOROC department (UMR 8546, ENS-CNRS-EPHE, Université PSL), associating the IPGP (Institut de Physique du Globe de Paris, UMR 7154), the INRIA (Institut national de de recherche en informatique et en automatique, Paris – Rocquencourt, UMR 8548) and the Jean Bérard Centre (USR 3133, CNRS – EFR), in collaboration with labex TransferS, ISTerre (UMR 5275), the University of Padua, the University of Naples Federico II, and the Pompeii Archaeological Park: see http://recap.huma-num.fr.

[64] The OPUR database was created in Filemaker 13 by Agnès Tricoche, under the supervision of Hélène Dessales, with contributions from Guilhem Chapelin (CNRS, CJB) and Julien Cavero (ENS, labex TransferS) for its design.

[65] After a series of tests, a 2 cm elevation difference between lines was chosen because it was the most effective both in representing the deformations accurately on a geometric level and in achieving good readability when superimposed and integrated with the archaeological analysis.

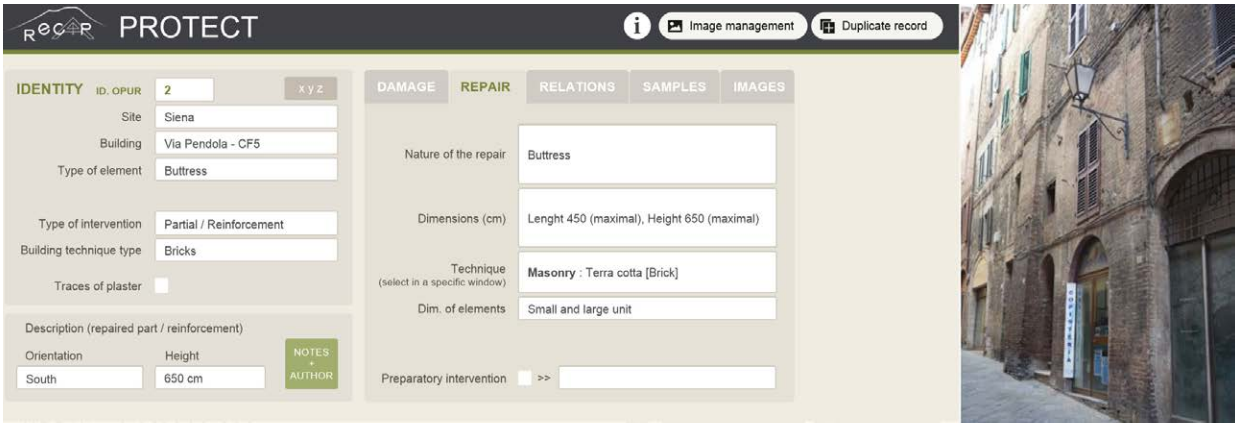

Figure 4.18 - Image of the user interface in the OPUR database updated by the PROTECT project.

maps" constitute a palimpsest comprising different types of information (historical-archaeological, architectural, structural) that are closely linked to each other, and become significant elements of the knowledge base used both for historical and archaeological interventions and technical and planning choices.

6. Results

When working in large, socially and politically complex situations with low economic impact, it is often necessary to achieve significant qualitative and quantitative results in a short time. The method applied in Via Pendola and Via Fontebranda was created to this end, namely, to document a 100-metre street front with an evident and complex stratification, measure accurately the time and resources needed to carry out the overall work, and assess the type of data returned. The first consideration that emerges from this experiment focuses on the time required for the work. In approximately 20 days, a three-person team, consisting of two archaeologists and one surveyor, mapped the complete geometry of the street front and also finalised the archaeological, material, and construction reading of it. Crack and deformation patterns, stratigraphy, and traditional and post-seismic construction techniques were documented, using digital tools. In addition, the quality of the data produced by the survey was verified by comparing the results achieved with different acquisition systems. A second consideration concerns the selection of the activities required for the archaeological analysis of the street front in relation to its documentation, which is useful for an initial restitution of the façades in terms of their construction history. The work carried out on the street fronts did not involve an analysis entirely in keeping with the modus operandi generally adopted by archaeologists working on historical buildings[66]. The unique aims that guide this type of research require a rethinking of the tools to be used so that they are as suited as possible to the task ahead. One can, therefore, speak in this case of an 'expeditious archaeoseismological analysis': among the tools in the archaeologist's armoury, those that achieve the necessary degree of thoroughness and detail are selected, favouring the steps that are truly useful to the cognitive process, according to the characterising elements of each case study. This inevitably produces a streamlining of the workflow and timescale. The reading by masonry stratigraphic units is thus used to satisfy the conditions that archaeoseismology demands in order to fulfil its aims. The observed building phases are then documented by means of the recording systems considered most

[66] The statement 'modus operandi generally adopted by archaeologists working on historical buildings' refers to an approach to interpreting historical buildings based on the levels of analysis structured in the manual that currently serves as a reference for archaeologists of architecture: Brogiolo and Cagnana 2012.

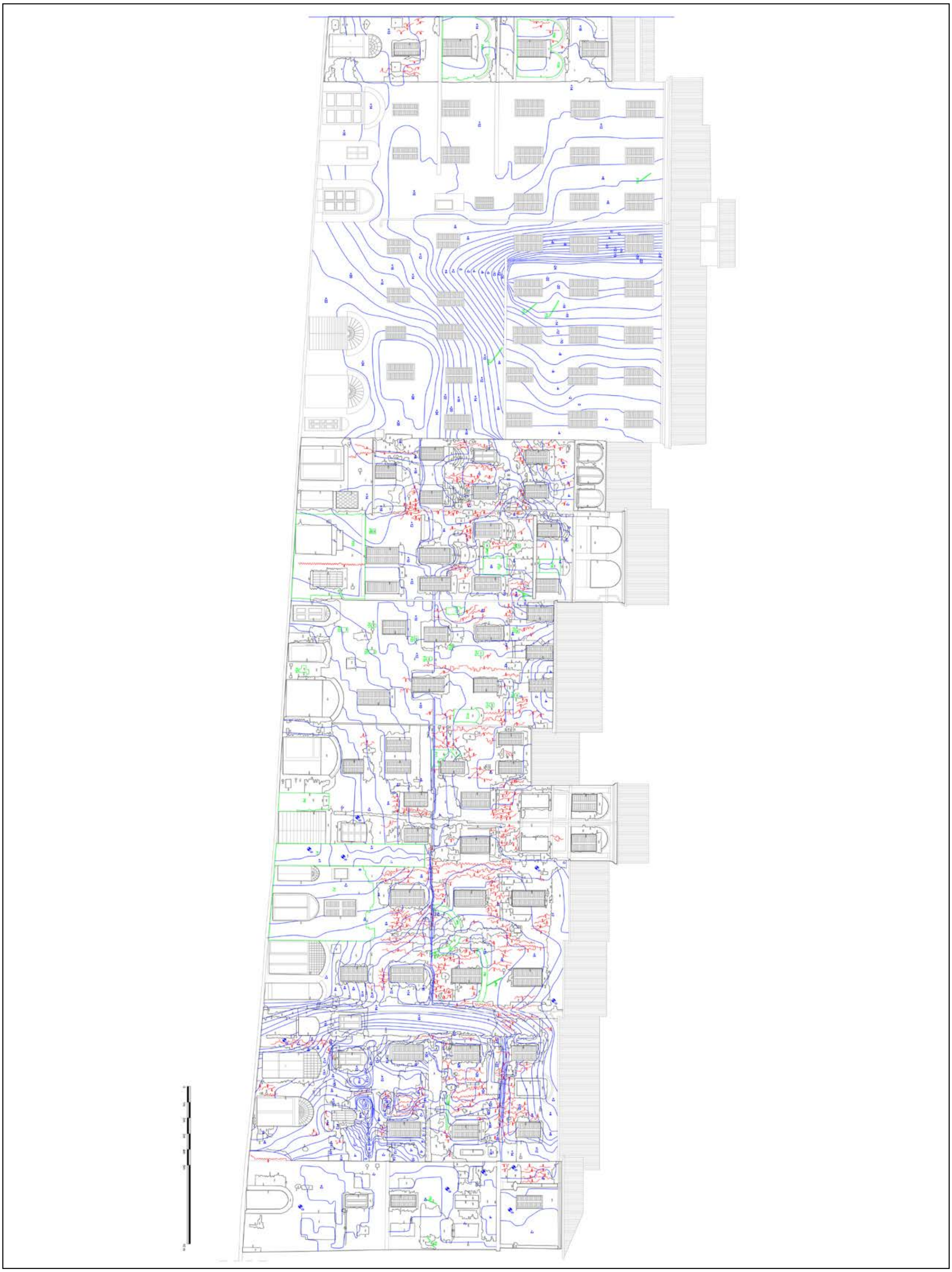

Figure 4.19 - The 'stratified instability map', i.e. the integrated representation of the deformation framework (in blue), the crack framework (in red), the stratigraphy (in black) and the post-seismic construction techniques (in green). Elaboration: Andrea Arrighetti and Marco Repole.

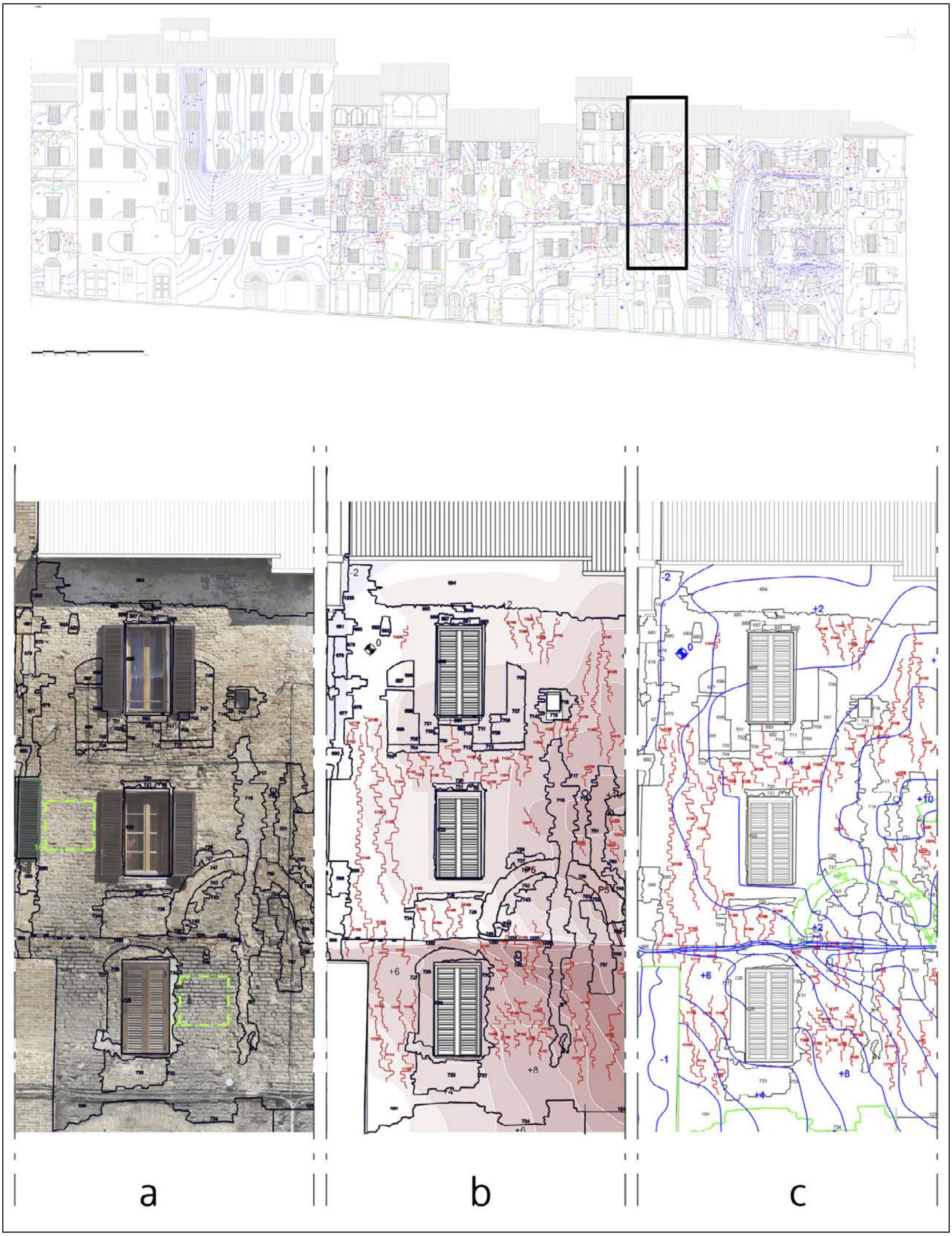

Figure 4.20 - Image showing: a detail of the archaeoseismological reading (in black) and the building techniques (in green) of the outer face of a street front (8a); the same detail with the layering of stratigraphy (in black), cracks (in red) and deformations patterns made by colours (8b); the same detail with the layering of stratigraphy (in black), cracks (in red), the post-seismic building techniques (in green) and deformations patterns made by isohypses (8c) (Image taken from: Arrighetti and Repole 2024)

effective for the ensuing interpretations. For example, it may be considered redundant to proceed to fill out individual USM sheets: Similarly, it may be considered superfluous to outline construction activities and phases. This has led to a significant reduction in the time needed for the documentation on paper during fieldwork and its subsequent digitisation onto specific databases. Furthermore, the decision not to outline the construction phases, which are important for a diachronic reading of the evolution of the structure, was taken because, in our opinion, it appeared redundant for the reading of the deformation and cracking patterns which already arranged in a relative chronology by comparing them with the USMs. Analyses of this kind would not only fail to provide elements of particular relevance to the archaeoseismological investigation, but would also greatly increase the time required to complete the research. A third consideration concerns the results obtained from this type of analysis. The comparison of the analysis of the crack and deformation palimpsest with the stratigraphy of the masonry allowed for numerous considerations. In some specific areas of the alley, close relationships were identified between stratigraphic interfaces and deformation that characterised the building over

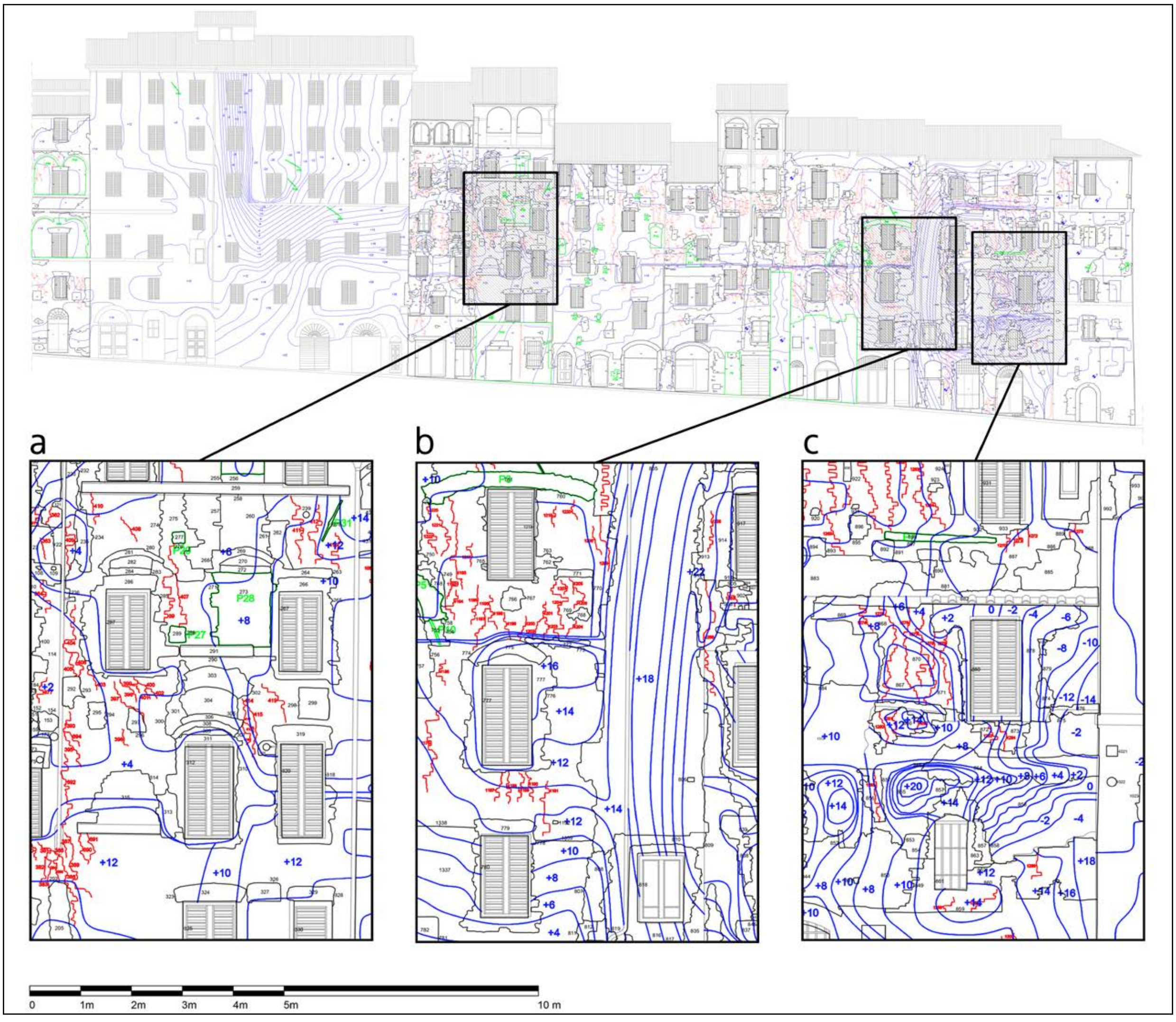

Figure 4.21 - The image shows how it is possible to quantify and integrate the deformation data with the archaeological data. The bottom part of the image shows details of the interactions between stratigraphy (in black), deformation framework (in blue), crack framework (in red) and post-seismic building techniques (in green). In particular, it is possible to appreciate the clear deformation that the isohypses undergo when they cross the stratigraphic interfaces of the infilling of the openings (a, b) or in the connecting masonry between two buildings erected in different periods (b). Furthermore, in figures b and c some cracks are clearly cut by the construction of new masonry or new openings within the buildings (Image taken from: Arrighetti and Repole 2024)

time. Figure 4.21 clearly shows us some examples, where the deformation lines change with reference to the cuts and reconstructions made following the construction of the masonry (fig.4.21, numbers a and c), and where some cracks are stratigraphically older than some masonry that has been built above them (fig.4.21, numbers b and c). In this way, the maps of deformations and cracks enter the archaeological analysis of the masonry walls, and become an essential element in the interpretation and periodisation of the stratigraphy. A fourth and last consideration may be expressed regarding the 1467 earthquake described in the Lira records. In this instance, the reading of the street fronts showed fairly specific signs of disrepair which, by means of archaeological examination, can be dated to a period in the region of the 15th century. Although devoid of a specific correlation between documentary and archaeological data, this piece of information nevetheless allows us to confirm the picture that emerges from the Lira records, showing a post-seismic scenario featuring the presence of fairly major effects on the architectural and structural components of the buildings analysed.This is therefore the first step in testing an expeditious operational procedure that springs from the dialogue between humanistic and scientific disciplines. The procedure is qualitatively and quantitively rich in data, and positively aids the complex task of recreating the construction and mechanical history of buildings, while also assessing the preservation of structural features in historical town centres.

