

**Ancient Mortar Production in Ostia, Italy:
Builders and their choices**

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Abstract

The main objective of the research discussed in this thesis was to evaluate the methods and materials used by builders in ancient Ostia to produce mortar for masonry structures. The work was conducted with an eye toward understanding why the ancient builders selected specific materials and employed specific techniques. The research design included scientific investigations of mortar samples from selected structures in Ostia, all dated from brick stamp evidence to the 2nd century CE. The methods employed for this study included thin section petrography, modal analysis via point counting, scanning electron microscopy, X-ray diffraction, and image analysis. Results concluded the samples comprised lime binder and primarily volcanic tuff aggregates derived from the Colli Albani and Monti Sabatini volcanic districts. The selection of these aggregates was integral to mortar performance, as they contained alteration products that would have facilitated pozzolanic reactions during the production phase, greatly improving long term mortar performance and durability. Three distinct types of mortar representing unique mix designs were identified based on the material properties of the mortar samples and the dominant aggregate types. Unique mixes may have been proprietary to specific groups of builders in Ostia, which had been identified by other researchers comparing the architectural features and construction styles of various structures. The results of material analyses showed that the builders from 2nd century Ostia were highly skilled, used sophisticated techniques to produce high quality mortar, and that separate groups of builders employed unique mix designs to achieve similar results.

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Chapter 1. Introduction

Ancient buildings are of unparalleled importance to many archaeologists. Structural remains are usually the largest and most visible artefacts on a historic site and they can delineate the extent of the site itself. Separate cultural groups or historical eras are quite often defined by unique construction techniques, the types of materials used, or the level of sophistication employed, and so the presence of standing structures ties a particular group of people to a specific location in time and space. The identification of ancient Roman buildings has informed the modern understanding of the classical world by confirming the extent of Roman occupation; generating a typology of construction techniques; revealing innovation and the spread of technology in the building trade; and exposing networks for trade and movement of materials. It is impossible to overstate the depth of useful information that can be gleaned from a well-designed – and properly applied – study of Roman architecture. Although mortar plays a large role in Roman architecture and the provenance of its materials and techniques of its manufacture are valuable sources of information about the ancient building trade, it is only recently that modern scientific methods have been applied in order to understand the decisions made in constructing Roman buildings.¹

The main objective of this project is to derive new useful information regarding the sophistication of Roman builders in Ostia in the 2nd century CE from a targeted study of the material remains of their work. Scientific analysis of the mortar that was designed, prepared, and installed by ancient builders has brought new information to light about

¹ Brandon et al. 2005; Jackson et al. 2010b; Vola et al. 2010; Jackson et al. 2010a.

their technical skill, the selection and distribution of building supplies, and the organization of the building trade in Ostia.

1.1. Why Ostia?

Ostia lies 30 km to the southwest of Rome, at what was then the mouth of the Tiber River (Figure 1.1). The archaeological site covers an area of over one square kilometre (Figure 1.2), though the geophysical surveys completed by Heinzelmann revealed that the standing remains represent only half of the original site.² The ancient city had a long history of occupation, starting as a relatively small Roman colony that grew into a major port for the city Rome.

The relatively good state of preservation throughout the site makes it possible to study ancient buildings within the context of the city as a whole. Much of the construction history is preserved *in situ*, leaving the ruins to function essentially as both an open air museum and laboratory for architectural historians. Epigraphic evidence from well-documented brick stamps allows the structures to be reliably dated, providing what DeLaine calls a “microchronology” for buildings from the same construction phase.³ Furthermore, abundant ancient textual references to Ostia provide a fairly robust image of the city's history and organization.⁴ The unique combination of well-preserved structures, well-documented epigraphic evidence, and a relatively well-attested social history makes Ostia a particularly attractive study site.

² Martin *et al.*

³ DeLaine 2003; Bloch 1941; Steinby 1987.

⁴ Meiggs 1960.

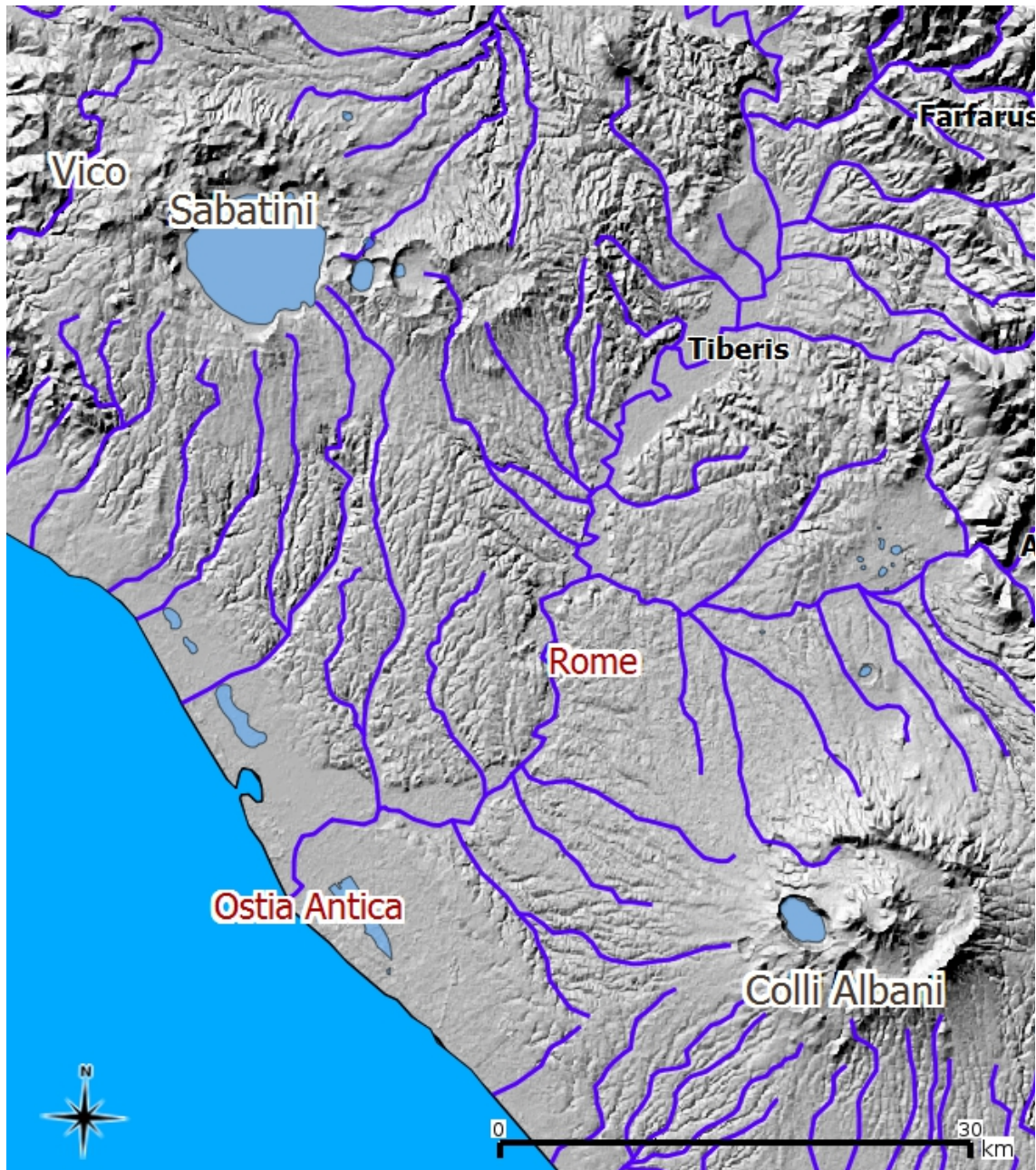


Figure 1.1: Location map of Ostia and Rome, showing major rivers and volcanic districts. Map generated with Quantum GIS, utilising data accessed from the Ancient World Mapping Center website (<http://awmc.unc.edu/wordpress/>), following Barrington Atlas of the Greek and Roman World (R. J. A. Talbert ed., 2000).

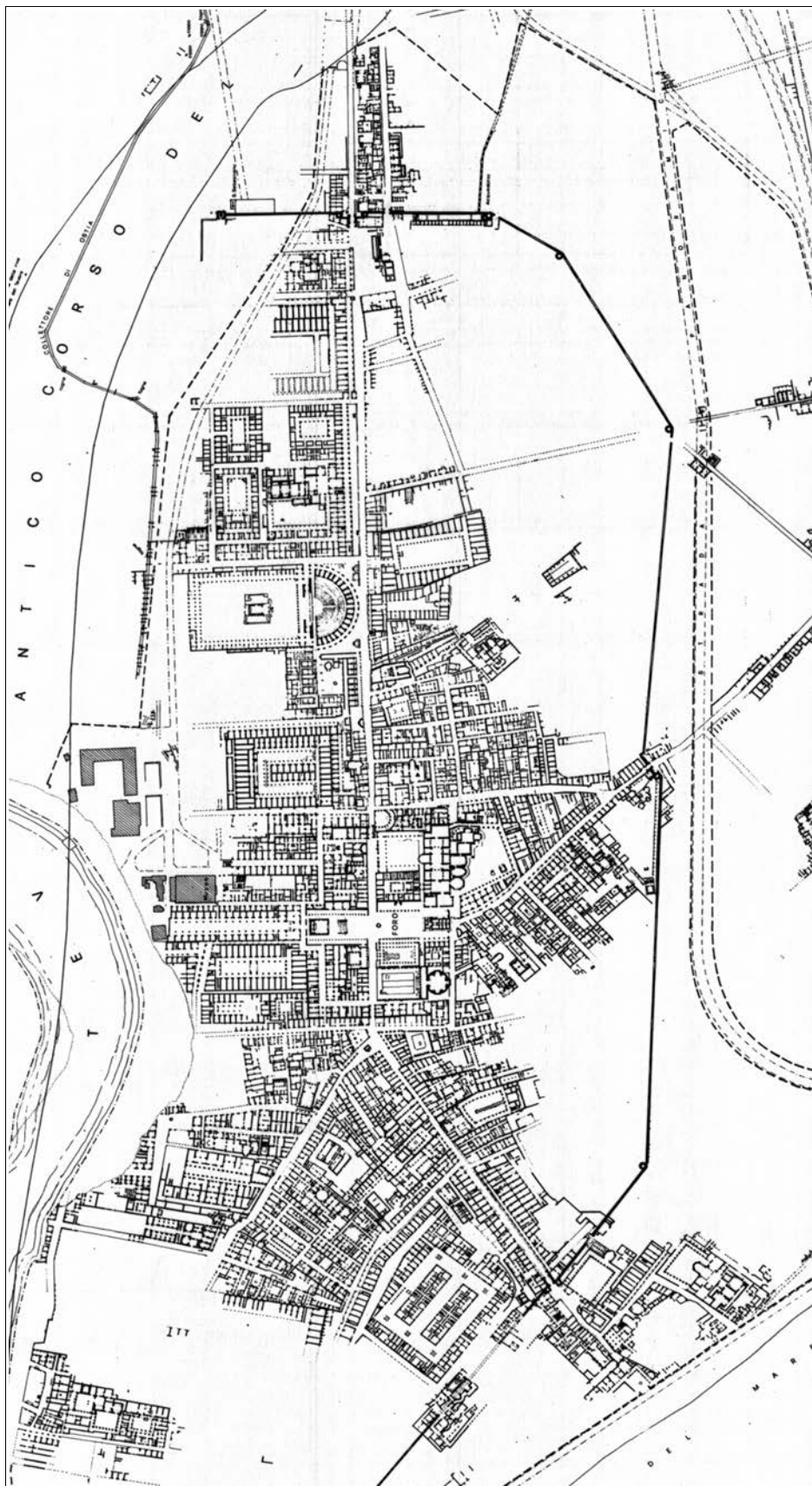


Figure 1.2: Plan map of Ostia Antica, showing extent of ruins. Originally published 1949 by Gismondi and Visca, updated 1961 by Pascolini and in 1996 by Ricciardi.

1.2. Theoretical frameworks

The possible approaches to the scholarship of ancient Roman architecture, and mortar studies in particular, are seemingly countless. The subject is vast and inherently interdisciplinary, incorporating aspects of Roman history,⁵ construction technology and material science,⁶ and local geology.⁷ Strictly archaeometric studies of historic mortar commonly use scientific methods to describe the samples but rarely address the more profound archaeological issues regarding the behaviour and methods of ancient builders and the construction industry in which they played a significant part.⁸ Clearly, ancient structures are complex objects that exist within complex systems. Furthermore, both the objects themselves and the systems in which they are situated have been influenced by the people involved at every step of building design, production, and use. The challenge here is to design a study that acknowledges such complexities without placing too much weight on any one material aspect or ignoring the effects of human agency.

In order to generate any useful discourse of ancient structures, architecture must be studied within multiple contexts, ideally deriving useful information from analytical data. The theoretical framework applied in this project comprises three distinct material contexts of study, each of which can be addressed individually from increasingly focused scales of direct inquiry. Research progressively advances to more tightly focused analyses, starting with broad-scale and ending with sample-specific micro-descriptions. Figure 1.3 provides an illustration of how this study of mortar from structures in Ostia

5 Ulrich and Quenemoen 2013.

6 Gotti et al. 2008; Goldsworthy and Min 2009; Bianchi et al. 2011.

7 Karner, Marra and Renne 2001; Marra et al. 2009; Cecconi, Scarapazzi and Viggiani 2010.

8 Miriello and Crisci 2006; Miriello *et al* 2010; Lancaster *et al* 2010.

has been organized. The columns represent the contexts of study, and the rows indicate the scales of inquiry; the nodes contain the specific topics to be addressed at each level.

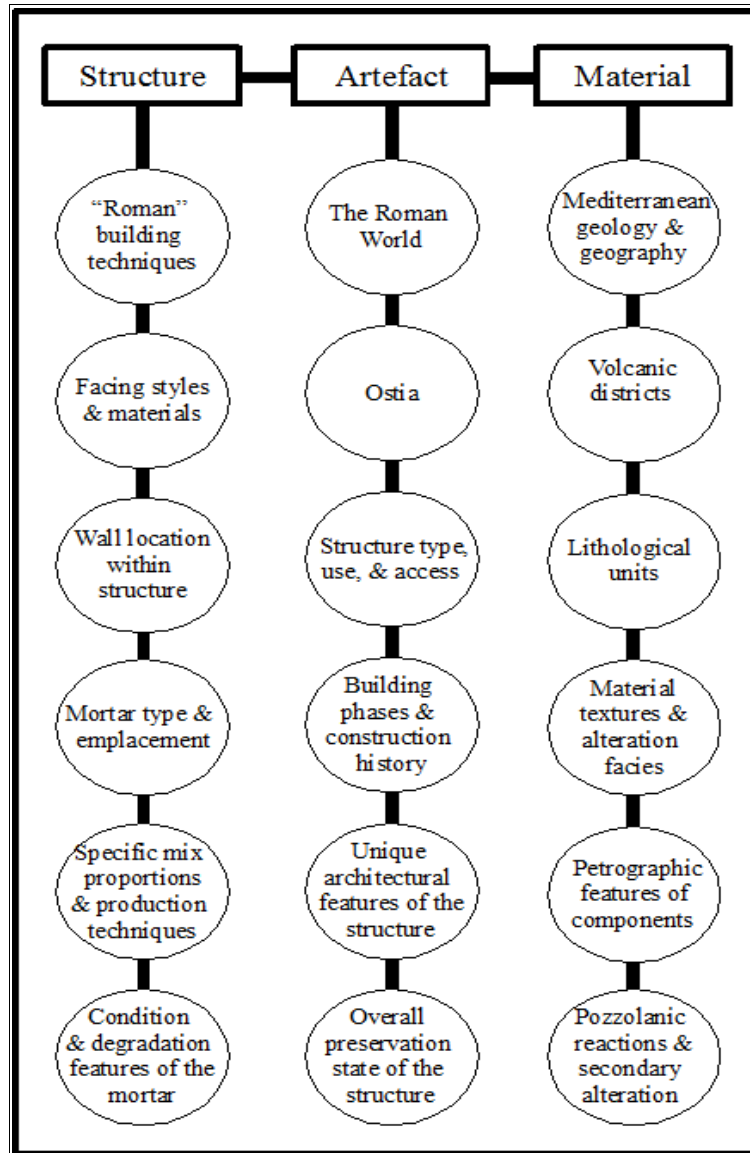


Figure 1.3: Theoretical framework developed for this research.

First, it is important to note that, despite their age, these are structures in the strictest sense. They were works of construction engineering that had to succeed as usable buildings. As such, each had its own specific function and requirements for use. The

same laws of physics and gravity that constrain construction techniques today were at work in the 2nd century CE. Ancient builders faced the same challenges and negotiated with the same forces to complete their projects. The complexity of their technical decisions gives testament to the level of skill the builders employed. Ancient buildings must be evaluated in terms of how the original construction techniques met physical requirements and allowed the structures to perform their intended functions.

Secondly, the ancient structures of Ostia are indeed historic artefacts, which can be studied with traditional archaeological methods. They have a specific archaeological context that can be defined easily in terms of cultural, temporal, and spatial parameters. Ancient builders produced these artefacts using techniques and materials that were influenced by the local building economy at that time. Additionally, historic buildings bear the marks of reconstruction, expansion, and repair which directly reflect their own individual histories within the city itself. The architectural history of a specific structure can be relatively easily interpreted by reading and recording these features. The stylistic typology and evolution of ancient Roman construction have been discussed extensively in archaeological literature (see Chapter 3 for brief review), so evaluating the structures in Ostia from an archaeo-historical perspective is relatively straightforward.

Finally, these masonry structures are, in the simplest definition, synthetic conglomerates of natural geological materials. Stone, clay bricks, concrete, lime, and mortar make good building materials because they react in predictable ways governed by chemical and environmental processes. For centuries, builders have been exploiting those processes to their advantage by combining materials in a way that creates solid, usable structures. The selection of materials for the binder and aggregates and how they

contributed to mortar performance are the keys not only to understanding the durability of the structures themselves (as described in Chapter 2) but also to inferring what level of expertise the builders may have had. Finding patterns in their choices in terms of material properties hopefully will lead to a better understand of what the builders knew about the aggregates they selected.

1.3. Approaches towards understanding builders' choices

Placing the mortar samples within three material contexts creates a theoretical framework that helps direct the research, but this project seeks to elevate the discussion from the realm of these simple properties to the complex human interactions inherent in the building process. The *chaîne opératoire* (“operational chain”) approach involves a systematic examination of the technical procedures required to create an object or engage with technology. This type of analysis has developed from the work of French archaeologist A. Leroi-Gourhan and often has been used to describe prehistoric lithic tool technology.⁹ Each step in the operational sequence is examined in terms of what choices must have been made in order to successfully complete the sequence. Once the sequence has been explored and understood, artefacts can be evaluated to describe how they fit within the sequence. The approach allows researchers to generate hypotheses regarding the specific choices ancient builders were making and, perhaps more importantly, opens the discussion of their agency, intent, and expertise. A systematic examination of the building process can reveal which components and aspects of production should be studied in detail to provide the most useful information.

⁹ Leroi-Gourhan 1993; see also Audouze 2002 and Bar-Yosef and Peer 2009 for further discussion.

An examination of the mortar production process (described more fully in Chapter 2) reveals that ancient builders were making key decisions throughout the sequence. Lime preparation, the type and quantity of aggregate, and mixing techniques all would have had great impact on the performance and quality of the final product. Certain identifiable features in the mortar samples are the result of specific production processes and can provide information about the choices made by builders during original construction. Such variations would represent specific technical decisions with an intended result.

When applied to the production of mortar for ancient buildings, the *chaîne opératoire* approach illustrates the complexity of the system of ancient construction and mortar production. Put simply, structures were only completed because many people made specific choices along the way. A building is designed, materials are selected and gathered, a team of labourers is mobilised, and so on. In this lens, the theoretical framework illustrated in Figure 1.3 actually represents a simplified decision tree that directs the mortar production process from inception to completion. The nodes mark points at which major technical decisions must have been made. Each decision would have been informed by the knowledge, technical skill, and intent of the individuals involved at every step, all of which have left their mark on the final product.

The simplicity of the framework above hides the breadth of experience required by the agents involved and the level of influence that could be exerted by any number of people at every stage in the process. Key elements of the system include funding and design at the higher levels, project management and organization on the local level, procurement of materials, delegation of site-specific labour, and finally, mortar production

and installation at the final stages. The social component, i.e. the collection of people directly involved, ranges from the Roman Emperor in the case of Imperial buildings, to architects, suppliers, site foremen, supervisors, producers, and finally the actual builders.

The degree of influence exerted at each level may vary, but they are all equally important to the process as a whole. Furthermore, decisions made at one level influence those made by individuals at the other levels; this is true in all directions up and down the scale and across the various contexts. When the building patron limits funding, the choice of materials may be restricted, possibly resulting in a necessary change to mortar design mixes, which could negatively affect the overall quality of construction, etc. Likewise, a decision by the building site manager on the lower levels to alter particular aspects of the structural design or to use untested materials could result in a structure of unknown stability and durability, ultimately reflecting poorly on the architect or building patron. The fact that these structures are still standing after nearly 2000 years strongly suggests a knowledgeable and competent group of decision makers at even the lowest levels. The choices made by these particular individuals, the designers and makers of mortar in Ostia in the 2nd century CE, form the basis of this study.

1.4. Research questions

The theoretical framework described above has been employed to carefully direct the focus of the research design and highlight areas that can be informed by scientific material analysis techniques. A key objective of this research project was to identify where in the operational chain individuals would have exerted the most *measurable* in-

fluence. Although the standing remains of Ostia are available for analysis, we have no access to the “invisible” steps in the sequence. In most cases, there are no records of who designed or paid for these buildings. There is no collection of receipts for the purchase of building materials nor a record from where they would have been transported. The samples of mortar are the only testament we have left to the physical process of production, and thus they are our best hope at beginning to understand the builders and the choices they were making. Material analysis can determine whether the final products were produced in a way that most likely would have fostered beneficial properties and limited deleterious features. The selection and material processing of aggregate, which has possibly the greatest impact on the mortar, will be the main focus of this study in the project.

Three general categories of study questions – corresponding to the theoretical framework described above – have informed the research design and the analytical protocol. The first line of questioning investigates the engineering and structural properties of the mortar samples. Key issues will include mortar “recipe” proportions, mixing technique and compaction, and extent of degradation. It will be important to note the proportion of binder, aggregate, and void space as well as the relative abundance of reactive, inert, and destructive inclusions. Evaluation of the macropores can differentiate between void spaces caused by excess water in the original mix, entrapped air and poor compaction during construction, or cracking and material loss from mortar degradation. Here, the mortar will be investigated with techniques defined by and developed for modern concrete science. This aspect of investigation hopefully will demonstrate the

level of skill employed by ancient builders during the original production and installation of mortar.

The suite of collected data also will be evaluated within its archaeological context. Of special note will be any evidence that mortar design mixes were used preferentially, e.g. in structures of different function or presumed social status. Similarly, construction typology will be compared to mortar properties to identify any association between specific mortar mixes and structural design features. Ideally, any obvious social components with direct influence on the original production of the mortar will be identified. Additional questions will investigate any correlation between the samples from Ostia and the archaeological record of structures from Rome.

The final category concerns patterns of material selection, specifically whether builders targeted certain lithological units or alteration provenances for use as aggregate. For example, can the provenance of aggregate materials be identified with petrography? If so, which components should be used for such determinations? Further, is it possible to identify the specific volcanic province, eruptive sequence, and alteration facies of the mortar aggregate? Were builders preferentially selecting specific material and why? Research in this area is primarily concerned with describing the geological aspects of the mortar components, which requires traditional petrographic methods ordinarily employed in the earth sciences. The aim of this section is to investigate how the specific choices made by the builders directly influenced the performance and durability of the final product.

It is worth noting here that the historical aspects, perhaps the most interesting to the traditional archaeologist, can only be answered with any reliability after rigorous

scientific analysis has been completed. Likewise, no reliable conclusions about local trends or regional patterns can be made until the finer details are understood at the lowest levels of the framework. The original conception of this research project began with broad questions about “Roman mortar and concrete” in a very general sense. Initial research began in the top right corner of the framework (Figure 1.3), focussing on the cultural aspects of mortar production throughout the Roman world. More practical, useful lines of inquiry emerged as the project focused more tightly down the scale to the microstructures of the aggregate material. It was quickly evident that the biggest questions could never be answered without detailed investigation of the finer details.

Preliminary research into the above lines of questioning has resulted in the following hypotheses:

1. Samples from all structures comprise lime mortar with volcanic sand fine aggregates.
2. The builders working in Ostia in the 2nd century CE used the same, or similar, materials and techniques in all structures, representing a characteristic building style for this period in this location.
3. The aggregate used in the mortar mixes was selected from the most readily available source of naturally pozzolanic material, resulting in a durable and well-preserved final product.

The scientific testing presented in the following chapters includes physical, chemical, and theoretical evaluations of the samples utilizing petrographic and archaeological methods to falsify the above hypotheses and describe important morphological, compositional, and historical features.

1.5. Thesis structure

Following from this introduction, Chapter 2 comprises a description of the materials and methods used in conventional Roman mortar production, with an explanation of the main components, standard production techniques, and the chemical reactions inherent to the process. Chapter 3 addresses the archaeological aspects of the material, including references to mortar production in ancient literature and the documentation of ancient Roman brick-and-mortar masonry in the archaeological record. The geological context of ancient Ostia is described in Chapter 4 along with petrographic descriptions of the major lithological units in the region, including the potential sources mortar components. The scientific methods used to analyse the mortar samples are detailed in Chapter 5. Summary descriptions of the buildings included in this study and details of mortar sampling locations are included as Chapter 6. Analytical results are reported in Chapter 7, and Chapter 8 presents a discussion and interpretation of the collected data. The conclusion in Chapter 9 summarizes the research aims and results and evaluates the success of this project in reaching the stated objectives.

Chapter 2. Structural and technical aspects of mortar and its production

This chapter introduces the type of masonry constructions observed at Ostia and describes the role of mortar within these structures. Mortar components and production processes are explained within the context of modern materials to simplify the description of technical details. The various chemical reactions that occur within mortars, both during production and after emplacement, are explained along with the petrographic features that may be observed in both preserved and degraded materials. Finally, the details of mortar components, morphology, and preservation are discussed in terms of what we can learn about builders choices by observing these features in collected samples.

2.1. Brick and Mortar Masonry Construction

The type of brick and mortar masonry structures studied in this project typically comprised a conglomeratic concrete core set between stone or brick facings of varying aesthetic styles, recognised widely as “typically Roman” constructions (Figure 2.1).¹⁰ The core of such structures would contain cobble-sized rock rubble coarse aggregate bound by a durable mortar, which was made from hydrated lime and various sand- to fine-gravel sized small aggregates. Rubble materials in the core could vary locally, but in Ostia they typically included tuff, scoria, or brick fragments, as well as fragments of travertine limestone and lava stone.

¹⁰ Adam 1994; Jackson *et al.* 2005; Jackson and Marra 2006; Jackson *et al.* 2009.



Figure 2.1: Remains of concrete walls in Casa a Giardino, Ostia, showing and fragments of extant brick facing on lower third of wall and the exposed wall core with coarse rubble aggregate. Photograph by author.

The construction methods for these structures have been addressed widely in historical literature,¹¹ and a summary of the basic procedure is included here for clarity. Mortar and coarse aggregate were laid as foundations, often compacted between wooden planks that held the material in place until the mass solidified enough to maintain its structural integrity.¹² The wall was then laid atop the foundation in alternating layers of mortar and aggregate, compacting this material while building up the concrete core of the wall in tandem with the outer facing. A masonry facing served as a type of permanent shuttering that would remain intact and eventually become part of the structure itself as the mortar and concrete core cured in place. Facing was constructed in either stone, brick, or a combination of the two, bound by lime mortar (Figure 2.2).

¹¹ See Adam 1994, Wilson Jones 2004, and Dobbins 2007 for broad overviews of Roman construction styles.

¹² Giuliani, *L'edilizia nell'antichità* (2006).

The various types of facings produced different aesthetic effects, but often they were covered with plain or decorated plaster. Unfaced rubble work was eventually replaced by the simplest facing called *opus incertum*, comprising rubble stones placed in semi-regular courses up the extent of the wall (Figure 2.3). Reticulate facing utilized pyramidal-shaped blocks of stone, often tuff, limestone, or basalt, set into a tidy net-pattern across the entire wall face (Figure 2.4). Reticulate evolved to include courses of bricks in regular intervals between sections of reticulate blocks (Figure 2.5). Finally, a great number of structures in Ostia comprise relatively simple facings of neat horizontal rows of brick work (Figure 2.6).

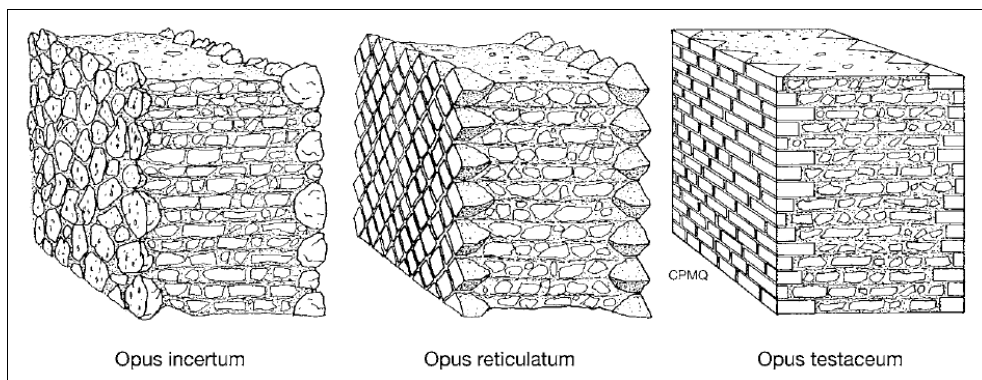


Figure 2.2: Section views of major ancient Roman facing styles. Drawing by L.F. Ball; image source Dobbins 2007, 114.



Figure 2.3: Unfaced rubble work in Casa delle Vestali, Pompeii, similar to the *opus incertum* facing style found in Ostia. B. Photograph by author.



Figure 2.4: Reticulate pattern of tuff blocks, Casa a Giardino, Ostia. Photograph by author.



Figure 2.5: Brick and reticulate work, public latrine, Ostia. Photograph by author.



Figure 2.6: Brickwork from Caseggiato del Larario, Ostia. Photograph by author.

The primary purpose of mortar in masonry is to evenly distribute forces through the structure.¹³ As noted by Binda *et al*,¹⁴ the mechanical performance of brick and mortar masonry depends not only on the materials used but also on the quality of workmanship during construction. The vertical and horizontal joints between bricks should be of consistent width maintaining good alignment; the ratio between the bricks and joints should be consistent and neither too large or too small. Masonry strength is improved with thin joints and potentially reduced with thicker joints, however the negative effect can be mitigated with larger aggregates.¹⁵

2.2. Major Mortar Constituents

When conducting mortar analysis, the major features of interest are the binder, the aggregates, and the void space. These three components play key roles in mortar performance, each contributing to the quality and durability of the mortar during its service life. Lime mortar production is a relatively straightforward process of calcination, hydration, and setting that belies the complexity of the procedure and the chemical reactions involved. The major components of mortar and the major steps of the production process are discussed individually below; Figure 2.7 is a simplified illustration of the mortar production cycle from the original carbonate source to the re-carbonated final mortar.

¹³ Gordon 1991.

¹⁴ Binda *et al* 2009, 35.

¹⁵ Binda *et al* 2010, 1335.

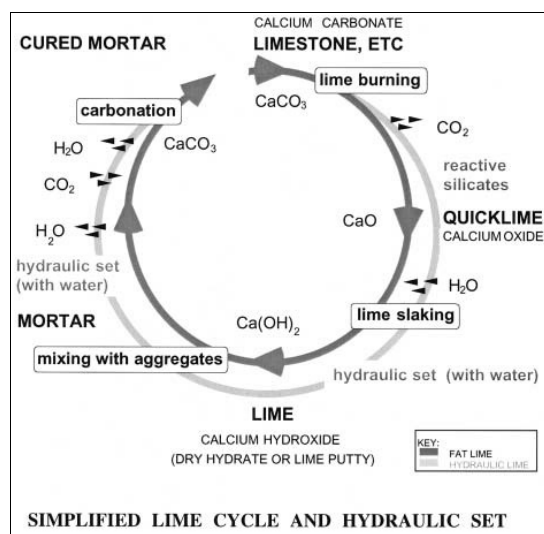


Figure 2.7: Simplified illustration of the lime mortar production cycle, from Leslie and Hughes 2002, 257. For descriptions of lime burning and lime slaking see Section 2.2.1.; for mixing with aggregates see Section 2.3.; and for carbonation see Section 2.4.2.

2.2.1. Binder

A primary constituent of lime mortar is the binder which, in the case of the mortars from Ostia, is lime produced from the calcination – or “burning” – of a carbonate material. One of the most common carbonate sources for lime is limestone, a calcium carbonate (CaCO₃) rock that converts to calcitic lime. Alternatively, calcitic lime also can be made from travertine or tufa, two types of friable limestone that are precipitated within hot or cool water systems respectively.¹⁶ Dolomitic limestone is a calcium magnesium carbonate (MgCa(CO₃)₂) that contains between 20% and 40% magnesium (Mg), and it will produce Mg-rich dolomitic limes. Both calcitic and dolomitic limes have been identified in ancient mortars throughout Italy, however calcitic limes are reported far more often in the literature.¹⁷ When the limestone contains additional constituents, primarily

¹⁶ The term “tufa” here is used in its correct geological definition of precipitous limestone. The traditional archaeological use of the word tufa incorrectly refers to volcanic tuff.

¹⁷ Bruni et al. 1998; Moropoulou, Bakolas and Anagnostopoulou 2005; Jackson *et al.* 2009; Jackson *et*

clays and reactive silicates, the resulting lime will contain calcium silicates, calcium aluminates, and aluminosilicates in addition to calcium oxide.¹⁸ Such limes are considered hydraulic and will harden in the presence of water or when entirely submerged.¹⁹

The carbonate source is calcined in a kiln that should reach maximum temperature of approximately 1100°C for calcitic lime,²⁰ however, the optimum temperature is approximately 900°C, which was typically achieved with traditional kilns.²¹ Dolomitic limes achieve calcination at lower temperatures, typically between 510°C and 750°C, and temperatures over 900°C will result in overburnt particles (Figure 2.8).²² Calcination drives off carbon dioxide (CO₂) leaving calcium oxide (CaO), also known as quicklime, or Mg-lime in the case of dolomitic limes. Quicklime is solid at room temperature but can be easily reduced to a powdery texture. The process results in weight reduction of 44% for calcitic limes or 48% for dolomitic limes.²³ In fact, 1.4 – 2.2 tonnes of limestone is required to generate a single tonne of usable lime.²⁴

al. 2010b; Miriello *et al.* 2013 for just a start.

18 Banfill and Forster, 176.

19 Ibid.

20 Hughes and Valek 2003, 2. The authors note the maximum temperature for lime calcination is lower than that required for the production of other cement compounds found in Ordinary Portland Cement.

21 Moropoulou, Bakolas, and Aggelakopoulou 2001, 633-634.

22 Chever, Pavia, and Howard 2010, 284.

23 Moropoulou, Bakolas, and Aggelakopoulou 2001, 635.

24 Environment Agency 2011.

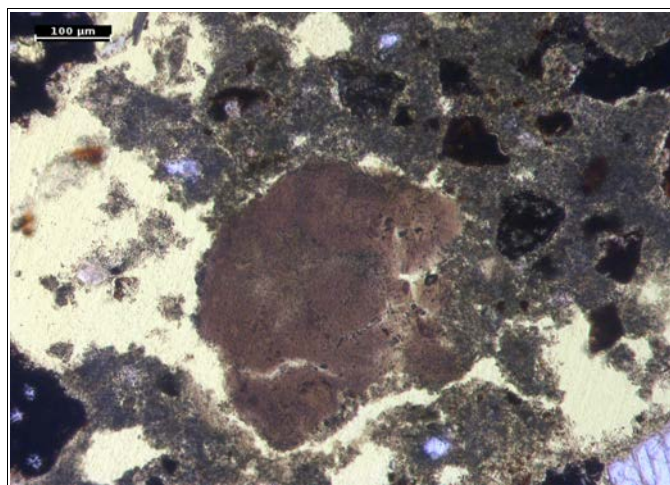


Figure 2.8: Photomicrograph of ancient mortar sample showing an overburnt lime particle (brown). Image collected by author in plane polarised light.

2.2.2. Aggregates

Aggregates, another key constituent, are typically alumino-silicate lithic materials that are mixed with lime to form the binder system. They are typically classed as either coarse or fine, depending on the average size of the particles and their application within a masonry structure. Coarse aggregates serve as bulk filler within the concrete core of a structure, while fine aggregates are found in the mortar that binds the coarse aggregates together in the joints of masonry facings (Figure 2.9, Figure 2.10). The two grades of aggregate are typically classified by size, with any material that would be retained on a 4 mm sieve designated as coarse and all <4 mm material classified as fine aggregate.²⁵ In modern parlance, coarse and fine aggregates are commonly described as gravel and sand, respectively. Although approximately half of the samples collected for this re-

²⁵ As defined in the glossary published by the Applied Petrography Group, Appendix A, which cites international standard BS EN 12620:2002+A1:2008.

search have been taken from the concrete cores, the work primarily focuses on the fine aggregates.

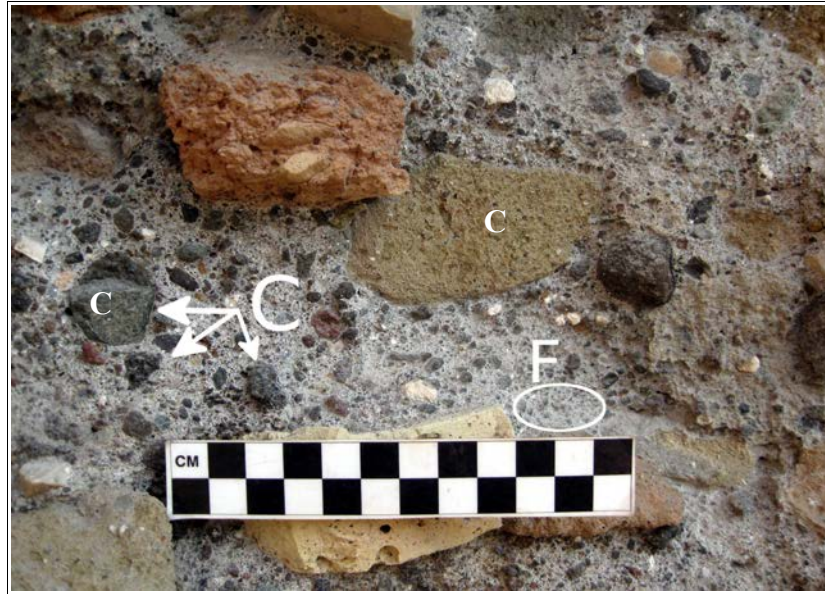


Figure 2.9: Detail photo of concrete core, showing coarse rubble aggregate (marked C) of brick and stone fragments, set in mortar containing fine aggregate (within the circle labelled F) particles of scoria and lava fragments. Photograph by author.

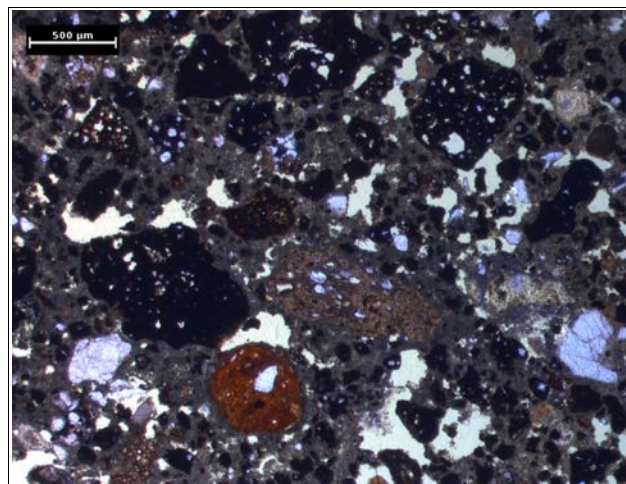


Figure 2.10: Photomicrograph of ancient mortar sample illustrating the variation of fine aggregate size and morphology, including rough, angular particles and smooth, rounded to sub-rounded particles. Image collected by author in plane polarised light.

The importance of selecting appropriate material for the binder and aggregate and employing them properly cannot be overstated. Fine aggregate particles exhibit morphological and chemical features that be either beneficial or deleterious to the mortar matrix. The right material in the right quantity will improve the stability of the matrix and the overall performance of the mortar during its service life.²⁶ Fine aggregates contribute to the strength of mortar through good cohesion with the binder, a bond that improves with surface roughness and vesicularity.²⁷ In the case of rough, vesicular aggregate, such as volcanic tuff, the binder can penetrate the pores on the outer surface of individual particles facilitating better physical cohesion. Furthermore, recent experiments with naturally hydraulic lime mortars have shown that rounded particles with a lower packing density resulted in lower compressive strength than mortars with angular, densely packed aggregates.²⁸

From a chemical perspective, fine aggregates can be either active, inert, or reactive in nature. Active aggregates combine chemically with the lime to produce beneficial calcium-silicate-hydrate (CSH) cements, which help to durably bind the mortar together. Inert materials act as a bulk filler, improving compressive strength without chemically contributing to durability.²⁹ Reactive aggregates are materials that contain unstable forms of silica, such as amorphous, opaline silica, which reacts with alkaline water moving through the binder:aggregate system to form an alkali-silicate gel.³⁰ This alkali-silica reaction (ASR) has been widely documented to cause degradation of the mortar as

²⁶ Stefanidou and Papayianni 2005, 914.

²⁷ Husem 2003, 157.

²⁸ Lanas et al. 2004, 2200; Kalagri, Karatasios, and Kilikoglou 2014, 472.

²⁹ Soroka and Setter 1977, 450.

³⁰ Diamond 1975, 330; Tunçoku and Caner-Saltık 2006, 1892.

the gel expands upon incorporation of water.³¹ The use of porous aggregates, such as scoria or tuff, can mitigate the ASR by incorporating some of the gel into vesicles or by absorbing alkali-rich water, which reduces the amount of gel produced during the initial reaction.³²

Particularly reactive aggregates can be mitigated by controlling the particle size. Smaller particles with a greater specific surface area have been found to increase beneficial activity in mortar during the early stages of setting.³³ Research has shown that the use of particles under 80 μm can reduce or prevent expansion.³⁴ Similarly, mortar with poorly sorted aggregate particles tend to show more ASR associated with particles between 0.63 – 1.25 mm and they show less ASR overall as the proportion of smaller particles increased.³⁵

An important element in mortar production is the size gradation of the aggregate. According to Gonilho Pereira *et al*, mortars with larger aggregates exhibit higher permeability than those with smaller aggregates and also increase the size of the interfacial zone.³⁶ This is the narrow region of transition between the binder and the aggregate, typically 10 to 50 microns wide. These zones are considered the weakest areas of the mortar, which makes them important for mechanical strength and durability.³⁷ The porosity of the interfacial zone can be reduced, and its binder density increased, if the aggregates

31 Urhan 1987, 141.

32 Collins and Bareham 1987, 95.

33 Mertens et al. 2009, 239.

34 Multon et al. 2010, 515.

35 Multon et al. 2010, 515.

36 Gonilho Pereira, Castro-Gomes, and Pereira de Oliveira 2009, 608.

37 Meddah, Zitouni, and Belâabes 2010, 505.

are saturated with water prior to mixing; as then they are less likely to absorb water from the binder which allows for better hydration behaviour within the matrix.³⁸

2.2.3. Void space

While not technically a constituent *per se*, mortar voids are an inherently important feature, typically described in terms of porosity. The total porosity of mortar comprises cracks and spherical pores, which can be distinguished as macropores, mesopores, and micropores, all of which contribute to mortar performance and durability.

Linear cracks observed within the matrix can range in size from large cracks visible in hand specimen, to fine microcracks. Larger cracks often result from structural movement or stresses and typically represent damage to the hardened mortar. These run through the mortar binder and either across or through fine aggregate particles and they can be filled with secondary deposits of redeposited calcite, gypsum, ettringite, or other degradation products (Figure 2.11). Smaller, randomly oriented microcracks often occur as shrinkage during the drying phase.³⁹ It has been shown that the length and width of shrinkage cracks are affected by the diameter and volume fraction of aggregates, with both larger aggregates and decreased volume fraction leading to increased permeability.⁴⁰

As noted by Klemm and Wiggins, pore size is important, as mortar with “large interlinked pores exhibited higher moisture handling capabilities than those with small interlinked pores for a given control porosity.”⁴¹ Macropores (>100 µm diameter) generally include entrapped air voids and entrained air voids, and they can be viewed with

38 Gonilho Pereira, Castro-Gomes, and Pereira de Oliveira 2009, 608.

39 Elsen 2006, 1421.

40 Grassl, Wong, and Buenfeld 2010, 91-92.

41 Klemm and Wiggins 2013, 7.

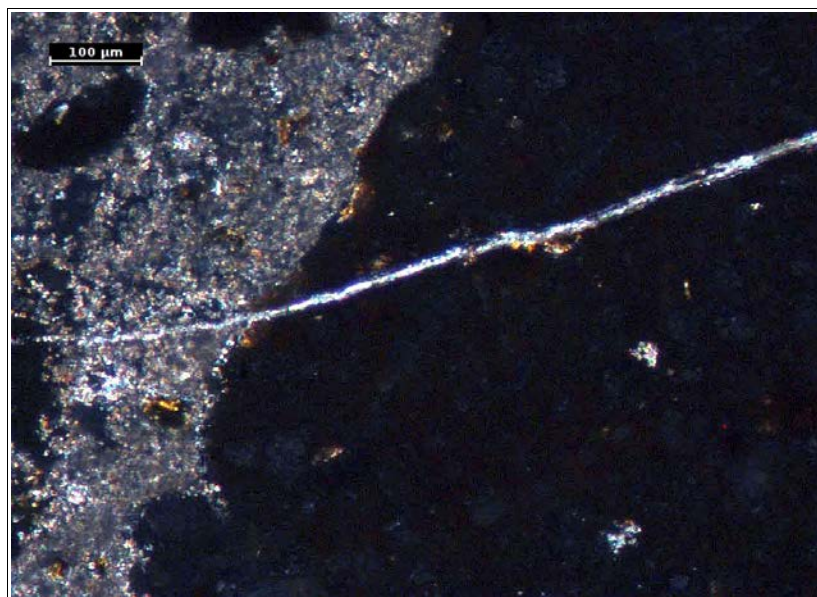


Figure 2.11: Photomicrograph of mortar from Terme del Foro showing a fine aggregate particle exhibiting a fine crack running through both the matrix and a fine aggregate particle. The crack is filled with a secondary calcite deposit. Photomicrograph collected by author in cross polarised light.

either visual assessment or with an optical microscope.⁴² Entrapped voids usually represent air pockets that occur during physical mixing adjacent to aggregate particles.⁴³ As the hydrated (and still plastic) mortar is agitated, irregularly shaped voids form below fine aggregate particles and remain void of any binder material. Air entrained voids are intentionally introduced and preserved within the matrix, which improves workability during production and protects the hardened mortar from freeze-thaw cycles.⁴⁴ Chemical admixtures are used for entraining modern materials, but ancient builders reportedly used protein-based organic materials, e.g. blood, milk, dung, etc., to perform the same function.⁴⁵ Well-rounded pores similar to modern entrained air voids have been observed in ancient and historic mortars (Figure 2.12).⁴⁶ In fact, recent studies have replic-

⁴² Stefanidou 2010, 2572.

⁴³ Elsen 2006, 1421.

⁴⁴ Du and Folliard 2015, 1463. It should be noted that true air entrainment is most commonly observed in ordinary Portland cement concretes.

⁴⁵ Elsen 2006, 1421.

⁴⁶ Elsen et al 2004, 292; Elsen 2006, 1421,

ated traditional lime mortars with added bovine blood, which performed as an agent of air entrainment and ultimately improved the mortars' resistance to weathering.⁴⁷

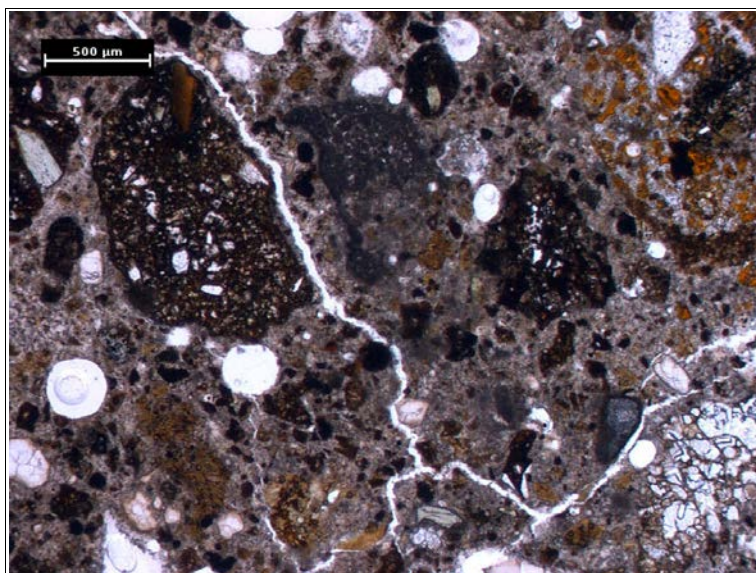


Figure 2.12: Photomicrograph of ancient mortar sample showing rounded to sub-rounded voids and interconnected fine cracks in the binder (appearing white in this image). Image collected by author in plane polarised light.

Mesopores, ranging in size from $0.1\ \mu\text{m}$ to $100\ \mu\text{m}$, and micropores, $<0.1\ \mu\text{m}$, form within the binder and along the binder-aggregate interface during hydration and setting.⁴⁸ These are usually measured with indirect techniques such as liquid absorption or mercury intrusion porosimetry.⁴⁹ Mortars with lower total porosity have less open space within the binder structure, which has been reported to exhibit higher strength values.⁵⁰ The ratio of water to binder is the key to controlling porosity, with less water resulting in a tighter, less open binder matrix.⁵¹ The amount of water incorporated into the

⁴⁷ Fang et al. 2015, 240.

⁴⁸ Stefanidou 2010, 2572.

⁴⁹ Stefanidou 2010, 2575.

⁵⁰ Papayianni and Stefanidou 2006, 702.

⁵¹ Papayianni and Stefanidou 2006, 704.

binder is determined by the method used to hydrate the lime itself and the mixing techniques employed.

2.3. Mixing the materials to make mortar

As noted above, lime mortar comprises lime, aggregates, and water which are combined to form a structurally sound cementitious system. The techniques and specifications used to produce the mortar are as influential to the process as the materials themselves. The traditional techniques most likely used by ancient builders are described below.

Quicklime is mixed with water in a process called “slaking” to create calcium hydroxide ($\text{Ca}(\text{OH})_2$), a hydrated lime slurry known in the modern building trade as slaked lime.⁵² Slaking produces an exothermic reaction, generating heat that evolves quickly and abates as the mixture hardens.⁵³ Experiments to replicate Roman lime plaster floors have measured slaking temperatures at nearly 250°C.⁵⁴ Bröckerbaum, Funke, and Zier have also shown that introducing large lumps of lime, rather than finer ground particles, can significantly increase the slaking temperature.⁵⁵ Quicklime doubles in volume once it has been slaked.⁵⁶ Traditionally, lime has been either wet slaked or hot mixed.

Wet slaked quicklime is hydrated to form a putty, which is then stored wet for a period of time (from several months to several years) before use, with better performance being achieved with longer storage times.⁵⁷ Mortars made from putty limes can ex-

⁵² Leslie and Hughes 2002, 257.

⁵³ Irabien, Toquero, and Ortiz 1989, 93-94.

⁵⁴ Bröckerbaum, Funke, and Zier 2013, 3.

⁵⁵ Bröckerbaum, Funke, and Zier 2013, 3.

⁵⁶ Copsey and Gourley 2013, 8.

⁵⁷ Hansen et al. 2000, 204.

hibit a high binder content and full coating of the aggregate particles.⁵⁸ Hot-mixed lime, or “dry slaked lime”, is hydrated on-site at the time of mortar production and emplacement, which produces a high-strength mortar.⁵⁹ In this method, dry quicklime is added to wetted aggregates and mixed with a minimal amount of water that generates a workable mixture and fosters the conversion from CaO to Ca(OH)_2 .⁶⁰

Recent works suggest dry slaked lime mortars exhibit an overall better performance in terms of compressive strength than lime putty mortars; dry-slaked mortars will triple in strength over a period of 15 months, while that of lime putty mortars will only double.⁶¹ However, the dry slaking technique requires a skilled application in order to ensure the mortar is mixed well enough to prevent large lumps of unincorporated lime in the binder and properly hydrated to prevent rapid drying and cracking from shrinkage, features that have been reproduced with recent experiments.⁶² Traditionally, it seems these issues have been addressed by builders in the past, as dry-slaked historic mortars have been widely reported in the literature to exhibit good compaction and an absence of significant cracking from rapid drying.⁶³

As noted above, discrete lime lumps and streaks of lime in the matrix are commonly viewed as the distinguishing features of dry-slaked lime.⁶⁴ It should be noted, however, that three different types of lime lumps can be present in the binder of cementitious materials: overburnt lime, underburnt lime, and what Elsen calls “lime lumps

58 Valek and Matas 2010, 1238.

59 Hughes and Valek 2003, 50; Callebaut et al. 2000, 123.

60 Henke and Thiemann 2013, 5.

61 Moropoulou et al. 2005, 291.

62 Valek and Matas 2010, 1235.

63 Valek and Matas 2010, 1239.

64 Copsey and Gourley 2013, 7.

sensu stricto.”⁶⁵ The first two form in the kiln during lime burning as a result of uneven temperature condition gradations or improper temperature controls, but the origin of rounded, porous *sensu stricto* type lumps may be directly related to the physical mixing process.⁶⁶ Recent studies suggest they form after incomplete or improper slaking or mortar mixing, because plasticity is lowered and workability reduced when the water/lime ratio is low.⁶⁷ Dolomitic lime requires more water and a longer slaking time than calcitic lime,⁶⁸ and thus lime lumps can form when lime has been produced from a dolomitic lime. On the other hand, Bruni *et al* hypothesize these lumps form as a “carbonate crust” when hydrated lime is left to cure before use, suggesting the mixing process is not to blame, but imprecise sieving of the hydrated lime during mortar production.⁶⁹ Experimental tests have reproduced these lumps with dry slaking using minimal amounts of water, which leaves some of the lime under-hydrated and therefore unincorporated into the binder.⁷⁰ Regardless of their cause, an over-abundance of these lime lumps *sensu stricto* in a mortar seems to indicate a lack of strict quality control somewhere in the process.

Attaining the appropriate proportion of binder to aggregate is essential for ensuring proper setting times and determining the overall quality of the final product. Recent experiments have shown that a binder/aggregate ratio of 1:3 will improve early strength values in lime-pozzolan mortars, but they cure more quickly through rapid carbonation, which limits the beneficial pozzolanic reaction.⁷¹ Mortars containing fine aggregates

⁶⁵ Elsen 2006, 1420.

⁶⁶ Ibid.

⁶⁷ Bakolas et al. 1995, 815; Hughes and Cuthbert 2000, 598.

⁶⁸ Arrizi et al 2012, 247; contra Chever et al. 2010.

⁶⁹ Bruni et al. 1997, 6.

⁷⁰ Elsen 2006, 1421 citing K. Callebaut and K. Van Balen 2000.

⁷¹ Gameiro et al. 2014, 271.

less than 4 mm in size with a binder/aggregate ratio between 1:1.5 and 1:3 also will exhibit good strength values after one year.⁷² A higher binder/aggregate ratio of 1:1 can increase long-term strength by encouraging pozzolanicity for longer, but these high-binder mortars can suffer from eventual shrinkage.⁷³

2.4. Chemical Reactions

After production and emplacement, mortar quality and performance depend on the chemical behaviour and interaction of the constituents. Cementitious phases form within the matrix during production via pozzolanic reaction and as the mortar cures after emplacement via carbonation. Secondary phases form through the interaction of the binder and the aggregate via pozzolanic reactions or through reaction degradation mechanisms. The type and nature of cementitious phases and secondary products are described below.

2.4.1. Cement phases in lime mortars

The cement phases that can form within the matrix of lime mortar include calcium carbonate (CaCO_3), calcium hydroxide ($\text{Ca}(\text{OH})_2$), alite (tricalcium silicate, C_3S in cement notation), and belite (dicalcium silicate, C_2S).⁷⁴ Calcium-silicate-hydrate (CSH) and calcium-silicate-aluminate-hydrate (CASH) are hydration products that also can form within the matrix, typically forming as amorphous gels.⁷⁵ The gel fills pore spaces in the binder, adding impermeability and lowering the porosity.⁷⁶

Studies of cementitious hydrates in mortars from Imperial-age structures in Rome have surprisingly high alkaline (high $\text{K}_2\text{O} + \text{Na}_2\text{O}$) compositions, with high silica:alu-

⁷² Stefanidou and Papayianni 2005, 919.

⁷³ Gameiro et al. 2014, 271.

⁷⁴ Pavia 2008, 2.

⁷⁵ Taylor 1964a, 167-232; Dolado, Griebel, and Hamaeckers 2007, 3938.

⁷⁶ Banfill and Forster 2000, 178.

mina ratios (Si/Al), and low calcium:silica (Ca/Si) ratios, in contrast to modern concretes which tend to have lower alkali concentrations and higher Ca/Si.⁷⁷ Cementitious hydrates with alkali- and alumina-rich compositions most likely result from the pozzolanic reaction with the alkali- and aluminium-enriched volcanic glass of Roman pyroclastic deposits.⁷⁸ The morphology of CSH and CASH phases can vary, but they tend to appear fibrous, platey, in a honeycomb-like structure, or a netlike (“reticular”) framework (Figure 2.13).⁷⁹ Their presence and abundance in the mortar fabric can indicate the degree of pozzolanic activity and possibly, the cohesion of the cementitious matrix. Certain radial spherulite crystals have been identified as strätlingite (C_2ASH_8 , Figure 2.14) through X-ray diffraction analyses.

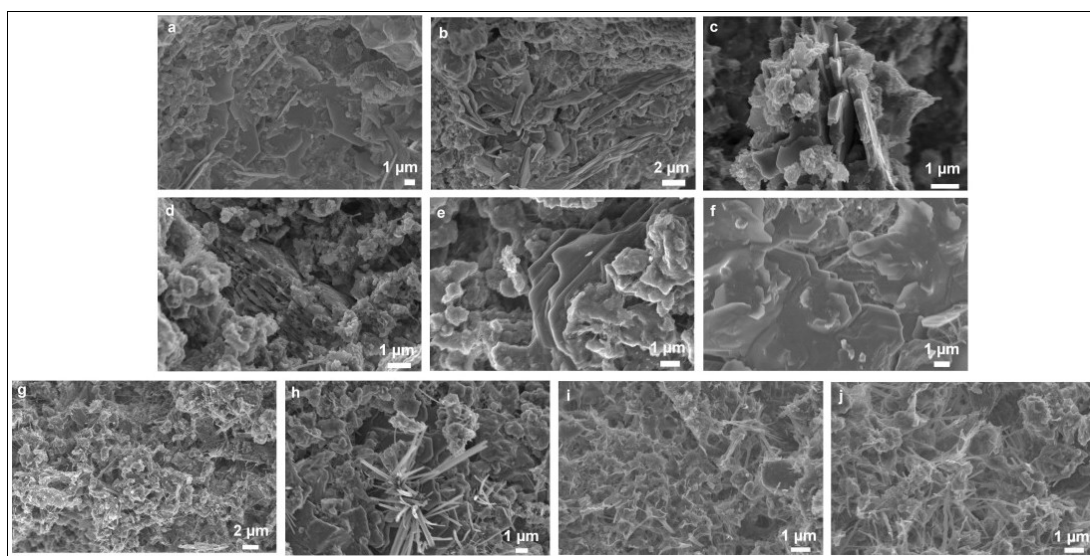


Figure 2.13: SEM images of the hydrated phases formed after pozzolanic reaction in mortars: Randomly oriented, hexagonal aluminate phases (a) and (b); overlapping sheets of aluminate observed (c) and (d); aluminate crystals oriented along the [001] direction (e); smaller aluminate crystals precipitated in the matrix with hexagonal habit and identical orientation (f); CSH fibres (g) and isolated flakes CSH (h); honeycomb structure (i) and reticular network (j) of silicate hydrates. Modified from Arrizi and Cultrone 2012, 139.

⁷⁷ Jackson et al. 2010a, 44.

⁷⁸ Jackson et al. 2010a, 44.

⁷⁹ Arrizi and Cultrone 2012, 139.

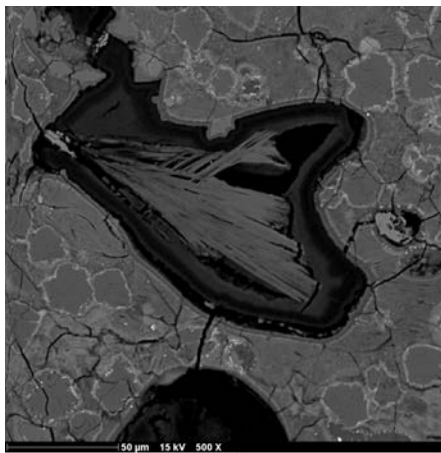


Figure 2.14: Strätlingite in vesicle of fine aggregate fragment in mortar sample from the Terme del Foro. Photomicrograph collected by author.

2.4.2. Carbonation

Lime mortars harden through carbonation, absorbing carbon dioxide (CO_2) from the environment, which moves through the internal pores of the binder and converts the calcium hydroxide ($\text{Ca}(\text{OH})_2$) to calcite (CaCO_3).⁸⁰ The process increases the weight of the hydrated lime by approximately 35%, closing the pores and reducing permeability.⁸¹ Carbonation requires the presence of moisture and will cease if the mortar becomes too dry too quickly, however, the carbonation reaction will slow if the mortar is too saturated. The carbonation rate of a lime mortar has been shown to be maximised when “about 50% of its pore volume is filled with water,” which sometimes requires active control during the mortar set.⁸² The carbonation front moves from the exterior of the sample inward, and continues until the CO_2 has converted all of the $\text{Ca}(\text{OH})_2$ or all of

⁸⁰ Moorehead 1986, 701. This section discusses the carbonation of lime mortars only. Carbonation in Portland cement materials is considered a form of degradation, a matter which is not addressed here.

⁸¹ Moorehead 1986, 701.

⁸² Moorehead 1986, 703.

the water within the system has evaporated from the exothermic reaction generated via carbonation.⁸³ The calcium carbonate formed with this reaction generally forms with an amorphous or microcrystalline structure, similar to that of the CSH/CASH gels, which improves mortar strength and reduces permeability.⁸⁴

2.4.3. Pozzolan reactions

Pozzolan materials are alumino-silicates that react with water and lime to form cementitious compounds in mortar or concrete both during production and over time, following the initial set. The silica involved must be glassy or amorphous to be reactive, meaning opaline silica, zeolites, clays, volcanic ash, and pumice are naturally pozzolanic materials.⁸⁵ Pozzolans provide numerous morphological, chemical, and mechanical benefits to the hardened mortar. During the initial reaction of mortar production, pozzolanic material releases alumina and silica into the pore solution that recombines with lime to form a silicate gel, the CSH and CASH phases described above.⁸⁶ These binding cements close pore spaces within the matrix, reducing permeability, and increasing compressive strength.⁸⁷ Most importantly, pozzolanic mortars are highly durable because they have a greater resistance to the destructive effects of the alkali-silica reaction and to degradation by the attack of sulphates.⁸⁸

Ceramic materials can act as a synthetic pozzolan that encourages the development of durable cementitious phases in the mortar as it sets, and under certain conditions impart hydraulic properties to the mortar. The ceramics must be made with a high percent-

83 Moorehead 1986, 704.

84 Moorehead 1986, 707.

85 Mumpton 1999; Lewis et al. 2003; Habert et al. 2008.

86 Mertens et al. 2009, 233.

87 Turanli, Uzal, and Bektas 2004, 2277; Gamiero et al. 2014, 266.

88 Mertens et al. 2009, 233.

age of clay, and they must have been fired at low temperatures (under 900°C).⁸⁹ The low firing temperatures attainable in ancient kilns meant that the ceramics produced were often naturally pozzolanic.⁹⁰

2.5. Evaluating mortar performance

The major components of lime mortar and their key properties have been described above, along with the chief chemical reactions that drive the system. The ultimate quality and durability depend on the interaction between the components, and the features of durability and degradation are observable with modern petrographic analysis techniques.⁹¹

2.5.1. Petrographic features of durability

Mortars that have maintained a good state of preservation will exhibit good cohesion *in situ* and will not show extreme friability, extensive cracking, or discolouration.⁹² Microscopical studies may also reveal a good bond between the binder and the aggregate, which should exhibit only limited parting at the interfacial zone. Well-produced lime mortar should exhibit a limited proportion of over- or underburnt lime particles. The binder of a well-preserved mortar should be well-distributed throughout the sample, with rare to no evidence of leaching, dissolution, or material loss. Cracking will be minimal and should not affect the binder-aggregate cohesion or otherwise disrupt the binder matrix.⁹³ A mortar in good condition generally will be free of destructive secondary

⁸⁹ Baronio and Binda 1997, 46.

⁹⁰ Philokyprou 2012, 314.

⁹¹ Poole and Sims 2015, 385-612.

⁹² Tikalsy 2009, 32.

⁹³ Examples of mortars exhibiting most of the above characteristics have been observed in ancient Roman mortars from Spain, Pavia and Caro 2008, 1811.

products, such as ettringite, gypsum, or ASR-related gels. It is expected that good quality lime mortars will be fully carbonated. It is perhaps simpler to describe mortars in good condition as lacking the major features of degradation, which are described below.

2.5.2. Petrographic evidence of degradation

One of the most immediately obvious signs of mortar instability is significant cracking in the mortar surface and the loss of bond between the mortar and the masonry. Structural damage results in large cracks, as noted above, and internal weakness of the binder matrix leads to finer microcracking. Environmental weathering can erode the outer surface, causing reduction of the binder, discolouration, and weakening of the binder-aggregate bond. One of the most damaging aspects of environmental exposure is the ingress of water through the mortar, which can cause a host of physical and chemical change that can lead to weakness, degradation, and eventual mortar failure.⁹⁴

The movement of moisture through the binder can cause dissolution and transport of the matrix, known as leaching, which leaves behind a weakened binder structure. Leached areas are observable with a petrographic microscope using fluorescent light, and can be identified with an electron microscope as areas with a lower calcium to silica ratio. Secondary degradation products are usually observable with petrographic methods, including microscopical analysis of thin sections or electron microscope studies of polished specimens.⁹⁵

As water moves through the matrix, causing dissolution, it can react with the binder to form new compounds that can be actively damaging. A number of secondary alteration minerals, including hydrotalcite, hydrocalumite, and ettringite, have been ob-

⁹⁴ Nijland et al. 2007, 2.

⁹⁵ Amo and Perez 2001; Poole and Sims 2015.

served in hydraulic lime mortars and ancient Roman concretes.⁹⁶ Ettringite is a well-known degradation product that forms in pores secondarily to mortar production.⁹⁷ Much like ASR-gels described above, such compounds cause degradation via expansion, which damages the mortar on a microstructural level. Likewise, the detection of soluble salts, such as halite (NaCl), gypsum ($\text{Ca}_2\text{SO}_4 \cdot 2\text{H}_2\text{O}$), thenardite (Na_2SO_4), and various nitrates or chlorides, can suggest some degree of mortar degradation.⁹⁸ Brucite ($\text{Mg}(\text{OH})_2$), can occur through degradation of marine concretes.⁹⁹

In summary, the condition of a particular sample of mortar is rather easily determined by investigating the material with common petrographic methods. While initial visual inspections can provide a good deal of information about the overall condition and state of degradation, deeper investigations can be invaluable. Evaluation of the binder microstructure and its interaction with aggregate particles can uncover the finer details of the mortar's current condition and reveal the nature of specific degradation mechanisms.

2.6. What we can learn about builders' choices from evaluating these features

It has been shown with the discussion above that a great many factors contribute to the quality and durability of lime mortar. The selection of individual components and mortar preparation techniques affect the properties of the hardened material in specific and observable ways. This material record makes it possible to investigate the choices made by the individual builders on these two fronts.

⁹⁶ Biscontin, Pellizon Birelli, and Zendri 2002. 35; Vola et al. 2010, 383-387.

⁹⁷ Sabbioni et al. 2001, 546, citing Taylor et al. 1994.

⁹⁸ Bendetti et al. 2004; Nijland et al. 2007, 2.

⁹⁹ Nijland et al. 2007, 2.

Identification and evaluation of the fine aggregate of ancient mortars might be the key to understanding what the ancient builders were doing. The specific type (lithology) of material they selected can reveal what they considered usable material, where they looked for aggregate sources, and how different types of material may have individually performed in these mortars. Evaluating the aggregates can determine to what degree the ancient builders controlled what went into their mortars. Choosing naturally pozzolanic materials, or supplementing mixes with additional pozzolans, would very likely have resulted in especially high-grade mortars that might be expected to perform well.

Aggregate morphology is another simple yet easily controllable factor that can affect the quality of mortar. If builders controlled particle size to less than medium gravel, they could have limited the influence of the weaker interfacial zones of the larger particles, increasing mechanical durability and reducing the permeability of the hardened mortar. Again, it is possible to not only evaluate the size and shape of aggregate particles, but to investigate the interfacial zones for potential weakness.

Similarly, one can investigate the properties of lime binder, the degree of mixing, and the unhydrated lime lumps present in the binder for evidence of the method and quality of mortar preparation. The quantity and properties of over- or underburnt lime particles can reveal details of the initial lime calcination, including potential temperatures in the kiln or the original carbonate source. The extent of shrinkage can indicate slaking methods or the abundance of water involved in the initial mix. These and other observations are invaluable to understanding the specific decisions made by the builders throughout the process, not just in terms of what they were doing, but how well they did it.

The monuments the ancient builders have constructed stand as testament to the craftsmanship they demonstrated in their day. Cataloguing and assessing the remains of ancient structures is one way to understand the level of expertise demonstrated by the producers of the ancient builders. The next chapter addresses lime mortar and concrete masonry in the archaeological record.

Chapter 3. Archaeological perspectives

This chapter discusses the archaeological context of the structures in this study examining the ancient texts, historical literature, and archaeological records devoted to the use of ancient mortar. The chapter starts with a review of ancient texts that describe lime mortar, its components, and production techniques. The next section introduces brick and mortar masonry as objects of fascination for archaeologists by examining their importance within Roman society, as discussed by scholars such as Ward-Perkins, MacDonald, and DeLaine. This is followed by a review of specific brick and mortar masonry structures that have been recorded in the archaeological records of Rome. Finally, this chapter discusses the problems with traditional archaeological investigations of lime and introduces the alternative approach utilised in this project.

3.1. Lime mortar constructions in ancient texts

As noted above, the development of brick and mortar masonry, and lime-based mortar and concrete in particular, apparently affected ancient Roman society in very real ways. Fortunately, the observations of archaeologists and architectural historians can be bolstered by the works of ancient writers, who have recorded their own thoughts on the subject. This section describes the extent to which the use of lime mortar in masonry construction is attested in ancient Latin and Greek texts.

The earliest surviving references to lime mortar masonry are found in *De Agri Cultura* by Marcus Porcius Cato (234 -149 BCE), dating from the middle of the 2nd century BCE, although the most well-known is Book II of *De Architectura*, a treatise on construction techniques and materials written between about 30 and 25 BCE by Vitruvius.

This book includes recommendations for the type, quality, source locations, and preparation techniques of limestone and pozzolanic aggregate, as well as preferred mixes for different types of mortar. Because they can be verified with extant structures, these texts offer some insight into the technological proficiency of ancient builders. They provide modern scholars with a framework from which to evaluate ancient building standards, preferences, and techniques.

In Book II, 8.17 of *De Architectura*, Vitruvius lauded *opus caementicium* above mud-brick structures, which were not structurally sound enough for more than a single storey without the walls becoming too thick. Regulations specified a maximum thickness for shared walls, and concrete construction could stay well within the requirements of one and a half Roman feet.¹⁰⁰ This new way of building at height provided accommodation for more people than ever before. Here, Vitruvius offers a solution to the problems arising from a growing population in a city with limited space for new housing. This passage exemplifies innovation in the building industry, offering new solutions to emerging problems.

Another regulation describes the expected life of these rubble and concrete walls, suggesting that the limitations of the components were understood as well. Vitruvius refers to a model of property valuation that accounts for a structure's age by deducting an 80th part of the initial build cost for each year that has passed. By implication, the walls should be expected to last no more than 80 years.¹⁰¹ By contrast, this formula was not applied to mud-brick walls, which were valued at their construction cost as long as they were structurally sound.¹⁰² The inherent differences between concrete rubble and

100 Vitr. De Arch. II, 8.17, translated by Rowland and Howe, 2001.

101 Vitr. De Arch. II, 8.8.

102 Vitr. De Arch. II, 8.9.

mud-brick masonry were apparently well-understood in terms of structural performance, to such a degree that property valuation was dependant on the constituent materials.

Cato briefly mentioned mortar as a standard necessity for the construction of agricultural buildings in his *De Agri Cultura*. He says the owner of a house under construction should provide “stone, lime, sand, water, straw, and earth for making mortar.”¹⁰³ That Cato mentions mortar as a necessity for domestic building suggests it had been in use for long enough that popular standards had developed prior to the 2nd century BCE.

Cato and Vitruvius described in detail the basic production techniques, engineering performance, and unique requirements of mortar and stone masonry. For example, Vitruvius refers to *opus incertum* as “the old style” that “is not pretty but is more durable than reticulate construction”, which has “discrete seams and junctures in every direction”¹⁰⁴ Here, Vitruvius exhibits some knowledge of the structural performance qualities of these building techniques. In fact, the relatively regular distribution and low number of joints between the rubble of the *opus incertum* facing has an advantage over reticulate, which has smaller, more abundant joints between small stones and/or bricks.

The same passage goes on to explain in more detail that, regardless of construction style, a good quantity of hydrated lime mortar will produce a more robust structure. Vitruvius specifically notes that soft, porous building stone will absorb moisture from the mortar, ultimately destroying the material, so the higher quantity of mortar used in *opus incertum* facing will prolong the service life of the structures compared to those with *opus reticulatum*.¹⁰⁵ The “soft and porous” stones he describes most likely refer to the

103 Cato *Agr. Org.* XIV.3.

104 Vitr. *De Arch.* 2.8.1.

105 Vitr. *De Arch.* 2.8.1.

volcanic tuff quarried in Italy's volcanic regions for use as building stone. The tuffs of Italy, primarily composed of lithified volcanic ash, are soft enough to be cut and shaped but durable enough to bear weight in structures.¹⁰⁶ Their naturally porous nature does indeed result in the tuffs taking on moisture, which could result in a less durable mortar by causing it dry too quickly but may also assist with the beneficial pozzolanic reactions, as noted in Chapter 2.¹⁰⁷ Such observations illustrate the ancient builders' knowledge and understanding of the mechanical behaviour of the materials commonly used in the construction industry at that time.

The sophistication of the ancient building trade appears to have extended to the recognition of the chemical behaviour of the individual components. Sextus Julius Frontinus (ca. 40 –103 CE) reveals his cursory understanding of technical requirements with recommendations for the preferred time of year to work with concrete. He writes in *De Aquaeductu Urbis Romae* that the ideal time is from April to November, with a break during the heat of high summer.¹⁰⁸ He goes on to explain that mortar sets best in moderate weather and that mortar masonry can be damaged by excessive heat.¹⁰⁹ This seems to reflect an empirical understanding of the importance of mortar hydration and reducing evaporation from the concrete as it cures to prevent rapid drying. These observations have been confirmed by modern researchers who have shown that consistent hydration throughout the curing mortar process will result in a more thorough cementation and improved durability.¹¹⁰

106 Jackson et al. 2005; Jackson and Marra 2006; Karner et al. 2001. The tuffs found in the vicinity of Rome and Ostia are described in more detail in Chapter 4.

107 Malacrino 2010, 117.

108 Frontin. *Aq.* II.123.2.

109 Frontin. *Aq.* II.123.

110 Valek and Matas 2010, 1235.

Cato details the specifics of lime kiln construction and operation, outlining the size and configuration of the kiln itself.¹¹¹ According to his instructions, the fire in the kiln should not be allowed to die down until the burning process is complete, which will be evident when the stones at the top of the kiln appear calcined and the flame emits less smoke.¹¹² Cato's observations are indeed correct; to ensure proper and complete burning of the entire load, the kiln must be heated right temperature, ideally 900°C, which must be maintained for a throughout the firing process.¹¹³

Cato outlines the stipulations for “proper terms of a contract for burning lime on shares,” in which the “burner,” (responsible for cutting the wood, preparing the kiln, and burning and removing the lime) is distinguished from the “owner” of a kiln, who furnishes the “necessary stone and wood for the kiln.”¹¹⁴ In this passage, Cato seems to refer to dedicated lime burning professionals who would be sub-contracted to supply the prepared lime for a specific structure. This hints at a sub-industry within the building trade that handled lime processing and kiln operation. Although the identity of the burner remains unclear, this passage adds an extra layer of complexity to the ancient building economy.

Ancient authors were equally aware of such stipulations and carefully outlined their preferences for lime source material in the ancient texts. It was believed the original limestone should be white in colour, as noted by Cato, who calls for “good stone, as white and uniform as possible.”¹¹⁵ Vitruvius likewise calls for “white stone” when se-

111 Cato *Agr. Org.* xxxviii.1-5.

112 Cato *Agr. Org.* xxxviii.4.

113 Moropoulou, Bakolas, and Aggelakopoulou 2001, 633-634.

114 Cato *Agr. Org.* xvi.

115 Cato *Agr. Org.* xxxviii.2.

lecting sources for lime.¹¹⁶ Ancient builders apparently used a simple aesthetic quality as a proxy evaluation to select for relevant chemical properties that are in fact beneficial to the mortar. However, limestone source material was evaluated further than by simple appearance. Vitruvius recommends dense, compact stone for structural walls, reserving more porous stones for plaster.¹¹⁷ His hard stone may refer to marine limestones; his references to stone from river-beds and to porous stone may refer to calcareous tufa, a type of limestone precipitated within cool, fresh water systems.¹¹⁸

Both ancient and modern sources make note of the physical changes inherent to calcination. Vitruvius correctly notes that lime retains its original bulk yet is reduced in weight, however he mistakenly attributes this to the loss of moisture.¹¹⁹ Vitruvius also writes that burning the limestone reduces its inherent strength and leaves the stone with “wide-open pores and voids,” which allow the lime to better combine with aggregate during the mortar mixing process.¹²⁰

In terms of slaking, Pliny cites “the old building laws” requiring the use of lime slurry (*calx intrita*) no less than three years old, which he notes is of better quality than freshly made lime.¹²¹ Here again, the reference to old standards indicate an element of regulation and a tradition of quality control standards within the building trade that would be difficult to identify without the ancient text. Unfortunately, it is difficult to determine the extent to which such standards were enforced or followed in practice. For his part, Vitruvius documented the natural exothermic reaction involved in the hydration

116 Vitr. *De Arch.* II.5.1.

117 Vitr. *De Arch.* II.5.1.

118 Ford 1996, 117.

119 Vitr. *De Arch.* II.5.3.

120 Vitr. *De Arch.* II.5.2.

121 Plin. *HN* 36.55.174.

of lime when it was submerged in water, providing a detailed description of sophisticated phenomena.¹²²

The different types of sand available to be used as aggregate were distinguished by several ancient authors, who also described their variable efficacy in the final product. Cato used the simple term *harena* for sand¹²³ without specification of its origin, though Blake believes he may have been referring to river sand (but offers no convincing argument for her supposition).¹²⁴ Vitruvius was careful to distinguish between the different types of sand available to Roman builders.

According to Vitruvius, pit sand (*harena fossicia*) is recommended for concrete and rubble masonry because mortar made with this material will dry quickly and will become strong enough to support vaulting when used soon after excavation.¹²⁵ The two remaining types of sand, river sand (*harena fluviativa*) and sea sand (*harena marina*), could be used when pit sand was unavailable; however this would create an inferior product that dried more slowly and could not support vaulting.¹²⁶ Vitruvius lists four types of pit or quarry sand, including “black, white, light red, and dark red,” but the best material “crackles when a few grains are together in the hand.”¹²⁷ It should be free of too much earth (*terra*) and would be considered suitable if it left no mark on a white garment.¹²⁸ Vitruvius claims fresh pit sand is preferable to stored *harena fossicia*, which can degrade and disintegrate with time and exposure.¹²⁹ He notes that pit sand is plenti-

122 Vitr. *De Arch.* II.5.2.

123 Cato *Ag. Org.* XIV.3.

124 Blake 1947, 316.

125 Vitr. *De Arch.* II.4.1, 3.

126 Vitr. *De Arch.* II.4.2.

127 Vitr. *De Arch.* II.4.1.

128 Vitr. *De Arch.* II.4.1.

129 Vitr. *De Arch.* II.4.3.

ful in Italy and Tuscany but is not available to the east of the Apennines.¹³⁰ Here, these authors have indicated a preference for specific types of sand—as well as the best conditions for its use—which suggests a complex understanding of material properties and performance. This level of understanding would have been indispensable during mortar production.

The benefit of using pozzolanic materials to improve cohesion in mortar and concrete was seemingly understood by Vitruvius. This material, often referred to as *pulvis puteolanus* and now recognized as volcanic ash, is found in Campania, near Baiae and close to Mount Vesuvius.¹³¹ Not only would *pulvis puteolanus* add strength to buildings, but it could set under water during the construction of piers.¹³² Vitruvius distinguished *pulvis puteolanus* from the various forms of *harena*, apparently recognizing it was imbued with unique material properties that affected mortar performance.

A number of other writers also describe this natural powder that was especially fit for purpose. Lucius Annaeus Seneca (ca. 3 BCE – 65 CE) recognizes the hardening capacity of “the dust of Puteoli becomes rock if it touches water,” though he does not mention lime.¹³³ Dio Cassius (between 155 and 164 CE – after 229 CE) later describes the tendency of this material to “become porous and when exposed to the dry air crumble into dust, but when mixed with water and lime become compact, and as long as they remain in the liquid they harden and petrify.”¹³⁴ The ancient references to this dust suggest an understanding of the behaviour of volcanic ash within the mortar and concrete mix. Here, these writers have described a technique for mortar *improvement*

130 Vitr. *De Arch.* II.6.5.

131 Vitr. *De Arch.* II.6.1.

132 Vitr. *De Arch.* II.6.1.

133 Sen. *Q Nat* 3.20.3.

134 Dio Cass. *Hist.* 48.51.4.

through specially selected materials, which illustrates sophistication, experimentation, and technological development within building industry.¹³⁵

The details of specific mortar mix designs also have been described by ancient authors, and they tend to vary according to material and function. For example, Cato suggest an optimal sand to lime ratio for enclosure walls: “one modius of lime and two modii of sand for each linear foot.”¹³⁶ Vitruvius stipulates that mortar for standing structures should be made with three parts pit sand to one part lime.¹³⁷ Vitruvius also specifies that mix proportions should change when river or sea sands are used. He writes that an additional one part of ground and sieved burned brick or crushed potsherds should be added to improve the mortar’s performance.¹³⁸

The ancient texts also include mix designs and technical recommendations for the use of lime-based mortar and concrete in flooring and pavements, evidence that they understood the different structural requirements for mortars used in this way. Cato prescribes a mixture of “gravel and sanded lime” topped with potsherds for the construction of foundation pavements in grape pressing rooms. Vitruvius describes his preferred mix-proportions for mortar used in pavements as one part lime to three parts fresh aggregate or two parts lime and five parts aggregate when using “old” material.¹³⁹ Here, Vitruvius differentiates the requirements when using new and old rubble, possibly referring to reused building materials, highlighting that these needed different proportions of lime. This mixture is meant to serve as a mortar bedding for the paving stones, which are then laid on top. The rather different proportion of lime for pavement indicates Vit-

¹³⁵ Oleson and Jackson 2010, 288.

¹³⁶ Cato *Ag. Org* XV.

¹³⁷ Vitr. *De Arch.* II.5.1.

¹³⁸ Vitr. *De Arch.* II.5.1.

¹³⁹ Vitr. *De Arch.* VII.1.3.

ruvius recognized the effect of the mix on mortar performance and that flooring pavement mortar performed differently than structural mortar in walls and thus required different preparation and handling.

Vitruvius describes still another mix design that was used for the construction of cisterns meant to hold water. He says the “strongest lime is to be mixed in a trough, five parts of sand to two to lime.”¹⁴⁰ He further stipulates that the sand should be “the purest and roughest” possible and the mixture should be packed with stone.¹⁴¹ He does not clarify which type of *harena* he is referring to, nor does he recommend the inclusion of ceramics or other pozzolanic additives. This seems curious, because such additions would help to ensure a waterproof mortar that would assist in making the cisterns watertight.

Vitruvius makes no such omissions in his treatment of concrete for harbour works and underwater structures. For these, he refers again to the much lauded “dust” (*pulvis*) from the modern-day region of Campania, specifically from near Naples and extending across the Bay of Naples to the Sorrentine peninsula.¹⁴² The dust he recommends can only be the deposited ash prevalent throughout this volcanic plain. As noted above this addition allows the concrete to set underwater, making it an ideal material for harbour works.¹⁴³

That various mix design specifications were preserved in ancient texts suggest an empirical understanding of the interaction between the binder and aggregate materials,

140 Vitr. *De Arch.* VIII.6.14.

141 Vitr. *De Arch.* VIII.6.14.

142 Vitr. *De Arch.* V.12.2.

143 A great body of work has been dedicated to the study of harbour concretes verifying the use of this volcanic material. See Brandon et al. 2005; Brandon, Hohlfelder and Oleson 2008; Jackson et al. 2010b; Vola et al. 2010; Brandon et al 2014 for a start.

as well as a familiarity with practical building techniques. By detailing specific mix proportions, these ancient authors display a clear understanding of the performance properties of different materials and how to manipulate them to best achieve the desired result. Such knowledge may have been borne of experimentation with mortar production, which must have occurred prior to 160 BCE, the approximate date of Cato's treatise. These experiments are not attested in the surviving literature, though Cato's specificity of lime:sand ratios leaves no doubt that an ideal mixture was at least known if not literally in use.

The sand and hydrated lime were mixed together in a technique that is described in the ancient texts. Both Vitruvius and Pliny describe the procedure of working the lime and sand together in a trough, beating it with wooden staves or poles, distinguishing various techniques for different materials.¹⁴⁴ Pliny additionally notes that stucco is properly mixed when it no longer sticks to the trowel, but when making whitewash "slaked lime should stick like glue."¹⁴⁵ The ROMACONS research group experimentally replicated the Vitruvian formula, employing the methods spelled out in the ancient texts. They described a very stiff, viscous mortar that was difficult to mix but ultimately became quite strong.¹⁴⁶ Such experiments can demonstrate the skill and abilities required to attain a usable mortar, but they serve as only an approximation of what the ancient builders *may* have been doing. One must look to the structures in the archaeological record for more direct evidence of common building practices by evaluating the material features known to result from variations in the mixing process, as described in Chapter 2.

144 Vitr. De Arch. VII.3.10; Plin. HN 36.55.177.

145 Plin. HN 36.55.177.

146 Hohlfelder, Brandon and Oleson 2005, 124–125.

3.2. *Lime mortar masonry in ancient Roman society*

The development of mortar and concrete in the late Roman Republican and early Imperial periods (3rd century BCE - 2nd century CE)¹⁴⁷ represents an important technological innovation. Early historians and archaeologists considered this an important shift in Roman building technology, dubbing it no less than an “architectural revolution” that included, in addition to technical construction processes, social and urban developments, changes in architectural styles, and novel uses of space.¹⁴⁸ Ward Perkins made his opinion of its importance clear when he claimed that the “whole subsequent history of European architectural thought” was altered by the use of mortar and concrete in the construction of *Domus Aurea* (60's CE).¹⁴⁹ However, the impact of the use of lime-based mortar and concrete can be seen in the social changes that followed its development.

The incorporation of lime-mortar and concrete allowed, or perhaps encouraged, the most Roman characteristic feature of Imperial-period architecture: the manipulation of space. By the very nature of the materials involved, concrete construction represented a transition in construction from subtraction (i.e. quarrying and then shaping dimension stones) to creation and definition, building up from the foundation.¹⁵⁰ The shift is from a passive reliance on and adherence to the limits of traditional building stone to the active generation and manipulation of wholly new materials.

The relatively light weight of concrete masonry gave architects and builders the freedom to experiment in new ways with old forms. Curvilinear shapes, high arches, and monumental vaults, which architectural historians tend to credit as hallmarks of Ro-

147 It should be noted here that Mogetta 2015 argues that the development of concrete began in the middle of the 2nd century BCE.

148 Ward Perkins 1956, 219; Boëthius and Ward Perkins 1970, 254.

149 Ward Perkins 1956, 219.

150 MacDonald 1965, 154.

man Imperial architecture, have been found in earlier constructions to the north of Rome in Etruria, including arches in domestic structures and vaulted tombs.¹⁵¹ These structural elements highlighted the importance of vast interior spaces, especially in public buildings constructed from the 1st century CE.¹⁵² As noted by Letchman and Hobbs, “the mass of the wall was subordinated to the spatial volume it created and enclosed” giving symbolic precedence to the *use* of a building over its solid construction.¹⁵³

New types of structures appeared which accommodated great numbers of people in new ways and for new purposes. Bath houses, for example, became major centres of public congregation and centres of social interaction. These structures spread through the empire, but only after the development of lime-based mortar and concrete construction that allowed for vast, expansive complexes. These buildings were public expressions of state power that ultimately changed the way Roman citizens interacted with each other and the city of Rome herself.¹⁵⁴ This is largely considered a metropolitan or urban feature, rather than a rural one.¹⁵⁵

The increased wealth and success of Rome in the Imperial period brought an increase in population in search of accommodation. Apartment complexes could now safely be extended upward without violating local building regulations that limited wall thickness of properties that abutted one another.¹⁵⁶ The new material also was less prone to fire than the earlier wooden structures, and it was the construction material of choice after the fire in Rome in 64 CE.¹⁵⁷ Here again, the development of brick and mortar ma-

151 Boëthius and Ward Perkins 1970, 76.

152 MacDonald 1976, 38–43; Letchman and Hobbs 1986, 85.

153 Letchman and Hobbs 1986, 84–85.

154 Letchman and Hobbs 1986, 81–85.

155 MacDonald 1965, 166; Letchman and Hobbs 1986, 82; Lancaster 2005; Wright 2005, 207.

156 Ancient building code referenced by Vitruvius in *De Architectura II*, 8.17, discussed above.

157 MacDonald 1965, 153.

sonry represented more than just a change in aesthetics or construction techniques for domestic structures, but an evolution in the way individuals could use and command their space.

As noted in Chapter 1, examination of the operational chain illustrates the complexity of the system required to successfully produce and install lime-based mortar. Not only do the structures themselves become more complex, but new stages of material processing are added to the construction process, new materials must be sourced and supplied, new types of workers employed, etc. MacDonald points out that the new way of building brought “order and system” to the process as new variables had to be managed, including the “fairly efficient deployment of thousands of men,” a feat he believes is as “characteristic of Roman civilization as the law or the army.”¹⁵⁸ The end result was a change in Roman construction, driven by the use of new materials, from a highly technical singular process to a segmentation of labour within the system of building processes.¹⁵⁹

Concrete and mortar masonry structures could be built quickly with standardized techniques that brought a uniformity of appearance throughout the Roman city. Part of the success of such building programs can be attributed to what various authors have considered “unskilled or semi-skilled labour.”¹⁶⁰ Most of the required labour was now related to the collection of materials, mixing or installing mortar, laying bricks, etc., rather than cutting, hauling, and finishing stone blocks. As noted by DeLaine, these are new and additional steps in the process, i.e. more links in the procedural chain.¹⁶¹ The

158 MacDonald 1965, 154.

159 Wright 2005, 191.

160 MacDonald 1965, 38–43.

161 DeLaine 2000, 230–231.

argument made here is that although the multiple jobs that went into the production of mortar and concrete were largely unskilled, the technology itself required a wealth of knowledge and practical understanding of the material and mechanical properties of components. The extant archaeological remains stand as testament to the great skill of the builders who developed lime-based mortar.

3.2.1. The archaeological record

Unfortunately, a reliable date for the early development of pozzolanic concrete and mortar in the Roman world is unknown. Blake surmised that experimentation with pozzolanic aggregate most likely began as soon as the very concept of mortar production was introduced.¹⁶² On the other hand, Mogetta recently suggested that the pozzolanic concrete was more likely developed in the middle of the 2nd century CE.¹⁶³ Ward-Perkins believed that pozzolanic concrete was more an evolutionary product than a discovery, having been inspired by generations of builders applying empirical evidence gained through experience.¹⁶⁴ The historical record of ancient Roman construction benefits from extant structures that have been discovered and studied throughout the Mediterranean region over the last two centuries. By examining such monuments, archaeologists have been able to record and describe ancient building techniques and materials, often in terms of their typology and morphology.

One of the earliest known examples of the use of concrete is widely believed to be the 2nd century BCE in the colony of Cosa, a location which Boëthius gave credit for “ushering in” the use of rubble and mortar masonry.¹⁶⁵ This site also brings into sharp

¹⁶² Blake 1947, 311.

¹⁶³ Mogetta 2015,

¹⁶⁴ Ward-Perkins 1970, 246.

¹⁶⁵ Boëthius 1970, 105.

focus the necessity of more science-based material analysis of the concrete itself. Further studies of the port and a fishery in Cosa, both concrete constructions, have instigated controversies regarding the early date. Estimates made by a team of archaeologists led by McCann, working in the 1960s and 1970s, used associated pottery to assign a date to the first half of the 2nd century BCE.¹⁶⁶ Ambiguities inherent in the indirect dating method and inconsistencies in the report sparked doubt from one of those the collaborators. Gazda publicly challenged the published date, putting forth her own hypothesis that the port actually was built much later, in the first century BCE.¹⁶⁷ This, in turn, elicited a response defending the original report and methodology.¹⁶⁸ While this type of debate is ultimately good for the field of archaeology, the argument brought the question no closer to a reliable answer. The reliance by both parties on indirect dating evidence from pottery typologies leaves the age of the concrete constructions in Cosa in some doubt, which hopefully could be clarified with more rigorous scientific analysis.¹⁶⁹

The Temple of Magna Mater on the Palatine Hill in Rome, consecrated in 204 BCE has long been considered another early example, though new research indicates it is possible that the concrete actually belongs to a later reconstruction phase of the structure.¹⁷⁰ Here again, it seems interpretations have been made and then later called into question using only associations of other structures and construction phases, with little to no examination of the actual material remains. Excavations in Ostia have revealed domestic properties built with *opus incertum* facings dating from the 3rd and 2nd centur-

166 McCann *et al* 1987.

167 Gazda 2008, 287.

168 McCann 2008, 294.

169 The ROMACONS research team discovered a fragment of carbonized wood embedded in a concrete core they collected from the Portus Cosanus at Cosa. Carbon14 dating determined a possible range of 57 BCE to 33 CE. The authors acknowledge that this single data point does not resolve the question, but they do offer it as alternative to subjective dating methods (Brandon *et al* 2014, 68).

170 Jackson and Kosso 2013; Mogetta 2015, 10.

ies BCE; although Meiggs argues that *opus incertum* construction appears later in Ostia, between the 2nd and 1st centuries BCE.¹⁷¹

The so-called Porticus Aemilia was reportedly constructed in 193 BCE as an early example of successful experimentation with pozzolanic concrete, yet more recent studies by Cozza and Tucci¹⁷² and Mogetta¹⁷³ have moved the date of this structure forward to the mid-2nd century BCE. Analysis of the mortar indicate a poorly cohesive, porous fabric with a variety of volcanic pozzolans.¹⁷⁴ In Pompeii, pozzolanic mortar with volcanic ash and scoria aggregate is evident in the fourth phase of the city walls, dated by Maiuri to the time before Sulla (roughly 120-89 BCE). It can also be found in the second-phase walls in the House of the Surgeon in Pompeii, dating to c. 150 BCE. To the southeast of Rome, the city walls of Terracina, which Ward Perkins dates to the 2nd century BCE, were extended by 200 meters using concrete and *opus incertum* on the upper courses of the city walls.¹⁷⁵ Unfortunately, these early structures do not provide a consistent narrative that fully explains early concrete experimentation and development. The best we can determine, as demonstrated by these isolated examples, is that pozzolanic mortar and concrete were certainly in use – at least outside of Rome – by the middle of the 2nd century BCE.