4.3 Micro-scale analysis: architectural complexes

A final level of development of analysis is the level applied to individual architectural complexes. In this case, the method used has been discussed many times in archaeoseismological articles and papers, and envisages a detailed archaeological analysis of the building per each Masonry Stratigraphic Unit, accompanied by specific analyses of construction materials (bricks, stones and bonding agents), and further investigation of all sources, both direct and indirect. Compared to the procedure discussed in the previous section, this process requires a greater effort in getting hold of information that cannot be directly correlated to the building during the investigation itself, and a multidisciplinary approach in all phases relating to gaining knowledge of the object of study. Finally, it also requires a construction and seismic history of the whole complex to be compiled. Thus, to obtain this kind of information, what is needed is a study context that is qualitatively suitable in terms of an analysis of its internal and external walls, and of the whole architectural unit in all its morphological complexity, as well as an adequate number of documents that record its transformations over time, in relation to both earthquakes and other natural events or events of anthropic origin. In response to these needs, two buildings of interest were identified for the city of Siena: the Sant'Agostino complex, in the Terzo di Città; and the church of the Servi di Santa Maria in the Terzo di San Martino. Given the short amount of time available, it was decided to focus attention on the Sant'Agostino complex, where laser scanner and photogrammetry surveys were conducted of the interiors and exteriors of the buildings, along with an overall observation-based analysis of the buildings, and a study of written sources relating to their construction history[67]. This information enabled a precise identification of the building's construction history, and therefore led to an understanding of how earthquakes have influenced the transformation dynamics of different parts of the buildings. On the margins of this work, record sheets and the OPUR database were used to identify and document traditional and post-seismic construction systems, comprising their function, use and chronology, to obtain data of interest in reconstructing the seismic history of the architectural complex.

[67] Collaborating in the work are Dott.ssa Raffaella Leporini, as regards archaeological aspects, and Marco Repole, for the survey and the graphic representation of morphometric data using laser scanner and photogrammetry.

1. The church of Sant'Agostino

The church of Sant'Agostino (fig.4.22) is one of the most important religious buildings in the city of Siena. The building's history stretches far back into the past, having originated in the 13th century. It dates to 1259, the year when there is evidence for the monastery's foundation stone being laid, in an area where the former church of Sant'Agata already stood. During building work on the new religious complex of Sant'Agostino, this earlier church, in a precarious state of conservation, was incorporated within the rear part of the building and in the new crypt, thereby forming a single architectural complex. Topographically speaking, the church of Sant'Agostino is situated in the Terzo di Città, namely the area in Siena's old city centre which written sources tell us was one of the zones with the highest incidence of recorded damage and disrepair of telluric origin, with special reference to the seismic periods that marked the 14th, 15th and 18th centuries (Rovida et al., 2022; Castelli et al., 1996). Furthermore, Sant'Agostino presents numerous indirect sources that inform us of its past, some of which are chronologically detailed and rich in information. This is the case with iconographic sources, first and foremost views of the city of Siena. In these, as of the 15th century, the church stands out clearly, since it was surrounded by a clear space that enabled it to be seen in its complete form.

Alongside these depictions we also have many written documents (Riedl and Seidel 1985-2006) bearing witness to the main construction phases of the religious complex. These sources allow us to subdivide the construction history of Sant'Agostino into three main macro-periods: an initial construction period, datable to between 1259 and 1348, evidencing the construction of the church, to which a transept was

Figure 4.22 - The church of Sant'Agostino (Image: Gianluca Fenili)

later added, in around 1292, which was interrupted in around 1348; a second period, between 1423 and 1495, when there is evidence for the final construction of the transept and choir complex; and a third and final period between 1747 and 1755, which featured a Baroque remodelling of the interior, and a number of transformations to the uppermost part.

In terms of its construction, the religious building features a Latin cross plan with exposed exterior elevations, apart from the south-east (the façade) and south-west sides (side wall), while the interior is totally plastered and was rebuilt in the Baroque period (fig.4.23). The outside lends itself very clearly to analysis, with extensive multistratification of the transformations which the building has undergone, starting with the original fabric and including the changes made in the contemporary era. It also has extensive signs of disrepair (lesions and deformations) and structural reinforcements (bonding stones, anchor plates, counterforts). In the south-western part we see the construction of a modern portico (CF2). The earliest building had six large ogive windows on both sides. The rear part has an apse and a transept, both made in modern times, in addition to the apsidal section, which it supported, and which has been incorporated within the modern structures.

In terms of methodology, setting out from this great mass of written, iconographic and architectural information, we proceeded to structure a complete archaeological analysis of the building. Accordingly, using a laser scanner and terrestrial and aerial photogrammetry, 3D surveys were executed of the building's external and internal parts and, at the same time, stratigraphic analysis was undertaken of the building's external masonry parts, the only parts devoid of plaster. Following these analyses, we then determined the traditional construction techniques, and the techniques whose implementation, both in preventive form and as post-event interventions, could have been associated with movements due to the effects of tremors of seismic origin. Finally, on the morphometric basis obtained from the survey, we opted for an analysis of the main deformation dynamics affecting the structural components of the building, both in terms of the floor plan and wall elevations, and their integration with archaeological findings. This information allowed us to evaluate the specific relations that existed between the disrepair and each stratigraphic unit, thereby allowing a precise understanding of the origin and development of this type of damage. Below we show the individual results of the historical and archaeological analysis, and the results obtained from the survey of the building features, before then proceeding to express a number of considerations resulting from the integration of the previous data.

Figure 4.23 - The interior of the church in Baroque style.

2. Written sources for the history of the construction phases

In line with the information given in the written sources available to us, the history of the construction of S. Agostino can be broadly subdivided into three main construction periods, during which the church took on its present appearance. The construction phases, whose vicissitudes have been reconstructed by cross-referring numerous published sources[68], are discussed separately here (minor structural alterations outside these phases are ascribed to later phases), and are followed by brief reflections on events after the 18th century.

- First construction period (1259-1348)

After the approval of their Order (1256), the Augustine hermits of Siena, who had earlier been scattered between several different urban sites, decided to found a great monastery. In 1259 a plot of land was purchased in the "Castellaccia di S. Agata", a fortified site standing opposite Porta all'Arco near the church of S. Agata. The first stone was laid that same year. Private donations in the form of wills and gifts contributed to its financial security. The Commune of Siena was especially helpful, offering an annual donation of 50,000 bricks "pro hedificatione ecclesie Sancti Augustini ibidem cepte" in 1262. The papal bulls of 1259, 1262 and 1305/06 ensured supplementary revenue. In 1287, 1293 and 1298 the Commune again intervened. In 1295 the building was ready. However, this does not mean that building work came to a halt. In the early 1290s the Augustinians decided that their church was too small, and they obtained financial aid from the Commune to build a monumental transept. Nevertheless, despite continued support from the city, the expansion was not completed. Starting in 1309/10 the Commune promised the monastery a large annual donation of 30 modii of lime and 30,000 bricks until the church's completion, in two annual instalments of 52 lire and 10 soldi (as of 1329 only 50 lire), which were duly paid, but the great plague of 1348 put a temporary end to all building work.

- Second construction period (1423-1495)

Around 25 years after the interruption in construction work on the transept of S. Agostino (1348), the Augustinians tried again to get completion of their church under way. Apparently the work involved did not extend much beyond restoration of damaged parts, probably owing to the continual political unrest, which was accompanied by food shortages in 1400 and the ensuing plague. Almost a quarter of a century more had to pass - around 130 years after the start of the transept – until major steps were finally taken to complete the church. In 1423 the monastery raised 1,000 gold florins from the sale of some of its property. In 1427, at the request of the assembly, the Commune issued aid to the tune of 1,200 gold florins for the transept that was under construction, and appointed four new workmen. The formulation of the document merits special attention, because it contains proof (if more proof were needed) that the transept complex was not a new project, but a part that had been planned for some time by the church, and that had been started some time earlier. Moreover, the five chapels that were to form the "head" of the church are expressly mentioned here for the first time. So the foundations had already been laid for the substructure of the choir chapels. In addition, it seems clear that the footings for the sections of the transept erected prior to 1348 had already existed for some time. The first task of the two architects hired by the monastery on 14 June 1428 was to raise these footings to the level of the floor of the church. In December 1439 the architects were still busy working on reinforcing the vault of the substruction. The work was only completed the following year, and the open-air building site was initially covered over with a makeshift roof. Meanwhile – as of 1436 – in the area of the choir of the old church a crack had appeared in the wall, leading to fears that the triumphal arch might collapse, along with parts of the nave and the roof. Repairing this damage as soon as possible was the foremost task of

[68] The main sources for historical information on the church of Sant'Agostino are contained in Riedl and Seidel 1985-2006.

1440, since the desire was to avoid endangering the new part of the church. On 13 March 1486 the time finally came, the wall separating the old church from the new transept was demolished. As well as the dividing wall, the three chapels that in all likelihood formed the ancient presbytery also disappeared once and for all.

- Third construction period (1747-1755)

In 1596 Archbishop Ascanio I Piccolomini expanded the chapterhouse as a family chapel, and from this time onwards it was part of the church. A few years later, in 1619, the other windows of the church were also modernised, but most of these were probably only re-clad. In 1671 a double set of steps was built from the Prato di S. Agostino to Via di S. Agata. In 1706, perhaps not for the first time, the Augustinians decided to decorate the church with whitewash. In 1719, when a new landing was installed, the marble lining of the church's main doorway was relocated to the exterior instead of the interior wall of the façade. At the same time, repairs became necessary to the structure of the roof. In 1731 the roof was in danger of collapsing. The precarious condition of the roof trusses above the nave of S. Agostino forced the monks to take concrete measures to remedy the threatening situation once and for all. In the mid-1740s they submitted a petition to the Congregation of Cardinals in Rome for the approval and financing of an important restoration of their church. The project, directed by Vanvitelli, expanded Minacci's layout, especially incorporating the transept within the architectural order of the church. Thus, the transept would have had a barrel-vaulted ceiling and a crossing dome. In 1748 a number of pillars below the nave were reinforced in order to improve the foundations of the lower part of the church. In July 1748 Sebastiano and Giuseppe Minacci began to lay the foundations for the pillars of the cross dome and of the transept, which were to get a new vaulted ceiling. With the construction of the nave trusses, the transept and the dome, in the summer of 1755 the refurbishment of S. Agostino came to an end.

- Building work after 1755

After the refurbishment that was completed in 1757, the church no longer saw any major changes, and it remained essentially in the form it was given by Vanvitelli and Bibiena. The 1798 earthquake, which caused serious damage to the sacristy and to the Piccolomini chapel, caused less damage to the church itself. It left some lesions and deformations, but did not cause collapses.

3. The survey of the structure

The survey of the church of Sant'Agostino was conducted by means of an operational procedure determined by using the technology described above in section 3.4 for the documentation of the alleyways. What changed considerably in the analysis of this architectural complex was the application of laser scanners and photogrammetry both within and outside the structure, to get complete three-dimensional results that would allow preliminary considerations and evaluations to be made, with reference to the following: wall thicknesses; architectural elements and their interaction with masonry; and the complexity and discretisation of the patterns of cracks and deformations. To this end, specific analyses were conducted within the structure on the verticality of the columns, or the profile of the intrados of the arches, seeking possible indicators of disrepair witnessed by possible morphologies of these elements that were atypical or out of plumb (fig.4.24). The results of these analyses, largely involving the fact that the church was transformed internally in the Baroque era, were wholly negative, thus showing a substantial geometric harmony of all the structure's interior architectural elements. Meanwhile the same products as used in the analysis of Via Fontebranda and Via Pendola were created on all the elevations of the external portion, i.e.: orthophoto plans; architectural drawings with stratigraphic analysis by Masonry Stratigraphic Unit and crack mapping; elevation maps (fig.4.25); and maps of stratified damage.

These graphic renderings were essential for managing the large quantity of data produced by means of the archaeological analyses of buildings parts, and for integrating structural information (Cangi 2018) with stratigraphic information, in order to understand as well as possible the historical and construction dynamics that involved the church of Sant'Agostino over time.

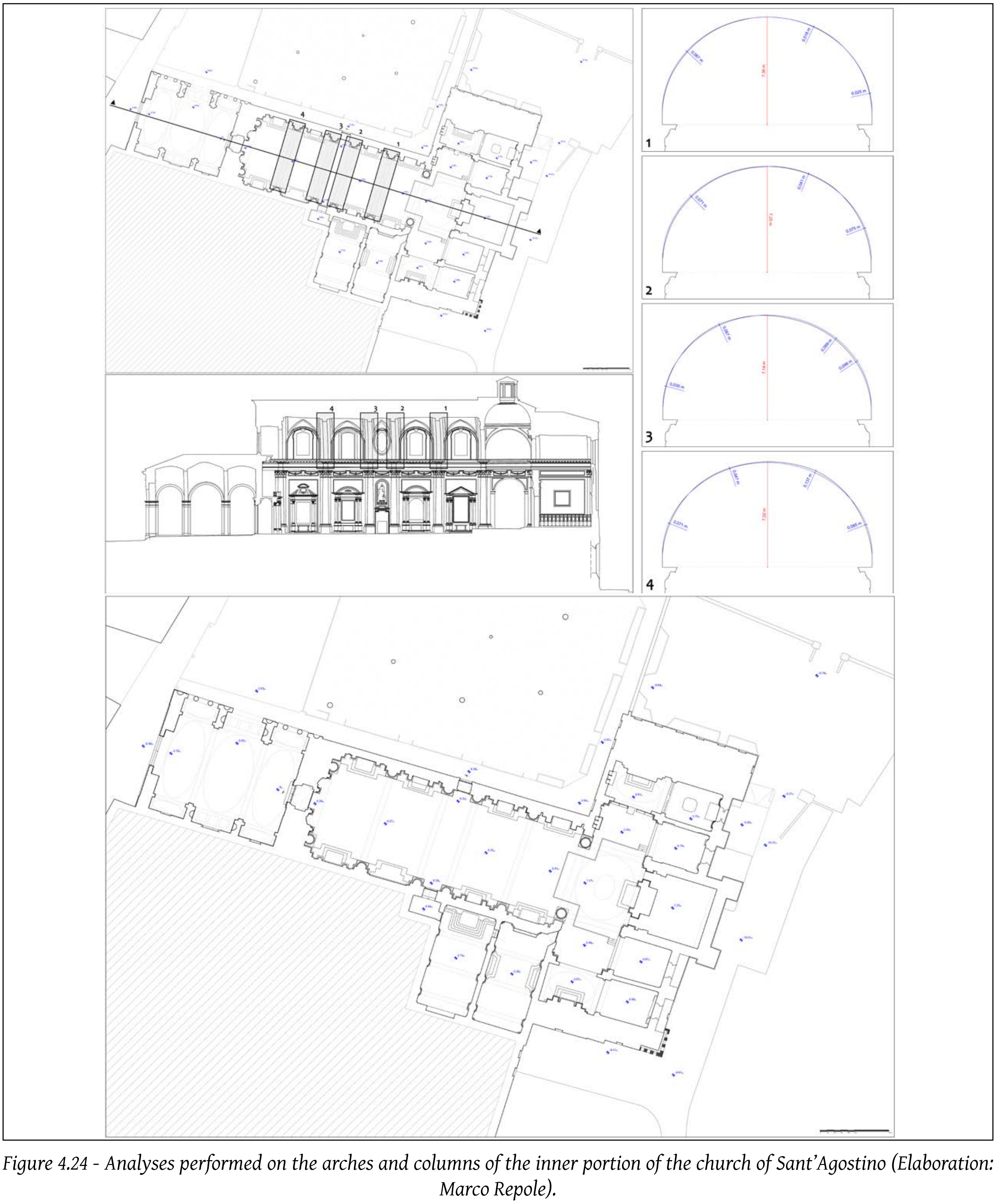

Figure 4.24 - Analyses performed on the arches and columns of the inner portion of the church of Sant'Agostino (Elaboration: Marco Repole).