The archaeological record fares better within the city of Rome itself, although concrete examples are slightly younger than those mentioned above. The evolution and improvement of mortar and concrete in Rome from the mid-2nd century BCE through the 1st century CE has been catalogued by a number of earlier authors, including van De-

171 Becatti et al 1949; Meiggs 1960, 120; Boëthius 1970, 106.

172 Cozza and Tucci 2006, 176-202.

173 Mogetta 2015, 13-14.

174 Jackson and Kosso 2013.

175 Boëthius and Ward-Perkins 1970, 149.

man,¹⁷⁶ Frank,¹⁷⁷ and Blake.¹⁷⁸ These works were early attempts to classify the material properties of the mortar, and they serve as a starting point for the modern understanding of these ancient mortars.

The general sequence in the city of Rome begins with conglomeratic concretes, which include a greyish, friable mortar of the Republican period found in the reconstructed *podia* of the temples of Concord (121 BCE) and Castor (117 BCE), some of the earliest reliably dated structures in Rome.¹⁷⁹ The friable nature of this mortar may have been due to poor compaction and the inclusion of various volcanic ashes, including re-worked volcanic ash apparently deposited as alluvium along the Tiber River and its tributaries. Despite the friability of these mortars, van Deman describes a “full mastery of technique” in the production and installation of this material, suggesting the technology is considerably older than these specific structures.¹⁸⁰ Her reference here was perhaps a commentary on the quality of workmanship and sophistication of ancient builders' techniques – questions which this project seeks to address through material analysis of the mortar itself.

The building projects of the Sullan period (82-79 BCE) are not well-preserved within the city of Rome, so analysis of mortar from this period is limited. The only well-attested Sullan-era structure studied to date is the Tabularium dated to 78 BCE. According to van Deman, the mortar in this structure is the same ashy colour, but is less friable than the earlier mortar; it contains a different type of sand inclusion which she describes

¹⁷⁶ van Deman 1912a, 1912b.

¹⁷⁷ Frank 1924.

¹⁷⁸ Blake 1947.

¹⁷⁹ Frank 1924, 36-38; Jackson and Kosso 2011, 17.

¹⁸⁰ van Deman 1912a, 244.

as “darker in colour and less *terrosa* than earlier.”¹⁸¹ This darker ash corresponds to re-worked volcanic sands from the mid-Pleistocene Aurelia formation, a mixture of mainly volcanic sands deposited by the Tiber River and its tributaries.¹⁸²

The concrete structures built from the time of Julius Caesar until the end of the Republican period can be generally divided into two types. The first type, found in the Forum of Julius Caesar, is similar in appearance to Sullan mortar but is a better quality and “of a finer texture and harder.”¹⁸³ The lime is a better quality and present in higher abundance, and van Deman describes the volcanic inclusions as “of the same general type as earlier but less *terrosa*.” More recent analysis indicates the mortar actually contains a combination of material from the greatest alteration facies of the Pozzolane Rosse pyroclastic flow (pumiceous volcanoclastic sediments excavated from the San Paolo formation at the building site) and glassy pumices from Monti Sabatini and Somma-Vesuvius.¹⁸⁴ The second type employs what van Deman calls a “true pozzolana,” namely red, reddish-brown, and dark grey angular fragments of the middle horizons of the Pozzolane Rosse pyroclastic flow.¹⁸⁵ She also noted that the selection of this material marked a great innovation in concrete technology, and this mix was used throughout the early Imperial Period.¹⁸⁶

Slightly before the Augustan period (27 BCE – 14 CE), builders developed a mortar formulation based on reddish, scoriaceous pozzolanic volcanic aggregate that corresponds to the middle horizons of the Pozzolane Rosse pyroclastic flow. This mortar ag-

181 van Deman 1912a, 247.

182 Jackson et al. 2010a, 39.

183 van Deman 1912a, 249–250.

184 Jackson et al 2007; 45–50.

185 van Deman 1912a, 250.

186 van Deman 1912b, 387–406.

gregate produced more coherent concrete fabrics and quickly became the Augustan age standard, possibly because of its natural pozzolanic qualities that strengthened the mortar and improved durability.¹⁸⁷ Eventually, this mortar formulation was used to build monumental structures such as the Forum and Markets of Trajan and the Colosseum. By the 1st century BCE, *opus caementicium* was firmly entrenched in the Roman building economy. Concrete masonry had apparently become the preferred medium for repairs to older fortifications, including those at Alba Fucens, Fundi, Pompeii, and Ostia.¹⁸⁸ It was sturdy enough for use in flooring and pavements, either on its own or covered by mosaic.

It has been observed by Blake¹⁸⁹ and Heres¹⁹⁰ that the aggregate in Roman mortar was sieved before use, and Blake further suggested that sieving improved as pozzolanic mortar evolved. It is clear that ancient builders controlled particle size for aesthetic reasons, i.e. for decorative brick façades with smaller joints (approximately 5-10 mm wide) than the structural brickwork with joints typically 15-20 mm wide (Figure 3.1). There is still some question, however, whether particle size was controlled specifically for mechanical reasons, but builders maintained remarkable regularity in joint-width between bricks – and by extension the particle size of mortar aggregate.

187 Jackson et al. 2010a, 38.

188 Boëthius 1970, 149.

189 Blake 1947, 314.

190 Heres 1994, 57.

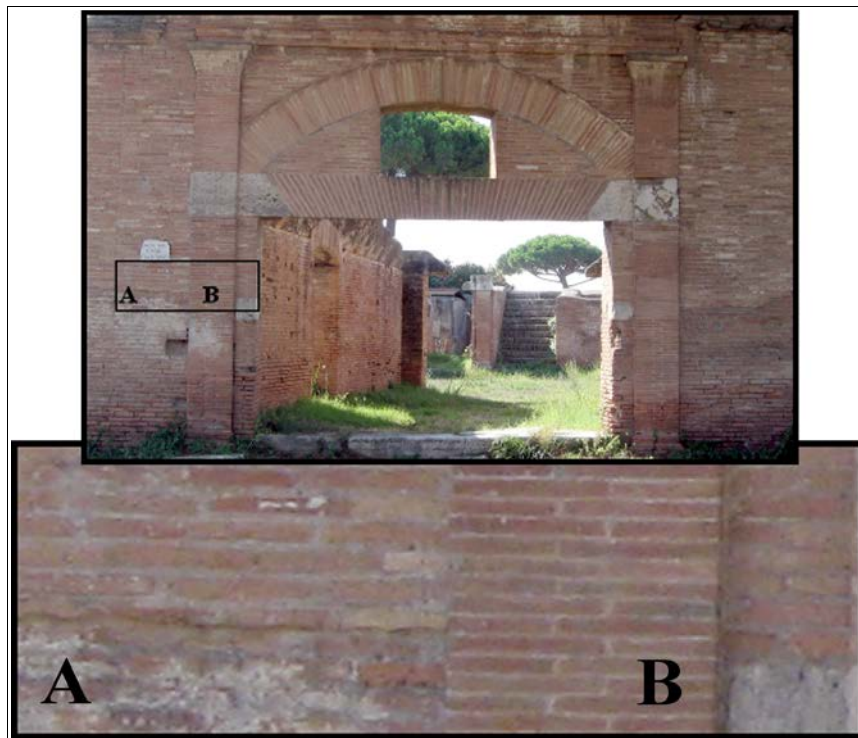


Figure 3.1. Frontage of Casa a Giardino (top) with detail photo (bottom) showing the difference in joint widths in the structural brick (A) and decorative façade (B). Photograph by author.

The innovations in construction engineering and technology described in the ancient texts occurred within the context of a society undergoing significant changes at an important point in its history. Scholars and have placed great emphasis on the interplay between material and technique and how their cooperative influence revolutionized the building economy as the Roman world expanded from Republic to Empire. Only after the material aspects of those innovations are explained fully can we begin to understand the technical expertise of these ancient builders.

3.3. Problems with traditional approaches to mortar investigations and material assessments

As noted in Chapter 2, mortar performance depends on the interaction between the binder and aggregate, and the selection of mortar aggregate has been a subject of in-

terest to archaeologists for many years. The works of van Deman and Blake attempted to create a chronology of buildings in Rome based on the colour of inclusions identified in the mortar.¹⁹¹ Although such studies made for a good first approximation, such a simplified method of analysis cannot provide the relevant detail to properly identify the aggregate. As noted by Meiggs, even these simple distinctions are not possible in Ostia, because different types of tuff were used as mortar aggregate at the same time and usually occurred near each other.¹⁹² Multiple lithologies were available in the region, many of which share similar macro features such as colour or mineral inclusions, so little useful information can be derived from colour alone.¹⁹³ Furthermore, Blake considered it “quite impossible to locate the sources from which most of that used in ancient buildings came,” which is no surprise given the simplistic approach to analysis.¹⁹⁴ On the contrary, a number of ancient quarry sites have been identified and associated with specific lithological units known to have been used as both building stone and mortar aggregate.¹⁹⁵ However, more robust petrographic analysis techniques are required to distinguish between these materials, which are best differentiated by their microstructures and authigenic textures.¹⁹⁶

The authors mentioned above were concerned, at least superficially, with identifying the mortar aggregate from a qualitative perspective. More recently, works by

¹⁹¹ van Deman 1912a; van Deman 1912b; Blake 1947.

¹⁹² Meiggs 1960, 543.

¹⁹³ Chapter 4 of this work addresses the textural features and morphology of various aggregates known to have been used in the region.

¹⁹⁴ Blake 1947, 43.

¹⁹⁵ Russell 2013.

¹⁹⁶ See full discussion in Chapter 4.

Lamprecht,¹⁹⁷ Peterse,¹⁹⁸ Karner et al.,¹⁹⁹ and Lancaster,²⁰⁰ have ushered in a more scientifically rigorous approach by analysing building materials to describe and attempt to date Roman structures. The last decade has seen a rapid increase of laboratory studies by archaeological scientists who apply petrographic, geochemical, and mineralogical analyses to describe the physical and material properties of the mortars, as well as the characteristics and provenance of their raw geological components.²⁰¹ These studies have begun to examine the ancient mortars as one would examine modern materials, by assessing the components, condition, and quality of hardened samples. In this way, scientific analysis and technical identification of the materials work alongside the traditional archaeological descriptions to provide a more precise and coherent history of mortar development in Rome.

3.4. Chapter Conclusion

Modern researchers must analyse the standing remains for clues to the specific mortar production methods employed centuries ago. Fortunately, these can be checked against the testimony of ancient authors writing about contemporary construction methods at the time. It is unclear from ancient texts whether the methods for the production of construction mortar and concrete prescribed in ancient texts were widely followed by Roman builders, but there is no such ambiguity about the nature of the materials actually being mixed together. The improved strength and durability of the

¹⁹⁷ Lamprecht 1996.

¹⁹⁸ Peterse 1999.

¹⁹⁹ Karner et al. 2001.

²⁰⁰ Lancaster 2005.

²⁰¹ Jackson and Marra 2006; Jackson et al. 2007; Jackson et al. 2010a; Mirielli et al. 2009, Mirielli et al. 2010, Mirielli et al. 2012; Belfiore et al. 2015.

mortar as it evolved can be credited to better quality lime that was more abundant in the mix and to the incorporation of pozzolanic aggregates suitable to mortar and concrete production. The ancient builders' use of local volcanic materials, which were naturally pozzolanic, allowed stone and brick masonry to be built with no additional internal reinforcements. Central Italian geology was certainly a boon to ancient builders in this regard. The most common type of sand available to them was a volcanic ash that contained the specific chemical and mechanical properties that allowed for an unusually durable and water-proof product, the hallmarks of Roman concrete. The particular materials used by the ancient builders are discussed individually in the next chapter.

Chapter 4. Geological perspectives

Ostia is located in central Italy, approximately 15 kilometres to the south-west of Rome, on a sedimentary delta near the western coast (Figure 4.1). The coastline has extended west since the 2nd century CE, meaning that the site, which once sat at the confluence of the Tiber River and the Mediterranean Sea, is now located 3 kilometres inland. This chapter explains the geological context of ancient Ostia, describing the nearby carbonate mountains, the local volcanic setting, and the coastal delta.

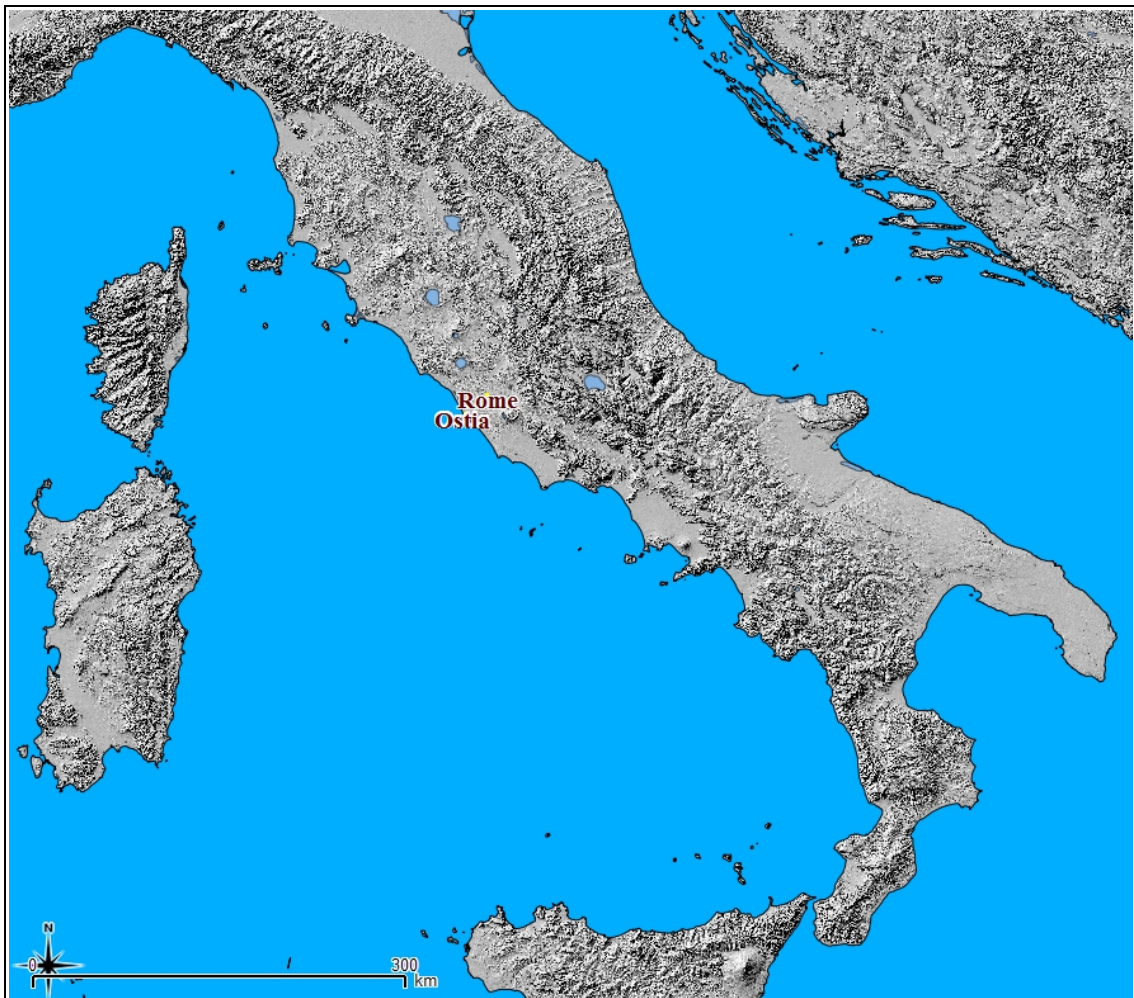


Figure 4.1: General location map of the Italian peninsula, showing the locations of Rome and Ostia along the ancient Mediterranean coast. Map generated by author with Quantum GIS; city and ancient coastline location data from Talbert 2000.

4.1. Geographic location

Ostia lies to the southwest of the central Apennines mountains within the Roman Magmatic Province, which comprises several volcanic districts: Vulsini, Vico, Colli Albani (sometimes referred to as Alban Hills), Monti Sabatini, and Roccamonfina in the northern Latian district, as well as the southern volcanoes of the Neapolitan districts, including, Ischia, Procida, Campi-Flegrei, and Somma-Vesuvius (Figure 4.2).²⁰² The nearest volcanic districts to Ostia are Monti Sabatini to the north and Colli Albani (the Alban Hills) to the south (Figure 4.3).



Figure 4.2: Location map of Rome and Ostia along the ancient coastline, showing rivers and volcanoes within the Roman Magmatic Province. Map generated by author with *Quantum GIS*; city, river, and ancient coastline location data from Talbert 2000.

²⁰² Mattei, Conticelli, and Giordano 2010, 14.

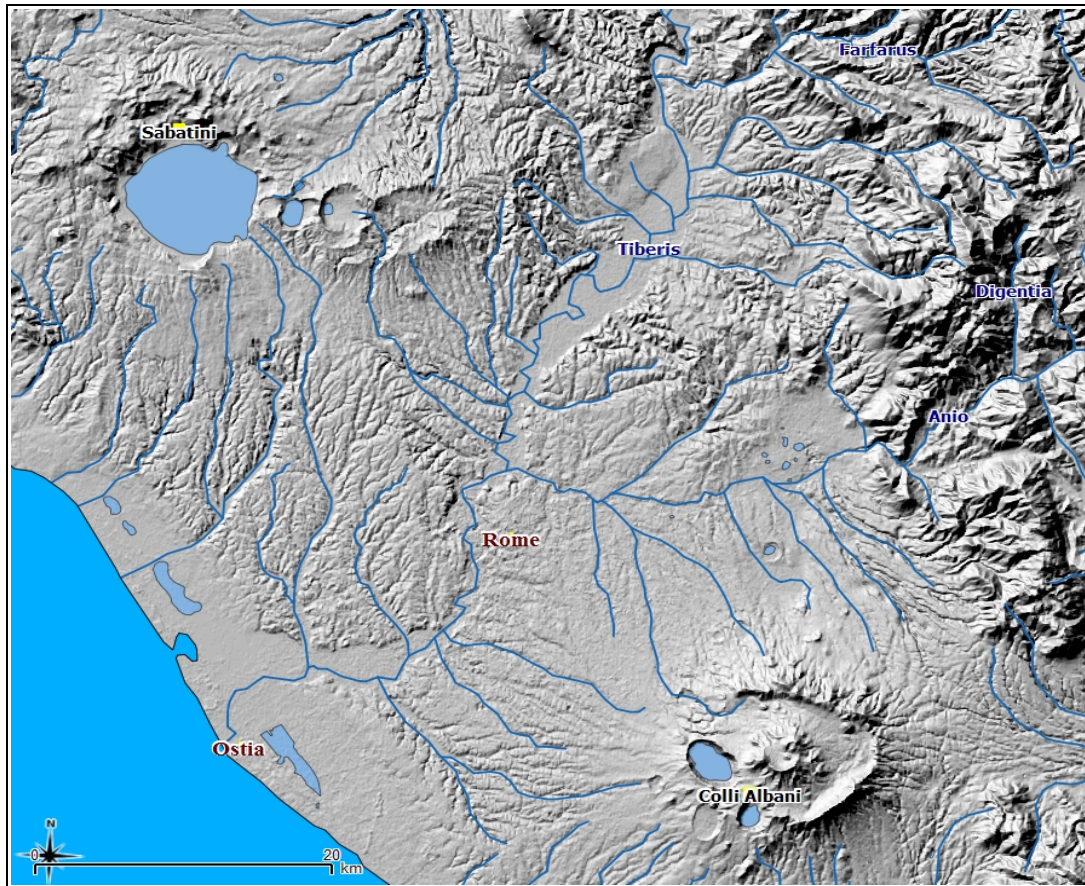


Figure 4.3: Detail map of Ostia's location along the ancient Mediterranean coast between the Monti Sabatini and Colli Albani volcanic districts, also showing major rivers. Map generated by author with Quantum GIS; city, river, and ancient coastline location data from Talbert 2000.

4.2. Carbonate mountains

Travertine, marble, and limestone are the main carbonate sources in the region of Rome and Ostia.²⁰³ These materials outcrop throughout the region, most commonly along the centre of the Italian peninsula in the Central Apennines. The nearest limestone formations to Rome are Monte Soratte, the Monti Cornicolani, the Monti Tiburtini, and the Monti Prenestini (Figure 4.4).²⁰⁴

²⁰³ Fichera et al. 2015, 85.

²⁰⁴ Facenna et al. 2008, 300; Fichera et al. 2015, 85.

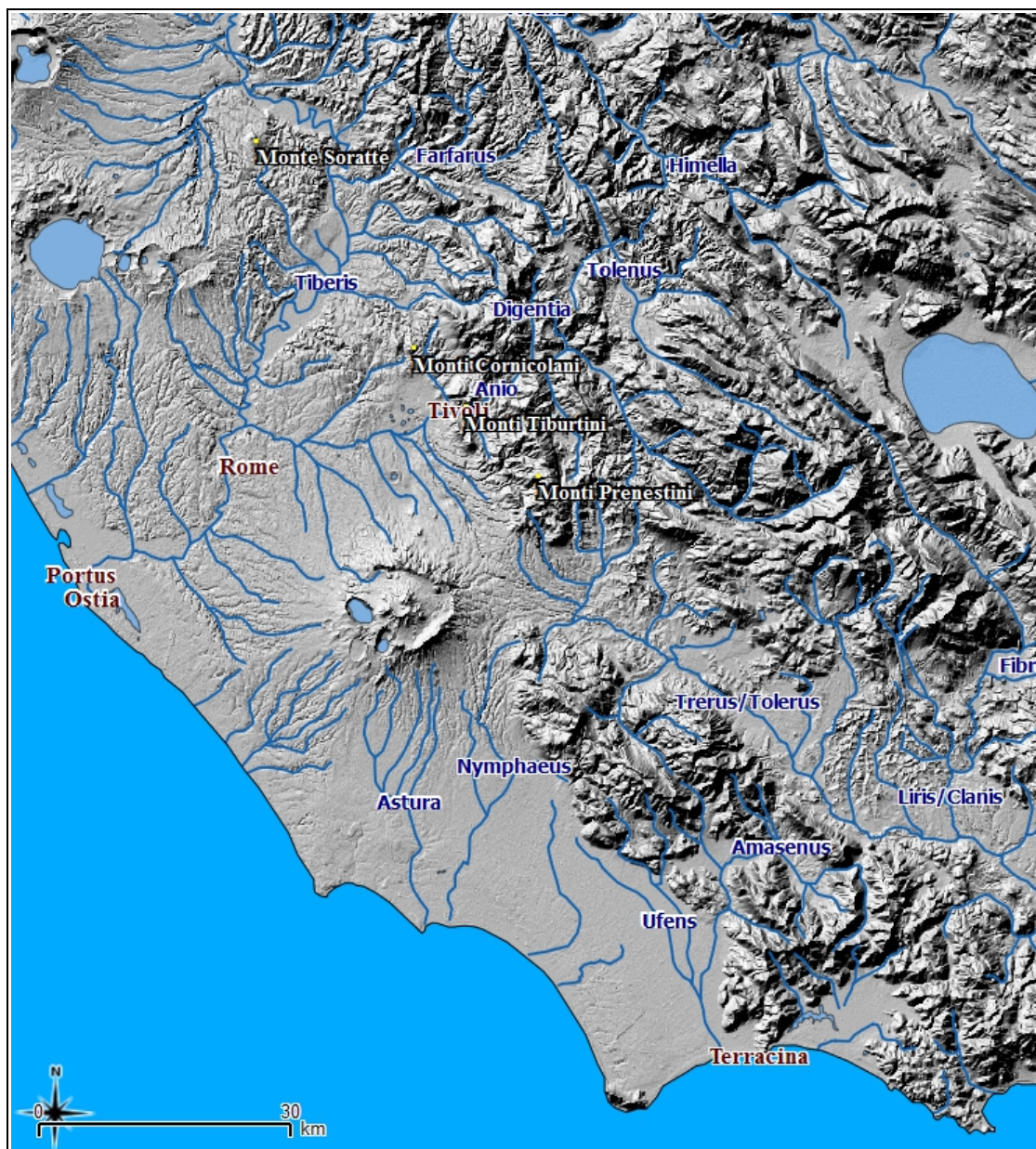


Figure 4.4. Detail map of central Italy, showing the ancient Mediterranean coastline, location of major cities (labelled in red), major rivers (labelled in blue), and the nearest major limestone hills to Ostia (white labels). Map generated by author with Quantum GIS; city, river, and ancient coastline location data from Talbert 2000.

A number of authors have suggested the Monti Cornicolani was the most likely source location for ancient Roman lime, and recent studies have offered support for this hypothesis.²⁰⁵ Samples of Calcare Massiccio and Calcare Maiolica were collected from

²⁰⁵ DeLaine 1995, 560; Jackson and Marra 2006, 424; Fichera et al. 2015, 81.

outcrops in the Cornicolani Mountains for comparison to the lime lumps found in mortars from Villa dei Quintili.²⁰⁶ The Calcare Massiccio Formation is a rather pure limestone, while the Calcare Maiolica Formation often exhibits dolomitisation.²⁰⁷ Lime produced from the former would be calcitic lime, while the latter could exhibit a more magnesian composition. The lime lumps *sensu stricto* in the mortars exhibited a trace element chemistry that was consistent with the samples from Monti Cornicolani, making it a viable possible source.²⁰⁸

Other possible sources of lime included the Tiburtini, the Prenestini mountains, and Monte Soratte, which Vitruvius mentions was quarried for limestone building stone.²⁰⁹ DeLaine suggests that another possible source of lime in Ostia was the city of Terracina, which supplied Portus with lime and firewood during the late empire.²¹⁰ The significance of Terracina was its location near the sea. She goes on to point out that moving lime into Rome from Terracina by water was significantly cheaper than carting by it road from Tivoli and only slightly more than moving from Monte Soratte along the Tiber or from Tivoli along the Anio.²¹¹

4.3. Roman Magmatic Province

Volcanism in the region is relatively recent, dating from the Pleistocene, (2.58 million – 11,700 years before present) to the Holocene (11,700 years BP to present day).²¹² The magmas from the Roman Magmatic Province are characteristically highly potassic

206 Fichera et al. 2015, 81.

207 Billi et al 2007, 392.

208 Fichera et al. 2015, 97.

209 DeLaine 1995, 560.

210 DeLaine 1995, 560. citing *Codex Theodosianus* 14.6.3 and cf. Symmachus, *Relationes* 40.3.

211 DeLaine 1995, 560.

212 Mattei, Conticelli, and Giordano 2010, 14.

with low silica content, exhibiting very high potassium-sodium oxide ratios ($\text{K}_2\text{O}/\text{Na}_2\text{O}$), aluminium oxide (Al_2O_3) up to 20.5 weight percent (wt%), sodium oxide (Na_2O) up to 2.6 wt%, calcium oxide (CaO) up to 14.5 wt%, and titanium oxide (TiO_2) less than 1 wt%.²¹³ The majority of the rocks produced in the Roman Magmatic Province can be classified as leucitites or plagioclitites containing major leucite and clinopyroxene, with minor olivine, biotite, sanidine, opaques, and occasional plagioclase.²¹⁴ Phlogopites, nepheline, garnet, vesuvianite, calcite, melilite, and apatite also have been reported in rocks from Colli Albani.²¹⁵

The full volcanic histories of Colli Albani and Monti Sabatini have been well-documented in geological literature, including detailed stratigraphic histories from various authors (Figure 4.5).²¹⁶ This chapter, however, is dedicated to eruptive events that are most relevant to this study. Each of the lithological units described below have been identified in ancient mortars from Rome, reported to have been excavated from ancient quarries, and observed as aggregate in the mortar samples in this study (mortar aggregate determinations are described in Chapter 7).²¹⁷

²¹³ Mattei, Conticelli, and Giordano 2010, 14.

²¹⁴ Mattei, Conticelli, and Giordano 2010, 14.

²¹⁵ Gaeta, Fabrizio and Cavarretta 2000, 181.

²¹⁶ Karner, Marra, and Renne 2001; Gaeta, Fabrizio and Cavarretta 2000; Jackson et al. 2005; Marra et al. 2009; Mattei, Conticelli, and Giordano 2010.

²¹⁷ Jackson et al. 2007; Jackson et al. 2009; Jackson et al. 2010a; Jackson et al. 2011; Russell 2013.

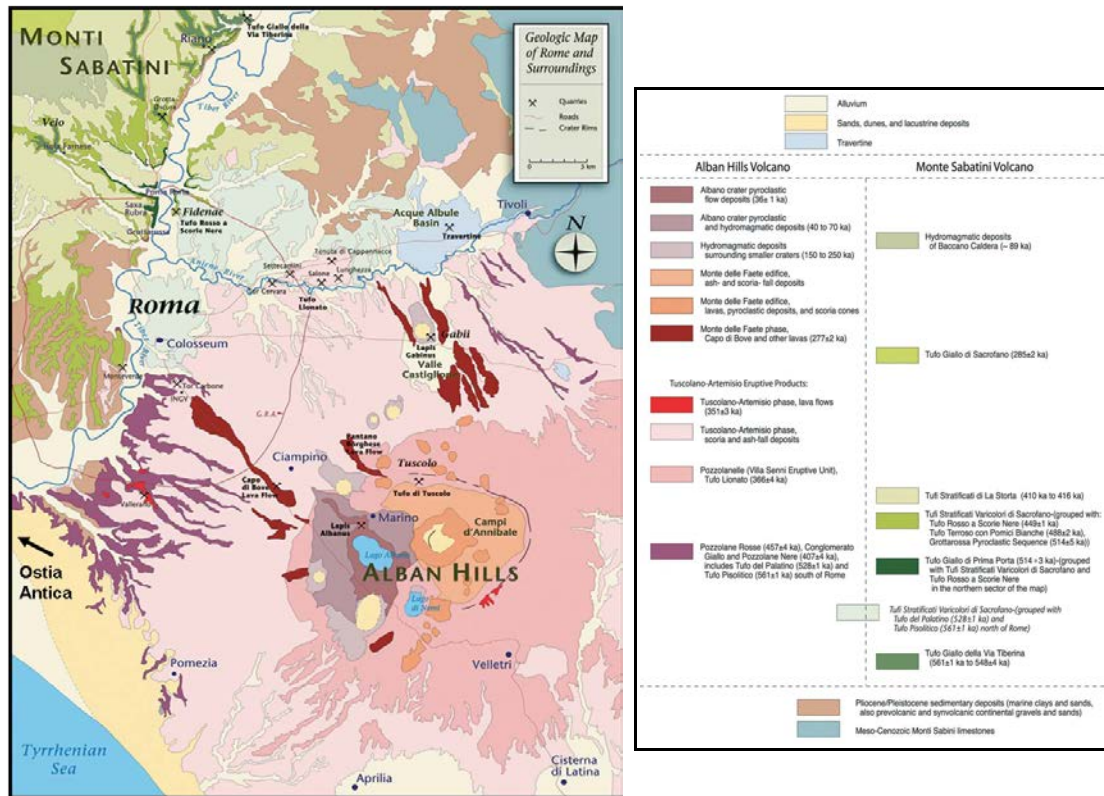


Figure 4.5: Geologic map of Rome and the surrounding area, showing major eruptive products of Monte Sabatini and Colli Albani. After Jackson and Marra 2006.

4.3.1. Colli Albani

The Colli Albani district first became active 561 ± 1 thousand years ago (ka), beginning with the first cycle of the Tuscolano-Artemisio eruptive phase (Figure 4.6).²¹⁸ The oldest eruptive unit of this cycle includes deposits called Tufo Pisolitico di Trigatoria, known variously as Tor de' Cenci unit, Tufo Grigio Pisolitico, Tufo Pisolitico, and Pisolitico Tuff. Karner, Marra, and Renne have reinvestigated these materials and ultimately determined that the unit comprises two pyroclastic flow subunits, called Pisolitico di Trigatoria-a and Pisolitico di Trigatoria-b.²¹⁹

²¹⁸ Karner, Marra, and Renne 2001, 189.

²¹⁹ Karner, Marra, and Renne 2001, 206.

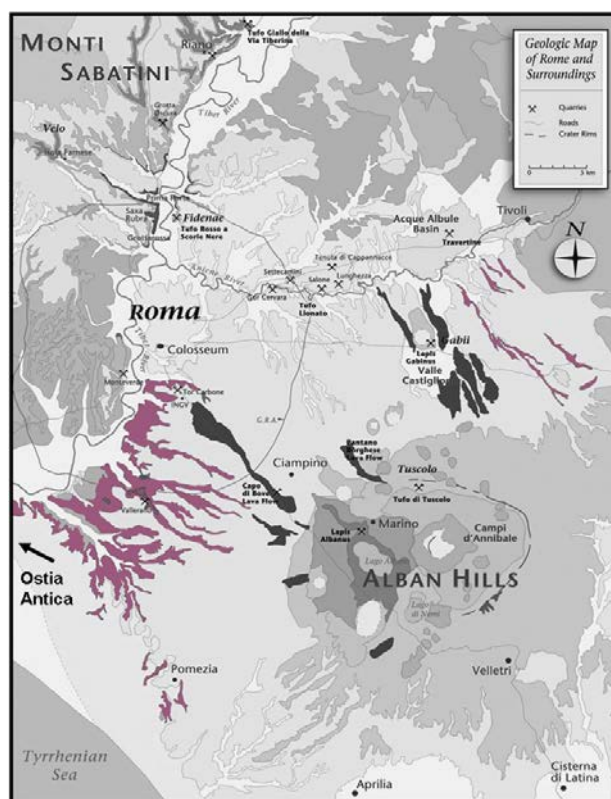


Figure 4.6: Geological map of the area highlighting the outcrop of materials from the first, second, and third Tuscolano-Artemisio eruptive cycles (in purple). After Jackson and Marra 2006.

Subunit-a includes 13 cm of lapilli topped with 40 cm of grey ash, closely followed by subunit-b, which is composed of ash containing grey scoria, yellow pumice, altered leucite, and lapilli embedded in a matrix of yellow ash.²²⁰ Following the Pisolitico- Trigroria unit of the first cycle is a dark ignimbrite with grey lapilli at its base, and which overlain with brown ash. Karner, Marra, and Renne refer to this material as Tufo del Palatino, after the significant outcropping on the Palatine Hill in Rome.²²¹ Earlier studies have referred to Tufo Palatino with different names, including Peperino Grigio, Tufo Grigio Granulare, Cappellaccio, and the Palatino Unit. After roughly 517 ± 1 ka, pyro-

²²⁰ Karner, Marra, and Renne 2001, 208.

²²¹ Karner, Marra, and Renne 2001, 209.

clastic fall deposits from the Monti Sabatini Volcanic District reached the region, interrupting major eruptive sequences of Colli Albani.²²² The resultant epiclastic material is described below in section 4.3.3.

The second cycle of the Tuscolano-Artemisio eruptive phase commenced 460 ± 4 ka with the Vallarano Lava, followed by Pozzolane Rosse pyroclastic granular ash.²²³ This major deposit comprises a red, yellowish-brown, or grey matrix containing red or grey scoria, phenocrysts of leucite, clinopyroxene, biotite, and sanidine, and clasts of lava and metamorphosed sedimentary material.²²⁴ Quartz is noticeably absent from Pozzolane Rosse.²²⁵ Post-deposition alteration has left the material with highly distinctive textures. The key features of alteration include disaggregation of scoria and ash particles, highly altered glass, analcime phenocrysts altered from leucite, zeolites (phillipsite and chabazite), root traces, and coatings of opaline silica and poorly-crystalline clay on grain edges.²²⁶ Pozzolane Rosse occurs primarily as fine gravel size, 2 – 4 mm.²²⁷

Vertical sections of this material exhibit three separate facies with decreasing degrees of alteration:²²⁸

- The greatest alteration facies (upper level) is scoria with dense rinds of halloysite clay, leucite grains that are wholly altered to analcime or fully dissolved, very low occurrence of zeolites and opaline silica, and scoria with dark grey or brown, opaque groundmass (Figure 4.7).

222 Mara et al.2009, 226.

223 Karner, Marra, and Renne 2001, 212; Marra et al.. 2009, 227–229.

224 Karner, Marra, and Renne 2001, 212; Jackson et al. 2010a, 47.

225 Jackson et al. 2010a, 29.

226 Jackson et al. 2007, 37.

227 Jackson et al. 2010a, 29;

228 Jackson et al. 2010a, 61.

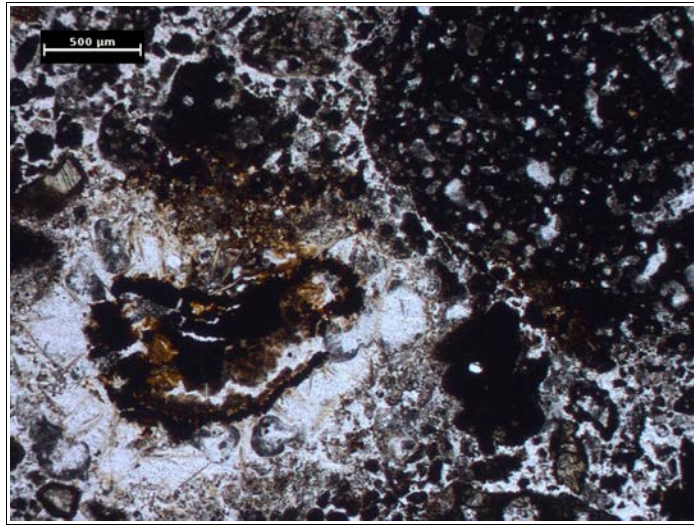


Figure 4.7: Photomicrograph of the greatest alteration facies of Pozzolana Rosse, with a root trace on the left side half of the image. Image collected by author in plane polarised light.

- The intermediate alteration facies (middle level) is poorly consolidated scoria and ash with thin surface coatings of opal and halloysite clay; larger leucite crystals remain fresh while smaller grains are dissolved or replaced by analcime (Figure 4.8).

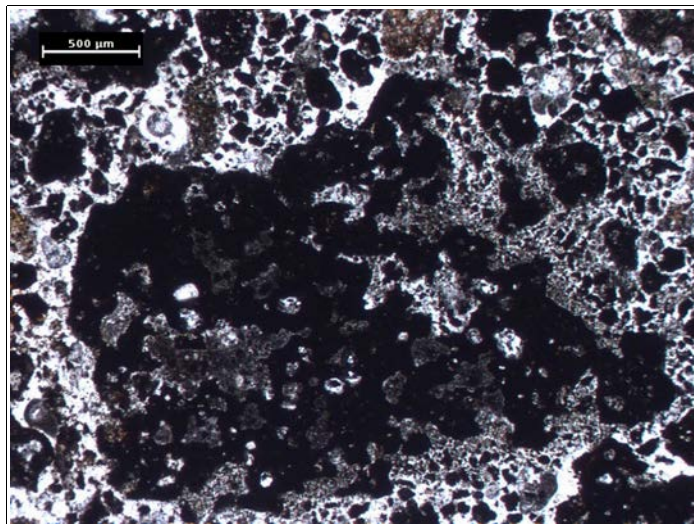


Figure 4.8: Photomicrograph of the intermediate alteration facies of Pozzolana Rosse. Image collected by author in plane polarised light.

- The least alteration facies (lowest level) is altered palagonite and scoria ground-mass that has altered to clay, exhibiting only sporadic dissolution or alteration of fresh leucite and abundant zeolites (phillipsite and chabazite) (Figure 4.9).

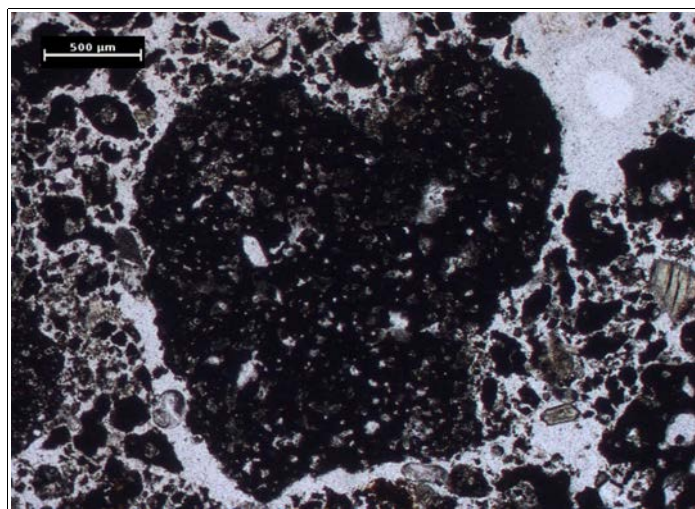


Figure 4.9: Photomicrograph of the least alteration facies of Pozzolana Rosse. Image collected by author in plane polarised light.

The reddish colour of the Intermediate Alteration Facies is most likely responsible for the “dusky-red” colour of mortar and concrete in Imperial-period structures in Rome.²²⁹ Jackson and Marra have suggested that Pozzolane Rosse was the preferred aggregate from the 1st century BCE.²³⁰ The material has been directly observed in mortar samples from multiple structures in Rome, including the Markets of Trajan, Trajan's Forum, and Basilica Ulpia, and the Villa dei Quintili, all from the 2nd century CE.²³¹

The third cycle of the Tuscolano-Artemisio sequence, approximately 407±4 ka, produced Pozzolane Nere, which primarily outcrops along the east side of Colli Albani. Pozzolane Nere is similar in texture and mineralogical composition to Pozzolane

²²⁹ van Deman 1912a, 235.

²³⁰ Jackson and Marra 2006, 422.

²³¹ Jackson et al. 2005; Jackson and Marra 2006; Jackson et al. 2007; Jackson et al. 2009; Jackson et al. 2010a; Bianchi et al. 2011; Belfiore et al. 2015.

Rosse,²³² though it is darker in colour and leucite is almost completely dissolved (Figure 4.10).²³³ The material typically occurs as fine sand sized particles, 125 – 250 μm .²³⁴ This material has been identified aggregate in mortar from the Temple of Castor and Pollux, dating to 117 BCE.²³⁵

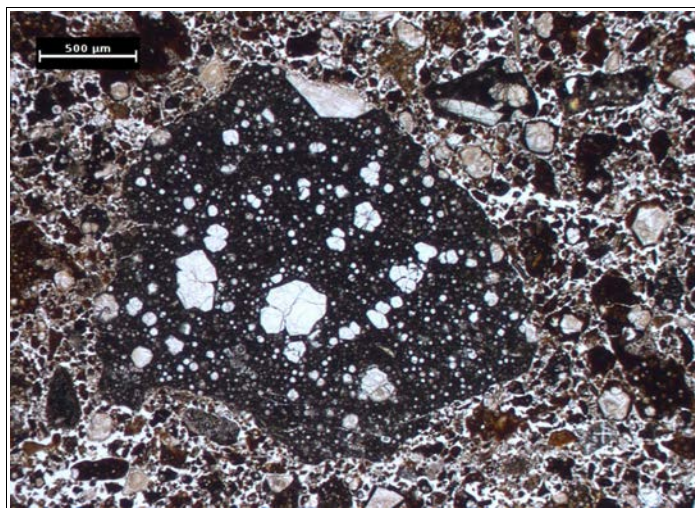


Figure 4.10: Photomicrograph of excavated Pozzolana Nere. Image collected by author in plane polarised light.

The Villa Senni eruptive sequence (Figure 4.11) is the fourth cycle of the Tuscolano-Artemisio sequence of Colli Albani. Primary deposits include Tufo Lionato followed by Pozzolanelle, which have traditionally been interpreted as lower and upper levels of pyroclastic flows the same eruption (355 ± 2 ka).²³⁶ More recent dating of leucite crystals from Tufo Lionato have been dated to 357 ± 2 ka, however the lack of any paleosol between the two supports initial interpretations.²³⁷

²³² Karner, Marra, and Renne 2001, 213.

²³³ Jackson et al. 2007, 37.

²³⁴ Jackson et al. 2010a, 29.

²³⁵ Jackson et al. 2007, 37.

²³⁶ Karner, Marra, and Renne 2001, 214.

²³⁷ Karner, Marra, and Renne 2001, 214; Marra et al. 2009, 228.

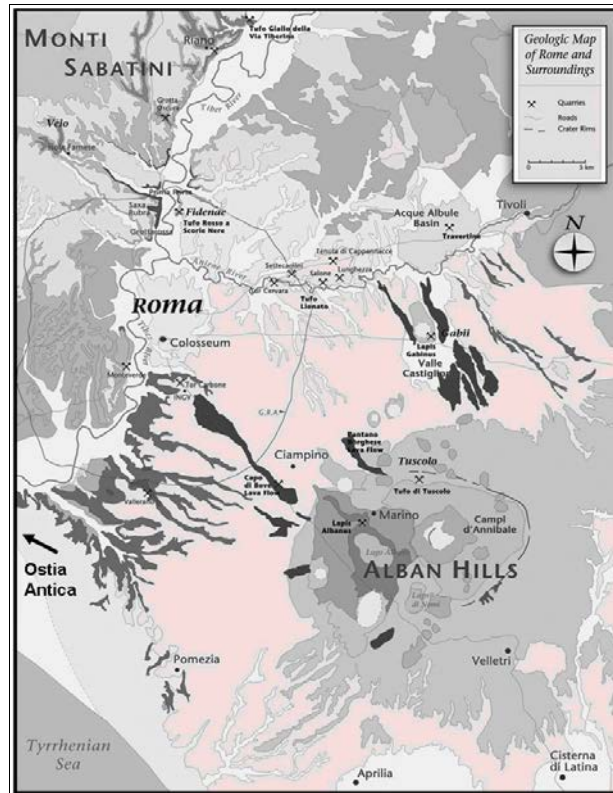


Figure 4.11: Geological map of the area highlighting the outcrop of the Villa Senni eruptive cycle, including Pozzolanelle and Tufo Lionato (in pink). After Jackson and Marra 2006.

Tufo Lionato is a tuff of primarily yellow to orange scoria and leucite crystals within an ashy, zeolitized matrix (Figure 4.12).²³⁸ Phillipsite is the most common zeolite present, and chabazite occurs in the upper levels of the deposit; the two zeolites rarely occur together.²³⁹ Tufo Lionato was quarried as a building stone from multiple sites in Rome as early as the 6th century BCE and from near the Anio River after the middle of the 2nd century BCE.²⁴⁰ Tufo Lionato has been observed as building stone in structures from the late Republican period, including the Temple of Portunus and the Auditorium

²³⁸ Karner, Marra, and Renne 214.

²³⁹ de Gennaro and Langella 1996, 458.

²⁴⁰ Jackson et al. 2005, 504.

of Maecenas.²⁴¹ The Basilica Ulpia and Trajan's Forum were constructed with mortar containing Tufo Lionato fine aggregate.²⁴²

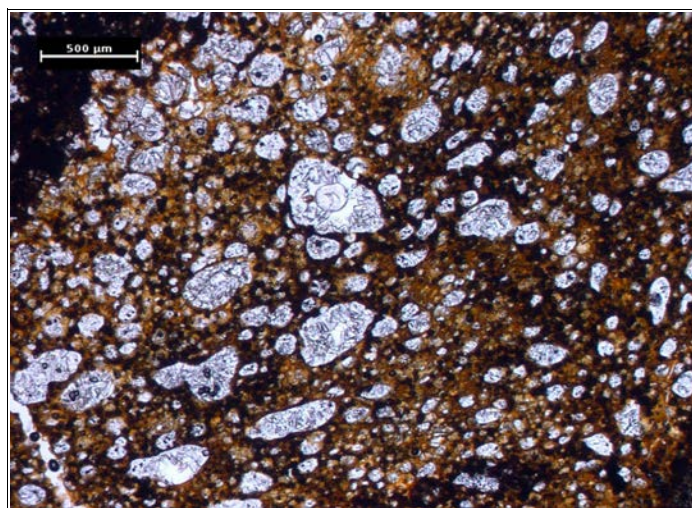


Figure 4.12: Photomicrograph of excavated Tufo Lionato, showing significant development of chabazite in vesicles. Image collected by author in plane polarised light.

Pozzolanelle, the upper-level material in this unit, is less consolidated than Tufo Lionato and notably lacks zeolitic alteration (Figure 4.13).²⁴³ Large phenocrysts of mica are another distinguishing feature. Cecconi, Scarapazzi, and Viggiani have described Pozzolanelle as a welded lapilli-tuff comprising light reddish brown sub-angular clasts within a pinkish white matrix, exhibiting medium to high porosity.²⁴⁴ The material typically occurs as very fine to fine sand (63 – 125 μm).²⁴⁵ Pozzolanelle has been identified in mortar samples the earliest phase of the so-called Porticus Aemilia in Rome and in portions of the Aurelian Wall at Via Giotto (3rd century CE).²⁴⁶ Pozzolanelle also has

²⁴¹ Bianchi et al 2011, 74; Jackson et al. 2005, 505.

²⁴² Bianchi et al. 2011, 76.

²⁴³ Karner, Marra, and Renne 2001, 214.

²⁴⁴ Cecconi, Scarapazzi, and Viggiani 2010, 192.

²⁴⁵ Jackson et al. 2010a, 29.

²⁴⁶ Jackson and Marra 2006, 422; Jackson et al. 2007, 25.

been identified in mortar samples from the Villa dei Quintili in Rome, dating to the 2nd century CE.²⁴⁷

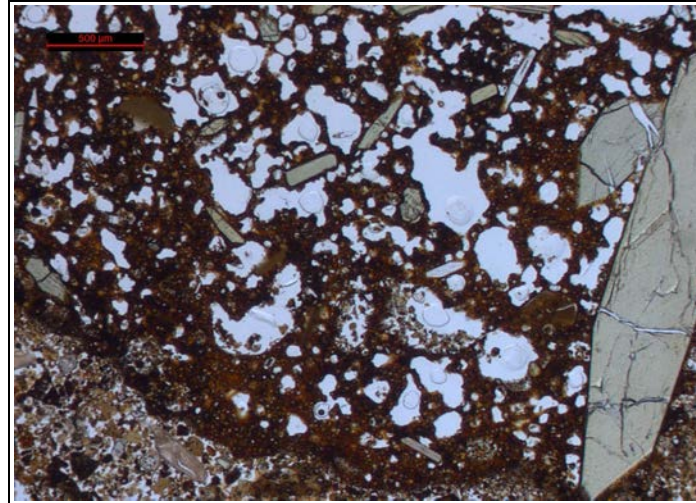


Figure 4.13: Photomicrograph of excavated Pozzolanelle. Image collected by author in plane polarised light.

4.3.2. Monti Sabatini

Deposits from Monti Sabatini initially can be differentiated from those of Colli Albani by their unique mineral assemblages. Both types contain leucite and clinopyroxene, but sanidine and plagioclase are only present in Monti Sabatini products. Material from the Sabatini district have been recognized as coarse aggregate (*caementa*) in ancient Roman concrete masonry, specifically identified in the Forum of Caesar (1st century BCE) and the Temple of Concord (2nd century BCE).²⁴⁸

The Tufo Giallo di Prima Porta ignimbrite (Figure 4.14) is a yellow solidified pyroclastic deposit that erupted from Monti Sabatini roughly 514±3 ka and was em-

²⁴⁷ Belfiore et al. 2015, 270.

²⁴⁸ Jackson et al. 2005, 496.

placed throughout the region between deposits from the first and second Tuscolano-Artemisio eruptive cycles of Colli Albani.²⁴⁹

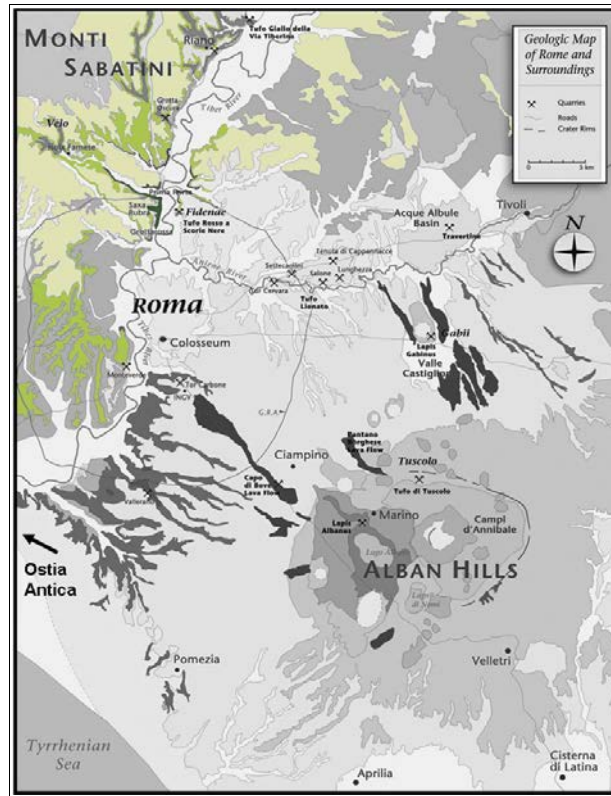


Figure 4.14: Geological map of the area highlighting the outcrop of material from the Monte Sabatini volcanic district (green areas), including Tufo Giallo di Prima Porta (dark green), After Jackson and Marra 2006.

This material occurs as a massive pyroclastic flow ash with an altered yellow-grey matrix containing chabazite, leucite crystals, dark-grey scoria, and lithic fragments.²⁵⁰ This tuff can be divided into two separate facies: the more consolidated facies occurs in the Tiber and Anio river valleys, and a large facies of unconsolidated ash is found in Rome on the Palatine and Capitoline hills.²⁵¹ It previously has been identified as part of the Tufo Giallo della via Tiberina deposit, but current studies distinguish the two materi-

²⁴⁹ Karner, Marra, and Renne 2001, 201.

²⁵⁰ Jackson et al. 2005, 496.

²⁵¹ Karner, Marra, and Renne 2001, 201.

als. The Tiberina ignimbrite is larger, better consolidated, and 30 ka older than Prima Porta (548 ± 4 ka).²⁵²

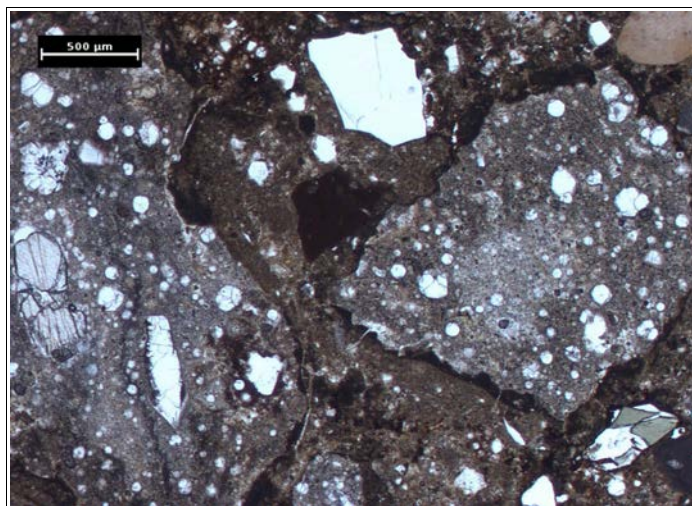


Figure 4.15: Photomicrograph of Tufo Giallo di Prima Porta. Image collected by author in plane polarised light.

4.3.3. Epiclastic deposits of Monti Sabatini reworked air fall ash

In addition to the primary lithologies described above, the Roman Magmatic Province also contains reworked epiclastic deposits of material from Colli Albani and Monti Sabatini. These units have been found between volcanic deposits throughout the region and primarily consist of altered primary deposits that have been eroded, reworked, and cemented with clay and/or zeolites. Sanidine crystals have been observed within clasts that include material from Colli Albani, which notably lacked these feldspars. The feldspars have been attributed to the Monti Sabatini ash.²⁵³ The presence of such deposits in the region indicates both authigenic and pedogenic alteration processes at work between major eruptions in the area.

²⁵² Karner, Marra, and Renne 2001, 201.

²⁵³ Marra et al., 2009; 236.

The San Paolo formation, which notably outcrops near the Capitoline Hill in Rome, represents a reworking of eroded Pozzolane Rosse ash and Monti Sabatini tephra. This deposit was subsequently overlain by the emplacement of the Pozzolane Nere ignimbrite.²⁵⁴ The San Paolo formation correlates to Giallo Conglomerato, which fills paleovalleys which around 406 ka.²⁵⁵ This deposit is usually found between the Pozzolane Rosse and Pozzolane Nere deposits in the north-west section of the Colli Albani complex.²⁵⁶

The Aurelia formation is another inland sedimentary unit, which followed the Villa Senni eruptive sequence of Pozzolanelle and Tufo Lionato.²⁵⁷ These deposits comprise primarily lake and marsh clays that proliferated both in valleys and atop the hills of Rome when the sea level reached its maximum height.²⁵⁸ This unit, found on the Capitoline and Esquiline Hills in Rome, is again composed of reworked material from Colli Albani and Monti Sabatini tephra. Material from both the San Paolo and Aurelia formations has been used as fine aggregate in Roman mortars from the Republican period, including the Temple of Concord (121 BCE) and the Temple of Castor and Pollux (117 BCE) in the Roman Forum, in the Forum of Caesar, and in the Domus Aurea.²⁵⁹

4.4. Coastal sediments

Ostia is located within the Tiber River delta along the western coast of the Mediterranean Sea. The delta plain originally formed during the Holocene period, which began

²⁵⁴ Jackson *et al.* 2010a, 47.

²⁵⁵ Marra *et al.* 2009, 228.

²⁵⁶ Cecconi, Scarapazzi and Viggiani 2010, 188.

²⁵⁷ Jackson *et al.* 2010a, 43.

²⁵⁸ Marra *et al.* 1998, 61.

²⁵⁹ Jackson *et al.* 2010a, 45–50.

11,700 calendar years before present (BP), as a brackish estuary at the confluence of the river and the sea.²⁶⁰ Its location has resulted in an ever-changing sedimentary landscape that has been affected by fluvial, oceanic, and volcanic processes in the thousands of years since its formation. In this wave-dominated estuary, redeposited volcanic sands and other sediments brought by the river are constantly redistributed by tidal action along the coast, increasing the size of the alluvial fan. The current coastline has extended three kilometres seaward since the Roman occupation of Ostia, and the course of the Tiber River has shifted significantly. Although Ostia was once a major seaport harbour, today the ruins are entirely inland. The harbours of Claudius and Trajan at Portus are conspicuously landlocked due to 2000 years of significant alluviation.

Repeated flooding of the Tiber deposited silt throughout the area, which is to be expected in a riverine location, but environmental changes caused the river's sediment load to increase.²⁶¹ Eight phases of beach ridges have been identified within the outer delta, which is the area of expansion from the ancient coastline.²⁶² Figure 4.16 illustrates the expansion of the Tiber basin in the period from the first occupations in the area to its present extent. The Tiber River channel itself has moved in the same period, with the eastern meander having been cut off in 1577 (Figure 4.17).²⁶³ Similarly, the channel ran through the harbour areas at Portus, but again those waterways have been completely filled and the river redirected.

260 Bellotti et al. 2011, 1106.

261 Giraudi, Tata and Paroli 2009, 380.

262 Bellotti et al. 2007, 523-529.

263 Bellotti et al. 2011, 1107.

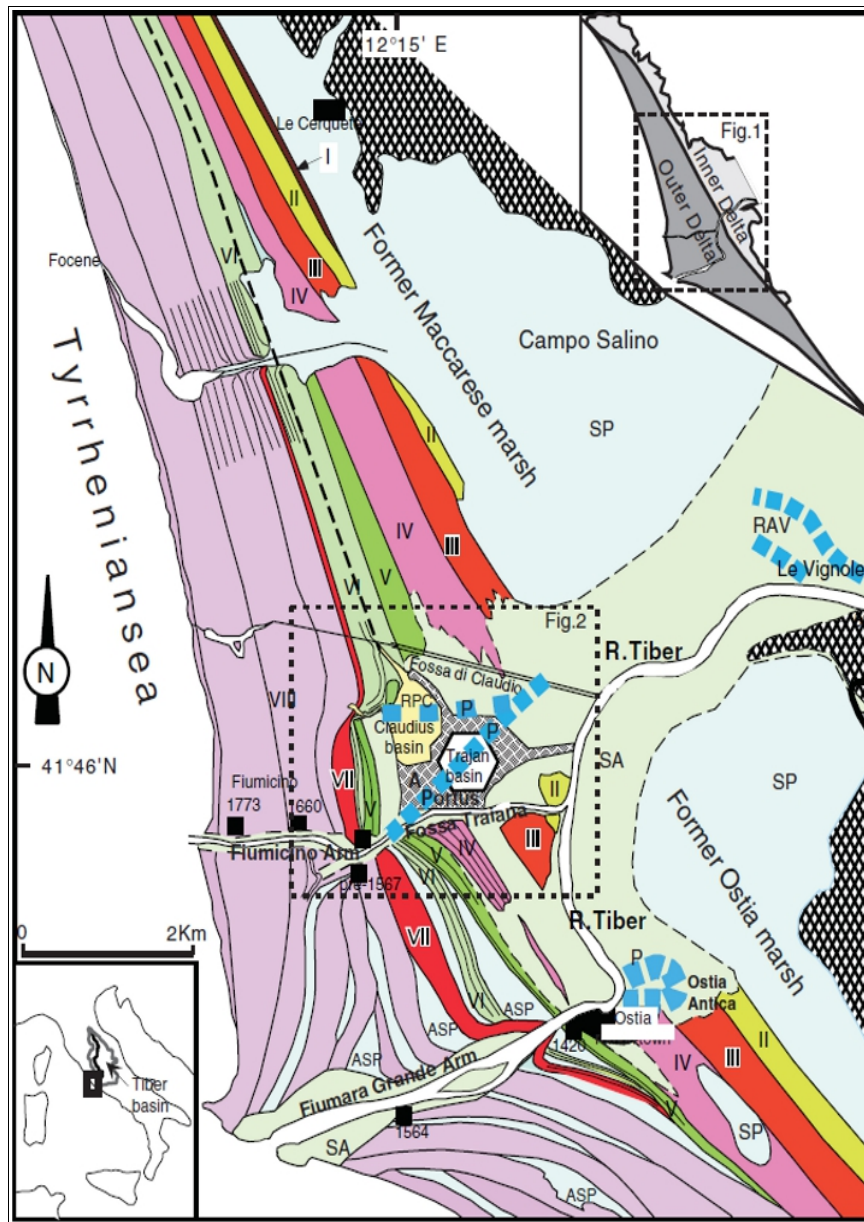


Figure 4.16. "Geology of the central portion of the Tiber delta. Legend: I–VIII = beach ridges of 8 phases from oldest to youngest; SP = mainly marsh sediments; SA = mainly alluvium; ASP = alluvial or beach or marsh sediments, in the areas between beach ridges of various phases; P = ancient channel of the Tiber; RAV = stream beds and crevasse splays of Le Vignole; RPC = deposits in the Claudius harbor; A = areas of human settlement in Roman times (towns, buildings, anthropic sand accumulations). Black squares mark the coastal towers (their age in yr A.D. is reported alongside)." Figure and caption from Giraudi, Tata, and Paroli 2009, 372.

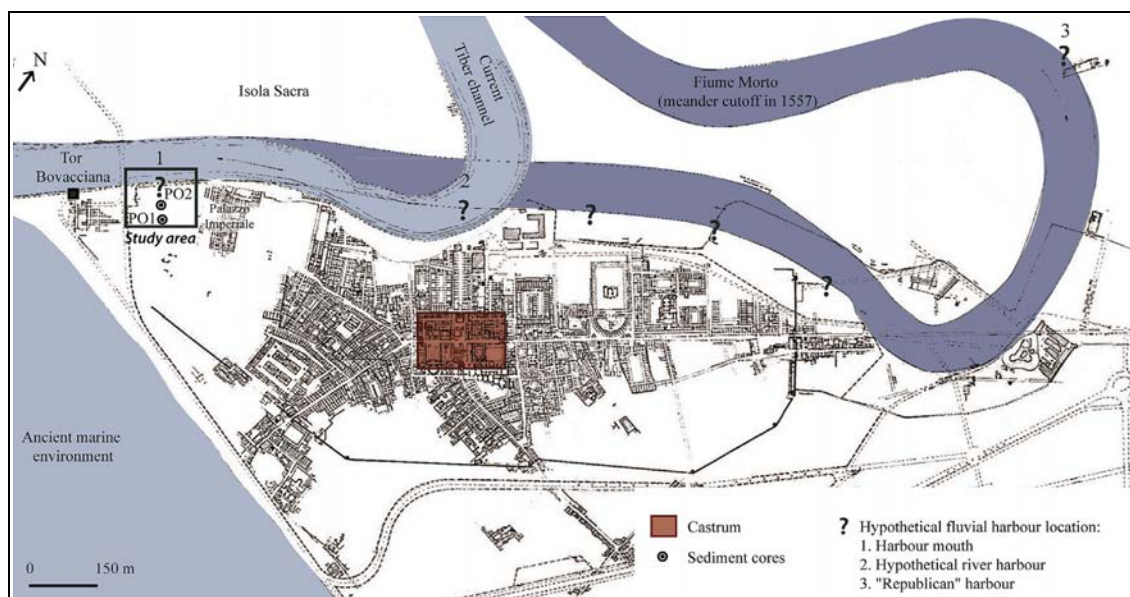


Figure 4.17: Plan map of Ostia illustrating hypothetical fluvial harbour locations and the previous location of the local channel of the Tiber River. PO1 and PO2 represent the location of sedimentary cores examined for stratigraphic sequencing. From Goiran et al 2014, 391.

The sedimentary sequence of sands in Ostia can be divided into three chief levels (Figure 4.18). The preoccupation levels comprised well-sorted, rolled particles of brackish sediments that included coarse, grey laminated sands intermixed with silty clay and shell-rich sands.²⁶⁴ The median grain size is typically 92 - 630 μm , fine to very fine sand.²⁶⁵ The deposits from the hypothesised river harbour basin levels exhibited alternating sands and silts, including fine, compact dark grey to blackish silty clay, laminated yellowish sands, and grey silty sands rich in organics and plant material.²⁶⁶ The sands were well-sorted and rolled, mixed with potsherds, oaks, olive, and cereal grains that marked active land-use in the area. The median grain size of the harbour level deposits is silt-sized, 5 – 50 μm .²⁶⁷ The abandonment levels included mostly rolled coarse

²⁶⁴ Goiran et al 2014, 393.

²⁶⁵ Goiran et al 2014, 393.

²⁶⁶ Goiran et al 2014, 393-395.

²⁶⁷ Goiran et al 2014, 393.

particles homogeneous, laminated yellow silty clay and sterile sands, with a median grain size of 20 μm , silt-sized.²⁶⁸

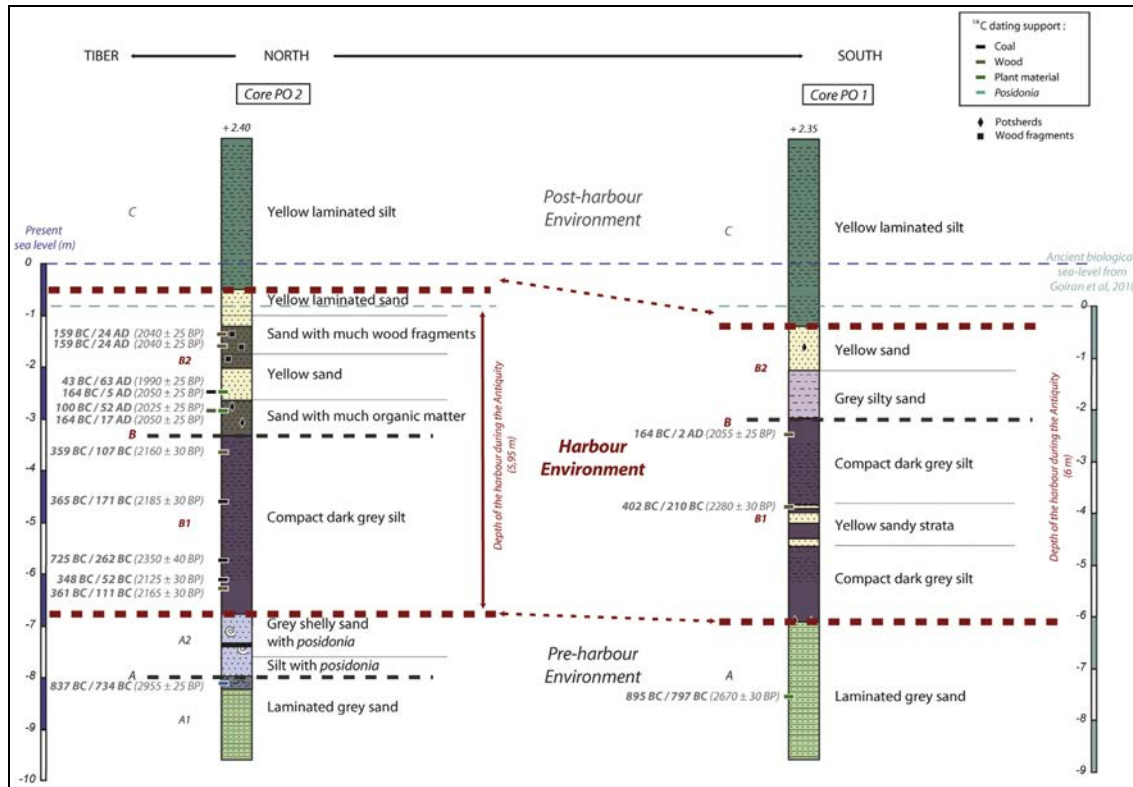


Figure 4.18: Summary of sedimentary sequence in Ostia, from Goiran et al 2014, 396.

4.5. How evaluating the geological material properties of components can improve our understanding of the mortars

Ancient builders in Ostia would have had a great deal of choice of different building materials and could, hypothetically, have simply used what was closest or easiest to supply. This fact begs the questions of which materials the builders used as aggregates and what we can infer from those choices. Given that ancient writers distinguish quarried sand (*harena fossicia*) from river sand and that Vitruvius expressed a preference for

²⁶⁸ Goiran et al 2014, 393-395.

the former, it is important to identify the origin of the aggregate material as thoroughly as possible. Ideally, a project of this nature would locate the original aggregate quarries, but the chemical and morphological changes that occurred during original mortar production and over the life of the structures makes it difficult to identify provenance with perfect reliability. It is possible, however, to make valid hypotheses combining petrographic observations with what is known about material from ancient quarries.

A great number of quarries for various tuffs and carbonate sources have been collated from literature and published by Ben Russell and the Oxford Roman Economy Project in a database that records their latitude/longitude coordinates.²⁶⁹ Certain areas of the city of Rome are known to have been exploited for building stone, with multiple tuff quarries located on the Palatine Hill and at the base of the Capitoline Hill.²⁷⁰ More recently, new tuff and/or aggregate quarries have been identified in ancient sites on the Esquiline Hill (at Piazza Dante and Piazza Vittorio)²⁷¹ and in suburban sites to the southeast of Rome.²⁷² The intricate commingled geology of the Roman Volcanic Province suggests that the types of aggregate found in the structures in this study could have been extracted from a number of quarries in the region (Figure 4.19). An evaluation of these quarries, including the specific materials excavated at each and their distance from Ostia, may provide some insight into the most likely aggregate source locations. This line of questioning is discussed further Chapter 8, incorporating the type and quantity of different aggregate lithologies that have been confirmed with scientific analysis and the relative costs of transporting material throughout the region.

²⁶⁹ Russell 2013.

²⁷⁰ Heiken, Funicello, and De Rita 2005, 51; Jackson and Marra 2006, 420.

²⁷¹ Serlorenzi 2014, 87-90.

²⁷² Buccellato and Coletti 2014,

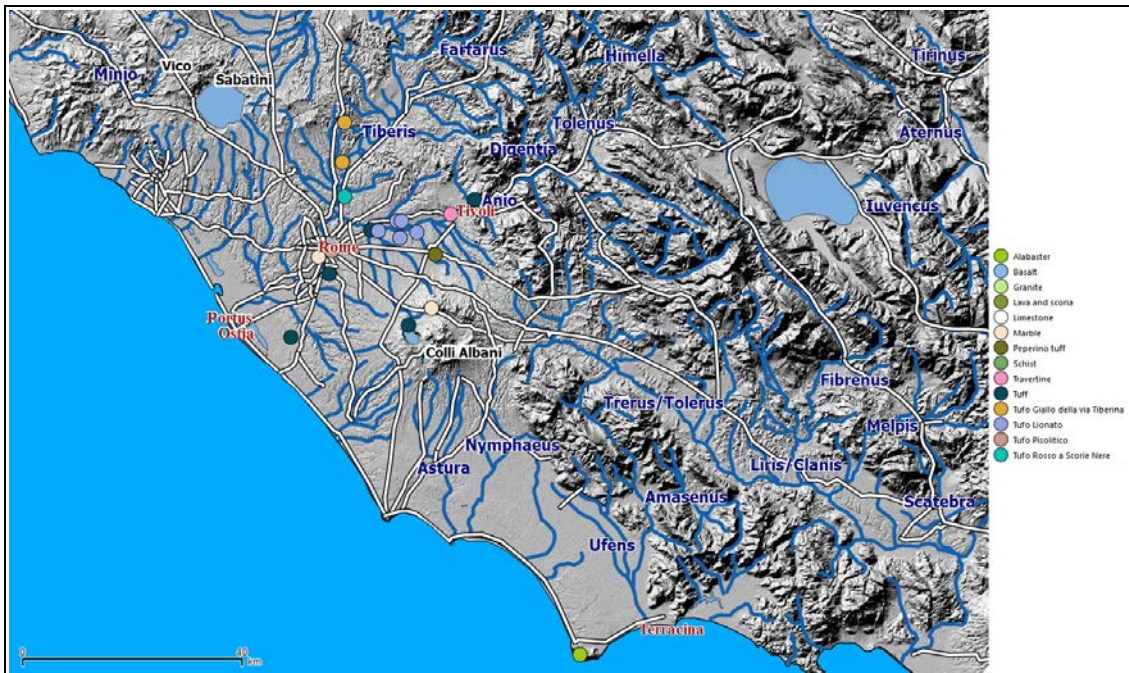


Figure 4.19: Locations of ancient cities (labelled in red), major volcanoes (labelled in black), rivers (labelled in blue), ancient roads (white) and stone quarries (marked). Map generated by author with Quantum GIS; quarry data after Russell 2013; city, road, river, and ancient coastline location data from Talbert 2000.

4.6. Chapter Conclusion

The eruptive and sedimentary histories of the Roman Magmatic Province are well-documented, as described above. Pyroclastic fall-out from Monti Sabatini and Colli Albani has intermingled during both primary deposition and subsequent fluvial alteration. The resulting geological profile is complex and quite varied across the region. Investigating the material available to the ancient builders has created a potential aggregate profile for the ancient mortars. As noted above, a number of authors have investigated the material properties of mortar samples to describe the components. Similar investigative techniques have been applied to samples of mortar from Ostia in order to evaluate the ancient builders' choices of material selection. The analytical techniques used in this study are described in the next chapter.

Chapter 5. Methods

Preliminary studies of structures in Ostia have helped define the research questions and direct the analytical protocol for a better understanding of the construction industry as a whole. Visual assessments of ancient structures and mortar *in situ* can provide valuable insight into construction techniques and materials, but the depth of information available using these methods is limited. Detailed material analysis is necessary in order to answer more detailed questions and to confirm or falsify the research hypotheses. As noted in Chapter 1, the research hypotheses for this project were:

1. Samples from all structures comprise lime mortar with volcanic sand fine aggregates.
2. The builders working in Ostia in the 2nd century CE have used the same, or similar, materials and techniques in all structures, representing a characteristic building style for this period in this location.
3. The aggregate used in the mortar mixes was selected from the most readily available source of naturally pozzolanic material, resulting in a durable and well-preserved final product.

The research methods described below have been chosen in order to glean the most information about the mortar samples that can be used to better understand the construction industry as a whole and, more importantly, the behaviour, the choices, and the expertise of the builders themselves.

5.1. Published guidance and industry standards

Professional and industrial standards for examining and testing hardened mortar and concretes are available for guidance, including the following British Standards: BSI 812 (1994) “Method for qualitative and quantitative petrographic examination of aggregates” and BSI 1881 (1988) “Testing Concrete” Part 124, “Methods for Analysis of Hardened Concrete.” Recommendations for testing historic concretes have also been developed and published by the RILEM technical committee Repair Mortars for Historic Masonry (TC 203-RHM). Specific recommended techniques for evaluating and describing the matrix, aggregate, and void spaces are detailed in *A Code of Practice for the Petrographic Examination of Mortars, Plasters, Renders and Related Materials*, published by the Applied Petrography Group (UK).

Extensive guidance in the examination of the samples and identification of volcanic lithology was provided by Dr Marie Jackson, who has studied Imperial-age mortar samples from Rome, underwater concrete core samples from Roman harbours, and relevant geological samples from the Roman volcanic province. Her research methods for the Rome samples, which have been adapted for this project, were originally designed as a geological study of the archaeological materials; her work and methodologies have been widely published. Each of the above resources recommends the use of optical and electron microscopy for the identification, description, and quantification of mortar constituents, including void space, binder, and aggregate inclusions. Collectively these standards have provided critical guidance to the key features that should be noted and recorded.

5.2. Sample selection and collection strategies

This project began with a suite of mortar samples from 13 different structures in Ostia, Italy, collected by Janet DeLaine, Marie Jackson and Fabrizio Marra in March 2004.²⁷³ The mortars range in age from the 2nd/1st century CE through the 4th century CE. The original sample set included 21 samples of mortar and one of *cocciopesto*, including nine thin sections of these materials. Five thin sections of representative pyroclastic rocks from the Roman volcanic province provided a critical reference to identify the volcanic materials in the Ostia mortars.

From this original suite of mortars, the samples from seven of the structures were selected for further study. The sample set comprised well-dated buildings constructed within a roughly 50-year time span, from 116-160 CE.²⁷⁴ This particular group of buildings potentially represented unique groups of builders working in Ostia during this period, as identified by DeLaine based on observed patterns of construction techniques and materials.²⁷⁵ Limiting the dataset to structures built in the 2nd century CE meant that significant differences in mortar components or production techniques most likely represented deliberate production choices rather than an evolution of the local technology over time.

It should be noted that the data set was ultimately limited by the low number of structures investigated and a relatively low number samples from each structure. The total of seven structures made for a fairly limited scope of investigation, however the analytical protocol was designed to improve the depth of investigation for each sample.

²⁷³ Marie Jackson provided a macroscopic and/or petrographic description of each sample, and these observations helped to define the scope of the present study.

²⁷⁴ Bloch 1947; Steinby 1987.

²⁷⁵ DeLaine 2004.

The objective here was not an attempt to generate a broad picture of mortar production in Ostia, but rather to focus in depth on material selection and processing from this group of structures built within a rather tight time frame. The results generated with this study were intended to illustrate the variability of mortar being produced at the same time across this location.

A research trip to Ostia in September 2011 allowed for visual inspection of each structure, providing valuable first-hand assessments of the multiple building phases, construction materials, techniques, and general state of repair. It was also possible to evaluate and record the mortar *in situ*. A preliminary survey of all structures was carried out over three days to observe each building and to identify the different types of mortar representing multiple construction phases. The original construction phase in all structures was easily distinguished from the later mortars based largely on the colour of the mortar binder matrix and the types of aggregate inclusions. It also was possible to study published plans for each building to validate field observations of construction phases, ensuring all samples were taken from appropriate sections of the walls. During this initial investigative phase, a number of brick stamps were located in most of the structures. These were recorded and photographed for later identification.

Because the act of mortar sample collection is inherently and necessarily destructive to the structures, considerable care was given to select appropriate sampling locations. The objective was to select locations that were undeniably part of the original construction phase, that provided access to a quantity of sample that could be usable for multiple analytical procedures, and limited the amount of new damage caused to the wall, all the while preserving the current aesthetic of each wall. For example, the join

between reticulate blocks and the brick *sesquipedales* would have provided easy access to relatively large chunks of sample, but would have created unattractive new damage to the wall facing that potentially would have exposed the inner facing to environmental damage and erosion (Figure 5.1). For these reasons, all samples were collected from areas of previous damage.



Figure 5.1: Example of reticulate facing, showing intact mortar at the interface between reticulate blocks and course of bricks. Lighter grey re-pointing mortar is visible at top of photo. Photograph by author.

Sampling the previously damaged areas of walls actually provided two key advantages. First and foremost, it preserved the walls both aesthetically and structurally and prevented the creation of areas of new damage. Secondly, previously damaged wall facing and edge damage to doorways allowed sampling from the core as well as the outer facing (Figure 5.2). Likewise, holes through walls (Figure 5.3) and the open face of windows allowed access to both facing and core mortar. This dual access reduced the number of walls necessarily damaged by sample collection. Ultimately, it was possible to collect core and facing mortar from the same wall in nearly all cases.



Figure 5.2: Edge of wall in the Casa a Giardino showing previous damage, intact tuff reticulate facing (A) and the exposed core (B). Photograph by author.



Figure 5.3: Hole in a wall in the Insula dell'Ercole Bambino with exposed core. Photograph by author.

The selection strategy described above benefited the research by limiting variables that could introduce uncertainty during analysis. Variations in samples could more confidently be attributed to material properties and construction choices if analytical parameters remain constant, for example, comparing only facing samples of different structures. Differential curing and mortar mix variation in different walls during original construction or weathering in different parts of the structure can not easily be accounted for in this type of study, so testing different parts of the same walls will help to limit these types of uncertainty.

After selecting the sampling locations detailed records were created at each site before any mortar was extracted. Information regarding wall location, construction technique and materials, mortar descriptions, and decoration were described on Wall Analysis Forms created for this project (sample form and description data included in Appendix B). All walls were photographed, including photos of the whole walls and close-ups of each the selected sample sites. The facing of each wall was illustrated in a technical drawing at 10 cm:1 cm scale. These drawings recorded sample locations, any identified brick stamps, identifiable damage, later mortar phases, remnants of wall decoration, and iron nails present in the walls. In cases when the wall extended beyond the limits of the graph paper, an additional drawing of the entire wall was produced at 50 cm:1 cm scale. A total of thirty-one drawings were completed.

In total, 28 new mortar samples were selected and removed from the walls. This represents four samples from each of the sample locations, including one facing and one core sample from both an interior and exterior wall. As noted above, in all possible cases facing and core samples were taken from the same walls. Mortar fragments were

loosened with a chisel or rock hammer and removed with a leaf trowel. The fragments and loose powder were caught in 4 ml-thick plastic sample bags and labelled with the structure, core or facing designation, and a sample ID. The sample identification scheme for this collection augments the system created by Jackson and Marra, in which each sample was labelled “OS-C” and then assigned sequential sample numbers from 1-22. For the new samples, a structure code has been added to the sample identifications (A-G, as assigned to each building), producing a trinomial code (i.e. OS-A-C23). To avoid confusion with the original 22 samples, the numerical sequence of this set begins with 23 and continues to 50 (Table 5.1). Additional notes were kept during sample collection to record the tools used, any difficulties encountered, the condition and hardness of the intact mortar, and the relative ease with which the mortar was removed.

Table 5.1: Sample list.

Structure	Construction Date	Facing Samples	Core Samples
Case a Giardino	125 CE	OS-C15 OS-A-C24 OS-A-C26	OS-A-C23 OS-A-C25
Caseggiato del Serapide	125 CE	OS-B-C29 OS-B-C30	OS-C16 OS-B-C27 OS-B-C28
Caseggiato del Larario	117 CE	OS-C-C31 OS-C-C33	OS-C5 OS-C-C32 OS-C-C34
Casa Basilicale	118 CE	OS-C2 OS-D-C36 OS-D-C37	OS-C3 OS-D-C35 OS-D-C38
Piccolo Mercato	118 CE	OS-C1 OS-E-C39 OS-E-C41	OS-E-C40 OS-E-C42
Terme del Foro	160 CE	OS-C8 OS-F-C43 OS-F-C45	OS-C9 OS-F-C44 OS-F-C46
Insula dell’Ercole Bambino	130 CE	OS-C21 OS-G-C48 OS-G-C50	OS-G-C47 OS-G-C49

The condition of all samples was carefully documented prior to analysis. Of the entire sample set, only a few consisted of single, contained chunks of mortar; most included only medium- to small-sized fragments and some quantity of powder. This indicates that their cohesion, overall, is somewhat compromised. All samples were individually photographed. The fragments were counted and weighed together, and the fine powder was weighed separately and stored in a plastic vial. The binder of each sample was assigned a Munsell Colour by examining its interior surface. These metadata have been collected and stored in a Microsoft Excel spreadsheet for quick reference (Appendix B).

5.3. Visual Inspection and Optical microscopy

Preliminary descriptions of macro-features for each sample were determined with visual inspection using a hand lens. Optical microscopy of the mortar samples comprised the main body of research presented in this thesis. The work began with investigations of sample fragments with a stereomicroscope. Primary macro-descriptions were generated by investigating each sample under the stereoscope and recording binder colour and cohesion, the presence of voids, cracks or other degradation features, and the size, colour, and shape of volcanic, brick or limestone inclusions. Additional features of note were reported, including the type and colour of lithic inclusions, the presence of lime lumps, mould, insects, or fibres. The apparent binder:aggregate ratios and the presence of any large voids were also recorded. Qualitative descriptions of the condition and cohesion of the mortar samples are included in Chapter 7. Thin section analysis using a Nikon Optiphot II polarizing microscope was used to evaluate the morphology and rela-

tionships of the mortar components and major structural features. A comprehensive list of key features appears in Chapter 7. Although both high and low power light microscopy were vital for initial evaluations and the identification of mortar components, thin section analysis comprised the bulk of this work.

Thin section investigation with the petrographic microscope has become a common tool for describing mortar components and microstructures. A number of research studies have used thin section analysis to describe ancient and historic mortars, including Elsen *et al.*'s work on historic mortars in Belgium;²⁷⁶ Pavia and Caro's work on ancient Roman mortars from Spain;²⁷⁷ Jackson *et al.*'s multiple studies of Roman mortars;²⁷⁸ and investigations into seawater concretes from harbour structures by the ROMACONS group²⁷⁹ to name but a few examples. Petrographic examination of thin sections yields qualitative descriptions of the mortar fabric and textures alongside identification of lithic fragments present as aggregate. Quantification of components is also possible with modal analysis.

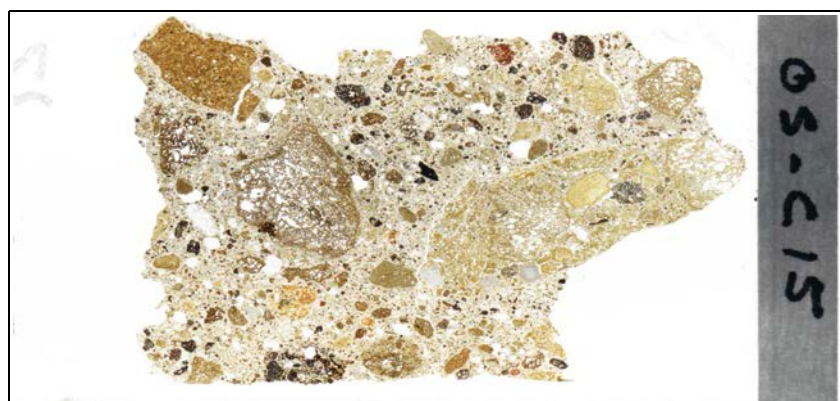


Figure 5.4. Example thin section.

276 Elsen *et al.* 2004.

277 Pavia and Caro 2008.

278 Jackson *et al.* 2009; Bianchi *et al.* 2011.

279 Brandon, Hohlfelder, Jackson, and Oleson 2014.

The International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM) has recommended modal analysis of thin sections by point counting to quantify binder and aggregate proportions.²⁸⁰ Quantitative point counts of thin sections involve the systematic identification of components in a thin section sample. A microscope stage attached to an electronic counter moves in regular linear transects across the slide. The type of material component (binder, void space, or aggregate) is recorded to the required degree of specificity at each point. With the electronic system, the stage moves a fixed distance when a point is recorded. The pre-configured grid size prevents the over-selection of certain particles and the introduction of bias into the process.²⁸¹ The required number of points varies for the degree of precision required, but fewer than 1000 points per thin section are usually necessary²⁸² and some authors recommend 500 points per thin section.²⁸³

Modal analysis is useful for directly quantifying individual mortar components, which can help determine material selection preferences and approximate binder:void space:aggregate ratios.²⁸⁴ The properties of the binder can be difficult to quantify through petrographic analysis, but qualitative observations can be recorded including cohesion, texture, and consistency.²⁸⁵ As these characteristics are influenced by the quality of the lime and the techniques of slaking and mixing, some inferences can be made about the original mortar production process. Void space can be quantified by void type, including macro-pores and cracks. Different types of voids result from either production

280 Lindqvist and Sandström 2000.

281 Lindqvist and Sandström 2000. 613.

282 Lindqvist and Sandström 2000. 613.

283 Allen et al 2012, 178.

284 Hughes and Valek 2003, 32.

285 Jackson *et al.* 2011 for example.

or degradation processes (as described in Chapter 2), thus quantification can provide information about the preparation and condition of the mortar. Specific aggregate lithologies can be recorded at each point, leading to aggregate profiles for each mortar sample based on the type and quantities of each type of material.

Modal analysis is subject to multiple types of error, including inherent error introduced by the nature of the sample itself or the sampling process and systematic error introduced by the operator during the point count.²⁸⁶ Inherent error can be attributed to the natural heterogeneity of the sample in terms of components and grain or particle size.²⁸⁷ Systematic or operator error typically refers to the misidentification of individual particles and can be avoided through experience and familiarity with the material under investigation.²⁸⁸ The various errors must be accounted for prior to modal analysis and when evaluating the point count data. In 1965, van der Plas and Tobi published a widely popular chart for the determination of relative error and the standard deviation of modal analysis (Figure 5.5).²⁸⁹ For a given volume percentage (p) of single component, the relative error will vary according to the total number of points counted (n). Neilson and Brockman have noted this chart is only applicable in simple cases when the size of the counting grid is larger than the largest grains in the sample and the grains themselves are compositionally independent.²⁹⁰ Howarth has produced updated charts for the determination of absolute error in point counting, which are more reliable for determining the upper and lower limits of error (Figure 5.6).²⁹¹

286 Neilson & Brockman 1998, 1328.

287 Allen et al 2012, 190.

288 Neilson & Brockman 1998, 1328.

289 van der Plas and Tobi 1965, 88.

290 Neilson and Brockman 1977, 1243.

291 Howarth 1998, 596-597.

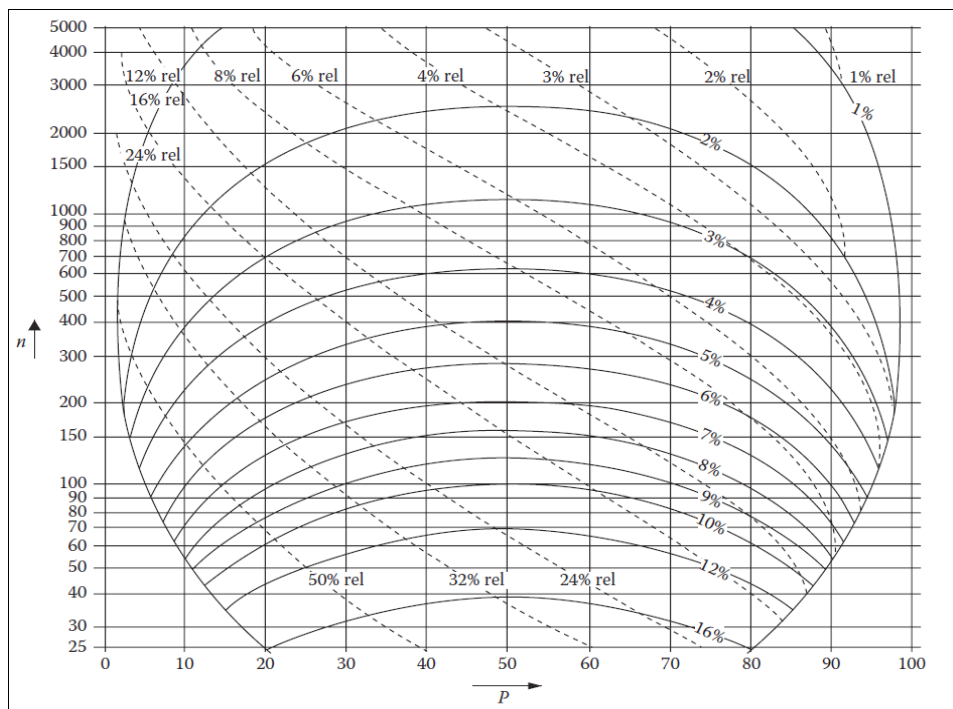


Figure 5.5: Chart for determining relative error of point counting results for a given component representing a given percentage (p) of a total count (n). Solid lines represent relative error; dashed lines represent standard deviation. After van der Plas and Tobi 1965, 88.

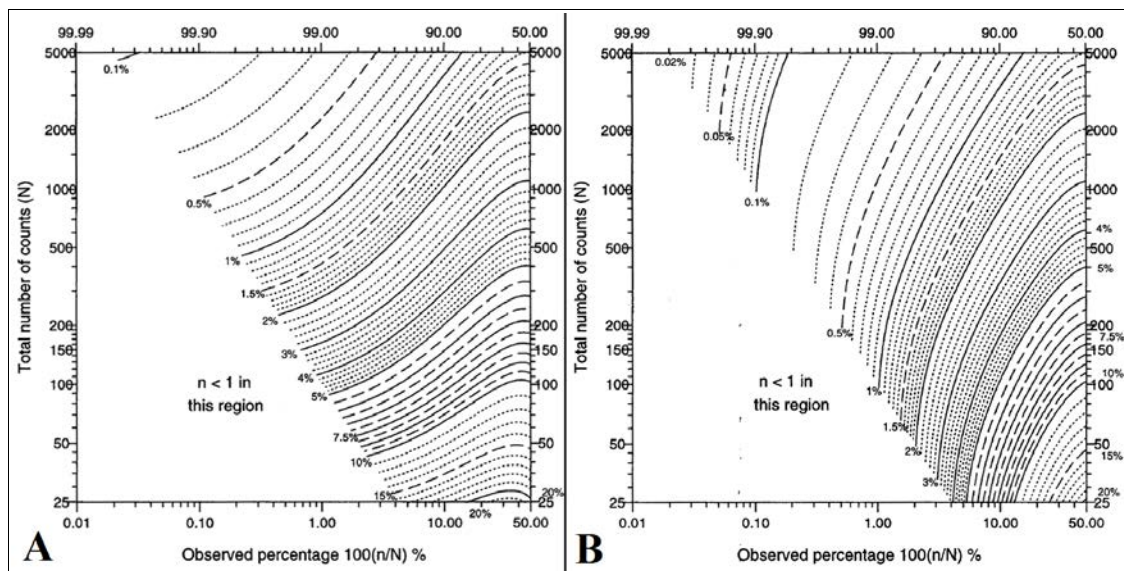


Figure 5.6: Updated chart for determining the upper (A) and lower (B) limits of error in point counting results for a given component representing an observed percentage of a total number of counts. After Howarth 1998, 596-597.

Thin sections of all samples from the seven structures were prepared for petrographic analysis and point counts. For thin section preparation, the mortar sample is cut to size on a kerosene-lubricated saw, and air-dried for 48 hours. Warm epoxy is then applied to the surface of the chip and allowed to penetrate under vacuum for 48 hours. The epoxied chip is then glued to a glass slide, sawn away at <1 mm thickness and ground with fine grit to a thickness of 30 microns. The porous, poorly-cohesive nature of the Ostia mortars and their cementitious hydrate components, which ideally should not be exposed to water or heat, contribute to the difficulty of making high-quality thin sections. The special handling techniques required were outside capabilities of what is possible in the RLAHA laboratory, so samples were submitted to the Open University and Petrolab Ltd. for professional thin section preparation.