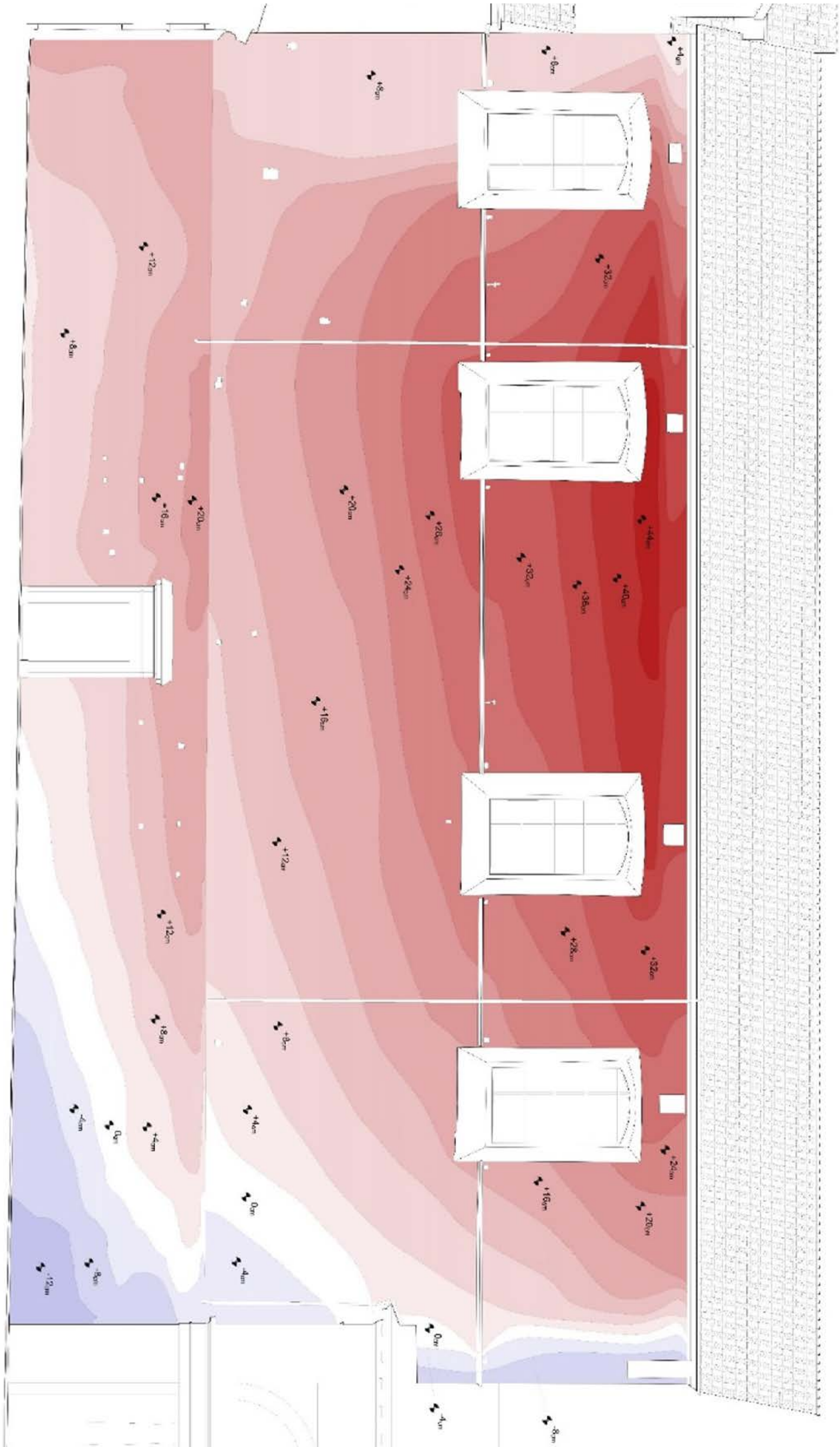

Figure 4.25 - Elevation Map of the northern external front of the church (Elaboration: Marco Repole).

4. The archaeological analysis of architectural parts

Archaeological analysis of the architectural features of the church of Sant'Agostino was initially conducted by breaking down the building's physical structure into its main Building Units (Corpi di Fabbrica, CF) (fig.4.26), complete with the stratigraphic relationships established between them. Thus the architectural complex appears as being formed of numerous individual building units. Two of these make up, respectively, the oldest religious building in stratigraphic terms (CF1) and the modern construction of the portico in front of the main façade (CF2), while three constitute the cloisters situated in the area south of the church (CF3, CF4 and CF5) and, lastly, a final unit consists in a tower-shaped building (CF6) standing at the intersection between CF3, CF4 and CF5.

Setting out from this initial subdivision into Building Units, the next step was to conduct a detailed analysis by Stratigraphic Masonry Unit (USM) of the oldest complex, namely the church (CF1). The analysis was conducted on the exterior masonry (fig.4.27), since the internal portion was rebuilt in the Baroque period, and was completely covered in plaster. This operation allowed us on the one hand to understand all the construction and destruction dynamics that have affected the church over time and, at the same time, to distinguish the main masonry construction techniques used in the various historical periods.

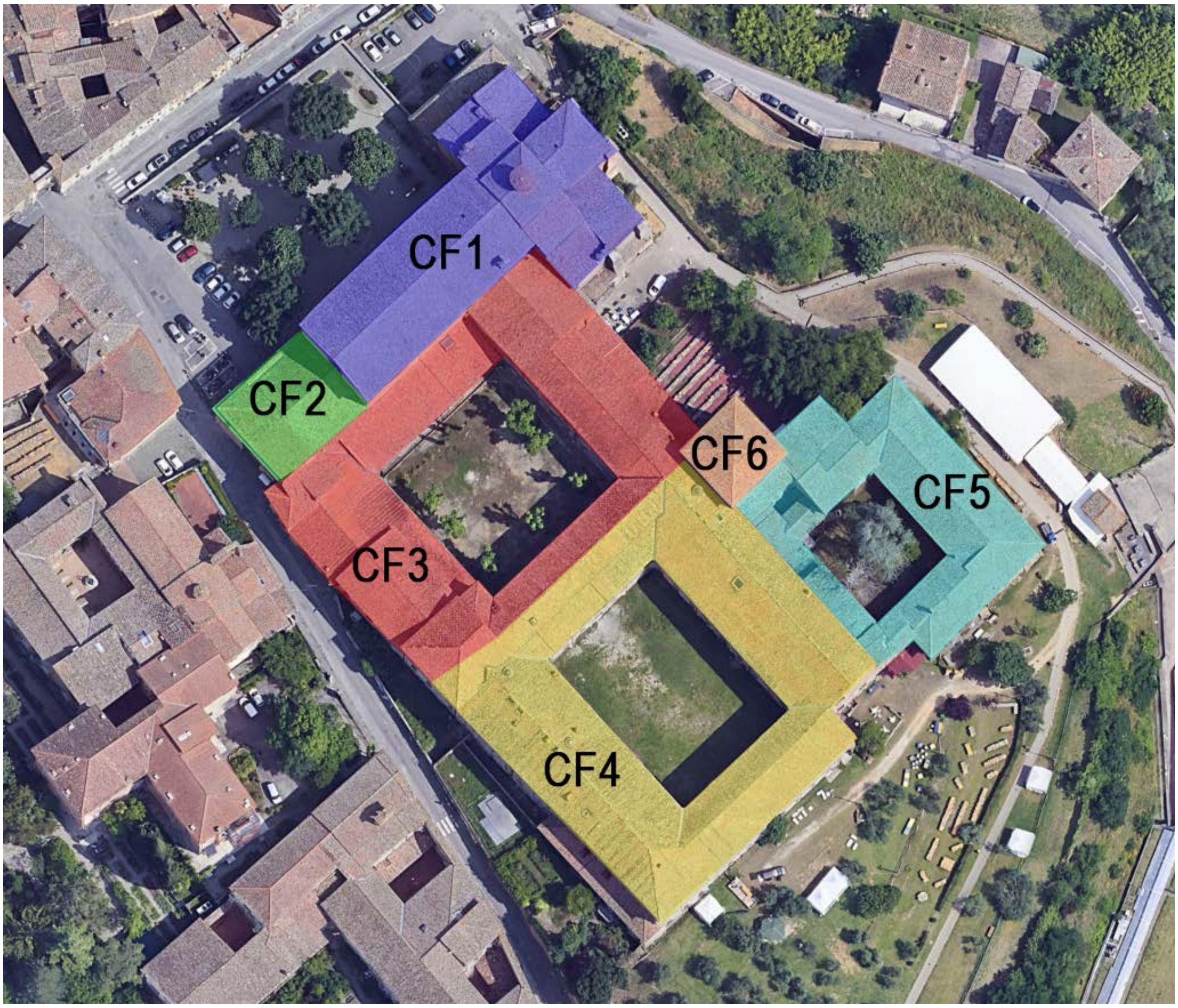

Figure 4.26 - Subdivision of the architectural complex into standing buildings.

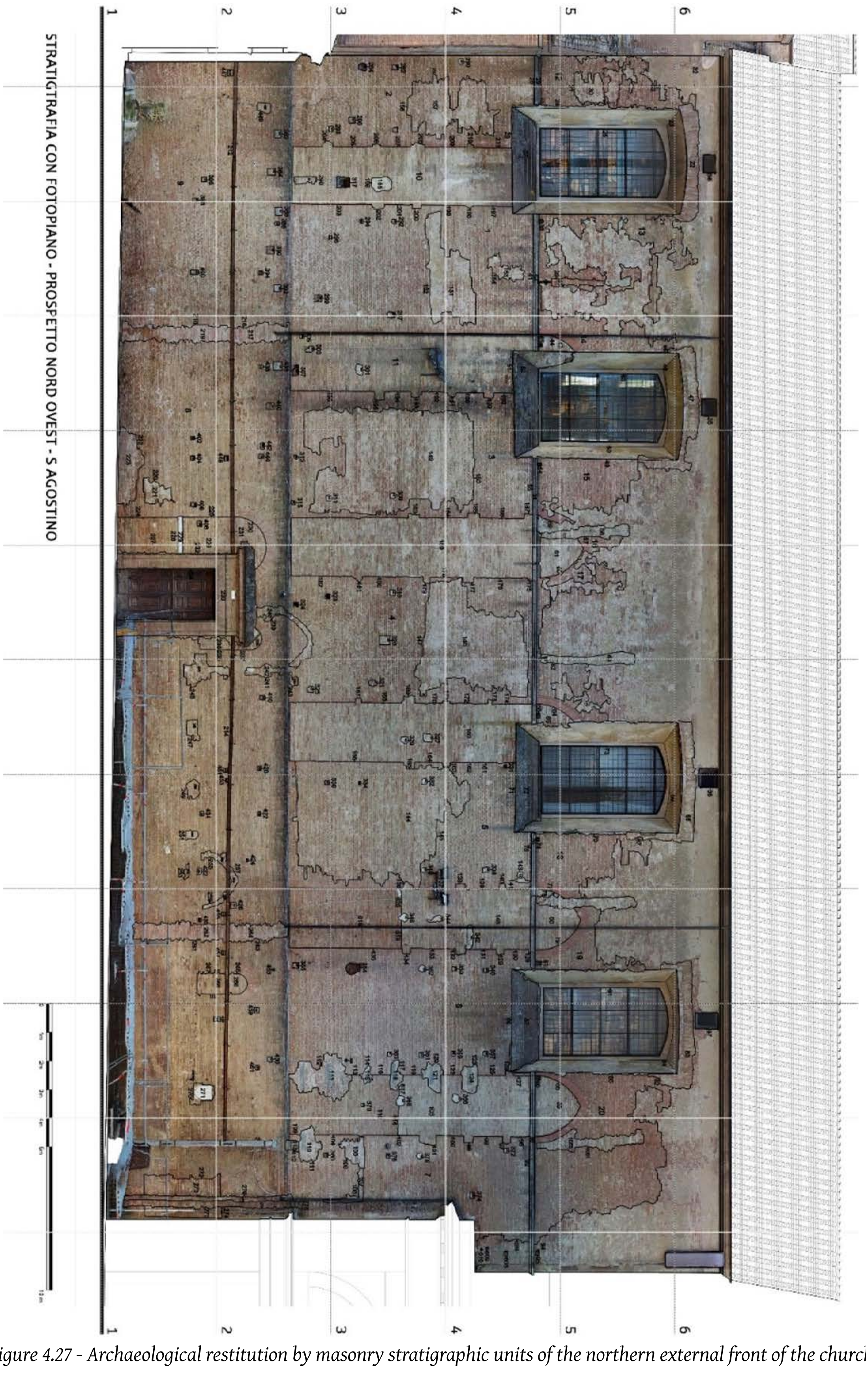

Figure 4.27 - Archaeological restitution by masonry stratigraphic units of the northern external front of the church.

Numerous construction phases emerged from the USM stratigraphic analysis. Together with the information deriving from the analysis of indirect sources, these allowed us to put forward the following construction history for the building, divided into general macro-periods (fig.4.28):

- Period 1 (1259-1292): in this period, we see the construction of the first version of the Sant'Agostino monastery. In archaeological terms, this period comprises phase 1 (pre-1259) and phase 2 (1259-1292) of the archaeological analysis, consisting in the creation of the new religious building (phase 2), incorporating the remains of the earlier structure, Sant'Agata (phase 1). The new building features six large windows surmounted by ogive arches on the north-west side, and a side door with a semi-circular arch. Furthermore, it also features a transept, which in the 13th century was perhaps partly unfinished, as borne witness to in written sources. In its western section this has a large window that matches those in the aisle. In the portion of the old church of Sant'Agata, in the area of the transept itself, there is a doorway with an ogival arch that has a decorated extrados.

- Period 2 (1374-1408): In this period we see probable completion of the area of the church transept that was later expanded in the subsequent period.

- Period 3 (1427-1486): In the third period, we see the construction of the choir and of the apsidal portion of the church, built using masonry featuring large-scale corner counterforts.

- Period 4 (1747-1798): In the period associated with the 18th century we have evidence of large-scale transformations of the uppermost part of the church, with the construction of a roof raised above the level of the previous roof, above the choir, and the construction of the dome that is still visible today. In addition to these new constructions, changes were also made to the structure both before and after the 1798 earthquake: numerous windows were blocked up or reduced in size; bonding stones and anchor plates were installed; and one bay was removed in the front part of the church, with the construction of a new façade.

- Period 5 (1818-1820): Dating to this somewhat short time period is the construction of the Collegio Tolomei, with the loggia built up against the façade of the church, at the same time as the bell-tower of the church of Sant'Agostino was demolished, since it was in a precarious state of conservation.

- Period 6 (20th century): the final period covers the transformations that took place in the church in the contemporary era by means of targeted operations in specific points of the structure, which do not however alter its general appearance.

In addition to these periods, there are a number of localised alterations to the building. In some cases, these interventions can be dated specifically, while in other cases they lead to the definition of broader timeframes, or ante quem or post quem terminuses. In the first instance, also comprised may be operations involving alterations to the size of some large windows in the apsidal section, testified to in 1611. By contrast, the construction of a probable aedicule shrine on the north-western lateral façade is to be ascribed to a broader time period, or a period that is hard to place precisely, as is the partial obliteration of the first two large windows near the façade, blocking up as much as half their original size.


PRE 1259
1259 - 1292
1374 - 1408
1427 - 1486
1611
1747 - 1798
1798
1818 - 1820
XX SEC
POST 1798
1259 - 1747

Figure 4.28 - Restitution of the exterior fronts of the church by construction phases.

5. Results

The church of Sant'Agostino is a very interesting case study when it comes to reconstructing medieval and post-medieval construction schemes in the city of Siena, since it offers almost total legibility of the building's external masonry parts. Moreover, the possibility of referring to multiple indirect sources that tell us about details of the main construction projects and alterations to the fabric over time, be they written, photographic or iconographic, provides us with a specific chronological detail that gives us vital help in dividing the building phases identified by archaeological analysis into periods. This factor is crucial, since it offers us the chance to reconstruct, albeit in broad terms, the morphology and characteristics of the external portion north of the structure in a period ranging from the 15th century to the present day.

Finally, by combining the information from archaeological analysis, from the typology of construction techniques, and from data obtained from the 3D survey renderings, it was possible to obtain data of interest regarding the building's seismic history, namely how it behaved in the wake of specific seismic events (fig.4.29). Indeed the analysis revealed quite clearly that, despite standing in an area that has been especially affected in its history by damage and disrepair of seismic origin, at least up until the 1798 quake the building had never experienced problems associated with such events. For the 1467 earthquake, as is the case with most of the religious buildings in Siena's original city centre[69], neither written sources nor analysis of its walled features show damage or disrepair caused to the church by the event. The 16th century earthquakes also do not seem to have led to particular damage to the architectural complex. This finding also needs to be viewed in reference to the completion of construction of the rear portion of the building (transept and choir), which features numerous corner buttresses which considerably reduced its vulnerability to problems of a static and seismic nature. By contrast, the 1798 earthquake seems to be the only quake that caused any actual damage to the building. The written sources, primarily, contain the most precise information, with specific references to renovation work on the roof, and the construction of the new dome, and other restoration interventions carried out to various parts of the structure (fig.4.30a-b). In addition, the effects of the earthquake are borne witness to by a number of specific structural expedients added to the building itself, such as: the use of bonding stones to secure the material used to fill in the 13th century windows, and prevent it from becoming detached; the infilling of numerous windows; and the implementation of anchor plates positioned in line with the springers of the internal arches.