Point counts of sample thin sections were conducted on a Nikon Optiphot-2 polarizing microscope using the PETROG hardware and software package generously supplied by Conwy Valley Systems, Limited.²⁹² The system included a digital camera attached to the microscope optics and a mechanical stage attached to the microscope stage, both controlled from within the computer software (Figure 5.7). Preliminary thin section investigation revealed that pozzolanic aggregate particles in all the samples varied from several centimetres to sub-millimeter in size. It was therefore necessary to calibrate the stepping stage to move at an interval that included as many of the smaller particles as possible without over-representing the larger clasts. Because the average particle size appeared to be approximately 1 mm, a step size of 1.000 mm was chosen for each count. The 10X objective lens was used for all point counting. A PixeLink

²⁹² The PETROG software and motorized stepping stage were generously made available as an academic loan, free of charge for the duration of this research project.

CMOS microscope camera was attached to the microscope to display a live video of the microscope field of view and collect high resolution digital images as each point was counted and recorded. Points were identified in the centre of the image under cross hairs on the computer video display (Figure 5.8). The target count was between 500 and 600 points, and each point count took between four and six hours to complete. The dataset components were divided into three main data classes: binder, void spaces, and aggregate. Each class contained several subdivisions to provide the most detailed and accurate descriptions possible, so that any specific mix designs that may have been in use at various times or in types of structures could be identified.

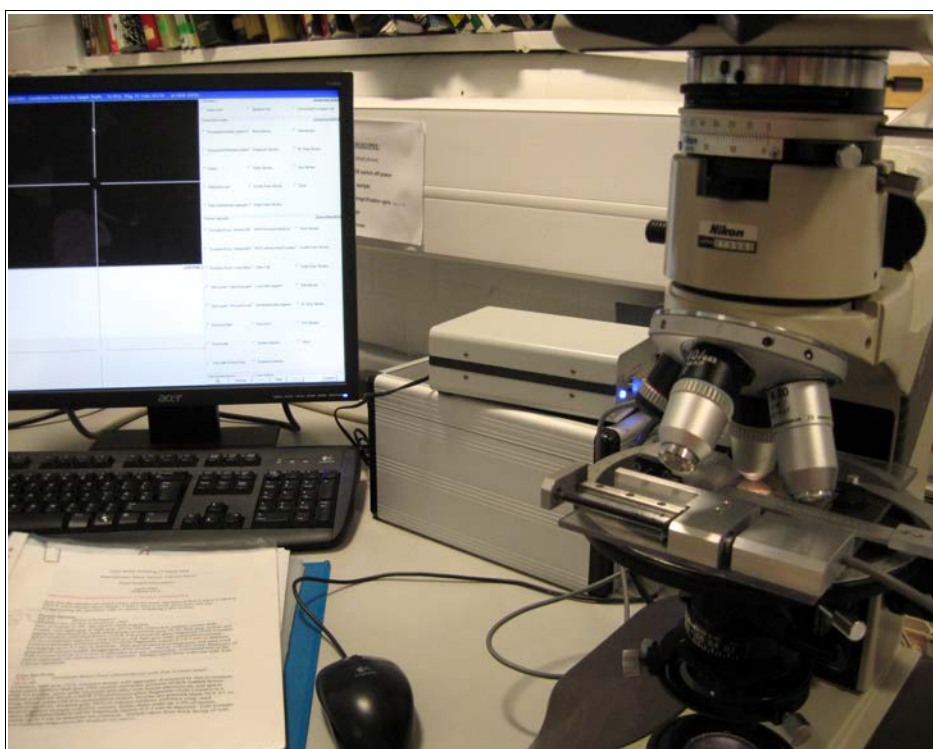


Figure 5.7. PETROG set-up, including mechanical stepping stage mounted to microscope stage (right), electronic control box (centre) and computer software display.

Points recorded in the Binder class were categorized as binder matrix, calcite crystals, pebble lime clasts,²⁹³ or relict aggregate fragments smaller than clay-sized particles (0.001 mm) that were too small to confidently identify lithologic provenance. The Void Space class included item options for linear cracks, spherical voids, and sub-rounded to angular voids. Fine aggregate particles were identified by their observed lithology and alteration facies, and any apparent alteration products within the aggregates such as zeolite or clay textures also were recorded.

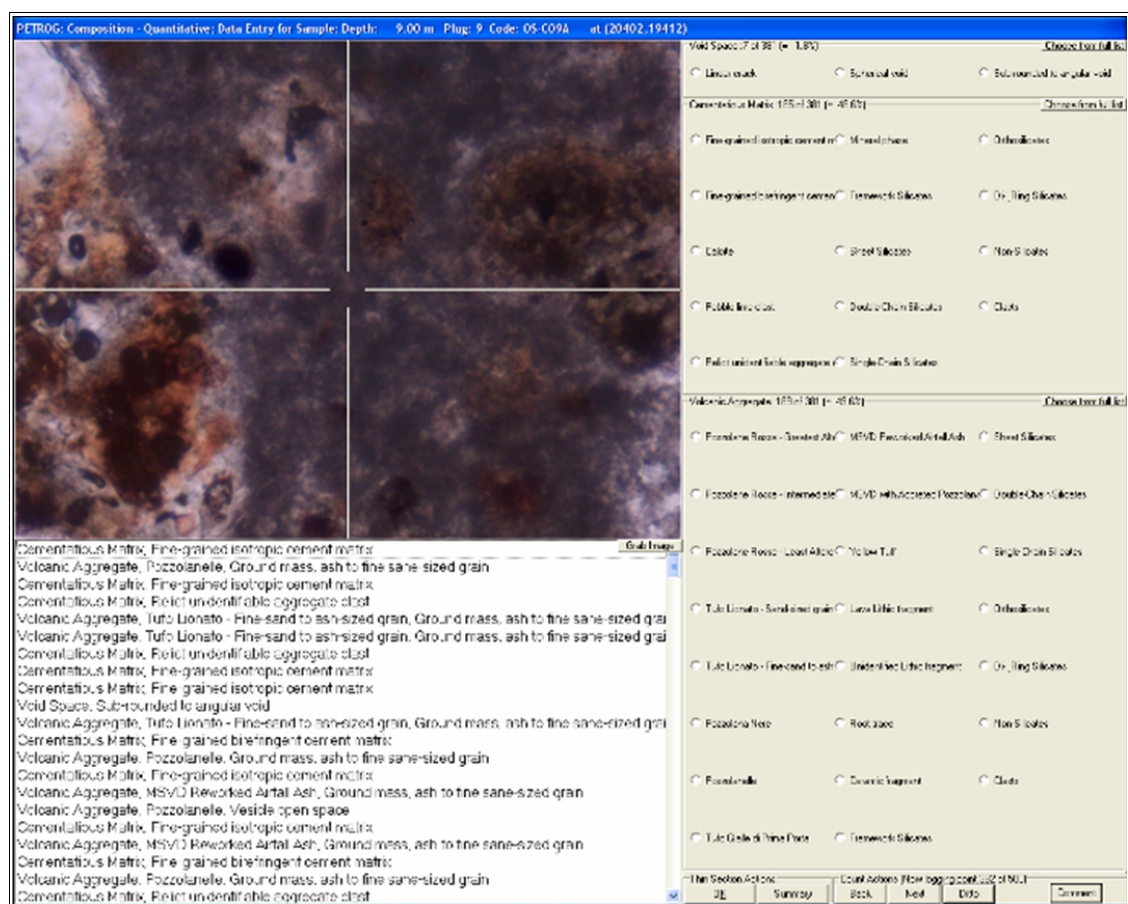


Figure 5.8. PETROG software data entry screen.

²⁹³ These lime lumps *sensu stricto* were initially included among the cementitious matrix but were counted among the aggregate during data analysis.

Point counting the thin sections allowed for direct quantification of binder material, aggregate particles, and the macro-pores visible in the binder. The PETROG software stored all records in a fully searchable relational database, which means that data could be analysed and compared easily after all thin sections have been counted. Individual sections can be analysed separately or collapsed to provide general results. From the qualitative descriptions and point counts, it was possible to identify individual mortar mixes and key areas for further investigation, such as fibrous cements and redeposited binder matrix material.

5.4. Scanning electron microscopy

Scanning electron microscopes (SEM) and electron microprobes (EMP) are powerful analytical tools used to examine the micro-structures of mortar materials and identify their chemical compositions. A sample, such as a chip of mortar or a polished thin section, is scanned with an electron beam that interacts to produce multiple types of energy. Samples must be polished smooth to attain accurate readings and coated with a thin layer of carbon in order to direct and conduct the beam across the surface.²⁹⁴ Backscattered electrons (BSE) are deflected as the beam interacts with the nucleus of atoms in the sample.²⁹⁵ Individual elements deflect energy at predictable intensities and an energy dispersive detector (EDS) “reads” the deflected energy allowing qualitative identification of the major elements present in a given area.²⁹⁶ When the electron microscope is fitted with a wavelength dispersive detector (WDS) microprobe, quantitative data are collected from discrete points to identify the chemical composition of individual

²⁹⁴ Kjellsen *et al.* 2003.

²⁹⁵ Pollard *et al.* 2007.

²⁹⁶ Pollard *et al.* 2007.

particles. The system can also produce a high-resolution magnified image of the sample from the backscattered electrons. These images are rendered in greyscale, which varies across the sample according to the atomic number of the elements present. Heavier elements appear brighter in the image, allowing for rapid preliminary evaluation of the sample during data collection. Semi-quantitative data are recorded as an energy spectrum, with peaks representing the specific elements present in a sample.

SEM analysis is a common tool for mortar studies and is often employed for both qualitative and quantitative descriptions of mortar samples.²⁹⁷ High magnification images allow for a more detailed visualisation of the relationship between mortar components. The size, texture, and morphology of sub-microscopic cements can be recorded at higher magnifications than is possible with thin section analysis, allowing a more complete characterisation of the binder microstructure. The beam can be directed at the binder/aggregate interface to evaluate the fine-scale microstructures of these components and measure the extent of cement penetration into aggregate clasts, in order to infer their cohesion with the binder.²⁹⁸ The greyscale variation in BSE images gives a qualitative illustration of relative compositions, which can be supplemented with SEM analyses for more precise atomic compositions. Areas of significantly lower calcium than silica could indicate leaching of binder material, which can result in loss of strength and mortar degradation.²⁹⁹

SEM analysis was performed on the epoxy-impregnated off-cut fragments from thin section preparation or small sample fragments when no off-cut was available, as in

297 A great number of SEM mortar studies have been published. Some examples include: Marusin 1995; Jackson *et al.* 2009; Miriello *et al.* 2010.

298 Scrivener, Crumbie and Laugesen 2004.

299 Yang *et al.* 2012.

the case of OS-C15 and OS-C21. These were well-suited for analysis because they were already consolidated with epoxy and were sliced for thin sectioning, which left a flat surface that would be easier to polish. The off-cuts needed additional processing before they could be introduced to the instrument, primarily to reduce their size to fit into 1-inch circular mounts and to polish the surface. Before treatment, the off-cuts were digitally scanned on an Epson Perfection 1650 flatbed scanner at 600 dots per inch and saved as JPEG images. This step recorded their original fabrics and allowed for later comparison to assess whether any voids or cracks were created during sample preparation. It was evident that the epoxy resin had not fully penetrated the samples, so additional preparation was required.

The surface of the off-cuts was coated with Caldofix2, an epoxy resin with a long pot life that cures under low heat; sample fragments OS-C15 and OS-C21 were placed in a 1-inch round mount and covered in Caldofix2.³⁰⁰ All samples were placed in a plastic, domed chamber attached to a vacuum pump that was pumped down to slowly evacuate the air in the sample, replacing it with epoxy. The vacuum pump was bled and slowly re-pumped to facilitate impregnation and minimize the formation of air bubbles in the epoxy resin as the vacuum was reached. After several minutes in the vacuum the samples were removed, recoated with epoxy, and slowly returned to the vacuum. This procedure was repeated until no more epoxy could be seen to enter the interior of the samples through visible voids in the surface. The samples were then gently heated at 75°C for 90 minutes and left to cool over a weekend. After 72 hours it was clear that the epoxy had continued to soak into the samples, leaving the top surface uncoated. The entire procedure was repeated to ensure that all samples were properly impregnated. Once

³⁰⁰ Caldofix2 is prepared by mixing resin and hardener at a ratio of 25:7 by weight.

properly prepared, a water-lubricated circular saw was used to cut the off-cuts down to approximately 1 cm² so they would fit into a 1-inch round mount. The cut fragments were placed face-down at the bottom of the mount and backfilled with epoxy, cured at 75°C for 90 minutes, and left to cool overnight.

The resultant sample rounds were ground and polished to achieve a uniformly smooth surface that could be properly analysed with the SEM. Grinding was done by hand to control the process and minimize the amount of material removed. The analytical face of the sample was rubbed in a circular motion for several minutes onto Beuhler Silicon carbide grinding papers of progressively finer grit sizes, listed in Table 2. Between each grit paper, the samples were rinsed in a Grant Ultrasonic Bath to dislodge any fine grit left on the sample face. Final polishing was conducted on a Metaserve 2000 electronic machine polisher using diamond compound polishing pastes on felt mats. With the sample rounds installed, the machine's arm rotated at 150 revolutions per minute for three minutes for each polishing cycle using progressively finer diamond paste (Table 5.2). Between each cycle, the samples were again cleaned and subjected to a sonic bath to remove all traces of the paste before moving to a finer grit. Samples were also evaluated under a microscope to ensure that no damage was being inflicted to the analytical face and that the polish procedure was progressing adequately.

Table 5.2: Grinding and polishing grit sizes and time spent

Grinding Paper Grit Sizes	Approximate Time spent
P320	4 minutes
P600	6 minutes
P1200	3 minutes
P2500	5 minutes
Diamond Polish Paste Grit Sizes	Approximate Time spent
9 micron	3 minutes
3 micron	3 minutes
1 micron	3 minutes
¼ micron	3 minutes

The properly polished sample rounds were digitally scanned at 1200 dots per inch, creating high resolution JPEG images that could be used as reference images during analysis (Figure 5.9). These required processing in Adobe Photoshop to adjust the midtone colour levels to improve their clarity. The processed images functioned as sample maps to record the locations of spot analysis and collected backscatter images.

A JEOL electron microprobe equipped with EDS/WDS was employed for analysis, with accelerating voltage of 15Kv with a 10.000 nA electron beam. Qualitative analysis included visual assessment of the samples, specifically targeting fibrous cements and the interface between aggregate particles and the binder. BSE images of these areas were collected to document the morphology and texture of these major components. Additional BSE images illustrating regions of binder matrix were collected to evaluate the extent and effects of any leaching of the matrix. Semi-quantitative chemical data and BSE images were collected from aggregate clasts, secondary clay material lining aggregate vesicles, fibrous cements, and binder cement grains.

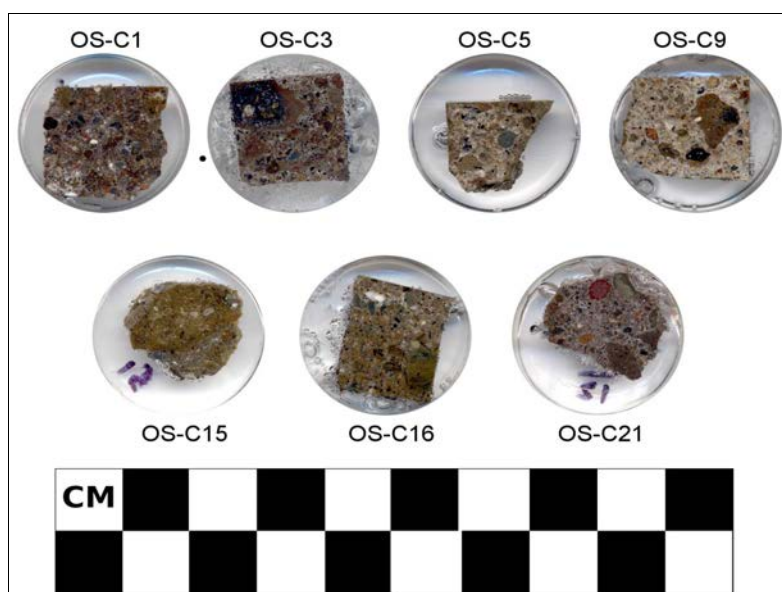


Figure 5.9: Polished sample rounds for SEM analysis.

5.5. X-ray Diffraction

X-ray diffraction (XRD) analysis is a technique employed by petrologists and crystallographers to identify the mineralogical compositions and characteristics of crystalline and poorly-crystalline materials. When X-rays of a known wavelength are directed at a sample, they pass through the atomic layers of a crystal and are reflected in predictable ways based on the crystal and atomic structure of the minerals present.³⁰¹ The diffracted energy is detected by the instrument and recorded as peaks in a diffractogram. Each peak indicates the presence of a specific crystallographic reflection, and most minerals produce multiple peaks of different intensities. Qualitative mineralogical identification is confirmed by comparing the diffractogram to empirically-derived, widely published patterns. In bulk samples, identification can be difficult when the peaks are broad or occur close together, causing overlaps, or the minerals are present in very low abundances; therefore, it is common to physically or chemically separate the sample to isolate the desired components that would be difficult to identify.³⁰² The Reitveld technique uses the least squares method to refine peak shape, height, and width until all peaks can be more easily identified.³⁰³ Quantitative analysis of diffractograms to determine relative abundance also is possible with this additional treatment of the data. In recent studies, XRD analysis has proven to be a useful tool for qualitative and quantitative mortar studies of both the aggregate and binder components.³⁰⁴

Because the number of minerals that occur in mortar samples is potentially quite high, the diffractograms often contain a great number of overlapping peaks, which

301 Pollard *et al.* 2007.

302 Moore and Reynolds Jr. 1997.

303 Gualtieri, Viani and Montanari 2006.

304 Biscontin, Pellizon Birelli, and Zendri 2002; Bendetti *et al.* 2004; Sanchez-Moral *et al.* 2005; Genestar, Pons, and Mas 2006.

makes it difficult to resolve all components. These come from the original volcanic crystals of the pyroclastic rock aggregate, authigenic surface textures of clay and zeolite minerals, and the mineral constituents of the binder of the mortar. The minerals expected in the sample suite is listed below in Table 5.3.³⁰⁵ The list was determined from preliminary investigation of thin sections, examination of published XRD results for the given lithologies, and published XRD results for mortar and concrete.

Table 5.3: List of suspected minerals that may be identified with XRD.

Primary Minerals	Chemical Formula
Leucite	$\text{KAl}(\text{Si}_2\text{O}_6)$
Clinopyroxene (diopside or augite)	$\text{CaMg}(\text{Si}_2\text{O}_6)$ or $(\text{Ca,Na})(\text{Mg,Fe,Al,Ti})(\text{Si,Al})_2\text{O}_6$
Biotite	$\text{K}(\text{Mg,Fe}^{++})_3[\text{AlSi}_3\text{O}_{10}(\text{OH,F})_2]$
Phlogopite	$\text{KMg}_3(\text{Si}_3\text{Al})\text{O}_{10}(\text{F,OH})_2$
Nepheline	$(\text{Na,K})\text{AlSiO}_4$
Sanidine	$(\text{K,Na})(\text{Si,Al})_4\text{O}_8$
Plagioclase	$(\text{Na,Ca})(\text{Si,Al})_4\text{O}_8$
Hauyne	$(\text{Na,Ca})_{4-8}\text{Al}_6\text{Si}_6(\text{O,S})_{24}(\text{SO}_4,\text{Cl})_{1-2}$
Secondary Alteration Minerals	Chemical Formula
Analcime	$\text{NaAlSi}_2\text{O}_6 \cdot (\text{H}_2\text{O})$
Chabazite	$(\text{Ca}_{0.5},\text{Na,K})_4[\text{Al}_4\text{Si}_8\text{O}_{24}] \cdot 12 \text{H}_2\text{O}$
Phillipsite	$(\text{Na,K,Ca})_{1-2}(\text{Si,Al})_8\text{O}_{16} \cdot 6(\text{H}_2\text{O})$
Halloysite	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$
Ettringite	$\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26(\text{H}_2\text{O})$
Opal	$\text{SiO}_2 \cdot n(\text{H}_2\text{O})$
Gypsum	$\text{Ca}(\text{SO}_4) \cdot 2(\text{H}_2\text{O})$
Cementitious Minerals	Chemical Formula
Calcite	$\text{Ca}(\text{CO}_3)$
Jennite	$\text{Ca}_9\text{Si}_6\text{O}_{18}(\text{OH})_6 \cdot 8(\text{H}_2\text{O})$
Tobermorite	$\text{Ca}_5\text{Si}_6\text{O}_{16}(\text{OH})_2 \cdot 4(\text{H}_2\text{O})$
Stratlingite	$\text{Ca}_2\text{Al}[(\text{OH})_6\text{AlSiO}_{2-3}(\text{OH})_{4-3}] \cdot 2,5(\text{H}_2\text{O})$

³⁰⁵ Chemical formulae taken from the Mineralogy Database at webmineral.com.

Mortar samples are often disaggregated manually or sieved to separate the aggregate and binder, with the binder representing the $<63\ \mu\text{m}$ fraction and the aggregate that $>63\ \mu\text{m}$.³⁰⁶ XRD analyses is used to identify the minerals present in the aggregate, confirming or supplementing those identified with petrographic analysis of thin sections.³⁰⁷ Habert *et al* used the technique to describe the reactivity of secondary alteration minerals in natural pozzolanic materials used as aggregate during mortar production.³⁰⁸ They determined that compressive strength is improved and preserved when secondary clays and zeolites are consumed in pozzolanic reaction.³⁰⁹ The Ostia mortars containing volcanic ash known to exhibit zeolitic alteration, such as Pozzolane Rosse, are of particular interest.³¹⁰ XRD coupled with petrographic analysis of thin sections should show whether zeolites in the ash aggregate have undergone a complete pozzolanic reaction, whether there remain traces of unreacted zeolites in the ash aggregate, and if zeolites might have formed *in situ* in the binder, as has been observed in Roman seawater concretes from Portus Traianus.³¹¹ Therefore, zeolite identification was a priority during mortar analysis.

In previous studies, XRD analysis has been employed on separated mortar binders to evaluate the formation of cementitious compounds, to confirm the hydraulic nature of cements, and to identify secondary alteration products within the matrix.³¹² XRD can identify specific crystalline cementation products in the matrix, such as calcite and vari-

306 Genestar, Pons, and Mas 2006.

307 Biscontin, Pellizon Birelli, and Zendri 2002.

308 Habert *et al.* 2008.

309 Ibid.

310 Jackson *et al.* 2010a.

311 Vola *et al.* 2010.

312 Jackson *et al.* 2009; Vola *et al.* 2010.

ous silico-aluminates.³¹³ XRD with Reitveld refinement has been used successfully to identify and quantify the presence of free lime, portlandite, and calcium carbonate in hydraulic limes, which form in succession with exposure to humidity and atmosphere.³¹⁴ These studies indicate the utility of XRD as a tool to evaluate the nature and evolution of the binder and identify key minerals that are not entirely visible in thin section, thus, during the Ostia data analysis, the diffractograms were refined to search for these cementitious compounds.

Oxford's Research Laboratory for Archaeology and the History of Art (RLAHA) does not have access to an XRD instrument, so the seven selected facing samples were sent to Dr. Andrew Shortland, Reader in Forensic Archaeomaterials at Cranfield University, for analysis in his laboratory. Preliminary bulk analysis of the mortar samples was unsuccessful, so the samples were disaggregated to separate the aggregate fragments from the binder and resubmitted for analysis.

According to the report supplied with results, the sample was carefully crushed in a mortar and pestle. The sample was placed under a binocular microscope and visible clasts removed with tweezers. These steps were repeated until there were no visible clasts. The sample was then crushed to a fine powder in a mortar and pestle and transferred to an XRD plate. Professor Keith Rogers, Director of the Cranfield Forensic Institute, Cranfield University, conducted sample analysis using a Bruker D8 Discover diffractometer. The instrument utilized CuK α radiation, calibrated against NIST SRM and collimator with 500 μ m diameter. Professor Rogers evaluated raw data with Reitveld analysis to identify and quantify major components. The diffractograms were fur-

313 Silva, Wenk and Monteiro 2005.

314 Gualtieri, Viani, & Montanari, 2006; Mertens *et al.* 2007.

ther reduced to identify peak positions of the minerals present using Match2 software for Windows, which utilises the Crystallography Open Database for mineral identification.³¹⁵ Diffractograms and raw data were compared against published mineral data for identification.³¹⁶

5.6. Particle size determinations with image analysis

The most common technique for determining particle size distribution of mortar aggregate is disaggregation followed by mechanical sieving.³¹⁷ In this method, the sample is manually separated and subjected to hydrochloric acid (HCl) to dissolve any residual binder left on the aggregate particles.³¹⁸ This destructive technique can be problematic because not all aggregate material is fully resistant to the acid, which may skew the results.³¹⁹ It is also possible that the sieving process itself alters the size and shape of particles, breaking down the softer aggregate and generating smaller fragments. To avoid such problems, an alternate technique is required for this project, namely computer assisted image analysis.

Recent work has shown that particle size distributions obtained via image analysis have proven reliable and demonstrate a good fit when compared to sieve curves produced with traditional mechanical sieving.³²⁰ In each of these studies, digital images of either thin sections or single planes of concrete and mortar were converted to binary images with the objects (aggregate) separated from the background (the binder). The indi-

315 Gražulis et al 2012; Gražulis et al 2009; Downs and Hall-Wallace 2003.

316 Downs 2006.

317 Mora, Kwan, and Chan 1998.

318 Mertens and Elsen 2006.

319 Mertens and Elsen 2006.

320 Mora, Kwan and Chan 1998; Marinoni *et al.* 2005; Mertens and Elsen 2006; Barbosa *et al.* 2012.

vidual particles were then counted and measured with computer software. The binary images were created using common thresholding techniques: establishing the difference in grey-level between the matrix and aggregate and then converting the image to binary colours, with black (RGB value 0) representing aggregate particles, and white (RGB value 255) representing the binder.³²¹ In some studies, additional steps have been taken to identify the matrix void space, allowing for binder:aggregate ratio determination.³²² The binder of the Ostia mortars contains a fine fraction of volcanic ash aggregate particles (Figure 9). These are commonly intergrown with pozzolanic cementitious hydrates in the mortars of the monuments in Rome and can be considered part of the binder.³²³ Therefore, a complex thresholding method was developed to identify the fine aggregate particle size distribution in the binder, which should be applicable to other archaeological mortar studies.

Seven samples were evaluated with image analysis techniques to assess the builders' degree of control over the size fraction used in mortar. Particle size evaluation was conducted on the same thin sections chosen for point counts and modal analysis. Each thin section was digitally scanned on an Epson Perfection 1650 flatbed scanner at 3200 dots per inch and saved as an uncompressed TIFF file with 125.98 pixels per millimetre to preserve the high resolution and detail. Unfortunately, conventional thresholding techniques were not successful because of the heterogeneity of the binder, the strong colour variations of the aggregate, and close proximity of individual ash particles. Bin- arization required a much more complicated, time consuming, and less automated process.

321 Mertens and Elsen 2006.

322 Marinoni *et al.* 2005.

323 Jackson *et al.* 2009; Jackson *et al.* 2010a; Vola *et al.* 2010.

Using GIMP image editing software, the image background was removed with the magic eraser tool, and colour levels adjusted so that binder and aggregate were visibly distinct. A 5-mm grid was superimposed over the image to provide a guide for subdividing the entire image into more manageable sections of 5 mm² (Figure 5.10). The grid squares were extracted and converted to individual binary images by manually adjusting the white and black colour levels as needed, essentially removing the binder from the image, leaving the aggregate particles (Figure 5.11). Aggregate vesicles were filled in black by hand, and all grid squares recompiled to a single image (Figure 5.12), as described in Elsen et al.³²⁴

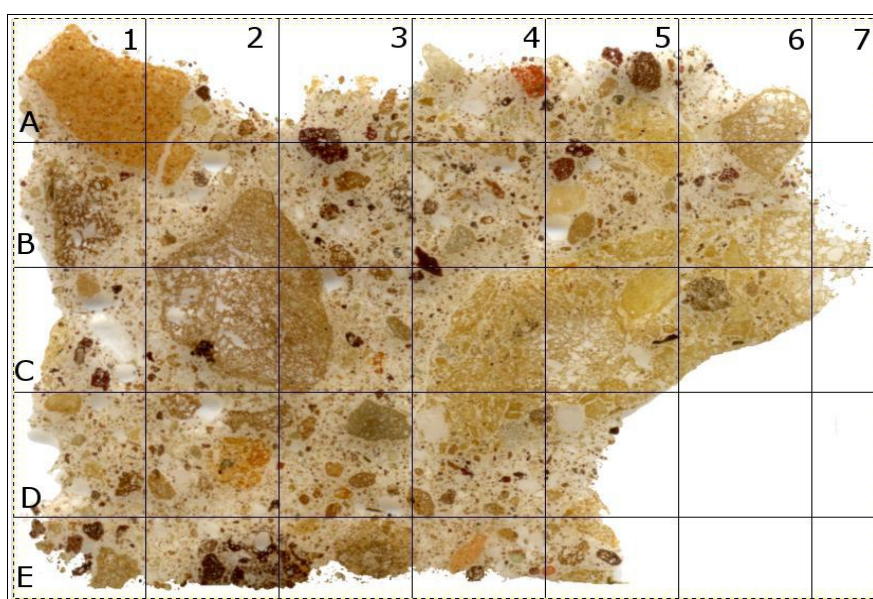


Figure 5.10: Digital scan of thin section with 5-mm grid, Sample OS-C15.

³²⁴ Mertens and Elsen 2006.

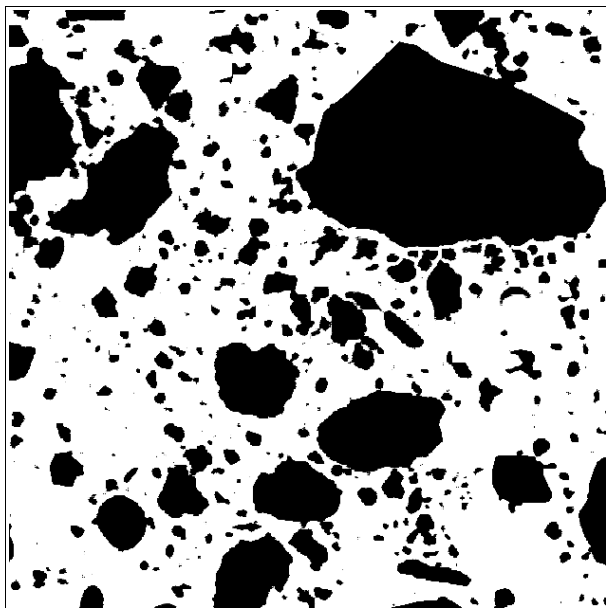


Figure 5.11: Enlarged image of grid square D3 after thresholding and binarization.

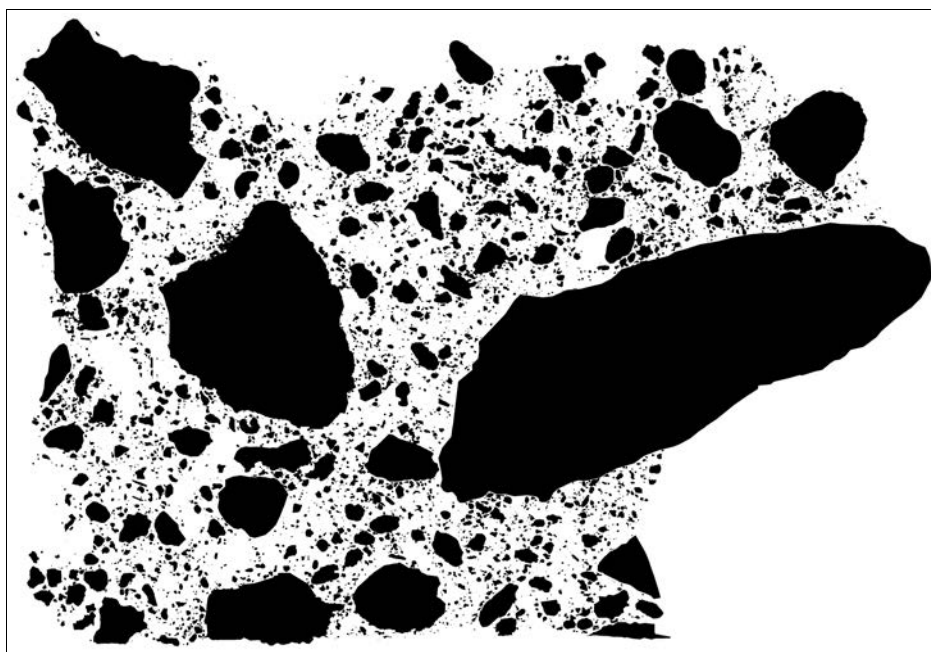


Figure 5.12: Compiled image.

With the unique particles separated from the matrix, the images were prepared for quantitative analysis using ImageJ, a software package designed by the US National In-

stitute of Health expressly for this purpose.³²⁵ The “Analyse Particles” function identified and measured and counted each particle. Only those particles that measured larger than the clay-sized fraction on the Wentworth Scale (0.0039 mm) were counted and included in the results. All data were recorded in a results table configured to record each particle ID number, area in mm², perimeter length (mm), minimum Feret diameter (mm), and the following shape descriptions:

Circularity $4\pi \times [Area] / [Perimeter]^2$ with a value of 1.0 indicating a perfect circle. As the value approaches 0.0, it indicates an increasingly elongated shape.

Aspect ratio The aspect ratio of the particle’s fitted ellipse, i.e., $[Major Axis] / [Minor Axis]$.

Roundness $4 \times [Area] / \pi \times [Major axis]^2$ or the inverse of Aspect Ratio.

Solidity $[Area] / [Convex area]$ ³²⁶

ImageJ also calculated median, arithmetic mean, and mode for the area, perimeter, and circularity of each sample for comparison across samples. Results were exported from ImageJ to Microsoft Excel for further analysis and comparison. Frequency data for minimum Feret diameter were graphed as cumulative percentage curves and compared to standard particles sizes as described by Wentworth.³²⁷ The perimeter of the particles, an approximation of specific surface, and circularity were compared across samples to further describe the particle morphology.

³²⁵ Abramoff, Magalhaes and Ram 2004.

³²⁶ <http://imagej.nih.gov/ij/docs/guide/userguide-27.html#toc-Subsection-27.2>.

³²⁷ Wentworth 1922.

5.7. Chapter Conclusion

The analytical methods described above were selected to generate data that would hopefully answer the research questions and satisfy the research objectives spelled out in Chapter 1. The primary concerns of this research regarded the behaviour and choices of the ancient builders, and these questions are best answered with material analysis of the mortar they produced. Using the petrographic methods described above, it was possible to identify and quantify the mortar components, evaluate the degree of material processing prior to mortar production, and visualize and describe the microstructure of different mortars in terms of degradation and durability. The results of analytical testing are presented in Chapter 7, but first, the next chapter describes the structures included in this study and the individual sampling locations.

Chapter 6. The Site, Structures, and Samples

Details of Ostia, the relevant structures, and the material samples involved in this project are described in this chapter. The first section very briefly describes the early development of ancient Ostia and presents what is known about the specifics of the construction industry in Ostia in the second century CE. This section also introduces previous research regarding the identification of separate groups of builders who were working both independently and cooperatively in the city during this period. The structural context is described in section 6.2, which discusses the typical building styles and materials used in the 2nd century. Section 6.3 describes the different mortar types found in the structures included in this project as identified visually *in situ*. The final section introduces the structures included in this study with brief descriptions of their individual archaeological histories, the construction styles and materials used in the original build, dating evidence from identified brick stamps, and details of the mortar sampling locations.

6.1. Ancient Ostia

6.1.1. Early settlement and development

Archaeological and ancient textual reports of the earliest settlement in Ostia differ by several hundred years. According to Livy, Ostia was established by King Ancus Marcius, who reigned in the middle of the 7th century BCE (642-617 BCE).³²⁸ He reportedly established salt mines in the area, making use of the marsh lands to extract natural resources on behalf of the city of Rome. Thus began Ostia's history as a locus of material

³²⁸ Liv. 1, 33.

supply and provider to the capital, according to traditional ancient sources. Livy, Pliny the Elder, Suetonius, Plutarch, Tacitus, and Strabo have all specifically mentioned Ostia as a salt works,³²⁹ a Roman colony,³³⁰ a naval harbour,³³¹ and finally a merchant port.³³² Unfortunately, no archaeological remains of the first occupation have ever been found. On the other hand, the earliest known structures belong to the *Castrum*, a military installation dated by Meiggs to the end of the fourth century BCE.³³³ While physical evidence for the conditions of Ostia's original foundation is sparse, it is clear that the city eventually grew in regional importance.

Ostia's proximity to both the Mediterranean Sea and the Tiber River, which leads directly to the capital at Rome, made the city an ideal location for both the seat of the navy in the 3rd century BCE and the later commercial port. Military ships here could prevent both enemy boats and pirates from travelling up the Tiber to Rome. Early harbour structures were installed during the Republican period, cementing Ostia's position as the main port for the city of Rome.

During the Imperial period (beginning in the late 1st century BCE, Ostia grew into a true cosmopolitan city with new public structures, including a large theatre, temples, a forum, and bath houses. Ostia's roots as a commercial centre were maintained, as evident from the numerous warehouse structures (*horrea*) located throughout the city. During the reign of the emperor Claudius (41 – 54 CE), an artificial harbour basin was constructed at Portus, approximately four kilometres to the west of Ostia, along with a system of canals used for transporting goods into Ostia for storage and subsequent move-

329 Liv. 1.33.

330 Plin., *HN*, 3.9.

331 Liv. 22.11, 23.38; Tac. *Hist.* 1.80.

332 Strab. 3.2; Plut. *Caes.* 58.

333 Meiggs 1973, however this date is a subject of debate,

ment to Rome. While it was once believed that Ostia shifted away from its primary role as a commercial port when the major harbour works were constructed at Portus, recent studies have challenged that perception.³³⁴ Heinzelmann suggests the architectural style of the *horrea* in Ostia suggests they were locations of active market trade, rather than simply temporary storage depots.³³⁵

A larger hexagonal port structure was built by Emperor Trajan from approximately 103-111 CE.³³⁶ The earthworks were major construction projects that demonstrated the degree to which Roman engineers could dominate the landscape. Furthermore, these constructions improved and expanded the infrastructure available for shipping to and from the whole of the empire.

As the shipping industry grew, so did the wealth of the city. Ostia flourished through the 2nd century and the emperors Trajan (98 – 117 CE), Hadrian (117 – 138 CE), and Antoninus Pius (138 – 161 CE) sponsored local building projects alongside private enterprises that brought in new residences and shops. Because Ostia has been preserved to the extent it has, different types of structures can be studied within a city-wide context.

6.1.2. The building trade in Ostia, 2nd century CE

The second century was a boon for the local building industry, when a growth of activity marked its place of importance within the local economy and Ostian society. Direct evidence for the builders in Ostia in the second century CE – above and beyond the buildings they created – is relatively good, including both archaeo-structural and

334 Heinzelmann 2010.

335 Heinzelmann 2010, 7.

336 Keay 2011, 11.

epigraphic evidence. The construction industry in Ostia was regulated by a professional organization (*collegium*) called the *fabri tignuarii*. Its headquarters is believed to have been the *Caseggiato dei Triclini*, just to the north of the *Terme del Foro* near the Forum.³³⁷ The group was quite large, and the names over 300 members have been preserved in funerary monuments and inscriptions.³³⁸ The collection of names includes only free-born citizens or freedmen, but no actual slaves.³³⁹ Other inscriptions have revealed that some members of the *fabri tignuarii* were connected with other *collegia*, local religious cults, or offices of local government.³⁴⁰ Clearly, the *fabri tignuarii* was a group of some distinction in Ostia, whose members probably held some level of influence and wealth. This suggests that members of the organization of builders made up a considerable sector of the local economy and played a key role in the success of the city as a whole.

With ranking members of the building trade highly placed and presumably holding influence within the social fabric of Ostia, organizational networks extended beyond isolated events of construction. Important questions can be posed regarding how far those networks reached and to what extent their influence was felt. Is it possible, for example, to connect otherwise unrelated building projects to each other based on the types of materials or styles of construction? Finally, how much can we really know about who built what? As noted in a number of recent studies, it may be possible to address such questions through careful evaluation of the buildings themselves.³⁴¹

DeLaine posits that clusters of specific decorative and structural elements found in buildings throughout Ostia represent different working groups of builders that can be

337 Hermansen 1981, 108.

338 DeLaine 2003a, 727.

339 DeLaine 2003a, 727.

340 DeLaine 2003a, 727-729

341 DeLaine 1995; DeLaine 2002; DeLaine 2003a.

readily identified.³⁴² Packer also cites a high level of precision and regularity in building styles throughout the city, suggesting a standardized program of construction that reused what he refers to as “standardized plans” which were adapted as needed.³⁴³ Packer does not, however, make any assumptions regarding the mechanisms behind his observations nor the organization of the builders themselves. Such regularity could only come about through cooperation between teams of builders or the repeated use of architectural plans by a single group.

A simple example of a standard building plan is the *medianum* type apartment. Though not identical, these units are common throughout Ostia, comprising several small rooms that adjoin a larger central room that faces outward (Figure 6.1).³⁴⁴ This is not to claim that all *medianum* apartments necessarily were built by the same workers, but that it would be feasible to look for some reasonable connection between them. The design of these structures is too regular to be coincidence and may be evidence for standardized design and/or a close network of builders working together.³⁴⁵

342 DeLaine 2003, 724; DeLaine 2004.

343 Packer 1968, 361.

344 Hermansen 1981, 25.

345 DeLaine 2003, 725-726.



Figure 6.1. Aerial photograph of medianum apartments in Case a Giardino, showing the nearly identical layout of two different groups of residential units. Image source: www.maps.google.com

In addition to specific structural elements, individual contractors may be identified by investigating the assortment of brick stamps in each building. DeLaine suggests the collection of bricks used for construction would have been dictated by the supplier of materials, which presumably would have been ordered by the contractor.³⁴⁶ Tracing the link from brick clay materials to brick producers and eventual users would be impossible were it not for a series of studies that documents and examines a unique collection of epigraphic evidence that allows just that.³⁴⁷

Beginning in the 1st century BCE, stamps were impressed into the wet clay before firing, in rectangular or circular shapes usually containing names, but also sometimes consular dates and/or glyphs. A great deal of rather specific information could be recorded in brick stamps, such as the clay district where the bricks were made (*figlina*), the owner of the brick yard where they were produced (*dominus*), and the actual brick manufacturer (*offinator*). Other features of note sometimes included the consular date, al-

³⁴⁶ DeLaine 2003, 724.

³⁴⁷ CIL vol XV, Bloch 1947b; Bloch 1948; Steinby 1987.

lowing for precise dating, and a pictographic element known as the *signum*. Multiple hypotheses have been proposed to explain the true function and utility of these stamps, but it is possible they served as identifiers to maintain stock control during production. Examples of such use would include tracking the productivity of individual *officinatores* or identifying the output of multiple *domini* from the same *figlini*. The nature of this stock control is not entirely clear because not all of the above features were included on every stamp and not every brick was stamped.

Despite the remaining questions regarding the specific function of the stamps, they have provided a great deal of information about the brick-making industry in the 1st and 2nd centuries CE. First and foremost, a large body of work by Bloch and Steinby has been dedicated to understanding non-dated stamps and refining the chronology of these stamps.³⁴⁸ This is important work that serves as the backbone to modern scholarship involving the sequencing of architecture in Ostia. The precise dates of Roman buildings can be inferred by referencing Bloch and Steinby to identify stamps that have been found *in situ* and in rubble deposits found during excavations. Recent studies have examined the brick stamp data in more detail, creating a prosopographical network of land owners and brick makers.³⁴⁹ By tabulating the information included in brick stamps, researchers have been able to generate profiles of the collection of bricks used in a particular building. Patterns have emerged that reveal strong connections between certain *domini*, given that their bricks often were found together, as is the case with bricks from the *domini* of Asinia Quadratilla and Flavius Aper.³⁵⁰ Perhaps both of these individuals sent their bricks to the same location for storage before use. Furthermore, some *domini*

348 Bloch 1941; Bloch 1947a; Steinby 1987.

349 See Helen 1975; DeLaine 2003; Graham 2006 for examples of such studies.

350 DeLaine 2002, 50.

usually operated within the same *figlini* or frequently employed the same *officinatores*, which again implies specific connections between the individuals who owned and operated the brickworks.³⁵¹

It is possible to relate specific structures to each other based on the information found in their brick profiles. DeLaine's application of this concept in Ostia has resulted in the possible identification of relationships between the builders of some of structures included in this project.³⁵² This is all very important work, as these studies are a good example of information about people and social networks being generated from material analysis.

A great number of brick stamps have been recorded in *Caseggiato del Serapide* (n=646), over 90% of which date from 123-126 CE, making this structure contemporary with the nearby *Case a Giardino*.³⁵³ Interestingly, the collection of brick stamps from *Caseggiato del Serapide* is quite different from those in *Case a Giardino*, and is in fact unique within Ostia, which suggests the bricks were supplied through different routes, i.e. from different suppliers, than those normally used by the builders of Ostia.³⁵⁴ Despite both structures having been built at roughly the same time and quite near to each other, it is clear the bricks were ordered separately from different sources. While it would be easy to categorize these structures as part of the same building program – in terms of both time and space – it seems they were fundamentally separate projects. Here, DeLaine highlights an important feature of architectural studies and one of the influences of the theoretical framework designed for this study: ancient structures retain

351 DeLaine 2002, 49.

352 DeLaine 2002.

353 DeLaine 2002, 54.

354 DeLaine 2002, 56.

evidence of every aspect of the original construction, all of which were chosen for specific, potentially identifiable reasons. In other words, it is possible to make hypotheses and draw conclusions about the behaviour and decisions made by the ancient builders through a systematic study of the methods and materials they used. Detailed descriptions of the structural elements, materials, and brick profiles for each of the buildings in this study are included in the next chapter.

The gathering of materials for new constructions was no simple matter and may have been influenced as much by personal connections within the network as by economics or practical concerns. DeLaine cites the example of the *Terme del Foro* as a good example to explore this issue because the patron of the building has been identified.³⁵⁵ The bathhouse was built with bricks from a limited number of sources by Gavinus Maximus, a Praetorian Prefect of Emperor Antoninus Pius in 160 CE. Nearly a third of the stamped bricks were from a specifically imperial source: the *dominus* L. Aelius Caesar, who was the adopted heir of Antoninus. A full 66% of the stamps were from the *domini* Asinia Quadratilla and Flavius Aper, which are often found together in structures in Ostia. Asinia Quadratilla was a member of an important family in Ostia, as her father was both consul and patron at the end of the first century CE. The Asinia Quadratilla group of bricks can possibly be connected to bricks from imperial *domini* through the *officinatores* noted in their stamps.³⁵⁶ This would suggest individual manufacturers working for multiple *domini*, thus connecting them together within the greater network.

³⁵⁵ DeLaine 2002, 50-52.

³⁵⁶ DeLaine is careful to point out that these connections have been determined through circumstantial epigraphic evidence and are therefore hypothetical. However, they are illustrative of the depth of inquiry possible with the study of brick stamps.

The collection of brick stamps in the *Terme del Foro* represented a tightly controlled small group of brick sources, all of which were highly-placed socially. As noted by Bloch, this is by no means unique.³⁵⁷ By the end of the 1st century CE, the majority of *figlini* and *domini* were held by wealthy Roman landowners who were also members of the ruling elite. They profited from their lands by leasing the lands, or at least the land-use rights, to independent operators and managers of the brick yards. Many of the individuals named in brick stamps can be recognized as members of the ruling elite.

Upon inspection, the picture painted here in the example of *Terme del Foro* is rather complex. A patron with immediate connections to the Imperial family has financed a massive public works project (a large bathhouse) in a prominent location (the Forum) almost exclusively built with bricks from suppliers who also have connections to the Imperial family. A direct network of local and regional influences is revealed in the connections between the Imperial *domini* and Asinia Quadratilla, whose brickworks may have been owned by members of Ostia's aristocracy. Furthermore, as DeLaine points out, in this case the building's patron may have been directly involved with the procurement of materials, relying on personal contacts to fulfil the order for his building.³⁵⁸ The fact that Gavinus Maximus would maintain control over such a relatively mundane aspect of the building as the brick supply begs the question of how far he extended his hand. Would the aggregate materials also have been so carefully controlled by the patron himself? Is it possible that structures with the same brick profile as *Terme del Foro* also share the same type of mortar and aggregates?

³⁵⁷ Bloch 1941, 4–6.

³⁵⁸ DeLaine 2001, 52.

Archaeological studies of architecture in ancient Ostia have benefited from a great body of primary evidence for the dates of structures and organization of builders. The researchers cited above have done tremendous work identifying the human networks directly involved in the making of the city. Literary texts and epigraphic evidence from brick stamps and public monuments have been used to connect individual structures to the actual people who built them – a rare occurrence in archaeological studies. The social networks can be easily traced when the materials are marked for such purpose, such as the case with bricks and their stamps. It is entirely possible that similar complex networks existed for the trade and acquisition of other building materials, including mortar aggregate. In the absence of direct evidence, these networks can only be inferred from what information we do have about the nature of the materials, how they were used in structures, and their mostly likely source locations.

6.2. Construction techniques and facing styles of Imperial-era buildings in Ostia

The changes in building styles through the first and second centuries represent at most two or three generations of builders working in the city, who would have followed and then evolved the traditions set by those that preceded them. The efforts of these individuals are well-preserved in the buildings they left behind, and the fact that they still stand today is a tribute to their skill and ingenuity. The structural context of these buildings at the local scale requires an investigation of the construction techniques used by these individuals.

Concrete masonry with various types of facing was widespread throughout Ostia, and by the 2nd century CE the most common type of facing included both brick and re-

ticulate. Some of the brickwork on monumental façades incorporated engaged columns, decorative arches, and pediments which very likely would not have been decorated further (Figure 6.2). The bricks appear to have been selected for uniformity in colour and size, creating an aesthetically pleasing homogeneous face. On the other hand, a number of interior walls faced in brickwork, reticulate, or both still carry evidence of painted plaster or stucco decoration. This is true even in cases where great care has been taken with the reticulate work to create a pleasing aesthetic effect. As seen in Figure 6.3, reticulate blocks have been carefully shaped and placed with regular spacing between joints, which were themselves smoothed to create a clean finish.



Figure 6.2. Decorative façade at entrance of Case a Giardino exhibiting engaged columns and undecorated brick pediment. Photograph by author.



Figure 6.3. The remains of decoration covering wall with brick and reticulate facing in Case a Giardino, showing the carefully crafted pattern of reticulate and brick courses, both covered with plaster. Photograph by author.

Early studies have assigned a strict chronology to stylistic changes in masonry facings, such as those by Ramage and Carrington in Rome;³⁵⁹ Mau, Maiuri, and Heres in Pompeii;³⁶⁰ and Gismondi, Lugli, Meiggs, Blake, and Packer in Ostia.³⁶¹ The generally accepted sequence is as follows:

- the Trajanic period (98-117 CE) and the Hadrianic period (117-138 CE) – brick and reticulate
- the reign of Antoninus Pius (138-161 CE) – brickwork only
- mid-3rd century to mid-5th century CE - *opus vittatum* (small squared blocks of stone interspersed with rows of brick).

The basic time line above creates a template for assigning dates based solely on aesthetic elements of the facing. Meiggs asserted that brickwork appeared in Ostia “not earlier than the late second century,” a view that can only be upheld if one allows that

³⁵⁹ Ramage 1829; Carrington 1933.

³⁶⁰ Mau 1899; Maiuri 1942; Heres 1982.

³⁶¹ Becatti et al 1949; Lugli 1957; Meiggs 1960, 543; Blake 1962; Packer 1968, 359–360.

Meiggs referred specifically to the complete abandonment of any reticulate elements in favour of only brickwork.³⁶² On the other hand, Packer presents a more complicated view that includes an overlap of styles. He claims that the Hadrianic period brought in more brickwork while still maintaining some use of reticulate until the shift to solely brick and mortar construction during the Antonine period.³⁶³ Packer's ideas paint a neat picture of development, incorporation, and then widespread adoption of brickwork throughout the city, though again it seems rather simplistic to map major stylistic changes to the installation of new ruling emperors.

The most likely scenario is a natural and gradual shift over several decades from brick and reticulate work to *opus vittatum*. The archaeological record of the standing remains actually shows a great deal of overlap and simultaneous use of the different styles within the 2nd century CE, and thus other authors have treated such prescriptions with caution.³⁶⁴ Fortunately, more rigorous dating methods have been developed with the careful study of brick stamps as noted above, and all dates assigned to the structures in this study refer to brick stamp dates determined by these authors. Although the time line for the evolution of architectural styles has been widely discussed in terms of aesthetics, the reasons behind the shift are not a subject of much debate by the above authors. It seems quite possible that the practicalities of brickwork became more attractive to Ostia's builders than reticulate work when time and financial implications were considered.

Concrete masonry carried an inherent cost that included not only the cost of raw materials and their transport but also the time required for builders to complete the installation. There is some evidence to suggest brickwork would have been both quicker

³⁶² Meiggs 1960, 543.

³⁶³ Packer 1968, 359–360.

³⁶⁴ Wheeler 1932, 133; Helen 1975; DeLaine 2003; and Graham 2006.

and cheaper than the reticulate facing. Using formulae from various historic sources, DeLaine derived productivity estimates for different types of concrete construction.³⁶⁵ The work-rate for simple brick facing, i.e. structural walls intended for decoration, was estimated as 1000 pieces per day, slowing to 500-700 pieces per day for finer brickwork such as that found in decorative façades. Reticulate work would be slower than even simple brickwork because the individual pieces would have been mortared into place separately, therefore DeLaine assigned an estimated work-rate of 700 pieces per day. The core would have presumably taken less time to complete than the facing because there was no need to take special care to finish the joints nor to shape or carefully select the coarse aggregate pieces. The final estimated work-rate for placement of the core is roughly 2000 pieces/day.³⁶⁶

DeLaine applied these figures to various structures in Ostia, including the *Casa dei Dipinti* which contained both reticulate and brick. She calculated that reticulate work, including the costs of all new materials and their transport, would cost approximately 22 – 24 man-days of labourer equivalent (mle) per cubic metre (m³) of wall; brick facing, on the other hand, would cost 14 – 15 mle/m³ of wall.³⁶⁷ Despite the hypothetical nature of such calculations, even a cursory glance at these figures suggests a clear economic advantage for the transition from brick-and-reticulate facing to brick only, at least for large-scale projects. First, the building costs would be reduced by nearly one-third, a considerable savings for the building's patron who must finance the structure. Secondly, the increased demand for bricks would benefit the *domini*, many of whom were directly connected to building patrons, as in the case of Imperial building projects.

³⁶⁵ DeLaine 2000, 235.

³⁶⁶ DeLaine 2000, 236.

³⁶⁷ DeLaine 2000, 242–243.

6.3. Identifying mortar phases

Given the complex evolution of Ostia's construction industry over only a few centuries, facing styles alone cannot be used to distinguish multiple phases of construction within a single building. A reliable method is to locate and identify multiple types of mortar, often of different colours or textures, that occur within a given structure. Correlating mortar types to construction materials or techniques offers a great deal of information about the life of a particular building, and the buildings included in this study are certainly no exception.

During the initial visual assessments, multiple phases of construction were noted in all structures. Different mortars were clearly distinct from each other, yet they were consistent across most of the structures. The mortar described as “original” referred to the mortar used in the first phase of construction in each building. On initial visual inspection, the original mortar in each structure appeared similar enough to describe it as “the same.” This mortar generally contained variously-sized aggregates that occurred within a white to grey coloured cementitious matrix (Figure 6.4). The same basic composition was found in both facing and core mortars, although the size of mortar aggregate was smaller in the facings.

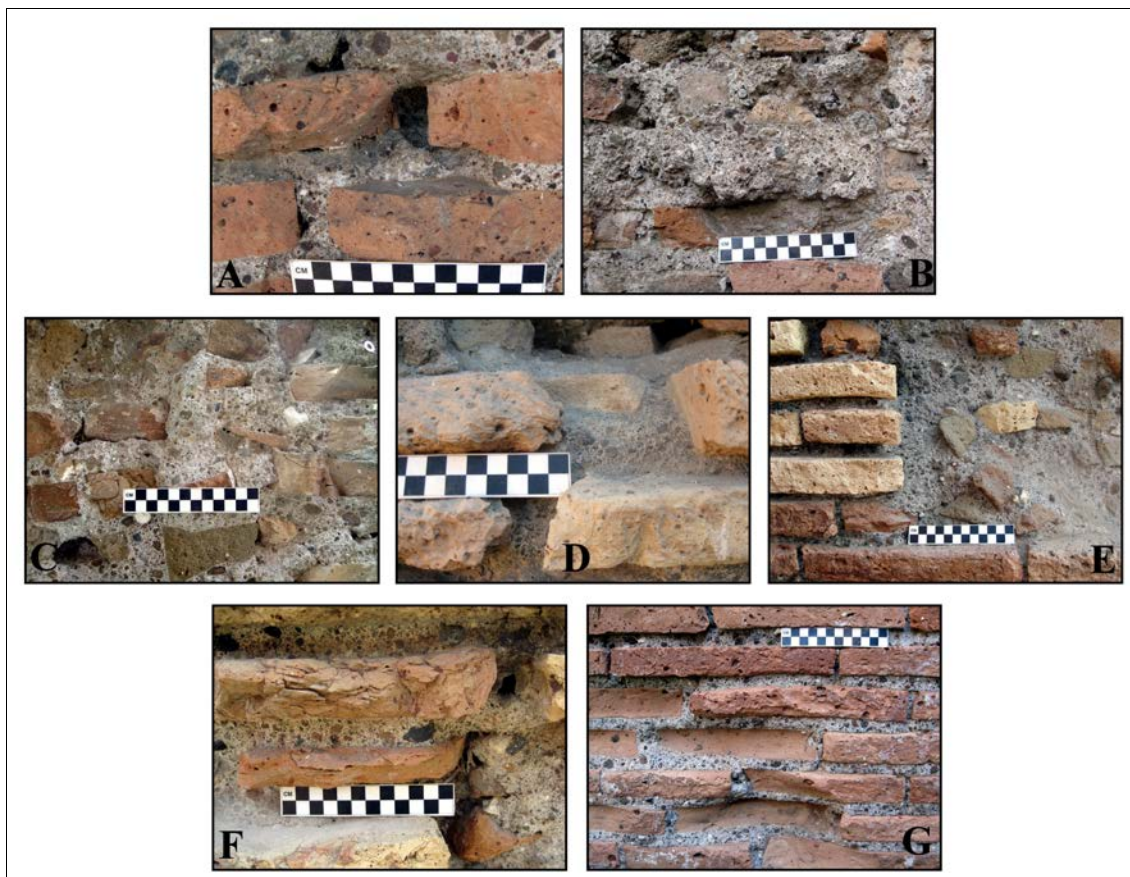


Figure 6.4. Details of original phase mortar from each structure, at sampling locations. A – Casa a Giardino; B – Caseggiato del Serapide; C – Caseggiato del Larario; D – Casa Basilicale; E – Piccolo Mercato; F – Terme del Foro; G – Insula dell'Ercole Bambino. Scale = 12 cm. Photographs by author.

Other varieties of mortars were found in all buildings, all of which represented secondary phases, including both ancient and modern repairs or reconstructions. Most of these construction phases were quite clear and easy to spot, such as the obvious section over the doorway in Caseggiato del Serapide (Figure 6.5). The new bricks in this area were set back from the original and were obviously less weathered. Additionally, the joints between the bricks were much wider than in the original construction phase. Some of these more modern restoration events have been marked with a small plaque

inscribed with the date of the repair, seen in the centre of Figure 6.5. Another example of this was found in *Casa Basilicale*, where one of these repairs was carried out and marked in 1969 (Figure 6.6).



Figure 6.5. Repair over a doorway in Caseggiato del Serapide, showing new bricks set back from the original construction area. Photograph by author.



Figure 6.6. Detail of plaque marking area of restoration completed in Casa Basilicale in 1969. Photograph by author.

In cases where the bricks within areas of repair were not so distinct from the original construction phase, mortars could be distinguished by texture, colour, and the nature of inclusions. One of the most distinctive mortars was a dense, dark-purple colour that occurred in areas of repointing (Figure 6.7). In this case, it would appear that the new mortar was installed between bricks that were still *in situ*, as a way to consolidate the existing structure without necessarily reconstructing the walls. The new mortar was often found to overlies the original mortar and occasionally overlapped the bricks themselves, both of which indicated a later-phase installation. By comparison, the newer mortar shows more consistency in the degree of alteration, with the original mortar showing erosion and degradation along the height of the structure.

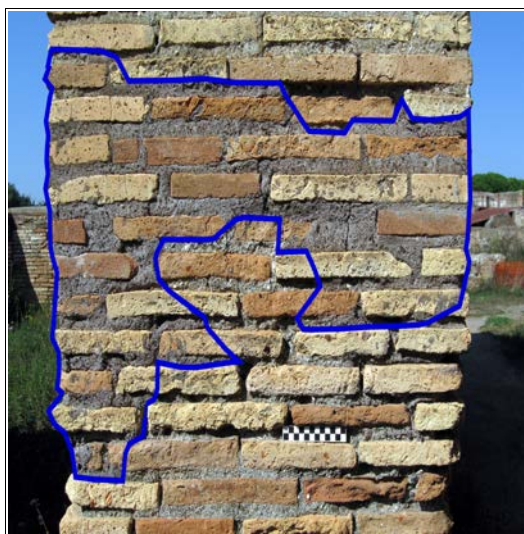


Figure 6.7. Dark purplish repointing mortar (outlined in blue) on a brick pier in Caseggiato del Serapide. Scale = 12 cm. Photograph by author.

A rather different type of repointing mortar appeared in a number of locations throughout Ostia. This was a light-coloured “speckled” mortar with very fine-grained aggregate inclusions (Figure 6.8). This mortar seemed to have been installed as *in situ* repairs or consolidation, most often in doorways where fine detail work may have been

desired. The difference in aggregate size made this easily distinguishable from the original coarser-grained mortar.

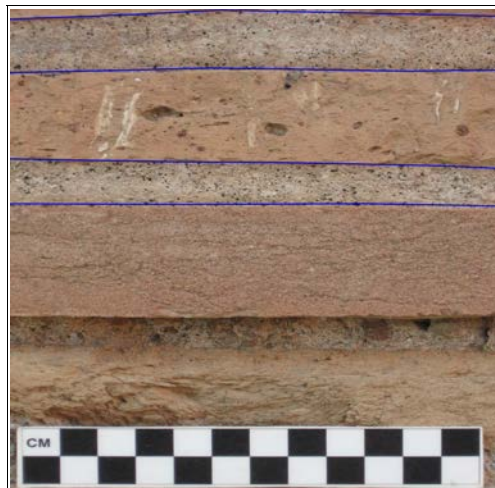


Figure 6.8 Very fine-grained “speckled” restoration mortar in upper two brick joints (outlined in blue) from a pier in Case a Giardino. Original coarser mortar is visible in the lowest brick joint. Scale = 12 cm. Photograph by author.

Yet another type of mortar was installed during reconstruction of larger areas, as it was visible within what would have been the core of the wall. This mortar was a light to medium grey colour with numerous white inclusions, most likely lime (Figure 6.9). This mortar was relatively soft and friable, easily damaged, and obviously suffered from ongoing degradation. This was an especially “dusty” mortar that disintegrated easily with even a gentle cleaning with a small paint brush. By comparison, all other mortar types, including the oldest original mortars, were quite resistant to brush cleaning and in some cases were better preserved and harder than the bricks.

Another very obvious later-phase mortar was a gritty dark mortar with light-coloured inclusions (Figure 6.10). Here again, this mortar was located in repaired sections of walls, clearly distinguishable from the original phase mortar as well as other repair



Figure 6.9. Very soft degrading mortar in Caseggiato del Larario. Scale =12 cm. Photograph by author.

mortars. One type of restoration mortar looked fairly similar to the original mortar in terms of size and type of inclusions. However, the binder was a darker grey and had a distinct smoothed texture. In the section of wall visible in Figure 6.10, this smoothed grey mortar can be seen overlapping a small section of lighter coloured original phase mortar.

One of the primary techniques of architectural evaluation is to use various structural features and the materials of a given wall to establish its history. These features can identify the type and number of construction events and repairs throughout the life of a structure. An example is illustrated in Figure 6.11, which shows a number of different building phases in *Casa Basilicale*. This particular image of an *opus mixtum* wall is a good example of the care required during these types of studies, given that some of the distinguishing characteristics can seem rather subtle at first. In this example, the reticulate has degraded in a number of places but has not been repaired consistently.

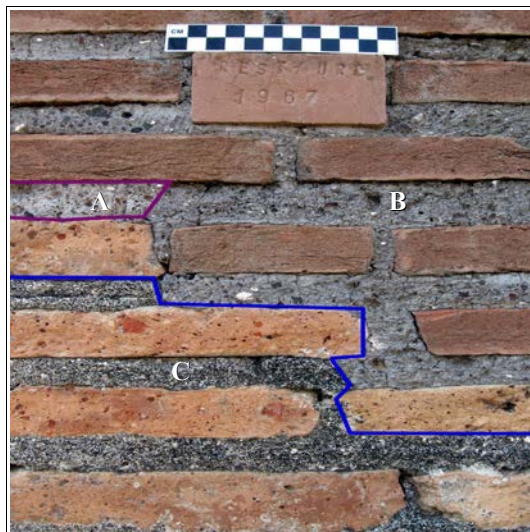


Figure 6.10. Three types of mortar in wall from Caseggiato del Larario. A=Small section of original mortar. Later mortars separated by blue line: B=smoothed grey mortar marked with restoration plaque from 1967; C=dark gritty mortar on lower half of image. Scale = 12 cm. Photograph by author.

The section labelled A in Figure 6.11 is an area of relatively intact reticulate pieces; section B, outlined in blue, is an area where the reticulate has degraded and been replaced with new pieces. The lower section C is an area of degraded reticulate that has not been repaired, such that much of the mortar has disintegrated and some of the core has been exposed. Despite the differential degradation of both the stones and the mortar, careful inspection made it clear that sections A and C are contemporary. The differences between these three areas were only made clear after a careful examination and detailed illustration of this wall.

The less subtle repairs are more easily distinguished. A section of brickwork has been added to the top of the wall where the bricks meet the upper section of intact reticulate blocks, labelled D and outlined in red. A subsequent phase of consolidation, labelled E and outlined in yellow, has been applied to both the top of the wall along its entire extent as well as along the top of the doorway fill. Consolidation is usually applied

to prevent further degradation to the very top edge of a wall. A major reconstruction event blocked the doorway with a fill of stone rubble set in mortar. This area, labelled F and marked in purple, effectively closes one of the structure's entrances and would have represented a major shift in the use of the space. “Reading” the structures in this way helps with understanding the history of a particular building and with the positive identification of the original construction phase.



Figure 6.11. Opus reticulata wall in Casa Basilicale, showing multiple reconstruction phases and repairs. A – original phase reticulata, intact; B – degraded reticulata has been replaced with rubble; C – original phase reticulata, degraded; D – later-phase brick work repair; E – consolidation; F – rubble in-fill of blocked doorway. Scale rods = 2 m. Photograph by author.

Studies that are more generally focused than the one presented here would analyse every wall in this detail, determining a relative dating sequence for each phase in all walls of the structure. In this study, however, visual assessments were conducted on

complete structures during the September 2011 field season but only recorded in full detail for the walls chosen for sampling. Limiting the extent of analysis in this way has provided enough information to assure the sampled mortars are from the original construction phases of the chosen walls.

It is important to investigate ancient structures from a construction engineering perspective by tracing the various building phases and reconstructions. Evaluation of the different types of brick and mortar masonry used can provide insight into contemporary local traditions and how they may have changed over time.

6.4. *The Structures*

The seven structures chosen for mortar sampling and analysis, listed in Table 6.1, were selected for a number of qualities that maximised their research potential. First, they were built within a relatively short time frame, which makes them part of the same broader construction phase of the city as a whole. Most of them date to the Hadrianic period (117-138 CE), excepting only the public bath (*Terme del Foro*) which was built at the end of the reign of Antoninus Pius, sometime after 160 CE. Both brickwork and brick-and-reticulate facing styles are represented in this group, in the hope that any material differences between the mortar used in these two styles will be revealed. As can be seen in Figure 6.12, the structures are located throughout Ostia, representing construction projects from all regions of the archaeological site. Finally, the structures vary greatly in size and function, which makes it possible to investigate the use of mortar under the varying conditions seen in this collection of buildings. The following section

presents each of the seven structures with an introduction to their archaeological histories, key structural features, and construction materials.

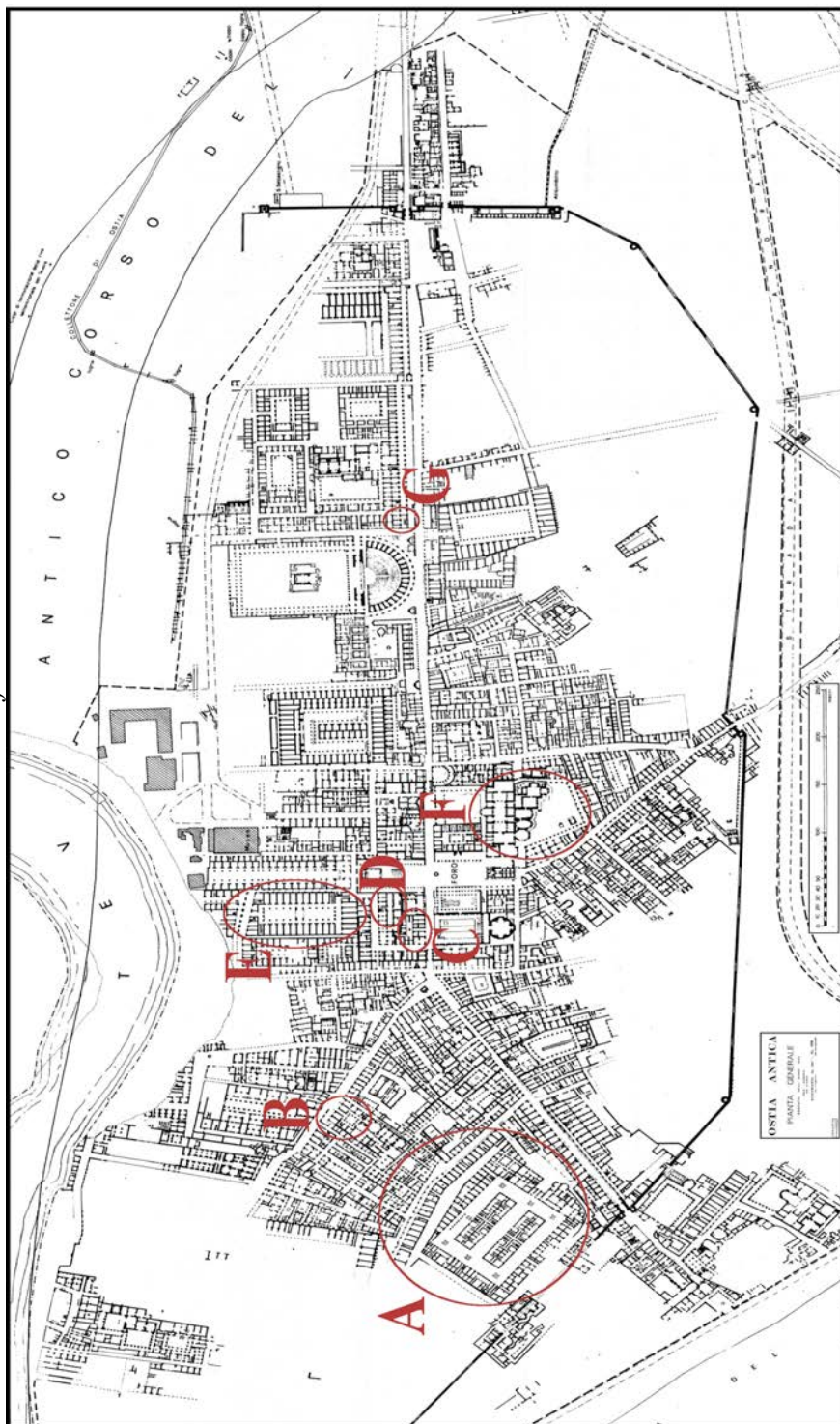
Table 6.1: Structures included in this study.

	Date³⁶⁸	Address³⁶⁹	Building function	Access	Facing materials
Casa a Giardino	125 CE	III, IX, 1-23	Apartments and shops	Mixed-use	Brick and reticulate
Casggiato del Serapide	125 CE	III, X, 3	Residence	Private	Brick
Casggiato del Larario	117 CE	I, IX, 3	Residence and shops	Mixed use	Brick
Casa Basilicale	118 CE	I, IX, 1	Residence and shops	Mixed use	Brick and reticulate
Piccolo Mercato	118 CE	I, VIII, 1	Storage, warehouse	Public	Brick and reticulate
Terme del Foro	160CE	I, XII, 6	Public bath house	Public	Brick
Insula dell'Ercole Bambino	130CE	II, VI, 3-4	Residence and shops	Mixed use	Brick

368 Dates reported by DeLaine from brick stamps (DeLaine 2002: 77-99).

369 Addresses follow the standard Regio, Insula, Building nomenclature.

Figure 6.12: Archaeological plan of Ostia Antica. Structures included in this study marked in red: A – Case a Giardino; B – Caseggiato del Serapide; C – Caseggiato del Larario; D – Casa Basilicale; E – Piccolo Mercato; F – Terme del Foro; G – Insula dell'Ercole Bambino. After Scavi di Ostia 1996.



6.4.1. Structure A - Case a Giardino- Regio III, Insula IX, 1-23



Figure 6.13. Archaeological plan of Case a Giardino. Sampling locations marked in red. After Scavi di Ostia 1996.

The *Case a Giardino* (Figure 6.13) is a large multi-use group of structures in *Regio III* in the southwest corner of the city. The complex represents a private building enterprise featuring residential apartments and commercial shops, which dates to between 123-125 CE.³⁷⁰ As DeLaine points out, all but three of the 151 recorded stamps have consular dates from this very limited period, which provide a tightly constrained date for original construction.³⁷¹ Twenty-five different *domini* are represented in the collec-

³⁷⁰ Gering 2002.

³⁷¹ DeLaine 2002, 53.

tion of stamps, most of them with direct ties to the Imperial family. The structure includes a number of apartments and shops that make up the outer perimeter surrounding a central courtyard. A group of eight *medianum* apartments occupies the centre of the courtyard. A main entrance with a decorative façade on the northeast side of the complex leads from the main street through a corridor into the open courtyard. It appears that all properties within the complex are accessible from the courtyard, and several of the shops along the northeast and southwest sides of the perimeter also have open access to the street.

Only the ground floor of the entire complex is still standing, but the remains of stairways and recesses for drain-pipes provide direct evidence for upper storeys.³⁷² The walls of the outer ring of buildings are faced in brick, including monumental façades of decorative brickwork. The interior walls of the central *medianum* apartments include the diamond-pattern reticulate work, proof that both styles were in use at the same time, even within a single structure. Many of the interior walls show the remains of painted plaster decoration. DeLaine notes that the uniformity of the red coloured bricks in the façades along the outer perimeter serves as an example of careful and consistent material selection, presumably to maintain a desired visual effect.³⁷³ Just beyond the doorway in the entrance corridor, the bricks are less mono-chromatic and incorporate more pink and yellow bricks.

Four samples, listed in Table 6.2, were collected from the *Case a Giardino* during the 2011 field season utilising the structural assessment and sampling methods described in Chapter 5. Core sample OS-A-C23 was taken from an exterior wall of the

³⁷² Stevens 2005.

³⁷³ DeLaine 2002, 54.

outer ring which faces into the courtyard (Figure 6.14), and facing sample OS-A-C24 was collected from a door jamb that is keyed into a decorative façade (Figure 6.15). All samples exhibited a weathered surface. From the north-easternmost of the central apartments, a facing sample (OS-A-C25) and a core sample (OS-A-C26) both were collected from approximately a 10 cm depth from the original outer surface, the facing sample was collected from between reticulate blocks and the core sample was taken from the exposed core itself (Figure 6.16).

Table 6.2: Details of samples from the Case a Giardino.

Sample ID	Wall Type ³⁷⁴	Sampling Location ³⁷⁵	Sampling Depth ³⁷⁶	Sampling Height ³⁷⁷	Munsell Code	Colour	Total weight
OS-C15	Unknown ³⁷⁸	Core	Unknown	Unknown	5Y 8/1	White	46.39 g
OS-A-C23	Exterior	Core	10 cm	84 cm	2.5Y 7/1	Light grey	7.09 g
OS-A-C24	Exterior	Facing	10 cm	131 cm	2.5Y 8/1	White	11.13 g
OS-A-C25	Interior	Core	13 cm	175 cm	10YR 8/1	White	19.39 g
OS-A-C26	Interior	Facing	5 cm	160 cm	2.5Y 8/1	White	19.99 g

³⁷⁴ For this and all subsequent sample tables, “exterior” walls are load-bearing walls that define the property boundaries and are visible from outside the structure; “interior” walls are those which primarily divide the space into rooms and not necessarily visible from outside the structure.

³⁷⁵ Sampling location refers to whether the mortar was collected from either the central core or the outer facing of the wall. “Facing” refers specifically to mortar from the brick joints. “Core” mortar was collected from the internal matrix from between coarse aggregate fragments

³⁷⁶ Sampling depth has been measured in centimetres from the outer surface of the wall.

³⁷⁷ Sampling height has been measured in centimetres from the ground surface.

³⁷⁸ Samples with “Unknown” qualities were received without the relevant information.

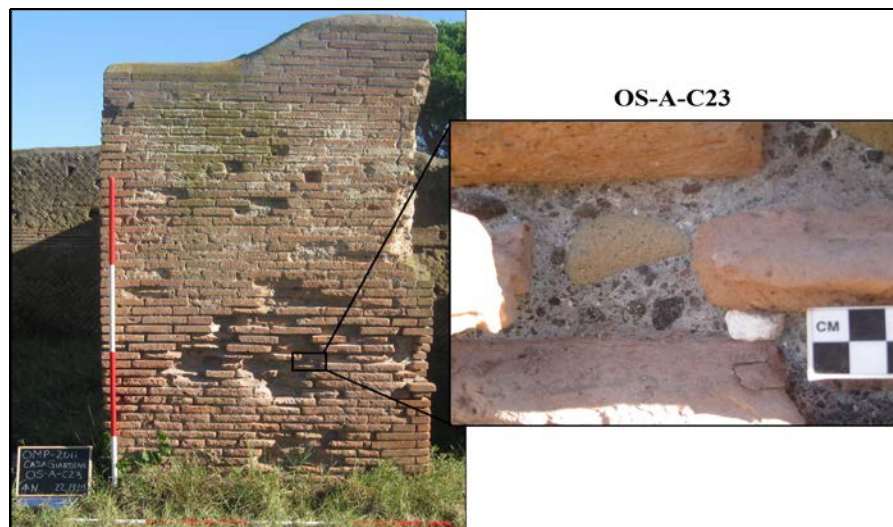


Figure 6.14: Photographs of sampled wall and detail of core mortar sample (OS-A-C23) location from exterior wall, facing into the courtyard of the Case a Giardino. Photographs by author.



Figure 6.15: Photographs of sampled wall and detail of facing mortar sample (OS-A-C24) location from exterior wall, the facade of the Case a Giardino. Photographs by author.

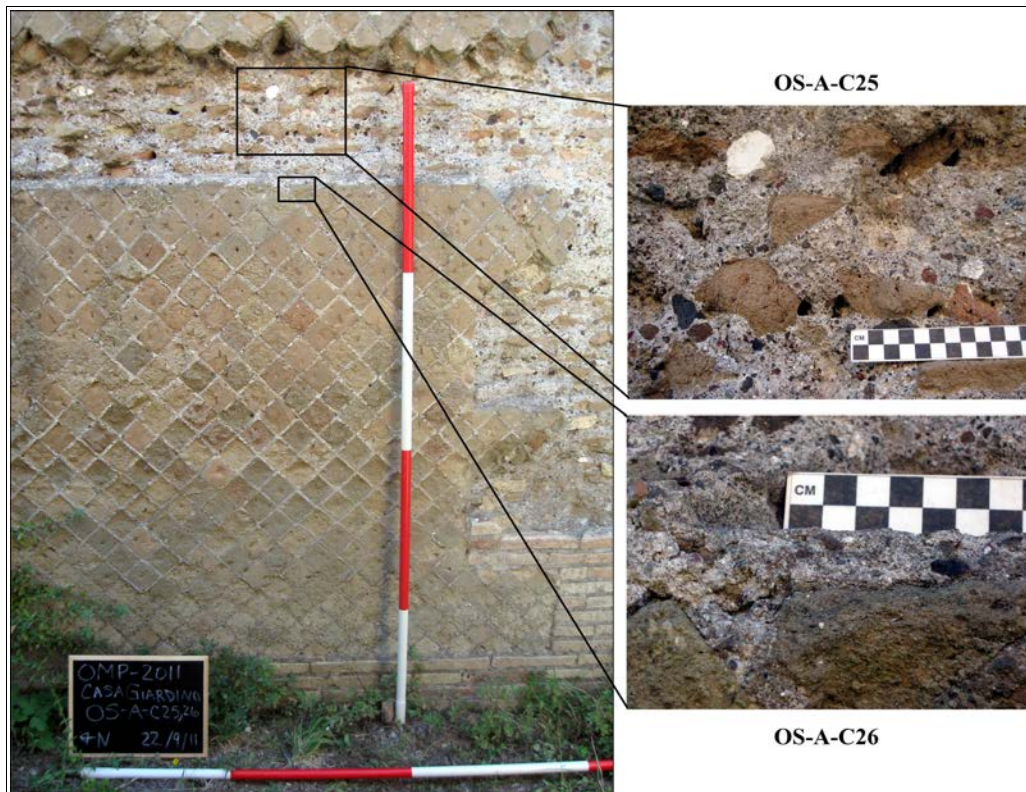


Figure 6.16: Photographs of the sampled wall and detail of core (OS-A-C25) and facing (OS-A-C26) mortar sample locations from the central apartments of the Casa a Giardino. Photographs by author.

6.4.2. Structure B - Caseggiato del Serapide - Regio III, Insula X, 3

Caseggiato del Serapide is another private structure in *Regio III* that has been interpreted as a mixed-use property with commercial shops on the ground floor and residential apartments on the upper storeys. Shop rooms at the front of the structure flank a narrow corridor leading from the *Via del Foce* to a rectangular courtyard (Figure 6.17). To the rear of the courtyard is a recess that includes a large painted niche and a small altar, which is typically referred to as a cult room. The central interior space retains fragments of columns and a section of the original tiled floor near the rear passageway



Figure 6.17. Archaeological plan of *Caseggiato del Serapide*. Mortar sampling locations marked in red. After Scavi di Ostia 1996.

through to a private bathhouse, *Terme dei Sette Sapienti*. This doorway and threshold are intricately decorated with plaster and stucco, essentially creating a façade that leads to the bath. The stairway to the second storey is still intact and usable, leading to an upper floor that still retains low fragments of walls. A very late addition to the structure is a possibly Medieval-era lime kiln that is accessible only from the side street to the southeast.

Over 600 brick stamps have been recorded in *Caseggiato del Serapide*, with 40 individual *domini* identified in the collection. The brick profile indicates a construction date of 125 CE. During the field trip in September 2011, 23 stamps were located in one wall of the entrance corridor and three in the wall fragments of the upper floors. Every one of the stamps found in these locations was the rectangular variety, rather than orbic-

ular, with text only and no signum. DeLaine believes the collection of *domini* represented in the recorded stamps suggests the builders of the *Caseggiato del Serapide* may have been come directly from Rome.³⁷⁹

Although much of the structure is still covered with plaster or stucco, the visible facings are brickwork with no apparent reticulate. There is no obvious pattern of chromatic design in the brick placement, as highly decorative plasterwork has been installed instead. The bricks are generally light-coloured, including the salmon-pink and yellow varieties. Two core and two facing samples were collected from this *Caseggiato del Serapide*, all taken from the stairwell (Table 6.3). The first sampling location was nearby in the landing of the stairwell, where a fragment of the exterior wall and broken window framing allowed access to both facing and core mortar (Figure 6.18). This location along the southeastern side of the property is undoubtedly an exterior wall. The second location was the long boundary wall along the steps, which abutted the walls of the bathhouse and would have been covered with vaulting (Figure 6.19). This wall is considered an interior wall for the purposes of this project, as it served as a boundary between properties but was not generally exposed to the elements on either of its faces.

Table 6.3: Details of samples from the Caseggiato del Serapide.

Sample ID	Wall Type	Location in Wall	Sampling Depth	Sampling Height	Munsell Code	Colour	Total weight
OS-C16	Unknown	Facing	Unknown	Unknown	2.5Y 8/1	White	83.63 g
OS-B-C27	Exterior	Core	31 cm	114 cm	10YR 8/1	White	23.1 g
OS-B-C28	Interior	Core	9 cm	164 cm	10YR 8/1	White	22.14 g
OS-B-C29	Interior	Facing	5 cm	59 cm	2.5Y 8/1	White	61.02 g
OS-B-C30	Exterior	Facing	5 cm	155 cm	10YR 8/1	White	25.15 g

³⁷⁹ DeLaine 2002, 76.

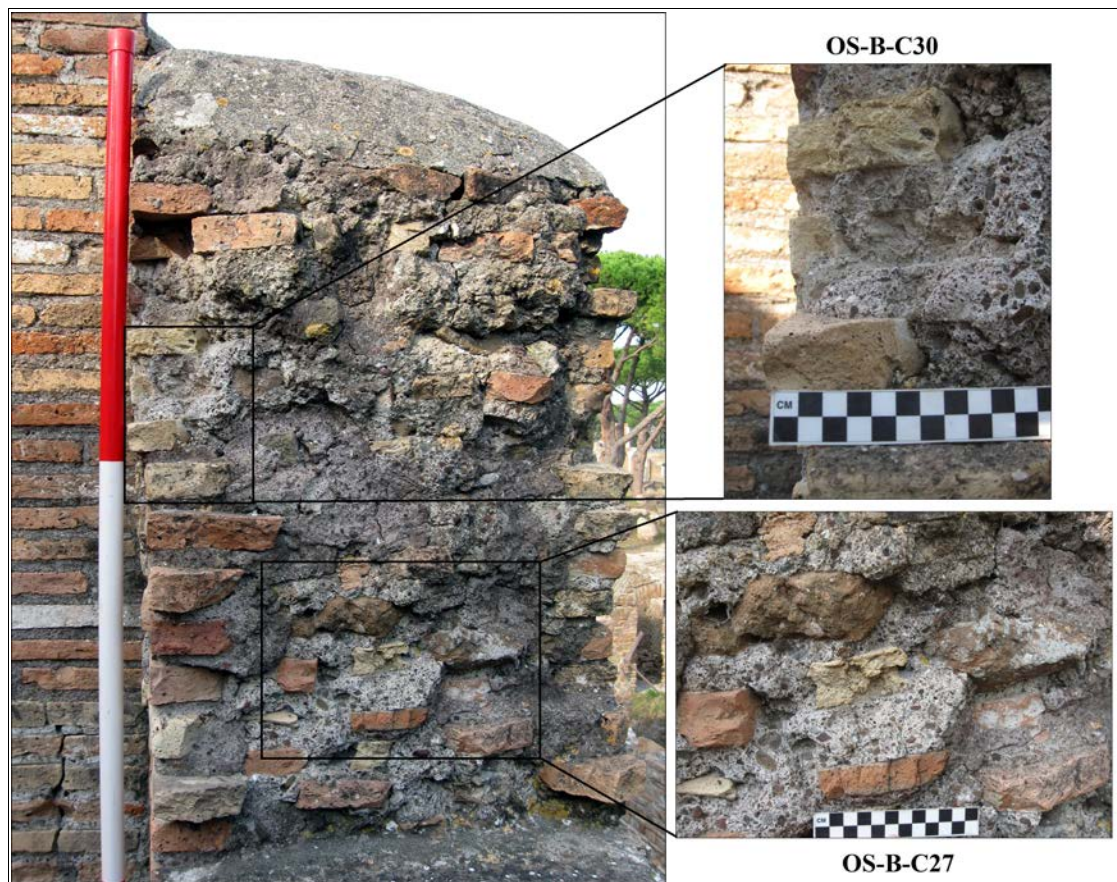


Figure 6.18: Photographs of sampled wall and detail of facing (OS-B-C30) and core (OS-B-C27) mortar sample locations from the Caseggiato del Serapide. Photographs by author.

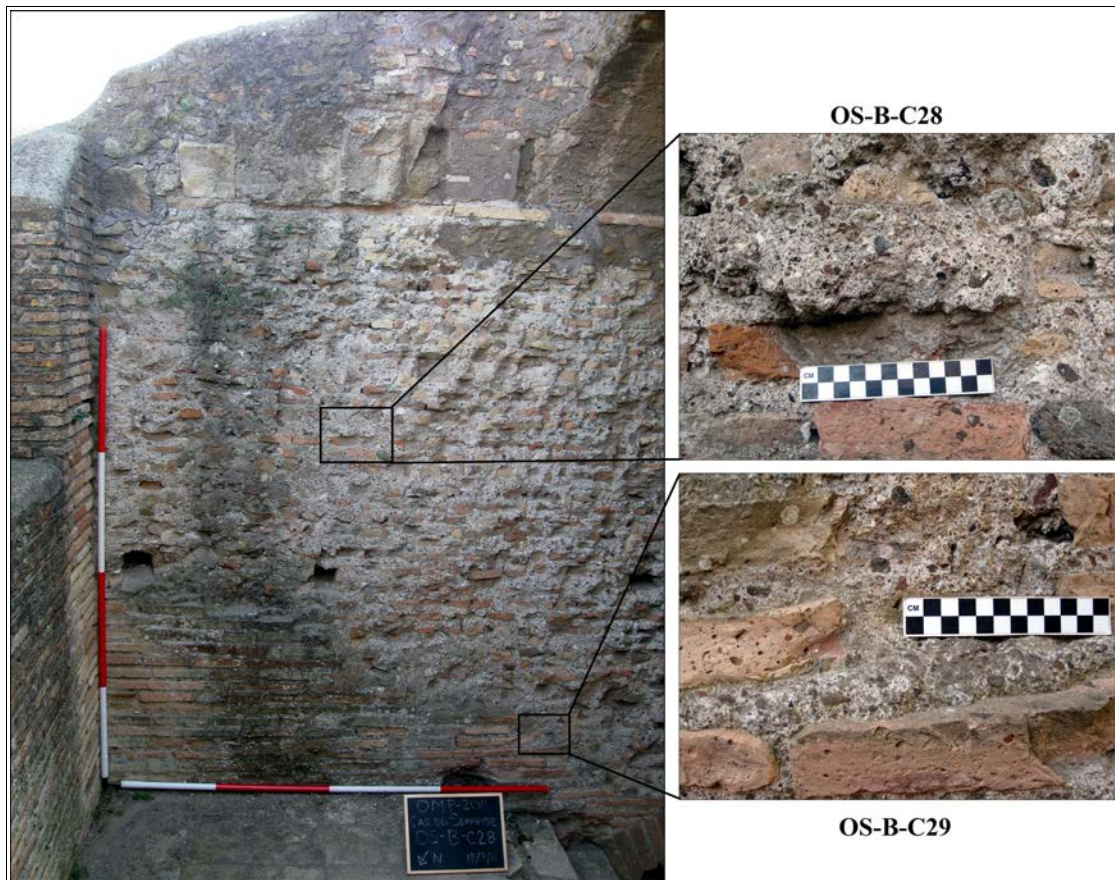


Figure 6.19: Photographs of sampled wall and detail of core (OS-B-C28) and facing (OS-B-C29) mortar sample locations from the Caseggiato del Serapide. Photographs by author.

6.4.3. Structure C - Caseggiato del Larario - Regio I, IX, 3

The *Caseggiato del Larario* is yet another mixed-use structure built in the Hadrianic period, approximately 114-120 CE. The structure incorporates a number of shops on the ground floor and a central courtyard that is approached from the street through one of two corridors on the south and the west (rooms 4 and 10 in Figure 6.20). Not all of the shops are accessible from the interior of the structure, just as some are not accessible

from the streets, creating a separation of activities in these parts of the property. The fragmentary remains of stairways are visible in several of the rooms, providing direct evidence for upper floors. These are presumed to have been residential apartments.

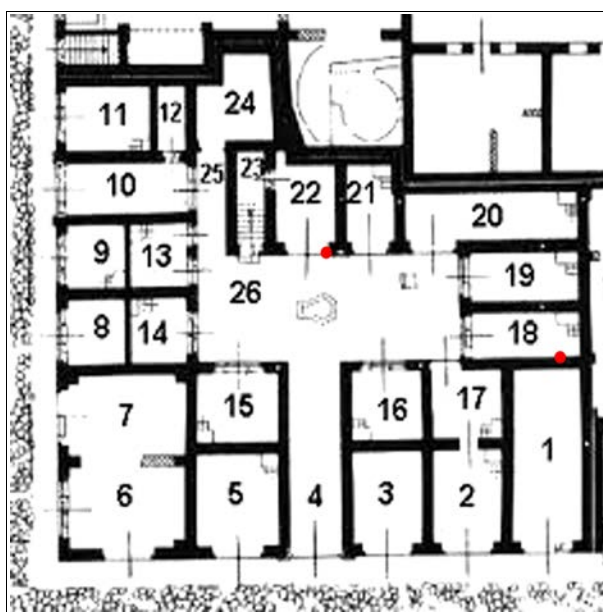


Figure 6.20. Archaeological plan of Caseggiato del Larario. Mortar sampling locations marked in red. After Scavi di Ostia 1996.

The facing throughout *Caseggiato del Larario* is all brickwork, including the remains of brick arches, with no reticulate in the structural facing of any of the remaining walls of the ground floor. The collection of bricks in the facing includes primarily the light-red variety, with a small proportion of yellow and pink bricks. The walls facing the central courtyard are nearly mono-chromatic, using only red bricks, but the interior walls contain a less-controlled mixture of the other colours. Only these heterogeneous walls contain evidence of plaster and stucco decoration, which suggests the intentional selection of red bricks for aesthetic purposes to decorate the courtyard. A small number of stamps have been recorded in this structure, with only two known *domini* recoded. Two were located during the 2011 field season; both are rectangular in shape, one with

impressed lettering and the other with raised. Unfortunately, both stamps are fragmentary and unreadable and thus cannot be reliably identified.

The courtyard includes additional decorative features that are unique among the structures included in this study. An amphora-shaped feature occupies the middle of the floorspace, presumably a water feature of some kind. Its location in the centre of the space alludes to the *impluvia* often found in the centre of the *atrium* in a “typical” Roman house. There is also a highly decorated niche in one of the walls, called a *lararium* by the original excavators, leading to the structure's modern name, *Caseggiato del Larario*. The niche is visible immediately upon entry of the courtyard from the southern corridor, and is highly decorated with carefully selected and placed polychrome reticulate.

This structure contains L-shaped door jambs that seem to have no obvious function and which may be a decorative element unique to the group of builders associated with this structure. DeLaine suggests these may be the signature of a specific contractor or designer.³⁸⁰ The door jambs also contain travertine blocks, seen elsewhere in the façade of *Case a Giardino* and in a number of structures throughout Ostia. These blocks in the doorways seem to be the right shape and placement to be part of the infrastructure for the actual doors. Their symmetrical placement at a standard height in the doorways leading off the courtyard suggest that some aesthetic value was considered during construction despite their function, if only to ensure a regular height for the doors.

Four mortar samples were collected during the 2011 field season (Table 6.4). The first location was an interior wall in one of the shops on the east side of the courtyard (Figure 6.21). A large hole provided access to the core of this wall, allowing both facing

380 DeLaine 2002, 45.

and core samples to be collected. Mortar was also taken from the doorway into Room 22 (Figure 6.22), which was damaged on the eastern side, again allowing access to both facing and core mortars.

Table 6.4: Details of samples from the Caseggiato del Larario.

Sample ID	Wall Type	Location in Wall	Sampling Depth	Sampling Height	Munsell Code	Colour	Total weight
OS-C5	Unknown	Core	Unknown	Unknown	2.5Y 8/1	White	92.1 g
OS-C-C31	Interior	Facing	5 cm	101 cm	10YR 8/1	White	16.89 g
OS-C-C32	Interior	Core	23 cm	97 cm	2.5Y 8/1	White	121.15 g
OS-C-C33	Exterior	Facing	3 cm	69 cm	10YR 8/1	White	28.79 g
OS-C-C34	Exterior	Core	10 cm	76 cm	5YR 8/1	White	13.14 g

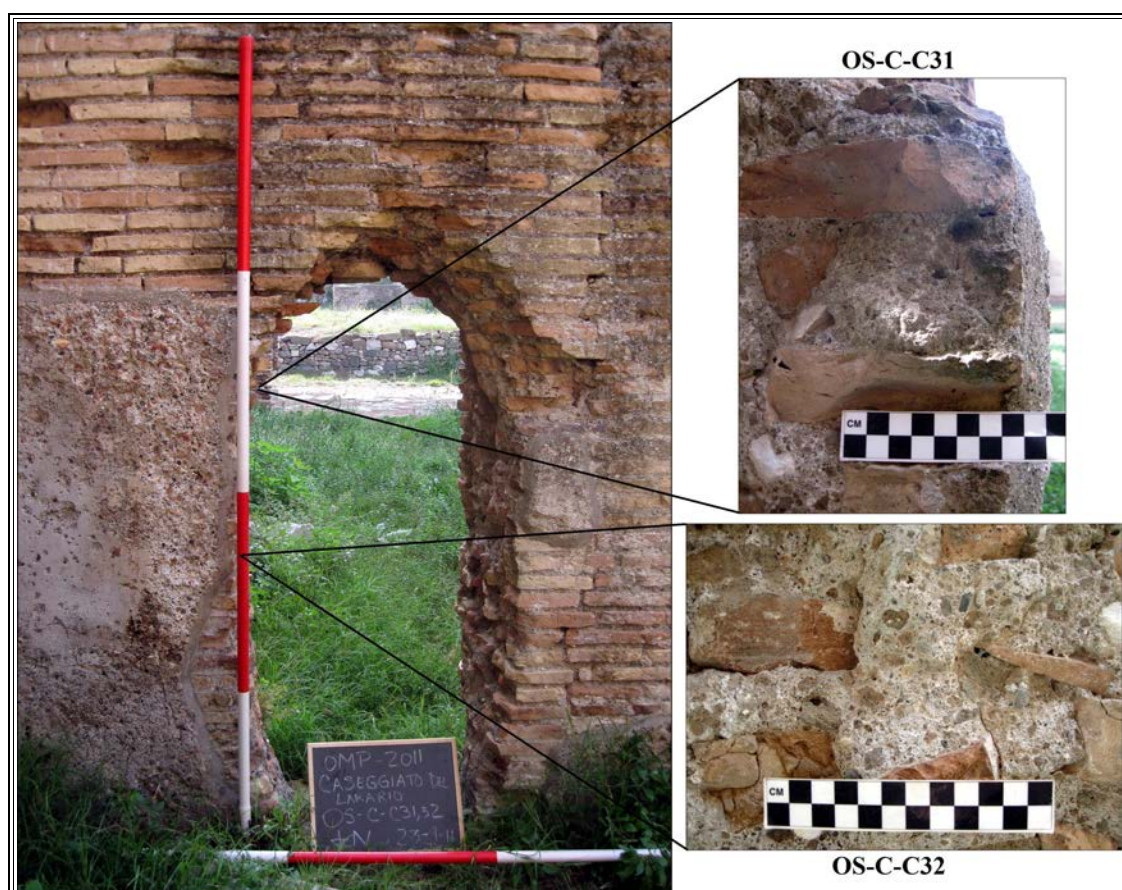
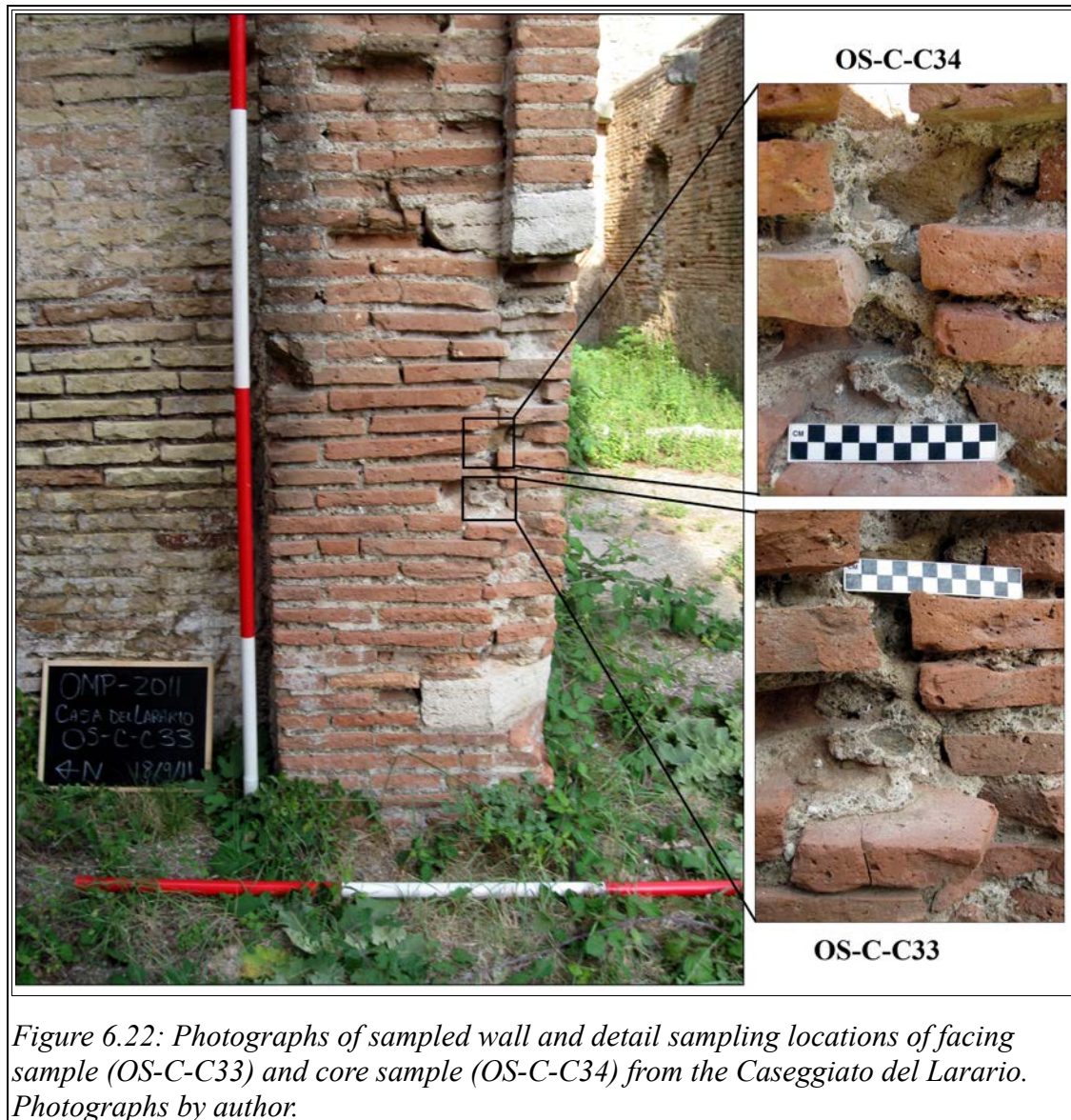


Figure 6.21: Photographs of sampled wall and detail sampling locations of facing sample (OS-C-C31) and core sample (OS-C-C32) from the Caseggiato del Larario. Photographs by author.



6.4.4. Structure D - Casa Basilicale – Regio I, Insula IX,1

The *Casa Basilicale* is a brick and reticulate structure in the same block as *Caseggiato del Larario*, built 117-120 CE. The use of the structure appears to be mainly com-

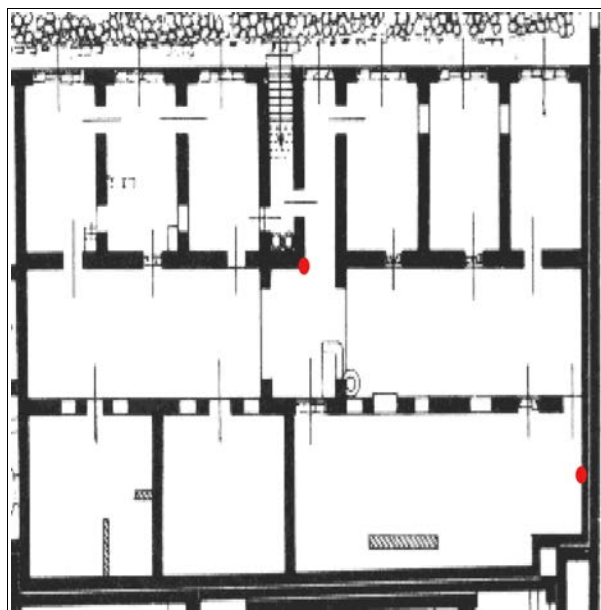


Figure 6.23. Archaeological plan of Casa Basilicale. Mortar sampling locations marked in red. After Scavi di Ostia 1996.

mercial, although the remains of an earlier Republican-era residential property are visible in the southern portion of the structure. Six shops are situated along the street frontage on the north side of the building; they are all inter-connected and open to the centre of the structure (Figure 6.23). A central corridor leads from the street alongside a stairway that is still partially intact but currently inaccessible. Throughout the structure, the facing includes a mixture of brickwork and reticulate, most of which is located on the upper half of the walls. The bricks themselves are primarily yellow with the inclusion of some light-pink. Darker red bricks are mostly absent from the original structural elements of the ground floor walls, but they do appear in the upper portion of the northern façade and occasionally interspersed within the brick facing of interior walls.

According to DeLaine, *Casa Basilicale* is an example of the variability in construction details within a relatively small area.³⁸¹ The control of brick types and colours on

³⁸¹ DeLaine 2002, 44.

the façade and the use of reticulate on interior walls distinguish the building from its immediate neighbours. Such features may specifically indicate different property owners or building patrons who developed their properties independently.³⁸² Furthermore, these owners may have even hired different contractors and builders, evident from the variation in what DeLaine calls “minor construction details” such as the colours of bricks chosen for the facade.³⁸³ This suggests that all elements of construction, no matter how seemingly minor, can be important in understanding the overall history and local context of a specific structure.

A single, unreadable stamp was found during visual assessment of the structure, and only a small number of stamps – from only three individual *domini* – have been recorded in the literature. The bricks of one of these, M. Rutilius Lupus from the Brutian-ae *figlina*, are ubiquitous throughout Ostia and have been recorded in five of the seven structures in this study. One implication of this paucity of evidence is that the source of brick was tightly controlled and limited to perhaps a single source. It is more likely, however, that most of the stamped bricks in this structure simply have not been located or are situated so that the stamps themselves are not visible in the facing.

Mortar samples were collected in two locations from *Casa Basilicale* (Table 6.5). Facing and core samples were accessible from a brick-faced doorway that was damaged along its edge (Figure 6.24). This particular doorway at the end of the main entrance corridor faces an open courtyard in the middle portion of the property. Another two samples were taken from an area of degraded reticulate, where it was possible to access to the interior core (Figure 6.25). This wall on the eastern edge of the structure abuts the

382 DeLaine 2002, 44.

383 DeLaine 2002, 44.

western boundary wall of the Forum. This particular wall includes a blocked doorway that presumably would have lead into the Forum from *Casa Basilicale*, but the date of its closing is unknown.

Table 6.5: Details of samples from the Casa Basilicale.

Sample ID	Wall Type	Location in Wall	Sampling Depth	Sampling Height	Munsell Code	Colour	Total weight
OS-C3	Unknown	Core	Unknown	Unknown	Gley 1 8/1	White	119.66 g
OS-D-C35	Interior	Core	15 cm	92 cm	Gley1 7/1	Light grey	47.58 g
OS-D-C36	Interior	Facing	5 cm	72 cm	5Y 6/1	Grey	38.7 g
OS-D-C37	Exterior	Facing	4 cm	91 cm	2.5Y 6/1	Grey	85.5 g
OS-D-C38	Exterior	Core	12 cm	111 cm	Gley1 7/1	Light grey	13.76 g

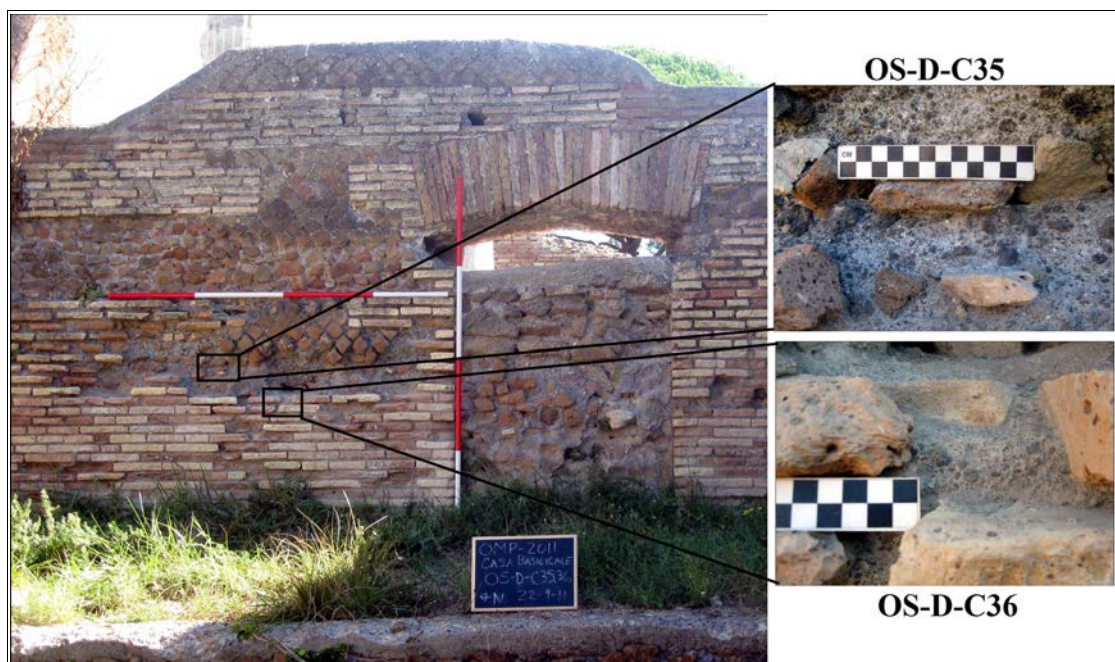


Figure 6.24: Photographs of sampled wall and detail sample locations from the Casa Basilicale. Photographs by author.

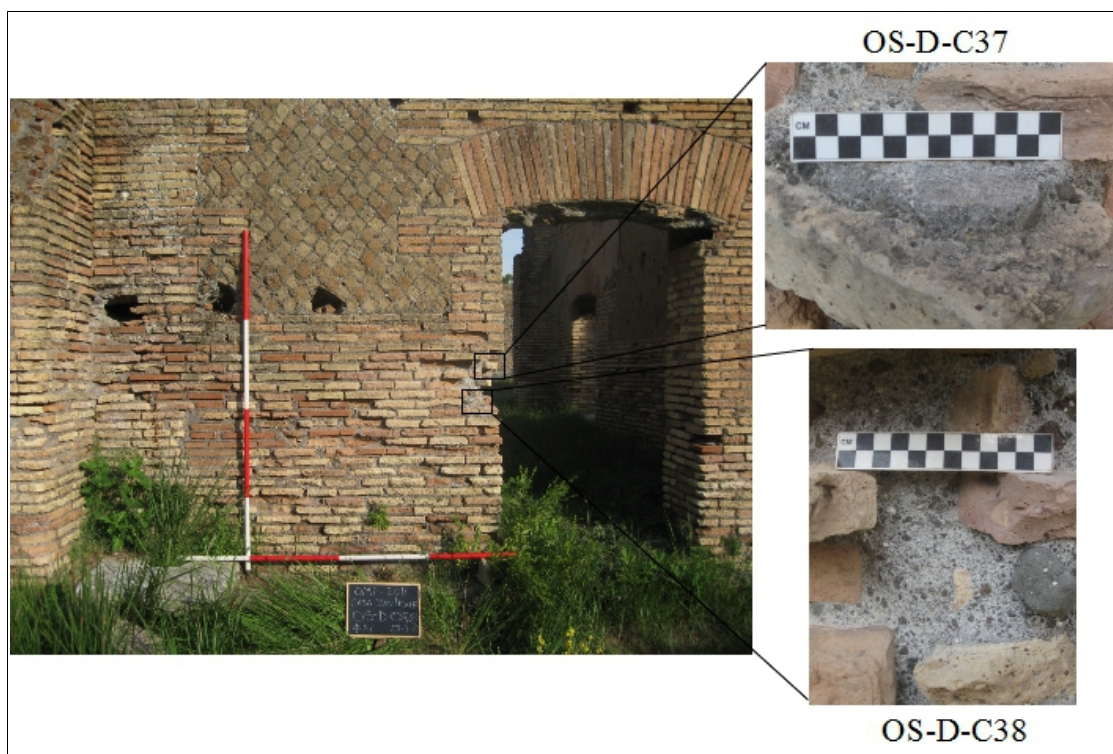


Figure 6.25: Photographs of sampled wall and detail sample locations from the Casa Basilicale. Photographs by author.

6.4.5. Structure E - Piccolo Mercato - Regio I, Insula VIII, 1

The *Piccolo Mercato* is one of the city's warehouse structures (*horrea*) on the north edge of Regio I.³⁸⁴ Original construction has been dated from brick stamps to 118 CE. The primary function of this structure is assumed to be a storage warehouse, possibly for goods off-loaded in Portus and then shipped throughout the region. It is one of three such storage houses that are clustered together in Regio I. The other two (Horrea I,VIII,2 and Horrea Epagathiana et Epaphroditiana) are located on the west side of *Piccolo Mercato* and the two together match the length of the structure's central axis. Determining private or public ownership of these buildings is complicated at best, and

³⁸⁴ Rickman 1971.

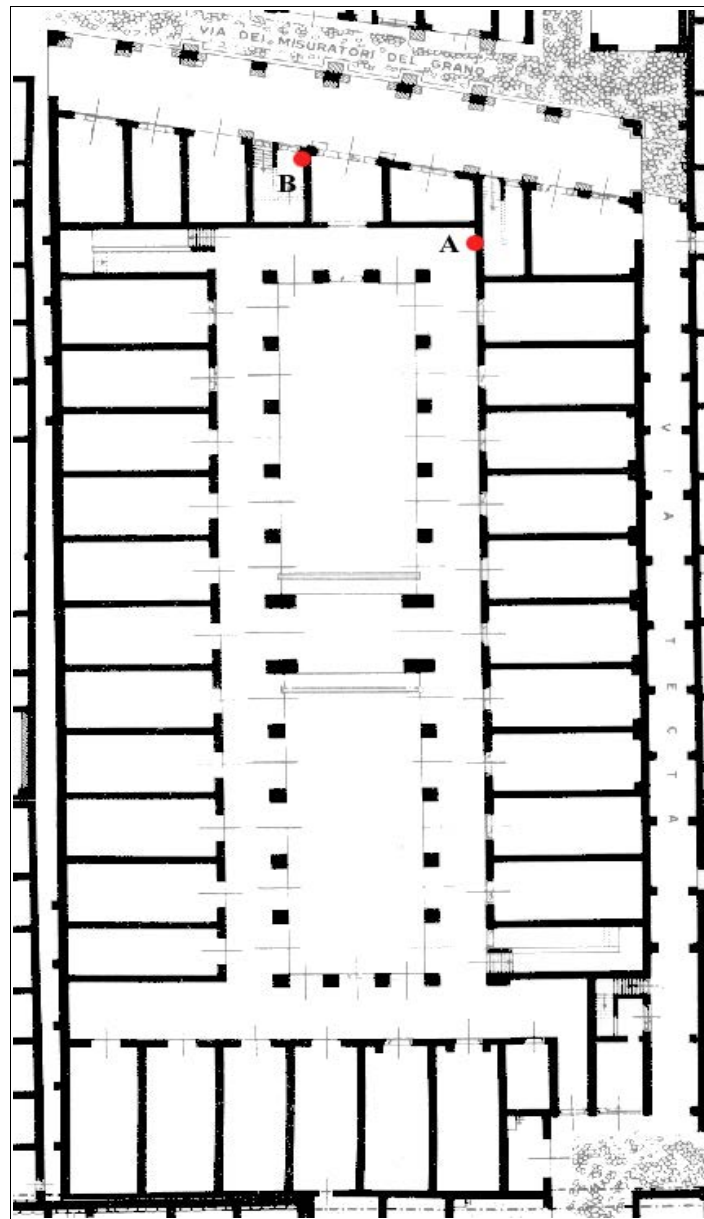


Figure 6.26. Archaeological plan of Piccolo Mercato. Mortar sampling locations marked in red. After Scavi di Ostia 1996.

would most likely depend on the type of goods stored within. If, for instance, the public grain stores were housed here this would suggest the structures were under government administration. On the other hand, private business owners, e.g. importers or exporters, may well have stored any type of commercial goods for resale, suggesting the buildings were kept in private hands. Unfortunately there is currently no direct evidence to confid-

ently discern what was kept there, and by extension no strong evidence to confidently describe the nature of ownership.

The main entrance of *Piccolo Mercato* is on the north side, with a secondary entrance in the south (Figure 6.26). The northern frontage includes five rooms and an entrance corridor, all of varying sizes. The graduated size of these rooms creates an alignment between the angle NW-SW running Via dei Misuratori del Grano and the squared N-S orientation of the warehouse. The remains of two stairways in the northwest corner and another in the southeast indicates the structure was at least two storeys. The interior of the structure comprises regularly sized rooms leading off of three sides of a long central courtyard lined with brick piers and presumably a portico. An arched passageway still stands in the centre of the room, on the east side of the courtyard, which once separated the area into two halves.

The facing style of *Piccolo Mercato* is a mixture of brickwork for the façade, piers, and boundary walls with brick and reticulate on the interior walls. This structure contains potential evidence for multiple working groups, including the different types of bricks used in different locations within the structure. A specific instance is the discontinuity of brick colours where the brick meets the reticulate in one of the walls on the north side of the courtyard (Figure 6.27).

Mortar samples were collected from two different walls with reticulate facing, both of which were damaged enough to allow access to both core and facing samples. One of the sampled walls was located along the north-eastern side of the courtyard, which has been treated as the exterior wall (Figure 6.28). The interior sampling location was inside one of the shops along the street frontage in the north (Figure 6.29). During visual as-



Figure 6.27. Discontinuity in brick types, Piccolo Mercato. Photograph by author.

assessment of these walls, brick stamps were found in both locations. All stamps found the courtyard were *litteris cavis*, rectangular inscriptions with the text impressed rather than raised, and all were found on yellow bricks. One orbicular stamp was found near the base of the door jamb in the front room on the north side of the structure.

Table 6.6: Details of samples from the Piccolo Mercato.

Sample ID	Wall Type	Location in Wall	Sampling Depth	Sampling Height	Munsell Code	Colour	Total weight
OS-C1	Unknown	Core	Unknown	Unknown	2.5Y 8/1	White	31.92 g
OS-E-C39	Interior	Facing	9 cm	105 cm	7.5YR 7/1	Light grey	33.19 g
OS-E-C40	Exterior	Core	23 cm	86 cm	2.5Y 7/1	Light grey	20.40 g
OS-E-C41	Exterior	Facing	9 cm	58 cm	10YR 8/1	White	12.25 g
OS-E-C42	Interior	Core	14 cm	103 cm	7.5YR 8/1	White	33.60 g

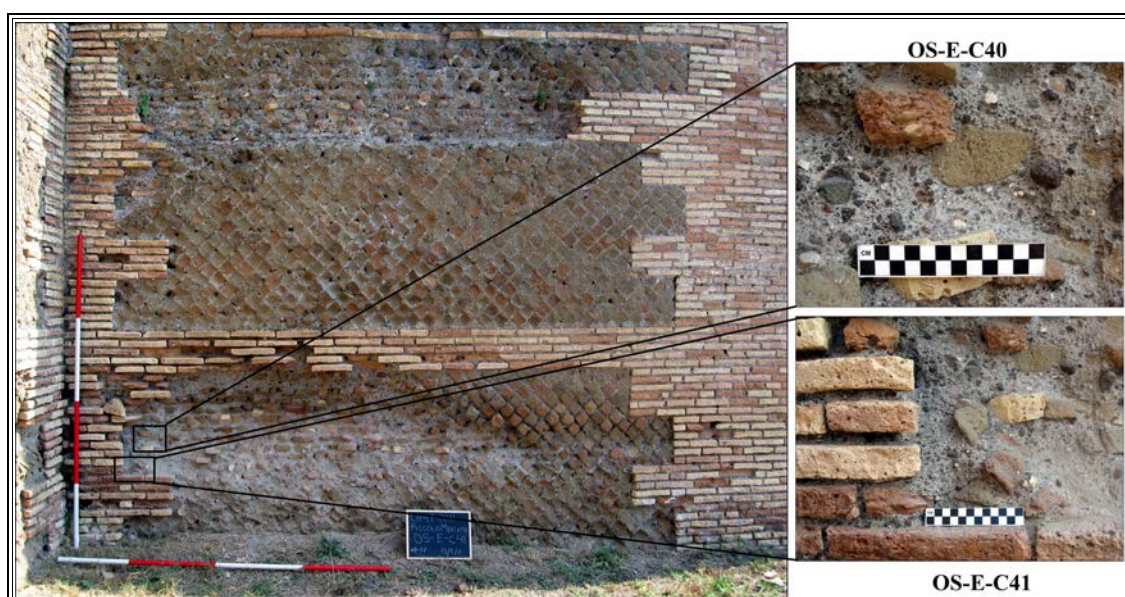
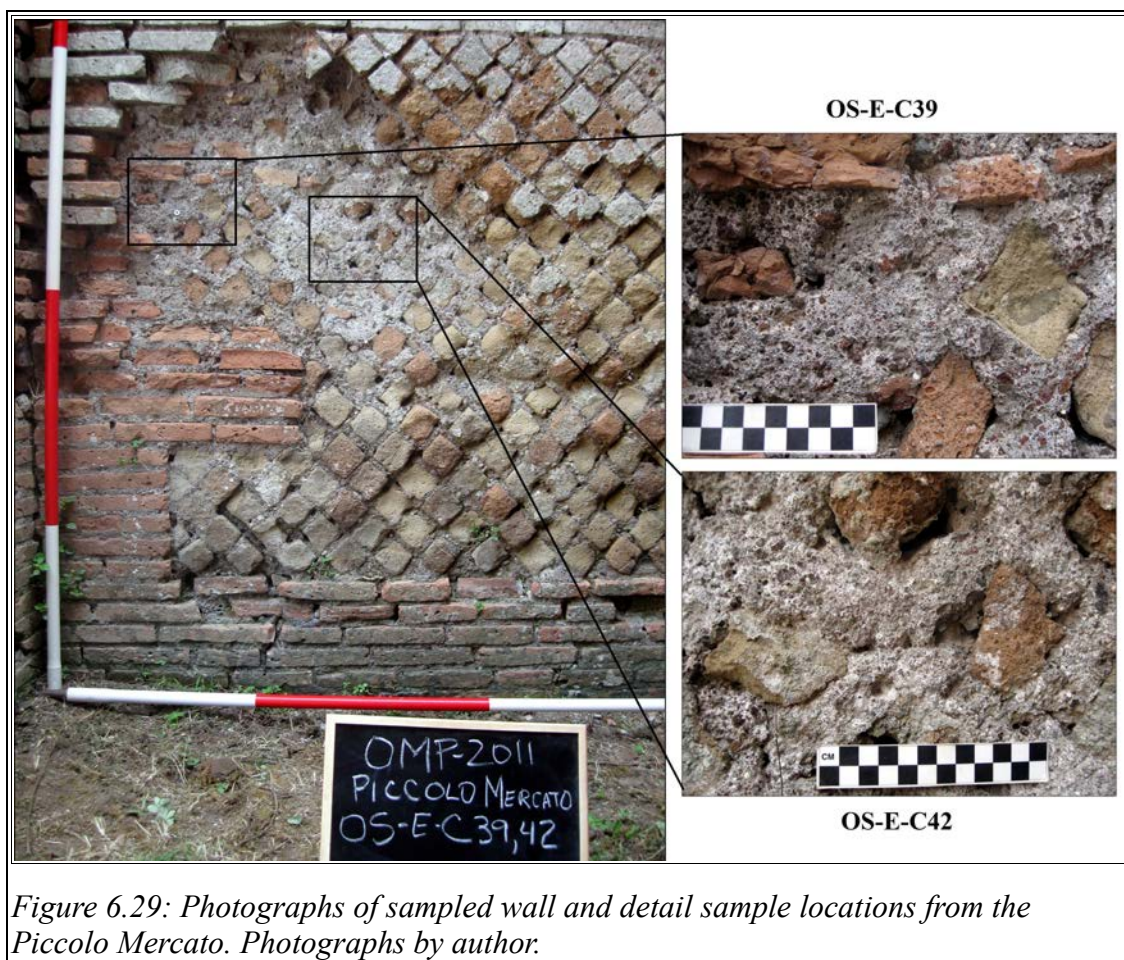


Figure 6.28: Photographs of sampled wall and detail sample locations from the Piccolo Mercato. Photographs by author.



6.4.6. Structure F - Terme del Foro - Regio I, Insula XII, 6



Figure 6.30. Archaeological plan of Terme del Foro. Mortar sampling locations marked in red. After Scavi di Ostia 1996.

The large bathhouse near the forum, *Terme del Foro*, is the youngest of this group of structures, dating to 160 CE.³⁸⁵ As noted above, the bath house was originally built by Gavinus Maximus, a Praetorian Prefect of Emperor Antoninus Pius. Given its highly ranked patron, *Terme del Foro* may have had direct ties with builders from Rome, a relatively unusual arrangement in the Ostia, where much of the building workforce would have been primarily local.³⁸⁶ The relationship between this structure and the city of Rome is reinforced by its brick profile. Of the nearly 200 individual stamps have been

385 Cicerchia and Marinucci. 1992.

386 DeLaine 2002, 76.

identified and recorded in this structure, 23 unique *domini* are represented and of these have direct ties to the Imperial family.

The original main entrances to this large public structure were through rooms 2 and 14 on the north side, from *Via della Forica* (Figure 6.30). The bath was built entirely with brickwork facings using a mixture of yellow, pink, and red bricks placed in no obvious intentional pattern. This structure was originally lavishly decorated with marble on the walls and floors, along with black and white mosaics. The cold rooms were located on the northern half of structure, and mortar samples were collected from at the facing and core of a doorway from Room 10 to Room 6, into the *frigidarium* (Figure 6.31). The warm and hot rooms to the south overlook the *palaestra*. The *caldarium* was Room 19 (Figure 6.30), with three intact pools on the north, east, and south sides of the room. Two more samples were collected from a wall between the north and east basins at a location where the facing and core were both accessible (Figure 6.32). This wall still bears fragments of ceramic flues that were embedded in the wall between the marble covering and the wall facing to carry heat up and out of the room.

Table 6.7: Details of samples from the Terme del Foro.

Sample ID	Wall Type	Location in Wall	Sampling Depth	Sampling Height	Munsell Code	Colour	Total weight
OS-C9	Unknown	Core	Unknown	Unknown	10YR 8/1	white	51.33 g
OS-F-C43	Exterior	Facing	6 cm	149 cm	10YR 8/1	white	40.63 g
OS-F-C44	Exterior	Core	9 cm	172 cm	10YR 8/1	white	27.10 g
OS-F-C45	Interior	Facing	6 cm	140 cm	10YR 8/2	very pale brown	32.59 g
OS-F-C46	Interior	Core	12 cm	124 cm	10YR 7/2	light grey	38.51 g

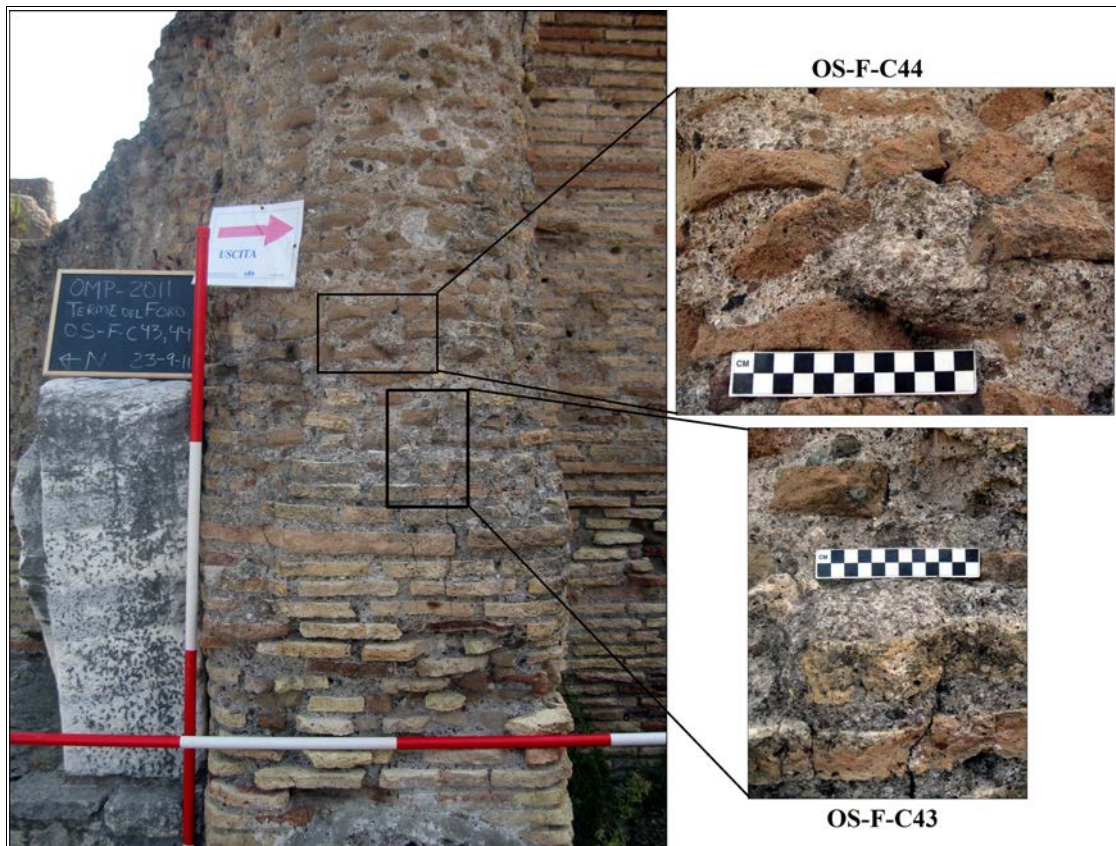


Figure 6.31: Photographs of sampled wall and detail sample locations from the Terme del Foro. Photographs by author.

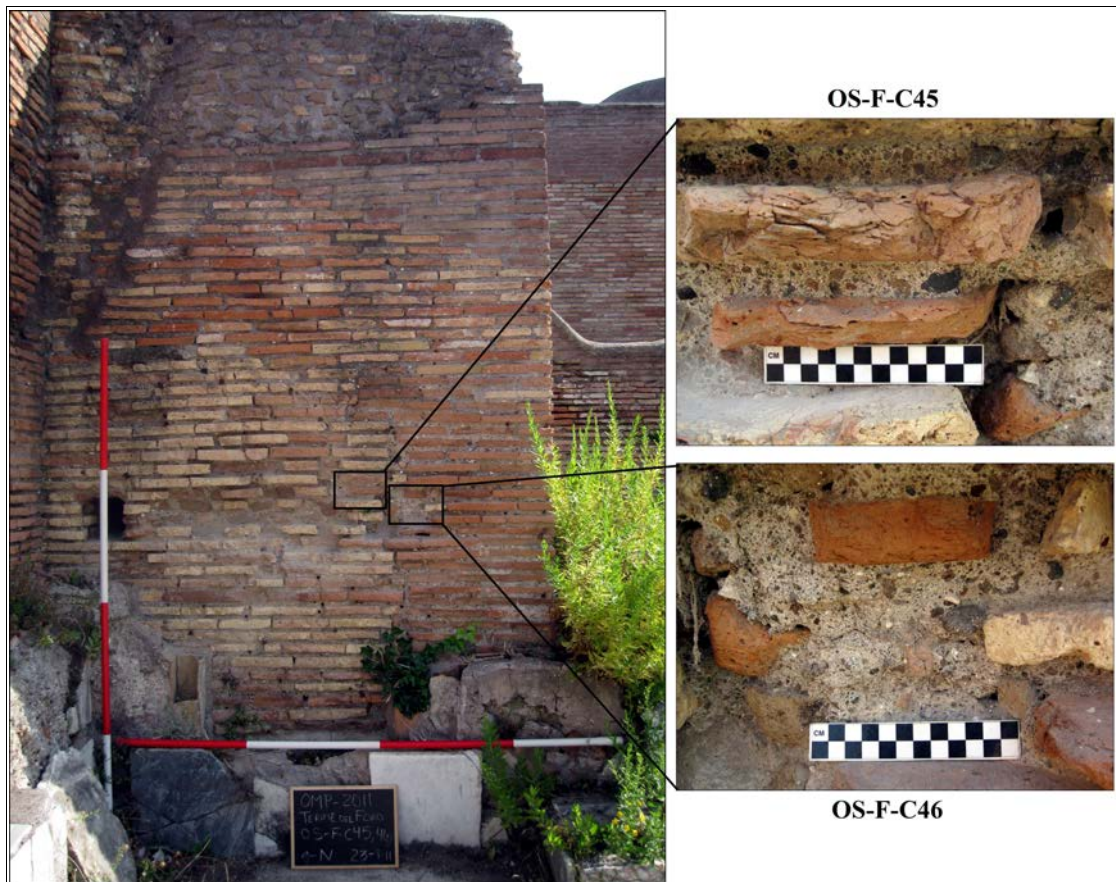


Figure 6.32: Photographs of sampled wall and detail sample locations from the Terme del Foro. Photographs by author.

6.4.7. Structure G - Insula dell'Ercole Bambino – Regio II, Insula VI, 3-4

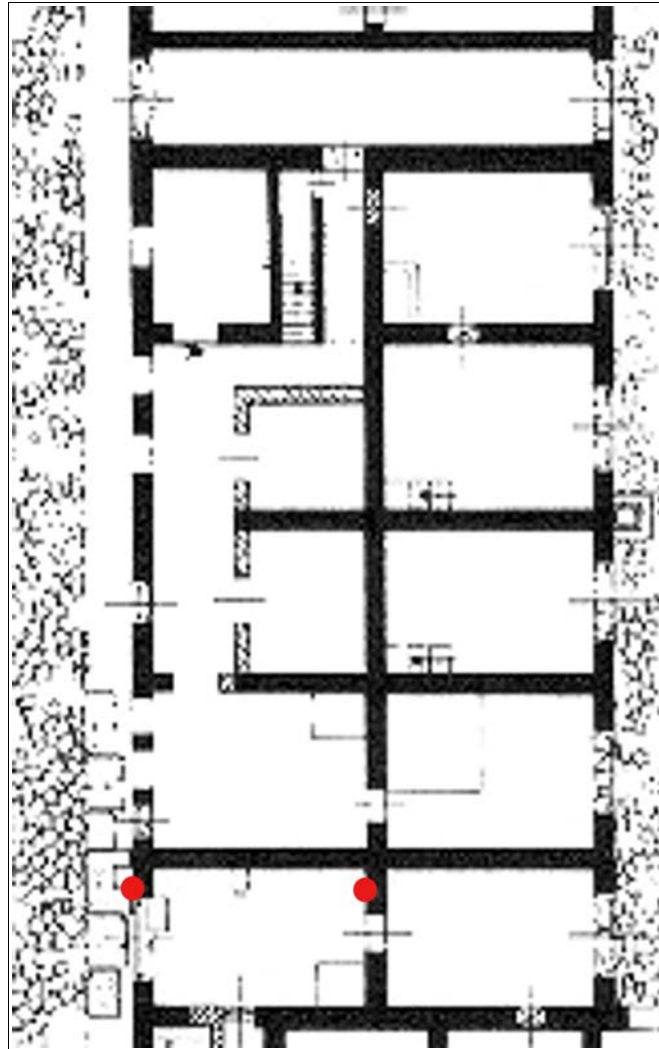


Figure 6.33. Archaeological plan of *Insula dell'Ercole Bambino*. Mortar sampling locations marked in red. After Scavi di Ostia 1996.

The *Insula dell'Ercole Bambino* is a multi-use structure that includes five shops on the eastern side, with two shops and a *medianum* apartment to the west. It was built in 130 CE as part of a larger complex that incorporated a number of other properties, including a bath house (*Terme di Nettuno*), a structure described as the barracks of the fire brigade (*Caserma dei Vigiles*), and multiple *insulae* that mirror the size and layout of

Insula dell'Ercole Bambino. The unified design, contemporary age, and interconnectivity of these structures suggest these properties were part of a single construction project. However, the *Insula dell'Ercole Bambino* had a different brick profile than the bath and the barracks. In the *insula*, only 23% of the stamps were from *domini* related to the Imperial family, in contrast to over 50% in the other two structures. This suggests a different supply of materials was used for the private commercial/residential properties than for the public properties.

The shops of *Insula dell'Ercole Bambino* are accessible from the streets on both the east and west of the structure, with a doorway through the central wall in each of the southernmost shops. The façades and exterior walls have been constructed with a nearly mono-chromatic brick facing and occasional lighter-coloured pink and yellow bricks on the interior walls. The interior walls were decorated with plaster, some of which remains attached in small patches on the walls of the shops.

Mortar sampling was conducted in two locations, including the outer façade and along an interior wall in the southernmost shop room (Figure 6.33). Edge damage to the doorway on the frontage allowed both core and facing samples to be collected (Figure 6.34). Two more samples were collected from a square hole in the wall between the southwest and southeast shops that provided access to the core (Figure 6.35). Orbicular stamps were found in the facing at both locations, but they were not exposed well enough for positive identification.

Table 6.8: Details of samples from the Insula dell'Ercole Bambino.

Sample ID	Wall Type	Location in Wall	Sampling Depth	Sampling Height	Munsell Code	Colour	Total weight
OS-C21	Unknown	Core	Unknown	Unknown	2.5Y 8/1	White	9.13 g
OS-G-C47	Interior	Core	18 cm	107 cm	Gleyl 7/1	Light grey	27.59 g
OS-G-C48	Interior	Facing	8 cm	102 cm	2.5Y 8/1	White	24.00 g
OS-G-C49	Exterior	Core	13 cm	75 cm	2.5Y 7/1	Light grey	46.25 g
OS-G-C50	Exterior	Facing	10 cm	68 cm	10YR 7/1	Light grey	25.50 g



Figure 6.34: Photographs of sampled wall and detail sample locations from the Insula dell'Ercole Bambino. Photographs by author.



Figure 6.35: Photographs of sampled wall and detail sample locations from the Insula dell'Ercole Bambino. Photographs by author.

6.5. Conclusion

The construction industry in ancient Ostia was clearly a complex and sophisticated system. The city as a whole sits in the middle of the theoretical framework as a local example of greater Roman building traditions, employing common aesthetics, structural techniques, and materials while evolving within its own local history. The individuals involved have left their marks on the archaeological record in the form of direct architectural and epigraphic evidence. The structures were built using techniques that had been developed over the centuries of Roman building traditions, and their success can be measured by the longevity of the buildings themselves. Visual inspection has revealed the basic materials used in construction were mortar, bricks, and volcanic tuff, all of which were in common use in the region during the 1st and 2nd centuries CE. The geo-

logical profile of Ostia, however, dictates that most, if not all, of these materials most likely would have been transported into the city, as they would not have been available locally. Evaluating the archaeological, technical, and material contexts of the buildings in this study has generated additional questions that can only be answered with evaluations at tighter scales. The results of analyses are reported in the following chapter.

Chapter 7. Analytical Results

This chapter begins with a discussion of the key petrographic features of the aggregate lithologies as seen in the mortar samples compared to their natural counterparts. A summary of results for the sample set overall follows the discussion of aggregate petrography. Macro-descriptions of mortar samples and detailed analytical results from scientific testing are then presented for each structure. Notable trends in the data set are summarized at the end of this chapter, but interpretation and discussion of the data are reserved for Chapter 8.

7.1. Important petrographic features of aggregates

Thin sections of fresh samples of each aggregate type were examined with a polarising microscope to identify their key petrographic features, optical properties, and overall textures. Their key features are illustrated with photomicrographs in Chapter 4. The degree of alteration and characteristic secondary alteration products are often the most recognizable diagnostic features of these materials in their fresh state, however, they were sometimes difficult to identify or even entirely absent from the mortar aggregates in this study. While the loss of alteration products from individual particles occasionally made identification more difficult, it actually provided useful information about the chemical reactions within the mortars.

Relict features of alteration were more useful as evidence for pozzolanic reaction than for particle identification. The clay zeolites, coatings, and opaline silica deposits that were common in Tufo Lionato and Pozzolane Rosse quarry samples generally were missing from the fine aggregate particles in the mortars (Figure 7.1).

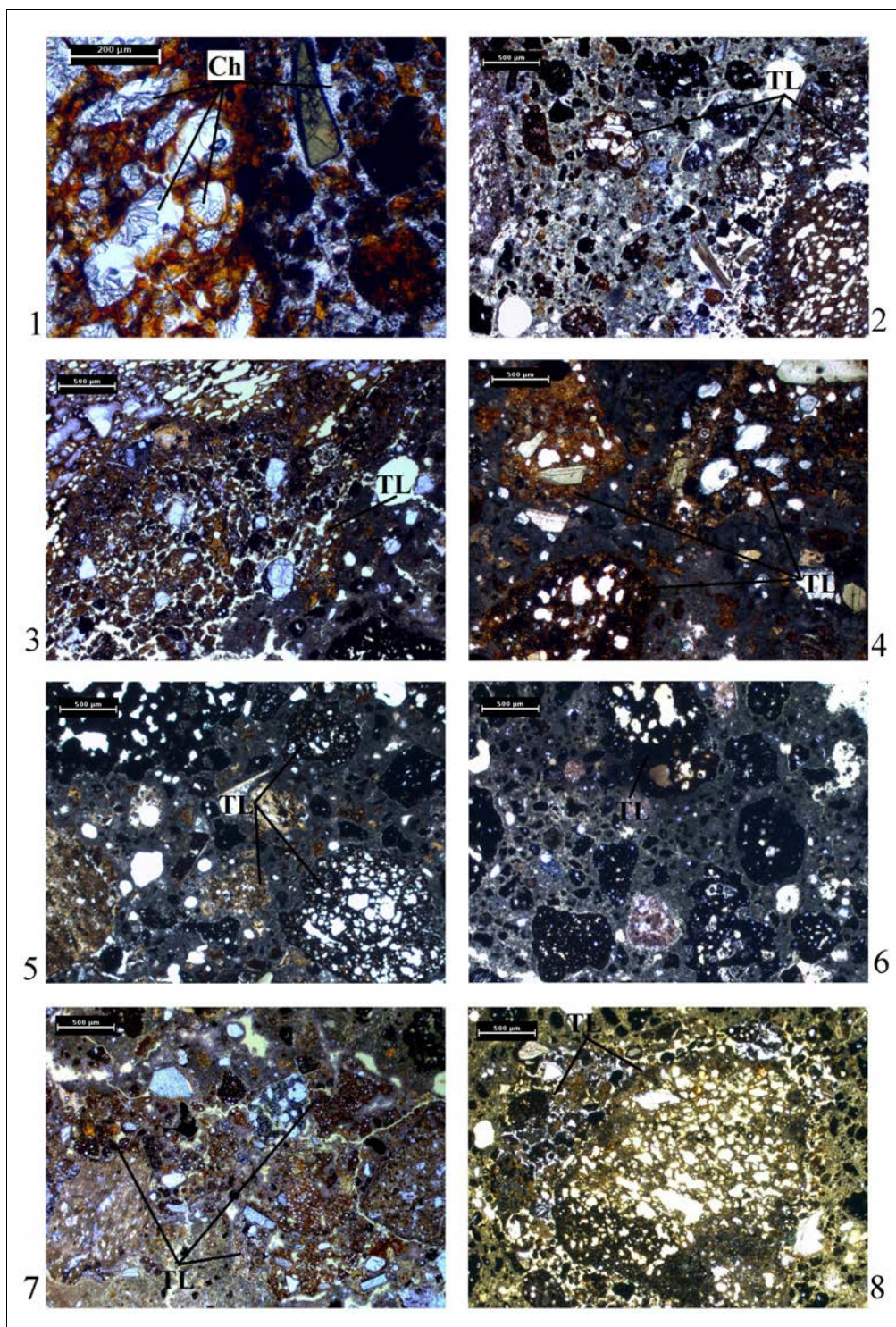


Figure 7.1: Comparison of fresh Tufo Lionato exhibiting chabazite in vesicles and acting as cement for smaller particles within a large clast (1) and Tufo Lionato fine aggregate in mortar samples with no chabazite (2. Case a Giardino; 3. Caseggiato del Serapide; 4. Caseggiato del Larario; 5. Casa Basilicale; 6. Piccolo Mercato; 7. Terme del Foro; 8. Insula dell'Ercole Bambino). All images collected by author in plane polarised light.

As individual aggregate particles reacted with the lime and water, their pozzolanic components – authigenic zeolites and clays – were either partially or wholly consumed during the reaction. The degree of this consumption provided an indication of the effectiveness of the reaction itself. Intact zeolites were not counted during modal analysis, but trace amounts of chabazite were observed in the mortars from the Case a Giardino, the Terme del Foro, and the Insula dell'Ercole Bambino. In all cases, chabazite occurred within Tufo Lionato clasts. Mortar from five of the seven structures contained aggregate fragments exhibiting the relict zeolite texture of calcite grains that have replaced chabazite. Phillipsite was visible in Pozzolane Rosse clasts from the Caseggiato del Serapide and the Insula dell'Ercole Bambino and in rare particles of Tufo Lionato from the Terme del Foro samples. Only the mortars from Caseggiato del Larario exhibited no intact zeolites or calcite with relict zeolite texture, suggesting the fine aggregate in these samples had fully reacted.

Sporadic particles of Pozzolane Rosse exhibited evidence of secondary calcite deposition, which has subsequently partially converted to clay. (Figure 7.2). The fresh material did not contain vesicular calcite, suggesting it was in fact a secondary reaction product of the lime mortar. The deposition of calcite within aggregate particles indicates dissolution, movement, and redeposition of calcite from the binder.

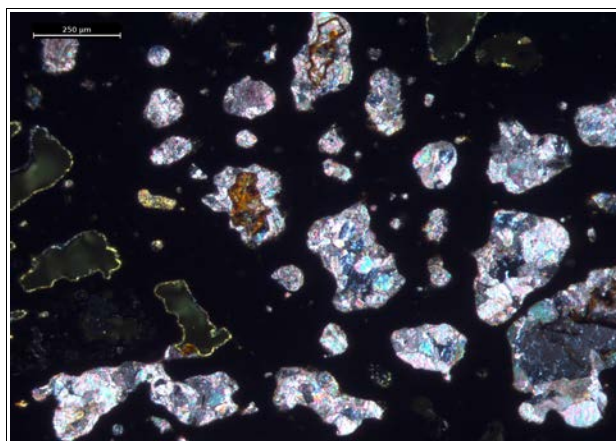


Figure 7.2: Pozzolane Rosse fragment within mortar from the Casa Basilicale exhibiting secondary calcite in vesicles (pink, blue, green) and partial conversion to clay (reddish brown). Photomicrograph collected by author in cross polarised light.

7.2. Summary results of mortar analysis

7.2.1. Thin section analysis

For the purpose of summary comparisons, Table 7.1 reports the important petrographic features identified during qualitative thin section analysis of mortar from each structure. All mortars comprised lime binder exhibiting variable carbonation, secondary crystalline calcite, and particles of unhydrated and unincorporated lime. Fibrous cements were observed in all mortars apart from those from the Caseggiato del Larario. Fine aggregate in all mortar samples comprised primarily silt-sized to fine sand-sized feldspathic volcanic sand exhibiting variable degrees of alteration. All samples contained loose mineral crystals, most likely broken free from lithic fragments during mortar mixing. Only the mortars from the Case a Giardino and the Terme del Foro contained crushed ceramic fragments, see Figure 7.3. No significant differences were observed between the core samples and facing samples in terms of texture, condition, or constituents of the mortar (see below, Figures 8.4 and 8.5).

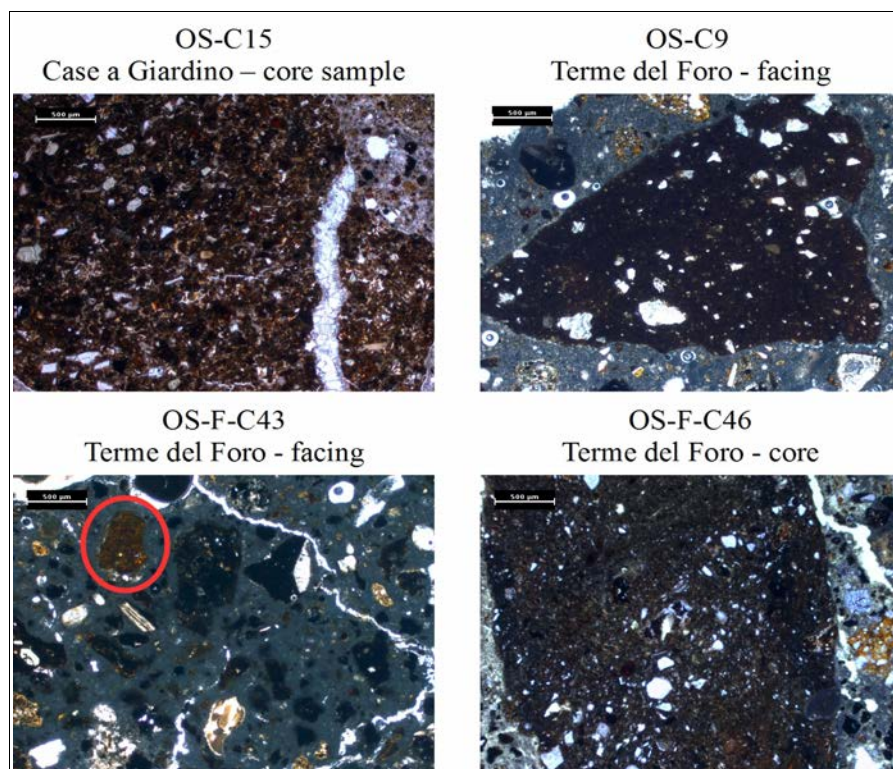


Figure 7.3: Ceramic fragments in mortar samples, circled in OS-F-C43. Photomicrographs collected by author in plane polarized light.

Table 7.1. Summary of petrographic features identified in thin section. – = rarely to commonly observed; + = commonly to frequently observed.

	Case a Giardino OS-C15	Case a Giardino Apartment	Case a Giardino Courtyard	Case a Giardino Façade	Cas. del Serapide	Cas. del Larario	Casa Basilicale	Piccolo Mercato	Terme del Foro	Insula dell'Ercole Bambino
Fibrous Cements	–	–			–		–	–	–	–
in Agg. Vesicles		–			–		–	–	–	–
in Binder Voids	–				–					
in Binder Matrix	–				–					
Calcite with relict zeolite texture	–				–		–	–	–	
Phillipsite					–				–	–
Chabazite	–								–	–
Lime lumps	+	+	+	+	+	–	+	–	–	+
Under/over burnt lime	–	–	–	–	–	–	–	–	–	–
Mobilised cement	–					–		–	+	
Spherical Voids	+				–	–	–	–	–	+
Linear cracks	+				+	–	+	+		–
Loose crystals	+				+	+	+	+	+	+
Ceramic fragments	–								+	
Crystalline calcite	–				–	–	–	–	–	–

Sample components were quantified with modal analysis from point counting. Summary results are reported in Table 7.2 and relative proportions illustrated in Figure 7.4. Separate entries are included for different areas within the Case a Giardino because of the conspicuous variation between samples (as discussed below). The remaining structures exhibited relative homogeneity across samples, with no significant differences between core and facing samples, and therefore are presented as mean values of all samples from each structure. Table 7.3 reports the estimates of relative error and the upper and lower absolute error for 95% confidence limits.

All mortars from Ostia contained aggregates from both the Colli Albani volcanic district to the north and the Monti Sabatini district to the south. Aggregates from the two locations exhibited distinct mineralogical and morphological characteristics indicative of their natural alteration processes. The observed aggregate particles from the Colli Albani volcanic district comprised approximately 88% of all observed aggregate particles, including, in descending order of abundance, Pozzolane Rosse (which alone represented 25.1% of the aggregates), Tufo Lionato (26.5%), Pozzolanelle (13.8%), and Pozzolane Nere (2.8%). These particles typically exhibited an angular to sub-rounded shape, and they varied in size from sub-10 μm up to 2 mm, with rare examples over 5 mm. Fine aggregates from Monti Sabatini comprised approximately 7% of the observed aggregates, including Monti Sabatini reworked airfall ash (5.6% of the aggregates counted) and Tufo Giallo di Prima Porta (1.7%). These particles were typically sub-rounded and varied in size from 250 μm to 2 mm. The relative proportions of aggregate lithologies for each structure are illustrated in Figure 7.3. Traces of other lithics, including chert, clay

Table 7.3: Percentage of estimated relative (Rel^{387}) and absolute (Abs^{388}) error for each mortar component, estimated from total counts from each structure during modal analysis. Absolute error reported as upper and lower analytical error for 95% confidence limits.

	Case a Giardino OS-C15		Case a Giardino Apartment		Case a Giardino Courtyard		Case a Giardino Façade		Cas. del Serapide		Cas. del Larario		Casa Basilicale		Piccolo Mercato		Terme del Foro		Ins. dell' Ercole Bambino	
	Rel	Abs	Rel	Abs	Rel	Abs	Rel	Abs	Rel	Abs	Rel	Abs	Rel	Abs	Rel	Abs	Rel	Abs	Rel	Abs
Binder	8	1.3-1.4	7	1.3-1.3	10	1.3-1.3	10	1.3-1.3	4	1.3-1.3	4	1.4-1.4	5	1.3-1.3	5	1.3-1.3	45	1.3-1.3	5	1.3-1.3
Void space	24	0.6-0.6	20	0.6-0.7	30	0.5-0.6	50	0.7-0.7	12	0.7-0.7	12	0.7-0.7	12	0.8-0.8	12	0.7-0.7	12	0.6-0.7	8	0.8-0.9
Pozzolane Rosse	24	0.7-0.8	5	1.4-1.4	12	1.2-1.2	8	1.4-1.4	7	1.1-1.1	14	0.5-0.6	3	1.4-1.4	3	1.4-1.4	8	1.8-1.9	5	1.3-1.3
Pozzolane Nere	24	0.1-0.2	24	0.4-0.5	40	0.1-0.2	50	0.3-0.3	14	0.4-0.4	25	0.07-0.1	16	0.3-0.4	16	0.5-0.6	24	0.2-0.2	12	0.5-0.5
Pozzolanelle	24	0.7-0.8	34	0.3-0.4	16	1.0-1.1	50	0.3-0.3	7	1.0-1.0	6	1.1-1.2	20	0.3-0.4	24	0.02-0.2	8	0.9-0.9	12	0.5-0.6
Tufo Lionato	6	0.9-1.4	14	0.8-0.9	16	1.0-1.1	16	0.9-1.0	6	1.1-1.1	5	1.3-1.3	12	0.6-0.6	12	0.6-0.6	6	1.2-1.2	10	0.8-0.9
Tufo Giallo di Prima Porta	-	-	30	0.2-0.3	40	0.4-0.5	50	0.3-0.3	16	0.3-0.3	20	0.2-0.3	20	0.3-0.4	20	0.4-0.4	24	0.2-0.3	20	0.2-0.3
MSVD reworked air fall ash	24	0.2-0.3	24	0.5-0.6	50	0.3-0.3	50	0.4-0.4	12	0.3-0.4	20	0.3-0.4	20	0.3-0.4	12	0.6-0.6	10	0.8-0.9	12	0.5-0.6
Other Lithics	24	0.2-0.3	25	0.1-0.2	50	0.3-0.3	50	0.2-0.3	20	0.2-0.3	20	0.2-0.3	20	0.2-0.3	20	0.3-0.4	24	0.1-0.2	24	0.2-0.1
Ceramic	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	20	0.3-0.3	-	-
Lime lumps	24	0.2-0.3	25	0.3-0.4	-	-	30	0.7-0.8	20	0.4-0.4	20	0.2-0.3	20	0.2-0.3	20	0.02-0.1	20	0.3-0.3	12	0.6-0.6
Free Crystals	24	0.2-0.3	25	0.3-0.4	50	0.3-0.3	50	0.2-0.3	20	0.3-0.4	12	0.4-0.5	18	0.4-0.5	20	0.3-0.3	16	0.4-0.4	16	0.4-0.5
Root traces	24	0.2-0.3	-	-	-	-	-	-	-	-	-	-	24	0.04-0.1	24	0.02-0.1	-	-	24	0.02-0.1

387 Relative error estimated according to van der Plas and Tobi 1965.

388 Absolute error estimated according to Howarth 1998.

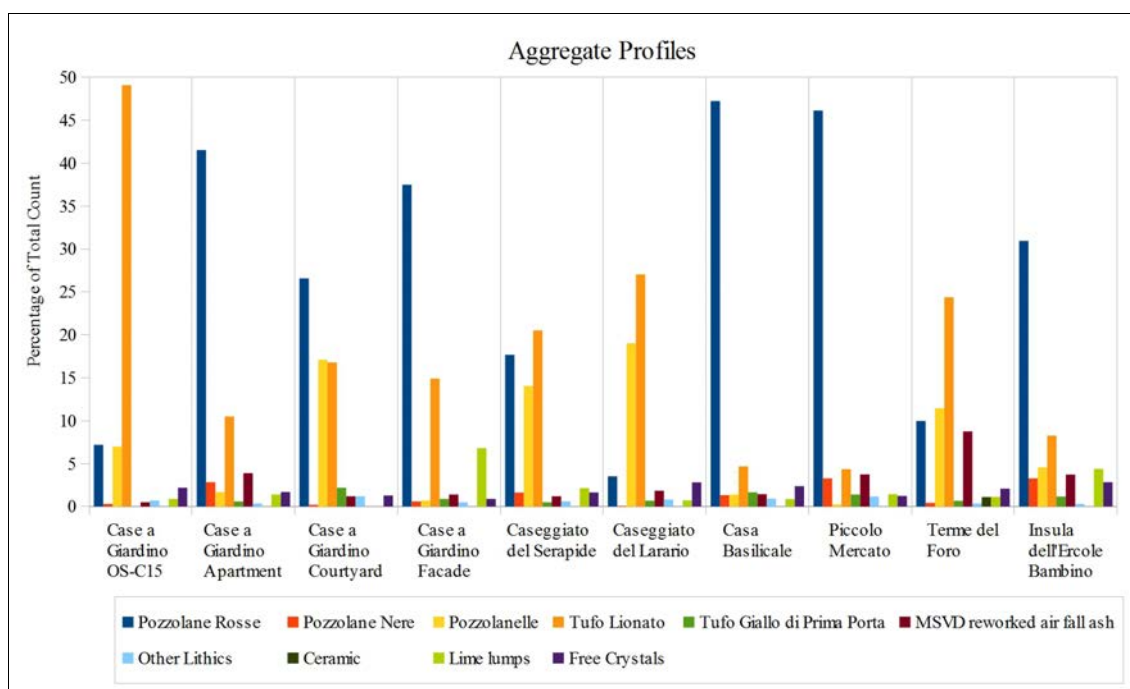


Figure 7.4: Relative proportion of aggregate lithology, illustrated as mean percentage of the total count of all samples.

The first approximation of mix proportion for the mortars was determined from the ratio of binder, aggregates, and void space recorded with modal analysis (Figure 7.5, Table 7.4). Results indicated that binder content varied from approximately 27% to 38% of the total count, with an overall average of 33%. The aggregate accounted for 57% to 63% of all constituents, with an average of approximately 61%. The average void content across all samples was 6%, including the anomalously high value of 9.1% in the mortar from the Insula dell'Ercole Bambino and the low value of 4% in the mortar from the courtyard of the Case a Giardino. The binder:aggregate ratios of the mortars from the Case a Giardino varied between 1:2.2 and 1:2.5, indicating a high proportion of aggregate. All other structures exhibited a binder:aggregate ratio of 1:2 or less.

Table 7.4: Basic proportions of mortar components. Data reported as averaged percentages of total count of all samples.

	Case a Giardino OS-C15	Case a Giardino Apartment	Case a Giardino Courtyard	Case a Giardino Façade	Cas. del Serapide	Cas. del Larario	Casa Basilicale	Piccolo Mercato	Terme del Foro	Insula dell'Ercole Bambino
Binder	27.4	29.2	29.4	29.6	33.9	37.7	31.3	31.2	34.5	31.3
Void space	4.7	6.2	4.0	6.2	6.1	5.7	6.7	5.7	5.2	9.1
Aggregate	67.9	64.5	66.6	64.2	60.0	56.6	62.0	63.1	60.3	59.6
Binder:Aggregate	1:2.5	1:2.2	1:2.3	1:2.2	1:1.8	1:1.5	1:2.0	1:2.0	1:1.7	1:1.9

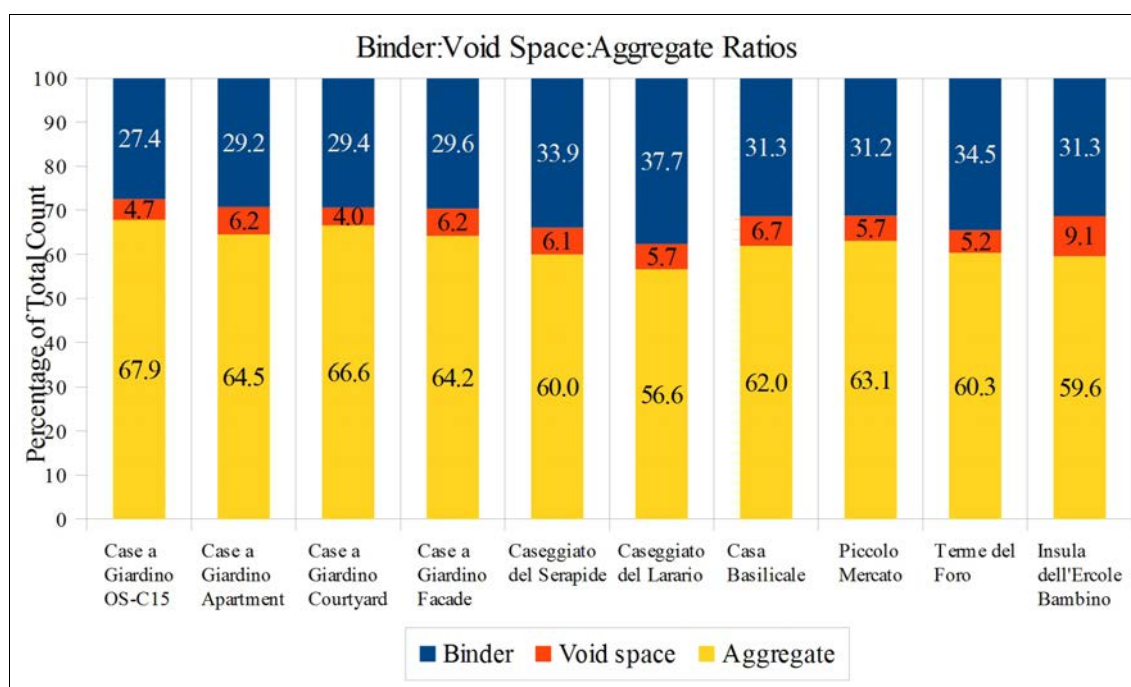


Figure 7.5: First approximation of mix proportions, mean percentages of total count for all samples.

7.2.2. SEM analysis

SEM analysis of polished samples from each structure revealed the microstructures of fibrous cements, basic chemistry of the lime, and the nature of the interfacial zone between aggregate particles and the binder. These features are discussed individually for

each structure below, but a general comparison of the chemical nature of the mortar binders was determined with backscatter images and wavelength dispersive spectroscopy.

The binder of all samples typically comprised calcium oxide (CaO) with minor proportions of silica (SiO₂), aluminium oxide (Al₂O₃), magnesium oxide (MgO), sodium oxide (Na₂O), and potassium oxide (K₂O). Traces of chlorine were detected in the samples from the Caseggiato del Serapide and the Piccolo Mercato, but this was most likely contributed by the chlorine-rich epoxy. Regions that were brighter in colour represented areas of binder richer in calcium, while darker areas contained more silica, as seen in the element map of sample OS-C5 from the Caseggiato del Larario (Figure 7.6). The smaller images illustrate the distribution of different elements, and specifically illustrate the Ca-rich and Ca-poor regions of the sample (the image labelled “Ca Ka1”). Silica (“Si Ka1”) and aluminium (“Al Ka1”) also appear more prevalent in the Ca-poor regions. Magnesium (“Mg Ka1”), sodium (“Na Ka1”), and potassium (“K Ka1”) are fairly evenly distributed throughout the sample.

Areas of mortar binder that were low in calcium represent regions that have lost calcitic binder material, leaving behind residual silica from the binder. All samples exhibited both light and dark regions, but six of the seven mortar samples were dominated by the brighter, more calcium-rich binder material (Figure 7.7). Only the binder of the mortar from the Case a Giardino (sample OS-C15) contained more depleted, silica-rich material.³⁸⁹ This suggested that most of the mortars have maintained the integrity of their binder and have not suffered from significant loss of binder material over time.

³⁸⁹ Unfortunately this was a received sample that was collected without precise provenance information, so it was not possible to infer information about binder depletion in any specific location.

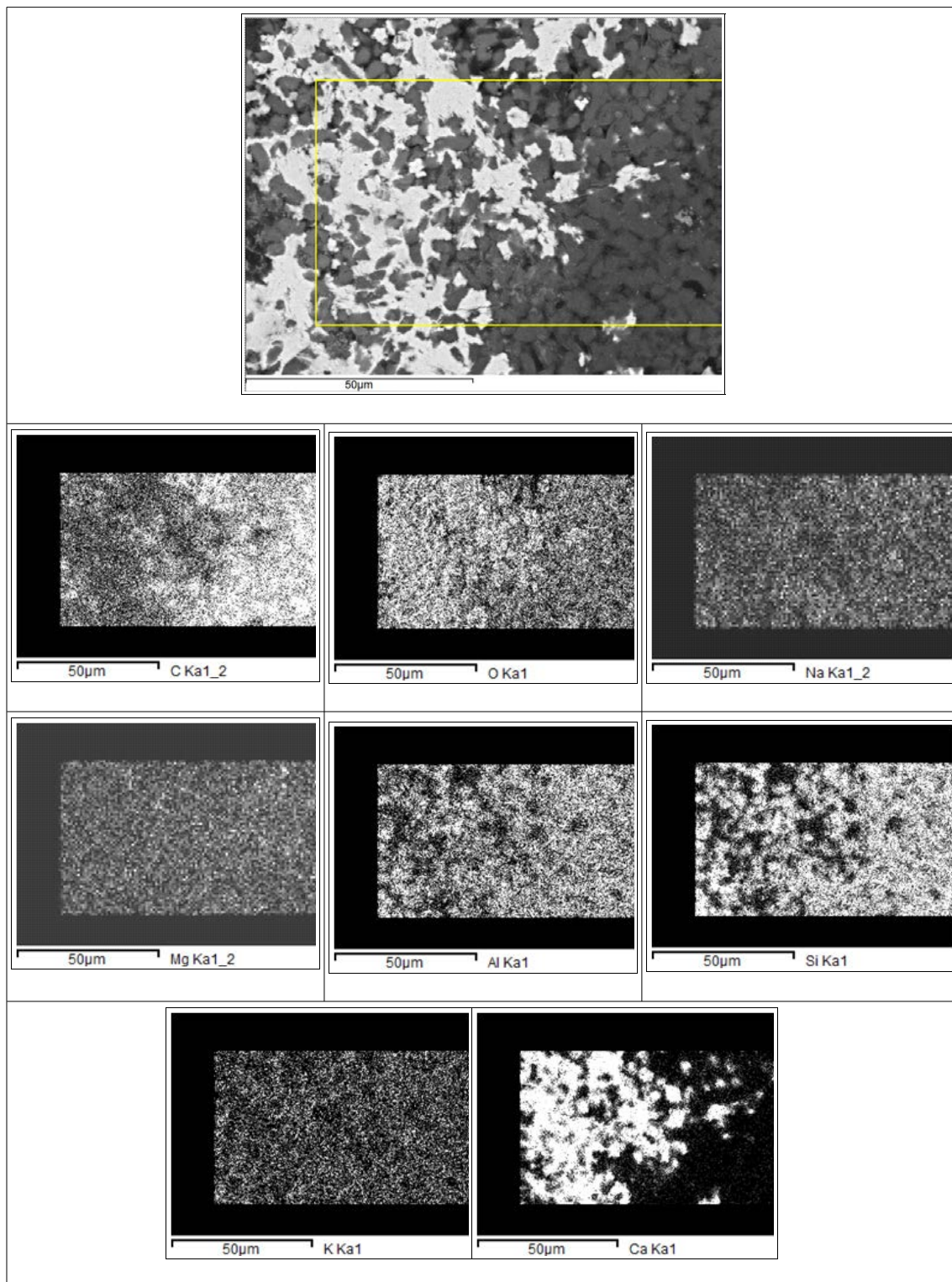


Figure 7.6: SEM image and element maps of sample OS-C5 from the Caseggiato del Larario, showing the variation in binder composition.

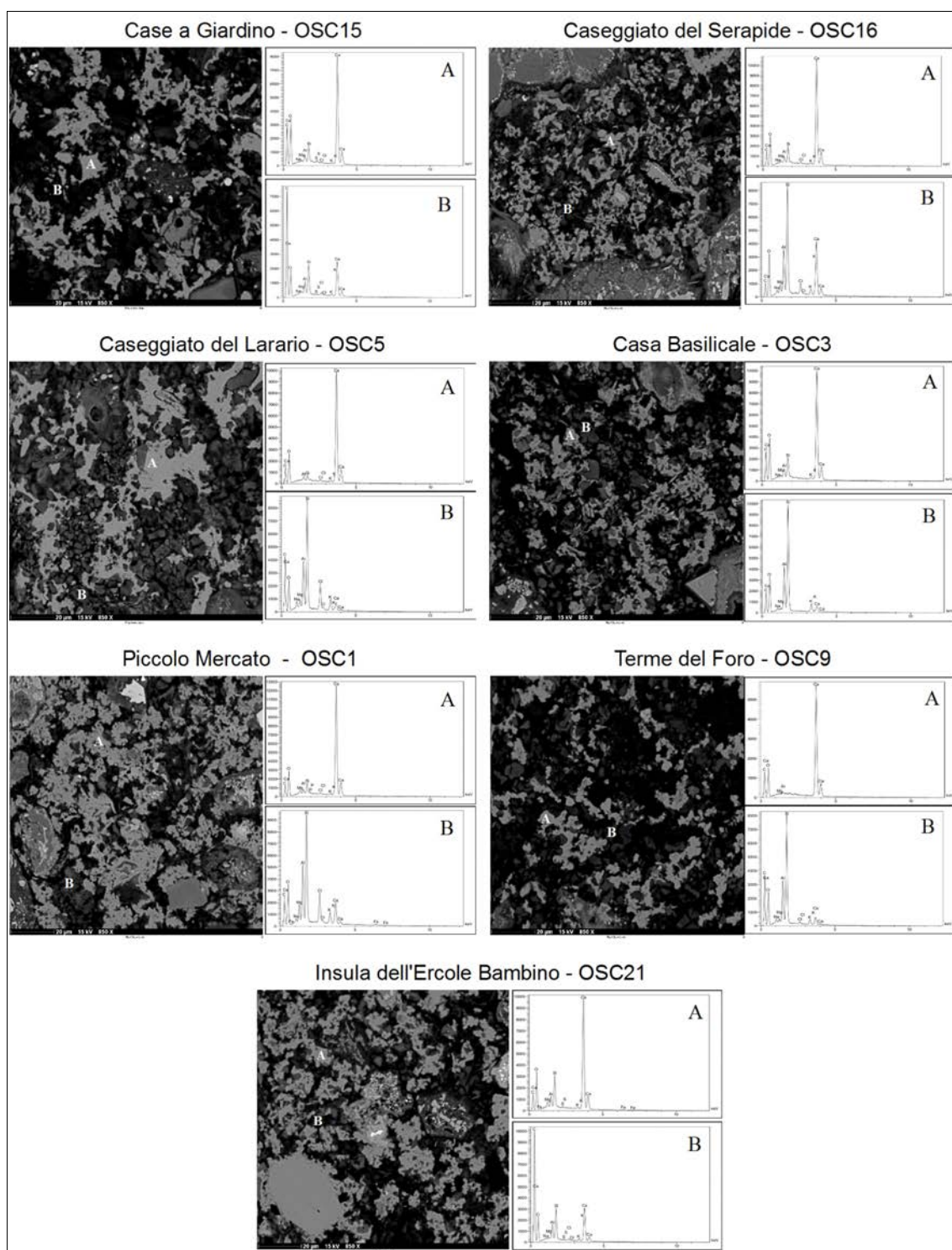


Figure 7.7: SEM backscatter electron images and WDS spectra of light (A spectra) and dark (B spectra) areas of binder in analysed samples from all structures.

Individual lime lumps in each sample were analysed semi-quantitatively with SEM/microprobe; Table 7.5 and Figure 7.8 illustrate the findings. Particles of lime typically comprised major proportions of calcium, with minor or trace proportions of silica, magnesium, aluminium, and sodium. The chlorine detected in the samples can most likely be attributed to the epoxy mounting medium. The lime in samples from the Terme del Foro, the Insula dell'Ercole Bambino, the Case a Giardino (sample OS-C15), and the Caseggiato del Larario exhibited the “cleanest” lime with the fewest components besides calcium oxide (Ca+O).

*Table 7.5: WDS data from SEM/microprobe analysis (WDS) of lime lumps in samples from all structures, with data expressed as atomic weight percent. += data reported as mean values of 3-5 data points from single lumps of lime. *= data from single readings. BD= below detection limits.*

	Case a Giardino (OS-C15)⁺	Caseggiato del Serapide⁺	Caseggiato del Larario[*]	Casa Basilicale⁺	Piccolo Mercato⁺	Terme del Foro[*]	Insula dell'Ercole Bambino[*]
O	50.070	49.274	49.659	50.350	50.499	49.966	49.863
F	0.227	0.531	BD	BD	0.192	BD	0.157
Na	0.026	0.153	0.467	BD	0.144	0.018	BD
Mg	0.221	0.594	0.895	0.416	1.175	0.208	0.696
Al	0.072	0.739	0.399	0.321	0.959	BD	BD
Si	0.544	1.316	0.126	0.529	1.883	BD	0.028
P	0.070	0.050	0.044	0.124	0.093	0.050	0.041
Cl	0.009	1.456	0.492	0.409	0.635	0.005	0.008
K	0.027	0.071	0.004	0.099	0.126	0.005	0.041
Ca	48.608	45.764	47.896	47.620	44.311	49.411	49.108
Ti	0.009	0.006	0.010	0.035	0.004	BD	0.006
Mn	0.011	0.005	BD	BD	0.016	0.161	0.002
Fe	0.107	0.043	0.008	0.051	0.013	0.178	0.050
Total	100.000	100.000	100.000	99.952	100.000	100.000	100.000
Ca+O	98.677	95.038	97.555	97.969	94.759	99.377	98.970

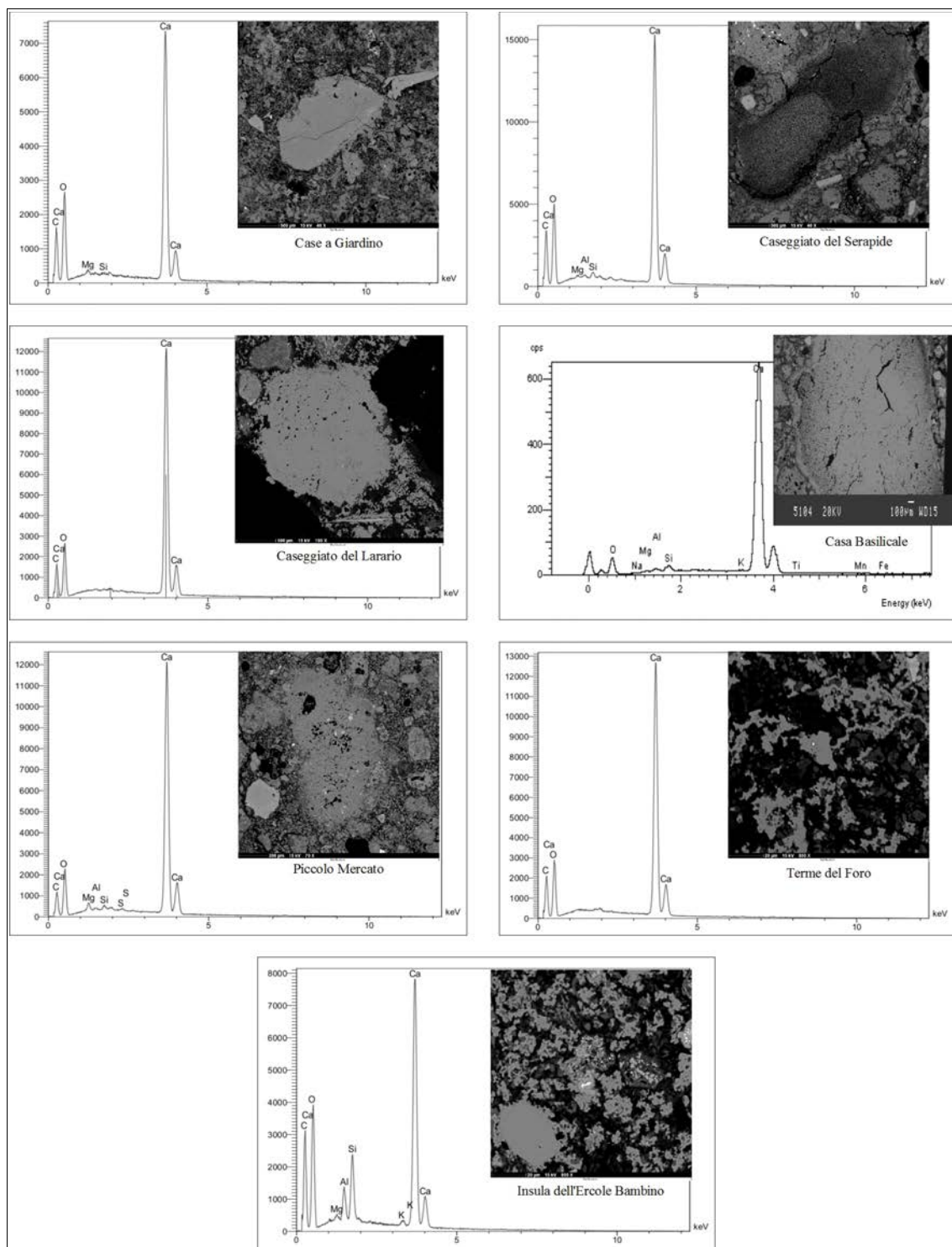


Figure 7.8: SEM backscatter electron images and WDS spectra of lime lumps in analysed samples from all structures.

Two samples, sample OS-C15 from Case a Giardino (Figure 7.9) and sample OS-C9 from Terme del Foro (Figure 7.10), contained flecks of copper and zinc alloy, which were only found within the binder in very low quantities. The WDS spectrum of the sample from the Terme del Foro also indicated calcium (Ca), which may have been contributed by the surrounding binder matrix. Because these copper-zinc alloy flecks appeared as randomly distributed discrete particles that were only rarely observed within the binder, they most likely represent contamination of some kind. Their presence suggests the builders could have been using tools made of copper alloy when they mixed the mortar, and those tools may have left microscopic particles behind.

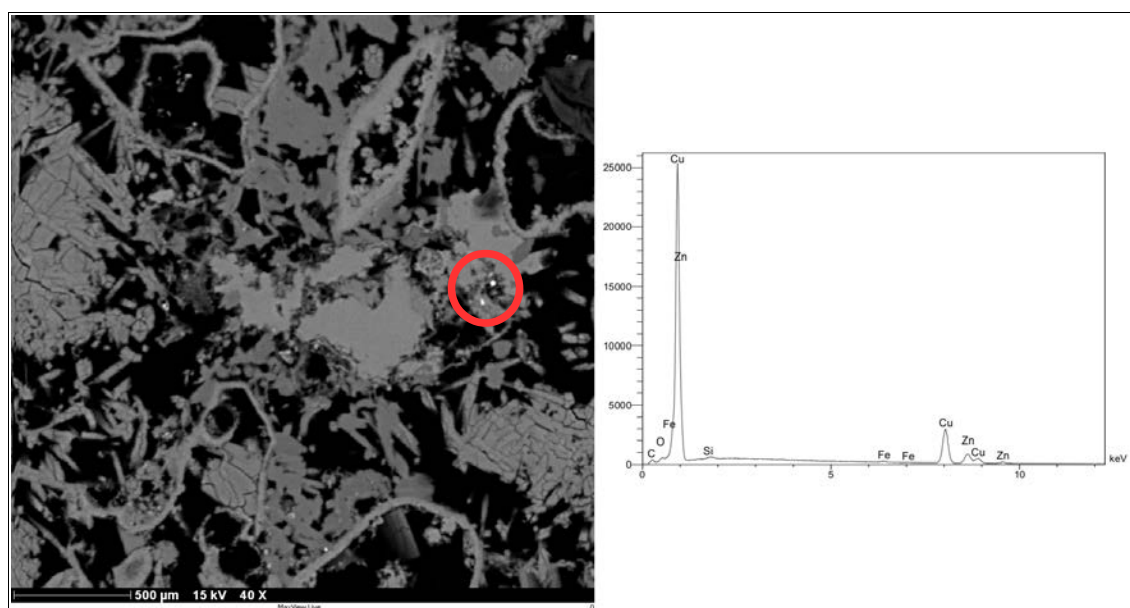


Figure 7.9: SEM photomicrograph of binder of sample OS-C15 from Case a Giardino showing bright white flecks of copper and zinc alloy (circled in red), with associated WDS spectrum.

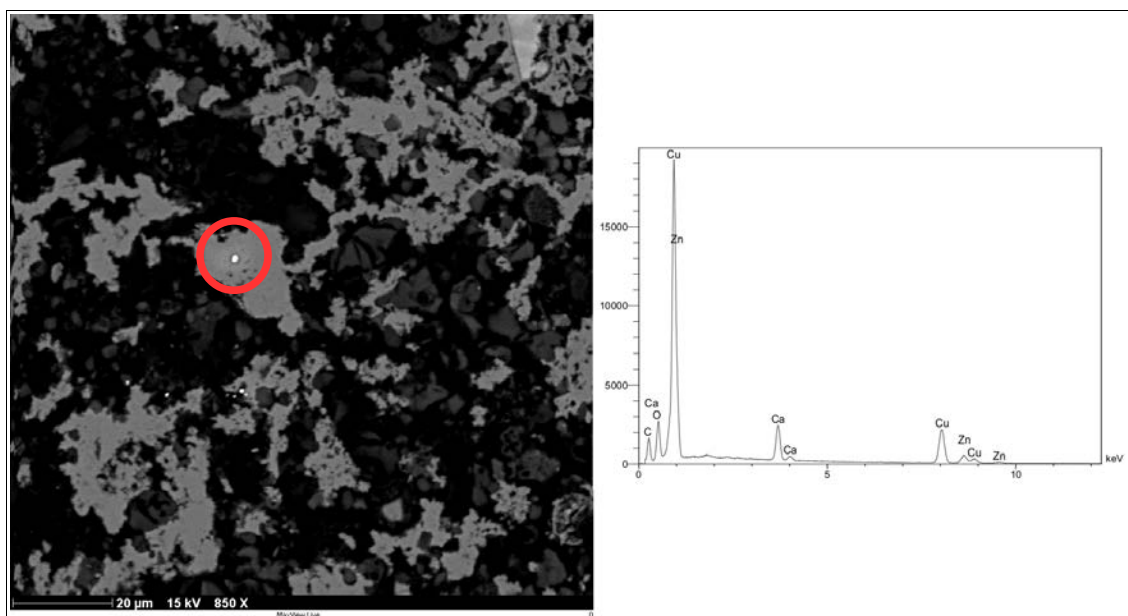


Figure 7.10: SEM backscatter image of binder from Terme del Foro, showing bright white flecks of copper and zinc alloy (analysed particle circled in red), with associated WDS spectrum.

Fibrous cements were observed with SEM analysis in all structures apart from the Caseggiato del Larario (Table 7.1).³⁹⁰ The crystals exhibited a blade-like habit, typically spanning vesicles of Pozzolane Rosse fine aggregate particles (Figure 7.11). As seen from the qualitative element spectra in Figure 7.11, the fibres appeared to be aluminosilicates containing variable amounts of magnesium, sodium, potassium, and calcium. The samples from the Caseggiato del Serapide and the Piccolo Mercato exhibited increased aluminium compared to the remaining samples. These two samples also contained chlorine, which was missing in the others. The fibres in sample OS-C15 from the Case a Giardino also contained iron. Quantitative data were collected from multiple examples of fibrous phases in all structures apart from the Case a Giardino (and of course the Caseggiato del Larario, where no fibres were observed with SEM analysis). Mul-

³⁹⁰ Fibrous crystals tentatively identified as possibly stratlingite were observed within the binder matrix with thin section analysis.

multiple readings were collected where possible, and the data are presented in Table 7.6. In general, the cements exhibited highly variable composition, making their identification problematic.

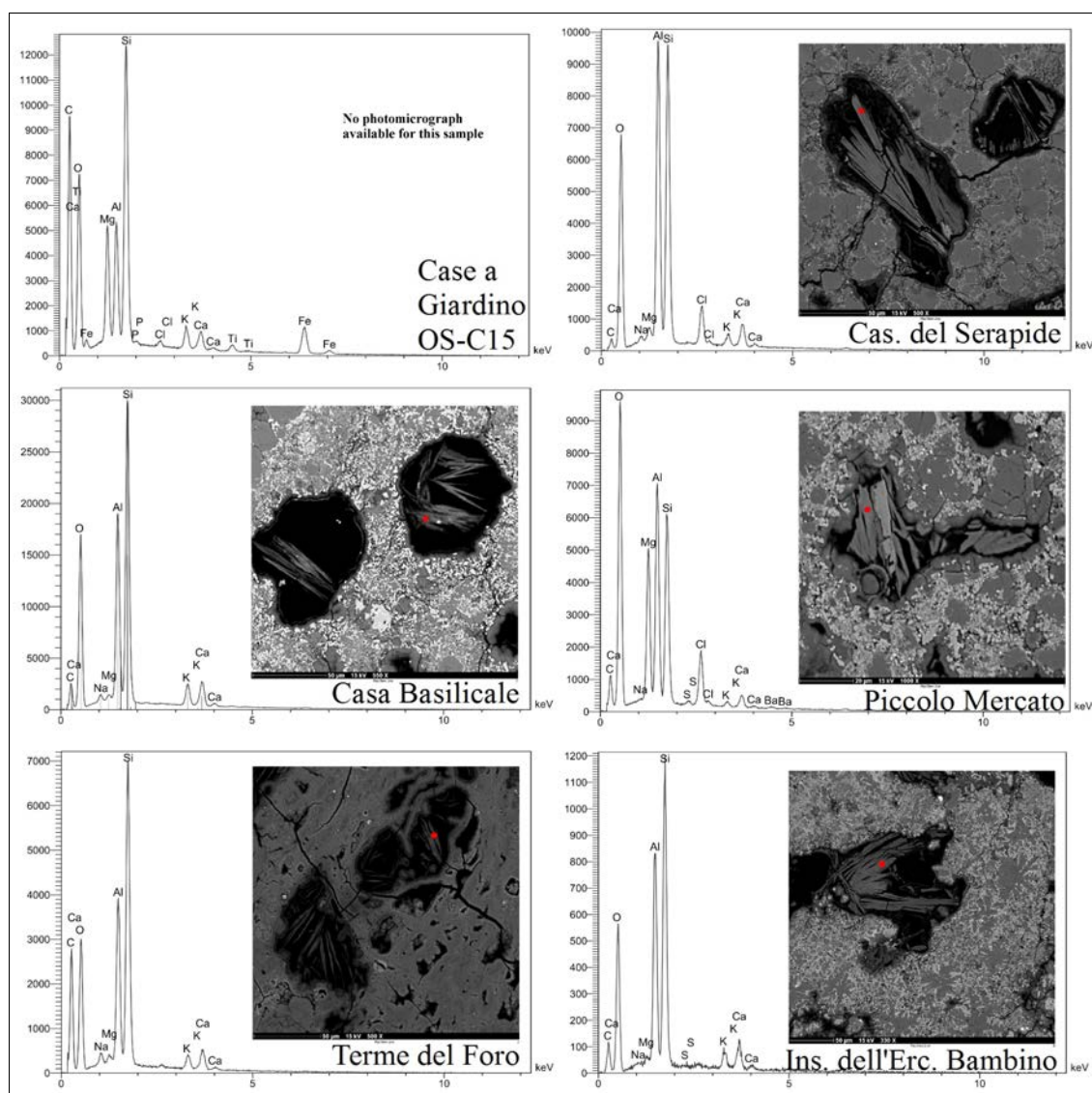


Figure 7.11: SEM photomicrographs and WDS spectra of cementitious fibres within vesicles of Pozzolane Rosse fragments in mortar samples. Red dots represent approximate location of probe analysis. No photomicrograph is available for the sample from the Case a Giardino, and fibrous cements were not observed in the sample from Casegiato del Larario.

Table 7.6: Chemical composition of fibrous crystals, determined with SEM/WDS analysis, reported as atomic weight percent. BD = Below Detection.

	Na	Mg	Al	Si	P	Cl	K	Ca	Ti	Mn	Fe	O	Total
Caseggiato del Serapide - 1	1.55	0.52	10.84	19.32	0.01	1.01	2.45	3.10	0.04	0.01	0.46	60.44	99.76
Caseggiato del Serapide - 1	0.65	0.82	10.74	19.24	0.02	4.66	1.74	2.53	0.09	0.01	1.23	58.25	100.00
Caseggiato del Serapide - 1	3.15	0.02	11.48	21.96	BD	0.04	0.06	0.11	0.01	BD	0.16	63.02	100.00
Caseggiato del Serapide - 2	1.71	0.96	6.12	15.29	0.02	2.78	1.09	14.68	0.11	0.02	0.64	55.99	99.40
Caseggiato del Serapide - 2	0.84	0.30	11.79	19.55	0.02	2.61	1.10	3.28	0.02	0.02	0.15	60.16	99.83
Caseggiato del Serapide - 3	1.10	0.67	7.09	15.10	0.03	6.04	1.04	14.49	0.01	0.01	0.17	54.25	100.00
Caseggiato del Serapide - 4	0.81	0.65	11.86	20.00	0.03	3.24	1.07	1.90	0.04	0.02	0.30	60.08	100.00
Casa Basilicale - 1	0.28	6.40	1.84	18.36	0.15	BD	0.04	9.75	0.25	0.13	2.97	59.83	100.00
Casa Basilicale - 1	BD	0.65	0.19	0.07	0.05	BD	0.06	48.68	BD	0.06	0.08	50.18	100.02
Casa Basilicale - 2	0.50	5.24	4.40	16.40	0.50	0.05	0.15	7.95	0.52	0.08	4.45	59.75	99.99
Casa Basilicale - 2	BD	0.76	7.02	9.82	0.11	1.00	0.57	23.04	0.13	0.03	0.73	56.48	99.68
Casa Basilicale - 3	0.16	0.51	2.97	8.18	0.51	0.27	0.59	20.87	1.91	0.48	7.15	56.12	99.72
Casa Basilicale - 3	0.59	0.72	6.09	15.56	0.67	0.09	1.14	1.80	2.03	0.55	10.16	60.47	99.87
Casa Basilicale - 4	0.34	0.27	11.33	21.24	0.03	0.04	1.40	2.18	BD	0.01	0.17	62.95	99.97
Piccolo Mercato - 1	0.20	9.16	14.12	13.25	BD	1.30	0.45	1.15	0.02	0.02	0.04	59.71	99.43
Piccolo Mercato - 1	0.20	9.16	14.12	13.25	BD	1.30	0.45	1.15	0.02	0.02	0.04	59.71	99.43
Piccolo Mercato - 2	0.08	8.60	14.42	13.25	0.01	1.76	0.51	1.19	BD	BD	0.07	59.54	99.45
Piccolo Mercato - 3	0.12	0.93	13.13	17.30	0.02	0.32	4.65	1.06	0.45	0.03	1.13	60.83	99.97
Piccolo Mercato - 4	BD	0.05	0.05	33.20	BD	0.04	BD	0.08	BD	BD	0.05	66.61	100.09
Terme del Foro - 1	1.29	0.30	9.26	22.20	0.01	0.23	1.17	2.76	0.01	BD	0.13	62.55	99.91
Terme del Foro - 2	0.52	0.45	13.07	19.60	0.02	0.15	0.83	2.42	0.02	BD	0.21	62.34	99.63
Ins. dell'Ercole Bambino - 1	0.84	0.42	11.55	20.65	0.03	0.46	1.17	2.28	0.01	BD	0.21	62.30	99.92
Ins. dell'Ercole Bambino - 1	0.43	0.47	12.27	20.41	0.06	0.21	0.80	2.28	0.02	0.00	0.20	62.60	99.74
Ins. dell'Ercole Bambino - 2	0.47	0.01	5.07	24.90	0.03	0.14	3.34	2.72	0.02	0.04	0.56	62.50	99.79
Ins. dell'Ercole Bambino - 3	0.65	0.40	13.10	19.51	0.03	0.21	1.42	2.11	0.02	0.01	0.15	62.22	99.83
Ins. dell'Ercole Bambino - 4	0.36	0.30	11.48	20.52	0.07	0.34	1.02	3.12	0.01	0.01	0.26	62.45	99.93

7.2.3. XRD analysis and mineralogy

X-ray diffraction analysis (XRD) confirmed the major minerals present in the selected mortar samples that were processed and analysed at the Department of Engineering and Applied Science, Cranfield University. Figure 7.12 compares diffractograms generated for all samples, with the primary peaks for major phases identified. All dif-

fractograms have been processed to reduce the background noise that hides reflections from smaller crystals, which tend to produce broad peaks with relatively low-intensity.³⁹¹ The data have been smoothed with the PowderX software resulting in a reduction of background noise and a refinement of smaller peaks.