The analysis of the church of Sant'Agostino thus enabled interesting findings to be made with reference both to the individual case study and to the whole context of analysis, going on to supplement the information compiled by other analyses conducted by the PROTECT project in Siena's old city centre. In particular, the church's detailed construction history revealed a number of specific construction- and destruction-related dynamics of the building in relation to the individual seismic events. This led to further thoughts on the impact of the historical earthquakes that have taken place in the context of Siena ever since the 13th century, the year when the building was built, with special interest in the events of 1467 and 1798, both years being the subjects of study under the PROTECT project. For these two events, as stated earlier, the church responded in a range of differing ways: no damage or disrepair for the mid-15th century quake; and extensive damage and implementation of specific post-seismic building features for the late 18th century event. If we correlate this finding with the findings that emerged from the analysis of Siena's historical centre at the macro-area level and involving steet fronts, the finding from the Sant'Agostino analysis begins to take on highly interesting historical connotations. Indeed, as suggested by the integrated analysis of the archive documentation, and documentation of material findings, the entire old city centre of Siena seems to have responsed in a very different way to the seismic stresses

[69] This statement is correlated with information given in the literature, and from studies carried out thus far on the city of Siena. We may choose to change it following further archaeoseismological research on the religious buildings in Siena scheduled for the near future.

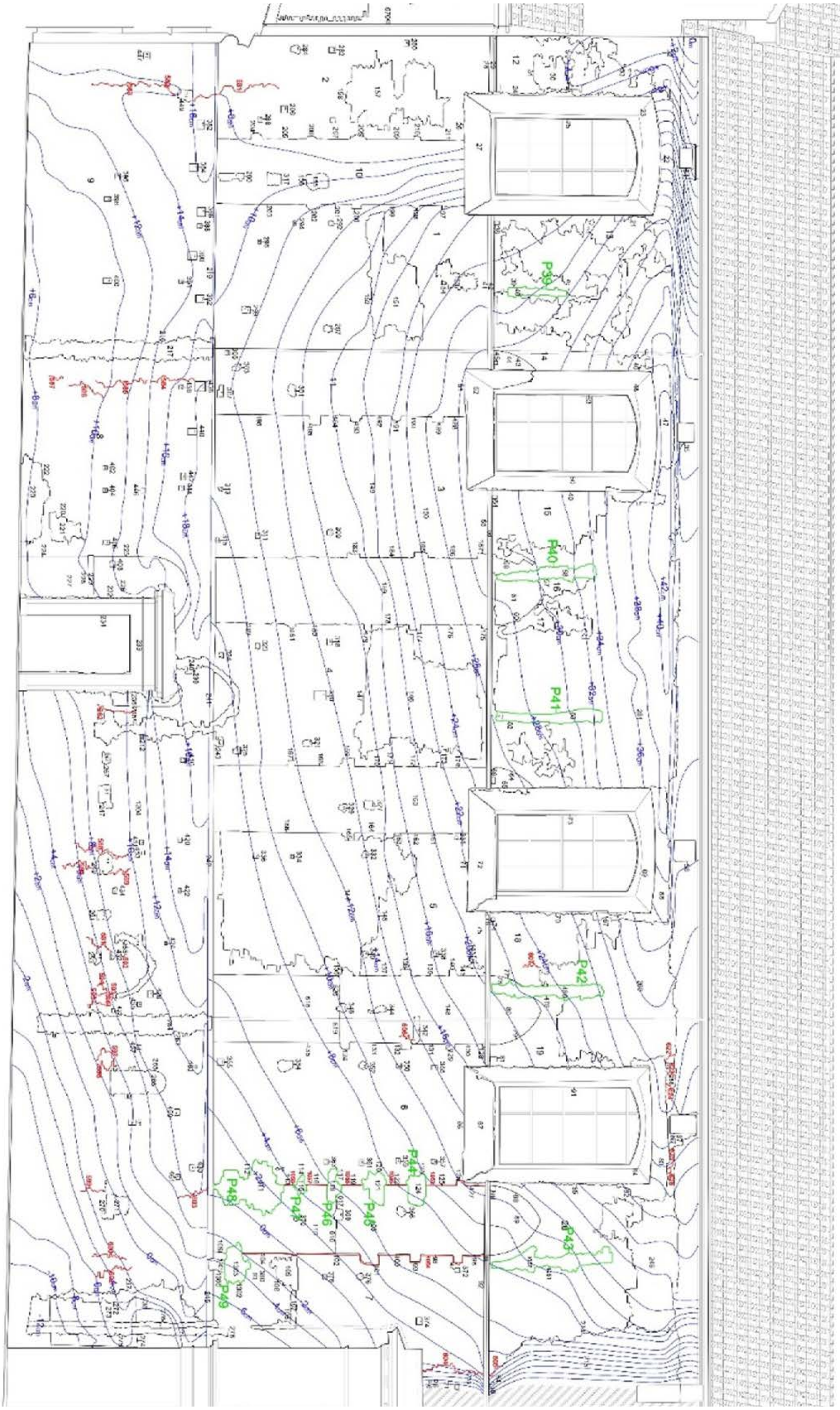

Figure 4.29 - Stratified instability map of the northern external front of the church created by superimposing: deformation framework (in blue), crack framework (in red), stratigraphy (in black) and post-seismic construction techniques (in green). Elaboration: Andrea Arrighetti and Marco Repole.

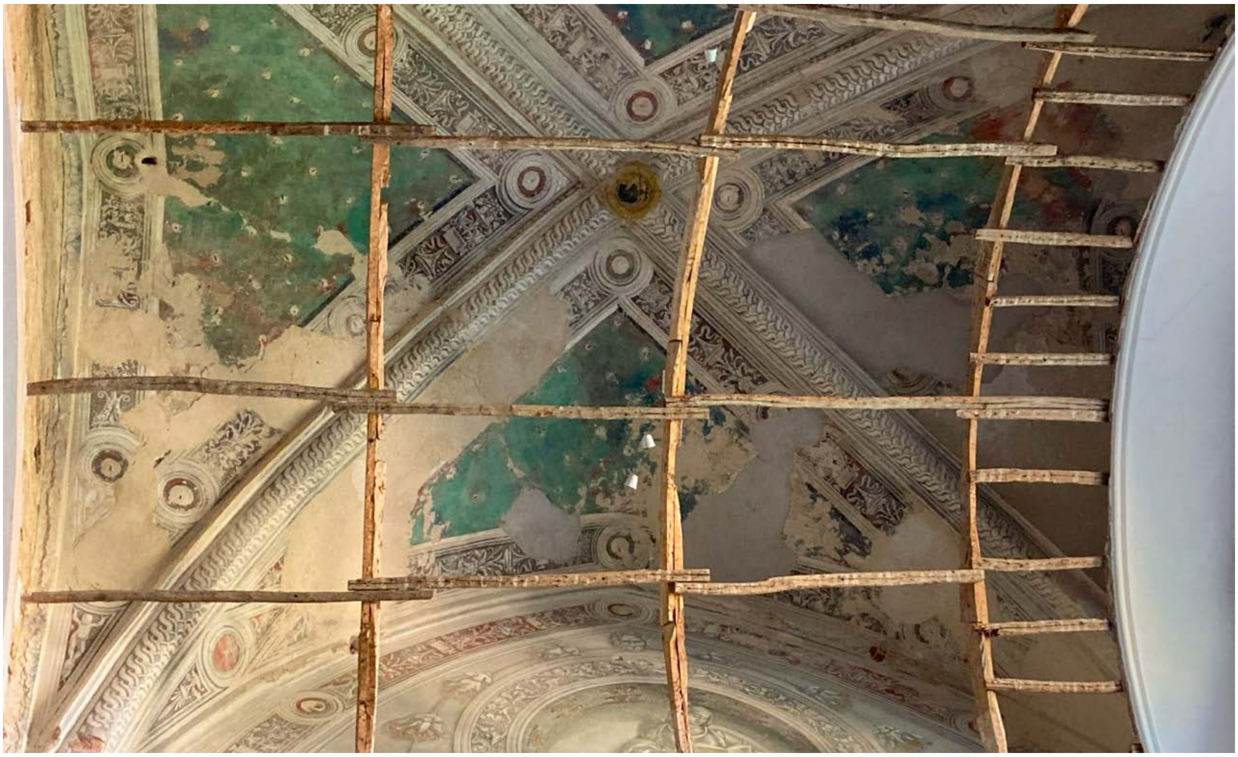

Figure 4.30a - Detail of a false vault made after the 1798 earthquake.

from the two main events described earlier. For the 1798 event, the architectural complexes that stand within the city's outer walls seem to be struck in their totality, with a range of damage and disrepair that differs depending on the state of conservation of the buildings, the construction techniques used, and their location in the old city centre[70]. In this instance, the church of Sant'Agostino tends to confirm this fact, displaying clear disrepair located on all sides subjected to structural analysis. For 1467 the findings from Sant'Agostino seem harder to interpret, since, despite the fact that earthquake caused extensive damage and disrepair throughout all the historic centre, the damage testified to by documentary and iconographic sources, and also by the analysis of some street fronts, no signs of the quake appear in the religious building or in the documentary sources that mention it. This appears even more interesting if placed in relation to the lack of evidence of post-seismic effects in all the other religious buildings in Siena's old city centre (Riedl and Seidel 1985-2006) and at Palazzo Pubblico, the main public and civic building, the seat of the Commune. All this therefore gives even more support to the suggestion that the difference in the contexts struck by the 1467 earthquake appears to be connected to the extensive, large-scale removal of the balconies which occurred in Siena in the mid-15th century, an operation that made the building involved in the intervention extremely vulnerable, and thus subject to disrepair and collapses following even low-energy seismic events. In this, the church of Sant'Agostino, devoid of balconies, in common with Palazzo Pubblico and the other religious buildings in the city centre, did not apparently see a sudden increase in its vulnerability, allowing it to react as well as possible to the 1467 earthquake, which was low-intensity but still probably having a great impact on private civil buildings in the centre of Siena[71].

---

[70] For more details of the 1798 earthquake and its effects on the built structures in the city of Siena, reference may be made to: Gennari 2005.

[71] Regarding this last hypothesis, we are conducting further, targeted investigations within the old city centre to understand the real impact of the 1467 earthquake on the historical centre.

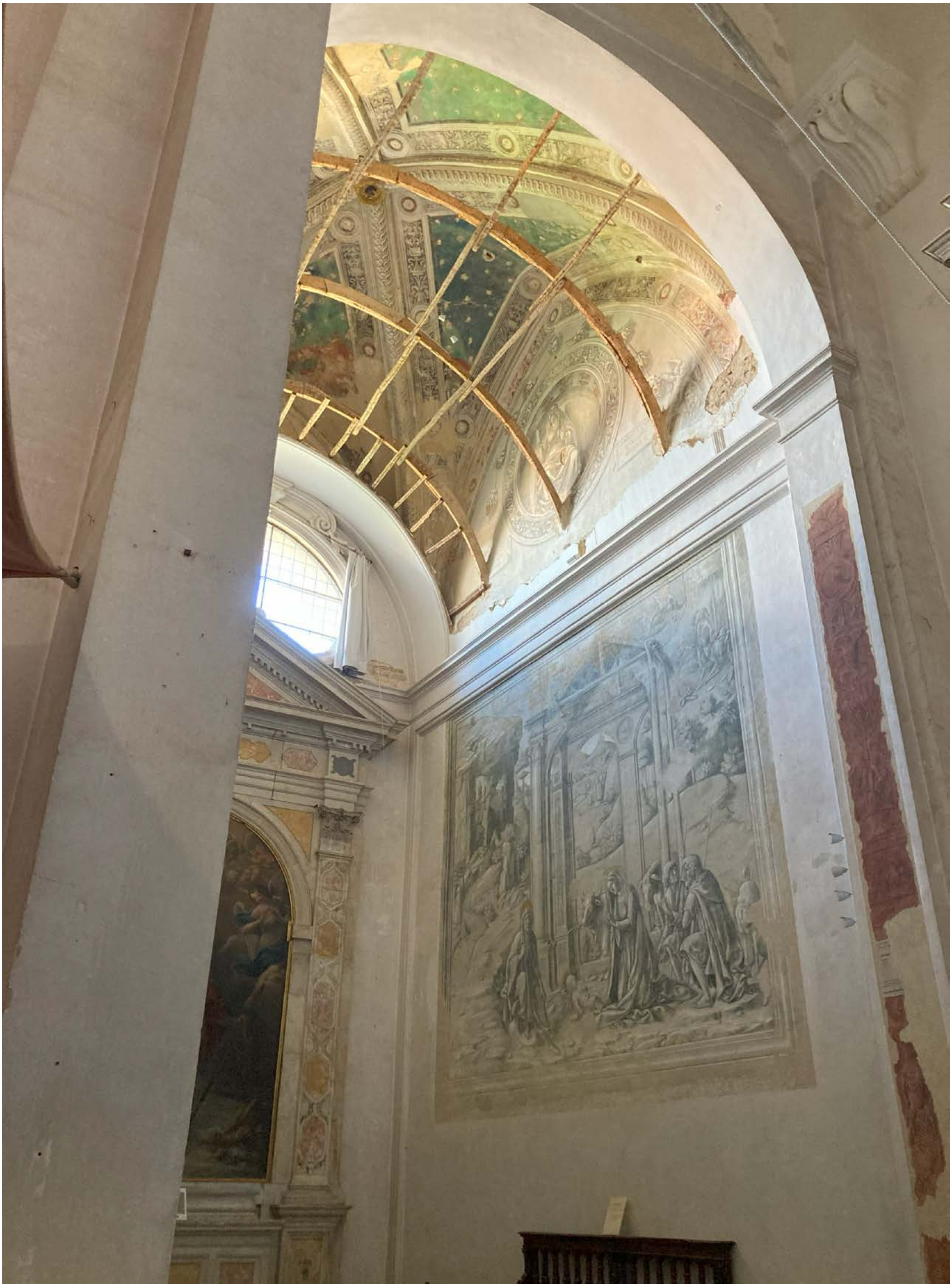

Figure 4.30b - Detail of a false vault made after the 1798 earthquake and subsequently brought to light during the latest restoration work on the structure.

CHAPTER V

First steps towards an operational protocol for historic city centres

5.1 The analysis protocol

The work conducted under the PROTECT project has made it possible to develop guidelines with a view to putting forward an archaeoseismological operational protocol for analysing an historic town centre. This process involves three specific levels of detail, closely described in the previous sections, but it is worthwhile summing them up here both regarding their methods and the results advanced.

Level 1

The first level of the overall investigation is the analysis of Siena's old centre, in which the old city centre is regarded as a single, unified organism. This analysis has in turn seen a dual criterion of investigation: an historical analysis focusing on the dynamics associated with the 1467 earthquake; and a second, archaeological analysis involving documentation of construction systems that can probably be related to seismic events, and their classification as chronotypes.

Regarding the first analysis (fig.5.1), the project concentrated on the proposal to compile a thematic map, subsequently transferred to a GIS, onto which were entered data relating to the actual state of the city of Siena in 1468, a year after the earthquake of 1467. Following an initial bibliographic survey of the main evidence relating to the seismic events that affected the Siennese context, the work went on to explore in more detail a specific archive source that is unbelievably rich in information of interest, namely the 1468 Lira tax records. This series of documents made it possible to provide a very precise insight into the state of conservation of the buildings found in the various 'Popoli' of Siena in that specific year. The information garnered from this analysis presents a picture of a city in a profoundly critical condition, with clear signs of damage to the buildings that formed its basic urban fabric, in some

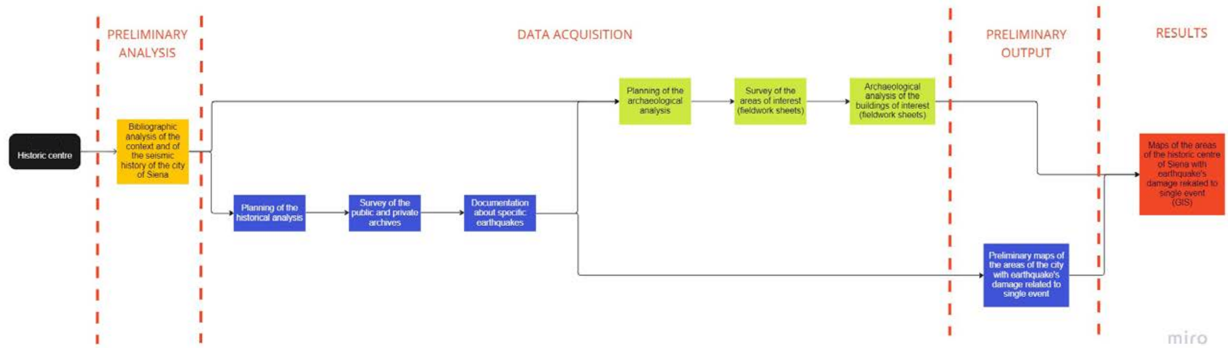

Figure 5.1 - Flow chart illustrating the conceptual framework underpinning the Level 1.1 of the macro-analysis of the historical centre of Siena.

cases with whole neighbourhoods having been evacuated in what we might today call a "red zone". This information thus formed the basis for addressing detailed but rapid archaeological analyses of specific architectural complexes, serving to check whether the information given in written sources could also be seen in the stratigraphy of the actual buildings. The results of the investigation, obtained by comparing archive data and archaeological data, allowed us to form interesting conclusions regarding the characteristics of the individual seismic event, probably not a high-magnitude event, and regarding the possible interaction between the numerous reports of collapses and disrepair found in the sources, and the high vulnerability of the city's old buildings. Indeed, the built heritage in the historical centre, as well as featuring large areas with problematic features in terms of construction and conservatiom, had been further weakened by the enactment of the measure to eliminate balconies, issued a few years earlier. Since, in the case of many buildings, these balconies were structural features serving a static function, once eliminated they had a highly negative impact on the response of buildings to seismic stresses, and thus on their vulnerability, thereby ultimately amplifying the real effects of an earthquake that, under normal conditions, would only have had mild effects, or none at all.