The samples were disaggregated to remove any visible aggregate fragments in the hope that XRD would be able to identify cement minerals without the patterns being dominated by mineral grains from aggregate clasts. Despite these efforts, the mineral phases contributed by the aggregate particles dominated the diffraction patterns. All samples contained calcite, analcime, and diopside; each of these minerals generated multiple reflections across the diffractogram, resulting in a rather complicated pattern. These three minerals accounted for 90% of the peaks in each diffractogram.

All samples produced reflections for diopside ($\text{MgCaSi}_2\text{O}_6$), calcite (CaCO_3), and analcime ($\text{NaAlSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$), in order of abundance according to Reitveld analysis (Table 7.7). Each of these minerals generated multiple reflections across the diffractogram, resulting in rather complicated diffraction patterns.

391 Mierzwa and Pielaszek 1997, 544.

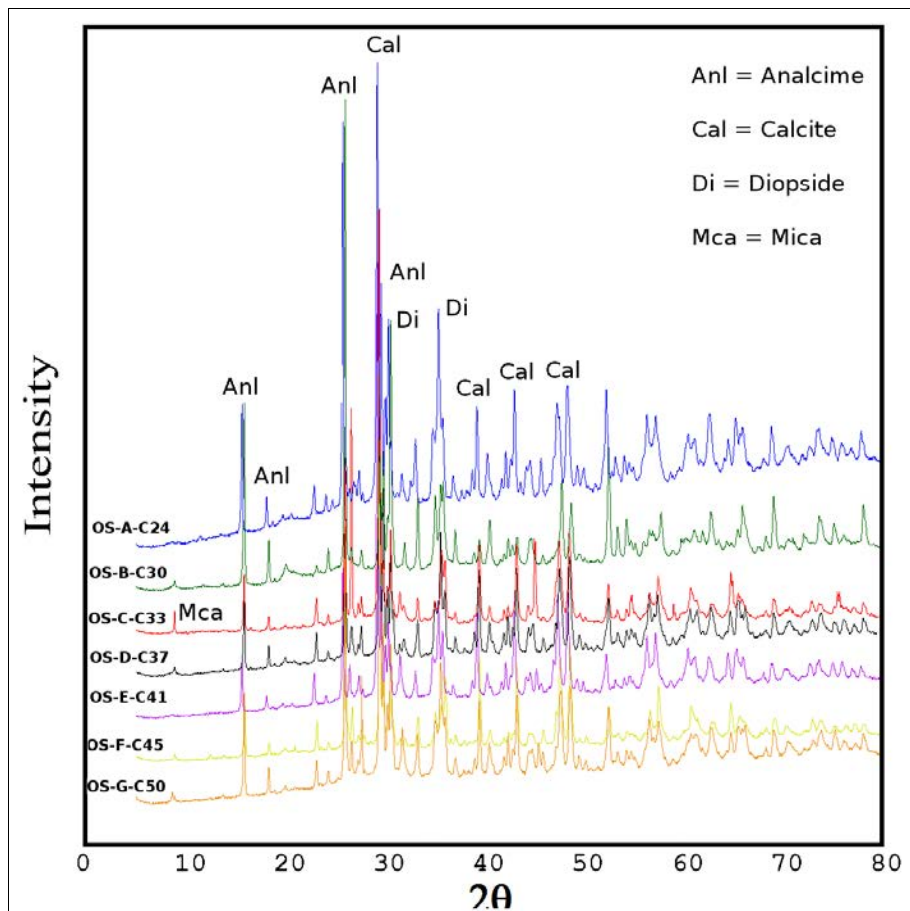


Figure 7.12. X-ray diffractograms of samples from all structures showing reflections of calcite, diopside, analcime, and mica (probably biotite).

Table 7.7: Reitveld analysis of XRD results, reported as weight percent (Wt%) and standard deviation (s.d.).

	Case a Giardino Façade		Caseggiato del Serapide		Caseggiato del Larario		Casa Basilicale		Piccolo Mercato		Terme del Foro		Insula dell'Ercole Bambino	
	Wt %	s.d.	Wt %	s.d.	Wt %	s.d.	Wt %	s.d.	Wt %	s.d.	Wt %	s.d.	Wt %	s.d.
Calcite	15.5	0.5	6.8	0.3	16.8	0.6	19.8	0.6	25.5	0.7	17.3	0.4	13.8	0.4
Diopside	46.5	1.6	78.5	1.3	75.2	1.6	68.8	1.4	62.8	1.3	67.8	1.0	73.5	1.2
Analcime	8.0	1.8	1.6	1.3	5.8	1.7	11.4	1.6	10.2	1.6	15.0	1.1	11.5	1.3

The proportions of calcite, diopside, and analcime determined with Reitveld analysis are reported in Table 7.7 as weight percent (wt %) along with the standard deviation (also in wt %). The results from this analysis were of limited value, because they represented the quantity of each mineral after manual separation. It was impossible to reliably quantify the components in this way, as the resulting powder was not a randomized sample. Given that the intent was to focus on the cementitious phases in the binder by removing as much of the visible aggregate as possible, it would be unwise to rely on these results for anything beyond relative comparisons.

A mica phase, probably biotite ($\text{K}[\text{Mg,Fe}]_3\text{AlSi}_3\text{O}_{10}[\text{F,OH}]_2$), generated reflections in the diffractograms of five of the seven samples, but was missing from the Piccolo Mercato (OS-E-C41) and the façade of the Case a Giardino (OS-A-C24). However, biotite was observed with optical microscopy and recorded during point counts of the samples from both structures. Most of the observed biotite was present as free crystals or as inclusions in Pozzolanelle and Tufo Lionato clasts, with rare biotite grains identified within clasts of Monti Sabatini Reworked Airfall Ash. Biotite was never associated directly with particles of Pozzolane Rosse, Pozzolane Nere, or Tufo Giallo di Prima Porta.

The X-ray diffractograms showed no reflections for leucite ($\text{K}[\text{AlSi}_2\text{O}_6]$), but euhedral leucite was observed in thin section in most samples. It occurred as free crystals in minor proportions in the Caseggiato del Larario, the Terme del Foro, and the Insula dell'Ercole Bambino, with trace amounts in the apartment and courtyard samples from the Case a Giardino, the Caseggiato del Serapide, the Casa Basilicale, and the Piccolo Mercato. Trace amounts of other mineral phases were observed as loose crystals in

samples from all structures, and the full mineral assemblage observed with thin section modal analysis is provided in Table 7.8.

Table 7.8: Mineral phases observed with thin section analysis, reported as the mean percentage of the total count during modal analysis.

	Case a Giardino OS-C15	Case a Giardino Apartment	Case a Giardino Courtyard	Case a Giardino Façade	Cas. del Serapide	Cas. del Larario	Casa Basilicale	Piccolo Mercato	Terme del Foro	Insula dell'Ercole Bambino
Analcime	0.6	0.4	0.7	0.7	0.8	0.5	0.7	0.3	0.6	0.7
Biotite	0.1		0.2		0.1	0.2	0.1	0.02	0.1	0.1
Calcite	0.1	0.3			0.1	0.5	0.8	0.3	0.4	0.4
Chabazite	0.1									
Clinopyroxene	0.7	0.2	0.2		0.3	0.4	0.2	0.3	0.5	0.4
Feldspar		0.1		0.1	0.03	0.03	0.1		0.2	0.2
Häüyne	0.1									0.02
Leucite		0.2	0.1		0.1	0.4	0.3	0.2	0.2	0.9
Light mica		0.05			0.03	0.05		0.02	0.1	
Phillipsite	0.1									
Quartz	0.1	0.2		0.1		0.1	0.1	0.1	0.1	0.1
Sanidine	0.2	0.05	0.1		0.2	0.5	0.1	0.1	0.1	0.2

The results from XRD analysis were actually of limited value, because they represented the quantity of each mineral after manual separation. It was impossible to reliably quantify the components in this way, as the resulting powder was not a randomized sample. Given that the intent was to remove as much of the visible aggregate as possible, it would be unwise to rely on these results for anything beyond relative comparisons. In fact, the objective of XRD analysis was to identify calcium-alumina-silicate-hydrate minerals, portlandite, or any other cementitious phases present after removing aggregate particles. Unfortunately, it was not possible to resolve reflections for any of common cement phases apart from calcite.

Perhaps most useful result of XRD analysis was the absence of reflections for gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and ettringite ($\text{Ca}_6\text{Al}_2[\text{SO}_4]_3[\text{OH}]_{12} \cdot 26\text{H}_2\text{O}$) in the X-ray dif-

fractograms. These minerals are both known to be common secondary alteration products in mortars and concretes.³⁹² While it is possible these phases may have been present in the mortars but destroyed during the sample preparation process, these particular alteration phases were not observed in thin sections either. Together, these data suggest the mortars were protected from internal degradation that would lead to the formation of these minerals.

7.2.4. Particle size analysis

Particle morphology was evaluated using image analysis of scanned images of thin sections. The Feret diameter represents the width of a particle as projected against a single plane, similar to the measurement that would be taken using a caliper.³⁹³ Multiple values can be measured and averaged to describe a particle as needed, but in this case the minimum Feret diameter values were used to convert the results of image analysis to traditional-style particle size distribution curves from sieve analysis.

The mean, standard deviation (Std Dev), minimum (Min) and maximum (Max) values, median, and the interquartile range (IQR) of various particle size parameters are presented compared below: particle minimum Feret diameter is reported in Table 7.9 and illustrated in Figure 7.13. Image analysis determined that the fine aggregate of all samples comprised primarily coarse silt- to fine sand-sized, sub-rounded particles, which was corroborated by visual assessment of mortars in hand sample and in thin section. Mortar from the Piccolo Mercato contained the most angular particles, exhibiting both the lowest mean circularity and longest mean particle perimeter. Mortar from the

³⁹² Sabbioni *et al* 2001, 540.

³⁹³ Merkus 2009, 15.

Insula dell'Ercole Bambino exhibited the most circular particles, conversely exhibiting the shortest mean particle perimeter. The mortar from the Insula dell'Ercole Bambino also exhibited the lowest standard deviation in all parameters, suggesting the builders of this structure exerted the most control over the size and shape of aggregate particles mixed into the mortar.

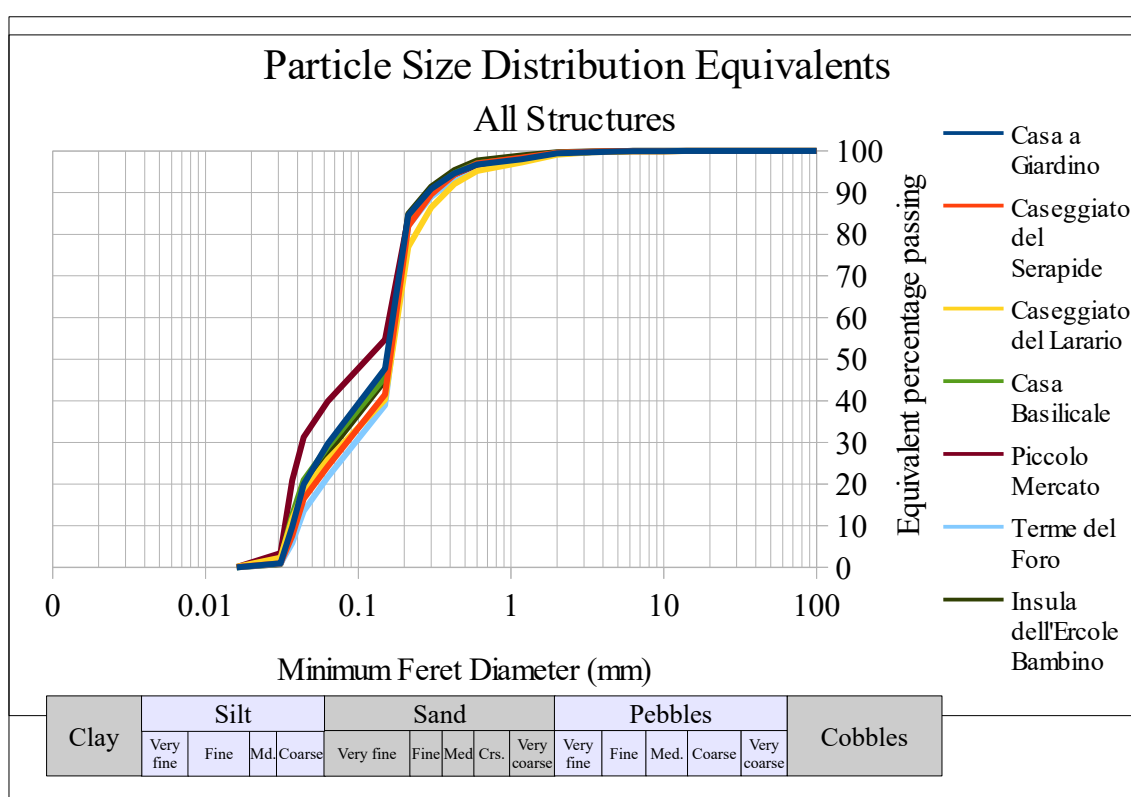


Figure 7.13: Minimum Feret diameter distribution curves for all samples, determined from image analysis.

Table 7.9: Descriptive statistics of fine aggregate morphology, determined from image analysis.

	Case a Giardino OS-C15	Caseggiato del Serapide	Caseggiato del Larario	Casa Basilicale	Piccolo Mercato	Terme del Foro	Insula dell'Ercole Bambino
Particle Minimum Feret Diameter, (mm)							
Mean	0.1128	0.1171	0.1398	0.1114	0.1074	0.1224	0.1029
Std Dev	0.2513	0.2544	0.3112	0.2041	0.2130	0.1943	0.1544
Min	0.0079	0.0079	0.0079	0.0079	0.0079	0.0159	0.0079
Max	7.2361	13.4616	7.6679	6.6333	6.0703	3.3649	4.7826
Median	0.0635	0.0714	0.0774	0.0665	0.0553	0.0715	0.0635
Mode	0.0318	0.0318	0.0238	0.0318	0.0237	0.0318	0.0318
IQR	0.0670	0.0742	0.1008	0.0749	0.0727	0.0745	0.0687
Particle Area, (mm²)							
Mean	0.0856	0.0746	0.0951	0.0534	0.0499	0.0496	0.0328
Std Dev	1.8116	2.0791	1.2519	0.8588	0.5530	0.3755	0.3357
Min	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
Max	97.0239	160.8511	48.6433	69.0624	31.6676	9.7312	19.3950
Median	0.0040	0.0050	0.0055	0.0043	0.0027	0.0054	0.0042
Mode	0.0006	0.0004	0.0005	0.0005	0.0004	0.0009	0.1103
IQR	0.0099	0.0123	0.0173	0.0113	0.0090	0.0131	0.3020
Particle Circularity							
Mean	0.7490	0.7094	0.6469	0.6803	0.5827	0.7502	0.7427
Std Dev	0.1875	0.1797	0.2027	0.2025	0.2327	0.1688	0.1640
Min	0.1131	0.1106	0.0589	0.0540	0.0288	0.1457	0.1412
Max	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Median	0.7920	0.7327	0.6583	0.6996	0.5779	0.7778	0.7642
Mode	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
IQR	0.2623	0.2538	0.2981	0.3096	0.3678	0.2393	0.2235
Particle Perimeter (mm)							
Mean	0.5321	0.5482	0.7139	0.5399	0.6106	0.5496	0.4511
Std Dev	1.5038	1.3714	1.9163	1.2505	1.7673	1.0207	0.7521
Min	0.0674	0.0674	0.0674	0.0674	0.0670	0.0674	0.0674
Max	48.6100	71.5506	47.0519	50.8624	64.6695	18.4139	20.7067
Median	0.2524	0.2935	0.3225	0.2795	0.2439	0.2954	0.2636
Mode	0.1103	0.1216	0.1103	0.1103	0.1098	0.1216	0.1103
IQR	0.3178	0.3589	0.4788	0.3655	0.3768	0.3608	0.3020

7.3. Mortar descriptions by structure

Summary results of all analyses are reported below for each structure. In the following sample descriptions, the term “exterior walls” refers to walls that were originally constructed as boundaries of the structure, normally exposed to the outside elements. The term “interior walls” refers to walls that were originally constructed inside the structures, usually meant to divide the property into separate rooms. Munsell colour determinations were made on the interior portion of the binder to ensure that colour determinations were made on freshly exposed material rather than the eroded outer surface. Thin sections were prepared in three batches:

1. a single example of the received samples from each structure, collected by M. Jackson (n=7);
2. a single facing sample from each structure, collected by author in September 2012 (n=7);
3. all samples from each structure, collected by author in September 2012 (n=28).

These samples were produced with fluorescent epoxy, making the thin section mounting medium appear yellow in some photomicrographs.

A total of six thin sections for structure were produced and analysed. The facing samples from batch two were repeated in batch three, and these have been distinguished by adding “-b” to the sample identification number.

7.4. Case a Giardino – Structure A

The sample set from the Case a Giardino included three core samples (OS-C15, OS-A-C23, OS-A-C25) and two facing samples (OS-A-C24, OS-A-C26). Information about the location, colour, and weight of the samples from this structure is summarized in Table 7.10. The mortar from the courtyard, which came from exterior walls, was generally more robust and cohesive in hand sample than mortar from the central apartments which came from interior walls.³⁹⁴ The samples from the courtyard (OS-A-C23) and the façade (OS-A-C24) were less friable than the samples from the central apartment, which came away from the wall in smaller and more numerous pieces. The high number of fragments and low average sample weight in the mortars from the apartment also represents further breakage that occurred in the packaging after sample collection.

Table 7.10: Samples from the Case a Giardino

	OS-C15	OS-A-C23	OS-A-C24	OS-A-C25	OS-A-C26
Core or Face	Core	Core	Face	Core	Face
Wall Location	Unknown	Exterior – courtyard	Exterior – façade	Interior – central apartment	Interior – central apartment
Munsell Code	5Y 8/1	2.5Y 7/1	2.5Y 8/1	10YR 8/1	2.5Y 8/1
Munsell Colour	White	Light grey	White	White	White
Total wt (g)	46.39	7.09	11.13	19.39	19.99
Number of Fragments	5	4	5	28	41
Total Fragment wt (g)	45.59	4.96	8.91	13.18	10.89
Powder wt (g)	0.8	2.1	2.2	6.21	9.08
Average Fragment wt (g)	9.12	1.24	1.78	0.47	0.27

The Munsell colour classification of the binder of these samples was white, apart from façade sample (OS-A-C24) which was light grey. These mortar samples contained visible fragments of Pozzolanelle up to 5 mm in size, Pozzolane Rosse up to 1 cm,

³⁹⁴ In this and all following sample descriptions, the term “exterior walls” refers to walls that were originally constructed as boundaries of the structure, normally exposed to the outside elements. The term “interior walls” refers to walls that were originally constructed inside the structures, usually meant to divide the property into separate rooms.

clasts of Monti Sabatini Reworked Airfall Ash up to 3 mm, and rounded fragments of Tufo Lionato from 1-2 mm. Loose biotite and feldspar grains were observed within the binder, along with the remains of modern plant fibres and insects. The frequency of visible inclusions varied from approximately 20-30% on the surface of the samples and from 3 to 5% on the sample interior. This variation was most likely due to the weathering effects of the exposed areas from which samples were collected, meaning that the softer binder material has eroded from the exterior surface leaving more of the harder aggregate particles. These mortar from the façade (OS-A-C24) contained white-coloured fibrous material that infiltrated the voids in a pervasive network, which lined, spanned, and radiated from large voids. The placement and texture of this material suggested it was redeposited cement that had been dissolved from the original binder, transported through the mortar by moisture, and then precipitated out into the void space.

7.4.1. Thin section and modal analysis

The thin section analysis and quantification with point counts reported below for the Case a Giardino mortar represent results from the five usable samples. The first sample OS-A-C24 that was initially submitted for thin section preparation in batch two suffered a great deal of material loss during the process. The slide was returned in a relatively poor state, representing a single over-large clast of Pozzolane Rosse with a small region of binder attached to one edge. Only 100 points could be counted on this sample, which was unsuitable for rigorous scientific analysis. Therefore, only a single sample from OS-A-C24 was included in the general and statistical analysis for the façade of Case a Giardino. Thin section analysis of the remaining samples confirmed the prelim-

inary identification of the aggregate material and the mortar textures. Pozzolane Rosse, Pozzolane Nere, Tufo Lionato, and Pozzolanelle clasts were observed in all samples (Figure 7.14). Large clasts of Tufo Lionato in sample OS-C15 contained significant chabazite in vesicles (Figure 7.15). Additional inclusions included ceramic fragments, limestone, leucitic lava, and quartzite lithic fragments, and loose crystals of analcime, clinopyroxene, leucite, and biotite.

The binder of all samples was uneven in colour and density, appearing the darkest in colour near the edges of large aggregate clasts. Lime lumps *sensu stricto* were present, totalling 2% of the total count across all samples from the Case a Giardino. The mortar was quite porous, with linear cracks and spherical to sub-rounded voids that ranged in size from 0.01 mm to 1 mm with an average size of 0.25 mm. In a number of places, linear cracks either radiated from or extended between spherical voids creating a network of connected voids. There was evidence of redeposited calcite around the edges of some rounded voids.

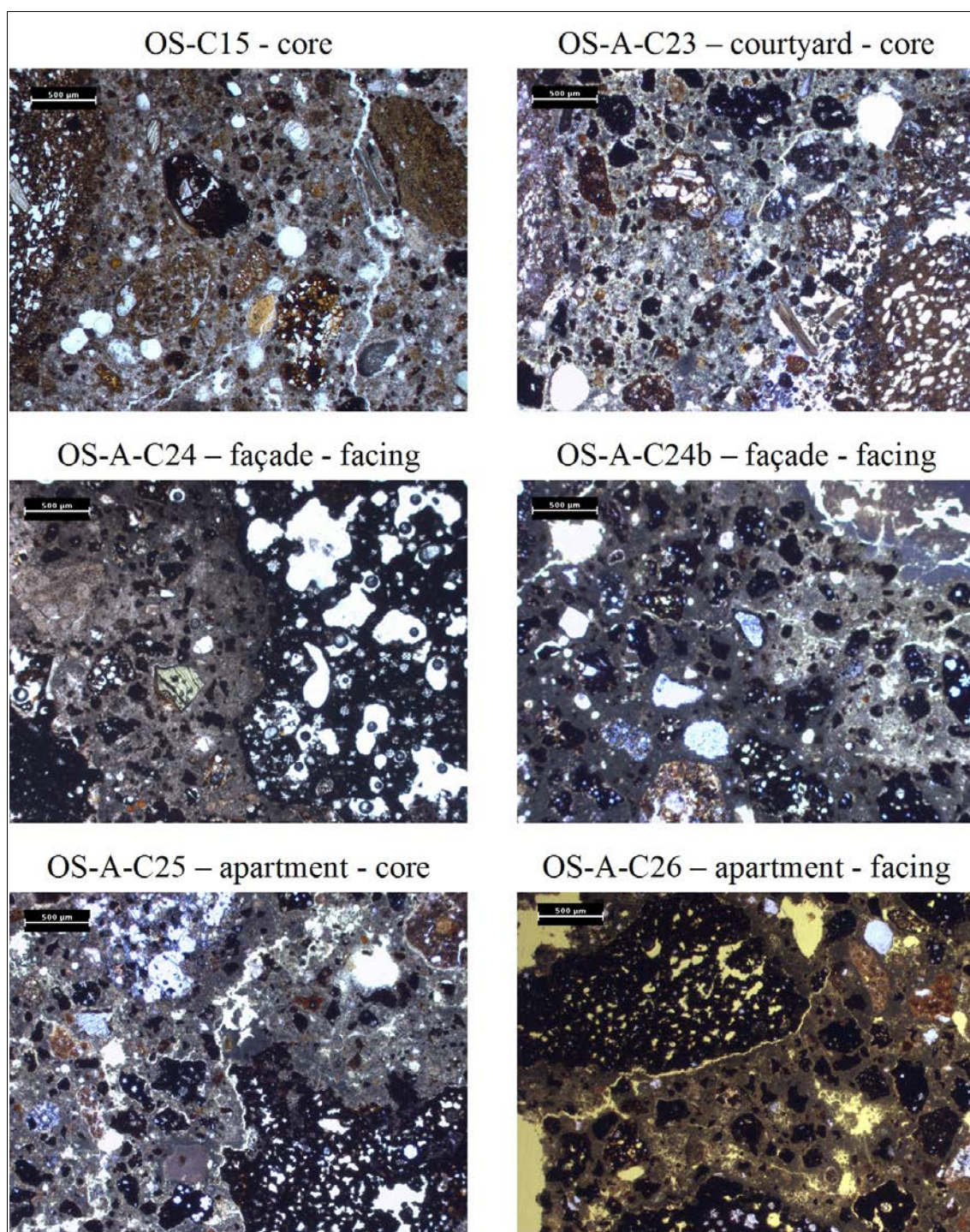
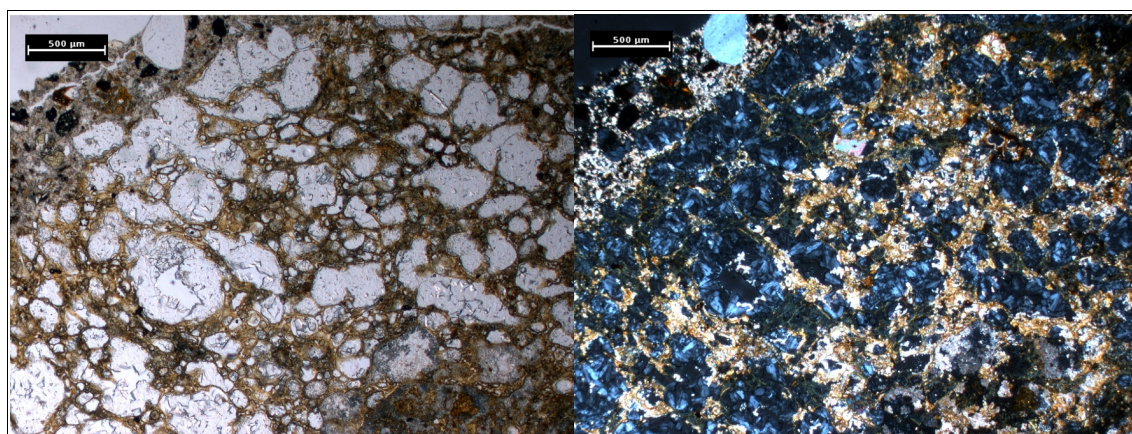


Figure 7.14: Photomicrograph set of mortar samples from the Case a Giardino. All images collected by author in plane polarised light.



A. Plane polarised light.

B. Cross polarised light.

Figure 7.15: Tufo Lionato clast in sample OS-C15 from Case a Giardino, showing numerous zeolites (white in A, grey in B). Photomicrographs collected by author.

Quantification of mortar components with modal analysis suggested the mortars from the Case a Giardino were of variable composition (Figure 7.16, Table 7.2). Pozzolane Rosse aggregates were predominant in the mortars from the central apartment (42.5% of the total count) and in the façade (37.5%). The mortar from the courtyard comprised similar amounts of Pozzolane Rosse (26.6%) and Villa Senni eruptive material (a total of 33.9%), including Pozzolanelle and Tufo Lionato in roughly equal amounts (17.1% and 16.8% respectively). Sample OS-C15 (of unknown provenance) was unique in that it was strongly dominated by Tufo Lionato (56.1%) with all other aggregate types totalling less than 12%, including 7.2% Pozzolane Rosse. In all samples, the majority of the Pozzolane Rosse fragments were from the intermediate alteration facies.

The average binder:void space:aggregate ratio of the mortar from the central apartment was 29.2%:6.2%:67.9% (Table 7.4). The average binder:void space:aggregate ratio of the mortar from the courtyard was 29.4%:6.2%:64.5%. The average binder:void

space:aggregate ratio of the mortar from the façade was 29.6%:6.2%:64.2%. The average binder:void space:aggregate ratio of core sample OS-C15 was 27.4%:4.7%:67.9%, indicating this mortar was slightly less binder-rich than the other samples, with 3-5% more aggregate overall.

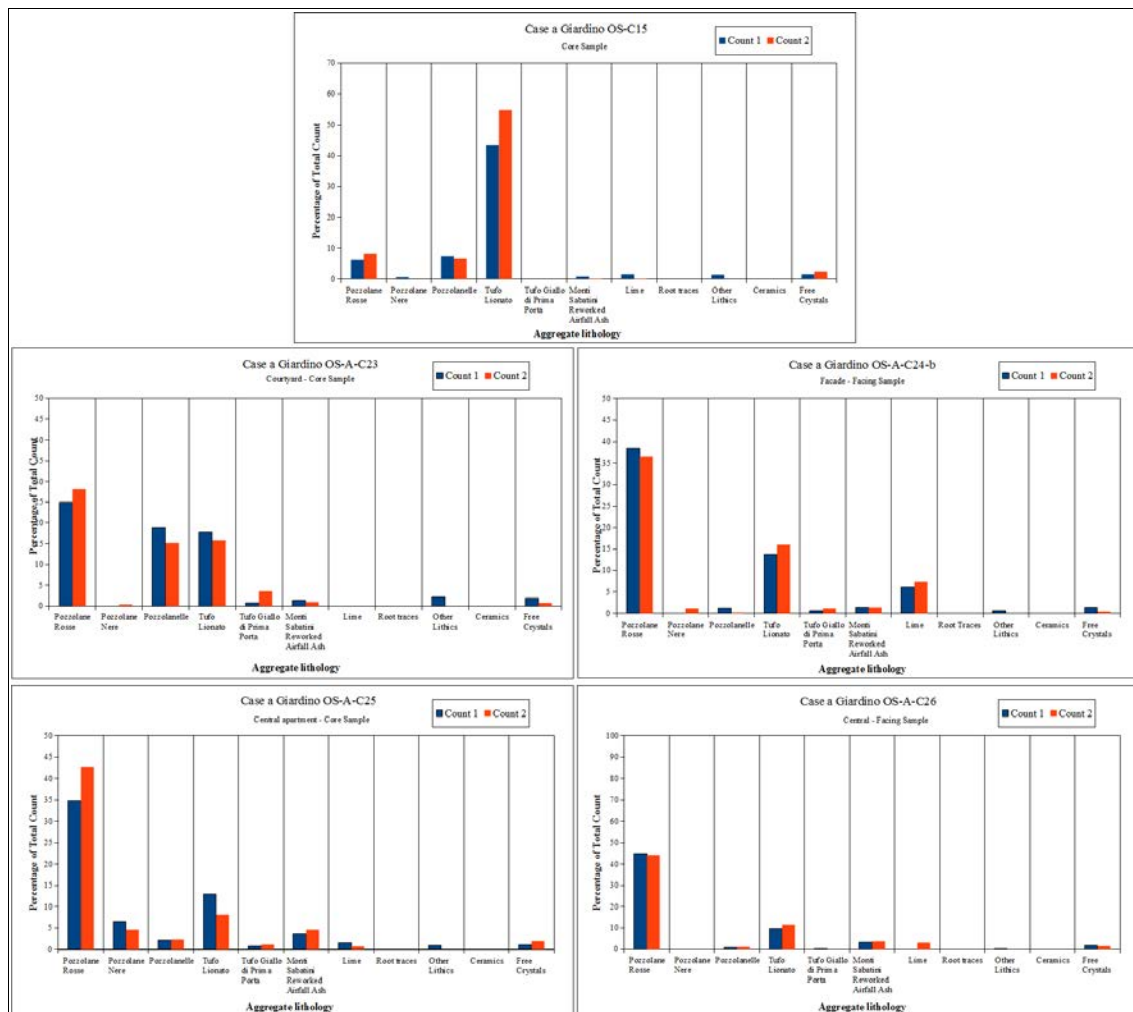


Figure 7.16: Relative proportions of aggregate lithologies from replicated point counts of all usable samples from the Case a Giardino.

7.4.2. Scanning electron microscope analysis

SEM analysis of sample OS-C15 demonstrated that this mortar actually exhibited a fairly porous microstructure, with areas of a “honeycombed” texture, exhibiting more darkened (Si-rich) binder than brightly coloured (Ca-rich) binder throughout the sample. Isolated regions of binder were Ca-rich (Figure 7.17). This mortar exhibited areas of conspicuously thin matrix, consistent with leaching of the binder. Sporadic pores exhibited evidence of redeposited calcite or calcium-rich binder matrix around the edges (Figure 7.18-H).

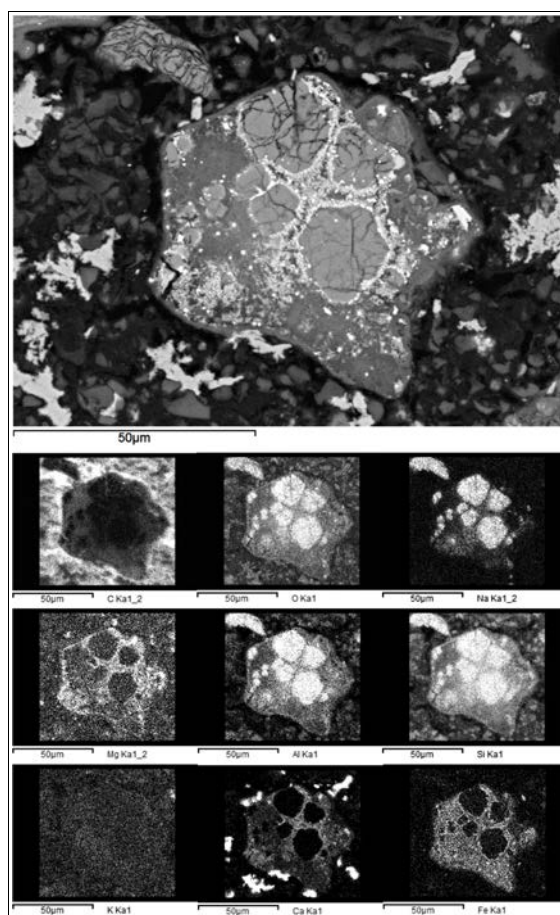


Figure 7.17: Backscattered electron image and element map of core sample OS-C15 showing a fine aggregate particle in a region of binder exhibiting isolated areas of high Ca, with widely distributed Si and K.

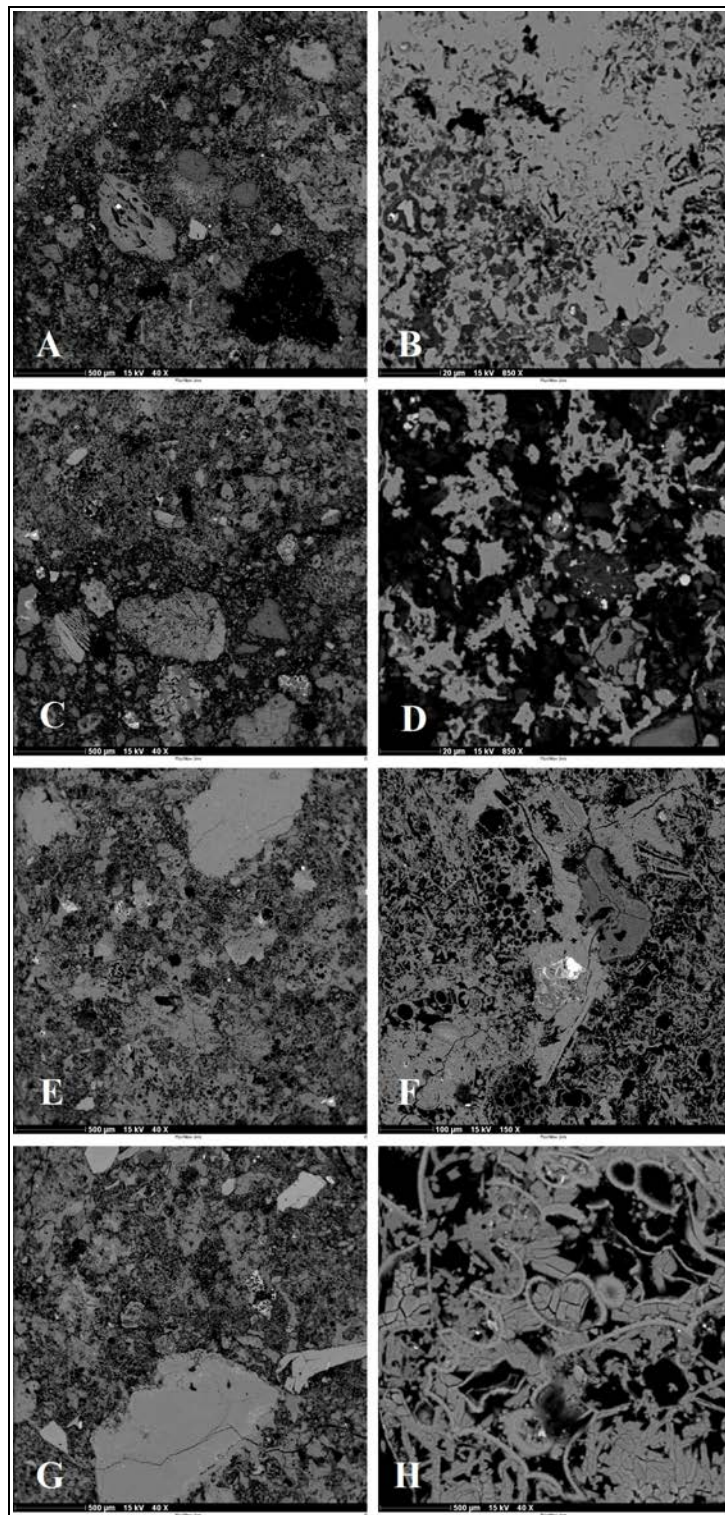


Figure 7.18: Backscatter electron images of mortar sample OS-C15, Case a Giardino, showing general views (A, C, E-H) and highly magnified detail views (B, D) of the mortar binder.

7.4.3. X-ray diffraction analysis

The diffractogram for sample OS-A-C24 (Figure 7.19) illustrates the major phases identified with X-ray diffraction analysis.³⁹⁵ Calcite, analcime, and diopside were the most common minerals present, and their reflections dominated the pattern.

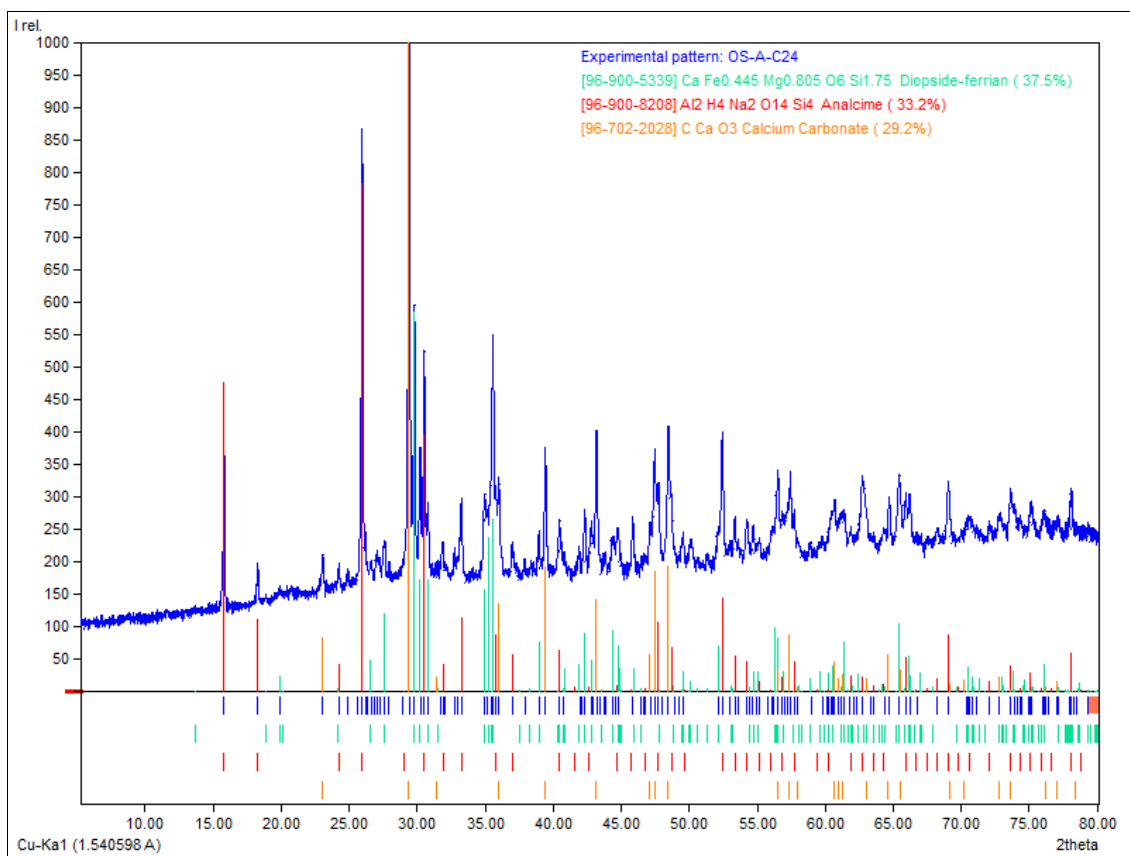


Figure 7.19: X-ray diffractogram of sample OS-A-C24 from Case a Giardino with major peaks labelled.

7.4.4. Image analysis

Particle size distribution determined with image analysis of the thin section of sample OS-C15 is displayed in Figure 7.20 as frequency of minimum Feret diameter.

³⁹⁵ Pattern matching, peak identification, and generation of graphics were completed with Match2 software.

The majority of the aggregate particles were classified as fine silt in size. Small amounts of sand and gravel-sized aggregate particles also were present. Clast size was variable, ranging from sub-millimetre to over 7 mm with a relatively high standard deviation of the minimum Feret diameter (0.25 mm), indicating a poorly-sorted mix of materials. The sample contained a relatively high proportion of rounded particles, with a mean circularity of 0.75, which classifies the particles as moderately circular, according to the classification scheme suggested by Blott and Pye.³⁹⁶

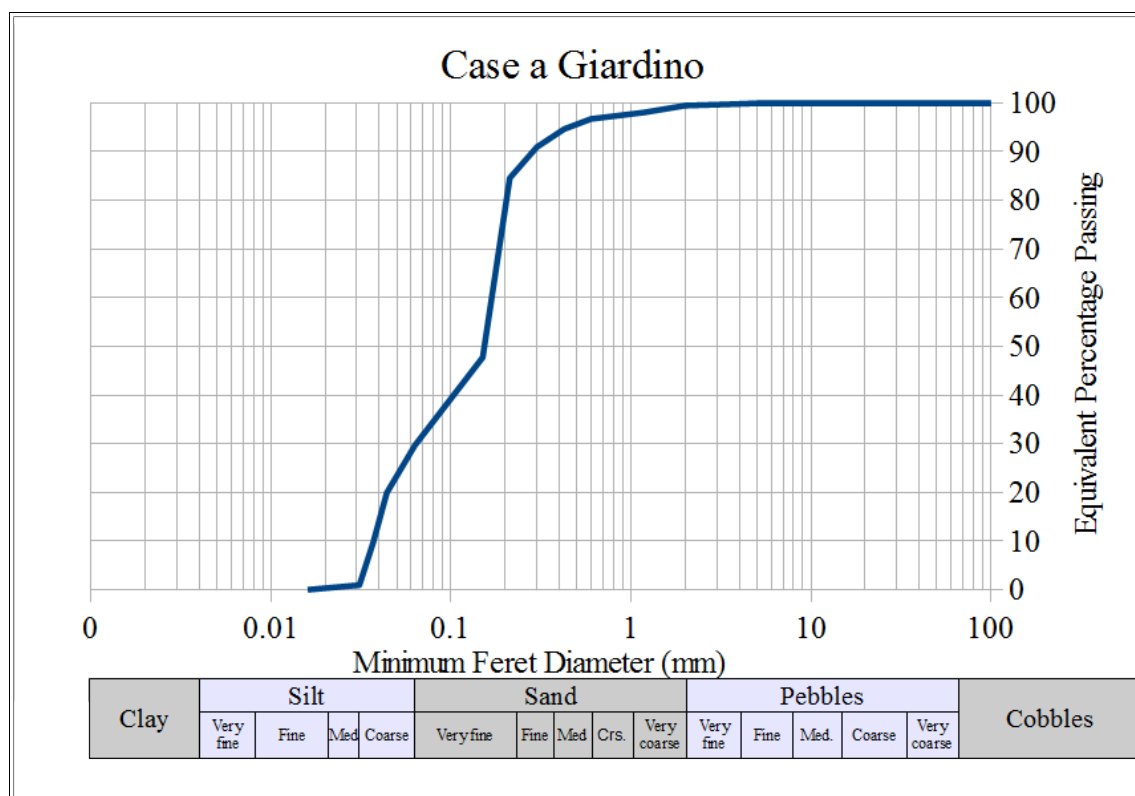


Figure 7.20: Particle size distribution for Case a Giardino, determined from minimum Feret diameter values determined with image analysis.

³⁹⁶ Blott and Pye 2008, 58. The classification scheme suggested by these authors is suggested for particles measured in two dimensions, using Riley 1941.

7.5. *Caseggiato del Serapide – Structure B*

The group of mortars from *Caseggiato del Serapide* included three facing samples (OS-C16, OS-B-C29, OS-B-C30) and two core samples (OS-B-C27, OS-B-C28). The location of sample sites, the colour, and the weight of these samples are reported in Table 7.11. The average fragment weight was less than 1 g for three of the samples, including both core samples and one from the facing. During sample collection, this mortar tended to break up rather easily and in most cases could not be removed in large chunks. The mortar from this structure showed poor cohesion overall.

Table 7.11: Samples from the Caseggiato del Serapide

Sample ID	OS-C16	OS-B-C27	OS-B-C28	OS-B-C29	OS-B-C30
Core or Face	Face	Core	Core	Face	Face
Wall Location	Unknown	Exterior – Outer wall	Interior - Stairwell	Interior – Stairwell	Exterior – Outer wall
Munsell Code	2.5Y 8/1	10YR 8/1	10YR 8/1	2.5Y 8/1	10YR 8/1
Munsell Colour	White	White	White	White	White
Total wt (g)	83.63	23.1	22.14	61.02	25.15
Number of Fragments	16	17	21	59	5
Total Fragment wt (g)	82.24	16.84	19.04	48.05	22.57
Powder wt (g)	1.39	6.32	3.1	12.93	2.58
Average Fragment wt (g)	5.14	0.99	0.91	0.81	4.51

7.5.1. Visual assessments

All samples were white in colour and showed sporadic brownish-yellow alteration. The inclusion density of the mortar was roughly 20% on the interior surface. A number of fragments of greyish-brown scoria (Tufo Giallo di Prima Porta) were visible up to 2.5 cm in size. These aggregate fragments contained grains of clinopyroxene and biotite, and in some cases the vesicles contained either intact zeolites or secondary fibrous cements. Tufo Lionato was visible as both scoria fragments from up to 1 cm (al-

though most were 1-5 mm in size) and as rounded fragments approximately 1 mm. The scoria contained massive clinopyroxene and analcime after leucite. Additional grains of clinopyroxene, biotite, and possible muscovite were loose within the binder along with white lime lumps from 3-5 mm. The voids, most of which were spherical in shape, showed no evidence in hand specimen of the precipitation of binder material.

7.5.2. Thin section and modal analysis

Thin section investigation revealed that the binder was fairly dense and dark in all samples (Figure 7.21). The mortar from Caseggiato del Serapide exhibited an average binder:void space:aggregate ratio of 33.9%:6.1%:60.0% (Table 7.4). This mortar appeared to have low porosity, with relatively little cracking (1.7% of the total count) and few spherical voids. Most of the void space identified (4.7%) was sub-rounded to angular in shape, possibly representing material loss or the decomposition of aggregate clasts. The aggregate comprised mostly large clasts of scoria, many of which contained a great deal of microscoria around the edges and in vesicles. The microscoria, coupled with the strongly altered phenocrysts of clinopyroxene and leucite suggested the clasts themselves were also highly altered. Lime lumps were present as 2.1% of the count.

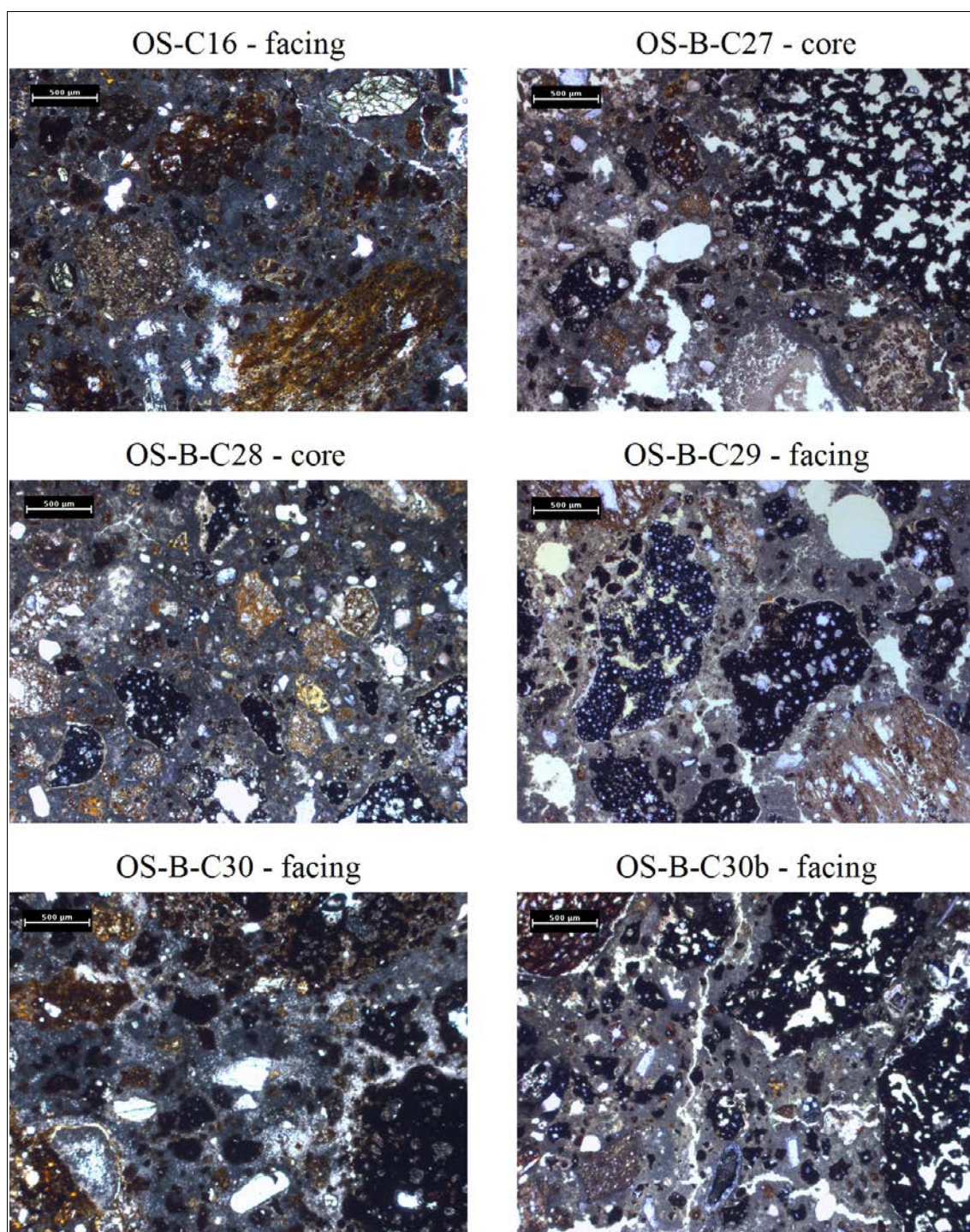


Figure 7.21: Photomicrograph set of representative images from all mortar samples from the Caseggiato del Serapide. All images collected by author in plane polarised light.

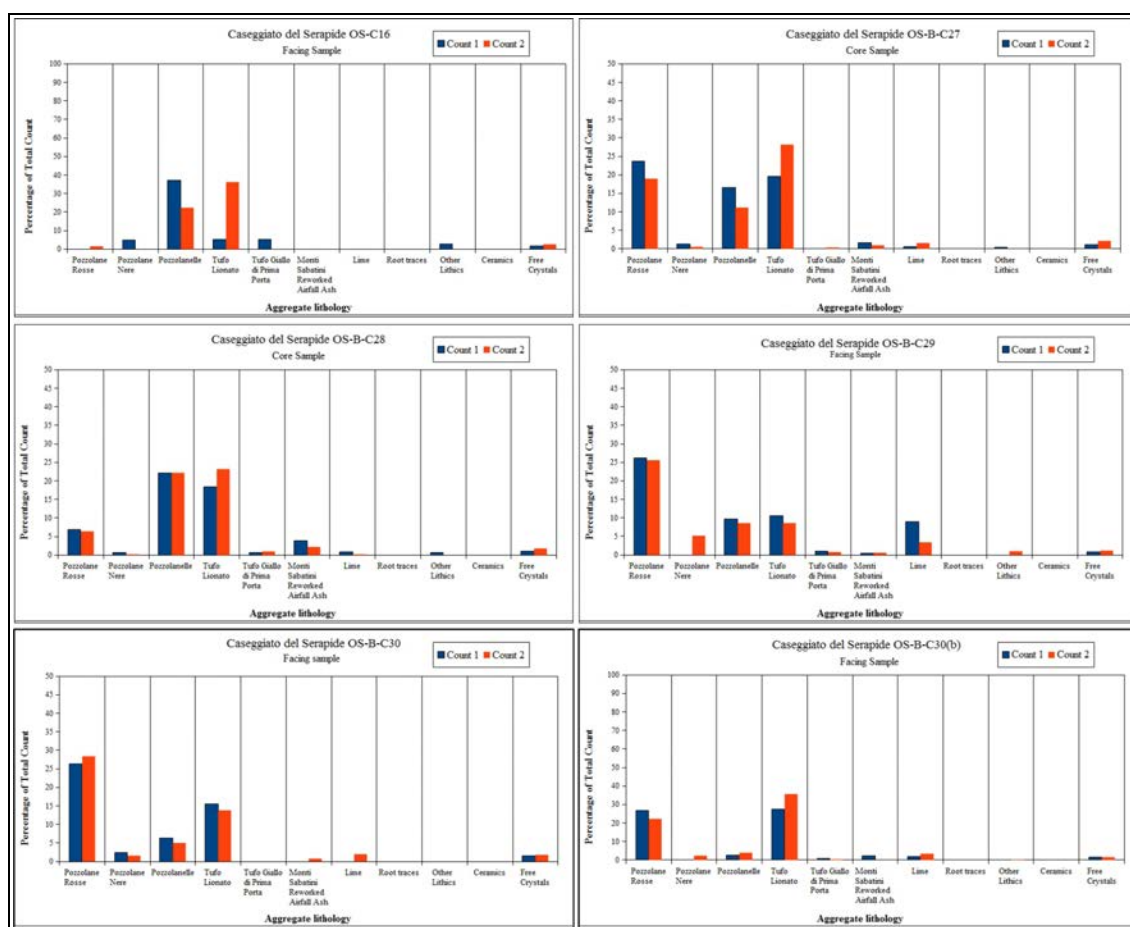


Figure 7.22: Relative proportions of aggregate lithologies from replicated point counts of all samples from the Caseggiato del Serapide.

None of the samples from the Caseggiato del Serapide contained any strongly dominant aggregate lithology (Table 7.2, Figure 7.22). Across all samples from this structure, Tufo Lionato comprised 20.5% of the total count, Pozzolane Rosse was 17.7%, with 14.0% Pozzolanelle, 1.6% Pozzolane Nere, and 6% other inclusions (Tufo Giallo di Prima Porta, MSVD reworked airfall ash, leucitic lava, and loose mineral crystals). All three alteration facies of Pozzolane Rosse were present, with roughly equal amounts of the greatest and intermediate alteration facies (8.1% and 8.5%) and only a trace (1.1%) of the least alteration. The absence of a single strongly dominant lithology

suggested the fine aggregates in this mortar may have been collected from an epiclastic or mixed deposit.

7.5.3. Scanning electron microscopy

SEM analysis of sample OS-C16 from the Caseggiato del Serapide demonstrated that this mortar actually exhibited a fairly dense microstructure, with good cohesion between the binder and the smaller fine aggregate fragments. This mortar sample exhibited more Ca-rich binder than Si-rich binder throughout the sample. Sporadic areas of the binder in this sample exhibited cementitious phases with a fibrous habit (Figure 7.23-B, F).

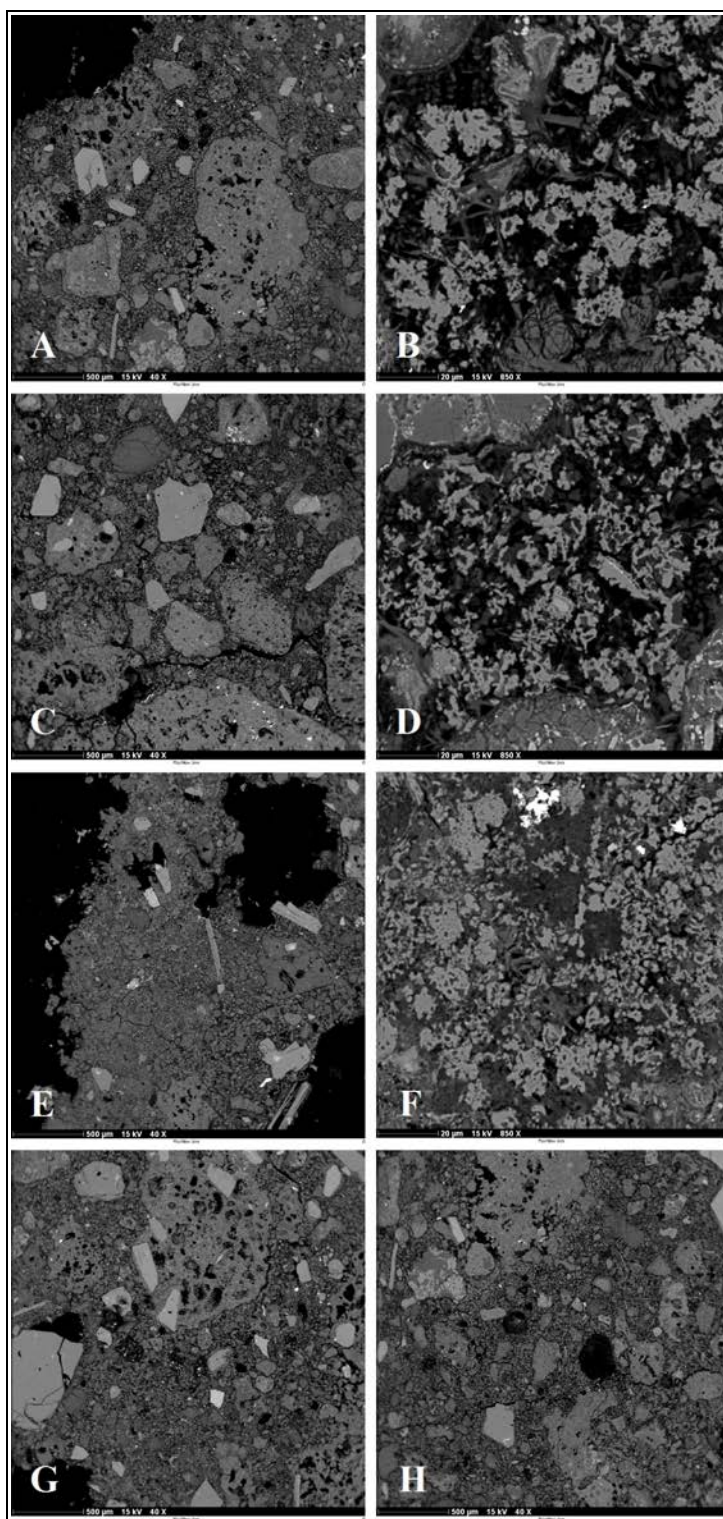


Figure 7.23: Backscatter electron images of mortar sample OS-C16, Caseggiato del Serapide, showing general views (A, C, E-H) and highly magnified detail views (B, D) of the mortar binder.

7.5.4. X-ray diffraction analysis

Figure 7.24 illustrates the reflections of mineral phases in the powdered binder sample from Caseggiato del Serapide (OS-B-C30) identified with XRD analysis. Calcite, analcime, and diopside were major mineral phases in the sample. A small reflection from biotite was also present at $8.89^\circ 2\theta$, most likely a shifted reflection of biotite.

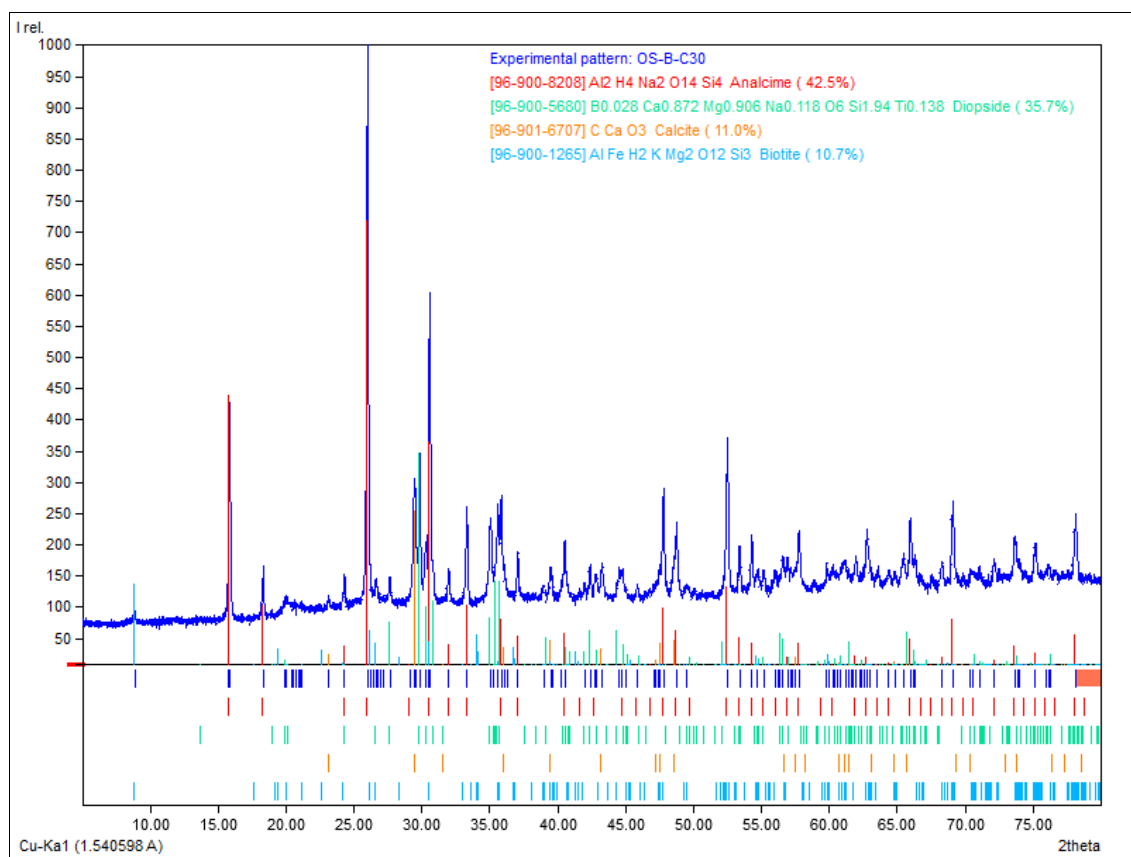


Figure 7.24: X-ray diffractogram of sample OS-B-C30 from the Caseggiato del Serapide with major peaks labelled.

7.5.5. Particle size determinations

Figure 7.25 illustrates the mean Feret diameter of aggregate particles determined from image analysis of the thin section of sample OS-C16. Most particles were silt

sized, exhibiting a mean Feret diameter of 0.12 mm, with occasional gravel fragments up to 13 mm (Figure 7.25, Table 7.9). The standard deviation of this the minimum Feret diameter was 0.25, indicating a relatively poorly sorted assemblage. Image analysis determined the particles were typically well-rounded to sub-angular, with a mean circularity of 0.71, which classifies the fine aggregate particles as moderately circular .³⁹⁷

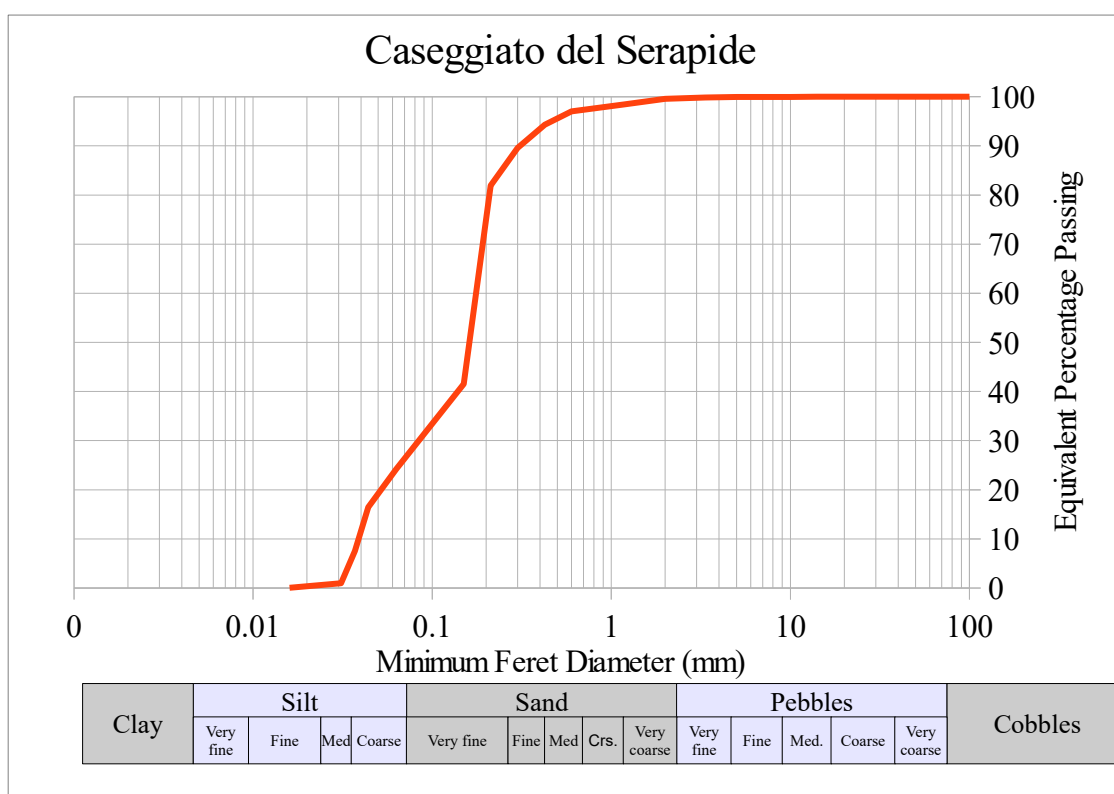


Figure 7.25: Particle size distribution for Caseggiato del Serapide, determined from minimum Feret diameter values determined with image analysis.

³⁹⁷ Blott and Pye 2008, 58.

7.6. Caseggiato del Larario – Structure C

7.6.1. Visual assessments

The sample set from this structure included three core samples (OS-C5, OS-C-C32, OS-C-C34) and two facing samples (OS-C-C31, OS-C-C33). Basic sample collection data, including sample site location, mortar colour, and size of mortar fragments, are listed in Table 7.12. This mortar was relatively cohesive, and all but one of the samples maintained their shape as intact fragments with very little powder. Only sample OS-C-C31, from the facing of an interior wall, broke into fragments that averaged less than 1g. This indicates a well-cohered mortar that was robust even after it was removed from the wall and transported from the site to the lab. All samples were white in colour on the interior, with some visible alteration to a yellowish colour.

Table 7.12. Samples from the Caseggiato del Larario

Sample ID	OS-C5	OS-C-C31	OS-C-C32	OS-C-C33	OS-C-C34
Core or Face	Core	Face	Core	Face	Core
Wall Location	Unknown	Interior – Shop wall	Interior – Shop wall	Exterior - Courtyard	Exterior - Courtyard
Munsell Code	2.5Y 8/1	10YR 8/1	2.5Y 8/1	10YR 8/1	5YR 8/1
Munsell Colour	White	White	White	White	White
Total wt (g)	92.1	16.89	121.15	28.79	13.14
No. Fragments	3	18	1	7	1
Total Fragment wt (g)	91.58	13.95	120.86	27.73	12.38
Powder wt (g)	0.52	2.9	0.59	1.05	0.72
Average Fragment wt (g)	30.53	0.78	120.86	3.96	12.38

The visible inclusion density of the mortar interior was 15-20%. The collection of aggregate inclusions was fairly homogeneous, with only two identifiable types of lithic material, but it was poorly-sorted overall. The size of inclusions ranged from sub-millimetre up to 3 cm. The largest inclusions were reddish grey (5 YR 5/2) fragments of Tufo Lionato that included massive clinopyroxene and biotite phenocrysts; zeolites

were visible in vesicles. Several small leucitic lava fragments were also present. Clinopyroxene and biotite were visible as loose crystal grains within the binder, along with a number of fibrous cement grains. In most cases, binder material was visible as deposits on and within the aggregate clasts, suggesting the in intermixing of the two components during original mortar production. A few lime lumps were visible within the sample but were not overly abundant. The broken edges of the samples contained small rounded holes, most likely due to the loss of material during sample collection.

7.6.2. Thin section and modal analysis

The binder of samples from the Caseggiato del Larario was fairly dense and relatively homogeneous, with relatively low porosity. The mean binder:void space:aggregate ratio was 37.7%:5.7:56.6% (Table 7.4). All samples from this structure exhibited a consistently high binder content (Figure 7.26), especially sample OS-C-C34 which comprised over 50% binder.

The mean void space across all samples was a relatively low 5.7%, however the individual samples varied from 2% - 8%. Sample OS-C5 contained rounded areas of dark, mottled lime binder that filled what had previously been voids formed during initial mortar production (Figure 7.26). These were different to the white lime lumps which were present in this mortar in only trace amounts (less than 1%, Table 7.2), suggesting that they represent transport of the binder material. The low porosity could be attributed to the redeposition of matrix material within these rounded pore spaces.

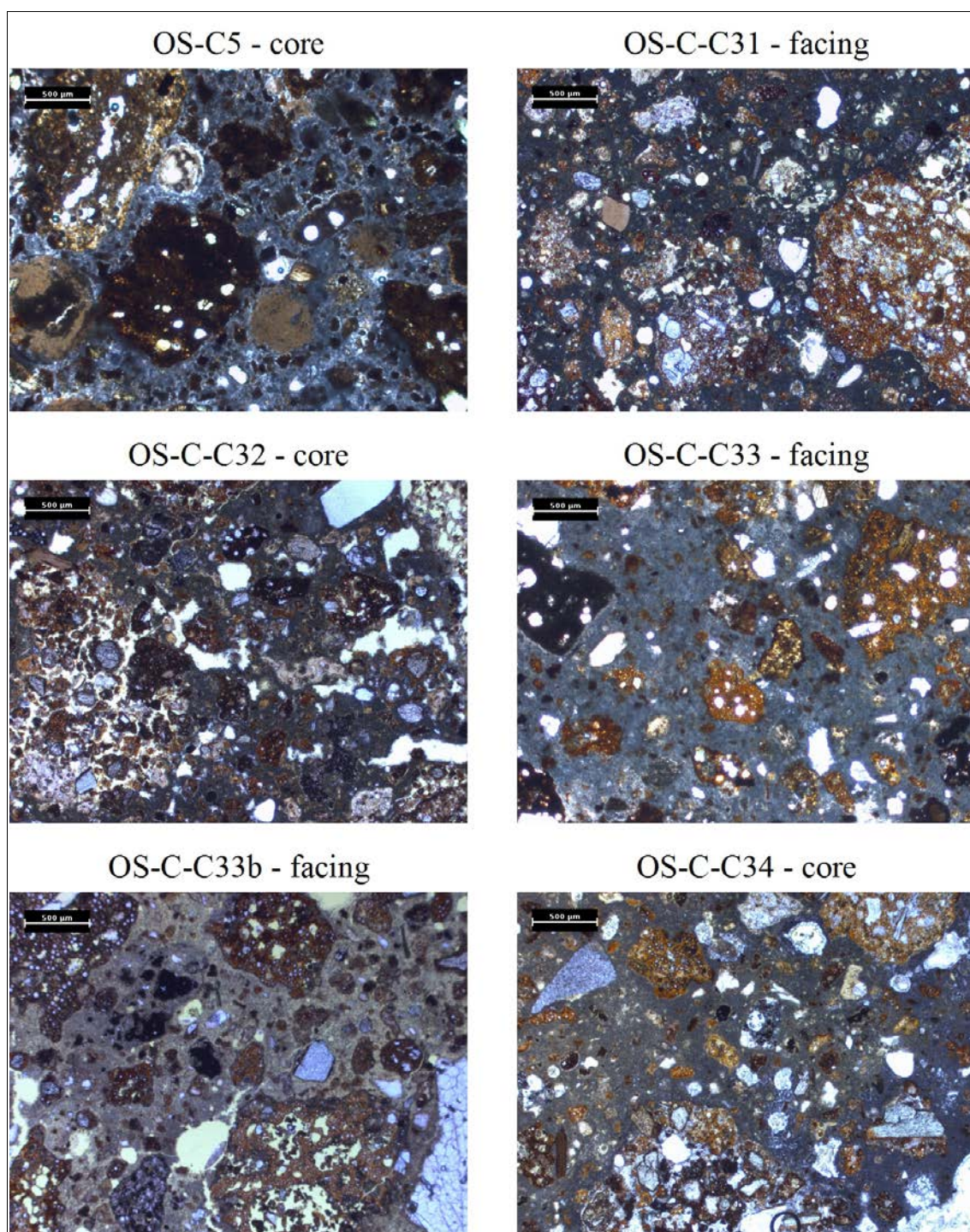


Figure 7.26: Photomicrograph set of representative images from all mortar samples from the Caseggiato del Larario. All images collected by author in plane polarised light.

The fine aggregate profiles of all samples from the Caseggiato del Larario were strongly dominated by Villa Senni eruptive material, including 27% Tufo Lionato (average across all samples from this structure) and 19% Pozzolanelle (Figure 7.27, Table 7.2). Minor proportions of Pozzolane Rosse (3.5%) and traces of Monti Sabatini Reworked Airfall Ash (2%) and Tufo Giallo di Prima Porta (<1%) were also identified. Other inclusions (totalling 3.6), included traces of chert, clay particles, leucitic lava fragments, quartzite, and loose crystal grains. All three alteration facies of Pozzolane Rosse were identified in the mortar from the Caseggiato del Larario, but more than half of the observed particles were of the intermediate alteration facies.

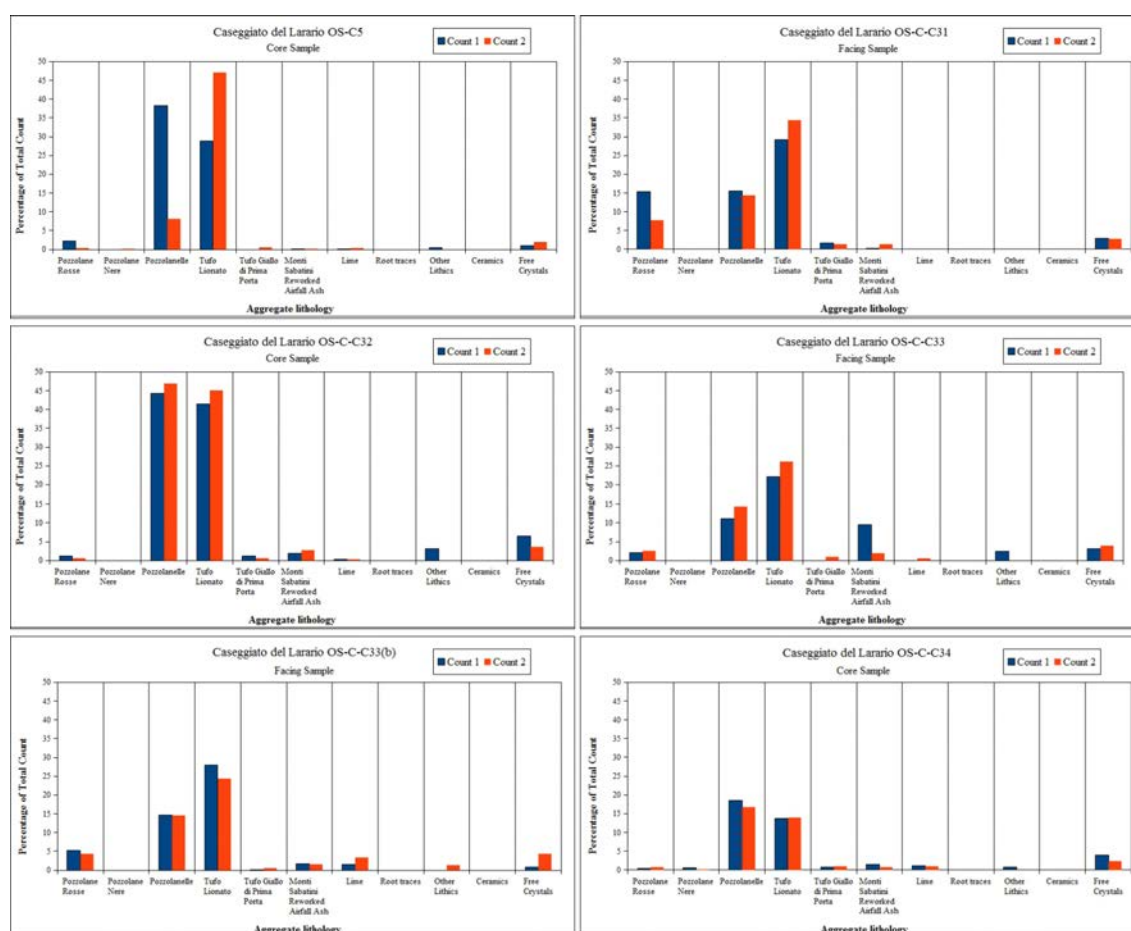


Figure 7.27: Relative proportions of aggregate lithologies from replicated point counts of all samples from the Caseggiato del Larario.

7.6.3. Scanning electron microscopy

SEM analysis of sample OS-C33 from the Caseggiato del Larario demonstrated that this mortar actually exhibited a fairly dense microstructure, with relatively even proportions of darkened (Si-rich) binder as brightly coloured (Ca-rich) binder throughout the sample (Figure 7.28-B, F). The fine aggregate particles exhibited good cohesion with the binder and penetration of the binder into the interfacial zone (Figure 7.28-A, C, H).

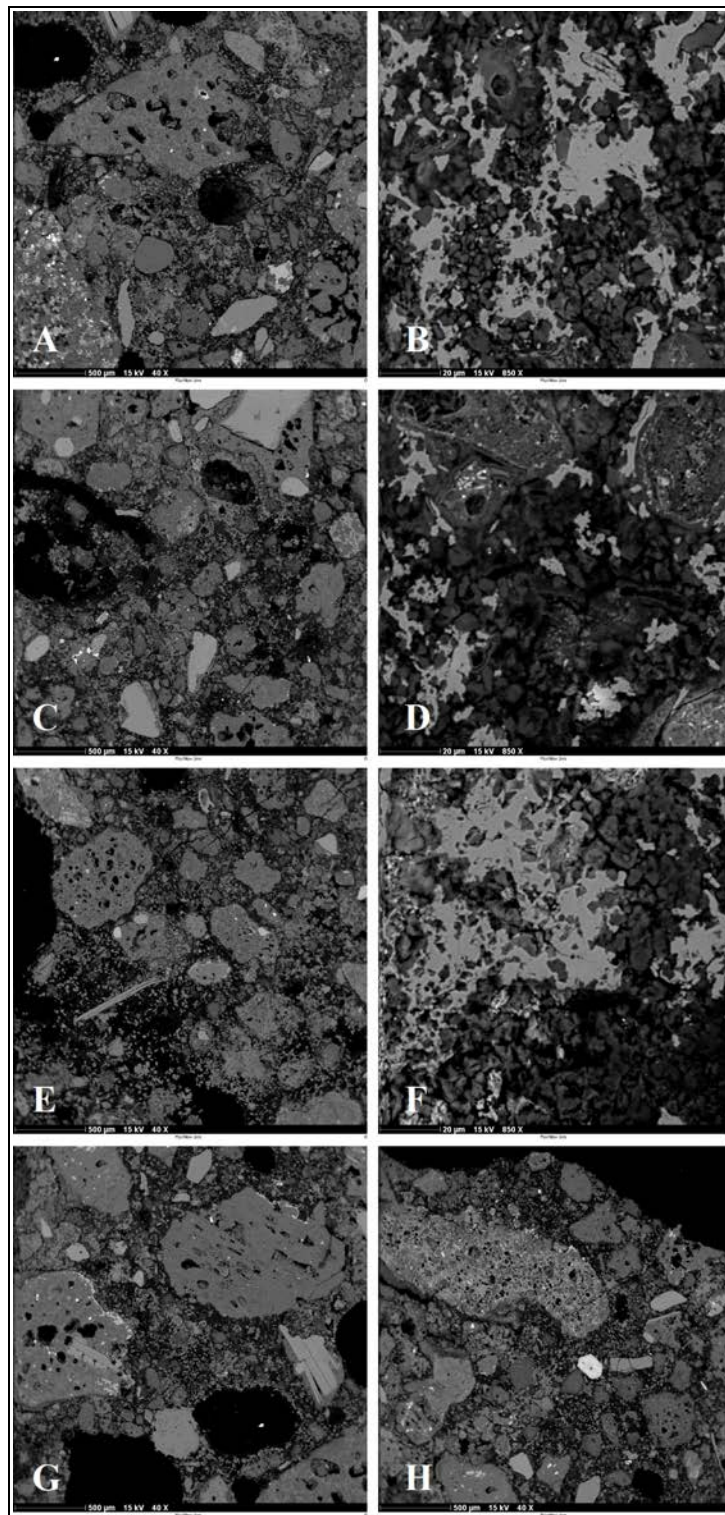


Figure 7.28: Backscatter electron images of mortar sample OS-C33, the Caseggiato del Larario, showing general views (A, C, E, G, H) and highly magnified detail views (B, D, F) of the mortar binder.

7.6.4. X-ray diffraction analysis

X-ray diffraction analysis confirmed major proportions of calcite, analcime, and diopside, with minor proportions of biotite (Figure 7.29).

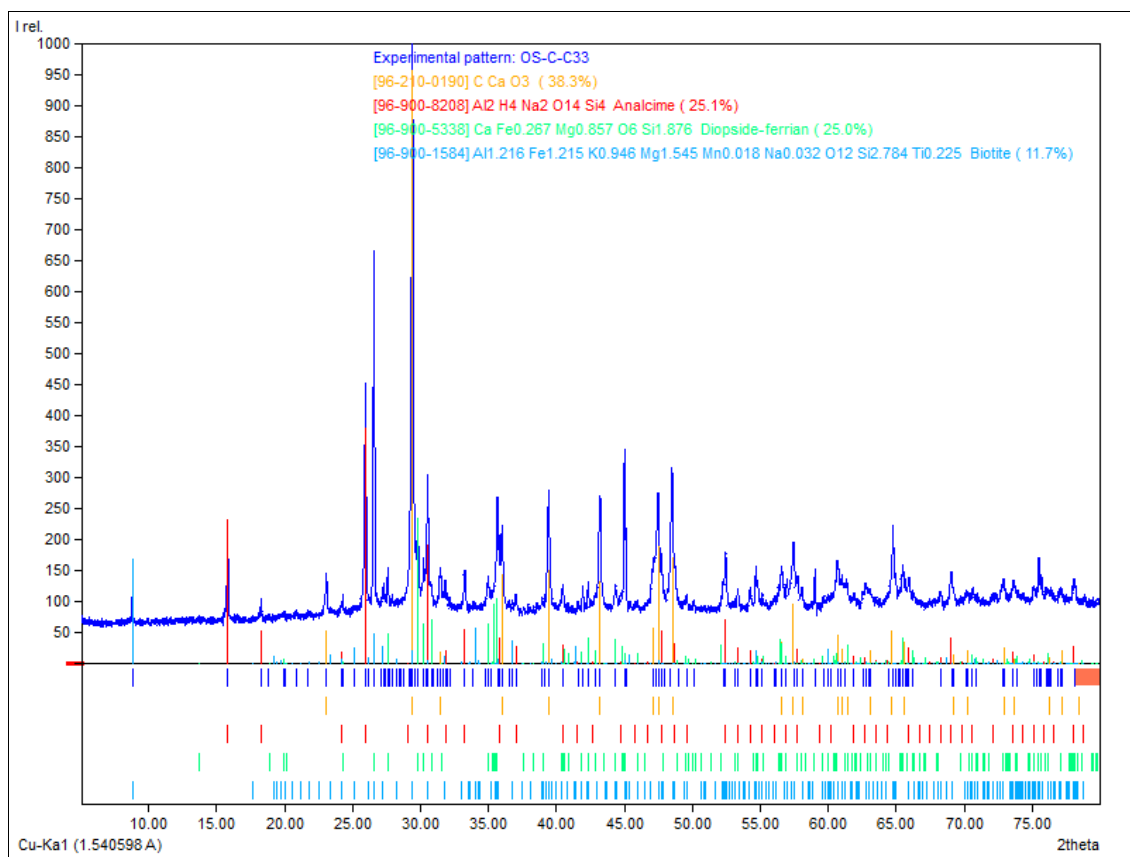


Figure 7.29: X-ray diffractogram of sample OS-C-C33 from the Caseggiato del Larario with major peaks labelled.

7.6.5. Particle size determinations

The majority of particles in sample were silt-sized, with a mean minimum Feret diameter of 0.14 mm, with a high standard deviation of 0.31 (Table 7.9, Figure 7.30). Sand- and pebble-sized particles up to 7.7 mm were also observed, confirming the poorly sorted nature of the fine aggregate. Image analysis determined that the particles

ranged from angular to well-rounded, with a mean value of 0.65, which classifies the particles as moderately circular.³⁹⁸

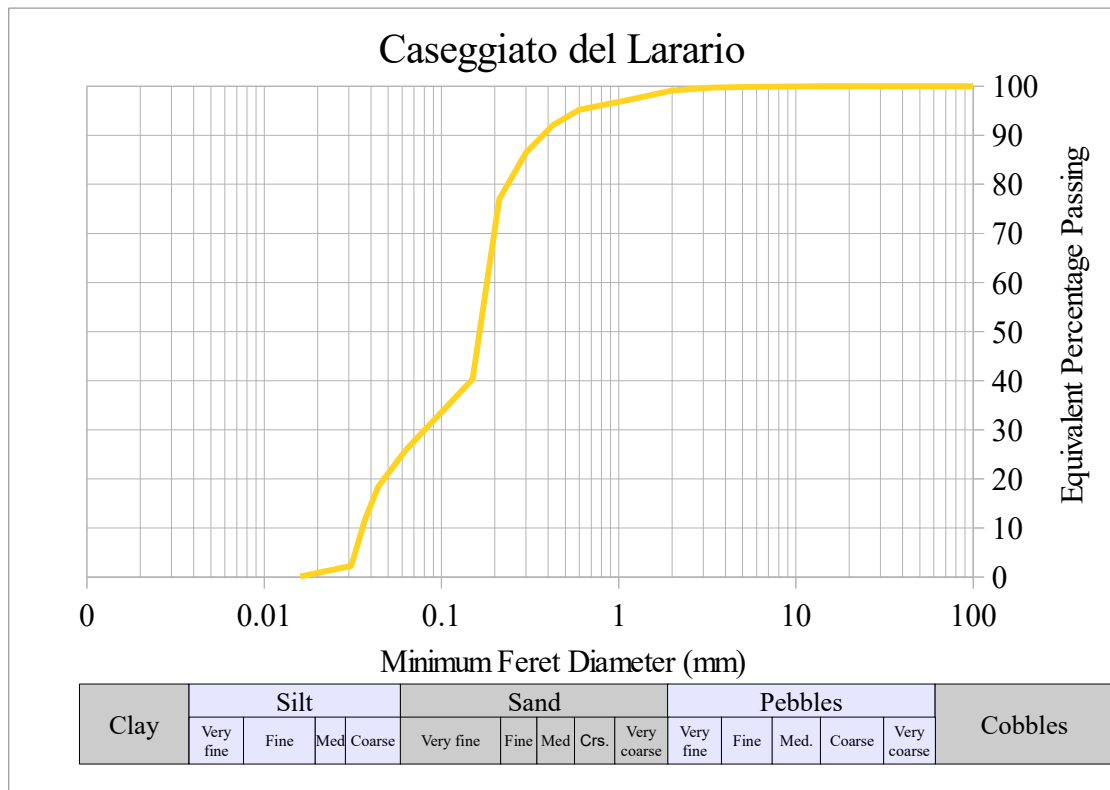


Figure 7.30: Particle size distribution for the Caseggiato del Larario, determined from minimum Feret diameter values determined with image analysis.

³⁹⁸ Blott and Pye 2008, 58.

7.7. Casa Basilicale – Structure D

7.7.1. Visual assessments

During the 2011 field trip, samples from the Casa Basilicale were collected in two locations: a doorway leading from one of the shop rooms on the north side and from the large rectangular room to the south of courtyard. The samples ranged from white to grey in colour with uneven yellowish alteration on the interior and dark-greyish alteration on the surface. The sample fragments exhibited variable cohesion, as some were easily removed in large chunks while others were more difficult to remove, resulting in a higher quantity of small fragments and powder (Table 7.13). The variation was apparently not related to sample location in the core or facing, nor was it related to the wall location. This mortar was quite porous, with voids that extended vertically into the binder, suggesting these were cracks and breaks in the sample rather than material loss. Many of these voids, as well as the spherical voids near the surface, were lined with cementitious material that most likely precipitated secondarily from fluids moving through the mortar.

Table 7.13. Samples from the Casa Basilicale

Sample ID	OS-C3	OS-D-C35	OS-D-C36	OS-D-C37	OS-D-C38
Core or Face	Core	Core	Face	Face	Core
Wall Location	Unknown	Interior – South Room	Interior – South Room	Exterior - Courtyard	Exterior - Courtyard
Munsell Code	Gley 1 8/1	Gley 1 7/1	5Y 6/1	2.5Y 6/1	Gley 1 7/1
Munsell Colour	White	Light Grey	Grey	Grey	Light Grey
Total wt (g)	119.66	47.58	38.7	85.5	13.76
No. Fragments	2	31	45	8	12
Total Fragment wt (g)	109.73	32.06	28.43	82.44	10.24
Powder wt (g)	9.93	15.41	10.57	2.93	3.47
Average Fragment wt (g)	54.87	1.03	0.63	10.31	0.85

The mortar from the Casa Basilicale exhibited an apparent inclusion density of 15-20% on the interior surface of the samples, with an apparent average particle size of approximately 2 mm. Pozzolane Rosse up to 1.5 cm, sub-millimetre Tufo Lionato, Monti Sabatini Reworked Airfall Ash clasts of 1-2 mm, and Pozzolanelle of 1-2 mm were identifiable with the stereoscope. Loose grains of clinopyroxene and biotite were present within the binder. The aggregate particles, including both the lithic clasts and crystal grains, appeared to be coated in small nodules of binder, suggesting good cohesion in the interfacial zones of the aggregate.

7.7.2. Thin section and modal analysis

The binder of this mortar contained distinct regions of under-processed lime that contained clay, calcites, and small mineral grains. All samples contained large white pebble lime clasts that were poorly bonded to the binder, with cracking around the perimeter. Authigenic calcite was evident in sample OS-C3. Linear cracking was evident in all samples, but most of the open space was in the form of sub-rounded to angular voids. The morphology of the void space was consistent with loss of mortar during sample preparation, most likely due to the poor cohesion of the material. The mortar exhibited a binder:void space:aggregate ratio of 31.3%:6.7%:62.0% (Table 7.4).

Thin section analysis confirmed the aggregate profile was dominated by Pozzolane Rosse (47.2% of the total count across all samples from the structure) with minor proportions of Villa Senni eruptive material, 4.7% Tufo Lionato and 1.4% Pozzolanelle (Table 7.2, Figure 7.32). Other fine aggregate particles were present in only trace amounts, including loose mineral grains (2.4%), Tufo Giallo di Prima Porta (1.7%), and

Monti Sabatini Reworked airfall ash, (1.4%), with rare chert, leucitic lava fragments, quartzite, and clay particles (totalling 0.9%). All three alteration facies were present in this mortar, but the highest proportion by far was the intermediate alteration facies. Point counting further revealed that the composition of the mortar samples from the Casa Basilicale was fairly consistent (Figure 7.32).