The second part of the project at the macro-area level takes the form of an extensive archaeoseismological analysis applied to the Terzo di Città area of Siena's old city centre, aimed at recording, documenting and typologising construction elements with characteristics that could be assimilated with post-seismic features and safeguards (fig.5.2). The decision to focus the analysis on the Terzo di Città was made because this area, according to the sources listed in seismological catalogues, and the results from the historical study described above, was recorded as having the largest number of effects of damage and disrepair on the buildings, correlating to the 15th and 16th century earthquakes. Given the fairly large size of the area and the wealth of well-preserved buildings of medieval origin, the fieldwork was based on a first-hand analysis of the safeguard interventions, correlating these to the local construction features. In operational terms, we opted in favour of using instrumentation and methods associated with the archaeology of architecture and the more recent discipline of archaeoseismology, as being those best suited to identifying these aforementioned interventions, and producing a typology of them. Once the features were recorded by means of surveys, on-site documentation and photographs, the next step in the investigation involved recording and geolocalising all the data acquired on a database on the GIS platform. The possibility of mapping and presenting the features that emerged from the survey on a cartographic base enabled numerous considerations to be made. Some of these were specific and closely connected to historical and architectural data, while others had to do with the characteristics of the subsoil, and the lie of the land in the urban centre itself. What immediately stands out is that there are specific areas in which these architectural safeguards are used, which can probably be ascribed to the zones where the effects of earthquakes or of other structural problems are especially amplified, as for example in the area behind the Cathedral, or in the Castelvecchio zone. Another point to be borne in mind, with reference to the features that emerged in the course of the investigations, is the probable precarious state of conservation of some buildings, a fact that definitely influenced the formation of building parts that were structurally compromised (of both natural and structural origin) that was

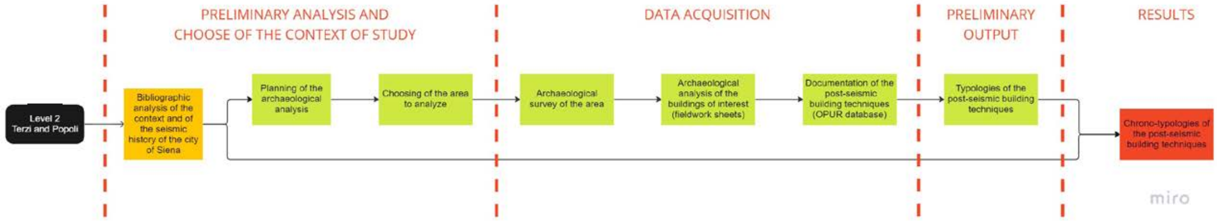

Figure 5.2 - Flow chart illustrating the conceptual framework underpinning the Level 1.2 of the macro-analysis of the historical centre of Siena.

behind the decision to use particular protective expedients for the structures involved. Finally it seems interesting that the findings for the use of some expedients rather than others allows us to understand the likely close correspondence between a given intervention and a given earthquake, thereby allowing us to formulate a number of hypotheses regarding the use of specific expedients for set chronological timespans.

Level 2

Moving on to the medium level of analysis, an attempt was made in the project to develop some predefined lines of analysis that would be useful both for a knowledge of the history of the study context and for its documentation, with a view to planning and design operations for prevention against seismic risk (fig.5.3). One of the first products associated with these approaches to intervention is rapid archaeoseismological analysis, ie. an archaeological study that allows a sufficiently detailed knowledge of the construction history and mechanical component of multi-layered units, such as street fronts built along alleys, but which also offered, at the same time, a database for formulating concrete suggestions regarding their state of conservation. Subsequently, two specific areas of the city were identified: Via Pendola in the Terzo di Città, and Via Fontebranda, limited to the section from Via di Città to Via Diacceto, in the Terzo di San Martino. These are sections of street fronts, around 100 mt in length, where several different methods of data acquisition, and palimpsest analysis, were tried out. As regards recording the information, we made use of a range of technologies in order to understand which of these was best suited to the goals set by this phase of the project. Accordingly mobile and traditional terrestrial laser scanners were used, along with a photogrammetry survey conducted by means of ground-based and drone-based acquisitions. In around 20 days of work in total, a team consisting of three people produced a map of the complete geometry of the street front, as well as an analysis of the same from the point of view of archaeology, materials and construction.

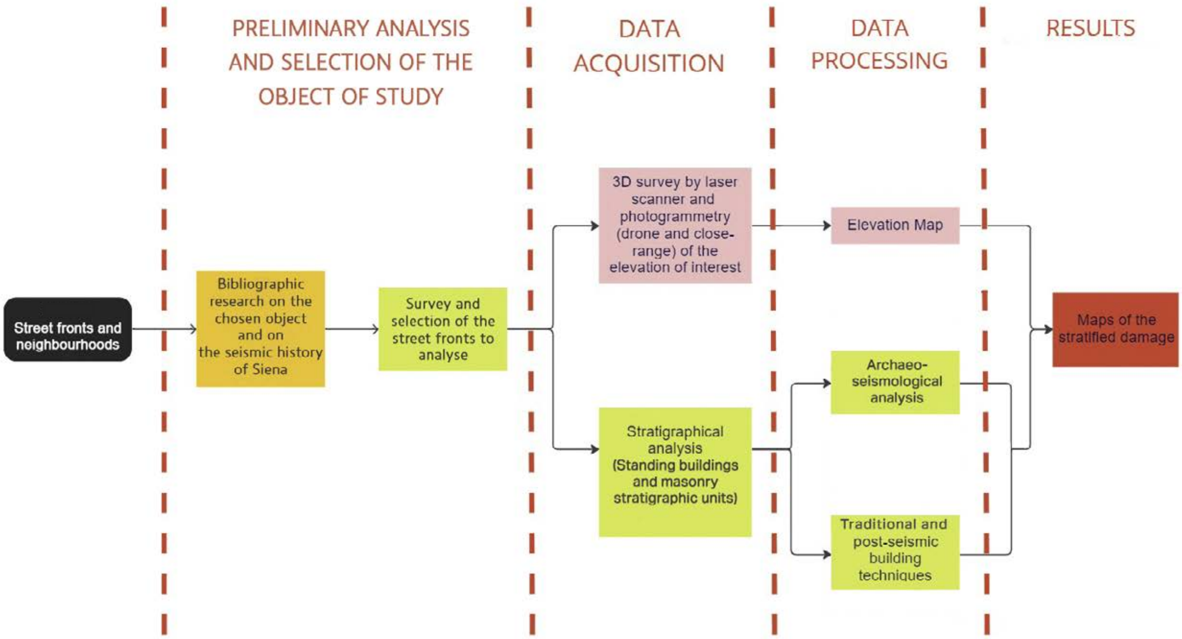

Figure 5.3 - Flow chart illustrating the conceptual framework underpinning the Level 2 of the medium-analysis of the historical centre of Siena: the expeditious investigation of street fronts.

Then the patterns of cracks and deformations were documented, as were the stratigraphy, and traditional and post-seismic construction techniques, by means of digital and hard-copy supports. In addition, a check was made on the quality of the information extrapolated from the survey by comparing it to a range of different acquisition systems. The possibility of having recourse to surveying technologies for point clouds enabled an accurate three-dimensional recording of buildings, proposing a characterisation and documentation of some kinds of disrepair, and monitoring of the structural problematics present in the physical structure of buildings. This type of information was later integrated with the large amount of information deriving from archaeoseismological analysis. This operation was translated into a process focusing on a profound knowledge of the built feature being examined. The result was the determination of the construction and mechanical history of each street front, accompanied by its seismic history. But how could all this information be encapsulated in one rendering? The goal ought to be to succeed not only in periodising the construction and destruction phases present in the buildings, and to draw up a structural analysis of these (Cangi 2018), but also to integrate this information so as to put forward a periodised characterisation of the traces of disrepair that have taken place over time in the building, and that are still in progress, placing the findings in relation to the historical and seismological documentation of a certain area. Using the data in our possession, and the documentation produced by several types of analysis, this process was later translated into the generation of "stratified disrupture maps", i.e. renderings that combine an archaeological analysis of the building with its main signs of disrepair, consisting in the system of cracks and deformations. However, unlike classic archaeological or structural analyses, in the aforementioned representations attention was also placed on the question of "when" the disrepair first appeared, and on its relationship with the stratigraphy present in the monument. What sprang from this was a periodised analysis of the physical components of the structure, which provided our experts with essential data, both as regards the chronological aspect (when an impairment was formed, or was transformed), and as regards interpretation (what are the causes that led to the formation of the disrepair), as well as the operational aspect (the disrepair is still under way, or there are factors that have led to it having a new static equilibrium). Thus, the "stratified disrupture maps" constitute a palimpsest of information of various kinds (historical and archaeological, architectural, structural) that are closely intertwined, proving to be highly important elements as an informational base, both for historical and archaeological activities and for technical and planning decisions.

Level 3

A final level of analysis, which we might call the micro-level, as it is deployed on individual architectural complexes (fig.5.4), is the level applied to the church of Sant'Agostino. This church is one of the most important religious monuments in the city of Siena. The building boasts a long-standing history that stretches back to the 13th century, to be precise 1259, the year when there is a report of the monastery's foundation stone being laid, in an area where it is known the former church of Sant'Agata was already standing. During construction work on the new religious complex of Sant'Agostino, this church, which was in a precarious state of conservation, was incorporated within the rear part of the building and in the new crypt, effectively forming a single architectural complex. In topographical terms, the church of Sant'Agostino stands in the Terzo di Città which, as stated earlier, was the area in Siena's old city centre which written sources tell us was one of the zones with the highest incidence of recorded damage and disrepair of telluric origin, with special reference to the seismic periods that marked the 14th, 15th and 18th centuries. Sant'Agostino presents numerous indirect sources that inform us of its past, some of which are chronologically detailed and rich in information. This is the case with iconographic sources, first and foremost views of the city of Siena. In these, as of the 15th century, the church stands out clearly, since it was surrounded by a clear space that enabled it to be seen in its complete form.

Alongside these depictions we also have many written documents detailing the operations forming part of the main construction phases of the religious complex. In addition to the indirect sources, a stratigraphic analysis was conducted of each of the building's elevations. Using a 3D architectural survey, this was placed in relation to the morphological complexity and complexity of construction of the church in its entirety. This allowed an evaluation of any features of disrepair or damage found inside the structure, and stratigraphic findings, documentary sources, the iconography and considerations involving building history were placed in relation to each other. This process enabled numerous construction phases to be suggested, characterising the building's construction history, and seismic history, divided by fixed macro-periods. This work meant that it was then possible to reflect in detail, and in a concrete way, on the effects of historical earthquakes on the physical make-up of the whole building. What was deduced from this is that, from the archaeoseismological viewpoint, the research findings showed a total absence of damage or disrepair relating to the 1467 earthquake, as opposed to a fairly major presence of reconstructions or specific interventions in the wake of the 1798 earthquake. Also for the other earthquakes that struck Siena there does not seem to be damage or disrepair that can be ascribed to those events.

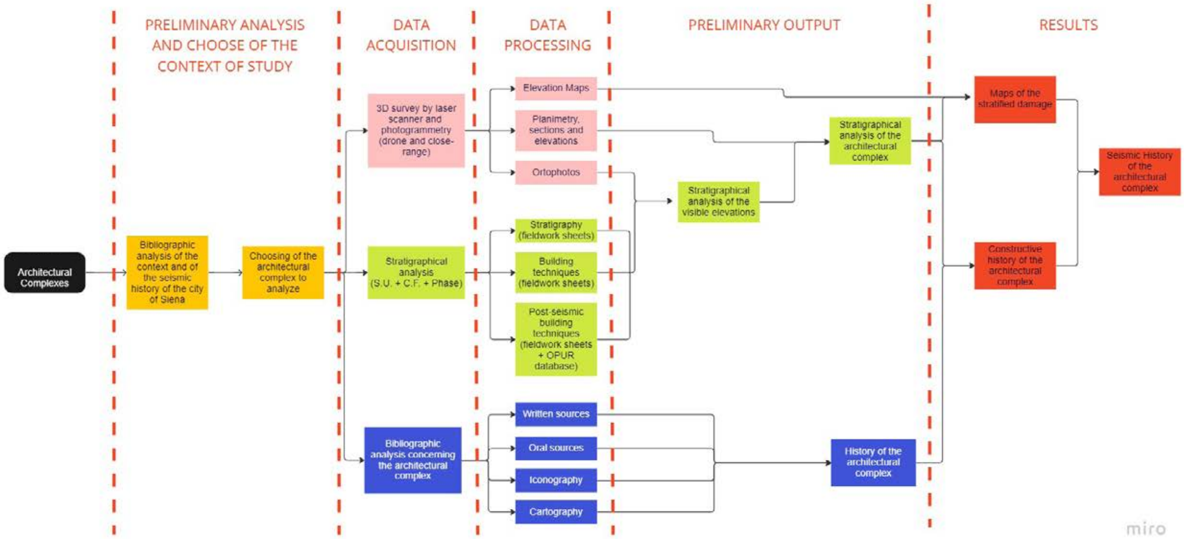

Figure 5.4 - Flow chart illustrating the conceptual framework underpinning the Level 3 of the micro-analysis of the historical centre of Siena: the architectural complexes.

Results

The operational procedure described has thus highlighted a number of interesting aspects connected both to the opportunities offered by the application of the archaeoseismological method to the data acquisition analyses in historical town centres for the prevention of seismic risk, and to the possibility of further developing this project, which is highly multidisciplinary, to other sites nationally and internationally. Following the the 1467 earthquake as a common thread, and the brand new historical and archaeological information obtained by the analysis of archives and of the urban fabric of the city of Siena in its complexity, we went into more and more depth in the search for clues and evidence that might provide data in addition to the data already in our possession. In this way, and as a result, analytical methods were developed based on techniques and technologies that were different, but also at the same time open to being integrated together, so as to enable the old city centre, or parts of it, to be viewed and interpreted from various points of view, but always through an overall, integrated lens.

In operational terms, what emerges clearly is the project's substantial financial sustainability. From the proposed analyses and results, it seems clear that a team made up of six people[1], in around a year or perhaps less[2], may be able to accomplish all the levels of examination and exploration described above, scheduling, as and when, along the way, the necessary adjustments in the level of knowledge of the study contexts. In addition, the techniques and technologies used offer an opportunity for several professionals, with differing specialisations, to work contemporaneously on more than one dataset, both raw data and final renderings. This enables the project's timescale to be shortened further, providing preliminary and definitive results hand-in-hand with the development of a range of analyses.

The proposed procedure, integrated with seismological, geological, architectural, planning and engineering analyses, is thus essential in scheduling both architectural and urban interventions, constituting important steps in the research projects, as well as in the development of strategic plans aimed at safeguarding the built heritage, and people's lives, too.

5.2 Validation of the method: Siena and the 2023 earthquake

Following the seismic events that struck the city of Siena in February 2023, the project had an opportunity to be put to the test. This test, conducted by means of a process of reviewing the sites involved in the previous analyses, took place one week after the quake, later comparing the findings that emerged from the two investigations. In operational terms, in 2023, in order to obtain a series of findings that were as much in line as possible with the 2022 survey, the same instruments and the same operational protocols were used, adopting an acquisition process such as to ensure total consistency between the two projects. In addition, the same procedure was used in the data editing phases. Once the renderings obtained by the two surveys, which featured perfect geometric and structural consistency between them, were generated and compared, a number of interesting variations were suggested and taken on board. Here below we show a number of preliminary considerations involving morphology and regarding stratigraphic evidence[3].

If, for example, we focus on the section of street front in Via Pendola, although the most important tremor was of a fairly low magnitude (around 3.7 Mw), across the whole elevation we note in general an accentuation of most of the previous deformations, and, in some cases, it is also possible to observe a change in the isostatic pattern (fig.5.5). Specifically, we note a number of points that display extremely interesting transformations, such as, for example, along CF2 at the level of the third order of windows, where we see a clear increase in the deformation at a point coinciding with the load-bearing wall, with a total movement of around 6 cm. A similar widening can also be seen in a particularly extensive point at the level of the footing of the front, near the anchor point between CF2 and CF3. Also along the bottom part of the front, at the line of contact between CF3 and CF4, there is an increase in the deformation of around 4 cm. As regards CF4 and CF5, where the movements do not seem to be particularly marked features of the low section of the façade, it is clear that the presence of the preexisting counterfort help to combat possible buckling of the façade.

---

[1] The team consisted in: two archaeologists, a historian, a seismologist, a surveyor and a structural engineer.

[2] At present it is difficult to determine precisely how long it may take to conduct an analysis such as the one conducted in Siena's old city centre. Indeed, since it is an experimental project, much research time was taken up in trying out and evaluating the best operations to be carried out. Calculating three months for the analysis of the 100-mt street fronts of two alleys, three months for the analysis of an architectural complex in its 3D form, and six months for bibliographic and archive analysis, and archaeological survey of the buildings in the entire historical centre with the creation of a GIS, we can estimate the total duration of the work as lasting one year.

[3] Most of the structural data and interpretations are currently being studied by a team that also includes structural engineers, architects and archaeologists.

As regards the church of Sant'Agostino, following the earthquake a detailed analysis was conducted of the preexisting deformations (fig.5.6a-b), with a view to evaluating them with reference to the stratigraphy and to the construction systems employed. Specifically, the map obtained by combining the pre- and post-quake deformation pattern, used as a graphic basis, and the stratigraphy, shows clearly two different dynamics which are subjected to stresses induced by the quake (fig.5.7a-b). One type relates to the implementation of deformations associated with pre-existing damage mechanisms, irrespective of the stratigraphic complexity of the structure, such as the deformation involving the upper section of the north façade, where the new isolines perfectly follow the geometry of the profiles of those identified in the pre-quake phases. A second type of deformation is associated with pre-existing features, or the clearest stratigraphic interconnections, such as the filling-in of the 13th century windows, where the isolines created by the new earthquake in contact with the stratigraphic interfaces are altered compared to the previous ones, tending to assume more pronounced features, linked to the stratigraphic complexity and to the new relationships that are present. In addition to this second example there is the infilling of the door on the ground floor, and the surviving portion of the old church of Sant'Agata. This church, incorporated in the 13th century in the construction of the new complex of Sant'Agostino, already displayed a pre-existing pattern of deformations compared to the one shown by the new church, which later developed autonomously with the seismic event of February 2023.

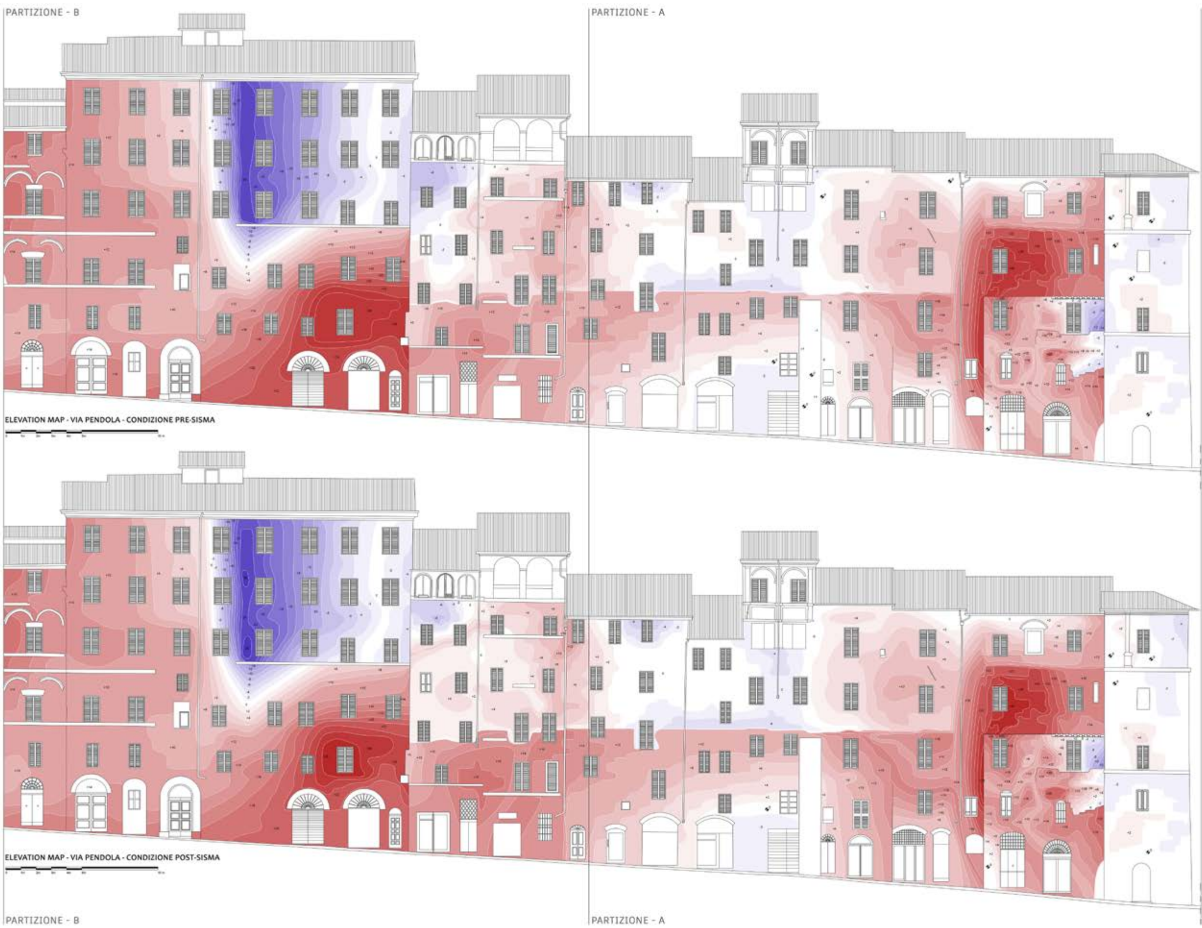

Figure 5.5 - The image shows the differences between the deformation framework of the street front of Via Pendola before (top) and after (bottom) the earthquake of February 2023. (Elaboration: Marco Repole)

The earthquake in Siena in February 2023 thus made it possible to reflect in depth, setting out from a diversified set of records consisting in an architectural complex analysed in its full complexity, and also represented by a street front documented only as regards its exterior walls, on the opportunities offered by the application of the archaeoseismological method not only in a preventive form, but also in assessing damage in post-seismic situations. Although the 2023 event was not of a high magnitude, and did not cause particular damage in the old city centre, the techniques and technologies applied following the quake went well beyond an assessment of the building's "health" alone. Evaluating the relationship between the movements triggered by the quake, the stratigraphy, and structural deterioration dating to before the quake, it was possible to understand how the complex construction history dynamics that distinguish both the church of Sant'Agostino and the street front in Via Pendola, if placed in relation to the movements set in motion by the earthquake, take on a leading role in the appearance or discretisation of one or more signs of disrepair. This fact, as specified earlier, does not only have a predictive function, in other words trying to effectively help experts in the field in their vulnerability analyses. Indeed, it also serves to evaluate and design restorations, or specific interventions in buildings.

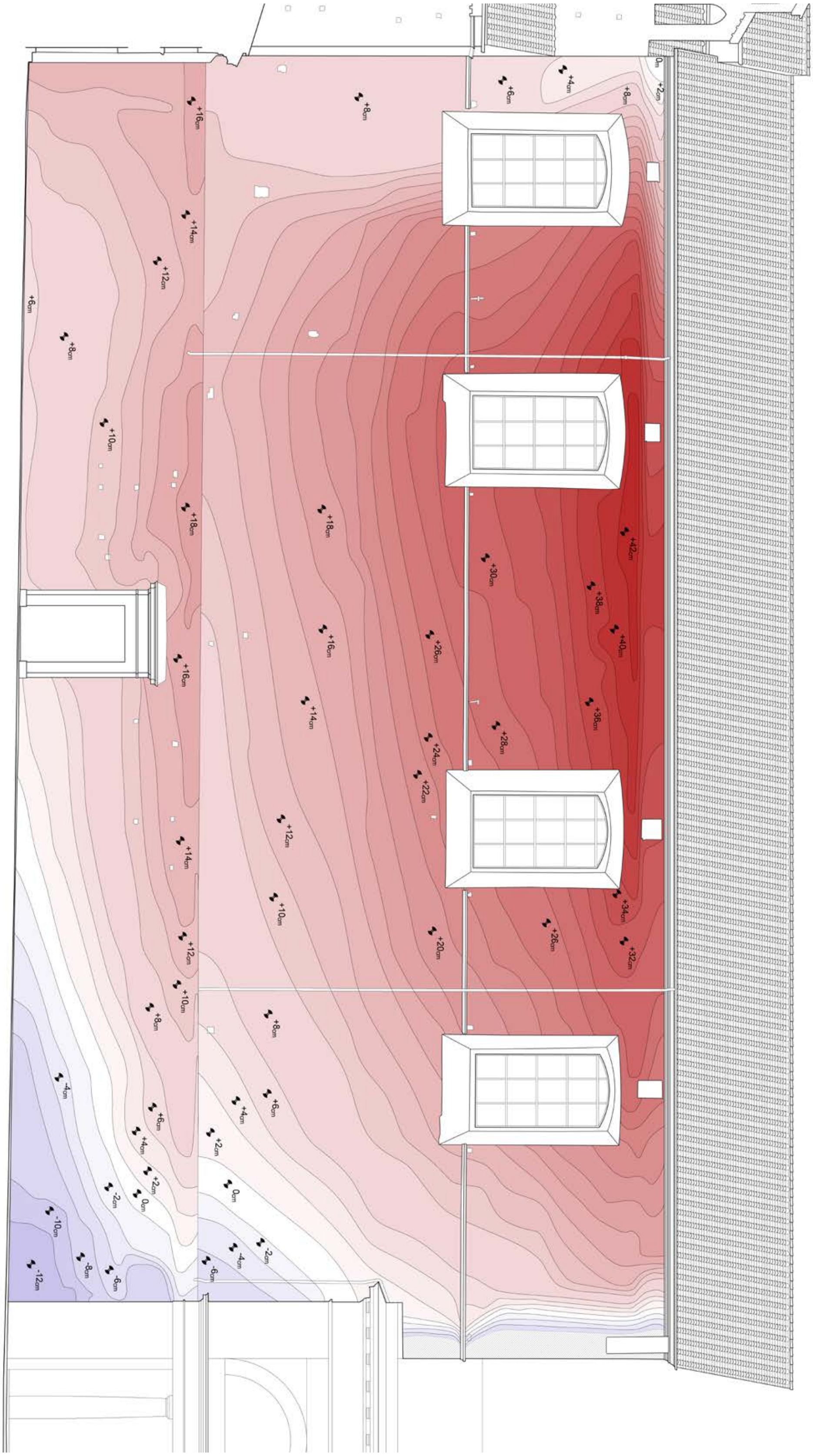

Figure 5.6a - The image shows the deformation framework of the northern external elevation of Sant'Agostino's Church before the earthquake of February 2023. (Elaboration: Marco Repole)

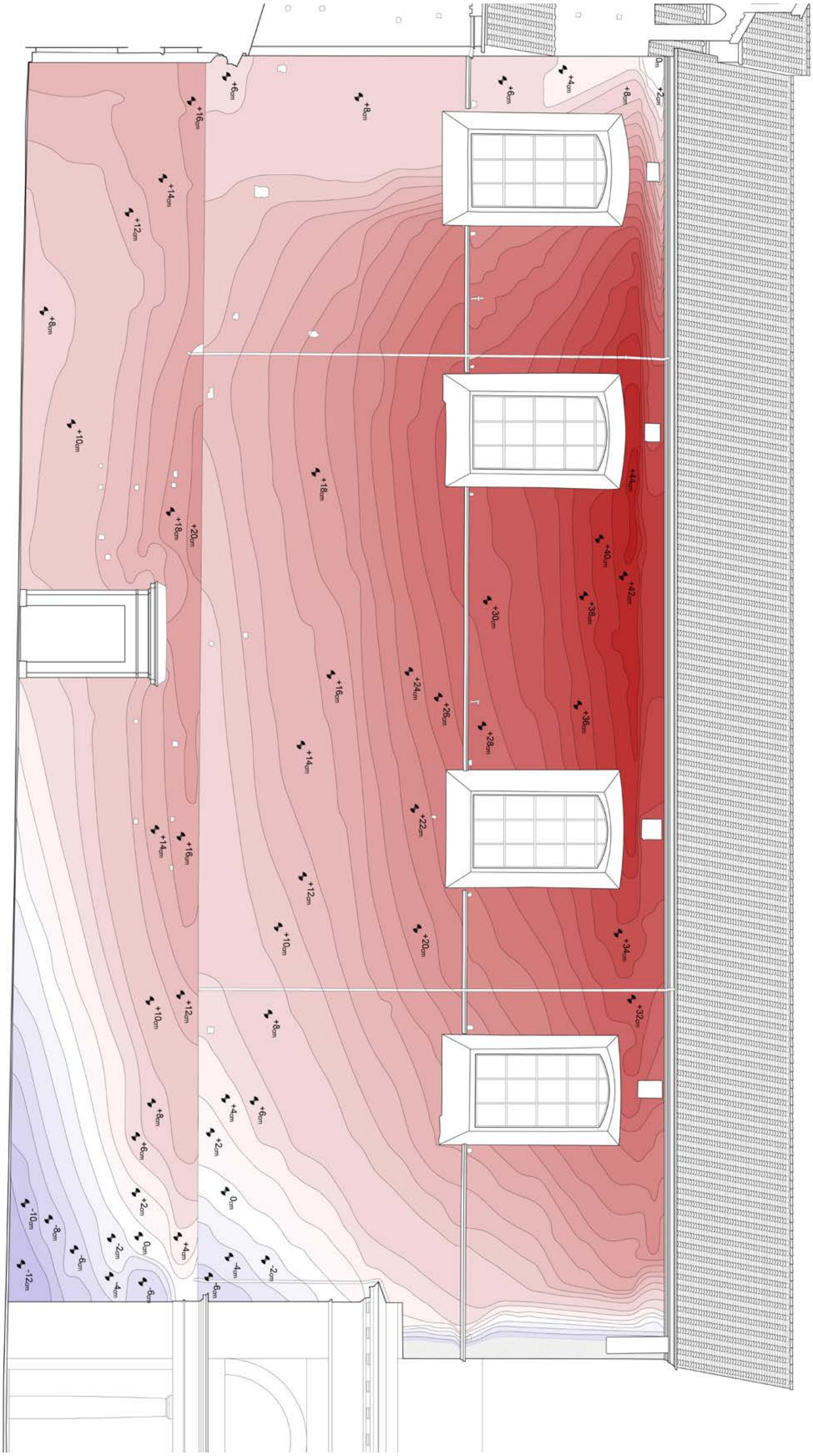

Figure 5.6b - The image shows the deformation framework of the northern external elevation of Sant'Agostino's Church after the earthquake of February 2023. (Elaboration: Marco Repole)

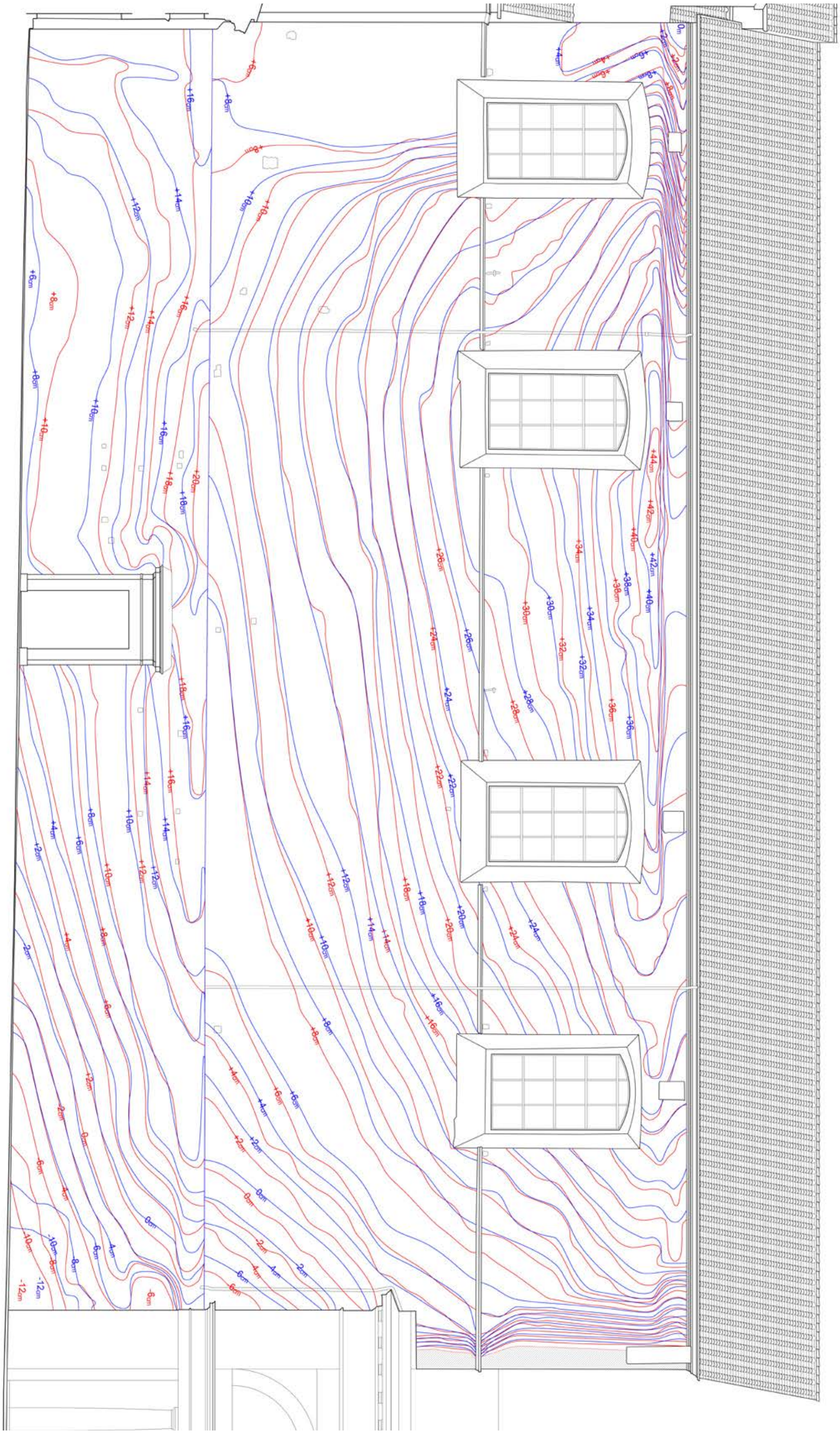

Figure 5.7a - Restitution of the northern external elevation of the church of Sant'Agostino with the isohypses of the old (in blue) and the new (in red) deformation framework modified following the earthquake of February 2023 highlighted.