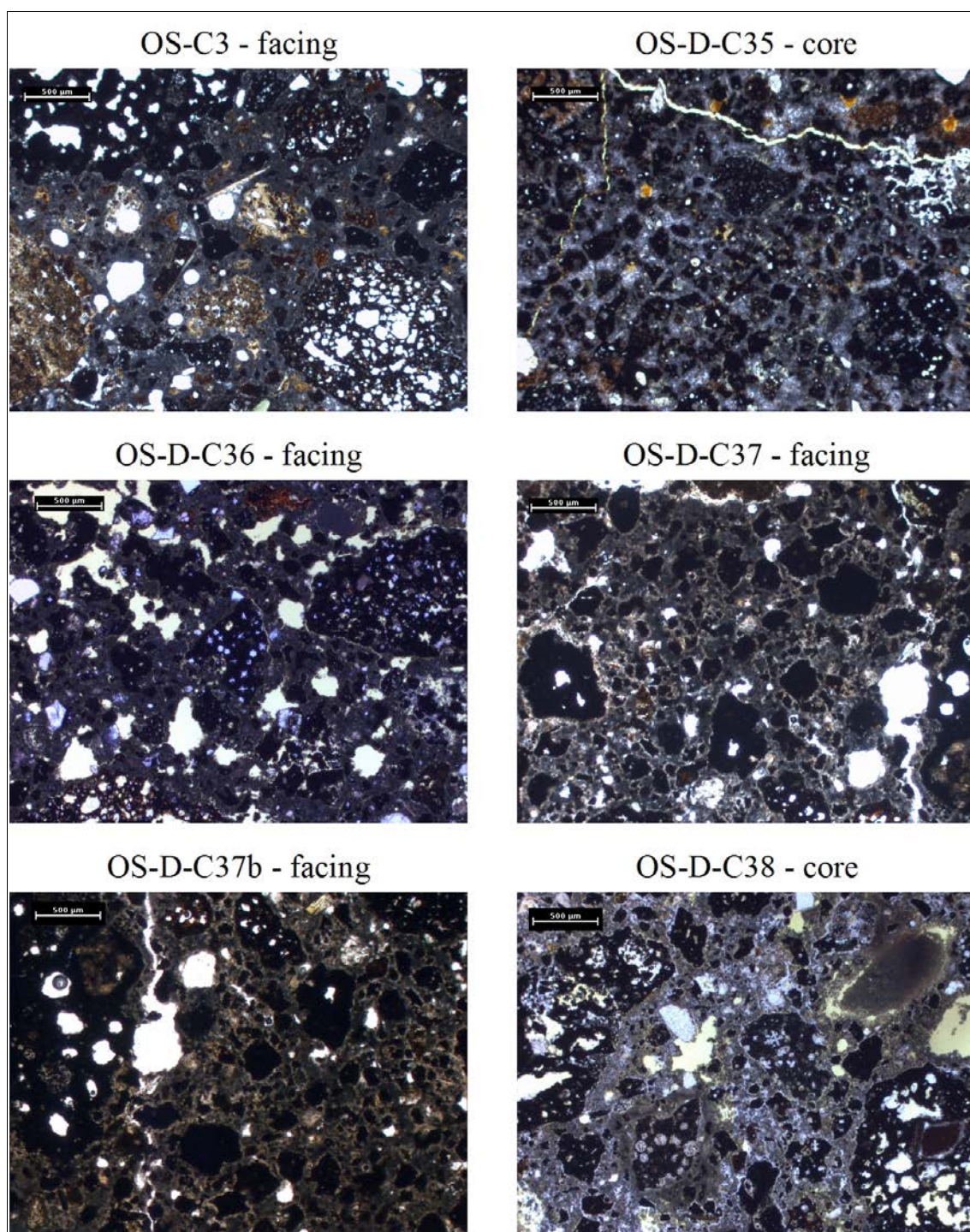


Figure 7.31: Photomicrograph set of representative images from all mortar samples from the Casa Basilicale. All images collected by author in plane polarised light.

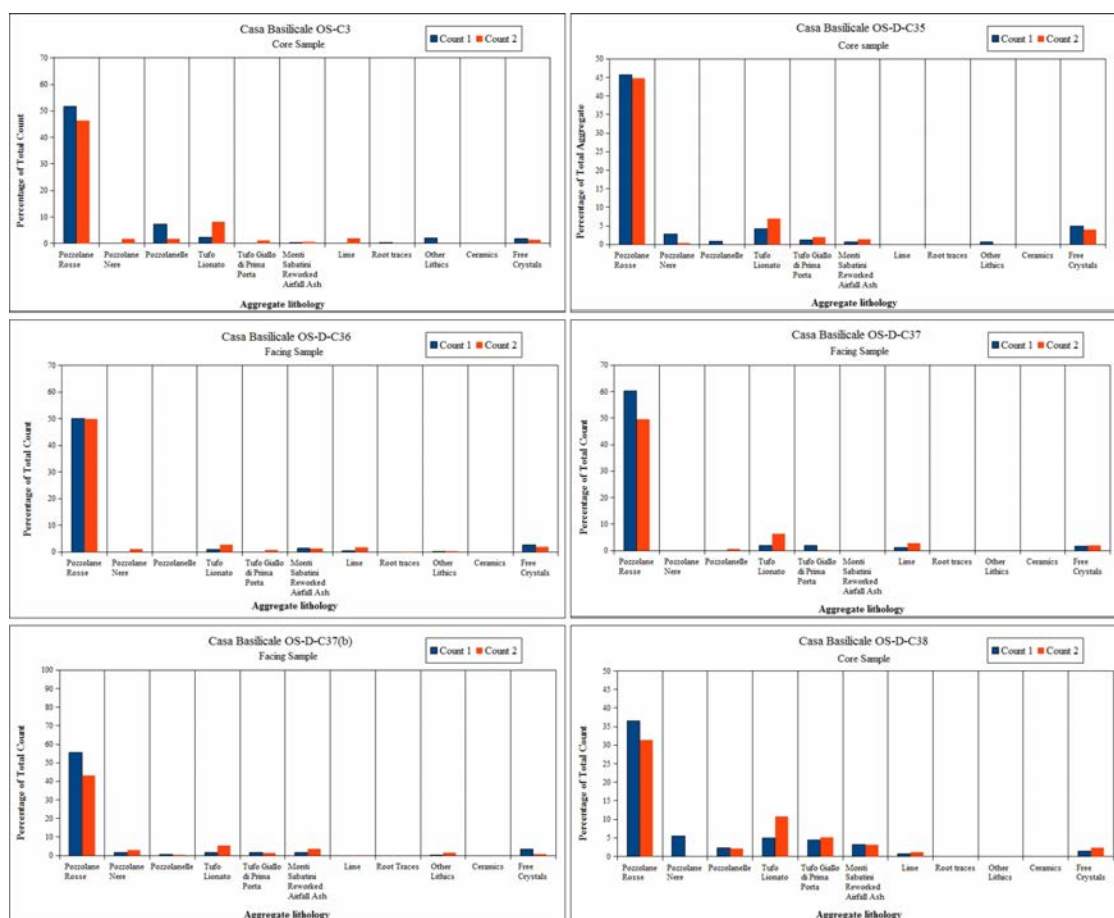


Figure 7.32: Relative proportions of aggregate lithologies from replicated point counts of all samples from the Casa Basilicale.

7.7.3. Scanning electron microscopy

SEM analysis of sample OS-C3, the Casa Basilicale, demonstrated that this mortar actually exhibited a fairly consistent composition, with relatively even proportions of darkened (Si-rich) binder and brightly coloured (Ca-rich) binder throughout the sample (Figure 7.33-B, D). The fine aggregate particles exhibited good cohesion with the binder and penetration of the binder into the interfacial zone (Figure 7.33-A, C, H). Fine

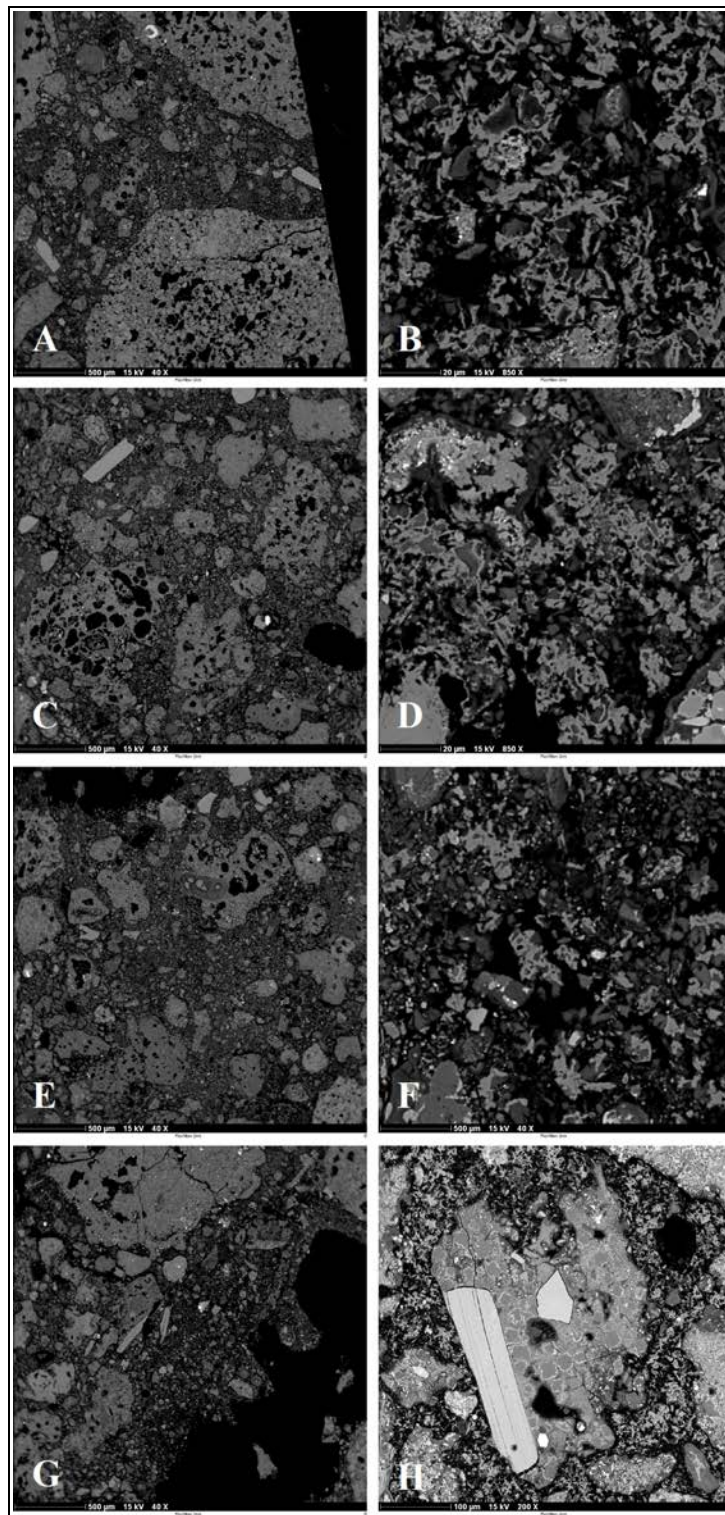


Figure 7.33: Backscatter electron images of mortar sample OS-C3, the Casa Basilicale, showing general views (A, C, E-H) and highly magnified detail views (B, D) of the mortar binder.

cracks were present in sporadic fine aggregate particles, but these cracks typically did not extend into the binder.

7.7.4. X-ray diffraction analysis

In keeping with the previous samples, XRD verified the presence of major calcite, analcime, and diopside, with minor biotite (Figure 7.34).

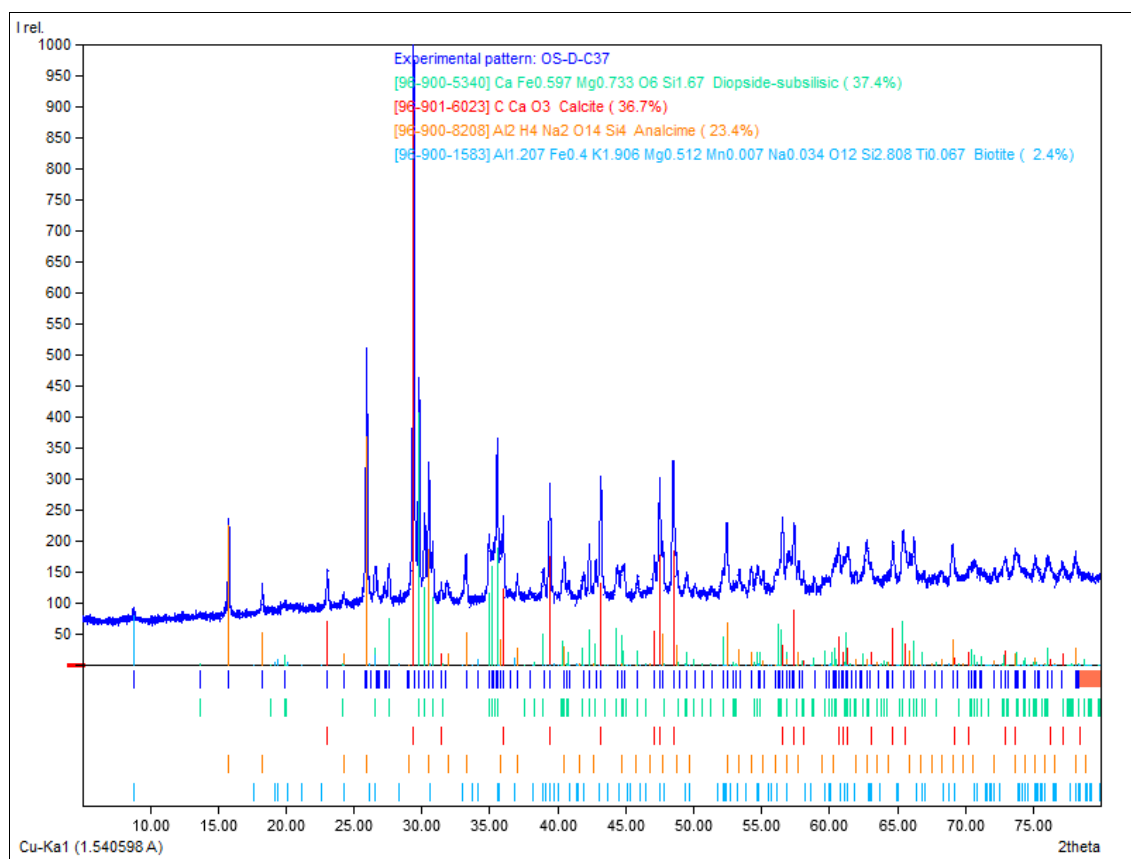


Figure 7.34: X-ray diffractogram of sample OS-D-C37 from the Casa Basilicale with major peaks labelled.

7.7.5. Particle size determinations

Most of the aggregate was silt-sized, with a maximum measured minimum Feret diameter of 6.6 mm (Figure 7.35, Table 7.9). The standard deviation of the minimum Feret diameter was 0.20, indicating a moderately sorted assemblage. Image analysis determined the particles were typically well-rounded to sub-angular, with a mean circularity of 0.68, which classifies the fine aggregate particles as primarily moderately circular.³⁹⁹

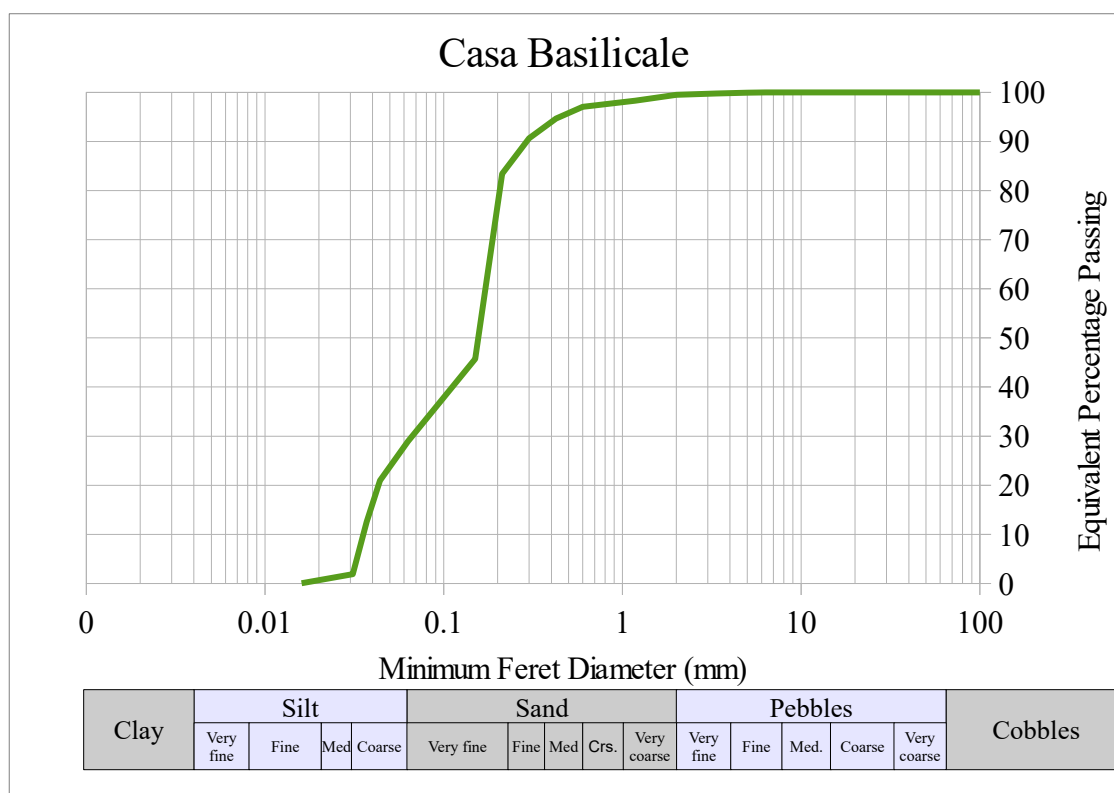


Figure 7.35: Particle size distribution for the Casa Basilicale, determined from minimum Feret diameter values determined with image analysis.

³⁹⁹ Blott and Pye 2008, 58.

7.8. *Piccolo Mercato – Structure E*

7.8.1. *Visual assessments*

The set of samples from the Piccolo Mercato comprised two core samples (OS-C1, OS-E-C40) and three facing samples (OS-E-C39, OS-E-C41, OS-E-C42) taken from the behind the structure's northern façade and from a wall facing a central courtyard. This mortar was fairly friable, and the samples crumbled to a high number fragments with a low average sample weight, ranging from 0.45 g – 1.76 g. (Table 7.14). This mortar was white or light grey, with no obvious yellow alteration of the binder.

Table 7.14. Samples from the Piccolo Mercato

Sample ID	OS-C1	OS-E-C39	OS-E-C40	OS-E-C41	OS-E-C42
Core or Face	Core	Face	Core	Face	Core
Wall Location	Exterior-Courtyard	Interior – Behind façade	Exterior - Courtyard	Exterior-Courtyard	Interior– Behind façade
Munsell Code	2.5Y 8/1	7.5YR 7/1	2.5Y 7/1	10YR 8/1	7.5YR 8/1
Munsell Colour	White	Light Grey	Light Grey	White	White
Total wt (g)	31.92	33.19	20.4	12.25	33.6
No. Fragments	10	39	28	9	43
Total Fragment wt (g)	17.63	20.5	12.52	10.82	23.38
Powder wt (g)	14.29	12.7	7.88	1.37	10.22
Average Fragment wt (g)	1.76	0.53	0.45	1.2	0.54

The inclusion density of the Piccolo Mercato mortar was estimated to be 30 – 40%, and the particles appear well-sorted with a fairly uniform size. Both Pozzolane Rosse and Pozzolanelle were identifiable with the low power microscope, and both types of material were fairly uniform in size. Although the largest visible aggregate fragments were approximately 1 cm sized, most of the visible inclusions were approximately 0.25 mm.

7.8.2. Thin section and modal analysis

The binder of this mortar was primarily dense and dark, with visible fine cracks and densely packed aggregates. Fine aggregate particles were typically coated with small white nodules of material from the binder. Larger lime lumps were present in this mortar, primarily over-burnt lime (Figure 7.36), and in some cases these lumps were coated with sub-millimetre chips of volcanic glass, mica, and clinopyroxene crystals. The mortar exhibited an average binder:void space:aggregate ratio of 31.2%:5.7%:63.1% (Table 7.4). The void spaces comprised minor proportions of sub-rounded to angular voids, which accounted for 4.6% of the total count in both samples, and moderate cracking (1.1%).

Modal analysis revealed the mortar was strongly dominated by Pozzolane Rosse aggregate (46.1% of the total count across all samples), with minor additions of Villa Senni eruptive materials, including 4.4% Tufo Lionato and 0.3% Pozzolanelle (Table 7.2, Figure 7.37). This mortar comprised a mean proportion of 3.7% Monti Sabatini Re-worked Airfall Ash and 1.4% Tufo Giallo di Prima Porta. The Pozzolane Rosse in these samples were fairly altered and dominated by the intermediate alteration facies (Figure 7.36).

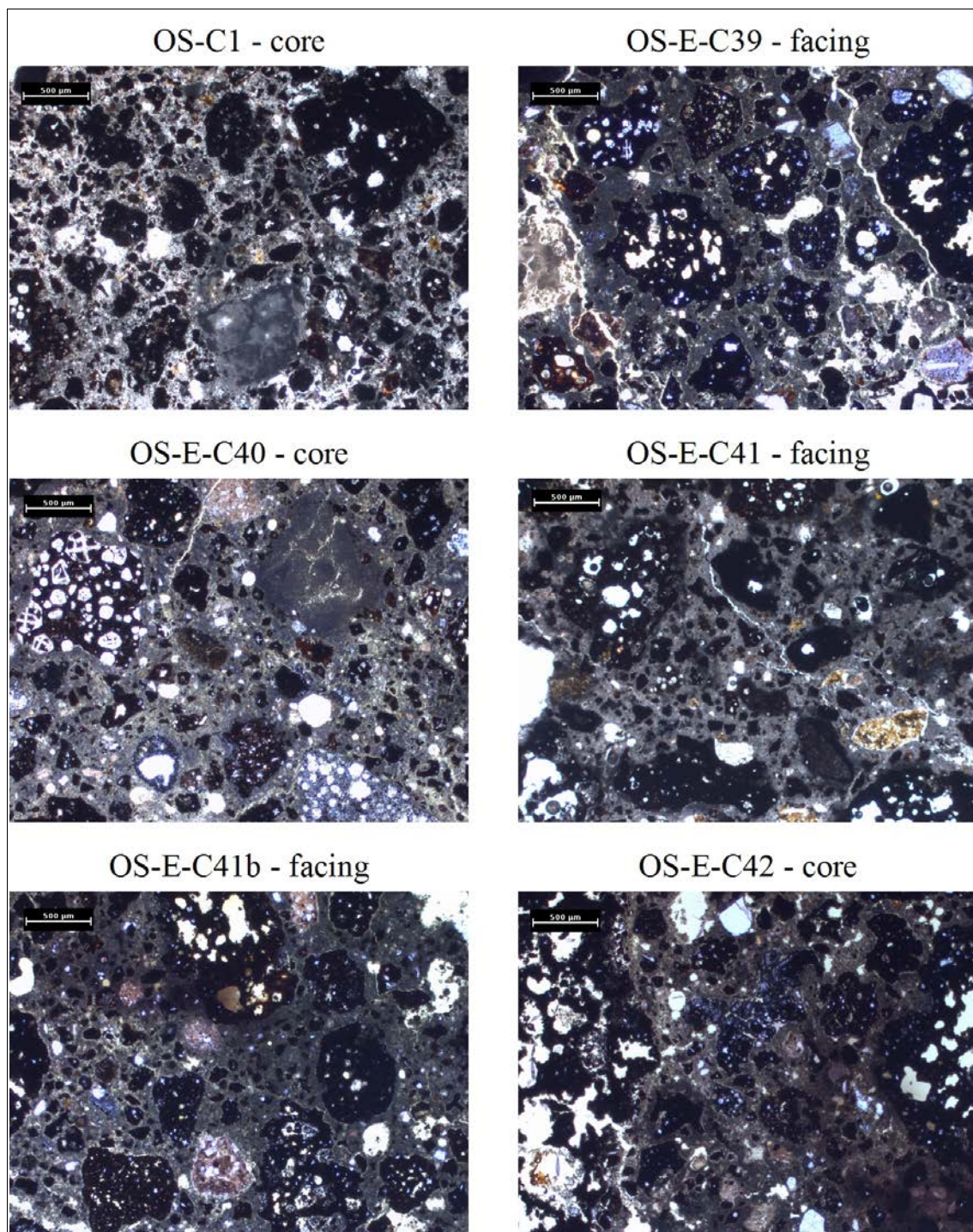


Figure 7.36: Photomicrograph set of representative images from all mortar samples from the Piccolo Mercato. All images collected by author in plane polarised light.

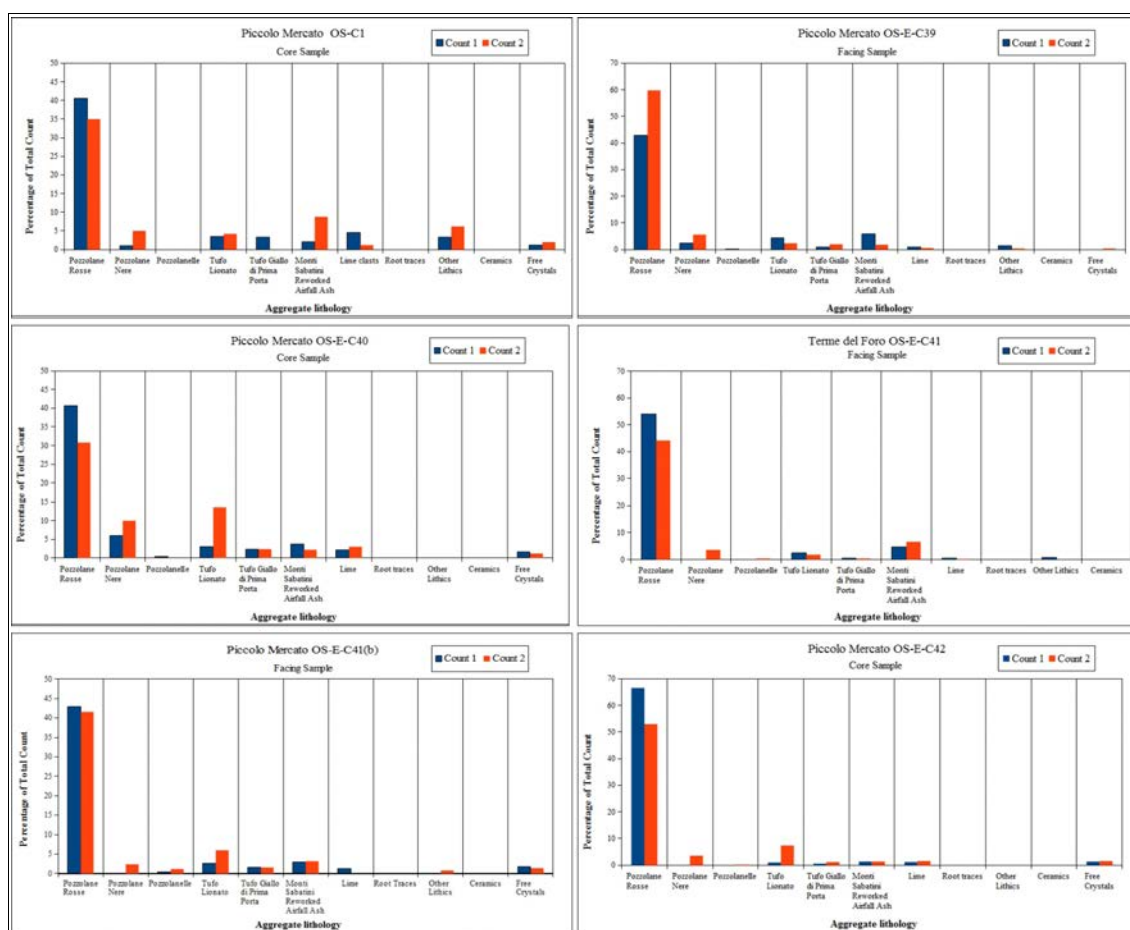


Figure 7.37: Relative proportions of aggregate lithologies from replicated point counts of all samples from the Piccolo Mercato.

7.8.3. Scanning electron microscopy

SEM analysis of sample OS-C1 from the Piccolo Mercato revealed that the binder was relatively calcite-rich, with only limited leaching of the calcitic binder and low silica content (Figure 7.38). A broken lime particle contains relatively high magnesium that has not been widely incorporated into the binder (Figure 7.38-Mg K1). The fine aggregate particles commonly exhibited parting from the binder (Figure 7.39-C).

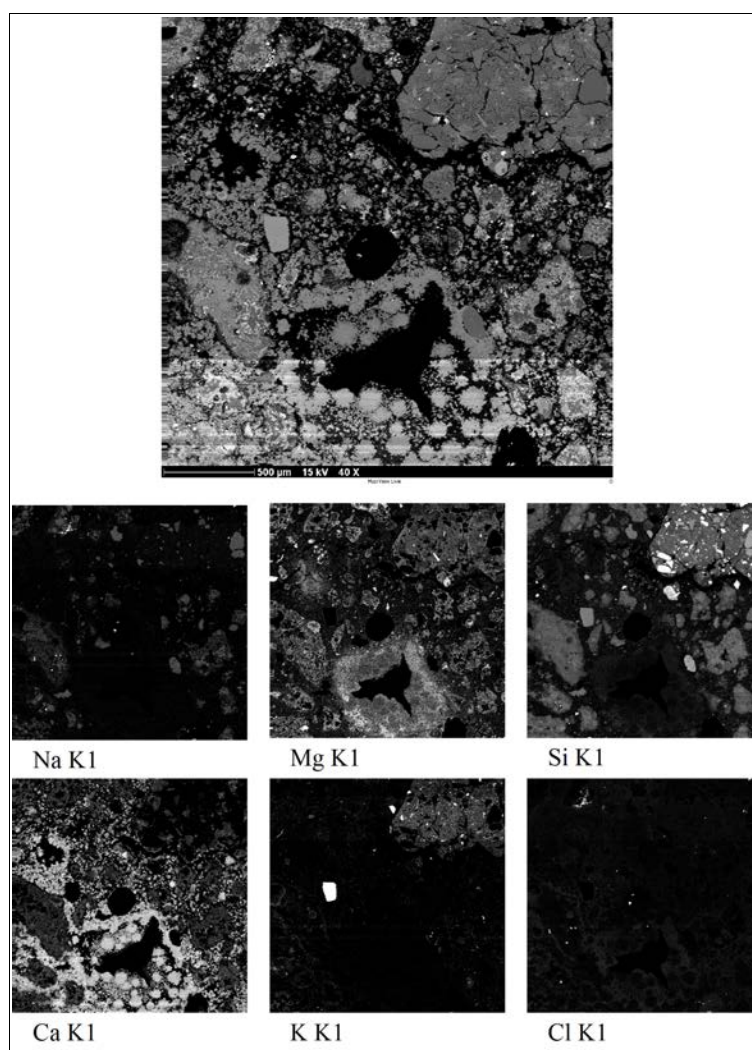


Figure 7.38: SEM image and element maps of sample OS-C1 from the Piccolo Mercato, showing the variation in binder composition and a lime lump with a high magnesium content (Mg K1).

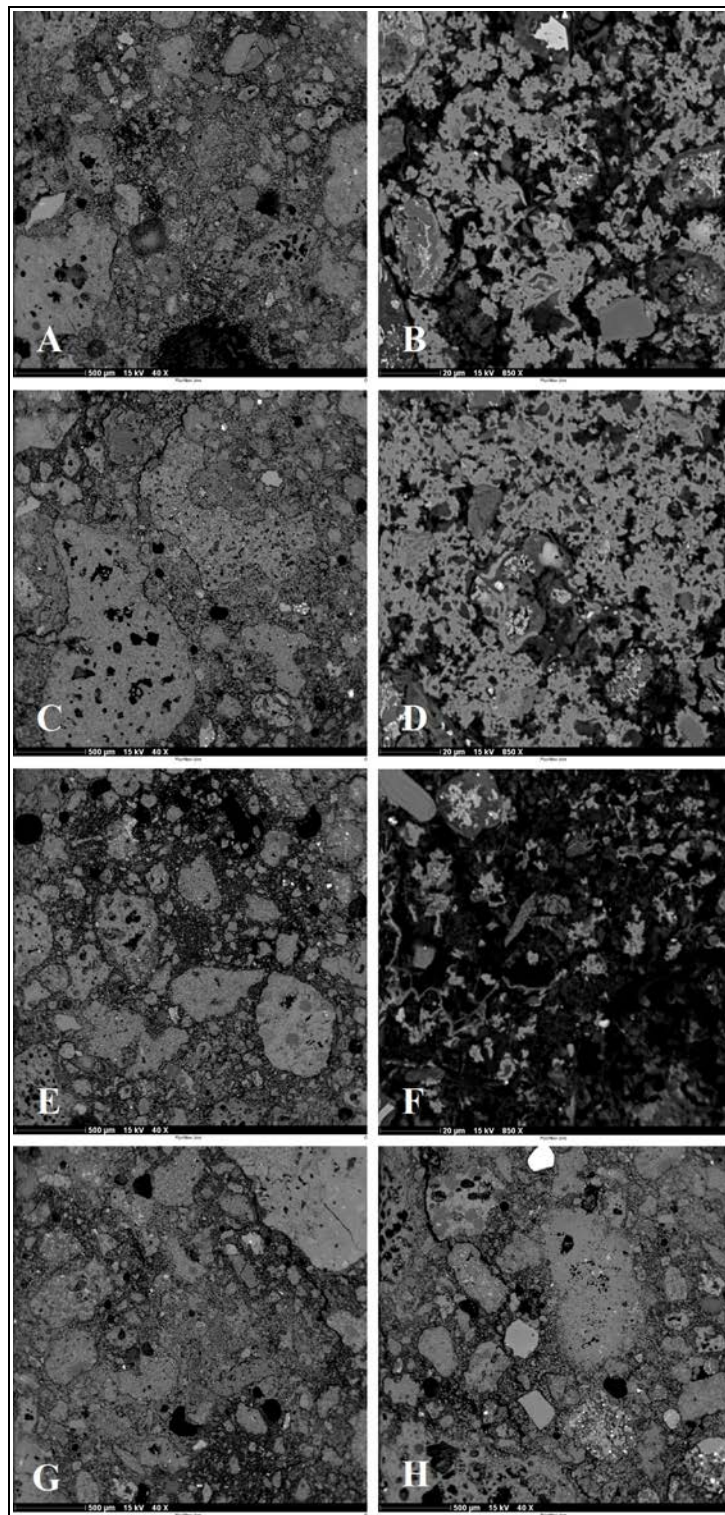


Figure 7.39: Backscatter electron images of mortar sample OS-C1, the Piccolo Mercato, showing general views (A, C, E-H) and highly magnified detail views (B, D) of the mortar binder.

7.8.4. X-ray diffraction analysis

XRD analysis resulted in a diffractogram dominated by calcite, analcime, and clinopyroxene (Figure 7.40). Biotite was absent from this sample and other micas were not identified in the samples with XRD.

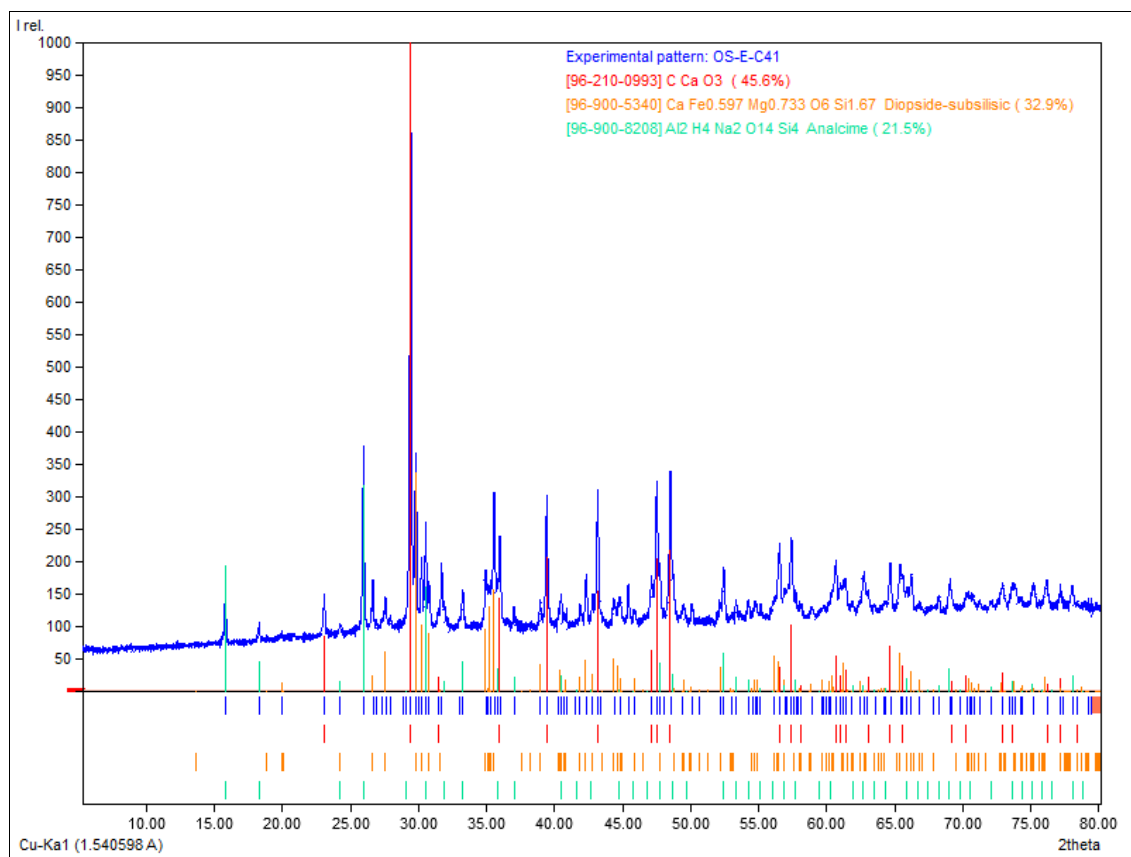


Figure 7.40: X-ray diffractogram of sample OS-E-C41 from the Piccolo Mercato with major peaks labelled.

7.8.5. Particle size determinations

Particle size analysis resulted in the same generic pattern of primarily fine silt-sized aggregate with low amounts of sand and gravel (Figure 7.41). Most particles were silt sized, exhibiting a mean minimum Feret diameter of 0.11 mm, with occasional gravel fragments up to 6.07 mm maximum sized (Figure 7.25, Table 7.9). The standard

deviation of the minimum Feret diameter was 0.21, indicating a relatively poorly sorted assemblage. Image analysis determined the particles were typically well-rounded to sub-angular, with a mean circularity of 0.58, which classifies the fine aggregate particles as having low circularity (Table 7.9).⁴⁰⁰

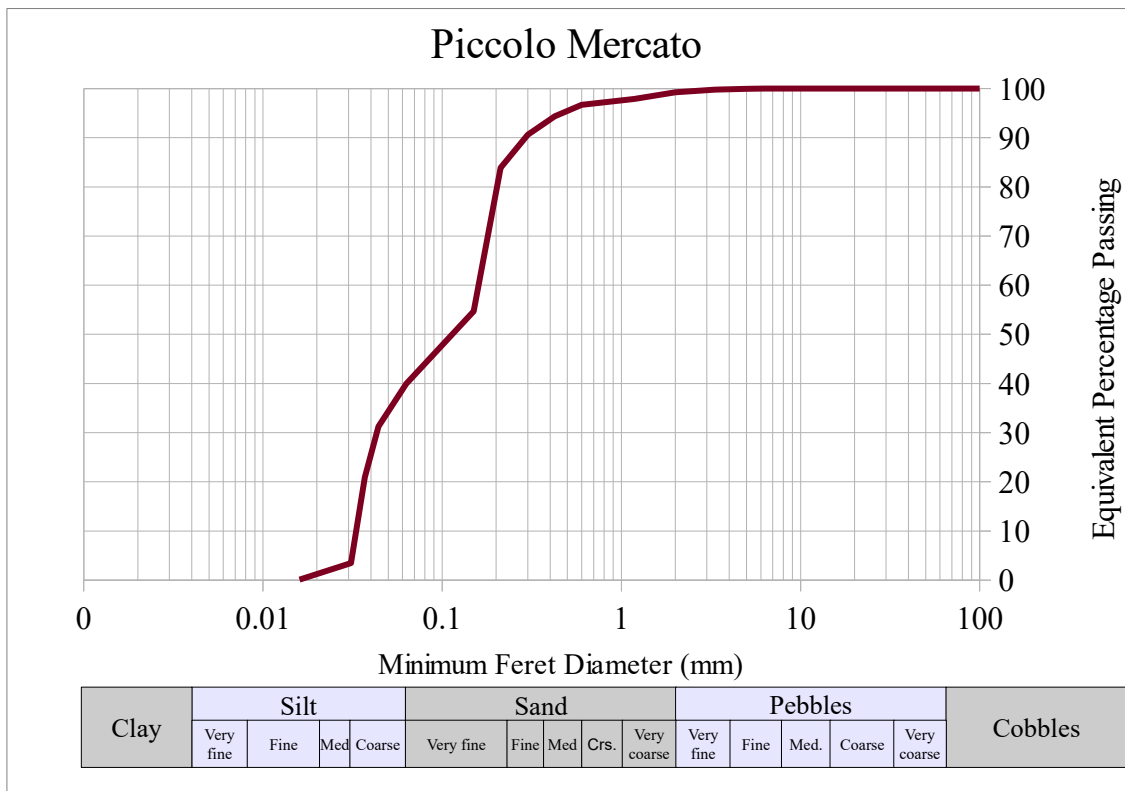


Figure 7.41: Particle size distribution for the Piccolo Mercato, determined from minimum Feret diameter values determined with image analysis.

⁴⁰⁰ Blott and Pye 2008, 58.

7.9. Terme del Foro – Structure F

7.9.1. Visual assessments

The sample set from the Terme del Foro included three facing samples (OS-C8, OS-F-C43, OS-F-C45) and three core samples (OS-C9, OS-F-C44, OS-F-C46). Samples were collected from the *caldarium* and from a passageway that lead to the *frigidarium*. In the case of this structure, only interior walls could be sampled. The samples from this structure varied in terms of mortar colour, cohesion, and average fragment weight (Table 7.15). Mortar colour varied from white, to grey, to very pale brown, but some yellowish alteration was visible with low power microscope investigation. The facing samples were difficult to remove from the wall and were especially friable upon collection. The facing samples also contained more powder and a higher number of fragments than those from the core.

Table 7.15. Samples from the Terme del Foro

Sample ID	OS-C8	OS-C9	OS-F-C43	OS-F-C44	OS-F-C45	OS-F-C46
Core or Face	Face	Core	Face	Core	Face	Core
Wall Location	Unknown	Unknown	Interior - Passage	Interior - Passage	Interior - Caldarium	Interior - Caldarium
Munsell Code	10YR 8/2	10YR 8/1	10YR 8/1	10YR 8/1	10YR 8/2	10YR 7/2
Munsell Colour	Very Pale Brown	White	White	White	Very Pale Brown	Light Grey
Total wt (g)	23.79	51.33	40.63	27.1	32.59	38.51
No. Fragments	3	1	41	18	45	6
Total Fragment wt (g)	22.46	51.15	31.12	25.95	22.78	36.86
Powder wt (g)	1.33	0.18	9.51	1.19	9.81	1.42
Average Fragment wt (g)	7.49	51.15	0.76	1.44	0.51	6.14

The apparent inclusion density of the interior surface of this mortar was approximately 10-15%, but that of the weathered exterior surface was 30%. The aggregate inclusions were poorly sorted, with a variable size range. The largest clasts were a dark grey scoria (10 YR 4/1 Dark Grey) of Pozzolanelle, which ranged in size up to 1.5 cm. Smal-

ler clasts of reddish-brown (5YR 3/4 Dark Reddish-brown) Pozzolane Rosse were present. Clinopyroxene grains up to 5 mm were observed in fragments of both Pozzolanelle and Pozzolane Rosse. The binder contained white lime lumps and loose grains of clinopyroxene, biotite, and feldspar. Irregularly shaped voids suggested loss of aggregate material during sample collection. The interior of this mortar contained vegetation within the binder and the remains of insects in some of the voids.

7.9.2. Thin section and modal analysis

Thin section analysis of mortar from Terme del Foro confirmed that binder exhibited variable density and cracking patterns, with some evidence that material has moved through the sample and been redeposited within voids, holes, and cracks. The strongest evidence for redeposition was the relatively high proportion of binder in the overall mixture, evident from less densely packed fine aggregate particles, and the fairly low void content, indicative of voids that have been filled with mobilized binder material (Figure 7.42). One of the core samples (OS-C9) exhibited possible evidence of self-healing, with structural cracks that extended from the matrix through aggregate clasts and then were secondarily filled with cements (Figure 7.43). This sample also exhibited clear mobilisation of the binder into the centre of Tufo Lionato fine aggregate particles (Figure 7.44). Rare fine aggregate particles exhibited near total replacement of the aggregate groundmass with calcitic binder exhibiting the distinctive birefringence (Figure 7.45).

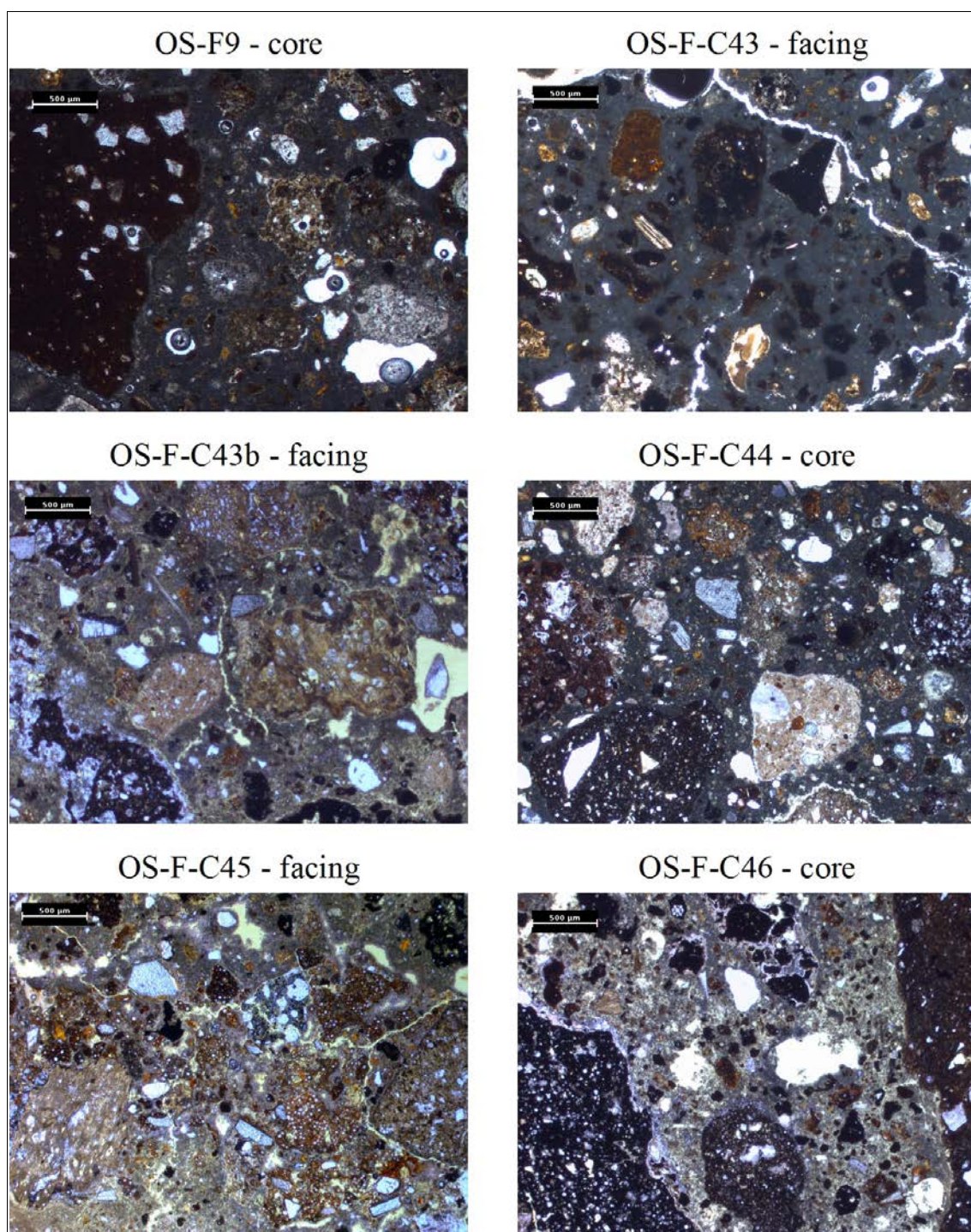


Figure 7.42: Photomicrograph set of representative images from all mortar samples from the Terme del Foro. All images collected by author in plane polarised light.

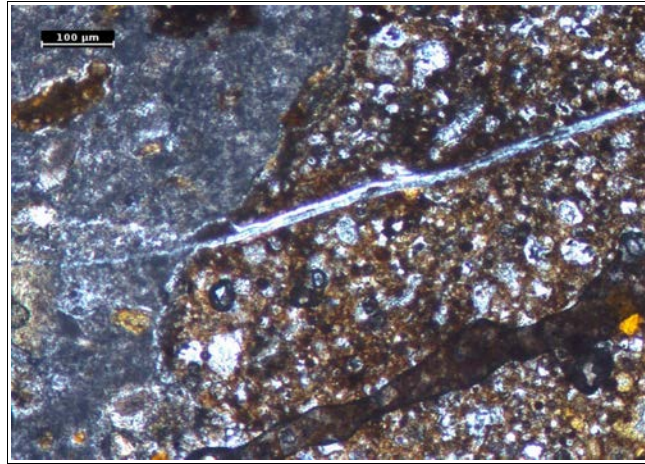


Figure 7.43: Crack in aggregate particle extending into the binder matrix and subsequently filled with calcite. Photomicrograph collected by author in plane polarised light.

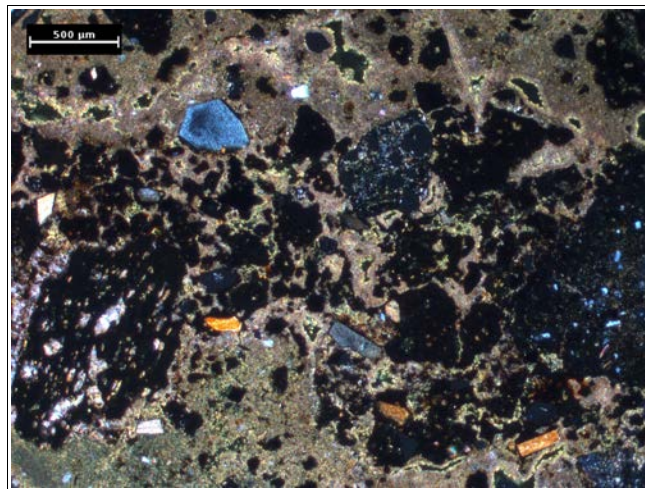


Figure 7.44: Tufo Lionato particle in mortar sample from Terme del Foro exhibiting mobilisation of the binder matrix into the centre of the particle. Photomicrograph collected by author in cross polarised light.

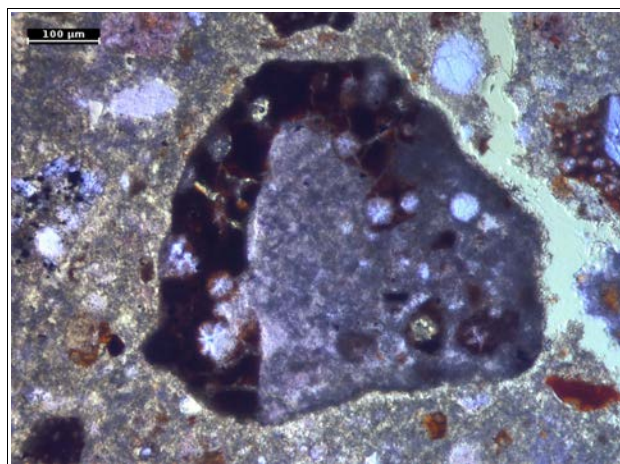


Figure 7.45: Pozzolane Rosse particle in mortar sample from Terme del Foro exhibiting near total replacement of aggregate ground mass with calcitic binder. Photomicrograph collected by author in plane polarised light.

The mean binder:void space:aggregate ratio for the mortar from the Terme del Foro was similar to mortar from other structures, with 34.5%:5.2%:60.3% (Table 7.4). This represented a relatively high quantity of matrix and relatively low proportion of aggregates, most likely related to the dissolution and transport of binder material through the sample, as noted above.

The mortar in the Terme del Foro included highly altered aggregate fragments, which were accreted together into sub-rounded clasts. Fragments of different lithologies were adhered together, suggesting the aggregate may have been epiclastic in nature. No single type of aggregate material significantly dominated the profile of any of these samples (Table 7.2, Figure 7.46). The samples comprised 24.4% Tufo Lionato, 11.5% Pozzolanelle, 8.8% Monti Sabatini Reworked Airfall Ash, 10.0% Pozzolane Rosse (primarily intermediate alteration facies), 0.7% Tufo Giallo di Prima Porta, 0.4% Pozzolane Nere, and 4.7% other inclusions, including ceramic fragments, chert, quartzite, and loose mineral crystals.

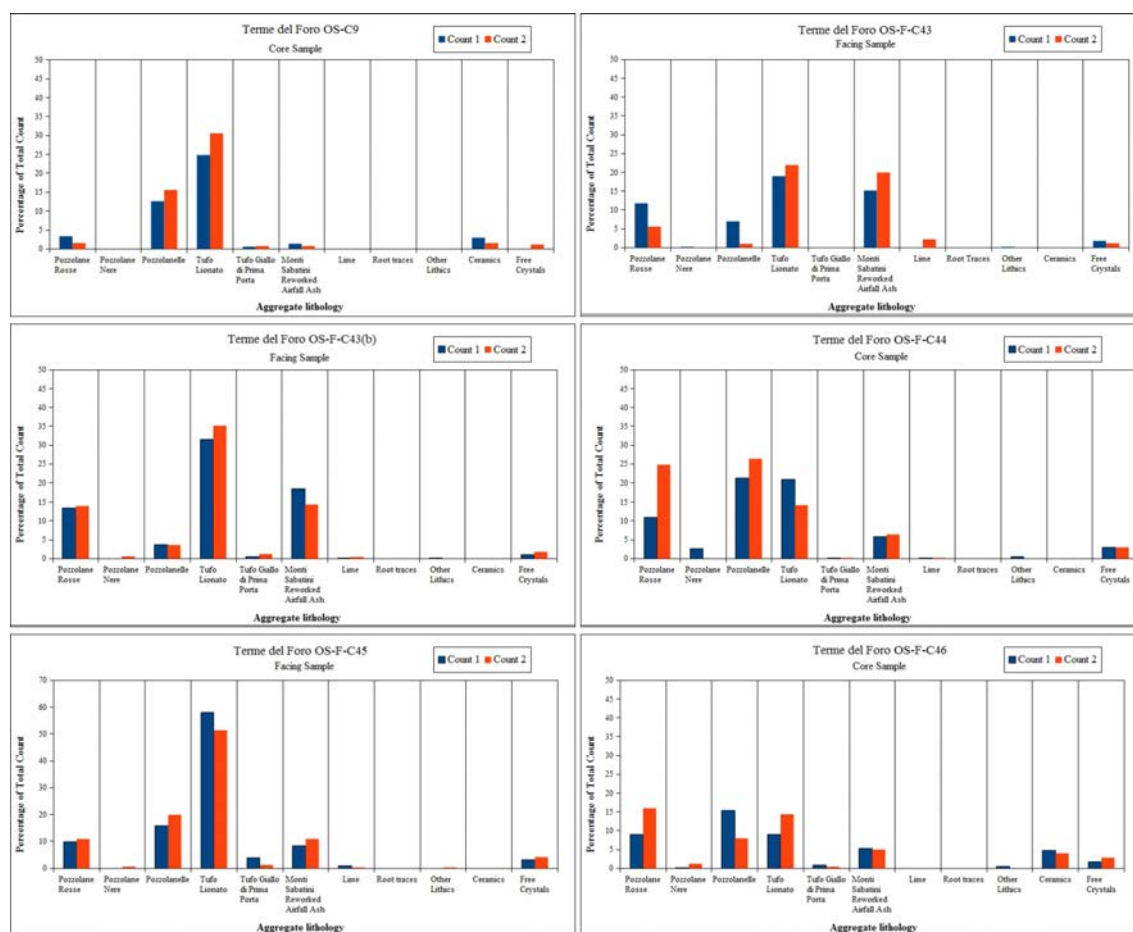


Figure 7.46: Relative proportions of aggregate lithologies from replicated point counts of all samples from the Terme del Foro.

7.9.3. Scanning electron microscopy

SEM analysis of sample OS-C9 from the Terme del Foro demonstrated that this mortar actually exhibited a fairly even microstructure, with relatively even proportions of darkened (Si-rich) binder as brightly coloured (Ca-rich) binder throughout the sample (Figure 7.47-B, F). Rounded voids commonly exhibited evidence of redeposited calcite or calcium-rich binder matrix around the edges (Figure 7.47-A, C, G, H).

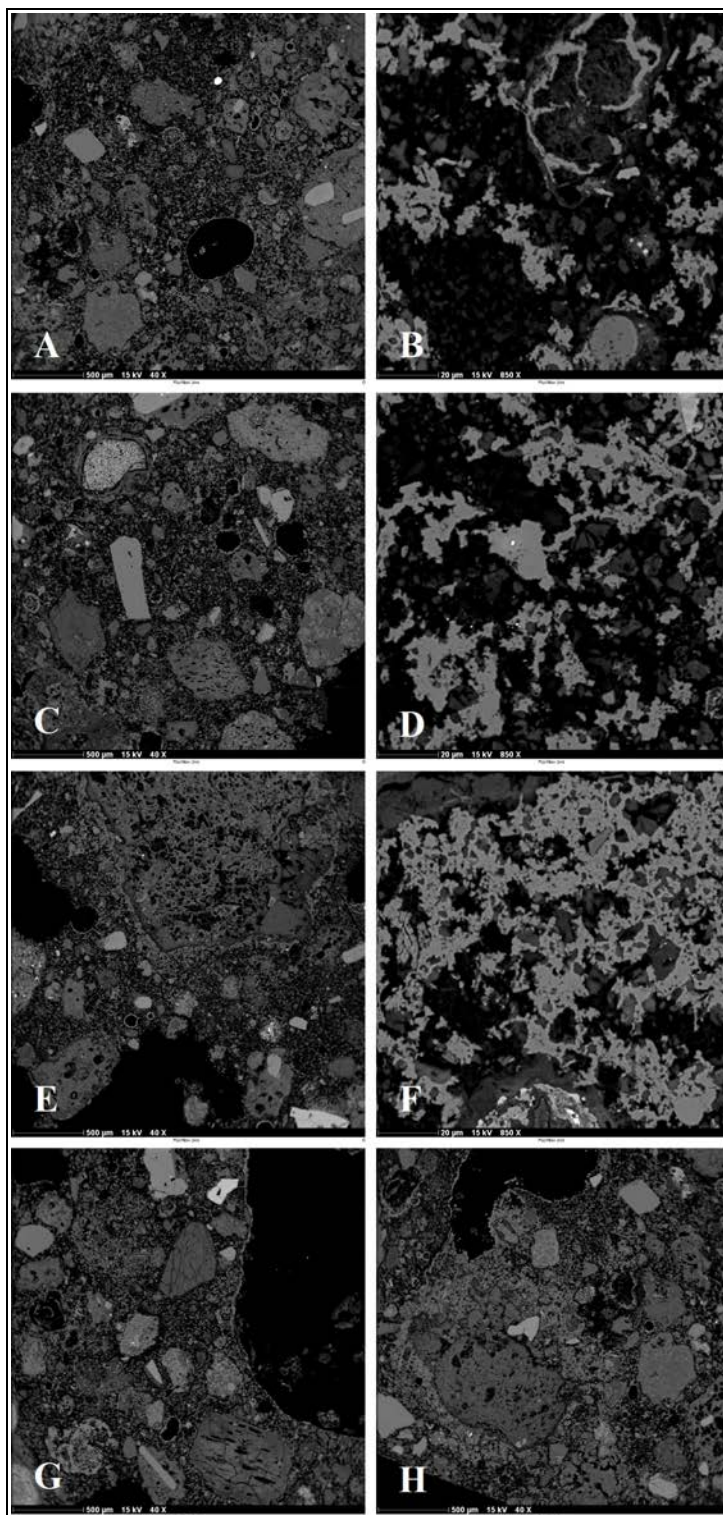


Figure 7.47: Backscatter electron images of mortar sample OS-C9, the Terme del Foro, showing general views (A, C, E-H) and highly magnified detail views (B, D) of the mortar binder.

7.9.4. X-ray diffraction analysis

XRD analysis confirmed the presence of calcite, analcime, diopside, and biotite in the binder (Figure 7.48).

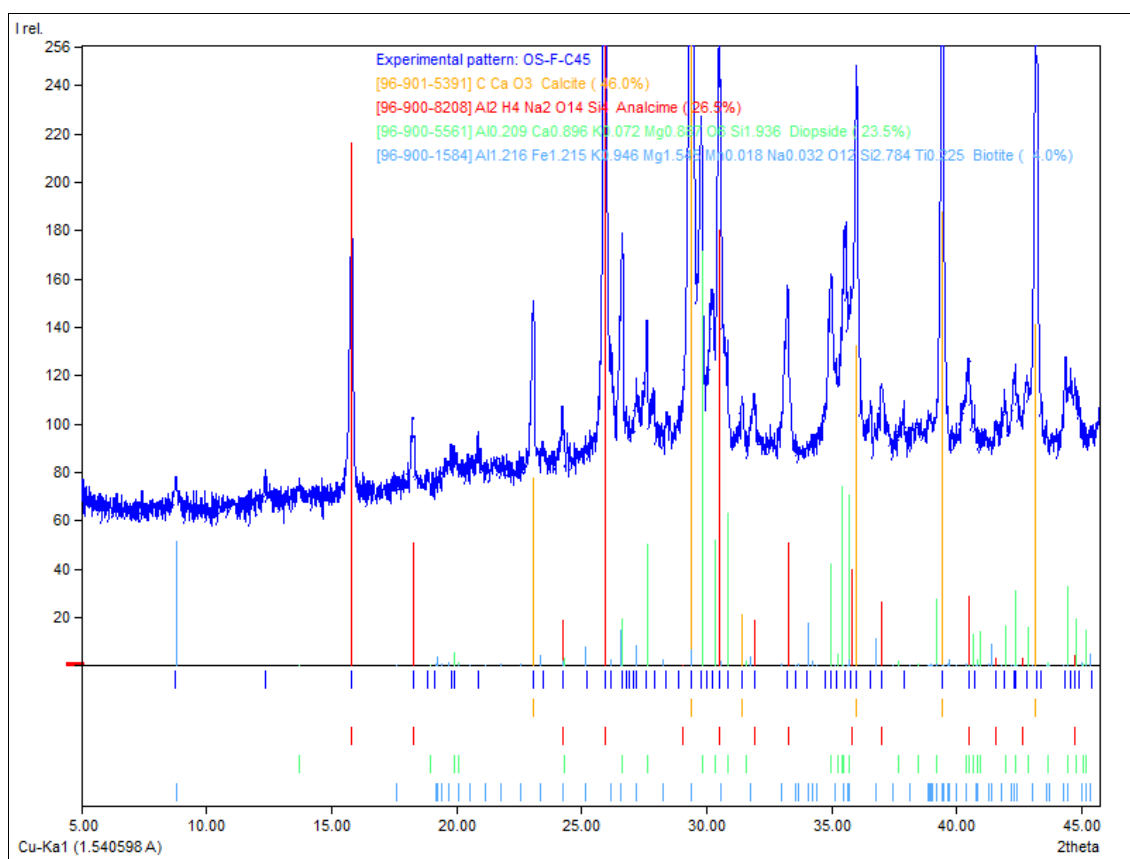


Figure 7.48: X-ray diffractogram of sample OS-F-C45 from the Terme del Foro with major peaks labelled.

7.9.5. Particle size determinations

Figure 7.49 illustrates the mean Feret diameter of aggregate particles determined from image analysis of the thin section of sample OS-C9 from the Terme del Foro. Most particles were silt-sized, exhibiting a mean Feret diameter of 0.12 mm, with occasional gravel fragments up to 3 mm (Table 7.9). The standard deviation of the minimum Feret

diameter was 0.19, indicating a relatively well-sorted assemblage. Image analysis determined the particles were typically well-rounded to sub-angular, with a mean circularity of 0.75, which classifies the fine aggregate particles as moderately circular.⁴⁰¹

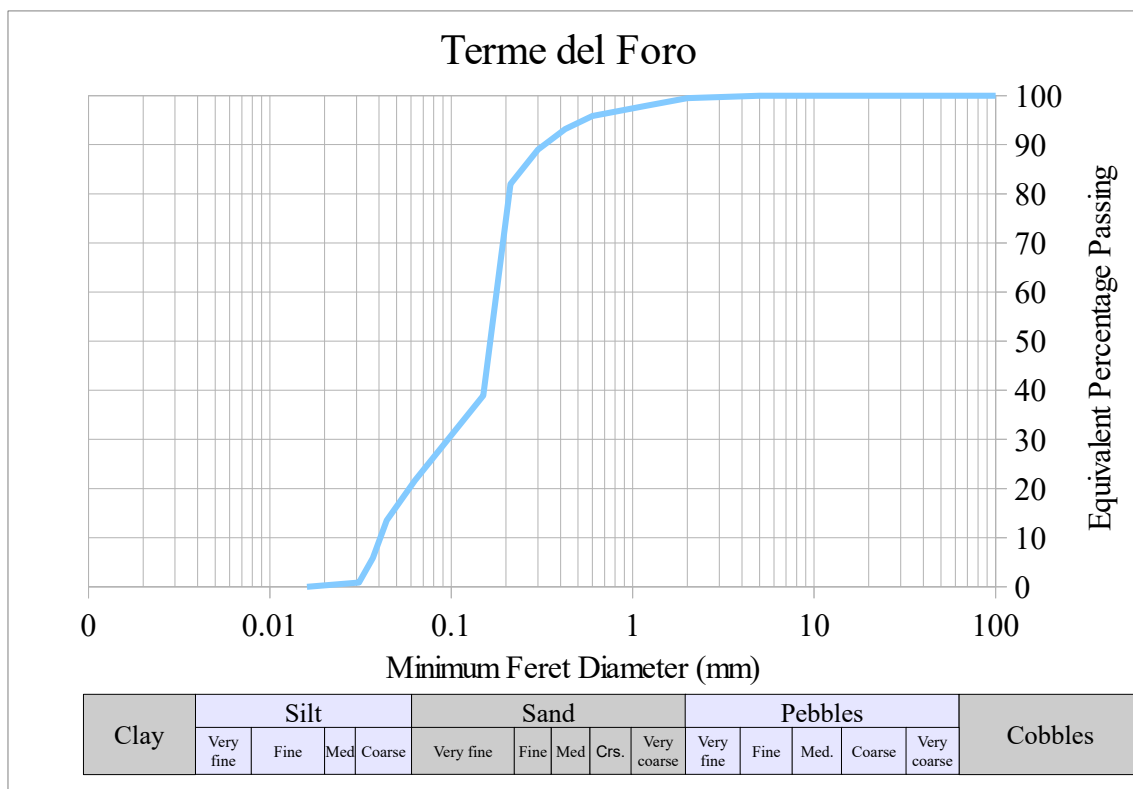


Figure 7.49: Particle size distribution for the Terme del Foro, determined from minimum Feret diameter values determined with image analysis.

⁴⁰¹ Blott and Pye 2008, 58.

7.10. The Insula dell'Ercole Bambino – Structure G

7.10.1. Visual assessments

The Insula dell'Ercole Bambino was sampled within a shop and on its frontage, resulting in three core samples (OS-C21, OS-G-C47, and OS-G-C49) and two facing samples (OS-G-C48, OS-G-C50). The interior of this mortar was white to light-grey in colour with some alteration to a light yellow-brown. The fragments of mortar were fairly cohesive during sample collection, resulting in a relatively low number of pieces and very little powder (Table 7.16). The average fragment weight was over 1 g for every sample.

Table 7.16. Samples from the Insula dell'Ercole Bambino

Sample ID	OS-C21	OS-G-C47	OS-G-C48	OS-G-C49	OS-G-C50
Core or Face	Core	Core	Face	Core	Face
Wall Location	Unknown	Interior - Shop wall	Interior - Shop wall	Exterior - Frontage	Exterior - Frontage
Munsell Code	2.5Y 8/1	Gley1 7/1	2.5Y 8/1	2.5Y 7/1	10YR 7/1
Munsell Colour	White	Light Grey	White	Light Grey	Light Grey
Total wt (g)	9.13	27.59	24	46.25	25.5
No. Fragments	1	3	19	19	8
Total Fragment wt (g)	6.84	27.52	22.72	44.24	24.96
Powder wt (g)	2.29	0.08	1.25	2.02	0.52
Average Fragment wt (g)	6.84	9.17	1.2	2.33	3.12

The hand specimens of this mortar contained visible white lime lumps from 1-2 mm, Pozzolane Rosse up to 3 mm with massive clinopyroxene grains, clasts of Tufo Giallo di Prima Porta from 2-3 mm, Pozzolanelle from 1-2 mm, and Tufo Lionato clasts under 1 mm. This mortar also contained a few poorly-consolidated clasts of a light-coloured yellowish ash, probably Monti Sabatini Reworked Airfall Ash. The visible loose crystal grains included clinopyroxene, biotite, and possible muscovite. The overall density of inclusions within the binder was 25-35%. Several of the visible void spaces were

obviously lined with what appeared to be redeposited binder material, but no fibrous cements were visible in the hand specimens.

7.10.2. Thin section and modal analysis

The mean proportion of components in the samples from the Insula dell'Ercole Bambino was 31.3% binder:9.1% void space:59.6% aggregate (Table 7.4). The binder contained areas of unincorporated and underprocessed lime that were distinct from the matrix itself but could not be characterized as white-coloured lime clasts. Several of these areas also included shrinkage cracks and crystalline calcite. The displayed relatively high porosity, with the highest proportion of void space within the entire sample set. The high void space is the result of damage during thin section preparation, during which all samples suffered sample loss which left irregularly shaped holes in the thin section. Several of the well-rounded spherical voids were lined with highly birefringent calcitic material, possibly redeposited binder.

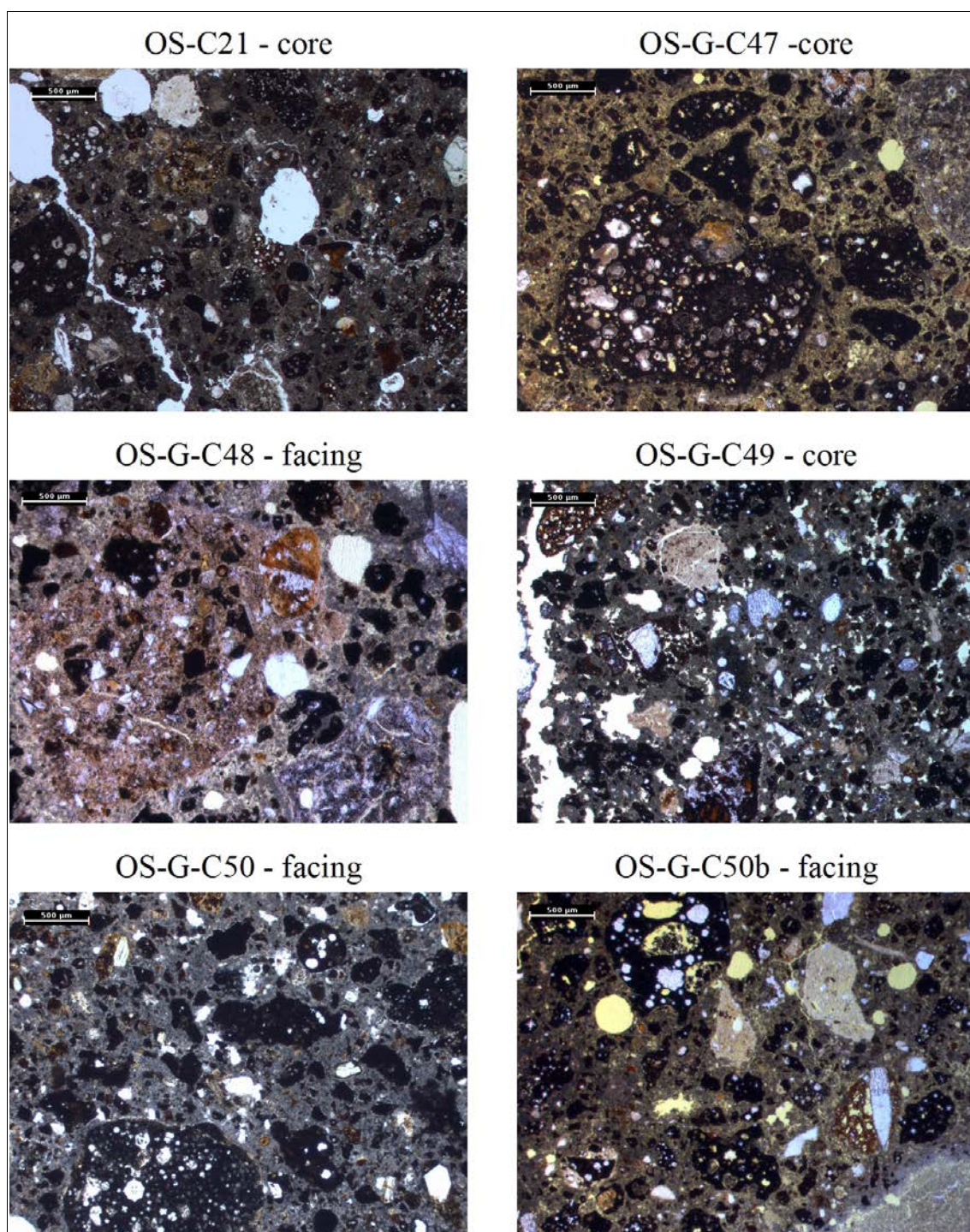


Figure 7.50: Photomicrograph set of representative images from all mortar samples from the Insula dell'Ercole Bambino. All images collected by author in plane polarised light.

The aggregate profile of the mortar from the Insula dell'Ercole Bambino was strongly dominated by Pozzolane Rosse, which comprised 31.0% of the total count, most of which was the intermediate alteration facies (27.2%) (Table 7.2, Figure 7.51). The remaining components included Tufo Lionato (8.3%), Pozzolanelle (4.6%), MSVD reworked airfall ash (3.7%), Pozzolane Nere (3.3%), and 7.6% other inclusions, such as lime lumps, chert, clay particles, leucitic lava fragments, quartzite, and loose crystals (Table 7.2).

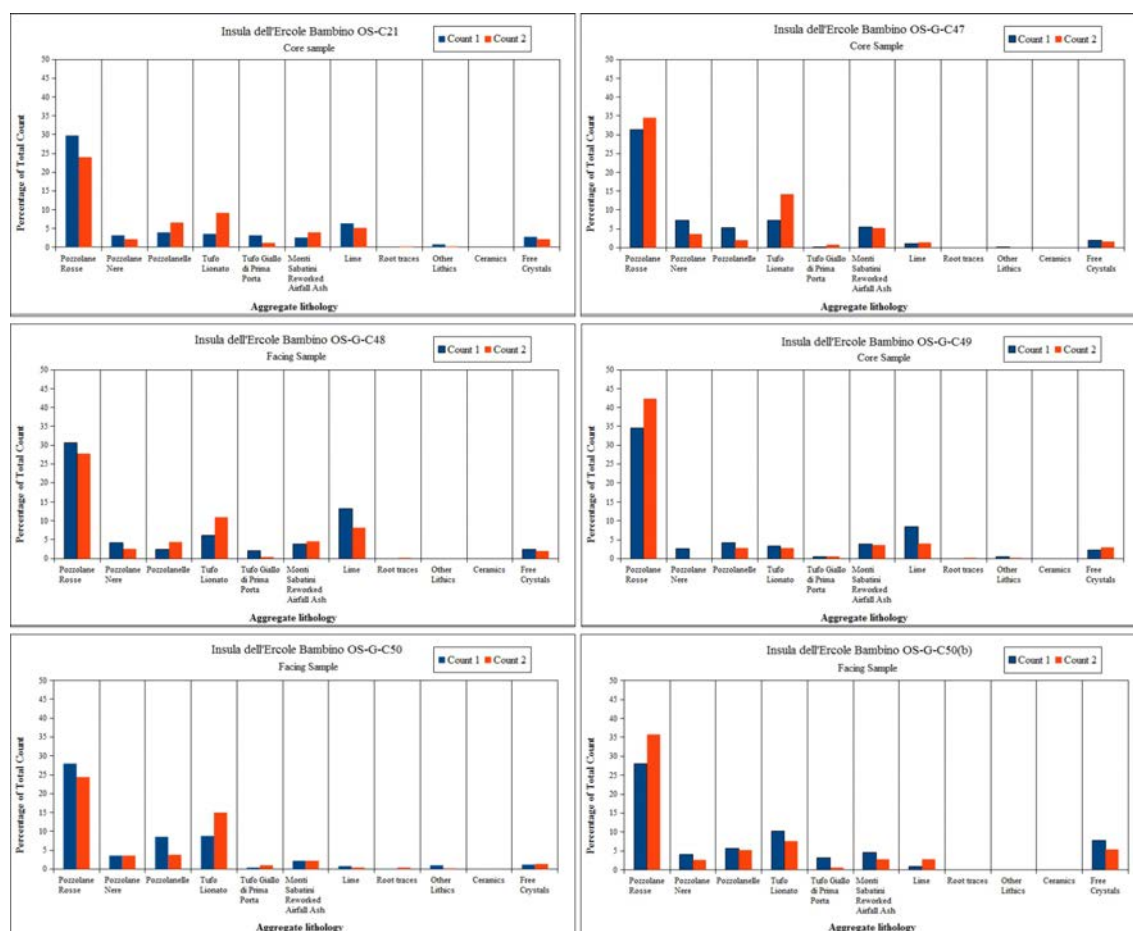


Figure 7.51: Relative proportions of aggregate lithologies from replicated point counts of all samples from the Insula dell'Ercole Bambino.

7.10.3. Scanning electron microscopy

SEM analysis of sample OS-C21 from the Insula dell'Ercole Bambino demonstrated that this mortar actually exhibited a fairly dense microstructure, with a primarily Ca-rich binder throughout the sample (Figure 7.52-B, F). The fine aggregate particles exhibited relatively poor cohesion with common partings from the binder (Figure 7.52-C, E, G, H).

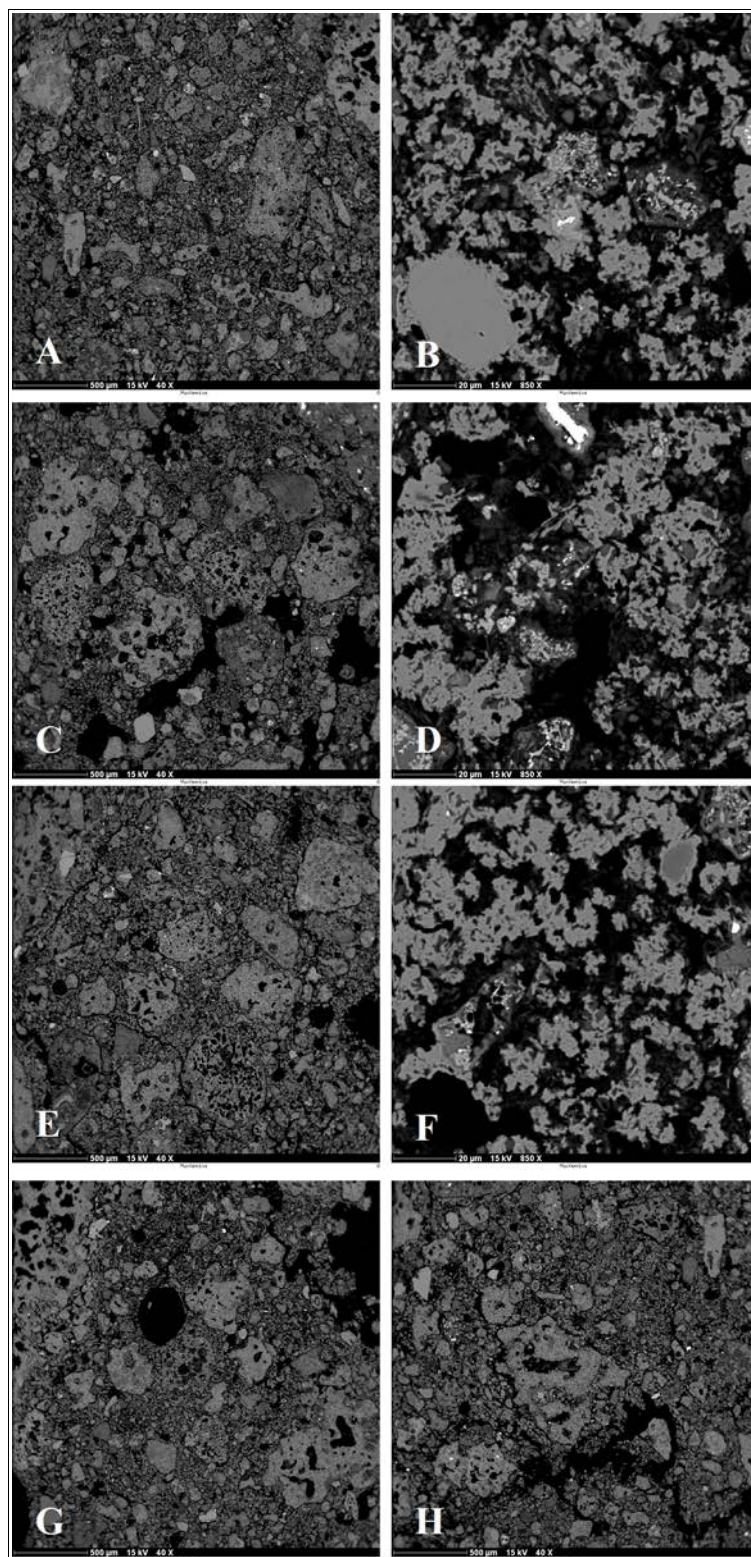


Figure 7.52: Backscatter electron images of mortar sample OS-C21, the Insula dell'Ercole Bambino, showing general views (A, C, E-H) and highly magnified detail views (B, D) of the mortar binder.

7.10.4. X-ray diffraction analysis

XRD analysis confirmed the presence of calcite, analcime, diopside, and biotite in the binder of the facing sample, OS-G-C50 (Figure 7.53).

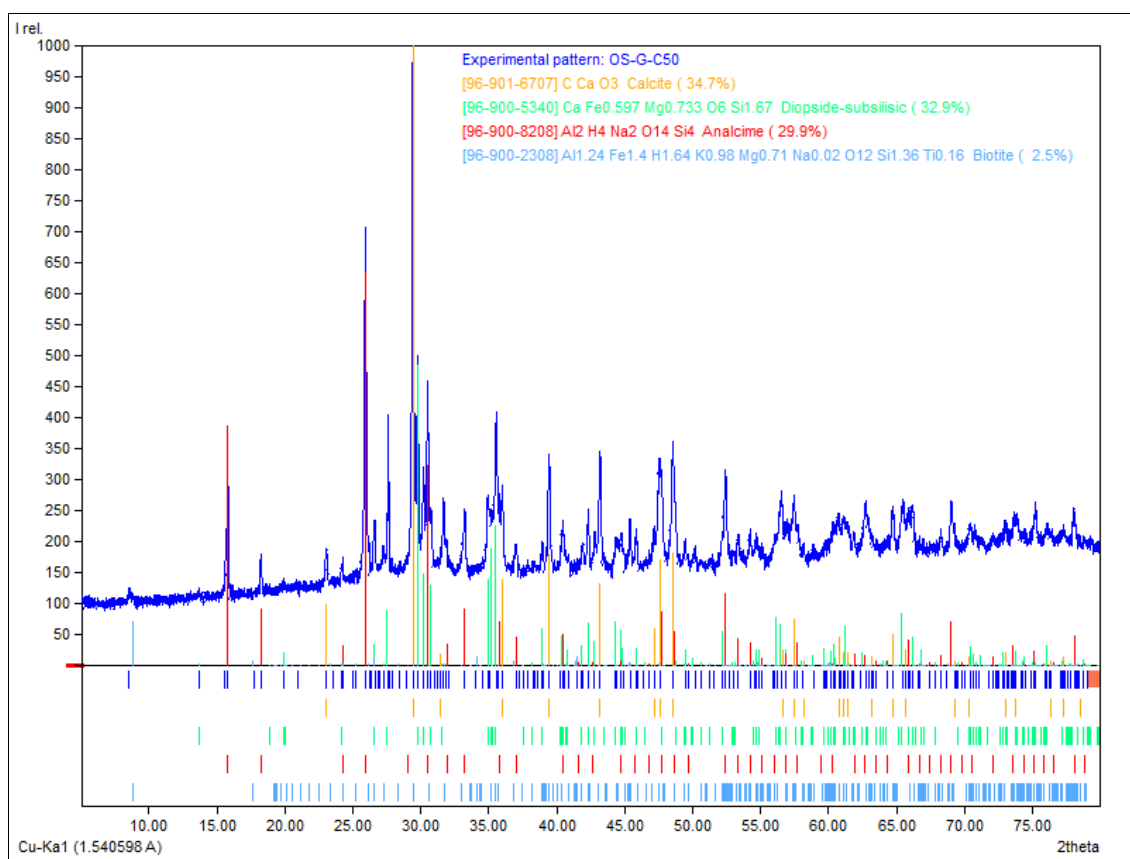


Figure 7.53: X-ray diffractogram of sample OS-F-G50 from the *Insula dell'Ercole Bambino* with major peaks labelled.

7.10.5. Particle size determinations

Particle size distribution followed the same trend as in all samples: a majority of silt-sized particles exhibiting a mean minimum Feret diameter of 0.10 mm, with particles up to 5 mm (Figure 7.54). The standard deviation of the minimum Feret diameter was 0.15, indicating a relatively well-sorted assemblage. Image analysis deter-

ined the particles were typically well-rounded to sub-angular, with a mean circularity of 0.74, which classifies the fine aggregate particles as moderately circular.⁴⁰²

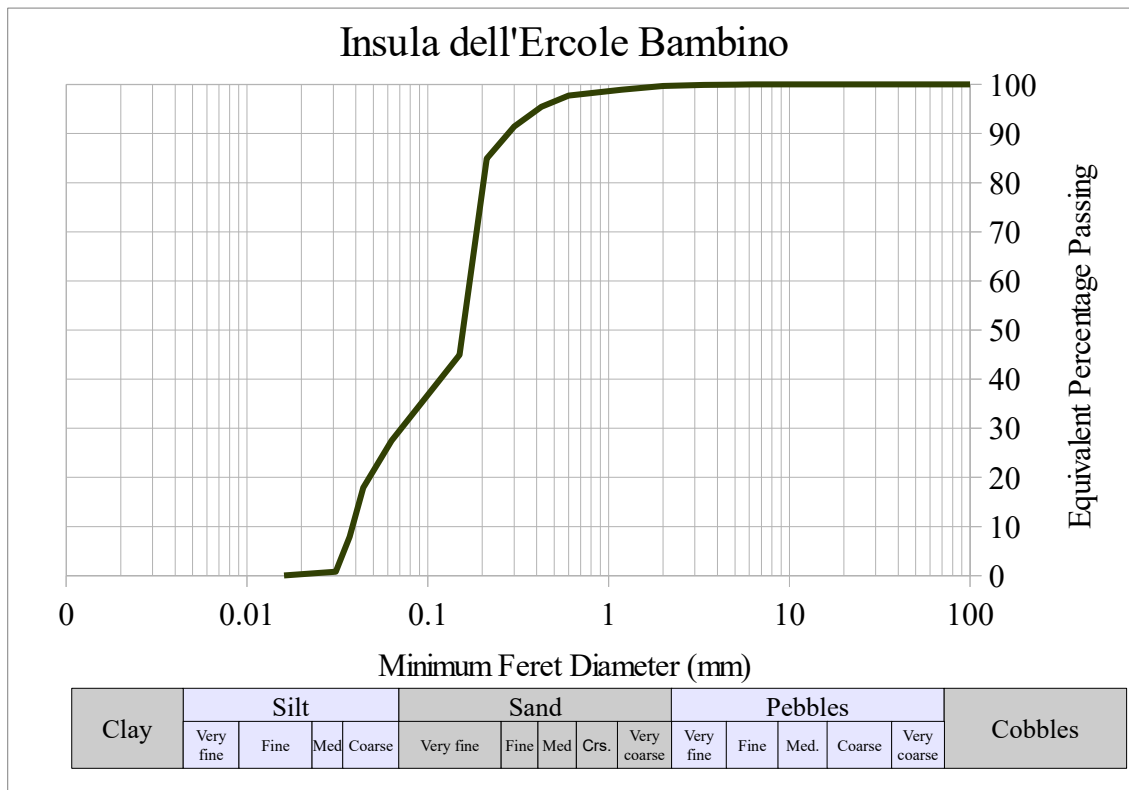


Figure 7.54: Particle size distribution for the Insula dell'Ercole Bambino, determined from minimum Feret diameter values determined with image analysis.

⁴⁰² Blott and Pye 2008, 58.

7.11. Conclusion

Scientific analysis of samples from Ostia has generated important new data about mortars from the 2nd century CE. Optical microscopy and SEM have revealed the components and textures of the mortars. Both qualitative and quantitative analysis was conducted with each of these techniques, allowing for detailed descriptions of each mortar sample and aggregate profile determinations. X-ray diffraction of powdered fragments of the binder from facing samples confirmed the presence of calcite from the lime as well as the major mineral phases from the volcanic aggregate. Image analysis conducted on high resolution scans of thin sections provided information about the size, shape, and number of aggregate particles. The interpretation and implications of these data are left for discussion in Chapter 8.

Chapter 8. Discussion of Results

The previous chapter presented the results of mortar analysis of samples from Ostia using modal analysis of thin sections, SEM analysis, XRD analysis, and particle size distribution with image analysis. The results have indicated that the mortars comprised different mortar types with unique compositions. Section 8.1 below describes how the data from material analysis have been used to identify three types of mortar with distinct design mixes. The major distinguishing features of the different mortar types and similar examples from Rome are described here. This is followed by a discussion of various aspects of the builders' operational processes during construction, including the selection and transport of material (Section 8.2), material processing (Section 8.3), and the mixing and installation of the different mortars (Section 8.4). Mortar performance has been discussed in section 8.5, comparing the durability of the different mortar types.

8.1. Identifying Distinct Mortar Mix Designs

The mortars in this study have been sorted into three types based on distinctive features identified through thin section observation and SEM analysis (reported in Chapter 7). The initial assessment was determined from the aggregate profiles by comparing the relative proportions of different lithologies. The data reported in Chapter 7 (see Figure 7.4) demonstrated that only Pozzolane Rosse and the Villa Senni eruptive materials were present in major proportions (a mean of 10% or greater across the total count of all samples).⁴⁰³ MSVD reworked airfall ash and loose minerals crystals occurred in minor proportions (mean of 2-10%), while the remaining aggregates (Pozzolane Nere, Tufo

⁴⁰³ As noted in Chapter 4, the Villa Senni eruption included both Tufo Lionato and Pozzolanelle. They have been considered together as a single type of aggregate for the assessment of mortar types.

Giallo di Prima Porta, other lithics, and ceramic fragments) occurred only in trace amounts less than 2%. Figure 8.1 compares the mean abundance of aggregate types in each point counted sample and showing the variation between samples, clearly illustrating the importance of Pozzolane Rosse and the Villa Senni aggregates.

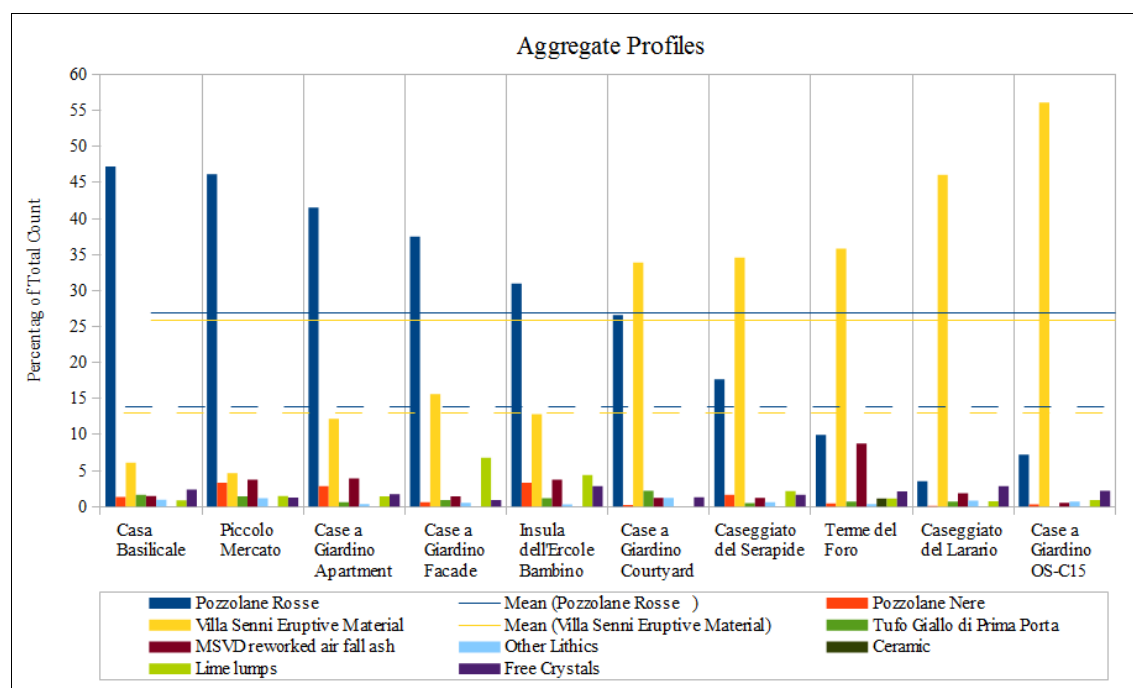


Figure 8.1: Aggregate profiles ordered by decreasing quantity of Pozzolane Rosse. Dashed lines represent half mean values for Pozzolane Rosse (blue) and the Villa Senni eruptive material (yellow).

Mortar types were primarily identified by the dominant aggregate lithology. The dominant lithology was recorded when a particular type of aggregate was present in a greater abundance than the average across all samples and no other aggregate type was present at greater than half of its mean. Apart from the unique case of the Case a Giardino, each of the samples from a single structure were consistently assigned to the same group, which allowed for a total mean for each structure. Because of the variation

in mortars from different parts of the Case a Giardino, they were treated separately and assigned to unique groups as appropriate. Three distinct groups were identified:

1. samples dominated by Pozzolane Rosse aggregate;
2. samples dominated by Villa Senni eruptive material; and
3. samples with relatively similar proportions of Pozzolane Rosse and Villa Senni eruptive material, neither classified as a dominant aggregate.

The Pozzolane Rosse mortars (Type 1) included the mortar from the Casa Basilicale, the Piccolo Mercato, the central apartment of the Case a Giardino, and the Insula dell'Ercole Bambino. The Villa Senni mortars (Type 2) included the mortar from the Caseggiato del Larario and the core sample of unknown provenance from the Case a Giardino. Type 3 included the mortars from the Caseggiato del Serapide and the courtyard of the Case a Giardino, which exhibited no clearly dominant aggregate type.

The remaining two structures represented edge cases that could be classified as Type 3 mortars according to the strict definition of dominant aggregate type. The Terme del Foro mortars comprised primarily Villa Senni aggregates, but the abundance of MSVD reworked airfall ash was more than half of its mean across the total count of all samples. Similarly, the mortar from the façade of the Case a Giardino contained primarily Pozzolane Rosse but the mean value of the Villa Senni aggregates was greater than half mean.

It was clear the main distinguishing factor between the samples was the ratio between Pozzolane Rosse and Villa Senni eruptive materials, which demonstrated a nearly inversely proportional relationship (Figure 8.2 and 8.3). Comparing the relative proportions of these two components alone helped to further distinguish the mortar type

categories, placing these two final structures satisfactorily into groups. The final grouping of the mortars after evaluating the full aggregate profile and the ratio of Pozzolane Rosse to Villa Senni aggregates is listed in Table 8.1.