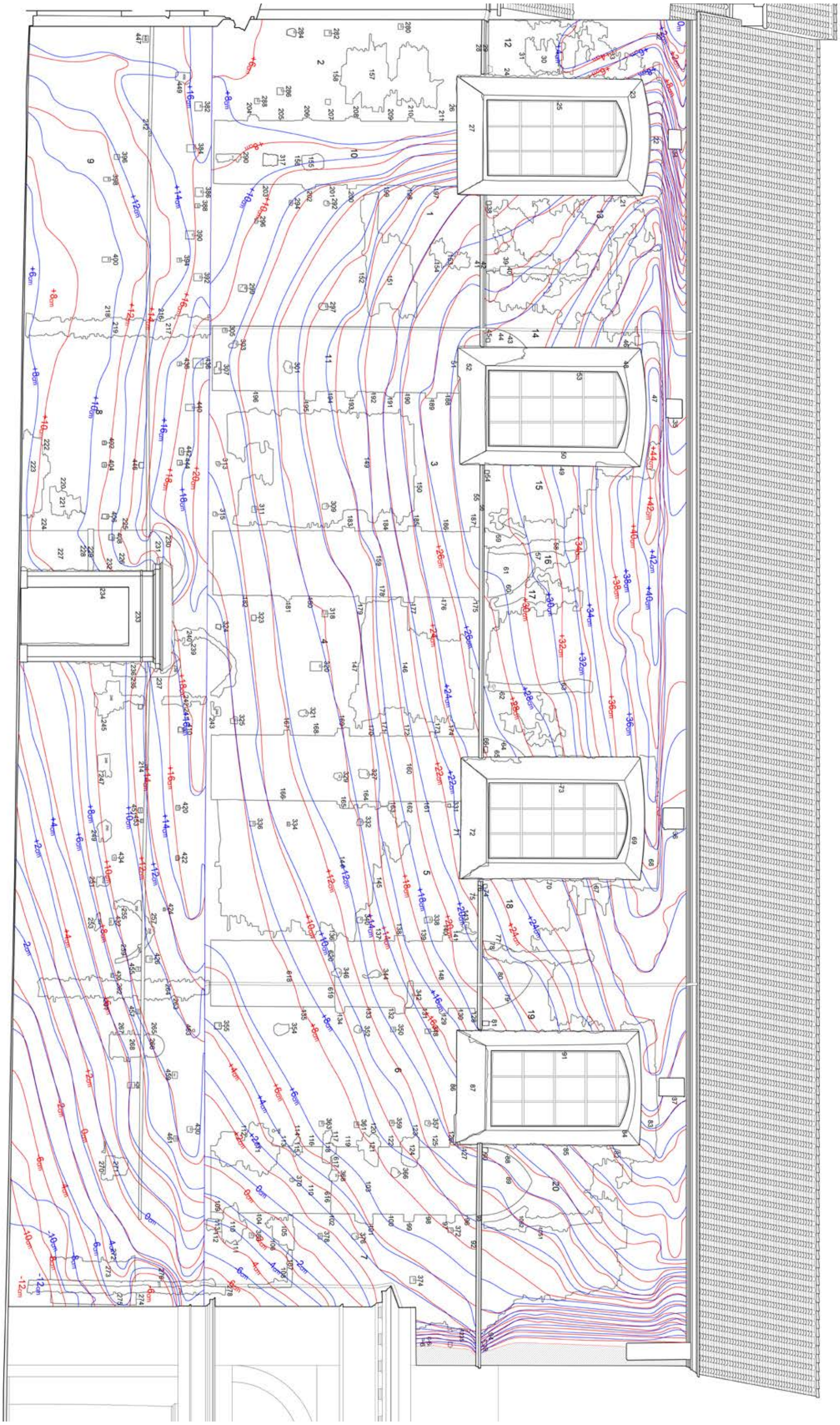

Figure 5.7b - Restitution of the archaeological analysis by Stratigraphic Units (in black) of the northern external elevation of the church of Sant'Agostino with the isohypses of the old (in blue) and the new (in red) deformation framework modified following the earthquake of February 2023 highlighted.

CHAPTER VI

Conclusions and prospects for research

The PROTECT project represents a concrete experimentation and direct application, in the field, of a method of multidisciplinary analysis which is still experimental, and which uses the archaeoseismological method, integrated with numerous other disciplines in the sciences and humanities, as its central pillar. The trial implementation of the project in Siena's old city centre gave rise to a number of considerations that could become fixed points in applying this method on a large scale in the near future, setting it alongside other, more "traditional" applications (e.g. microzonation, vulnerability analyses, planning emergency exit routes etc.), for studies of other old town centres in the Mediterranean area.

One initial point that deserves to be looked into involves the role of archaeoseismology, or archaeology in general, in preventive analyses of historical buildings in areas prone to seismic risk. Gathering knowledge is a vital operational phase in any project that envisages direct intervention on the historical built heritage. Reading the stratification of the natural and anthropic events involving buildings, and providing an assessment that is as attentive as possible to their complexity in terms of the history of their construction, is a vital step towards a full awareness of the formal and physical characteristics that distinguish the building that is the subject of analysis. Carrying out interventions without this type of investigation not only risks proving harmful to the building itself and to the people who live or work in it, leading to mistaken decisions at the planning stage, it also eradicates for all time the possibility, in the near future, of reading its history, both its construction history and seismic history, and thus of understanding all the historical and architectural information concealed in its masonry.

A second point relates to the perception that we "men of today" have of earthquakes in the past. The extensive historical-seismological and archaeological analysis conducted in Siena's old city centre with reference to the 1467 earthquake leads one to ponder the extent to which a correct evaluation of the dynamics associated with an earthquake may influence our evaluation of the earthquake itself, and how often we may produce evaluations that are mistaken, or only partially reliable, if we do not go into adequate depth in our study. The scenarios that appear following a telluric event always correlate with the dynamics that follow the effects of the decisions made by the people who live in that context, and who transform it. Given that today we cannot relive an earthquake that occurred in the past, the knowledge acquired by means of historical, archaeological and architectural documentation provides an essential basis for interpreting these phenomena, which we often lose trace of, or which seem to us profoundly different from how they actually appeared at the time, and from the effects associated with them.

A third consideration can be expressed regarding the technology and techniques used in archaeoseismological analysis. The testing of targeted, rapid analyses designed to find out about complex and multi-stratified units, such as building agglomerations and street fronts, was a vital step in order to understand and assess the limits and benefits of applying the integrated analysis method (fig.6.1). To that end, two main advantages seem to emerge. Firstly, it improves the knowledge base; by linking the stratigraphy to damage and disrepair, it offers an initial appraisal of the effects of earthquakes on buildings, facilitating interpretation, or providing preliminary data that can later be compared to written sources. Second, it provides a clear understanding of the state of preservation of the structures under investigation, especially with a view to planning suitable interventions in seismic

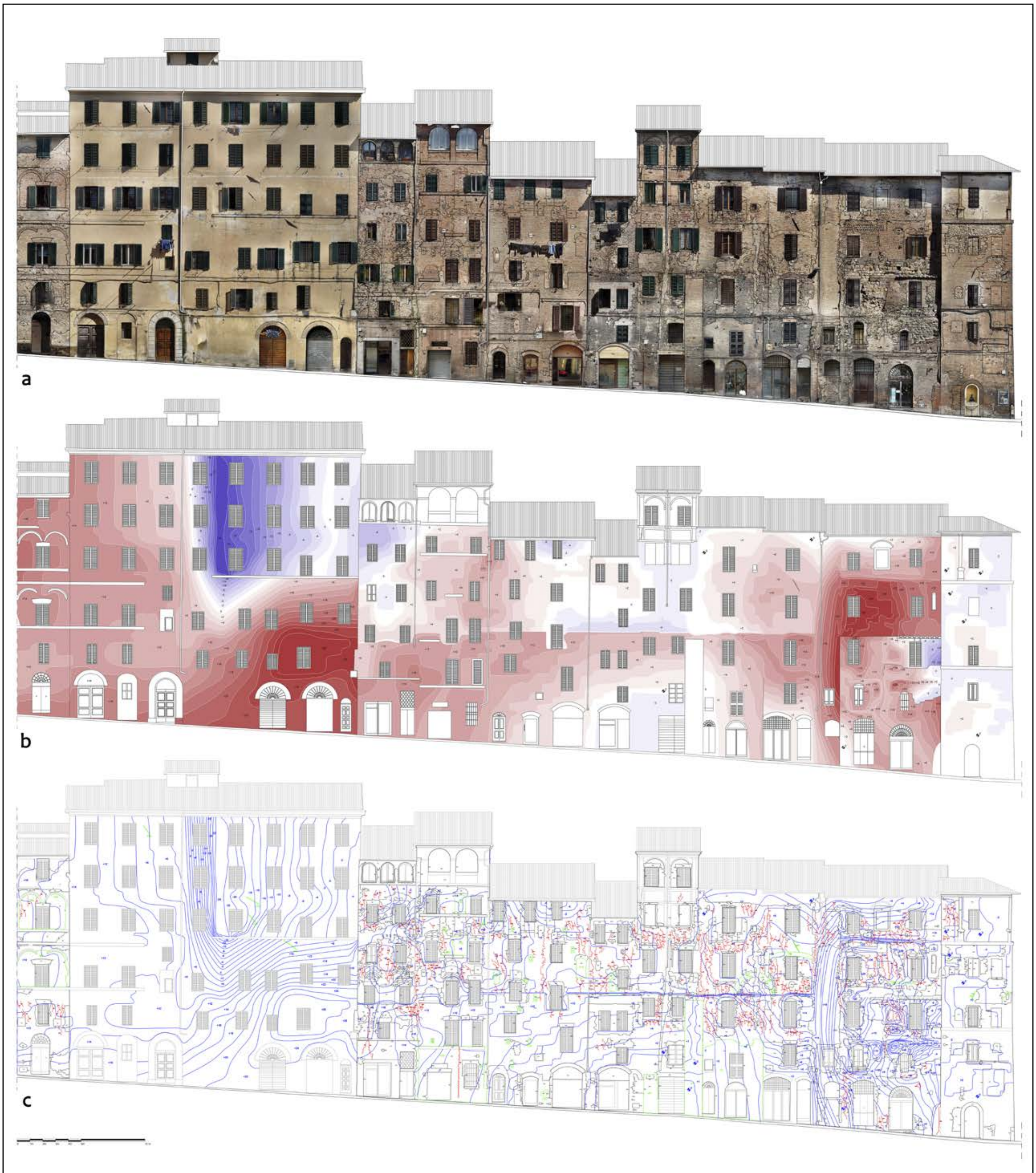

Figure 6.1 - The three restitutions created by the analysis of the street front: orthophoto, elevation map and the stratified instability map (Elaboration: Andrea Arrighetti and Marco Repole)

risk prevention, with a ranking of priorities that varies for each building. A practical example of the usefulness of this information is its application when planning the interventions and the analyses for the evaluation of CLE (Condizione Limite di Emergenza / Boundary Condition for Emergency). In Italy, CLE analysis involves the implementation of an operational procedure which includes an assessment of the structural condition of buildings with a view to prioritising interventions for each property located in a historic town centre or urban area. This data is essential for targeted knowledge aimed at mitigating the effects of one or more earthquakes on historic centres, and for the subsequent correct planning of urban intervention and organisational measures relating to the state of emergency in the wake of a seismic event[1].

A fourth element that should not be underestimated is the social impact of a project of this sort. Recent research conducted in areas at seismic risk in Italy and Europe suggests that in cultural contexts that have an ancient tradition there is a pronounced tendency to conserve a memory of dramatic events of the shared past (including earthquakes), as a form of social cohesion and a way of constructing a shared memory, also by means of ritual civic-cum-religious commemorations, and actual objects and products (images, inscriptions etc.). By contrast, the contemporary cultural context is not at all favourable to the preservation of the memory of such events, and an accumulated awareness, preserved over time, may rapidly be lost. Keeping alive the historical memory of the dangerousness of the areas in which a certain portion of the population lives, it is one of the possibilities, and one of the prerogatives, offered by the archaeological approach towards historical earthquakes. By means of conferences, meetings or simple guided tours with local people, and with local councils, it is possible to instill an awareness of the real risk that could be faced in the near future, conveying this information by retelling the dynamics of transformation undergone by Siena's old city centre, and experienced by the historical buildings and structures found within it, in other words the distinctive features that have shaped the past of the population that lives within these sites, and that has built up a deep connection to them (Fig 6.2).

Thus, to conclude, we can state that, as expressed by the MIBAC guidelines (MIBAC 2011), which appeared at the beginning of this book, and which we now refer to again here at the end, knowledge lies at the very foundation of any process of analysis of individual historical buildings, or of an entire old town centre. It is therefore down to political and technical bodies to take advantage of each and every opportunity to add a new piece to the jigsaw, and to improve our understanding of the dynamics affecting a local geographical area, and the heritage assets conserved within it. These are the essential conditions for determining future operational decisions linked to prevention against seismic risk, so as to safeguard not only examples of heritage but also people's lives.

[1] The Department of Architecture (DIDA) of the University of Florence, in collaboration with A. Arrighetti as archaeology consultant, has applied this methodology to the historic centre of Poppi, and the results have recently been published (Pancani 2017).

Figure 6.2 - An example of communicating the results of the PROTECT project to the population of Siena is the exhibition organised at the Palazzo di San Galgano in September 2023.

References

Archive sources

ASS Lira Archivio di Stato di Siena, Lira, 155, 157, 159, 166, 168, 172-173.

ASS 1467a Archivio di Stato di Siena, Concistoro, 605 (July-August 1467).

ASS 1467b Archivio di Stato di Siena, Concistoro, 606 (September-October 1467).

ASS sec. XV Archivio di Stato di Siena, Museo delle tavolette dipinte, Biccherna n. 34, 15th cent.

ASS 1798 Archivio di Stato di Siena, Governatore, n. 1152 (Affari e risoluzioni in occasione del terremoto del 26 maggio 1798 avvenuto in Siena).

Primary Sources

Allegretti, A. XV cent. "Ephemerides Senenses", in L.A. Muratori, Rerum Italicarum Scriptores, XXIII, Mediolani, col. 767-862, 1733.

Bandini, A.F. XVIII-XIX cent. "Diario sanese (1785-1838)". Biblioteca comunale degli Intronati di Siena, mss. D.III.1 - D.I.13.

Bonito, M. 1691 "Terra tremante, o vero continuatione de' terremoti dalla Creatione del Mondo sino al tempo presente...". Napoli (ristampa anastatica, Sala Bolognese, 1980).

Della Tuccia, N. XV cent. "Cronache di Viterbo e di altre città", in I. Ciampi, Cronache e statuti della città di Viterbo, Firenze 1872.

Fecini, T. XV cent. "Cronaca di Tommaso Fecini (1431-1479)", in Rerum Italicarum Scriptores XV/6: 841-874.

Ligustri, T. 1587 ca "Affresco raffigurante il pellegrinaggio senese al santuario della Madonna della Quercia". Viterbo.

Macchi, D. XVIII cent. "Terremoti stati più volte nella città di Siena, che si sono trovati scritti nell'infrascritti anni, e per memoria se ne fa qui mensione nell'infrascritto libro". Archivio di Stato di Siena. Manoscritti, D. 107, sec. XVIII, c. 366.

Manetti, G. XV cent. "De Terraemotu". Firenze: Sismel-Edizioni del Galluzzo, 2012.

Tizio, S. XV cent. "Sigismundi Titii Historiarum Senensium [...] ab anno 1459 ad Annum 1486 [...]". Biblioteca Comunale degli Intronati di Siena, Sienne, ms. B.III.11.

Bibliography

Albarello, D., Castelli, V., D'Amico, V., Gennari, M. and Pessina, V. 2007. Cos'è successo a Siena il 26 maggio 1798? Un'iniziativa interdisciplinare per la valutazione del possibile impatto di un futuro "massimo sismico" su una città-monumento, in *Atti del convegno Gruppo Nazionale di Geofisica della Terra Solida, 13-15 novembre 2007*: 381-383. Trieste: Gruppo Nazionale di Geofisica della Terra Solida.

Alberti, L., Azzara, R.M. and Clemente, P. (ed.s) 2019. Lessons from the past: the evolution of seismic protection techniques in the history of building. *Annals of Geophysics* 62/3. Rome: INGV.

Arrighetti, A., Gelli, B. and Castelli, V., 2025. Effetti diretti e indiretti del terremoto di Siena del 1467: una rilettura innovativa tra dati storici e archeosismologici inediti. *Mélanges de l'École Française de Rome - Moyen Âge* 137/1.

Arrighetti, A. and Minutoli, G. 2019. A multidisciplinary approach to document and analyze seismic protection techniques in Mugello from the Middle *Ages to Early Modern Time. Annals of Geophysics* 62/3: http://dx.doi.org/10.4401/ag-7991.

Arrighetti, A., Razzante, V. and Dessales, H. 2022. Archaeology and earthquakes in Siena (Italy). Preliminary data from the survey of the historical buildings of the Terzo di Città. *Restauro Archeologico* 1/2022: 14-31.

Arrighetti, A. (ed.) 2023. *Siena e i terremoti. Punti di vista multidisciplinari per una lettura archeosismologica del centro storico*. Sesto Fiorentino: All'Insegna del Giglio.

Arrighetti, A. 2022. Analisi e documentazione archeologica dell'edilizia storica in aree a rischio sismico: dall'atlante dei tipi costruttivi murari all'impiego delle moderne tecnologie di rilievo. *Archeologia e Calcolatori* 33.1: 201-218.

Arrighetti, A. 2019. Registering and documenting the stratification of disruptions and restorations in historical edifices. The contribution of archaeoseismology to architecture. *Journal of Archaeological Science*: Reports 23: 243-251.

Arrighetti, A. 2018a. Archeosismologia in architettura. Nuove prospettive di un dialogo multidisciplinare. *Archeologia dell'Architettura* XXIII: 11-17.

Arrighetti, A. (ed.) 2018b. *Archeologia dell'architettura e terremoti, Primo Seminario Interdisciplinare "Economia e tecniche della costruzione. Antichità, Medioevo, Età Moderna" (Siena, 18 maggio 2018)*. Sesto Fiorentino: All'Insegna del Giglio.

Arrighetti, A. 2016. Materiali e tecniche costruttive del Mugello tra basso Medioevo e prima Età Moderna. *Arqueologia de la arquitectura* 13: http://dx.doi.org/10.3989/arq.arqt.2016.001

Arrighetti, A. 2015. *L'archeosismologia in architettura. Per un manuale*. Firenze: Firenze University Press.

Ascheri, M. 2013. *Storia di Siena, dalle origini ai giorni nostri*. Siena: Biblioteca delle Immagini.

Balestracci, D. and Piccinni, G. 1977. Siena nel Trecento. Assetto urbano e strutture edilizie. Firenze: Clusf.

Banchi, L. 1868. La Lira, la Tavola delle possessioni e le preste nella Repubblica di Siena. *Archivio storico italiano* II e série, VII: 53-86.

Baratta, M. 1901. *I terremoti d'Italia: saggio di storia geografia e bibliografia sismica italiana*. Torino: Arnaldo Fondi Editore.

Biggi, L. 2020. I santuari gesuati, in Isabella Gagliardi (ed.) *Le vestigia dei gesuati: L'eredità culturale del Colombini e dei suoi seguaci*: 283-295. Firenze: Firenze University Press.

Broek-Parant, J.V. and Ismaelli, T. (ed.s) 2021. *Ancient architectural restoration in the Greek world: proceedings of the International workshop held at Wolfson College, Oxford*. Rome: Edizioni Quasar.

Brogiolo, G.P. and Cagnana, A. 2012. *Archeologia dell'architettura. Metodi e interpretazioni*. Sesto Fiorentino: All'Insegna del Giglio.

Calzona, A., Cantarella, G.M. and Milanesi, G. (ed.s), 2018. *Terremoto in Val Padana: 1117. La terra sconquassa e sprofonda*. Verona: Scripta Edizioni.

Camassi, R., Castelli, V., Molin, D., Bernardini, F., Caracciolo, C.H., Ercolani, E. and Postpischl, L. 2011. *Materiali per un catalogo dei terremoti italiani: eventi sconosciuti, rivalutati o riscoperti*. Roma: Quaderni di Geofisica.

Cangi, G. 2018. *Approccio metodologico all'analisi sismica delle strutture murarie in ambito archeologico e monumentale: dall'osservazione alla modellazione*. Archeologia dell'Architettura XXIII: 63-74.

Cantini, F. 2011. Prima dell'ospedale: Siena tra tarda antichità e XI secolo. Genesi della città altomedievale a partire dalla definizione della civitas christiana, in F. Gabbrielli (ed.) *Ospedale Santa Maria della Scala: ricerche storiche, archeologiche e storico artistiche. Atti della giornata di Studi, Siena, 28 Aprile 2005*: 33. Siena: Protagon Editori.

Castelli, V., Monachesi, G., Moroni, A. and Stucchi, M. (ed.s) 1996. *Revisione dei principali terremoti d'interesse per il territorio toscano, vol. 1*: Dall'anno 1000 al 1731. Macerata-Milan: rapporto interno INGV.

Castelli, V. 2023. La storia sismica di Siena: stato delle conoscenze (updated to January 2022), in A. Arrighetti (ed.) *Siena e i terremoti. punti di vista multidisciplinari per una lettura archeosismologica del centro storico*: 27-36. Sesto Fiorentino: All'Insegna del Giglio.

Castelli, V. 2004. Hidden behind the Ranges. How the 13 April 1558 "Sienese" Earthquake Was Put in Its Place. *Seismological Research Letters* 75.3: 342-351.

Castelli, V. 2009. Ricordarsi del terremoto. Tracce senesi di una "memoria sismica collettiva". *Bullettino Senese di Storia Patria* CXVI: 316.

Castelli, V. 2016. *I terremoti nella STORIA: 26 maggio 1798, un terremoto di fine secolo XVIII a Siena*. Bologna: INGV.

Catoni, G. and Piccinni, G. 1984. Famiglie e redditi nella Lira senese del 1453, in R. Comba, G. Piccinni and G. Pinto (ed.s) *Strutture familiari, epidemie, migrazioni nell'Italia medievale*: 291-304. Naples: Edizioni Scientifiche Italiane.

Catoni, G. and Piccinni, G. 1987. Alliramento e ceto dirigente nella Siena del Quattrocento, in D. Rugiadini (ed.) I *ceti dirigenti nella Toscana del Quattrocento, Actes des V et VI colloques de Florence, 10-11 décembre 1982 et 2-3 décembre 1983* : 451-461. Florence: Papafava Ed.

Ceppari, M.A., De Gramatica, M.R., Turrini, P. and Zarrilli, C. 2008. *Archivio di Stato di Siena. Museo delle Biccherne*. Viterbo: Archivi Italiani.

Correia, M., Lourenco, P.B. and Varum, H. (ed.s) 2015. *Seismic Retrofitting. Learning from Vernacular Architecture*. London: CRC Press.

D'Amico, S., Venuti, V. (ed.) 2022. *Handbook of Cultural Heritage Analysis*. Cham: Springer International Publishing.

Dessales, H. 2022. *Ricostruire dopo un terremoto. Riparazioni antiche a Pompei*. Napoli: Centre Jean Bérard.

Dessales, H. and Tricoche, A. 2018. *Un database per studiare le riparazioni post-sismiche*. Archeologia dell'Architettura XXIII: 19-24.

Ferrigni, F., Helly, B., Mauro, A., Mendes Victor, L., Pierotti, P., Rideuad, A. and Teves Costa, P. 2005. *Ancient buildings and earthquakes. The local seismic culture approach: principles, methods, potentialities*. Bari: Edipuglia.

Forlin, P., Gerrard, C. and Petley, D., 2015. ArMedEa project: archaeology of medieval earthquakes in Europe (1000-1550 AD). First research activities, in A.M. Blumetti, F. Cinti, P. De Martini, F. Galadini, L. Guerrieri, A.M. Michetti, D. Pantosti and E. Vittori (ed.s) *6th International Inqua Meeting on Paleoseismology, Active Tectonics and Archaeoseismology*: 166-169. Pescina: INGV.

Forlin, P. and Gerrard, C. 2017. The archaeology of earthquakes: The application of adaptive cycles to seismically-affected communities in late medieval Europe. *Quaternary International* 446: 95-108.

Gabbrielli, F. 2010. *Siena medievale. L'architettura civile*. Siena: Protagon Editori Toscani.

Galadini, F., Hinzen, K-G. and Stiros, S. 2006. Archaeoseismology: Methodological issues and procedure. *Journal of Seismology* 10: 395-414.

Gennari, M. 2005. *L'orribil scossa della vigilia di Pentecoste, Siena e il terremoto del 1798*. Monteriggioni: Il Leccio.

Gerrard, C.M., Forlin P. and Brown P.J. (ed.s) 2021. *Waiting for the end of the world? New perspectives on natural disasters in Medieval Europe*. Abingdon: Routledge.

Gigli, G. 1723. *Diario sanese: in cui si veggono alla giornata tutti gli avvenimenti più ragguardevoli spettanti sì allo spirituale, sì al temporale della città, e stato di Siena: con la notizia di molte nobili famiglie di essa, delle quali è caduto in acconcio il parlarne*. Lucca: Forgotten Books.

Guidoboni, E. and Comastri, A. 2005. *Catalogue of earthquakes and tsunamis in the Mediterranean area from the 11th to the 15th century*. Rome: INGV.

Guidoboni, E. and Stucchi, M. 1993. The contribution of historical records of earthquakes to the evaluation of seismic hazard. *Annali di Geofisica* 36: 201-215.

Guidoboni, E., Ferrari, G., Tarabusi, G., Sgattoni, G., Comastri, A., Mariotti, D., Ciuccarelli, C., Bianchi, M.G. and Valensise, G., 2019. CFTI5Med, the new release of the catalogue of strong earthquakes in Italy and in the Mediterranean area. *Scientific Data 6*: https://doi.org/10.1038/s41597-019-0091-9

Guidoboni, E., Ferrari, G., Mariotti, D., Comastri, A., Tarabusi, G. and Valensise, G. 2007. CFTI4Med, *Catalogue of Strong Earthquakes in Italy (461 B.C.-1997) and Mediterranean Area (760 B.C.-1500)*. Bologna: INGV-SGA.

Guidoboni, E. (ed.) 1989. *I terremoti prima del Mille in Italia e nell'area mediterranea. Storia, Archeologia, Sismologia*. Bologna: SGA.

Guidoboni, E. 1987. "Delli rimedi contra terremoti per la sicurezza degli edifici": la casa antisismica di Pirro Ligorio (Sec. XVI), in *Tecnica e società nell'Italia dei secoli XII-XVI, Atti dell'XI convegno internazionale, Pistoia 28-31 ottobre 1984*: 215-228. Pistoia: Viella.

Helly, B. 1995. Local Seismic Cultures: a European research program for the protection of traditional housing stock. *Annali di Geofisica* XXXVIII: 791-794.

Herlihy, D. and Klapisch Zuber, C. 1988. *I toscani e le loro famiglie. Uno studio sul catasto fiorentino del 1427*. Bologna: Il Mulino.

Isaacs, A.K. 1970. Popolo e Monti nella Siena del primo Cinquecento. *Rivista Storica Italiana* LXXXII: 33-80.

Lapini, A. 1900. *Diario fiorentino di Agostino Lapini dal 1252 al 1596*. Florence: Sansoni.

Leoncini, A. 1998. *Siena in fasce, topografia e immagini della Sena Vetus*. Monteriggioni: Il Leccio.

Locati, M., Camassi, R., Rovida, A., Ercolani, E., Bernardini, F., Castelli, V., Caracciolo, C.H., Tertulliani, A., Rossi, A., Azzaro, R., D'Amico, S. and Antonucci A. 2022. *Database Macrosismico Italiano (DBMI15), versione 4.0*. Bologna: INGV.

Marra, F., Milana, G., Pecchioli, L., Roselli, P., Cangi, G., Carlucci, G., Famiani, D. and Mercuri, A. 2020. *Historical faulting as the possible cause of earthquake damages in ancient Ostia (Rome, Italy): a combined structural, seismological and geological analysis*. Journal of Seismology 24: 725-728.

Mecca, S. 2022. La régénération des villages est un élément d'un projet de croissance durable et équitable, in Hadda L., Mecca S. Pancani G., Carta M., Fratini F., Galassi S. and Pittaluga D. (ed.s) *Villages et quartiers à risque d'abandon. Stratégies pour la connaissance, la valorisation et la restauration* : 29-33. Firenze: Firenze University Press.

MIBAC 2011. *Linee Guida per la valutazione e riduzione del rischio sismico del patrimonio culturale: allineamento alle nuove Norme tecniche per le costruzioni*. Roma: Gangemi Editore.

Minutoli, G. 2019. *Percorsi di conoscenza per la salvaguardia della città storica*. Firenze: Dipartimento di Architettura.

Molin, D., Bernardini, F., Camassi, R., Caracciolo, C.H., Castelli, V., Ercolani, E. and Postpischl, L. 2008. Materiali per un catalogo dei terremoti italiani: revisione della sismicità minore del territorio nazionale. *Quaderni di Geofisica* 57: 78.

Montabert, A., Mercerat, D., Clément, J., Langlaude, P., Lyon-Caen, H. and Lancieri, M. 2022. High resolution operational modal analysis of Sant'Agata del Mugello in the light of its building history. *Engineering Structure* 254: https://doi.org/10.1016/j.engstruct.2021.113767.

Montabert, A., Dessales, H., Arrighetti, A., Clément, J., Lancieri, M. and Lyon-Caen, H. 2020. Tracing the seismic history of Sant'Agata del Mugello (Italy, Tuscany) through a cross-disciplinary approach. *Journal of Archaeological Science*: Reports 33: https://doi.org/10.1016/j.jasrep.2020.102440

Nevola, F. 2000. "Ornato della città": Siena's Strada Romana as Focus of Fifteenth-century Urban Renewal. *Art Bullettin* 82: 26-50.

Nevola, F. 2009. Francesco Patrizi umanista e teorico di Pio II, in Nevola F. (ed.) *Pio II Piccolomini: il papa del Rinascimento a Siena*: 179-196. Siena: Protagon Editori.

Nucciotti, M., Vannini, G. 2020. Light archaeology and territorial analysis: experiences and perspectives of the Florentine medievalist school. *Archaeologia Polona* 50: 149-169.

Pancani, G. 2017. *La città dei Guidi: Poppi. Il costruito del centro storico, rilievi e indagini diagnostiche*. Firenze: Edifir.

Parenti, R. 2002. Dalla stratigrafia all'archeologia dell'architettura. Alcune recenti esperienze del laboratorio senese. *Arqueología de la Arquitectura* 1: 73-82.

Pecchioli, L. 2022. *Terrae motus: repair and prevention in Ostia, the harbour city of ancient Rome*, in Soussignan R., Diosono F. and Le Blay F. (ed.s) Living with Seismic Phenomena in the Mediterranean and Beyond between Antiquity and the Middle Ages: 399-408. Oxford: Archaeopress.

Pecchioli, L. (ed.) 2023. *Archaeoseismology. Methods and case studies*. Cham: Springer International Publishing.

Pecchioli, L., Cangi, G. and Marra, F. 2018. Evidence of seismic damages on ancient Roman buildings at Ostia: An arch mechanics approach. *Journal of Archaeological Science*: Reports 21: 117-127.

Pertici, P. 1995. *La città magnificata. Interventi edilizi a Siena nel Rinascimento. L'ufficio dell'Ornato (1428-1480)*. Monteriggioni: Il Leccio.

Pierotti, P. and Ulivieri, D. 2001. *Culture sismiche locali*. Pisa: Plus.

Postpischl, D. 1985. Catalogo dei terremoti italiani dall'anno 1000 al 1980, Progetto Finalizzato Geodinamica. *Quaderni de "La Ricerca Scientifica"* 114.

Redi, F. and Forgione, A. (ed.s) 2012. *VI Congresso Nazionale di Archeologia Medievale*. Borgo San Lorenzo: All'Insegna del Giglio.

Riedl, P.A. and Seidel, M. 1985-2006. *Die Kirchen von Siena*. Firenze: Edizioni Polistampa.

Romby, G.C. and Rovida, M.A. 2012. *Qualità dell'abitare nelle città toscane. Libri di fabbrica, muramenti, inventari (sec. XV). Firenze-Siena*. Firenze: Edizioni Polistampa.

Rovida, A., Locati, M., Camassi, R., Lolli, B., Gasperini, P. and Antonucci, A. 2022. *Catalogo Parametrico dei Terremoti Italiani (CPTI15), versione 4.0*. Bologna: INGV.

Rovida, A., Locati, M., Camassi, R., Antonucci, A., Bernardini, F., Caracciolo, C.H. and Maffezzoni, L. 2017. ASMI, Archivio Storico Macrosismico Italiano, in Di Bucci D. (ed.) *36° Convegno del Gruppo Nazionale di Geofisica della Terra Solida (GNGTS)*: https://doi.org/10.13127/asmi. Roma: INGV.

Rubinstein, R.O. 1968. Pius II's Piazza S. Pietro and St. Andrew's Head, in Maffei D. (ed.) *Enea Silvio Piccolomini, Papa Pio II*: 221-243. Siena: Accademia Senese degli Intronati.

Senatore, F. 2009. Callisto III nelle corrispondenze diplomatiche italiane: La documentazione sui Borgia nell'Archivio di Stato di Siena. *Revista Borja 2*: 141-186.

Soldani, A. 1798. *Relazione del terremoto accaduto in Siena il dì 26 maggio 1798 divisa in sei lettere*. Siena: Dai Torchi Pazziniani.

Soussignan, R., Diosono, F. and Le Blay, F. (ed.s) 2021. *Living with Seismic Phenomena in the Mediterranean and Beyond between Antiquity and the Middle Ages*. Oxford: Archaeopress.

Stiros, S. 2016. On the historical role of earthquakes in Antiquity, in Ghilardi M. (ed.) *Géoarchéologie des îles de la Méditerranée*: 10.4000/books.editionscnrs.28623. Paris: CNRS Éditions.

Tomei, A. (ed.) 2002. *Le Biccherne di Siena. Arte e finanza all'alba dell'economia moderna*, Roma: Bolis.

Turrini, P. 1997. '*Per honore et utile de la città di Siena'. Il Comune e l'edilizia nel Quattrocento*. Siena: Il Mulino.

Valluzzi, M.R. 2016. Challenges and perspectives for the protection of masonry structures in historic centers: the role of innovative materials and techniques. *RILEM Technical Letters* 1: 45-49.

Valtieri, S. 1980. Tutta una città come luogo teatrale per il "Corpus Domini" del 1462, una memorabile festa organizzata da Pio II a Viterbo. *Biblioteca e Società II*: 19-30.

Zullo, E. (ed.) 2018. *Restauro e terremoto. I Beni Culturali della Capitanata*, Foggia: Edipuglia.