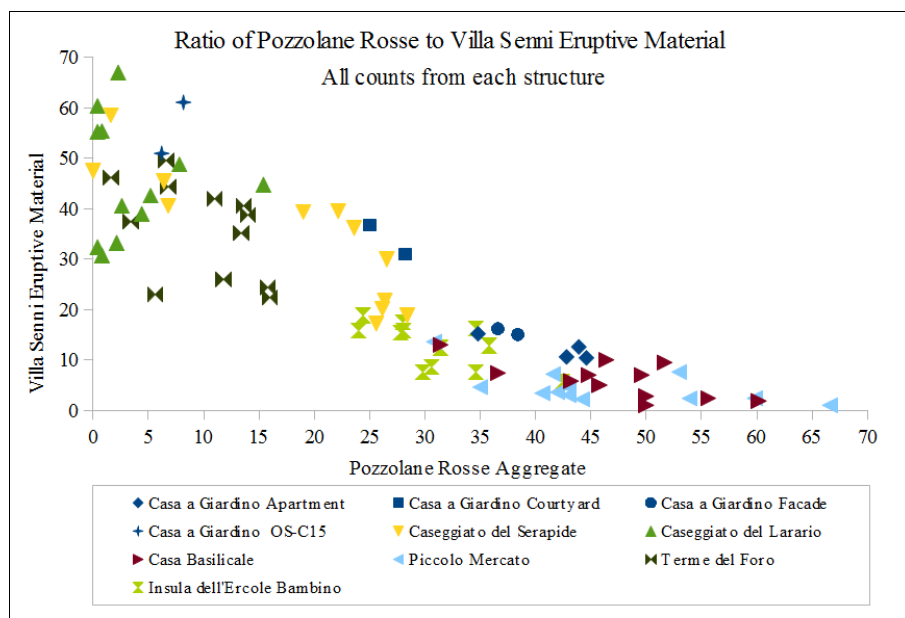


Figure 8.2: Comparison of the two major aggregate lithologies, all counts.

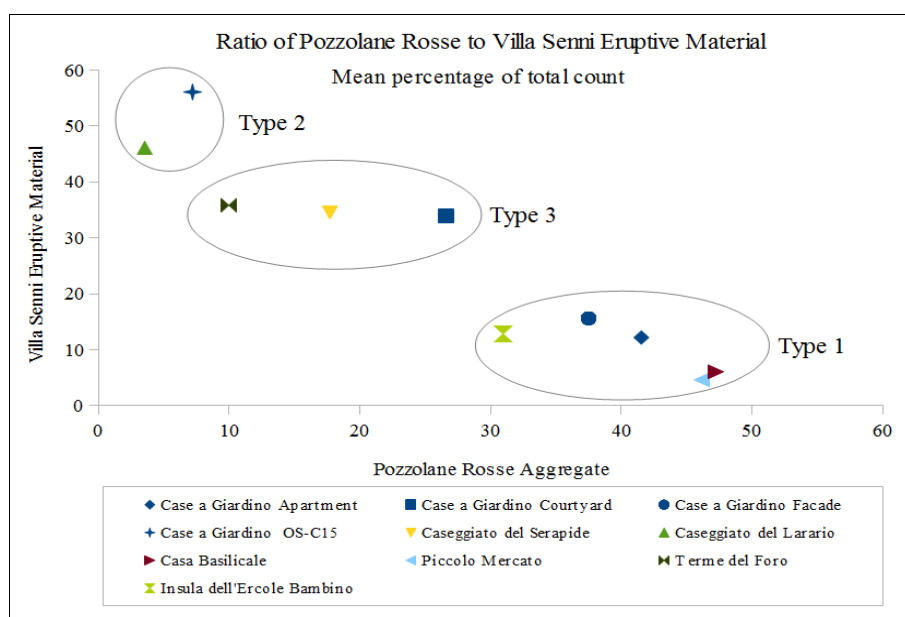


Figure 8.3: Comparison of the two major aggregate lithologies, mean values.

Table 8.1: Mortar types and associated structures.

Mortar Type	Structure	Date	Address in Ostia
Type 1 – Pozzolane Rosse Mortar	the Casa Basilicale	118 CE	I,IX,3
	the Piccolo Mercato	118 CE	I,VIII,I
	the Case a Giardino apartment	125 CE	III,IX,1-23
	the Case a Giardino façade	125 CE	III,IX,1-23
	the Insula dell'Ercole Bambino	130 CE	II,VI,3-4
Type 2 – Villa Senni Mortar	the Caseggiato del Larario	117 CE	I,IX,3
	the Case a Giardino sample OS-C15	125 CE	III,IX,1-23
Type 3 – Mixed Aggregates	the Caseggiato del Serapide	125 CE	III, X,3
	the Case a Giardino courtyard	125 CE	III,IX,1-23
	the Terme del Foro	160 CE	I,XII,6

The aggregate profiles and groupings remained unchanged when data from the cores were compared to data from the facings. Such comparisons were made by extracting the point count data from core and facing samples individually as subsets for evaluation. Mean data from point counts of core samples are illustrated in Figure 8.4, with a reference image of the same group of samples illustrating mean data of all counts (including data from both cores and facings). Likewise, data from facings are illustrated in Figure 8.5. The only obvious disparity was the sample from Caseggiato del Serapide, which demonstrated more Pozzolane Rosse in the facing samples than in the core samples. This perhaps reinforced the fact that this structure belonged to the group with no dominant aggregate type. The results of these comparisons, along with the results from the individual point counts (illustrated in Chapter 7), showed that there was no significant difference in the mix designs of core and facing mortars. This finding justified the use of mean data for point counts of all samples in each structure, including both core and facing samples. Therefore, the remaining discussions of aggregate profiles will

include both core and facing samples. Archaeologically, this finding suggests that the builders used the same mortar mix for cores and facings

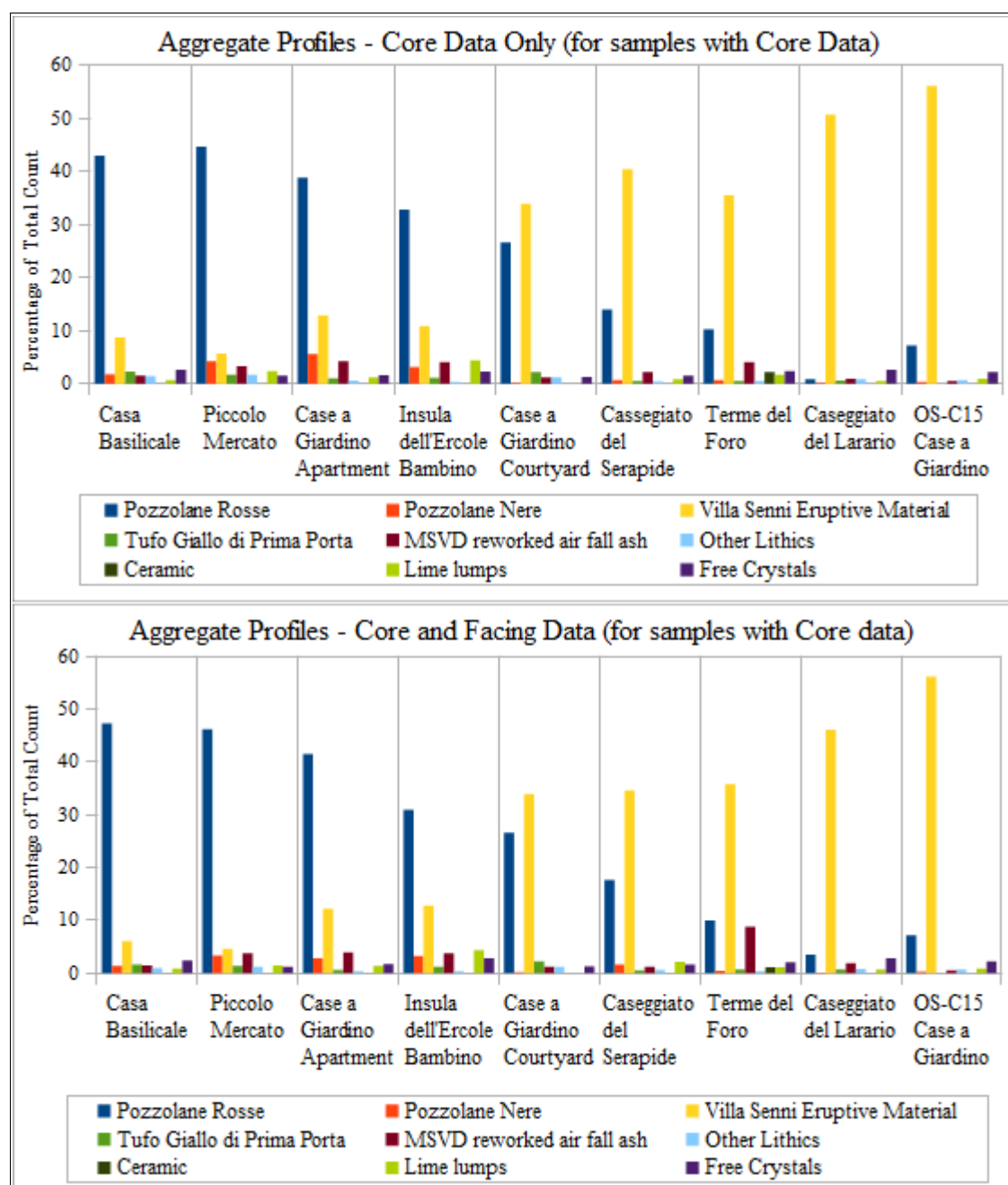


Figure 8.4: Aggregate profiles from core samples only (top) compared to data from the full sample set of core and facing data (bottom).

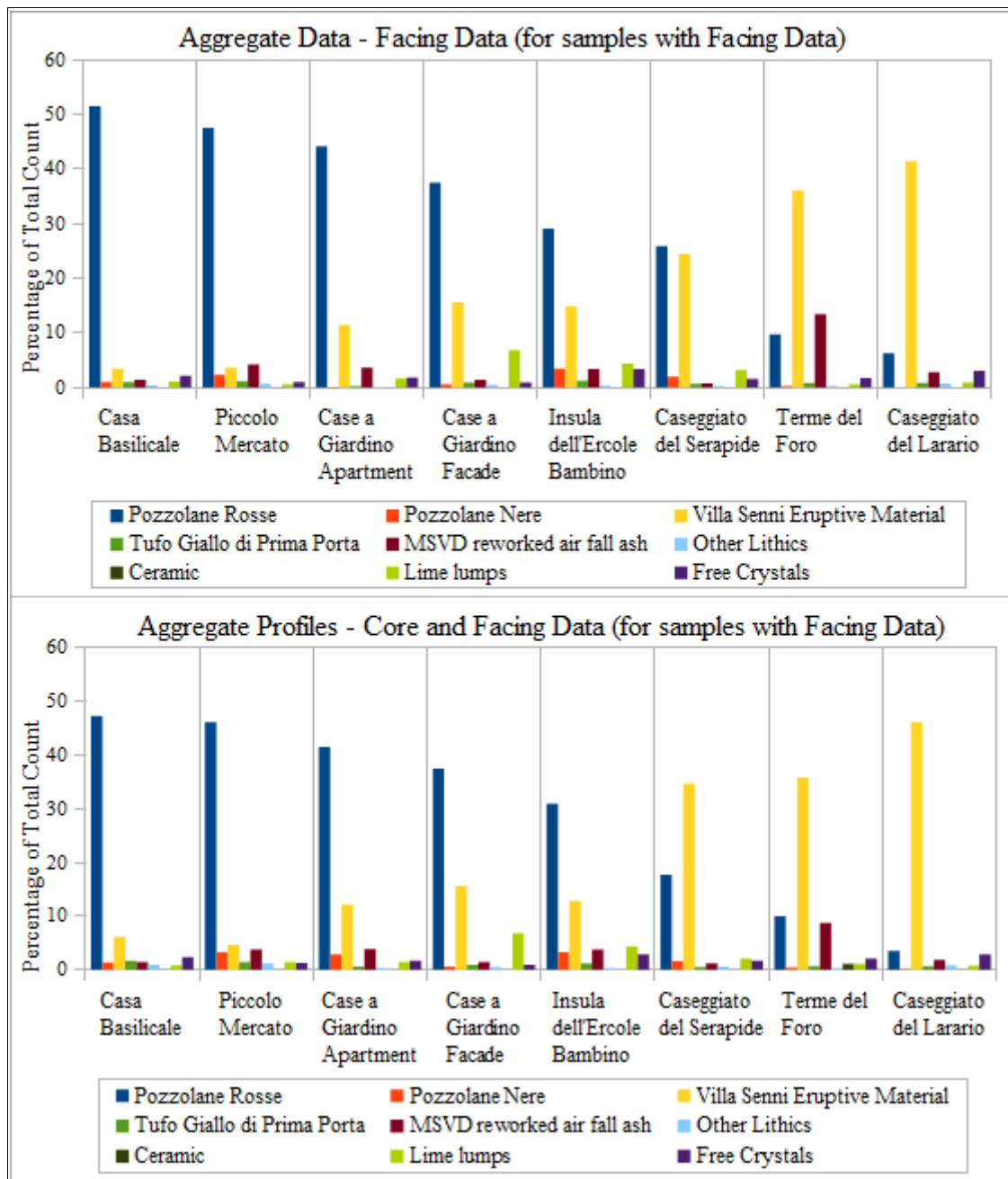


Figure 8.5: Aggregate profiles from facing samples only (top) compared to data from the full sample set of core and facing data (bottom).

8.1.1. Type 1 - Pozzolane Rosse mortar

The Pozzolane Rosse type mortar comprised over 30% Pozzolane Rosse and less than 20% Villa Senni aggregates. The samples in this group included those from the Casa Basilicale, the Piccolo Mercato, the Insula dell'Ercole Bambino, and the central apartment and façade of the Case a Giardino. The facings of the façade on each of these structures utilized a single colour of bricks, possibly for decorative effect. The Insula dell'Ercole Bambino was unique amongst this groups as the only one in which the builders used no reticulate in the facing and no travertine in door jambs. The structural features of these buildings suggest that the Casa Basilicale, the Piccolo Mercato, and the relevant elements of the Case a Giardino could have been designed and/or constructed by the same group of builders. However, the Insula dell'Ercole Bambino may have been designed and constructed by a different group using the same type of mortar.

In hand specimen, the type 1 mortars exhibited variable cohesion, with only the samples from the façade of the Case a Giardino and the Insula dell'Ercole Bambino remaining in good condition during and after collection. Samples from the central apartment of the Case a Giardino and the samples from the Casa Basilicale and the Piccolo Mercato exhibited moderate to poor cohesion with a generally low average sample weight.

Jackson *et al* have identified a number of structures in Rome built with mortar that included Pozzolane Rosse in the mix design:⁴⁰⁴

- Walls and steps of the Forum of Julius Caesar (46-44 BCE) – Pozzolane Rosse
greatest alteration facies

404 Jackson et al. 2010, 39–41.

- Theatre of Marcellus (40s – 13 BCE) – Pozzolane Rosse intermediate alteration facies mixed with crushed Tufo Lionato
- Tomb of Caecilia Metella (30 BCE) – Pozzolane Rosse least alteration facies
- Temple of Castor and Pollux (reconstruction 6 CE) – Pozzolane Rosse intermediate alteration facies
- Temple of Concord (restoration 7-10 CE) – Pozzolane Rosse intermediate alteration facies
- Colosseum (70-80 CE) – Pozzolane Rosse intermediate alteration facies
- Baths of Trajan (104-109 CE) – Pozzolane Rosse intermediate and least alteration facies mixed with 2-3% ground Tufo Lionato
- Markets of Trajan (107 – 113 CE) – Pozzolane Rosse intermediate and least alteration facies mixed with 2-3% ground Tufo Lionato
- Hadrianeum (145 CE) – Pozzolane Rosse
- Baths of Caracalla (217 CE) Pozzolane Rosse

While it is tempting to assume these structures still stand primarily due to the builders' superior workmanship and the high quality of Pozzolane Rosse mortar, there is some bias inherent in the sampling. The standing remains within the city of Rome are limited to these kinds of monumental structures, which have been repaired, protected, and preserved throughout centuries of growth as the city evolved around them. Most of these are public works, excepting only the Tomb of Caecilia Metella. In contrast, Pozzolane Rosse mortar was observed only in private structures in this study.

8.1.2. Type 2 – Villa Senni mortar

The Villa Senni type mortar was found in the mortar from the Caseggiato del Larario and the core sample from the Case a Giardino (OS-C15). These samples were dominated by aggregate from the Villa Senni eruption of the Colli Albani, i.e. Pozzolanelle and Tufo Lionato. The Caseggiato del Larario was faced entirely in brick with no reticulate facing. All of the mortar samples of this type exhibited very good cohesion with relatively high average sample weights.

The use of material from the Villa Senni eruption as aggregate has been documented in mortars from Rome. Jackson *et al* identified Pozzolanelle aggregate in mortar samples dating to the early 2nd century BCE from the Navalvia, concrete vaults formerly thought to be associated with the Porticus Aemilia.⁴⁰⁵ Tufo Lionato has been most often found mixed with Pozzolane Rosse in Roman mortars, as noted above (Section 8.1.1). It appears that in Ostia, as in Rome, Tufo Lionato was considered suitable for use in mortar in limited amounts and in cooperation with additional material. In the case of the mortars from the Caseggiato del Larario, as well as those identified by Jackson *et al* in Rome, the highly zeolitized Tufo Lionato has been mixed with less altered material such as the lesser altered facies of Pozzolane Rosse and Pozzolanelle.⁴⁰⁶ Once again, the ancient builders seem to have chosen aggregates that specifically contained zeolites, which ultimately contributed to the pozzolanic reaction that fosters mortar durability.

405 Jackson *et al.* 2010, 41.

406 Jackson *et al.* 2010, 39–41.

8.1.3. Type 3 – Mixed aggregate mortar

The mixed aggregate mortar was found in mortar from the Caseggiato del Serapide, the Terme del Foro, and the courtyard of the Case a Giardino. The facings of these structures comprised brick work only. The core sample from the Terme del Foro showed considerable redeposition of the binder matrix, with variable density of the binder across the sample and voids lined with thick rims of cement or wholly filled with matrix material. This was generally taken to be caused by the movement of moisture through the samples, which dissolved material from the binder and redeposited it into the voids. This may have been a function of the type and quality of the mortar mix, which allowed moisture to permeate through the structures more readily than the other formulations.

Overall the samples in this group exhibited variable cohesion during sample collection. Those from the Caseggiato del Serapide were rather friable, showing poor cohesion, while the samples from the courtyard of the Case a Giardino exhibited good cohesion. The samples from the Terme del Foro were variable amongst themselves, with core fragments exhibiting less friability than the facing samples.

The aggregates in the mortars of this group typically exhibited alluvial alteration features, including a high degree of alteration visible in thin section and clasts comprising multiple lithologies bound together with clay. These features suggested the aggregates actually may have been epiclastic in nature. As noted in Chapter 4, the Aurelia Formation comprises altered Tufo Lionato, while the San Paolo formation contains re-worked Pozzolane Rosse. The mortars in this group all contained more Villa Senni material than Pozzolane Rosse, suggesting this aggregate material could have come from the Aurelia Formation.

Jackson *et al* identified structures built with two different types of epiclastic aggregates from outcrops near Rome:⁴⁰⁷

- Temple of Saturn (380-360 BCE) – Aurelia Formation
- Temple of Concord (121 BCE) – San Paolo formation
- Temple of Castor and Pollux (reconstruction 117 BCE) – Aurelia Formation mixed with San Paolo Formation
- Tabularium (78 BCE) – Aurelia Formation mixed with San Paolo Formation
- Rostra Nova (Republican period) – Aurelia Formation mixed with San Paolo Formation
- Vaults in the Forum of Julius Caesar (46-44 BCE) – San Paolo Formation
- Golden House of Nero (64-68 CE) - Aurelia formation

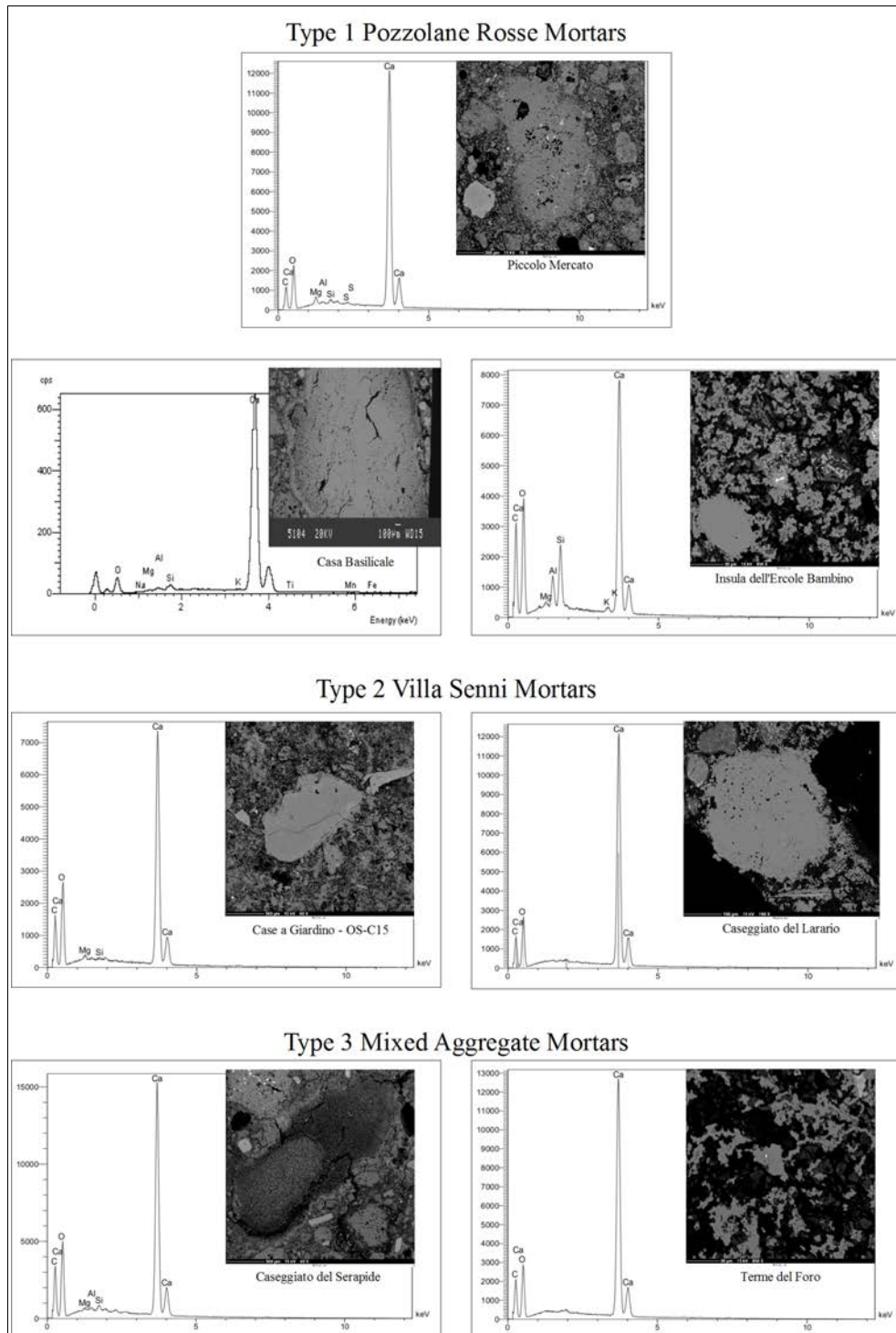
8.2. Material Selection and Transport

8.2.1. Lime composition and selection

Lime lumps evaluated with SEM indicated variable lime composition across the samples (see Figure 7.8). Even though using less pure lime technically violates the Vitruvian standard, this actually makes for a better binding cement because it is naturally hydraulic.⁴⁰⁸ SEM analysis showed that limes from all samples comprised primarily calcite with traces of impurities, including Mg and Si, the markers for at least partial dolomitisation and silicification (Figure 8.6).

⁴⁰⁷ Jackson *et al.* 2010, 39–41.

⁴⁰⁸ See Chapter 2.



grouped by mortar type.

In order to identify lime sources for these mortar samples, more in depth trace element analysis should be undertaken to compare the lime from these mortars to various impure limestones, such as the Calcare Maiolica Formation (see above, Chapter 4). This type of lime could have been transported easily into Rome down the Anio River and then down to Ostia along the Tiber.⁴⁰⁹

The lime lumps contained relatively low quantities of impurities compared to the binder, which included significant Si, Mg, Al, and alkalis (Figure 8.7). The incorporation of these elements was evidence for pozzolanic reaction and incorporation of those elements from the consumption of aggregates. All samples exhibited similarly elevated levels of these elements, suggesting good pozzolanic reactions in all mortar types. This was seen in all structures, supporting the hypothesis that the builders were choosing naturally pozzolanic aggregates.

Both the facing and core samples from the Terme del Foro contained ceramic fragments. It is possible ceramics were included in the mix to substitute for the natural pozzolans found in the other types of aggregates. As noted in Chapter 3, Vitruvius recommended that ceramics should be added to mortar when river or beach sand was used.⁴¹⁰ Clearly the ancient builders understood the benefits of natural pozzolans and worked to replace them when necessary. This once again reveals a high degree of intentionality and sophistication in the design of mortar mix for optimum performance.

409 Fichera et al. 2015, 81, citing DeLaine, 1997; Lancaster, 2005; Jackson & Marra, 2006; Jackson et al., 2007, 2009.

410 Vitr. *De Arch.* II.5.1.

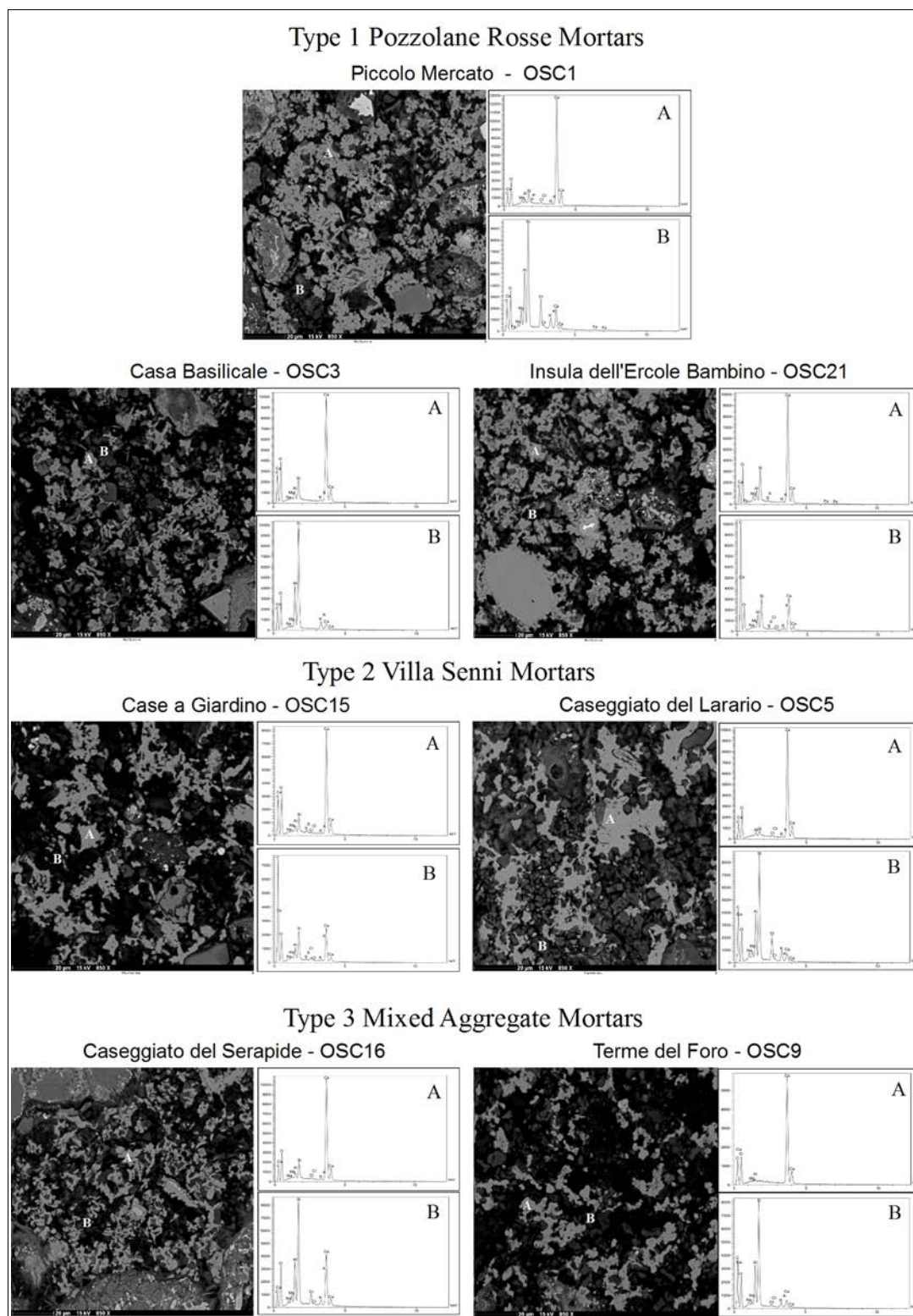


Figure 8.7: SEM photomicrographs and EDS spectra of the binder in mortar samples, grouped by mortar type, showing incorporation of additional elements via pozzolanic

8.2.2. Aggregate selection

The selection of Pozzolane Rosse with *in situ* weathering and zeolitization suggests that Roman builders understood the physical properties and their benefits in the mortar. The significance of the strong domination of Pozzolane Rosse in several of the mortar samples cannot be understated here. Unlike with the mixed aggregate (possibly epiclastic) mortar, and even the Villa Senni mortar to a lesser degree, the Pozzolane Rosse mortars exhibited a nearly homogeneous aggregate composition. This suggested a clear selection of a specific aggregate and control over the material supply at every stage of quarry, storage, collection, transport, and mortar production, which prevented the mixing of various materials.

As noted in Chapter 4, phillipsite was the most common zeolite present in outcrops of Tufo Lionato and only rarely occurs with chabazite, which is found primarily in the upper levels of the deposits.⁴¹¹ The fact that some Tufo Lionato fragments in the mortars exhibited intact chabazite or calcite with relict chabazite texture suggests the majority of the Tufo Lionato used for the mortars in this study was originally located in the upper levels of the outcrop. This material most likely came from the higher levels of the quarry from which it was procured. This type of weathered material may have been rejected as too unstable for structural wall stones or reticulate blocks, but ideal for the mortar itself. It should be noted here, that rare particles of Tufo Lionato within mortar from the Terme del Foro contained phillipsite, suggesting an aggregate that originated at the lower levels in the outcrop. No other structures contained Tufo Lionato with phillipsite, suggesting a unique source for this type of aggregate.

⁴¹¹ de Gennaro and Langella 1996, 458.

The Tufo Lionato clasts that retained chabazite or phillipsite obviously did not “give up” all of their zeolites during mortar production, therefore they were not consumed during the pozzolanic reaction. Zeolites in Tufo Lionato clasts within the mortars were mainly observed in pebble sized clasts (<3 mm), typically occurring along the clast edges, within vesicles, or acting as a cement to bind smaller particles within the larger clast. These larger fragments were generally less adhered to the binder and more likely to exhibit alteration and degradation within the interfacial zone. This suggests these larger fragments may have been less reactive and contributed less to the pozzolanicity than smaller fragments of Tufo Lionato. Clearly, material processing and size control was an important aspect of mortar mix design, and in most cases the builders seem to have been carefully controlling these variables.

8.2.3. Transporting aggregates into Ostia

The region in which Ostia was located was rich with volcanic and epiclastic deposits, specifically those observed in the mortars studied here. Members of the modern concrete industry tend to prefer local aggregates when appropriate in order to minimize transport costs, and a great deal of resources are dedicated to determining the usability of possible aggregate sources. When it comes to defining “local materials” in ancient Ostia, the problem becomes more complex. Distances that would be considered local by modern standards (i.e. easily deliverable by truck in a few hours) would have taken quite a bit longer when carried by cart or wagon. On the other hand, water transport routes also were available, which could have increased the number of usable quarries.

DeLaine estimates the cost of one man-day of skilled labour is 1.69 man-days labourer equivalent for unskilled work.⁴¹² That figure, when correlated to the relative travel costs of different modes of transport, provides an estimated cost of labour for moving aggregate material from a quarry to a building site (Table 8.2). The closest quarry to Ostia was Castel Porziano, which was accessible by road only (Figure 8.8).⁴¹³ However, a number of quarries in Rome were accessible by road and river travel, which would have reduced the cost of transport. The cost to travel the 30 km between Rome and Ostia, a distance of 44.4 Roman miles (1 Roman mile = 1.48 km), would have been 5.77 man-days labourer equivalent (mle) by river downstream, 11.54 mle by river upstream, or 63.93 mle by ox-cart.⁴¹⁴ The cost to transport material downstream by river makes it by far the cheapest route.

Table 8.2. Comparison of labour costs for different transport methods. a=DeLaine's figures for estimating relative travel cost ratios, derived from the Prices Edict of Diocletian and reported in DeLaine 2001, 233-234

Method of transport	Relative costs for each mode of travel^a	Estimated cost to move a tonne of material one Roman mile^a	Estimated cost to move a tonne of material from Rome to Ostia (44.4 Roman miles)
Sea	1 mle	0.04 mle	Not a valid direct route
River Downstream	3.9 mle	0.13 mle	5.77 mle
River Upstream	7.7 mle	0.26 mle	11.54 mle
Road Travel Via Ox-Cart	42 mle	1.44 mle	63.93 mle

The closest tuff and pozzolana quarries to Ostia are labelled in Figure 8.8. As noted in Chapter 4, the geology of this area is a complicated sequence of volcanic material that includes Pozzolane Rosse, Pozzolanelle, and Tufo Lionato (the most common ag-

⁴¹² DeLaine 2001, 247.

⁴¹³ Russell 2013.

⁴¹⁴ DeLaine 2001, 233-234.

gregate types identified in the mortars). Given the relatively homogeneous aggregate profiles of the Type 1 Pozzolane Rosse mortars and the Type 2 Tufo Lionato mortars, it is highly likely these aggregates were collected from areas where the volcanic stratigraphy was clearly delineated between these materials.

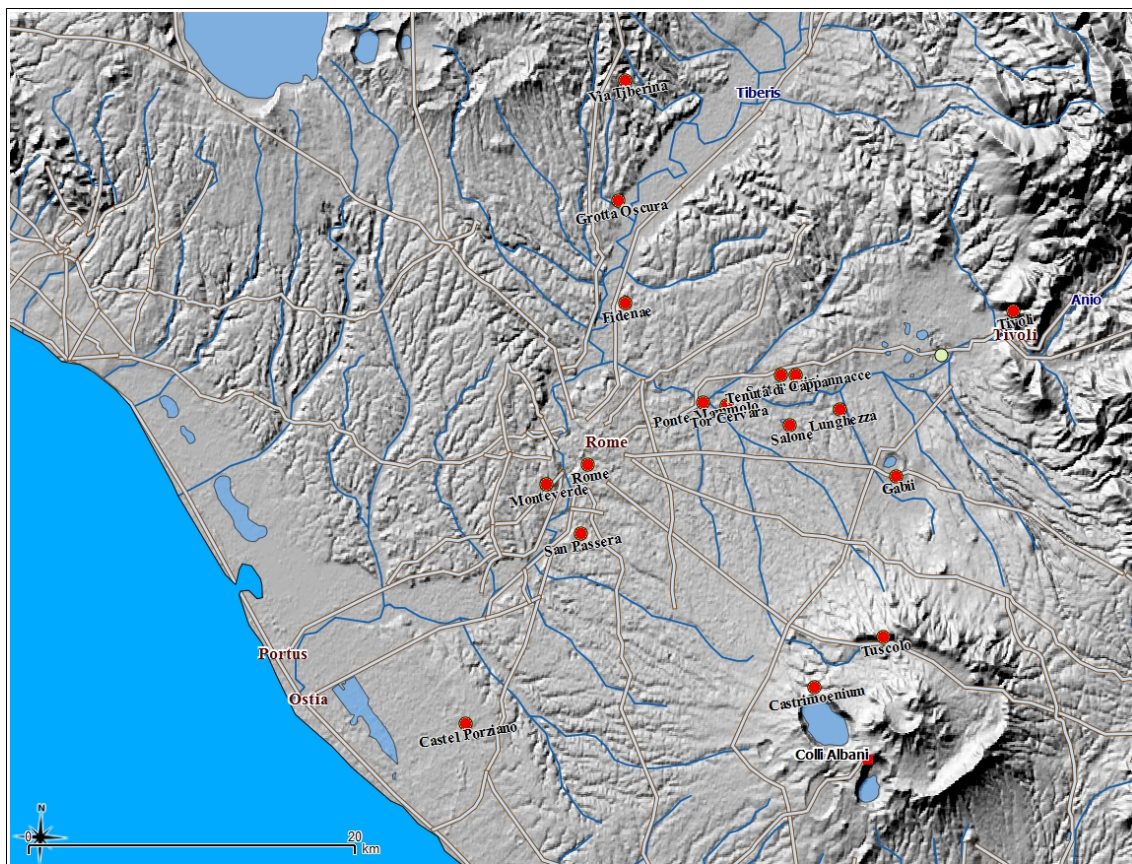


Figure 8.8: Location of tuff quarries (labelled and marked in red), rivers (blue), and ancient roads (white) in the Roman Magmatic Province. Map generated by author with Quantum GIS; quarry data after Russell 2013; ancient city, road, river, and coastline location data from Talbert 2000.

The case of Tufo Lionato is fairly straightforward, as it was quarried for building stone at Tor Cervara, Salone, Settecamini, Tenuta di Cappannacce, and Monteverde,

which is the nearest one of these to Ostia.⁴¹⁵ It is possible the fine aggregates either were excavated from areas of the quarry where the material was less consolidated or were generated as off-cuts from the preparation of the Tufo Lionato dimension stone blocks. Either way, positively identifying which quarry the aggregates came from may be addressed by comparing the trace element chemistry of the fine aggregates in the mortar and samples from a variety of quarries. Unfortunately, this is beyond the scope of this research.

Determining the provenance of Pozzolane Rosse is a more complicated task, because this material was not used as building stone and so its quarry sites are less widely reported. Pozzolane Rosse as was known to have been quarried at Fidenae and also possibly at Roman quarries, including those at the Palatine Hill, Piazza Dante, and Piazza Vittorio.

Specific lithologies are not recorded for Castel Porziano, San Passera. Mezzocammino, Selcetta, Tenuta dell Mandriola, or Tenuta di Tragoria-Quattro Maggiore, (the remaining quarries closest to Ostia).⁴¹⁶ However, they all lie within the range of Colli Albani eruptive materials, including Pozzolane Rosse, Pozzolanelle, and Tufo Lionato. It may be possible to evaluate the known depths of these quarries at different time periods to determine what material was being excavated throughout the life of the mine. Again, comparisons of trace element chemistry of the fine aggregates from mortar and excavated material from various depths of the quarry site may assist with positive identifications, but this is beyond the scope of this project.

415 Quarry data, including location and material output reported in Russell 2013.

416 Russell 2013, Serlorenzi 2014, Buccellato and Coletti 2014.

Less direct evidence may be found in the mineral assemblage associated with the mortar samples. The mineral haüyne was found in one sample each from the Piccolo Mercato and the Insula dell'Ercole Bambino, and both were core samples from structures constructed with Pozzolane Rosse mortar. The mineral was only present in low amounts, observed in thin section but not counted in the point counts. The haüyne was found as loose crystals within the binder, but they were closely associated with large lithic fragments. These large clasts were single examples of a unique type that occurred as incidental inclusions within the mix. Haüyne is a feldspathoid mineral often found associated with deposits formed in a small volcanic crater after water came into contact with magma. These deposits, called maars, occur in the Colli Albani near the Tuscolano-Artemesio caldera (Figure 8.9).⁴¹⁷ The ancient quarry closest to this location was Castrimoenium, most well-known for its peperino tuff that was used as building stone from the Archaic period to the Imperial period (Figure 8.8).⁴¹⁸ It is quite possible these fragments found their way into the mix from the coarse aggregate used in the core of these walls, however its present in mortars from two different structures with the same mortar type indicates some consistency of material selection by the builders who used Pozzolane Rosse mortar.

417 Sottili et al. 2010, 28.

418 Heiken, Funicello and De Rita 2005, 44.

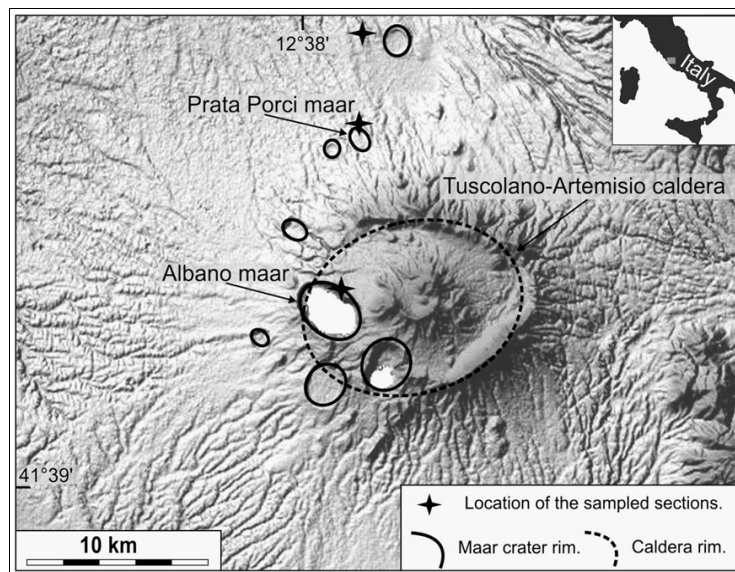


Figure 8.9. Location of the Colli Albani maar deposits. Image from Sottili et al. 2010, 28.

8.3. Material Processing

After aggregate was chosen and sourced, the material would have been processed in preparation for its use in mortar. The size and grading of the aggregate in these samples was recorded to evaluate the type and degree of such processing. The particle size data analysis indicated that all mortar types contained roughly the same grading of material. The largest proportion of material in all samples was silt-sized, suggesting well-sorted aggregates were generally preferred for mortar production. The maximum particle size of Type 1 mortars based on the minimum Feret diameter for these samples was approximately 5-6 mm (see Table 7.9). The maximum size in both of the Type 2 mortars was similarly consistent, approximately 7 mm, while the maximum aggregate size in the Type 3 mixed aggregate mortars varied from 3 to 13 mm. Recent particle size distribution analyses of freshly-dug samples of the aggregates in this study have determ-

ined that the fresh material is mostly gravel and sand-sized.⁴¹⁹ The ancient builders must have sieved or otherwise sorted the larger particles from the quarried material in order to control and regulate the size of aggregate mixed into the mortar. The tightly-controlled size, shape, and gradation across the entire group indicates the standard was widespread and generally accepted as best practice, regardless of the mortar type.

Particle size data have thus far been presented as frequency to illustrate the comparative control of aggregate size. The image analysis process only counted particles greater than 0.0039 mm², which is the distinction between silt- and clay-sized particles on the Wentworth scale. This limitation was chosen because clay-sized particles are generally too small to see with the naked eye, thus particles below this threshold could not have specifically chosen for inclusion. Fine silt is the smallest size that could have been included intentionally. The raw count of particles within this size range was considered in order to evaluate the density of inclusions. In order to account for varying sizes of the thin section images, the number of particles per square millimetre was calculated for each thin section. Comparing these values revealed a moderate level of consistency within the Pozzolane Rosse mortars, as well as within the mixed aggregate mortars (Table 8.3). The two Villa Senni mortars exhibited vastly different counts from each other, but the density was higher in these samples than in the other two mortar types. While these numbers are of limited value on their own, they illustrate once again the inherent differences between mortar types. More importantly, these disparities were designed and controlled by the builders during mortar production. The variations between samples seemed intentional.

419 Cecconi, Scarapazzi and Viggiani 2010, 194.

Table 8.3: Number of particles greater than 0.0039 mm² (clay-sized particles) in each thin section.

	Structure	Number of particles	Sample Dimensions (mm)	No. particles per mm ²
Type 1 – Pozzolane Rosse Mortar	the Casa Basilicale	4817	904.9 x 718.6	134.9
	the Piccolo Mercato	3862	1355.7 x 883.9	310.3
	the Insula dell'Ercole Bambino	4357	1276.6 x 694.8	203.6
Type 2 – Villa Senni Mortar	the Caseggiato del Larario	1322	1444.1 x 841.4	919.1
	the Case a Giardino sample OS-C15	1820	1079.8 x 774.2	459.3
Type 3 – Mixed Aggregate Mortar	the Caseggiato del Serapide	4064	1332.9 x 805.4	264.2
	the Terme del Foro	1933	928.9 x 710.7	341.5

As noted in Chapter 2, particles smaller than 0.63 mm are the best choice to prevent destructive alkali-silica reactions. The median value of the minimum Feret diameter – the most common size by count – was between 0.05 and 0.06 for the Type 1 mortars, between 0.06 and 0.08 for the Type 2 mortars, and a consistent 0.07 for the type 3 mortars, all well under the upper limit (see Table 7.9). Similarly, small particles with greater specific surface improve pozzolanic reactivity. Using the particle perimeter as a proxy for specific surface, the trend for the Ostia samples tended toward the higher end, between 0.45 and 0.71 mm across all samples (Table 7.9). In both cases, the particle size distribution suggested the aggregates chosen for all types of mortar conformed to modern standards and recommendations to ensure durability.

8.4. Mortar Mixing, Preparation, and Emplacement

A well-mixed mortar should show consistency in terms of binder density and the incorporation of the hydrated lime into the binder. Poorly incorporated, under-processed

lime may be the result of poor mixing during original production. While all samples exhibited under- or over-burnt lime, both of the Type 2 Villa Senni mortars exhibited lowest quantity of lime lumps, less than 1% (Table 7.2). The Type 1 Pozzolane Rosse mortars were less consistent, varying from approximately 1% in the Casa Basilicale, the Piccolo Mercato, and the central apartment of the Case a Giardino, to nearly 7% in the façade of the Case a Giardino. Such variation suggests less consistent mixing procedure in the latter structure. The Type 3 mixed aggregate mortars also exhibited inconsistent variation, from no lime lumps counted in the courtyard of the Case a Giardino (though observed in thin section in trace amounts) up to 2% in the Caseggiato del Larario. The variation in quantity of lime lumps could be attributed strictly to poor hydration or physical mixing during the mortar production, but it could also be related to the type, quality, and preparation of the quicklime itself.

Similarly, well-mixed and consistently produced mortar should exhibit similar proportions of matrix and aggregate across multiple samples. The Type 1 Pozzolane Rosse mortars showed some consistency between samples in terms of the proportion of binder (29-31%) to aggregate (60-65%) (Figure 8.10). Likewise, the Type 3 mortars exhibited a variance of less than 10% for both the binder and aggregate components. By contrast, the proportion of binder in the Type 2 Villa Senni mortars varied by more than 10%. Likewise, the variation in the proportion of aggregates in the two samples was over 10% in both structures. The significant difference in the two samples suggests different quality controls applied to the same mix design. The consistency in these data suggested the mix designs for the Type 1 and Type 3 mortars were carefully designed and consistently reproduced by the builders throughout construction. The mortar types exhibited the

most consistency when the samples from the Case a Giardino were discounted from the groups, suggesting unique conditions of production for these mortars.

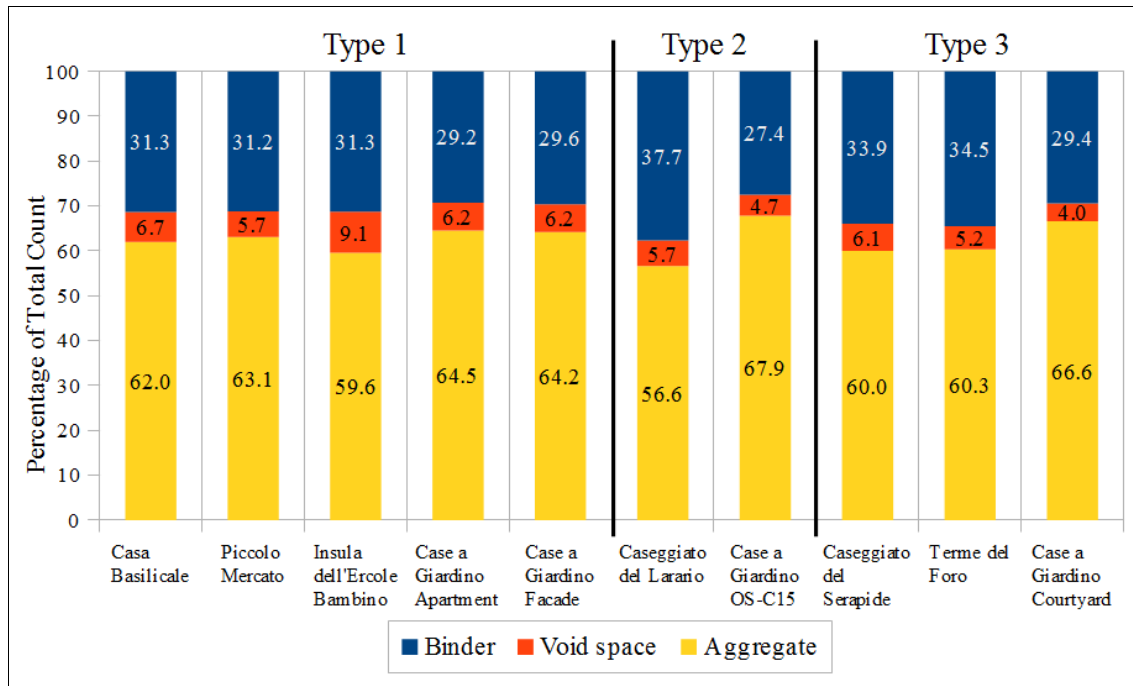


Figure 8.10: Relative proportions of binder, void space, and aggregate components, mean values for each structure, grouped by mortar types.

When the data were ordered according to binder content, the samples from the Case a Giardino showed tightly consistent values for the binder and aggregate proportions regardless of mortar type (Figure 8.11). The implication here was that production conditions were controlled across site, specifically quantities of lime and aggregate, despite variations in aggregates.

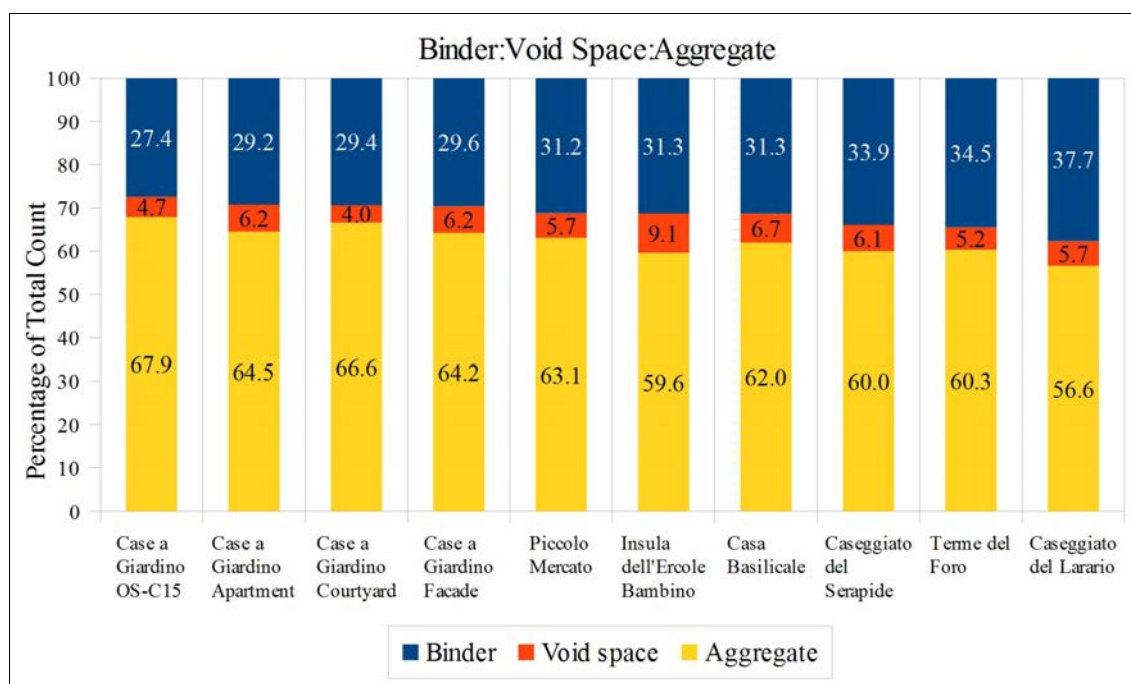


Figure 8.11: Relative proportions of binder, void space, and aggregate components, mean values for each structure, ordered in ascending order of binder content.

There was no clear pattern of facing styles connected to the mortar types identified in this study (Table 8.4). The three structures that contained reticulate facing all contained Type 1 Pozzolane Rosse mortar, including the Casa Basilicale (118 CE), the Piccolo Mercato (118 CE), and the central apartment of the Case a Giardino (125 CE). The remaining structures all utilised brickwork facings only.

The mortar types showed no evidence of any linear evolution when compared by the dates of the structures (Table 8.4). The different mortar types were in use at the same time across the city and even within the same structure, in the case of the Case a Giardino. The earliest structures illustrated this quite well: the Caseggiato del Larario (117 CE) contained Type 2 Villa Senni mortar, whereas the Casa Basilicale (118 CE)

and the Piccolo Mercato (118 CE) were both constructed with Type 1 Pozzolane Rosse mortar. These are the two types with apparently strongly preferred and selected aggregates. The fact that both types were in use at the same time suggests different sources for the supply of aggregate and a clear preference for the material in use.

Table 8.4: Comparison of construction dates, facing styles, and mortar types.

Date	Structure	Facing Styles	Mortar Type
117 CE	the Caseggiato del Larario	Brickwork	Type 2 Villa Senni mortar
118 CE	the Casa Basilicale	Brick and reticulate	Type 1 Pozzolane Rosse mortar
118 CE	the Piccolo Mercato	Brick and reticulate	Type 1 Pozzolane Rosse mortar
125 CE	the Case a Giardino sample OS-C15	unknown	Type 2 Villa Senni mortar
125 CE	the Case a Giardino central apartment	Brick and reticulate	Type 1 Pozzolane Rosse mortar
125 CE	the Case a Giardino façade	Brickwork	Type 1 Pozzolane Rosse mortar
125 CE	the Case a Giardino courtyard	Brickwork	Type 3 mixed aggregate mortar
125 CE	the Caseggiato del Serapide	Brickwork	Type 3 mixed aggregate mortar
130 CE	the Insula dell'Ercole Bambino	Brickwork	Type 1 Pozzolane Rosse mortar
160 CE	the Terme del Foro	Brickwork	Type 3 mixed aggregate mortar

8.5. Mortar performance and durability

In general, the performance of ancient mortar can only be discussed in terms of its current condition and resistance to degradation. The fact that these structures are all still standing – with only limited modern repair – proves they have performed to a somewhat equal standard.

Mortar durability was evaluated first by the physical properties of the samples observed with visual inspection. As noted above, the hand samples of Pozzolane Rosse mortar were more friable and less cohesive than the other types. The samples of this mortar also showed the most sample loss during handling and preparation for thin sec-

tion and SEM analyses, represented by consistently high irregular void space (Table 8.5). Microscopic cracks and the interconnectedness of void space can indicate the extent of mortar of degradation. All samples from all structures exhibited fine structural cracks in the matrix, often spanning between voids, though in all cases the cracking was a fairly low percentage of the total void space. Despite its friability, the Type 1 Pozzolane Rosse mortar was no more or less susceptible to cracking than the other mortar types.

Table 8.5: Abundance of linear cracks and irregular voids in all structures, expressed as percentage of the total count of all samples in each structure.

	Structure	Linear Cracks	Irregular Voids	Total
Type 1 – Pozzolane Rosse Mortar	the Casa Basilicale	0.8	5.9	6.7
	the Piccolo Mercato	1.1	4.6	5.7
	the Insula dell'Ercole Bambino	0.8	8.3	9.1
	the Case a Giardino central apartment	2.5	3.7	6.2
	the Case a Giardino façade	0.2	6.0	6.2
Type 2 – Villa Senni Mortar	the Caseggiato del Larario	0.8	5.0	5.8
	the Case a Giardino sample OS-C15	1.6	3.1	4.7
Type 3 – Mixed Aggregate Mortar	the Caseggiato del Serapide	1.4	4.7	6.1
	the Terme del Foro	1.0	4.1	5.2
	the Case a Giardino courtyard	0.3	3.7	4.0

In addition to cracks and voids, mortar performance can be evaluated by the presence or absence of certain minerals that can form in the binder as destructive alteration products, suggesting a poor performing mortar. According to Benedetti *et al*, the presence of sulphates, chlorides, or nitrates in a mortar sample indicates the degree of degradation.⁴²⁰ Very low amounts or the complete absence of these phases would indicate

⁴²⁰ Benedetti et al, 2004.

a relatively well-preserved mortar. Gypsum is a sulphate mineral that precipitates in mortar when atmospheric pollutants interact with the calcium carbonate in the binder.⁴²¹

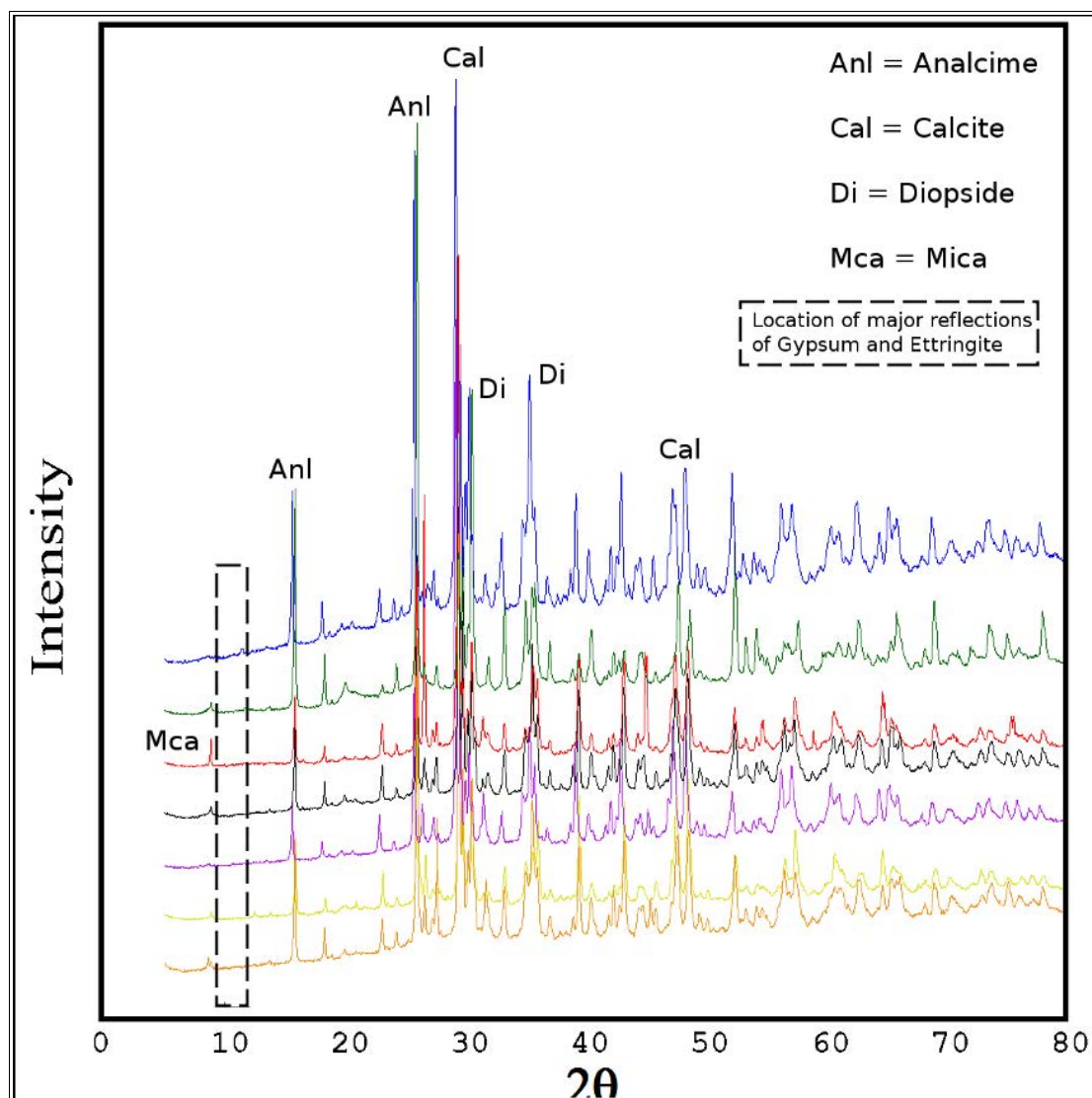


Figure 8.12: Detail of diffractograms showing the absence of major reflections for mineral phases commonly indicative of mortar alteration.

421 Sabbioni et al. 2001, 545.

The absence of ettringite ($\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12}\cdot 26\text{H}_2\text{O}$) offers further evidence that these mortars from the 2nd century CE were formulated for long-term durability. Ettringite can form early during mortar hydration, in which case it remains a benign component, or secondarily when sulphates attack the mortar's binder component – a process called delayed ettringite formation.⁴²² The required sulphates usually would come from gypsum in the binder. Secondary ettringite is a destructive by-product of alteration that physically breaks the bonds in the binder as the crystals expand. In either case, gypsum is required to provide the necessary sulphate component. The lack of ettringite is not surprising given the absence of gypsum in the majority of the samples. All mortar types in this study have been spared the destructive force of delayed ettringite formation.

The low amorphous component in samples from the Caseggiato del Larario (Type 2 Villa Senni mortar) and the Terme del Foro (Type 3 Mixed Aggregate mortar) indicated a lower abundance of amorphous materials such as fresh volcanic glass, opaline silica, or cementitious gel in these two samples. Whether this pattern is the result of mortar composition, mortar degradation, or the result of sample preparation techniques is difficult – if not impossible – to determine from XRD results alone. Thin section investigation showed no truly fresh glass in any of the samples, as all volcanic material was altered to some degree. Opaline silica was present in the vesicles of Pozzolane Rosse aggregate, which was only present in minor proportions in these two samples. A higher amorphous component may be indicative of the Type 1 Pozzolane Rosse mortar.

422 Sabbioni et al. 2001, 546.

The builders' incorporation of naturally pozzolanic fine aggregates should have improved the durability of their mortars. The evidence for pozzolanic reactivity in the mortars here was seen with both the optical and electron microscope. Thin section analysis showed that clays had been consumed from the rims of fine aggregate clasts, binder material had penetrated into aggregate particles, and in rare cases the fine aggregate clast itself had been replaced by the calcitic binder. Elemental maps produced by the SEM illustrated that the binder matrices of all three mortar types exhibited a fairly even distribution of potassium and sodium, alkalis that were absent from the lime particles. These would have been contributed from the dissolution of these elements from the fine aggregates and incorporation into the binder during the pozzolanic reaction.

The movement of binder through a mortar can indicate that it has been subjected to degradation in the form of dissolution. However, the fact that it has redeposited within the void spaces, as seen in several of the samples in this study, suggests the mortar is still somewhat cohesive, structurally sound, and relatively impermeable. The binder material cannot penetrate through to the mortar surface, where it would be washed away, so it stays within the system contributing to the mortar durability. As noted in Chapter 7, SEM analysis of the mortars showed a tendency toward retention of binder material within the system and relatively little dissolution in general.

The mortar from the Terme del Foro exhibited the most evidence for binder redeposition, including spherical voids and holes that been either heavily lined or completely filled with binder. This mixed aggregate mortar included aggregate that was not selected specifically for its pozzolanic properties. The weakness of the matrix structure may be the result of chemical processes indicating the pozzolanic reaction had not gone

to completion. However it was also possible that the mortar may have been made weaker by its location in the heated rooms of the bath house. These rooms would have been subjected to more moisture than the other structures because of the heating system in the buildings, which included ceramic *tubuli* attached to the walls that carried heat and humidity into the *caldarium*. Apparently the degradation of mortar from the Terme del Foro was exacerbated by the conditions in the building.

8.6. Chapter Conclusion

Results from analytical data have made it possible to derive new information about the various types of mortar used in Ostia in the 2nd century CE. The structures in this study have been shown to represent three types of mortar, all distinguished by their unique aggregate profiles. It has been made clear that the size and abundance of each material was carefully selected and controlled during mortar production and installation. The different mortar types have apparently performed to the same standard, strongly suggesting the individual mixes were formulated to achieve the same results.

The application of the different mortar types was not apparently related to the type of structure, date of construction, location within Ostia, style and material components of the building facings, or even the location within the walls themselves (i.e. core or facing). The absence of an obvious social, structural, or mechanical influence on the type of mortar used suggests the pattern can be attributed to the builders themselves.

The structures built with the Type 1 Pozzolane Rosse mortar was found in the Piccolo Mercato, the Casa Basilicale, the Insula dell'Ercole Bambino, and some elements of the Casa a Giardino. DeLaine investigated these structures for architectural details

and identified connections between the Piccolo Mercato and the Case a Giardino. She identified that these structures had what she described as the same “basic construction scheme” that included similar brick assemblages and decorative features at the main entrances and façades; similar connections were identified between the Case a Giardino and the Insula dell'Ercole Bambino, specifically in the design of the central apartments.⁴²³

According to DeLaine's study, the Casa Basilicale was evidently constructed by different contractors than other structures within Insula I, which included the Caseggiato del Larario. The most notable difference was the pattern and placement of brick types and the use of reticulate for the interior walls, which were entirely missing from the Caseggiato del Larario, offering a strong argument for different contractors and different workmen.⁴²⁴ Different contractors hiring their own workmen have apparently dictated different types of mortar or preferred sources of fine aggregates.

The Caseggiato del Larario almost uniquely contained the Type 2 Villa Senni mortar (the only other example was the unprovenenced sample from the Case a Giardino). DeLaine included the Caseggiato del Larario within a group that exhibits shared specific construction details, including distinctive L-shaped door jambs, extensive use of travertine blocks, and different materials for primary and secondary walls.⁴²⁵ The implication is that construction activities and materials for these structures were controlled centrally by an architect or a contractor.⁴²⁶ The Caseggiato del Larario was the only structure from this group to have been examined in this study, but it is possible the cent-

423 DeLaine 2002, 73.

424 DeLaine 2002, 44.

425 DeLaine 2002, 47.

426 DeLaine 2002, 48.

ral control extended to mortar production and aggregate selection. If so, the others would most likely have been built with the Villa Senni mortar as well. Analysis of mortar samples from the remaining structures could help verify the consistency of mortar production within this group of structures, further distinguishing this group of builders.

The Terme del Foro and the Caseggiato del Serapide both exhibited Type 3 Mixed Aggregate mortars. DeLaine described these structures as two of only “a few exceptional buildings” for having been designed and built by architects or workers from Rome.⁴²⁷ The nature of the mixed aggregates with epiclastic textures and alteration features is consistent with the Aurelia and San Paolo formations, which were quarried for aggregates in Rome. It is entirely possible that contractors, architects, or other workmen coming from Rome may have secured materials from well-established sources with whom they had previous working relationships.

The choices made by the ancient builders have left direct, measurable effects on the mortar which have affected their durability. The observed data have led to new information about the mortar, from which new information about the ancient construction industry has been inferred. These data have been used to evaluate the hypotheses formed by other authors regarding groups of builders within Ostia. The next chapter presents the conclusions that have been reached about the ancient builders, their choices, and their expertise.

427 DeLaine 2002, 76.

Chapter 9. Conclusion

The theoretical framework developed for this project and presented in Chapter 1 has greatly informed the research design. This exercise has allowed key aspects of ancient mortar production to be identified and placed within specific contexts of study. It is clear from the literature review that the structural, archaeo-historical, and geological aspects of lime-based mortar are interrelated, and they must be studied in tandem to generate useful discourse. The long history of mortar evolution is the result of builders who possessed the technical skills to experiment with new materials to improve upon traditional methods. The builders of Ostia in the 2nd century CE were beneficiaries of technological advancements and were able to make good use of the material. It is from this perspective that this project began: the material evidence can provide new information about the skills and practices of the ancient builders.

A combination of traditional archaeological research and scientific methods has been employed. By applying the *chaîne opératoire* approach to the subject, this research has addressed questions regarding the abilities, intent, and skill of the individuals who had a hand in producing the mortar. Evaluating the operational sequence of mortar production revealed the complexity of the process and the number of steps involved, all of which required the expertise of skilled decision makers. The choices made at every step left their marks on the mortar, and material analysis revealed a great deal about those choices and the individuals who made them. Approaching the topic in this way also made clear the aspects of mortar production that could provide the most measurable, and therefore reliable, information about the mortar production process. Following an analytical protocol of traditional petrographic techniques meant that the integrity of res-

ults are easily evaluated and can be compared to published studies conducted with the same methods.

The buildings selected for this project were all part of previous structural and architectural assessments by DeLaine which sought to identify unique builders groups working in Ostia in the 2nd century.⁴²⁸ This was an era when brick and mortar masonry was widespread in Ostia, which suggests the members of the construction industry shared traditions in both aesthetics and building techniques. This research was designed not only to address the question of who was producing different mortars in these structures, but also to identify how they were doing it and to assess their results.

Analytical results showed that the mortar aggregates were specifically chosen and imported from the Roman volcanic province apparently for their beneficial properties. Unsurprisingly, the common type of aggregate was volcanic tuff, which was ubiquitous in the Roman volcanic province. Different lithological units were represented in the aggregate profiles, including material from both the Monti Sabatini and Colli Albani volcanic districts. Material from Monti Sabatini was used in relatively low quantities, primarily as filler material. Tuffs from Colli Albani were included as reactive aggregates that facilitated the pozzolanic reaction, which fostered the growth of beneficial cements and improved durability. Particle size analysis revealed that the aggregates were processed to control size and shape in ways that are consistent with the standards of modern mortar production.

Material selection and handling was obviously an important step in the operational sequence, and the choices made by the builders have proven to be both sophisticated and technically sound. Quantitative analysis of mortar components produced clear ag-

428 DeLaine 2002.

gregate profiles for the mortars, allowing each to be evaluated alone and compared across the sample set. Three distinct types of mortar were identified based on the material properties and dominant aggregate material identified in each sample. The same types of aggregates have been previously identified in mortars from several monumental structures in Rome using scientific techniques similar to those in this study.⁴²⁹ This consistency creates a reliable comparison of analytical results and at least a superficial connection between the material provenance and supply lines between Rome and Ostia.

Because this research was intended to move beyond just simple material analysis, the mortar types were further evaluated from within the three contexts of study established in the theoretical framework developed for this project. The archaeological context addressed the question of the builders themselves, their working groups, and material selection for mortar production. The Type 1 Pozzolane Rosse mortars (from the Casa Basilicale, the Piccolo Mercato, the Insula dell'Ercole Bambino, and the main façade and the apartments of the Case a Giardino) roughly aligned with what DeLaine determined was a possible single working group. Results of all analyses showed a strong correlation specifically between the samples from the Casa Basilicale and the Piccolo Mercato, which were actually being constructed concurrently in c. 118 CE. While the Insula dell'Ercole Bambino (130 CE) did not seem to fit with these two structures regarding particle size, mixing parameters, or structural features, it did share structural features with the Case a Giardino (125 CE). It is possible these relationships represent the difference in mortar batches that were produced decades apart, possibly by the same working groups using the same basic mix design. The similar type, size, shape, relative abundance, state of preservation, and petrographic features of mortar samples from the Type 1

429 Jackson et al. 2005; Jackson and Marra 2006; Jackson et al 2009; Jackson and Kosso 2013.

Pozzolane Rosse mortars suggests they were produced to the same specifications using the same design mix. This, combined with the shared structural features within the properties themselves, strongly supports the hypotheses that these structures were built by the same group of builders, or perhaps closely associated groups that shared resources and technical practices. In future work, the degree of similarity in these structural features properties could be used as a baseline for identifying single or connected working groups of builders.

The Type 2 Villa Senni mortar dominated by Pozzolanelle and Tufo Lionato from the Villa Senni eruption of Colli Albani was identified in the Caseggiato del Larario and in one core sample from the Case a Giardino. DeLaine assigned the Caseggiato del Larario to a group of buildings that exhibited distinctive structural features, which suggested that they may have been designed and/or built by the same architect, contractor, or workmen.⁴³⁰ The aggregate profile of this mortar was equally distinctive, and this presents a good opportunity for future work to determine whether the mortar from the remaining structures in DeLaine's group can also be classified as the Type 2 Villa Senni mortar.

The remaining two structures, the Caseggiato del Serapide and the Terme del Foro, were built with Type 3 Mixed Aggregate mortar, which contained a mix of materials exhibiting epiclastic textures. These materials were consistent with aggregates known to have been extracted from quarries in Rome, where they were used as aggregates in mortars. It is perhaps no coincidence, then, that these buildings also exhibited construction features that may have been designed and/or built by contractors and workmen from Rome.

430 DeLaine 2002.

The structural context of study addressed how the individual mortar types related to structural design as well as mortar quality and durability. No reliable correlations were made between mortar types and structure type, brick profiles, construction techniques, facing styles, or any other specific structural aspect of the buildings in this study. This raises the question of why the different groups exist and suggests the answer is not as simple as basic mechanical variations.

The final hurdle to understanding the mortar and aggregate preparation techniques was identification of the geological source of the identified materials and their material properties. First and foremost, aggregates are lithics that still behave in geological ways. The lithological materials in these mortars are highly altered volcanics that contain clays and zeolites (in the case of Pozzolane Rosse and the Villa Senni materials). These alteration products have been shown to facilitate the pozzolanic reaction, which, as has been shown, greatly improves the mortar performance. These materials were presumably selected for their superior performance within the mortar.

The fact that the three mortar types were so clearly distinct suggests these mortars were intentionally formulated in different ways. Although aggregates were clearly sorted for size, it is not likely that the builders were collecting material from a single source and then separating out the different materials. The more plausible hypothesis is that the three types of aggregate were procured from different sources, which is the final context of study that was addressed in this project. The most likely extraction source for the Pozzolane Rosse used in Ostia would have been one of the established sources supplying the material for construction in Rome. Although material from the Pozzolane Rosse quarry at the base of the Palatine Hill could have been easily and relatively inex-

pensively shipped to Ostia down the Tiber River, this is not necessarily the most likely source. By the Imperial period the area had become urbanized and the Palatine became the home of the imperial palace. The quarry would have almost certainly ceased operation, but the lithological units would have outcropped elsewhere in the areas. One of the quarries close to the city of Rome is still a possible source for Pozzolane Rosse. A number of quarries for Tufo Lionato have been identified north of Rome, any of which could have produced fine aggregate materials as a byproduct. The question of where the mixed epiclastic aggregate was collected is nearly impossible to answer, as this material was deposited secondarily all along the Tiber River and its tributaries. The degree of alteration further complicates the question of material source, because the provenance of weathered materials is notoriously difficult to determine. Further examination of the authigenic clay coatings may help identify the source of final deposition and eventual extraction.

Mechanically, the original source of mortar aggregate is less important than how it performs. The three types of mortar performed fairly consistently. None of the mortars showed evidence of sulphate attack or the growth of deleterious materials, but they all fostered self-healing and the growth of fibrous cements in cracks and voids. Apparently the mortar mix designs determined with this study were similar in terms of performance and durability. This again raises the question why these separate formulations were developed.

Different mortar types were not related to the style or materials observed in the building facings, the quality of mortar performance, or cultural function of the buildings. Having ruled out the purely archaeological, structural, or material impetus behind

separate mix designs, the most plausible remaining hypothesis is the personal. The different mixes may have been unique to specific groups of builders using their own mix designs that performed to the same standard. Further research could be undertaken to verify or falsify the hypothesis that different mortar types were used by different groups of builders. It would be possible analyse additional samples of mortar from within the groups identified by DeLaine in order to confirm the mortar types. Identifying more examples of mortar with these particular mix designs could improve current understanding of mortar production technology and the builders who produced it.

The three contexts of study introduced at the start of this research serve as a framework for understanding the wider implications of the results produced in this research. The selection and use of materials with the specific benefits described above implies practical sophistication of the skill, workmanship, craftsmanship, and engineering understanding demonstrated by the ancient builders. This study also has revealed sophistication within the building trade itself, directly related to the fine aggregates that were the main focus of this research.

The identification of specific mix designs with distinctive fine aggregate profiles suggests the material was specially chosen for an intentional reason. While it is not possible to accurately intuit any specific reason for the choices made by these ancient builders, the consistently good durability of the mortars does suggest the possibility they were selecting material to enhance performance. As mentioned above, the type, quantity, morphology, and proportions of the mortar components were consistent with international standards for modern mortar production. It can hardly be an accident that this consistency remains true in all of the samples investigated from all structures, suggest-

ing there may have been some accepted standard practices or even a degree of regulation within the building trade in ancient Ostia.

Regardless of whether or not the ancient builders understood the inherent benefits of the pozzolanic fine aggregates they were using, this research has shown they targeted specific types of material. Given this, the fine aggregates should be considered a tangible commodity within the building trade. It was a consumable resource, much like bricks, building stone, and lime. Resources require an associated industrial infrastructure to facilitate the collection, storage, transport, and potential sale of these goods. The implication here is an added level of complexity within the construction industry. Someone had to quarry the material; and collection sites needed to be managed, maintained, and staffed. The material would have required storage after collection, if only temporarily at the start of building projects. The material had to be transported to the building site, either by cart, by boat, or by ship, again adding complexity to the system.⁴³¹

No assumptions have been made here about whether this would have been a discrete trade of its own accord or if the resource was traded opportunistically alongside established quarry works. Either way, the treatment of this material as a traded commodity (rather than an incidental to be acquired on site) creates an additional line item in the construction budget. Doing so raises questions of inherent value, pricing schedules and trade negotiations, and cost:benefit assessments during material selection. Initial assessments of potential sources suggest that better quality aggregates like Pozzo-

431 Verifying specific transport methods is beyond the scope of this project, but there is known precedent for large shipments of pozzolanic aggregates. The ROMACONS research group has determined that volcanic material from the Bay of Naples was shipped across the Mediterranean Sea to be used in the construction of the harbour works at Caesarea Palaestinae (Brandon et al. 2014, 77).

lane Rosse and Tufo Lionato were brought from further afield than was hypothesised at the start of this project. An interesting avenue of further research would be to map the use of these aggregates throughout Italy (and perhaps beyond) to determine the range of its use. Determining the spread of use, it would be possible to estimate material cost across the region based on the transportation cost model discussed by DeLaine and mentioned above.

This work has made clear the sophistication of the material itself, which in turn implies sophistication in its production. Following this logic creates an evocative picture of a highly evolved and fully realised system associated with mortar production. The picture of the system on the macro-scale has been made possible through rigorous scientific analysis of the material at the micro-scale.

Chapter 10. References

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Appendix A - Terminology

From: “Applied Petrography Group Special Report : SR3 Part 2: Concrete Terminology” (abridged)

Admixture – A substance other than binder, aggregate or water, added in small quantities to the concrete mix to alter its properties. These include chemical admixtures such as accelerators, plasticizers, and air-entraining agents and mineral additions such as pozzolanas.

Aggregate - Granular material used in construction, either processed from natural materials such as rock, gravel or sand, recycled materials, or manufactured such as slag. (BS 6100-6: 2008)(EN 13242, EN 12620).

Aggregate shrinkage - Some types of aggregates such as weathered basalts and greywackes contain significant quantities of swelling sheet silicate minerals that can undergo volume changes during cycles of wetting and drying. This can contribute to a shrinkage within the concrete.

Air-entrainment – Air entrainment is a process whereby many small air bubbles (typically between 10 µm and 1mm in diameter) are introduced into concrete. Entrained air has a lubricating effect on plastic cement paste and produces more workable concretes and mortars. The primary purpose is to increase the durability of the hardened concrete, especially in increasing resistance to freeze-thaw; the secondary purpose is to increase workability of the concrete while in a plastic state.

Air void – A space in cement paste, mortar, or concrete filled with air; an entrapped air void is characteristically 1 mm or more in size and irregular in shape. Air voids can be described as entrained (typically <1mm sized) or entrapped (typically

>1mm sized). Entrained air voids are a deliberate addition that can improve the durability of a concrete.

Alite – $(3 \text{ CaO} \cdot \text{SiO}_2)$ (C_3S) Tricalcium silicate, a calcium silicate and makes up the dominant part of Portland cement. Forms large euhedral pseudo-hexagonal crystals.

Alkali-silica reaction (ASR) – The reaction between the alkalis (sodium and potassium) in Portland cement binder, moisture and certain siliceous rocks or minerals, such as opaline chert, microcrystalline quartz, and acidic volcanic glass, present in some aggregates; the products of the reaction may cause abnormal expansion and cracking of concrete in service.

Alkali-aggregate reaction (AAR) – A general term covering both ASR and ACR. Chemical reaction in mortar or concrete between alkalis (sodium and potassium) released from Portland cement or from other sources, and certain compounds present in the aggregates; under certain conditions, harmful expansion of the concrete or mortar may be produced.

Alkali-carbonate reaction (ACR) – The reaction between the alkalis (sodium and potassium) in Portland cement binder and certain carbonate rocks, particularly calcitic dolomite and dolomitic limestones, containing finely divided clay, present in some aggregates.

All-in aggregate – Aggregate consisting of a mixture of coarse aggregate and fine aggregates. NOTE: It may be produced without separating into coarse and fine fractions, or it may be produced by combining coarse and fine aggregates. (BS 882:1992) (EN1260).

Anhydrite – CaSO_4 . Produced by calcining (heating at high temperature but below

the melting or fusing point) gypsum to temperatures in excess of 400 °C to produce anhydrite.

Anhydrous Portland cement phases – Mineral phases present in cement powders or clinkers. Portland cement contains four principal phases, tricalcium silicate, β -dicalcium silicate, tricalcium aluminate and tetracalcium aluminoferrite.

Artificial aggregates – Industrial by-products (blastfurnace slags, steel slags, lead-zinc slags) and industrial and municipal wastes (fly ash, ash, clinker, demolition wastes).

Bauxite – An off-white, greyish, brown, yellow, or reddish-brown rock composed of a mixture of various amorphous or crystalline hydrous aluminium oxides and aluminium hydroxides along with free silica, iron hydroxides, and especially clay minerals; a highly aluminous laterite. Bauxite is the principle commercial source of aluminium; the term is also used collectively for lateritic aluminous ores.

Belite – Dicalcium silicate. $(2\text{CaO} \cdot \text{SiO}_2)$ (C_2S) A calcium orthosilicate present as a constituent of Portland cement clinkers (see also felite).

Bleeding – Separation of water from the cement matrix of mortar or concrete after placing. Two types are recognised, water flows out to lie on the surface after compaction and water that segregates under aggregate, steel reinforcement and so runs up the interfaces between the concrete and formwork during or after compaction.

Blended Aggregate – Coarse or fine aggregate produced by the controlled blending of selected size gradings of gravel or crushed rock.

Blended Coarse Aggregate – Coarse aggregate produced by the controlled blending of gravel and crushed rock. (BS 882:1992).

Blended sand – Fine aggregate produced by the controlled mixing two or more size fractions in order to meet a specific grading requirement. (BS 882:1992).

Bound Aggregates – Aggregates mixed bound together with resin, hydraulic cement or bitumen. Typical uses include pavements, pavement surfacing or decorative features.

Brucite – A hexagonal mineral: $\text{Mg}(\text{OH})_2$. Can be found as fine-grained encrustations and fillings in concrete attacked by seawater.

Calcium silicate products – Calcium silicate products consist of a mixture either of siliceous sand or flour and about 10 - 15% of a well slaked, high calcium lime or pulverised quick lime. The mixture is pressure moulded while still ‘green’ and the product autoclaved for about 16 hours at around 170°C .

Calcium sulphate – see anhydrite.

Calcium sulphate hydrate – see gypsum.

Carbonation (in lime mortar) - The process by which lime (calcium hydroxide, $\text{Ca}(\text{OH})_2$) reabsorbs carbon dioxide (CO_2) from the ambient environment and reverts to calcium carbonate (CaCO_3). As a result of this chemical change the lime mortar becomes harder, more stable and less soluble than in its uncarbonated form.

Chalcedony – A cryptocrystalline, sometimes fibrous, variety of quartz. It has a lower density and lower indices of refraction than ordinary quartz.

Chert – A hard, extremely dense or compact, dull to semivitreous, microcrystalline or cryptocrystalline sedimentary rock, which may contain amorphous silica. Chert occurs principally as nodular or concretionary segregations in limestones and dolomites, and less commonly as really extensive layered deposits; it may be an original organic or

inorganic precipitate or a replacement product.

Clinker - The sintered product of burning limestone and an aluminosilicate rock (clay or shale) at temperatures of up to 1500 °C is known as Portland cement 'clinker'. The grey powder generally called 'cement' is produced by inter-grinding the clinker and ~5% gypsum to act as an early set retarder.

Coarse aggregate – Aggregate for use in concrete of which not less than 90% is retained on a 5mm test sieve. (BS 1047 : 1983). 4.75mm in the USA (ASTM C33), 4mm (BS EN 12620). In Europe the definition refers to the larger aggregate sizes with D greater than or equal to 4 mm and d greater than or equal to 2 mm (EN 12620).

Compaction – The process whereby the volume of freshly placed mortar or concrete is reduced to the minimum practical space, usually by vibration, centrifugation, tamping, or some combination of these; to mould it within forms or moulds and around embedded parts and reinforcement, and to eliminate voids other than entrained air.

DEF (delayed ettringite formation) – A form of sulphate attack where the source of sulphate is internally derived from the cement rather than from an external source. It is an expansive reaction resulting from the delayed formation of ettringite in a concrete subjected to temperatures above 60°C during curing and a moist environment.

Drying Shrinkage - The loss of moisture from a concrete or mortar either during setting or after hardening leads to a volume shrinkage which, if of sufficient magnitude, may lead to the development of cracks. Although the shrinkage is directionally proportional to the loss of water for simple laboratory cement paste specimens, aggregate type, grain sizes, mix design and curing conditions all influence the amount and pattern of drying shrinkage.

Efflorescence – superficial coating on concrete surfaces and from cracks due to moisture movement and bleaching of soluble salts from the concrete, evaporation and precipitation of the salts on the surface. The most common is calcium carbonate.

Entrained Air – See Air Entrained

Ettringite – $3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 26-32\text{H}_2\text{O}$ A calcium-sulpho-aluminate-hydrate mineral. Very common in voids in concrete where moisture ingress has occurred. Found in substantial quantities in cracks where sulfate attack has occurred.

Felite – An out-dated name given to dicalcium silicate, usually $\beta\text{C}_2\text{S}$, see also belite.

Fine aggregate – Concrete and mortar. The portion of an aggregate consisting of particles passing a 5mm BS882 test sieve, but retained on a 75 μm sieve, within specified limits. European Standard, EN 12620 sets a 4mm upper limit and ASTM, C125, specifies particles passing 4.76mm sieve but retained on a 75 μm sieve. The European designation refers to the smaller aggregate sizes with D less than or equal to 4 mm. NOTE Fine aggregate can be produced from natural disintegration of rock or gravel and/or by the crushing of rock or gravel or processing of manufactured aggregate (EN 12620).

Flint aggregate – A chert (a compact cryptocrystalline form of silica) originating as nodules or layers in Cretaceous chalk.

Freeze-thaw action/damage – The mechanical weathering process caused by alternate or repeated cycles of freezing and thawing of water in pores, cracks and other openings. Damage is usually most severe close to the concrete surface.

Frost damage - Characteristic features of hardened concrete affected by frost

damage are typically the development of shallow surface- parallel cracking, degradation of surface concrete and evidence for moisture ingress such as secondary ettringite formation within voids.

Glass – Synthetic or natural amorphous solid formed by rapid cooling which prevents crystallisation.

Grading of aggregates - The proportional distribution of particles of granular material of various sizes established by sieving, usually expressed in terms of cumulative mass percentages larger or smaller than each of a series of sizes (sieve openings), or the percentages between certain ranges of sizes. The European definition is given as the particle size distribution expressed as the percentage by mass passing a specified set of sieves. (EN 13242 and 12620)

Gravel – Natural coarse aggregate derived from unconsolidated deposits.

Gypsum – Calcium sulphate hydrate $(\text{CaSO}_4)_2\text{H}_2\text{O}$. A natural mineral which is associated with evaporate deposits, but may also be developed in concrete and mortars attacked by sulphate solutions and sea water.

Hardened cement paste – The cementitious matrix between aggregate particles. Portland cement pastes are principally composed of calcium silicate hydrates, calcium hydroxide and calcium aluminium hydrates.

Hydrated cement phases – The four principle cement constituents C_3S , C_2S , C_3A and CAF are each hydraulic and thus react with water on mixing to form a range of hydrated phases and calcium hydroxide. These have the general identification of calcium, silicate hydrates or CSH.

Hydraulic limes – A dry powder obtained from calcining limestone containing

clay materials, or a mixture of similar composition, and fired at temperatures up to 1250°C. Hydraulic lime contains a mix of hydrated lime, silicates and aluminates. Hardening occurs through direct reaction with water and by carbonation.

Leaching – Removal of soluble salts by water percolating through permeable material. With Portland cement concrete leaching often results in depletion of portlandite and other water-soluble components in cement paste.

Light weight aggregate – Natural or artificial aggregate materials of high porosity and low apparent specific gravity with aggregate bulk density of 400 – 1200kg/m³ (BS 3797, 1990). The European Standards definition is an aggregate of mineral origin having a particle density not exceeding 2000 kg/m³ (2,00 Mg/m³) or a loose bulk density not exceeding 1200 kg/m³ (1,20 Mg/m³) (EN 13055-1).

Lime – Quicklime, CaO, formed by calcining limestone at temperatures in excess of 900°C in hydrated form used in mortars and plasters and the manufacture of bricks, blocks etc. Both hydrated and quick limes are used extensively to stabilise soils especially in road construction.

Long-term drying shrinkage - Shrinkage cracking that takes place months or years after concrete has hardened. Cracks commonly appear mid-way between shrinkage joints on slabs and panels. The cracks pass through aggregate particles and the cement paste and tend to be parallel-sided.

Micropore – A small pore less than 10nm in diameter in hydrated cement paste. Two types are recognised, gel pores in CSH gel and slightly larger capillary pores originally occupied by air or mix water not used in the hydration.

Microporosity – Capillary porosity allows water movement through the

cementitious matrix, whereas the smaller gel pores are mostly isolated so have minimum permeability.

Mortar - A material composed of one or more inorganic cementitious binders, fine aggregate, water and admixtures used in brick and masonry construction to provide for bedding, jointing and bonding of brick or masonry units.

No-fines aggregate – Aggregate in which there is a minimum of particles passing a 10 mm test sieve. (BS 1047 : 1983).

Particle shape – The physical shape of particles in a concrete aggregate. Particle shape will significantly influence the properties of the mix as well as the degree of cement/aggregate bonding and component interlock within concrete and consequently the workability and ultimate strength of the concrete. Shapes are often described as equant, tabular, flaky elongate irregular and in terms of roundness and sphericity.

Particle size distribution – see grading.

Partly Crushed – Natural gravel with the over size material crushed to reduce its size to the specified grading requirement.

Peripheral cracks – Cracks that develop around aggregate particles in hardened concrete sometimes produced by aggregate shrinkage or by material defects or reaction such as differential thermal effects, non-adhesion between aggregate and cement matrix or delayed ettringite formation.

Petrography – The systematic description and classification of rock in hand specimen and thin section. In the context of concrete it is concerned with identifying aggregates, cementitious binders and features of deterioration.

Plastic shrinkage cracking – Early stage network cracking which initiates before

concrete has hardened. It may indicate poor curing, high water/cement ratios and/or excessive trowelling of the concrete surface. Cracks of this type tend to be restricted to the cement paste and commonly decrease in width rapidly with depth.

Point counting – A statistical method of counting features such as air voids or aggregate types on polished plates or thin sections using a binocular or petrological microscope. This is accomplished by incrementally stepping in x and y directions across the surface of the specimen, identifying the presence or absence of the feature of interest at each step. A method is described in ASTM C457 where it is used to measure volume proportions of features such as aggregate, paste and voids.

Portland cement – A world-wide and ubiquitous constructional material. A range of Portland cements are in use. They are all manufactured by heating crushed limestone and clay or shale at temperatures in excess of 1200°C. The resulting clinker is ground to a fine powder. Gypsum and other materials may be added or blended into the powder. The types differ in the proportions of the anhydrous minerals they contain, the possible additions of mineral admixtures and their particle size distributions. First patented in 1824.

Portland cement phases – See anhydrous Portland cement phases.

Portland limestone cement – 6 – 20% of limestone may be interground with Portland cement clinker. It primarily acts as a diluent allowing the production of a cement requiring less energy input for its manufacture. (BS 7583, 1996)

Portlandite - Calcium hydroxide mineral name, Ca(OH)_2 , one of the products of Portland cement hydration. Portlandite crystals tend to be more abundant and more coarsely crystalline as the water content of concrete mix is increased.

Pozzolana – Originally a volcanic dust used at Pozzuoli, Italy. A siliceous, or siliceous and aluminous material, which in itself possesses little or no hydraulic property but in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures in hydrating cement to form compounds possessing hydraulic properties.

Pseudomorphically hydrated cement- Hydrated cement grains retaining the structure of the original anhydrous grain but replaced by cement hydrates. It is a possible indicator of secondary cement hydration.

Rosin analysis - A linear traverse method used for measurement of volume proportions of aggregates or voids in thin sections or polished plates. (see also modal analysis).

Sand – A commonly used term for a fine grained material with maximum size of 5mm (UK) 4mm (EU) 4.75mm (USA). Typically for concrete or mortar fine aggregate passing a 5.0 mm BS 410 test sieve and containing no more coarser material than is permitted for the various gradings in the specification BS 882, 1992. (see also Fine Aggregate)

Partially crushed – Aggregate produced from a mixture of uncrushed sand and crushed sand resulting from the crushing of associated particles during product processing. (BS 882, 1992).

Secondary cement hydration - Occurs as a result of moisture ingress. Commonly results in pseudomorphic cement hydration.

Secondary ettringite formation – Ettringite normally formed during the initial hydration of Portland cement is converted slowly to calcium sulfoaluminate hydrate.

Secondary Ettringite is formed by recrystallization of cement hydrates in damp conditions, and tends to form in open cracks and voids. No external source of sulphate is required for secondary ettringite formation.

Shrinkage – The irreversible decrease in volume of a material as a result of loss of moisture and/or carbonation and/or temperature drop (plastic, drying & thermal shrinkage).

Structural cracking – Structural cracking refers to the cracking which is the result of structural damage of some kind, for example impact.

Sulphate attack – A general term relating to damage to concrete resulting from the expansive formation of secondary sulphate minerals such as minute ettringite or thaumasite crystals forming within the cement paste and in cracks. Generally involves externally derived sources of sulphate and requires damp conditions.

TF - Thaumasite Formation – An unusual form of sulphate attack causing deterioration and softening of the outer zones of concrete by the action of external sulphate solutions normally under low temperature conditions in the presence of a source of calcium carbonate. Early stage deposition of thaumasite within voids and pre-existing microcracks. This development is usually non deleterious, but occasionally involves expansive deposition.

Thaumasite - A calcium-silicon-sulphate-carbonate-hydrate, $\text{Ca}_3\text{Si}(\text{OH})_6 \cdot 2\text{H}_2\text{O}(\text{SO}_4)(\text{CO}_3)$ a mineral formed in concrete where there is a source of carbonate and sulphate. Most commonly seen in foundation and subterranean concrete where the ground contains pyrite or gypsum and the groundwater contains dissolved CO_2 .

TSA - Thaumasite Sulfate Attack - Deleterious thaumasite growth forming at the expense of the cement paste matrix, ultimately degrading the cement matrix to a soft mush.

Thin section - A slice of concrete or other material mounted on a glass slide and ground sufficiently thin for it to be transparent in transmitted light. Typical thickness for concrete would be 0.025 - 0.020mm.

Uncrushed – Natural aggregate that results from the natural disintegration of rock, or by the natural processes of erosion and deposition.

Uncrushed Gravel – A naturally unconsolidated gravel, typically from ancient river or beach deposits.

Vermiculite, exfoliated – A layered silicate clay mineral of the chlorite family which exfoliates when heated to 750 – 1100°C to produce a light cellular material used for thermal insulation and as a lightweight aggregate.

Voids and voidage – Most concrete inevitably retains some entrapped air and may contain small bubbles of deliberately entrained air, even when it is efficiently compacted. After hardening of the concrete, these entrapped and entrained bubbles are fixed in place and are referred to as air voids. (see also entrapped and entrained air voids).

Water/cement ratio – The ratio by weight between the water and cement in a concrete mix. In general terms the ratio may be considered Low (<0.35), Normal ($0.35 - 0.65$) and High (>0.65).

Appendix B – Sampling

Example Wall Analysis Form:

<i>Location</i>	DATE	WALL #	PHOTO #			
	SAMPLE ID #	ROOM #	DRAWING #			
	BRIEF DESCRIPTION AND LOCATION:					

<i>Wall Construction and Binder</i>	COMPOSITION: (Give rough percentages for materials visible)									
	Lava with White Flecks			Sarno Stone			White Limestone			
	Lava with Black Particles			Opus Signinum			Brick/Tile			
	Nocera Tufa			Cruma			Pottery Fragments			
	Marble Fragments			Other (describe)						
	CONSTRUCTION TECHNIQUES: (check)									
	Opus quadratum			Opus Incertum			Opus mixtum			
	Checker Work			Opus vittatum			Opus spicatum			
	Opus Africanum			Opus reticulatum			Opus testaceum			
	Opus craticium			Opus quasi-reticulatum						
SCOPE IMAGES:										
POWER		#	NOTES							
50x										
100x										
200x										
Mortar surface is		very hard		firm		soft		disintegrating		
Mortar interior is		very hard		firm		soft		disintegrating		
Inclusion size is		large		small						
Inclusion density		high		low						
Particles		grain		sand		clay				
Notes:					Additional Mortars	color	light	medium	dark	
						grey				
						brown				
						yellow				
						other				

<i>Aggregate</i>	COMPOSITION: (Give rough percentages for materials visible)									
	Leucite									
	Pumice									
	Lime									
Description:										

Visual Inspection Data of samples

Sample ID	Structure	Code	Date	Core/ Facing	Interior/ Exterior	Facing Style	Distance from facing	Munsell Code – Interior	Colour	Total Weight	Number of Fragments	Fragment Weight	Powder Weight
OS-C1	Piccolo Mercato	E	118CE	Core	Unknown	Reticulate	Unknown	2.5Y 8/1	white	31.92	10	17.63	14.29
OS-C2	Casa Basilicale	D	118CE	Facing	Unknown	Reticulate	Unknown	2.5Y 8/1	white	113.79	1	112.51	1.28
OS-C3	Casa Basilicale	D	118CE	Core	Unknown	Reticulate	Unknown	Gley 1 8/1	white	119.66	2	109.73	9.93
OS-C5	Cas del Larario	C	117CE	Core	Unknown	Brick	Unknown	2.5Y 8/1	white	92.10	3	91.58	0.52
OS-C8	Terme del Foro	F	160CE	Facing	Unknown	Brick	Unknown	10YR 8/2	very pale brown	23.79	3	22.46	1.33
OS-C9	Terme del Foro	F	160CE	Core	Unknown	Brick	Unknown	10YR 8/1	white	51.33	1	51.15	0.18
OS-C15	Casa a Giardino	A	125CE	Core	Unknown	Brick	Unknown	5Y 8/1	white	46.39	5	45.59	0.80
OS-C16	Cas del Serapide	B	125CE	Face	Unknown	Brick	Unknown	2.5Y 8/1	white	83.63	16	82.24	1.39
OS-C21	Insula del'Ercole Bambino	G	130CE	Core	Unknown	Brick	Unknown	2.5Y 8/1	white	9.13	1	6.84	2.29
OS-A-C23	Casa a Giardino	A	125CE	Core	Exterior	Brick	10cm	2.5Y 7/1	light grey	7.09	4	4.96	2.10
OS-A-C24	Casa a Giardino	A	125CE	Facing	Exterior	Brick	10cm	2.5Y 8/1	white	11.13	5	8.91	2.20
OS-A-C25	Casa a Giardino	A	125CE	Core	Interior	Reticulate	13cm	10YR 8/1	white	19.39	28	13.18	6.21
OS-A-C26	Casa a Giardino	A	125CE	Facing	Interior	Reticulate	5cm	2.5Y 8/1	white	19.99	41	10.89	9.08
OS-B-C27	Cas del Serapide	B	125CE	Core	Exterior	Brick	31cm	10YR 8/1	white	23.10	17	16.84	6.32
OS-B-C28	Cas del Serapide	B	125CE	Core	Interior	Brick	9cm	10YR 8/1	white	22.14	21	19.04	3.10
OS-B-C29	Cas del Serapide	B	125CE	Facing	Interior	Brick	5cm	2.5Y 8/1	white	61.02	59	48.05	12.93
OS-B-C30	Cas del Serapide	B	125CE	Facing	Exterior	Brick	5cm	10YR 8/1	white	25.15	5	22.57	2.58
OS-C-C31	Cas del Larario	C	117CE	Facing	Interior	Brick	5cm	10YR 8/1	white	16.89	18	13.95	2.90
OS-C-C32	Cas del Larario	C	117CE	Core	Interior	Brick	23cm	2.5Y 8/1	white	121.15	1	120.86	0.59
OS-C-C33	Cas del Larario	C	117CE	Facing	Exterior	Brick	3cm	10YR 8/1	white	28.79	7	27.73	1.05
OS-C-C34	Cas del Larario	C	117CE	Core	Exterior	Brick	10cm	5YR 8/1	white	13.14	1	12.38	0.72
OS-D-C35	Casa Basilicale	D	118CE	Core	Interior	Reticulate	15cm	Gley1 7/1	light grey	47.58	31	32.06	15.41
OS-D-C36	Casa Basilicale	D	118CE	Facing	Interior	Reticulate	5cm	5Y 6/1	grey	38.70	45	28.43	10.57
OS-D-C37	Casa Basilicale	D	118CE	Facing	Exterior	Reticulate	4cm	2.5Y 6/1	grey	85.50	8	82.44	2.93
OS-D-C38	Casa Basilicale	D	118CE	Core	Exterior	Reticulate	12cm	Gley1 7/1	light grey	13.76	12	10.24	3.47
OS-E-C39	Piccolo Mercato	E	118CE	Facing	Interior	Reticulate	9cm	7.5YR 7/1	light grey	33.19	39	20.50	12.70
OS-E-C40	Piccolo Mercato	E	118CE	Core	Exterior	Reticulate	23cm	2.5Y 7/1	light grey	20.40	28	12.52	7.88
OS-E-C41	Piccolo Mercato	E	118CE	Facing	Exterior	Reticulate	9cm	10YR 8/1	white	12.25	9	10.82	1.37

Sample ID	Structure	Code	Date	Core/ Facing	Interior/ Exterior	Facing Style	Distance from facing	Munsell Code – Interior	Colour	Total Weight	Number of Fragments	Fragment Weight	Powder Weight
OS-E-C42	Piccolo Mercato	E	118CE	Core	Interior	Reticulate	14cm	7.5YR 8/1	white	33.60	43	23.38	10.22
OS-F-C43	Terme del Foro	F	160CE	Facing	Exterior	Brick	6cm	10YR 8/1	white	40.63	41	31.12	9.51
OS-F-C44	Terme del Foro	F	160CE	Core	Exterior	Brick	9cm	10YR 8/1	white	27.10	18	25.95	1.19
OS-F-C45	Terme del Foro	F	160CE	Facing	Interior	Brick	6cm	10YR 8/2	very pale brown	32.59	45	22.78	9.81
OS-F-C46	Terme del Foro	F	160CE	Core	Interior	Brick	12cm	10YR 7/2	light grey	38.51	6	36.86	1.42
OS-G-C47	Insula del'Ercole Bambino	G	130CE	Core	Interior	Brick	18cm	Gley1 7/1	light grey	27.59	3	27.52	0.08
OS-G-C48	Insula del'Ercole Bambino	G	130CE	Facing	Interior	Brick	8cm	2.5Y 8/1	white	24.00	19	22.72	1.25
OS-G-C49	Insula del'Ercole Bambino	G	130CE	Core	Exterior	Brick	13cm	2.5Y 7/1	light grey	46.25	19	44.24	2.02
OS-G-C50	Insula del'Ercole Bambino	G	130CE	Facing	Exterior	Brick	10cm	10YR 7/1	light grey	25.50	8	24.96	0.52

Appendix C – Point Count Data

Case a Giardino	OS-C15		OS-A-C23 Courtyard		OS-A-C24 Facade		OS-A-C25 Apartment		OS-A-C26 Apartment	
	Count 1	Count 2	Count 1	Count 2	Count 1	Count 2	Count 1	Count 2	Count 1	Count 2
Binder	153	122	144	150	145	151	133	136	160	156
Cement matrix	123	106	124	114	109	125	111	121	124	132
Relict, unidentifiable aggregate clast	30	16	20	36	36	26	22	15	36	24
Void space	31	16	16	24	37	25	42	30	35	18
Linear Crack	10	6	1	2	0	2	17	12	13	8
Sub-rounded to angular void	21	10	15	22	37	23	25	18	22	10
Pozzolane Rosse	31	41	125	141	192	183	174	214	223	220
Greatest Alteration Facies	6	5	3	2	84	34	87	33	73	
Intermediate Alteration Facies	23	36	96	131	86	148	75	178	83	207
Least Alteration Facies	2	0	26	8	22	1	12	3	67	13
Pozzolane Nere	3	0	0	2	0	6	33	23	0	1
Villa Senni Eruptive Material	255	307	184	155	75	81	76	53	52	63
Pozzolanelle	37	33	95	76	6	1	11	12	5	6
Tufo Lionato	218	274	89	79	69	80	65	41	47	57
TGdPP	0	0	4	18	3	6	4	6	2	
MSVD reworked air fall ash	4	1	7	5	7	7	19	23	17	19
Root traces	0	0	0	0	0	0	0	0	0	0
Ceramic	0	0	0	0	0	0	0	0	0	0
Pebble lime clast	8	1	0	0	31	37	8	4	0	16
Other Lithics	7	0	11	1	3	2	5	1	1	0
Chert	2	0	0	0	3	0	0	0	1	0
Clay particle	0	0	0	0	0	0	0	0	0	0
Leucite-Analcime conglomerate	0	0	0	0	0	0	0	0	0	0
Leucitic lava fragment	5	0	9	0	0	1	3	0	0	0
Limestone	0	0	0	0	0	0	0	0	0	0
Quartzite	0	0	0	0	0	1	2	1	0	0
Tuff fragment	0	0	0	0	0	0	0	0	0	0
Unidentified lithic fragment	0	0	2	1	0	0	0	0	0	0
Free Crystals	8	14	9	4	7	2	6	10	10	8
Analcime	1	5	4	3	7	0	3	1	4	0
Biotite	1	0	2	0	0	0	0	0	0	0
Calcite	1	0	0	0	0	0	3	1	2	1
Chabazite	0	1	0	0	0	0	0	0	0	0
Clinopyroxene	5	2	2	0	0	0	0	5	0	0
Feldspar	0	0	0	0	0	1	0	0	0	3
Hauyne	0	1	0	0	0	0	0	0	0	0
Leucite	0	0	1	0	0	0	0	1	0	3
Light Mica	0	0	0	0	0	0	0	1	0	0
Phillipsite	0	1	0	0	0	0	0	0	0	0
quartz	0	1	0	0	0	1	0	0	4	1
Sanidine	0	3	0	1	0	0	0	1	0	0
Stratlingite	0	0	0	0	0	0	0	0	0	0
Total	500	502	500	500	500	500	500	500	500	501

Caseggiato del Serapide	OS-C16		OS-B-C30		OS-B-C27		OS-B-C28		OS-B-C29		OS-B-C30(b)	
	Count 1	Count 2	Count 1	Count 2	Count 1	Count 2	Count 1	Count 2	Count 1	Count 2	Count 1	Count 2
Binder	205	130	221	209	149	160	194	193	159	164	153	127
Cement matrix	142	110	159	163	127	134	181	161	131	140	127	119
Relict, unidentifiable aggregate clast	63	20	62	46	22	26	13	32	28	24	26	8
Void Space	22	28	38	21	26	19	32	18	53	61	30	23
Linear Crack	2	6	1	2	3	4	4	2	21	21	13	7
Sub-rounded to angular void	20	22	37	19	23	15	28	16	32	40	17	16
Pozzolane Rosse	0	8	144	142	118	95	34	32	131	128	133	111
Greatest Alteration Facies	0	3	144	57	66	34	2	10	37	20	53	67
Intermediate Alteration Facies	0	4	0	81	35	61	30	21	65	102	74	44
Least Alteration Facies	0	1	0	4	17	0	2	1	29	6	6	0
Pozzolane Nere	26	0	13	8	7	3	3	1	0	26	0	12
Villa Senni Eruptive Material	253	293	119	94	181	197	203	227	101	86	150	198
Pozzolanelle	198	112	34	25	83	56	111	111	48	43	13	20
Tufo Lionato	55	181	85	69	98	141	92	116	53	43	137	178
Tufo Giallo di Prima Porta	0	0	3	1	0	2	3	5	5	4	5	2
MSVD reworked air fall ash	0	9	0	4	8	5	19	11	2	3	12	0
Root traces	0	0	0	0	0	0	0	0	0	0	0	0
Ceramic	0	0	0	0	0	0	0	0	0	0	0	0
Pebble lime clast	0	16	0	10	3	8	4	1	45	17	9	17
Other Lithics	17	4	0	2	2	0	3	3	0	5	0	1
Chert	0	0	0	1	0	0	0	0	0	0	0	0
Clay particle	1	0	0	0	0	0	0	1	0	0	0	1
Leucite-Analcime conglomerate	0	0	0	0	0	0	0	0	0	5	0	0
Leucitic lava fragment	13	3	0	0	2	0	3	2	0	0	0	0
Limestone	1	0	0	0	0	0	0	0	0	0	0	0
Quartzite	0	0	0	0	0	0	0	0	0	0	0	0
Tuff fragment	0	0	0	0	0	0	0	0	0	0	0	0
Unidentified lithic fragment	2	1	0	1	0	0	0	0	0	0	0	0
Free Crystals	10	12	8	9	6	11	5	9	5	6	9	10
Analcime	0	6	4	5	2	5	2	4	3	5	8	7
Biotite	1	1	0	1	0	0	1	2	0	0	0	0
Calcite	1	0	0	1	1	0	0	0	1	0	0	1
Chabazite	0	0	0	0	0	0	0	0	0	0	0	0
Clinopyroxene	3	4	4	2	2	1	0	0	0	0	0	1
Feldspar	2	0	0	0	0	0	0	0	0	0	0	0
Hauyne	0	0	0	0	0	0	0	0	0	0	0	0
Leucite	0	1	0	0	1	3	0	1	0	0	0	0
Light Mica	0	0	0	0	0	1	0	1	0	0	0	0
Phillipsite	0	0	0	0	0	0	0	0	0	0	0	0
quartz	0	0	0	0	0	0	0	0	0	0	0	0
Sanidine	3	0	0	0	0	1	2	1	1	1	1	1
Stratlingite	0	0	0	0	0	0	0	0	0	0	0	0
Total	533	500	546	500	500	500	500	500	501	500	501	501

[illegible]

Casa Basilicale	OS-C3		OS-D-C37		OS-D-C35		OS-D-C36		OS-D-C37(b)		OS-D-C38	
	Count 1	Count 2	Count 1	Count 2	Count 1	Count 2	Count 1	Count 2	Count 1	Count 2	Count 1	Count 2
Binder	171	142	136	118	188	187	186	155	131	155	169	176
Cement matrix	123	114	97	93	148	157	133	124	107	109	142	137
Relict, unidentifiable aggregate clast	48	28	39	25	40	30	53	31	24	46	27	39
Void space	23	27	44	73	7	4	35	42	35	47	34	38
Linear Crack	3	4	6	3	1	3	5	4	5	8	2	4
Sub-rounded to angular void	20	23	38	70	6	1	30	38	30	39	32	34
Pozzolane Rosse	294	232	325	248	229	224	250	250	278	216	183	157
Greatest Alteration Facies	235	56	303	0	13	13	14	65	2	13	18	43
Intermediate Alteration Facies	43	144	22	195	148	189	206	181	190	191	115	104
Least Alteration Facies	16	32	0	53	68	22	30	4	86	12	50	10
Pozzolane Nere	0	9	0	0	14	2	0	6	8	15	28	0
Villa Senni Eruptive Material	54	50	10	35	25	35	5	14	12	29	37	65
Pozzolanelle	41	9	0	3	4	0	0	0	3	2	12	11
Tufo Lionato	13	41	10	32	21	35	5	14	9	27	25	54
Tufo Giallo di Prima Porta	0	6	10	1	6	10	0	4	9	7	22	26
MSVD reworked air fall ash	2	3	0	0	3	7	7	7	9	18	16	16
Root traces	2	0	0	0	0	0	0	1	0	0	0	0
Ceramic	0	0	0	0	0	0	0	0	0	0	0	0
Pebble lime clast	1	10	6	14	0	0	2	9	0	1	4	6
Other Lithics	12	14	0	1	3	11	1	2	1	8	0	4
Chert	0	0	0	0	0	0	1	0	0	0	0	0
Clay particle	1	1	0	0	0	6	0	0	0	0	0	1
Leucite-Analcime conglomerate	0	0	0	0	0	0	0	0	0	5	0	0
Leucitic lava fragment	5	13	0	1	3	5	0	1	0	0	0	3
Limestone	0	0	0	0	0	0	0	0	0	0	0	0
Quartzite	0	0	0	0	0	0	0	1	0	3	0	0
Tuff fragment	1	0	0	0	0	0	0	0	0	0	0	0
Unidentified lithic fragment	5	0	0	0	0	0	0	0	1	0	0	0
Free Crystals	10	7	9	10	25	20	14	10	17	4	7	12
Analcime	0	2	0	2	11	4	3	3	3	0	5	10
Biotite	0	1	3	2	0	0	0	0	0	0	0	0
Calcite	2	1	1	0	13	12	6	1	11	1	1	0
Chabazite	0	0	0	0	0	0	0	0	0	0	0	0
Clinopyroxene	3	1	4	2	0	2	0	0	0	1	0	0
Feldspar	0	1	0	1	0	0	0	0	3	1	0	0
Hauyne	0	0	0	0	0	0	0	0	0	0	0	0
Leucite	2	1	1	2	1	0	4	4	0	1	0	2
Light Mica	0	0	0	0	0	0	0	0	0	0	0	0
Phillipsite	0	0	0	0	0	0	0	0	0	0	0	0
quartz	0	0	0	1	0	0	1	2	0	0	0	0
Sanidine	3	0	0	0	0	0	0	0	0	0	1	0
Stratlingite	0	0	0	0	0	2	0	0	0	0	0	0
Total	569	500	540	500	500	500	500	500	500	500	500	500

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Appendix D - SEM/WDS Data

Expressed as oxide weight percent

Label	No	Ox%(F)	Ox%(Na)	Ox%(Mg)	Ox%(Al)	Ox%(Si)	Ox%(P)	Ox%(Cl)	Ox%(K)	Ox%(Ca)	Ox%(Ti)	Ox%(Mn)	Ox%(Fe)	Total
DummyPoint1_OSC3_mica_1	1	0.6057	0.1847	16.9685	15.807	35.1001	0	0.0168	9.6097	0.027	2.9634	0.154	11.9814	93.4183
DummyPoint2_sameMica_1	2	0.6302	0.1345	16.9102	15.9253	35.5178	0.0158	0.0064	9.7079	0.0709	2.6664	0.1473	11.8501	93.5828
OSC3_fibrous_1	3	0.0631	0.0107	0.0025	0.0557	0.1177	0.0053	0.1574	0.027	0.0467	0.011	0	0.129	0.6261
OSC3_fibrousB_2	4	0.0181	0.3464	0.356	18.8654	41.6717	0.0339	0.042	2.1586	3.9966	0	0.0126	0.3994	67.9007
OSC3_Pzl_mica_1	5	0.5256	0.1198	17.7754	15.9492	35.3954	0.011	0.0104	9.729	0.0291	2.7928	0.0812	11.8804	94.2993
OSC3_Pzl_Xtal_2	6	0	0.2431	13.123	4.8634	47.0412	0.0041	0.0049	0.0059	24.3419	0.7912	0.1085	7.4071	97.9343
OSC3J_PasteBright_1	7	0.0708	0.3631	0.298	4.9349	15.7626	0.027	0.0435	1.1767	37.6171	0	0	0.1734	60.4671
OSC9_PasteLinear_1	8	0.0001	0.2154	0.3254	0.1072	0.1051	0.047	0.5563	0.0446	13.3998	0.011	0.0169	0.0515	14.8803
OSC9_Lime_1	9	0.0001	0.0124	0.1926	0	0	0.0354	0.0037	0.0051	63.6636	0	0.262	0.294	64.4689
OSC9_fibers_1	10	0.0478	1.1142	0.3362	13.1783	37.2236	0.0097	0.2297	1.5399	4.3169	0.0136	0.0087	0.259	58.2776
OSC9T_fibresicles_1	11	0.184	0.4216	0.4743	17.5057	30.9324	0.02	0.1374	1.0246	3.5616	0.0402	0.0063	0.4011	54.7092
OSC9U_cementFill_1	12	0.1001	0.117	0.3554	1.4991	2.2347	0.0287	0.0134	0.0823	57.9025	0.0131	0.0186	0.2361	62.601
OSC1D_LimeTop_1	13	0.0078	0.1187	0.8546	1.3962	3.0993	0.0507	0.4475	0.1606	51.435	0.0156	0.0541	0.0305	57.6706
OSC1D_LimeMiddle_1	14	0.2316	0.0684	0.5052	0.3093	0.7815	0.0751	0.1773	0.0457	59.6659	0	0	0.0078	61.8678
OSC1D_LimeLower1	15	0.0044	0.1126	1.8881	1.5978	3.776	0.0681	0.9181	0.1958	56.0228	0.004	0.0227	0.0246	64.635
OSC1K_bright_1	16	0.3053	0.0341	3.9298	5.983	1.8204	0.1533	0.2821	0.1292	56.4218	0.0405	0.038	0.334	69.4715
OSC1K_dark_1	17	0.0676	0.2274	11.6866	23.2516	28.9627	0.0151	2.4931	0.8035	2.1005	0.0356	0.0273	0.3391	70.0101
OSC21K_vesFibers_1	18	0.0338	0.5756	0.3743	12.9919	27.3825	0.0182	0.3571	1.2117	2.8249	0.0145	0	0.3362	46.1207
OSC21K_vesFibers_2	19	0.1685	0.4591	0.6621	21.6977	42.511	0.0613	0.2562	1.3099	4.434	0.0531	0.0069	0.4885	72.1083
OSC21L_fibrous_1	20	0.0484	0.1756	0.0047	3.1107	18.007	0.0109	0.058	1.8921	1.8365	0.0198	0.0316	0.4815	25.6768
OSC21M_clastFiber_1	21	0.1153	0.7082	0.565	23.3831	41.0277	0.033	0.2598	2.3343	4.1431	0.0541	0.0233	0.3682	73.0151
OSC21N_globule_1	22	0.0675	0	0.6355	0	0.0386	0.0285	0.0066	0.0438	62.362	0.0111	0.0031	0.0814	63.2781
OSC21O_shard1	23	0.0285	0.1025	0.5384	0.5676	1.7095	0.0461	0.0603	0.1591	42.2251	0.016	0.0014	0.2418	45.6963
OSC21Q_PRvesfib_1	24	0.03	0.2528	0.2669	13.1008	27.6026	0.0454	0.2708	1.0795	3.9211	0.0252	0.0101	0.4158	47.021
OSC16M_clastfibs_1	25	0.1922	2.0025	0.8693	22.9718	48.2839	0.0083	1.4886	4.8015	7.238	0.119	0.0239	1.3867	89.3857
OSC16M_clastfibs_2	26	0	0.7309	1.196	19.7683	41.7406	0.0249	5.9652	2.9607	5.1248	0.2697	0.0207	3.1985	81.0003
OSC16M_clastfibs_3	27	0	4.2678	0.0414	25.5993	57.7069	0	0.0547	0.1229	0.2584	0.0227	0.0077	0.5006	88.5824
OSC16L_lime_1	28	0.0908	0.0752	0.2032	0.0618	0.0687	0.0259	0.106	0.007	61.2101	0	0	0.0188	61.8675
OSC16L_lime_2	29	0.0001	0.0165	0.0544	0.0121	0.0186	0.0085	0.1825	0	15.4968	0	0	0.0217	15.8112
OSC16L_lime_3	30	0.1309	0.07	0.5997	0.6085	0.5806	0.0266	1.0433	0.0264	37.932	0	0	0.0723	41.0903
OSC16L_lime_4	31	0.1066	0.0562	0.3603	0.1644	0.1963	0.031	0.138	0.0068	57.7281	0.0025	0.0224	0.0277	58.8403
OSC16L_lime_5	32	0.1401	0.058	0.119	0.5478	1.6198	0.0118	0.6638	0.0676	20.3977	0.011	0	0.0251	23.6617
OSC16O_centralXtal_1	33	0	0.1363	0.0015	25.2505	56.0068	0	0.004	18.1302	0	0.0296	0	0.3851	99.944
OSC16O_upperXtal_1	34	0	5.1011	0.0358	26.0348	59.0017	0.0043	0.049	0.1346	0.1379	0.0817	0.0042	0.413	90.9981
OSC16P_fiber_1	35	0.2117	0.9901	0.7235	5.8424	17.2087	0.014	1.8434	0.9639	15.4135	0.162	0.0238	0.864	44.261
OSC16P_fiber_2	36	0.0958	0.7818	0.3589	18.0918	35.3638	0.0171	2.7863	1.5635	5.5382	0.0438	0.032	0.3256	64.9986
OSC16E_PasteFiber_1	37	0	0.3698	0.2921	3.9208	9.8443	0.0098	2.3226	0.5319	8.8177	0.0083	0.01	0.1338	26.2611
OSC16R_vesFibers_1	38	0	0.6475	0.6818	15.6429	31.0769	0.0201	2.9704	1.3018	2.7554	0.0864	0.0381	0.5603	55.7816
OSC15J_limeLump_1	39	0.1795	0.0087	0.2976	0.0718	0.2154	0.034	0.0173	0	58.6368	0.007	0	0.5423	60.0104
OSC15J_limeLump_2	40	0.0801	0.0224	0.5016	0.2483	1.1252	0.0606	0.017	0.0404	62.2174	0.0272	0.0527	0.2951	64.688
OSC15J_limeLump_3	41	0.0055	0	0.1079	0	0.0506	0.0159	0.0045	0.0041	58.9945	0	0	0.0633	59.2463
OSC15K_mass_1	42	0.0806	0.1168	0.3704	2.2283	4.5356	0.2177	0.0423	0.6483	50.9793	0.5098	0	1.0947	60.8238
OSC15K_triangle_1	43	0.1202	0.1643	6.0834	11.151	32.2444	0.0362	0.2499	4.137	1.6351	1.2272	0.4547	18.2533	75.7567
OSC15O_lime_1	44	0.1943	0.0316	0.0007	0.0079	0.9979	0.0655	0	0.0389	57.1832	0.0212	0	0.1571	58.6983
OSC15P_Paste8_1	45	0.0635	0.0772	0.2206	1.3772	4.1661	0.0319	0.1159	0.2085	57.3764	0.0156	0.0269	0.0482	63.728
OSC15R_light_1	46	0.1576	0.1009	0.1929	0.6844	2.0634	0.1216	0.0352	0.4725	60.7928	0.0146	0.0093	0.2799	64.9251
OSC15R_dark_1	47	0.0111	0.2096	9.0681	4.5048	31.1416	0.023	0.6223	0.793	3.415	0.5026	0.0352	6.2395	56.5638

Expressed as atomic weight percent

Label	No	A%(O)	A%(F)	A%(Na)	A%(Mg)	A%(Al)	A%(Si)	A%(P)	A%(Cl)	A%(K)	A%(Ca)	A%(Ti)	A%(Mn)	A%(Fe)	Total
DummyPoint1_OSC3_mica_1	1	57.5018	0.7681	0.1436	10.1411	7.4698	14.0739	0	0.0114	4.9152	0.0116	0.8935	0.0523	4.0176	99.9999
DummyPoint2_sameMica_1	2	57.506	0.7969	0.1042	10.077	7.504	14.2002	0.0123	0.0043	4.951	0.0304	0.8017	0.0499	3.9621	100
OSC3_fibrous_1	3	25.7127	16.7597	1.7421	0.3157	5.5106	9.8768	0.8556	22.3924	2.8872	4.1972	0.6918	0.0011	9.057	99.9999
OSC3_fibrousB_2	4	62.9517	0.0291	0.3424	0.2704	11.3334	21.2412	0.0335	0.0363	1.4036	2.1827	0	0.0054	0.1703	100
OSC3_Pzl_mica_1	5	57.535	0.6587	0.0921	10.4984	7.4484	14.0255	0.0085	0.007	4.9177	0.0123	0.8322	0.0273	3.9369	100
OSC3_Pzl_Xtal_2	6	59.5947	0.0001	0.18	7.4707	2.1892	17.9669	0.003	0.0032	0.0029	9.9611	0.2272	0.0351	2.3659	100
OSC3J_PasteBright_1	7	55.8011	0.1522	0.4784	0.3019	3.9532	10.7139	0.0356	0.0501	1.0202	27.3947	0	0	0.0986	99.9999
OSC9_PasteLinear_1	8	47.532	0.0006	1.3161	1.5286	0.3982	0.3313	0.2873	2.9712	0.1793	45.2486	0.0262	0.045	0.1356	100
OSC9_Lime_1	9	49.9661	0.0001	0.0175	0.2079	0	0	0.0498	0.0045	0.0047	49.4105	0	0.1607	0.1781	99.9999
OSC9_fibers_1	10	62.554	0.0902	1.2881	0.2988	9.2611	22.1957	0.0112	0.2321	1.1713	2.7579	0.0061	0.0044	0.1292	100.0001
OSC9T_fibresicles_1	11	62.3412	0.3687	0.5179	0.4479	13.0723	19.5989	0.0245	0.1475	0.8281	2.4178	0.0192	0.0034	0.2125	99.9999
OSC9U_cementFill_1	12	50.8721	0.2304	0.165	0.3854	1.2856	1.626	0.0405	0.0166	0.0764	45.1396	0.0072	0.0115	0.1436	99.9999
OSC1D_LimeTop_1	13	50.9581	0.0194	0.1806	0.9991	1.2906	2.4309	0.0772	0.5948	0.1607	43.2234	0.0092	0.036	0.02	100
OSC1D_LimeMiddle_1	14	49.6905	0.5483	0.0992	0.5637	0.2729	0.5851	0.1091	0.225	0.0437	47.8575	0	0	0.0049	99.9999
OSC1D_LimeLower1	15	50.6971	0.0096	0.1522	1.9623	1.313	2.6328	0.0922	1.0849	0.1742	41.8518	0.0021	0.0134	0.0143	99.9999
OSC1K_bright_1	16	50.8867	0.612	0.0419	3.7122	4.4689	1.1537	0.1885	0.303	0.1045	38.3119	0.0193	0.0204	0.177	100
OSC1K_dark_1	17	58.8231	0.1069	0.2206	8.7148	13.7102	14.4902	0.0146	2.1139	0.5128	1.1259	0.0134	0.0116	0.1419	99.9999
OSC21K_vesFibers_1	18	62.3006	0.0807	0.8417	0.4208	11.5496	20.6543	0.0267	0.4565	1.1659	2.2829	0.0082	0	0.2121	100
OSC21K_vesFibers_2	19	62.597	0.2558	0.4272	0.4737	12.2748	20.4055	0.0571	0.2084	0.802	2.2804	0.0192	0.0028	0.1961	100
OSC21L_fibrous_1	20	62.5	0.2119	0.4708	0.0098	5.0695	24.9	0.0293	0.136	3.3375	2.7209	0.0206	0.037	0.5568	100.0001
OSC21M_clastFiber_1	21	62.2201	0.1735	0.6529	0.4004	13.1037	19.508	0.0305	0.2093	1.4159	2.1107	0.0194	0.0094	0.1464	100.0002
OSC21N_gobule_1	22	49.8627	0.157	0	0.6962	0	0.0284	0.0407	0.0082	0.0411	49.1076	0.0061	0.0019	0.05	99.9999
OSC21O_shard1	23	50.7378	0.09	0.1986	0.8015	0.6682	1.7074	0.0894	0.102	0.2027	45.1873	0.0121	0.0012	0.202	100.0002
OSC21Q_Prvestfib_1	24	62.4457	0.0704	0.3644	0.2957	11.4761	20.5161	0.0655	0.3412	1.0235	3.1225	0.0141	0.0063	0.2585	100
OSC16M_clastfibs_1	25	60.4448	0.2433	1.5539	0.5186	10.8357	19.3245	0.0064	1.0097	2.4514	3.1037	0.0358	0.0081	0.4641	100
OSC16M_clastfibs_2	26	58.2487	0.0001	0.6533	0.8219	10.7414	19.2441	0.0222	4.6609	1.7412	2.5315	0.0935	0.0081	1.2332	100.0001
OSC16M_clastfibs_3	27	63.0231	0.0001	3.1484	0.0235	11.4796	21.9569	0	0.0353	0.0597	0.1053	0.0065	0.0025	0.1593	100.0002
OSC16L_lime_1	28	49.7277	0.2165	0.1099	0.2282	0.0549	0.0518	0.0379	0.1353	0.0068	49.4193	0	0	0.0118	100.0001
OSC16L_lime_2	29	49.3016	0.0006	0.0951	0.2405	0.0423	0.055	0.0488	0.9172	0	49.2448	0	0	0.0539	99.9998
OSC16L_lime_3	30	48.5983	0.4699	0.154	1.0144	0.8139	0.6589	0.0585	2.0064	0.0382	46.1187	0	0	0.0687	99.9999
OSC16L_lime_4	31	49.7309	0.2666	0.0862	0.4246	0.1533	0.1553	0.0476	0.185	0.0069	48.9088	0.0015	0.015	0.0183	100
OSC16L_lime_5	32	49.4937	0.8571	0.2173	0.343	1.2485	3.1326	0.0444	2.1756	0.1667	42.2644	0.016	0	0.0407	100
OSC16O_centralXtal_1	33	60.6393	0.0001	0.095	0.0008	10.6962	20.13	0	0.0024	8.3125	0	0.008	0	0.1158	100.0001
OSC16O_upperXtal_1	34	62.8156	0.0001	3.6611	0.0198	11.3584	21.841	0.0031	0.0308	0.0636	0.0547	0.0227	0.0013	0.1279	100.0001
OSC16P_fiber_1	35	55.9903	0.5951	1.706	0.9583	6.1193	15.2933	0.0241	2.7763	1.0927	14.6762	0.1083	0.0179	0.6422	100
OSC16P_fiber_2	36	60.1558	0.1675	0.8382	0.2958	11.7905	19.5549	0.0184	2.6112	1.1029	3.2811	0.0182	0.015	0.1506	100.0001
OSC16E_PasteFiber_1	37	54.2489	0.0002	1.0998	0.6678	7.0884	15.1008	0.0291	6.038	1.0407	14.492	0.0096	0.013	0.1717	100
OSC16R_vesFibers_1	38	60.0755	0.0001	0.808	0.654	11.8649	19.9999	0.0251	3.2398	1.0687	1.8999	0.0418	0.0208	0.3015	100
OSC15J_limelump_1	39	49.7254	0.441	0.013	0.3446	0.0657	0.1673	0.0513	0.0228	0	48.8123	0.0041	0	0.3524	99.9999
OSC15J_limelump_2	40	50.2513	0.181	0.031	0.5341	0.2091	0.8039	0.084	0.0206	0.0368	47.6253	0.0146	0.0319	0.1763	99.9999
OSC15J_limelump_3	41	49.9919	0.0137	0	0.1266	0	0.0398	0.0243	0.006	0.0042	49.7516	0	0	0.0417	99.9998
OSC15K_mass_1	42	51.7665	0.1879	0.1669	0.407	1.9358	3.3433	0.3113	0.0528	0.6095	40.2615	0.2826	0	0.6748	99.9999
OSC15K_triangle_1	43	59.1843	0.1959	0.1641	4.67	6.7687	16.607	0.0361	0.2181	2.718	0.9023	0.4753	0.1984	7.862	100.0002
OSC15O_lime_1	44	49.9661	0.4859	0.0484	0.0009	0.0074	0.7891	0.1005	0	0.0392	48.4461	0.0126	0	0.1039	100.0001
OSC15P_Paste8_1	45	51.4602	0.1422	0.1059	0.2329	1.1495	2.9503	0.0438	0.1391	0.1884	43.5347	0.0083	0.0162	0.0285	100
OSC15R_light_1	46	50.3558	0.3529	0.1385	0.2035	0.571	1.4605	0.1669	0.0422	0.4266	46.103	0.0078	0.0056	0.1657	100
OSC15R_dark_1	47	60.2276	0.0226	0.2615	8.698	3.4166	20.0405	0.0287	0.6787	0.651	2.3546	0.2432	0.0192	3.358	100.0002
OSC15R_bright_1	48	51.316	0	0.0046	2.2982	1.0674	0.0621	0.0098	0	0.0176	0.2418	2.0572	0.8349	42.0904	100
OSC5J_light1	49	51.1561	0.0684	0.4733	0.3357	2.2063	4.9244	0.042	1.9899	0.7272	38.0189	0.0143	0.0068	0.0369	100.0002
OSC5L_PasteBright_1	50	50.2095	0.3371	0.1924	0.1016	0.7481	1.5261	0.052	0.4627	0.2666	46.0213	0	0.0272	0.0553	99.9999
OSC5M_Paste6_1	51	50.4661	0.4727	0.485	0.1123	1.4561	2.7403	0.05	0.884	0.4435	42.7658	0.0132	0.0162	0.0947	99.9999
OSC5P_lime_1	52	49.6589	0.0001	0.4665	0.8951	0.3989	0.126	0.0444	0.4916	0.0042	47.8962	0.0097	0	0.0083	99.9999

Reports generated after SEM analysis at the Oxford Materials Laboratory

Sample OS-C1

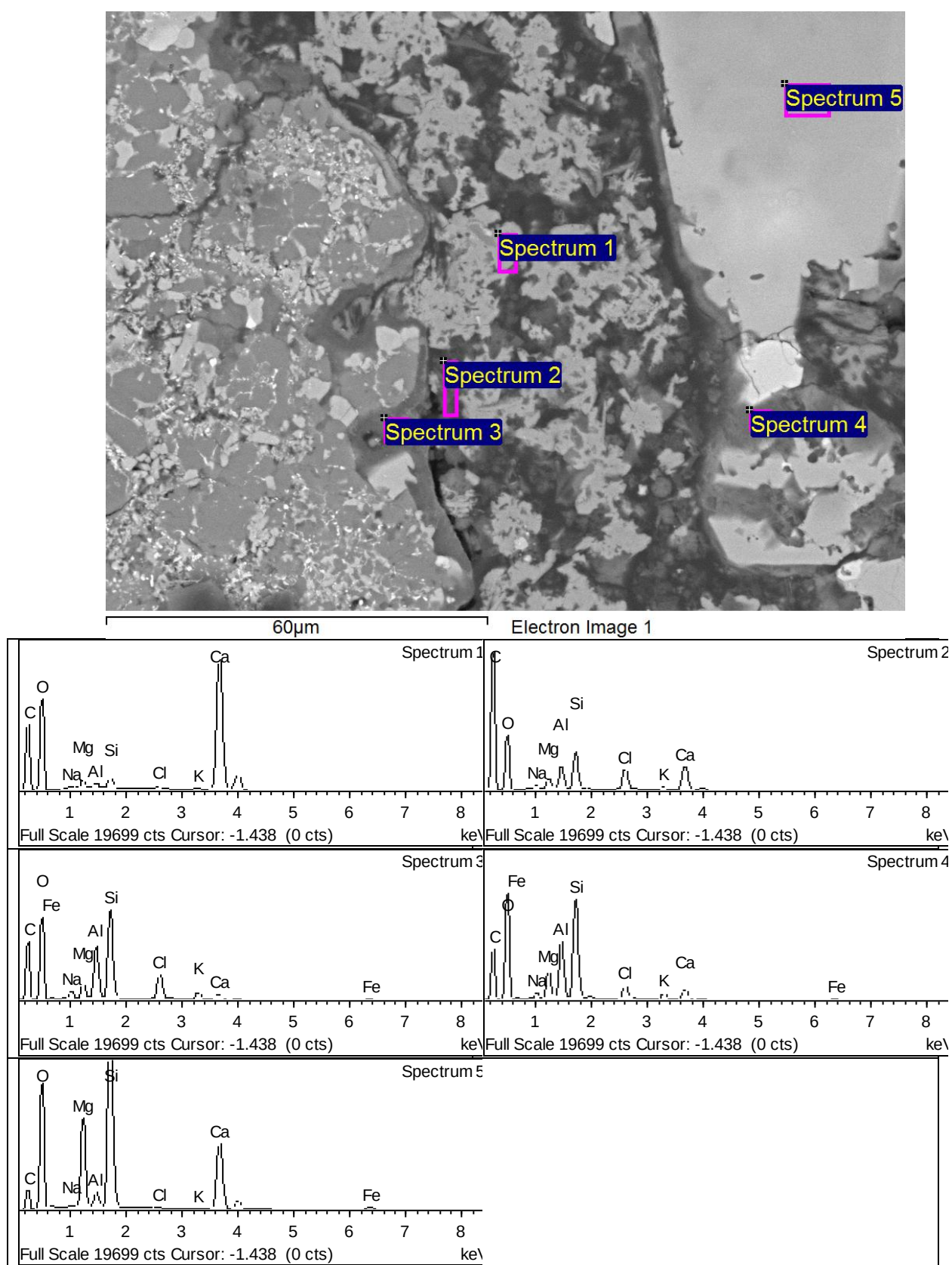
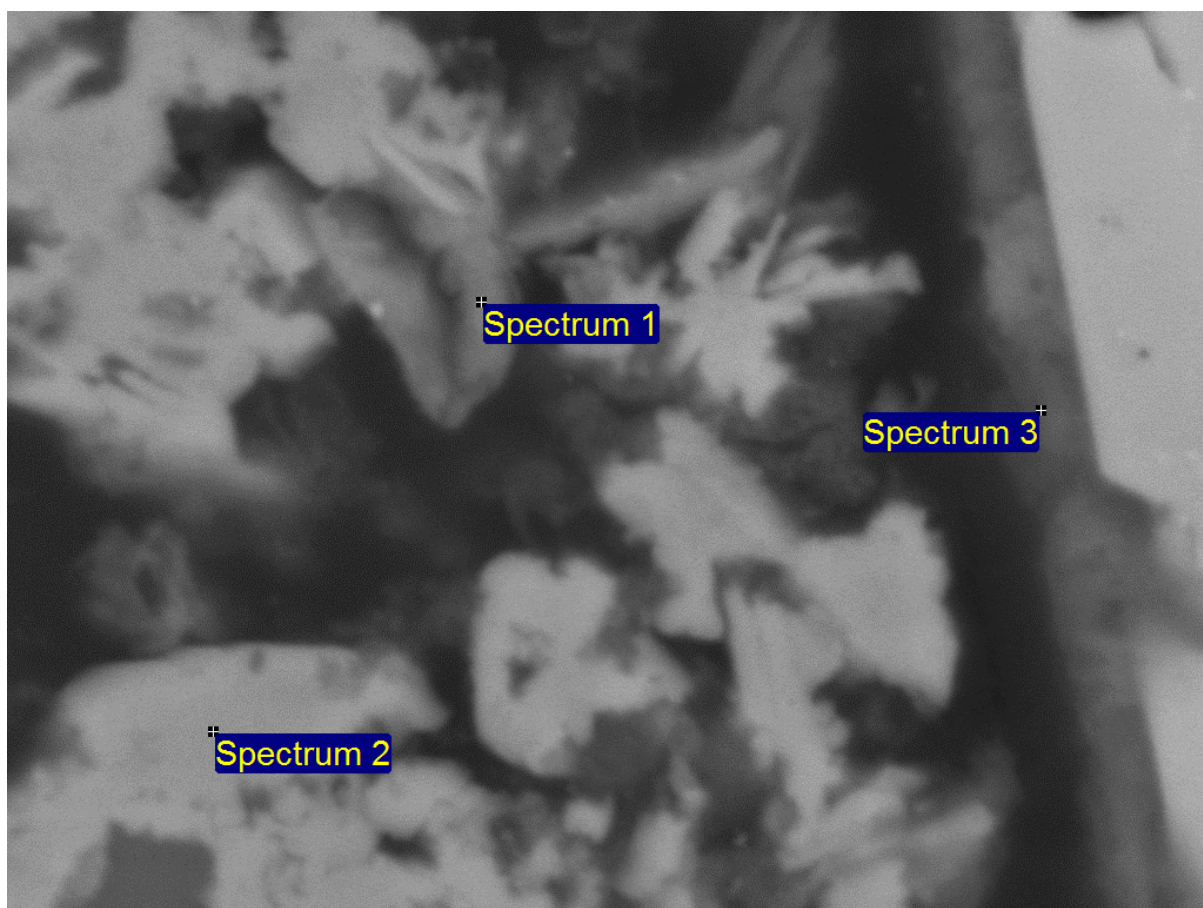


Figure 1 Site 1



10μm

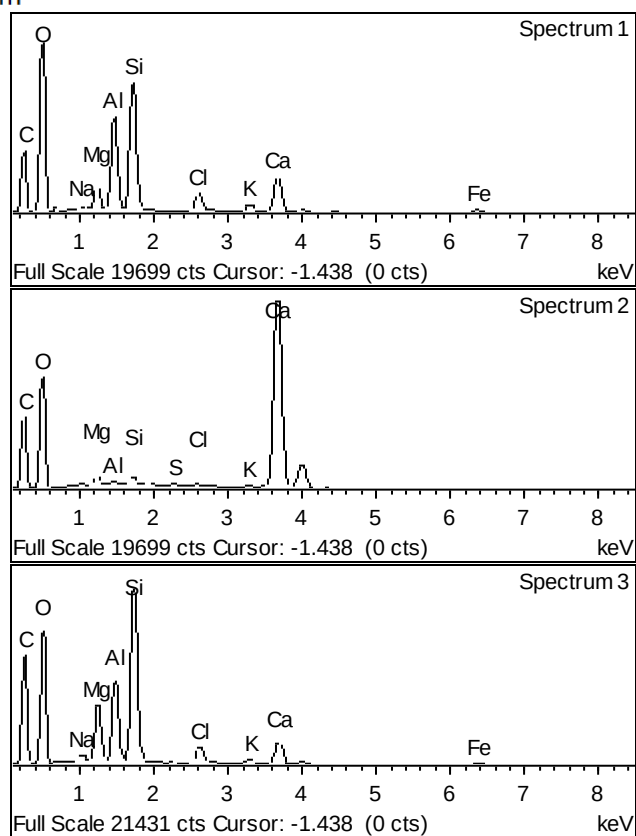


Figure 2 Site 2

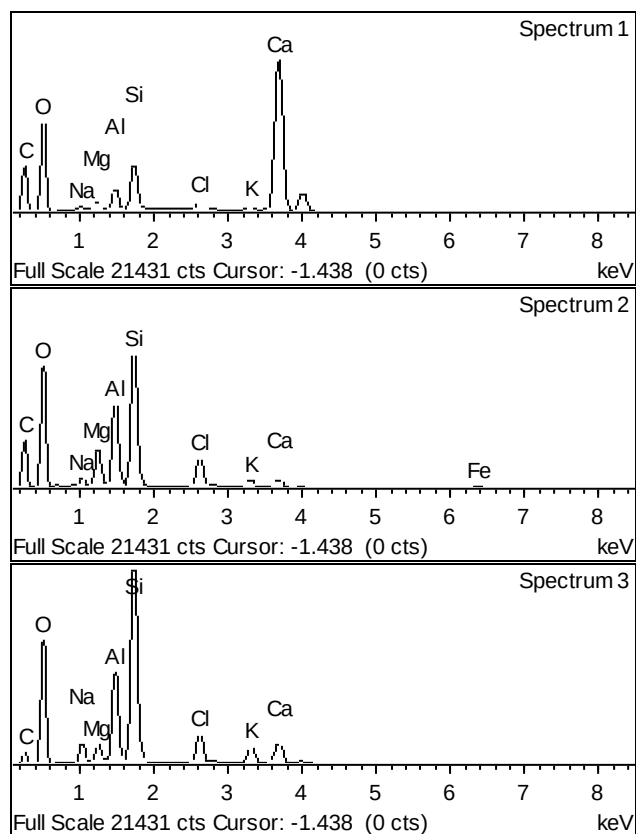
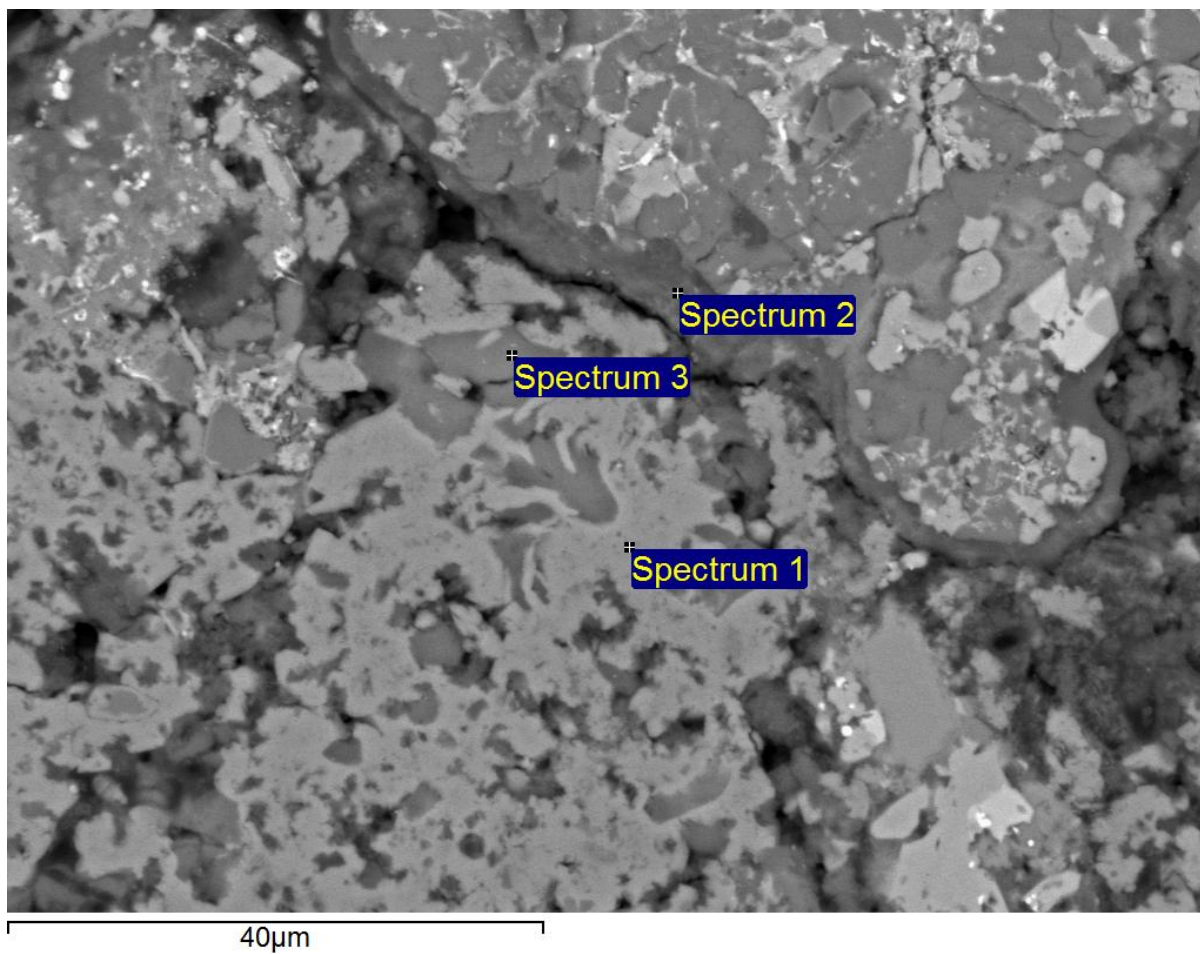


Figure 3 Site 3

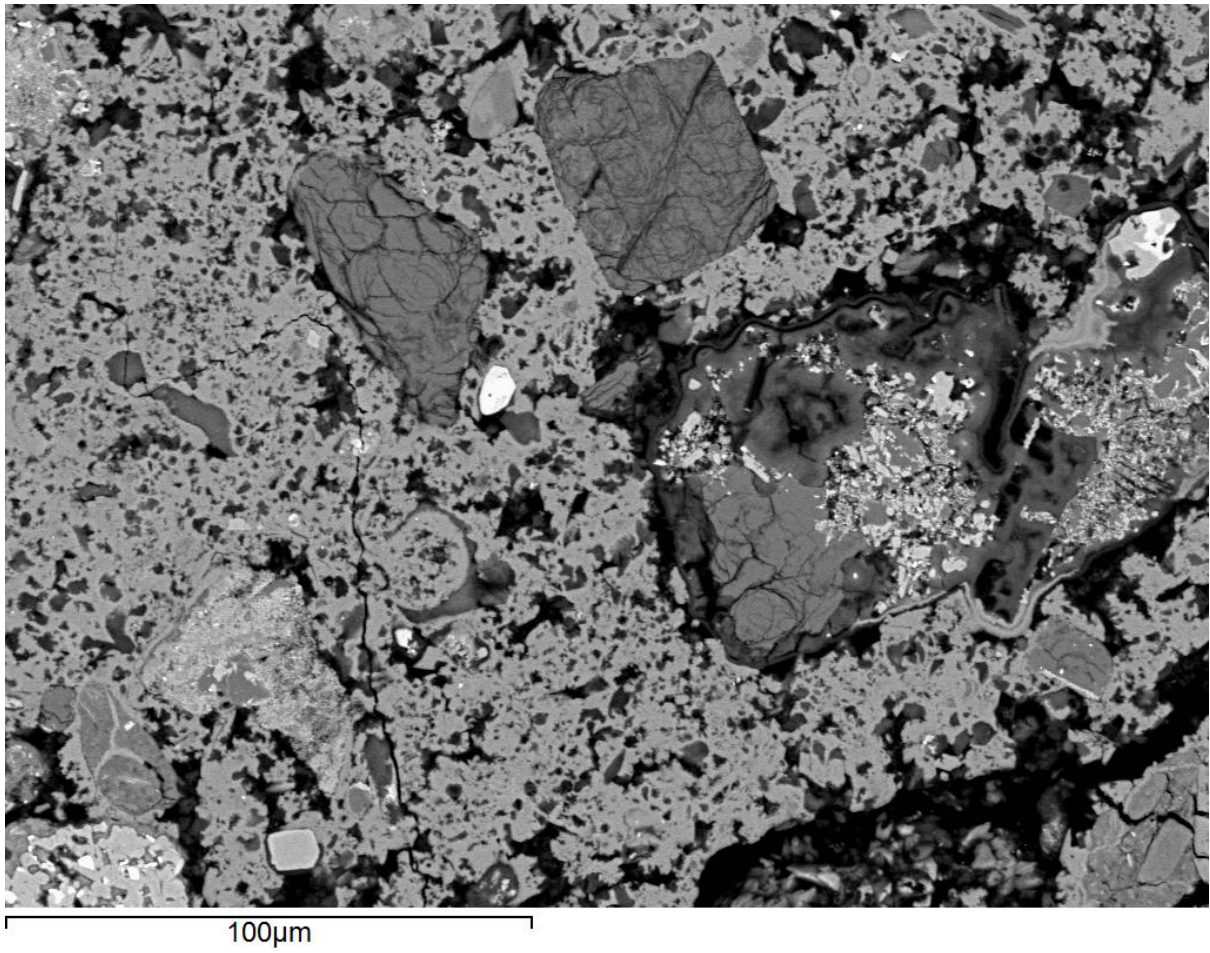
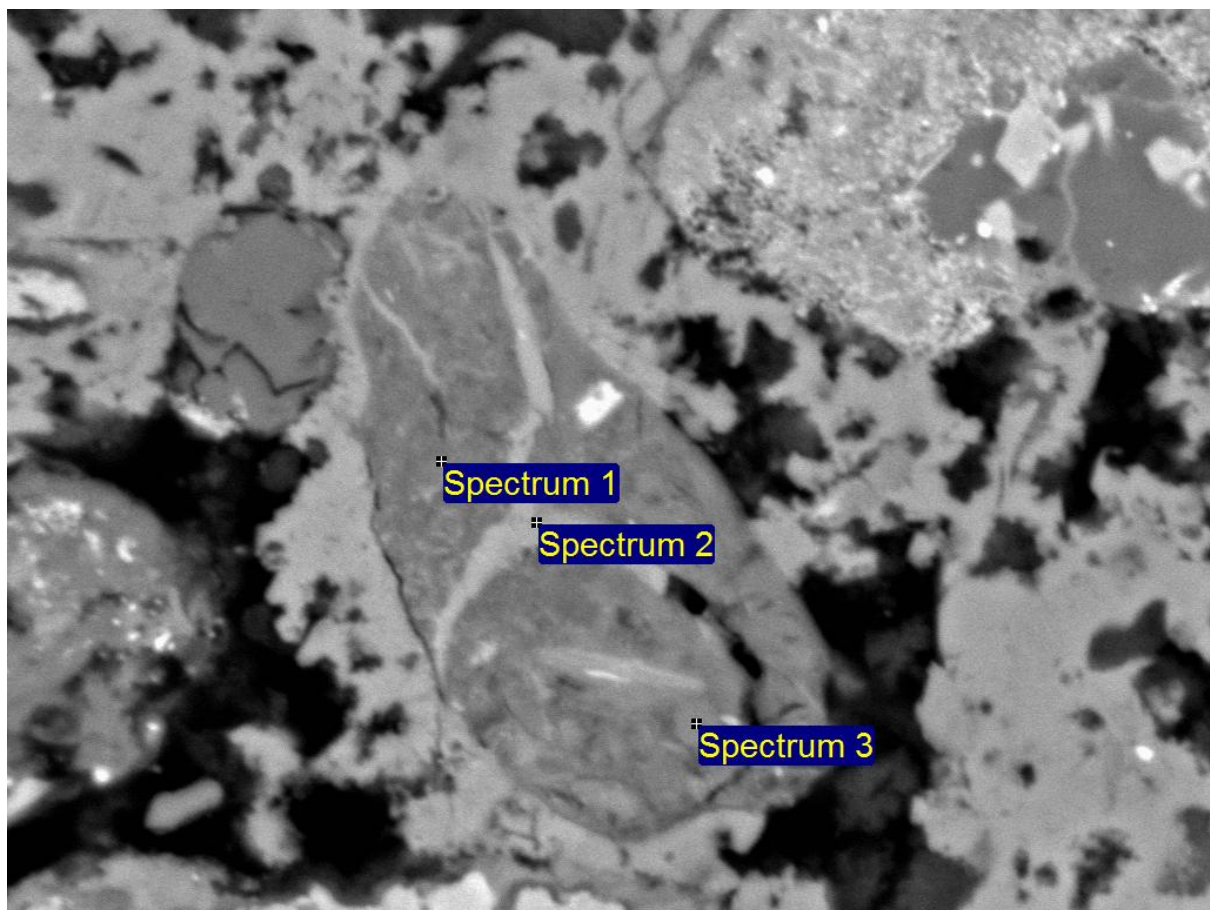


Figure 4 Site 4



20μm

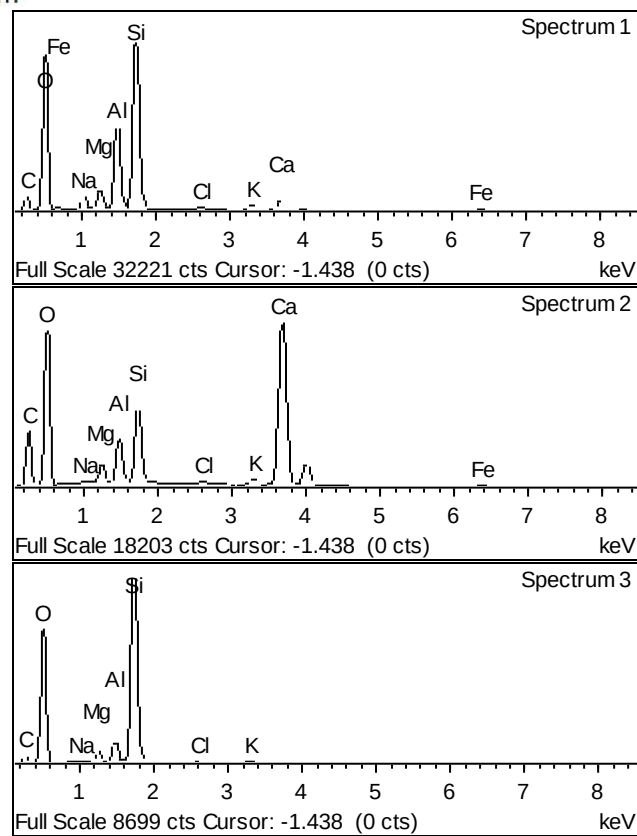
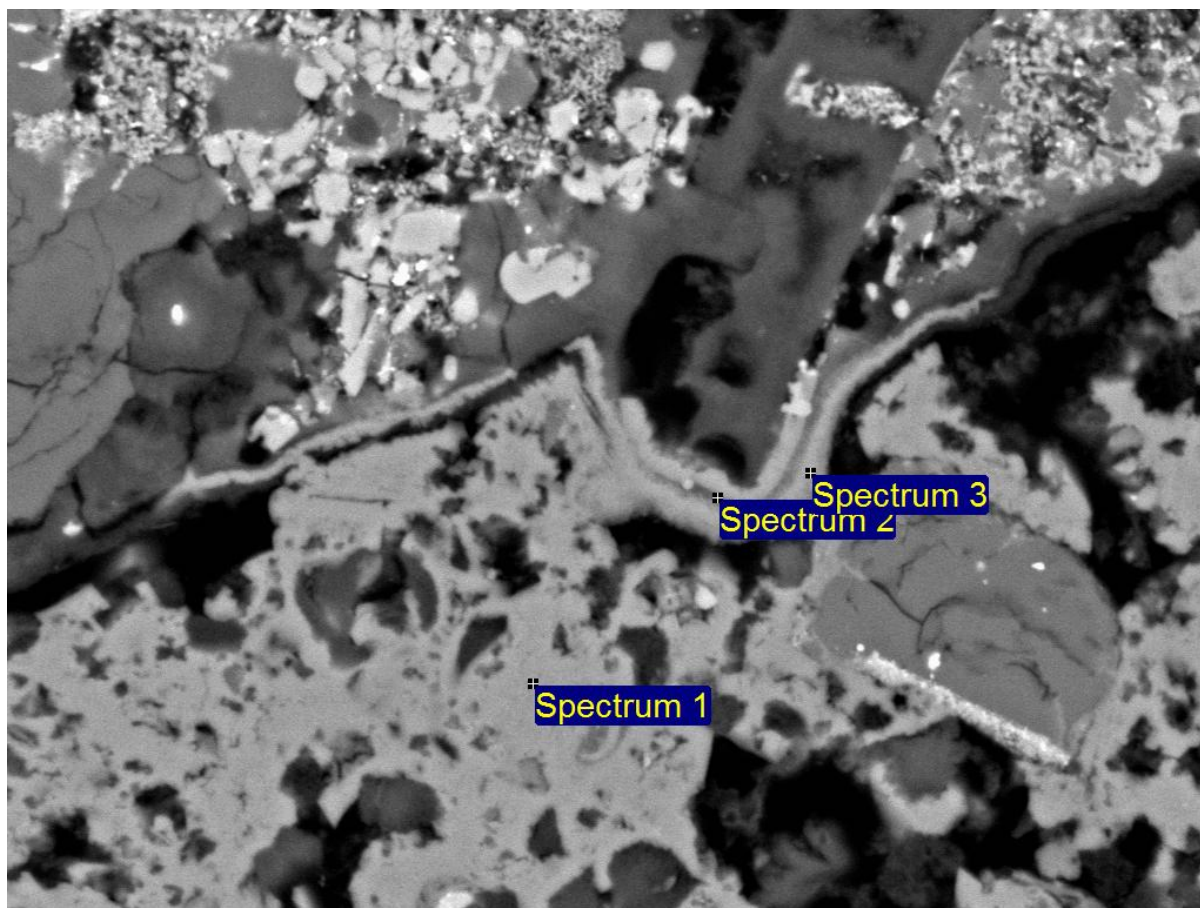


Figure 5 Site 5



30μm

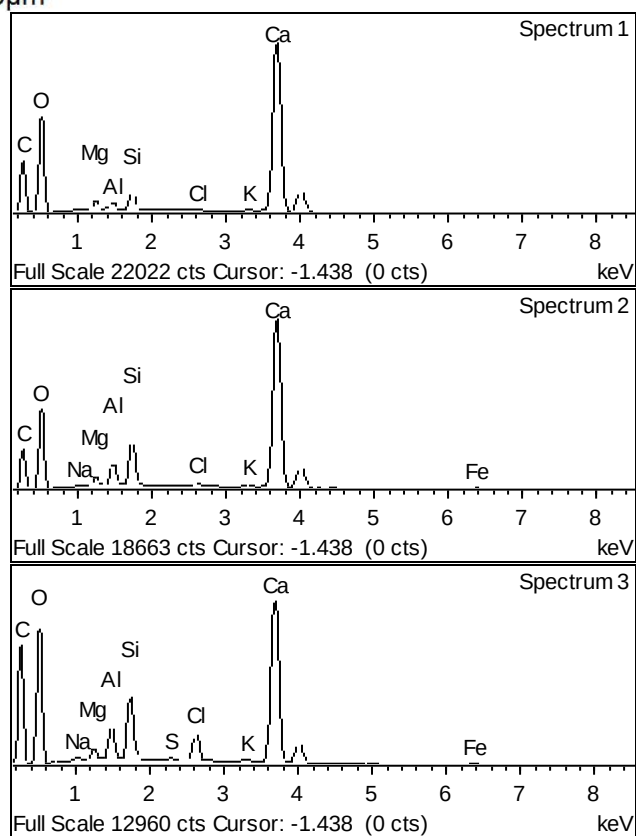


Figure 6 Site 6

Sample OS-C5

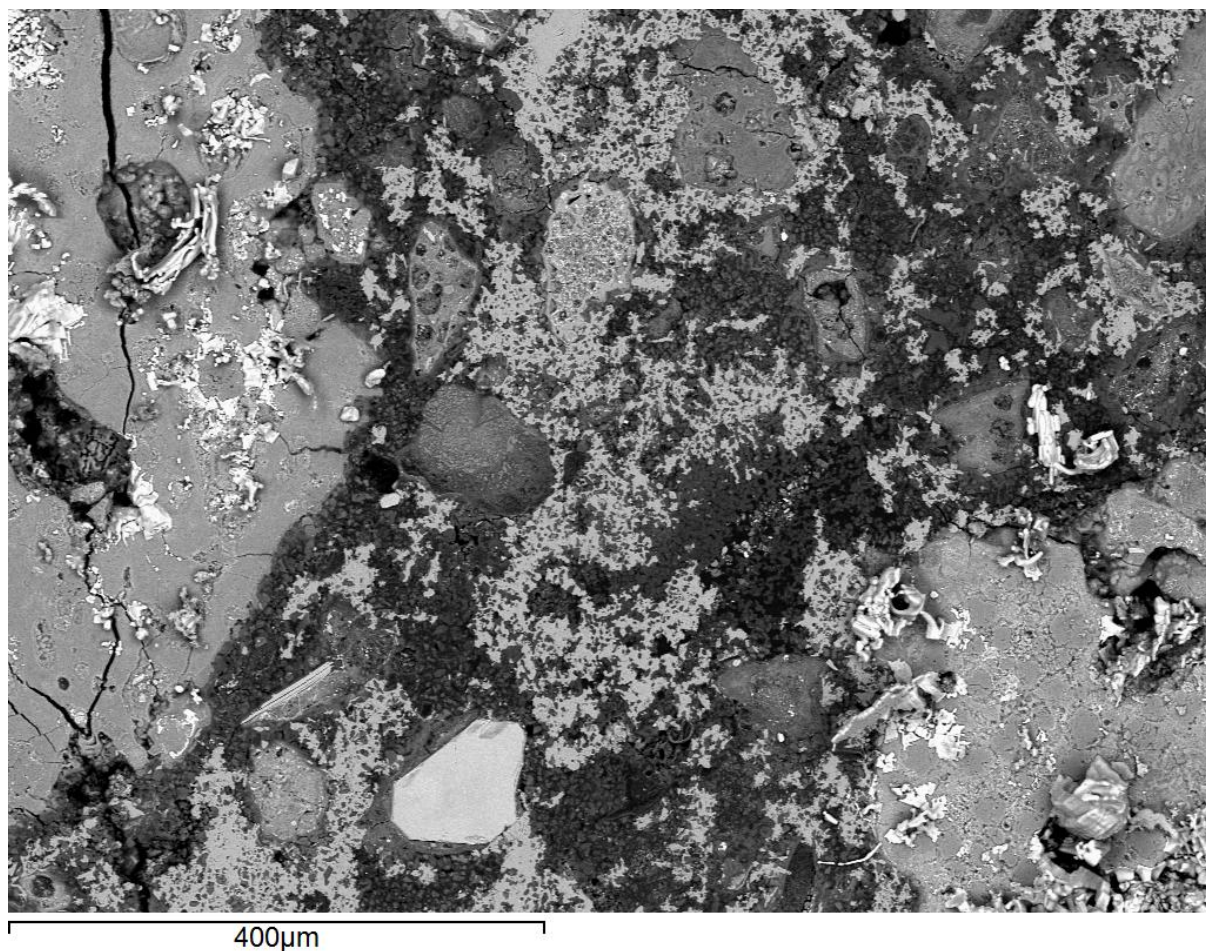


Figure 1 Sample 5 Site 1



Figure 2 Site 2

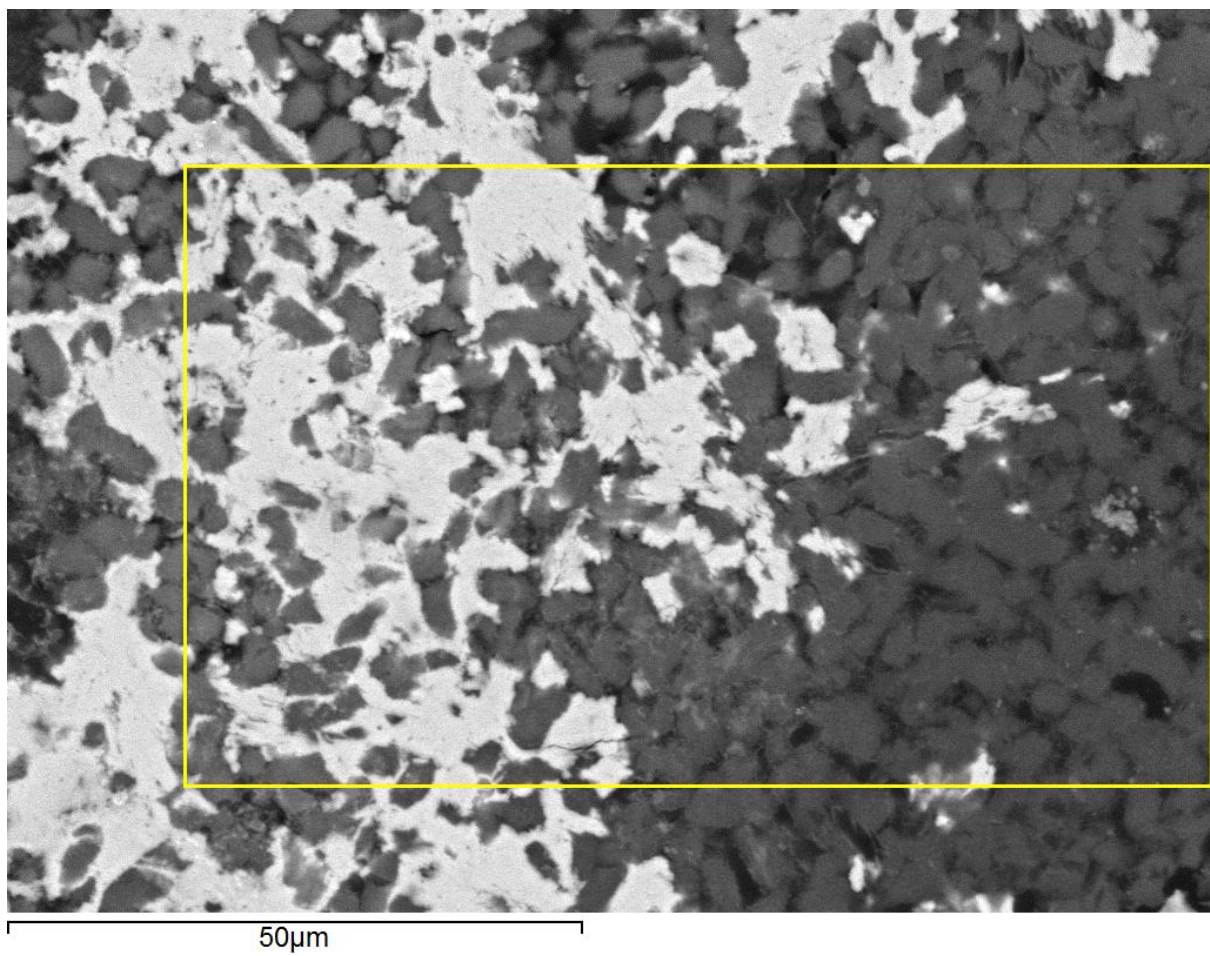
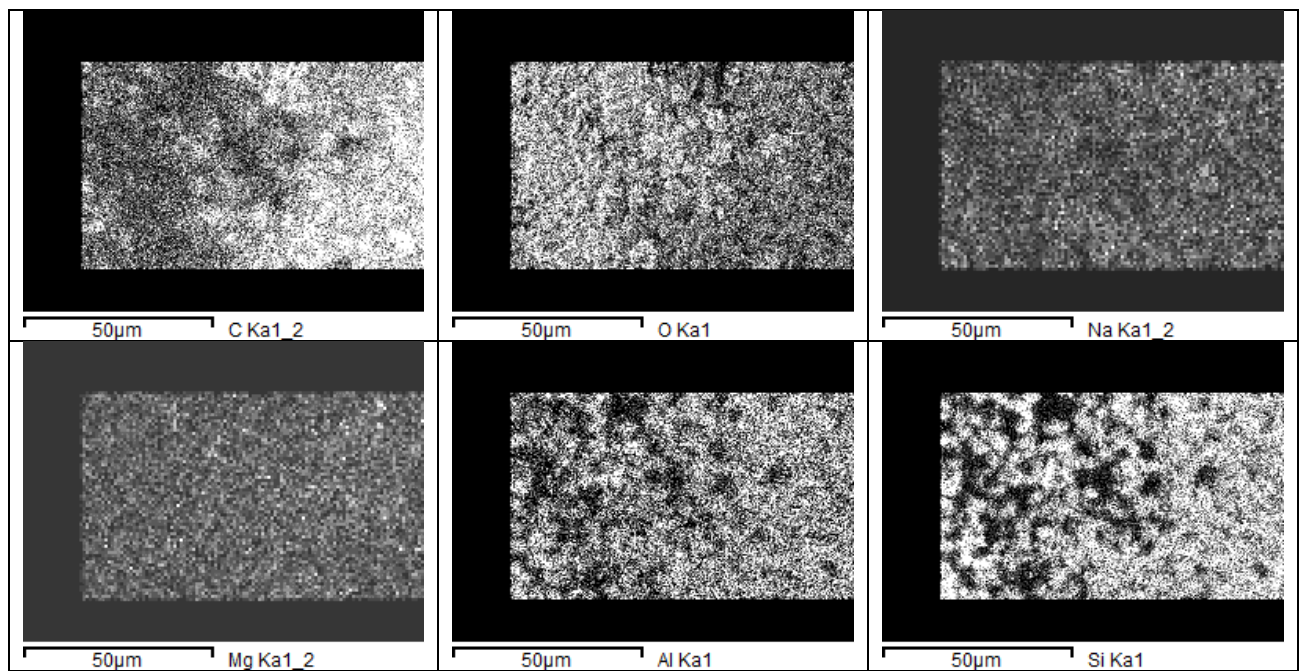


Figure 3 Site Image



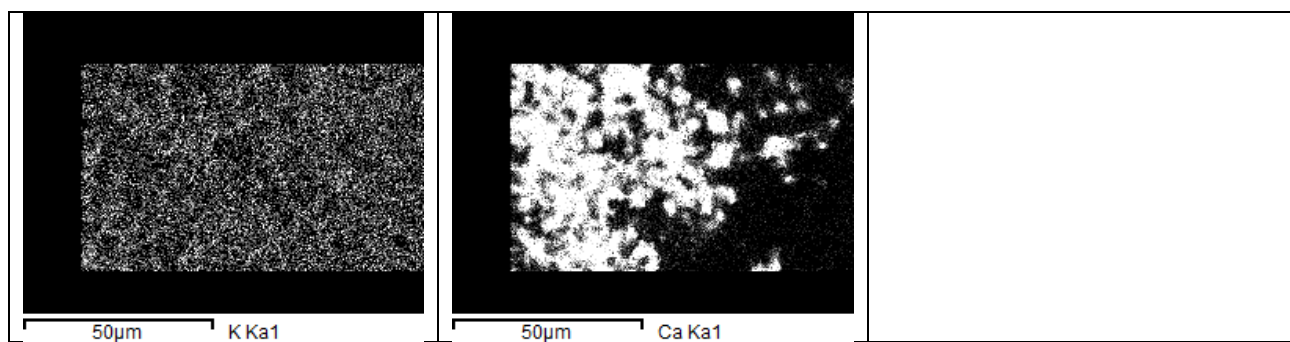


Figure 4 Site 3 Elemental maps

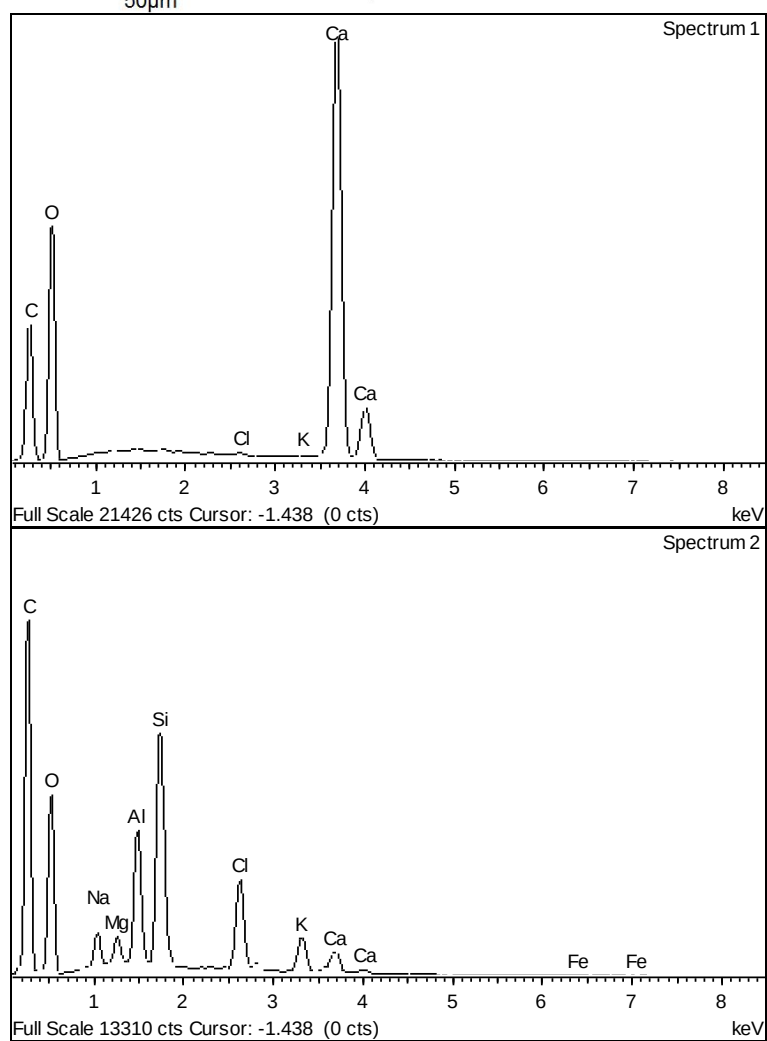
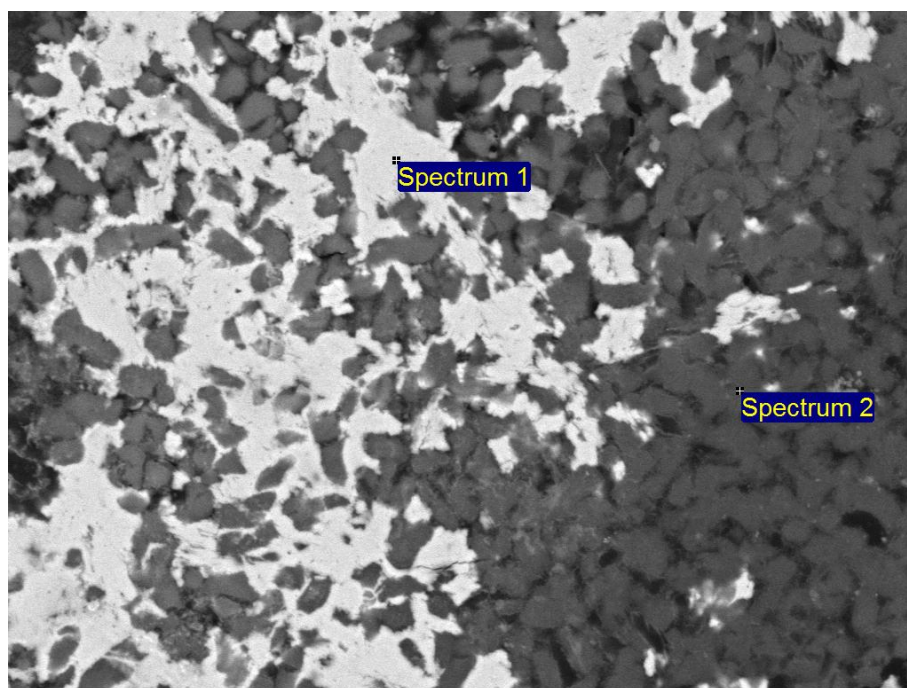


Figure 5 Site 3 Spectra

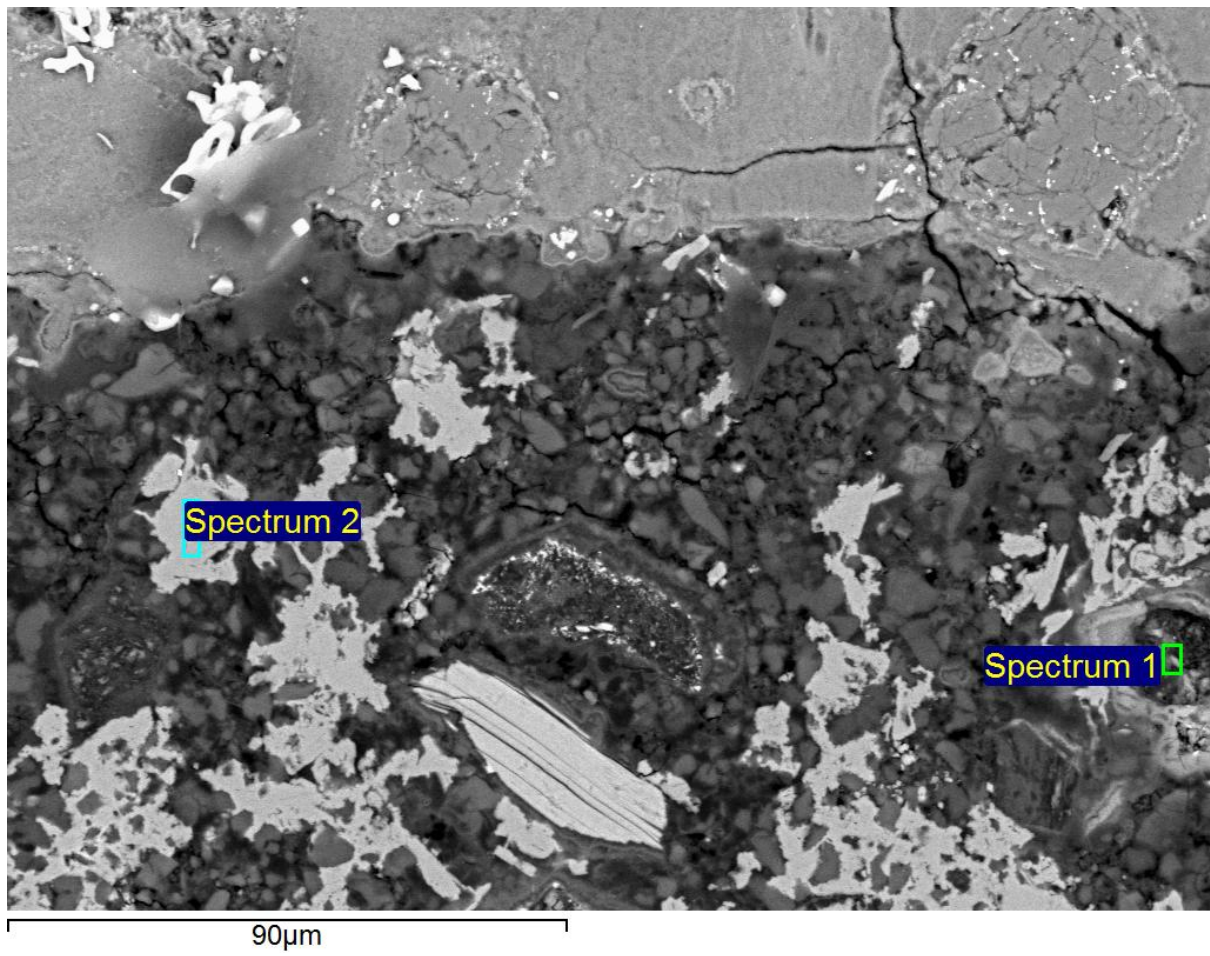


Figure 6 Site 4 Image

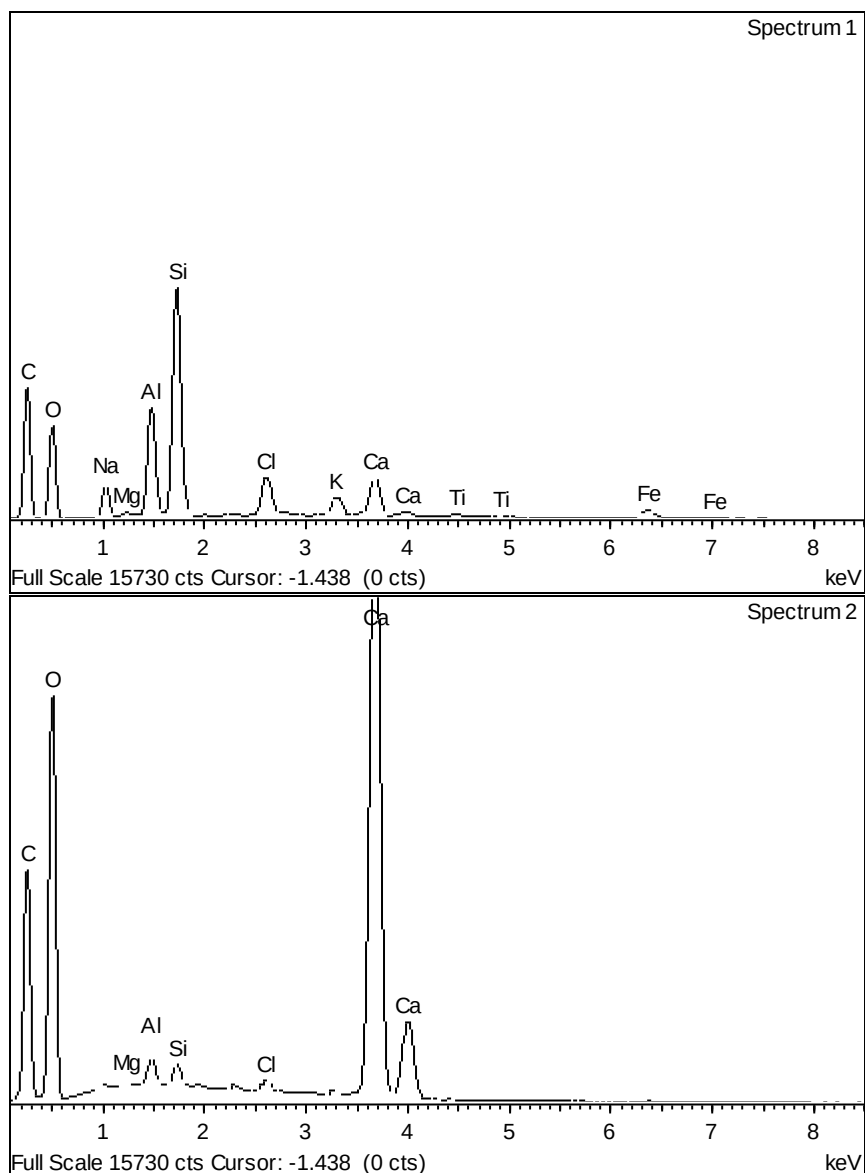


Figure 7 Site 4 Spectra



300µm

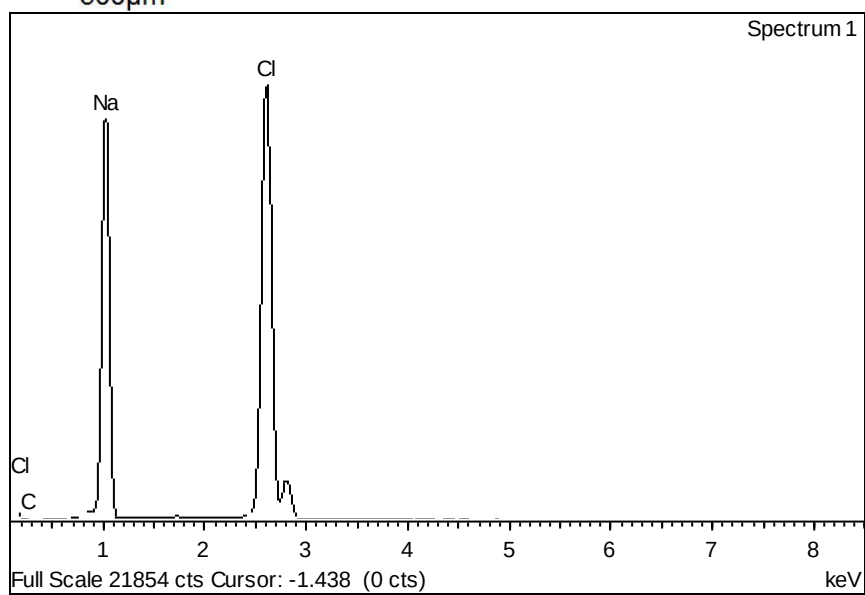


Figure 8 Site 5

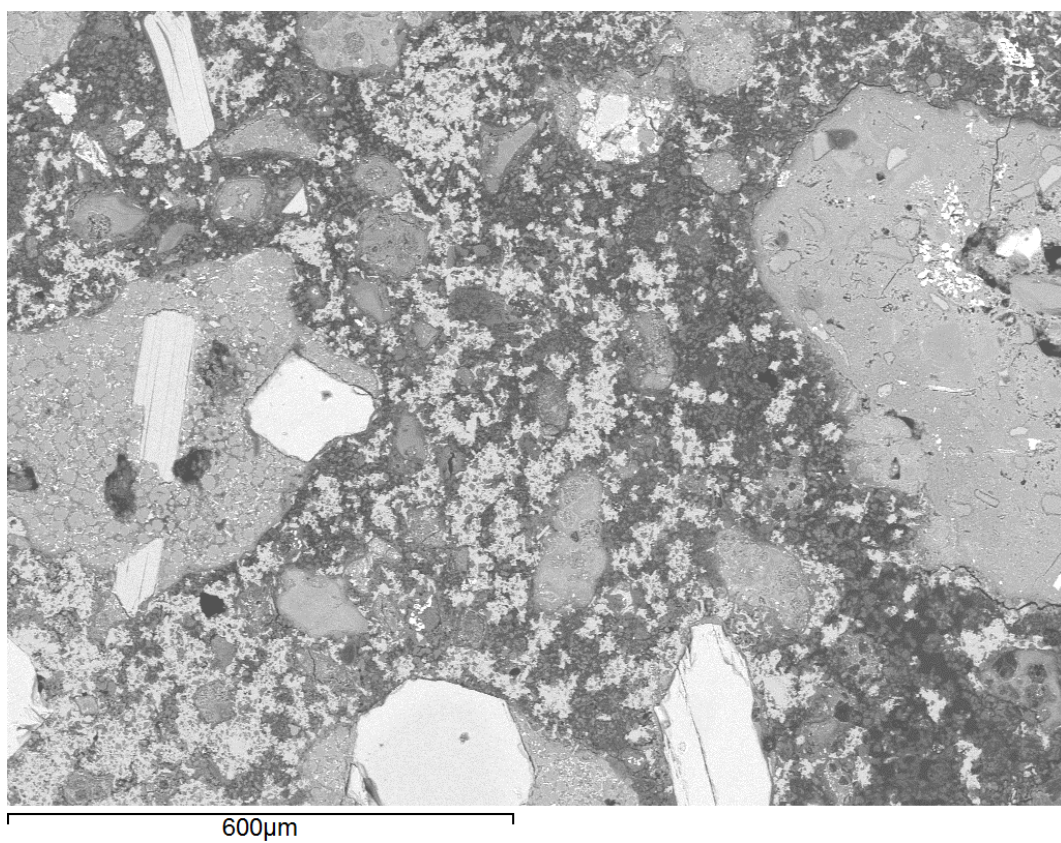
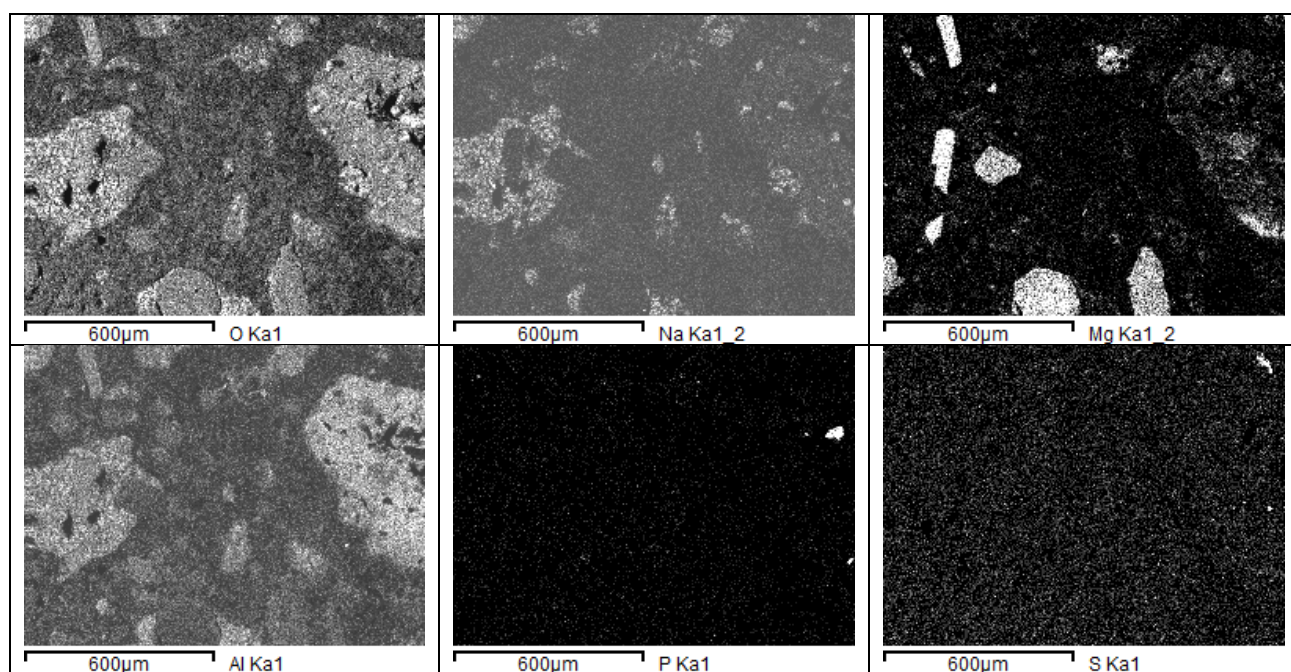


Figure 9 Site 6 image



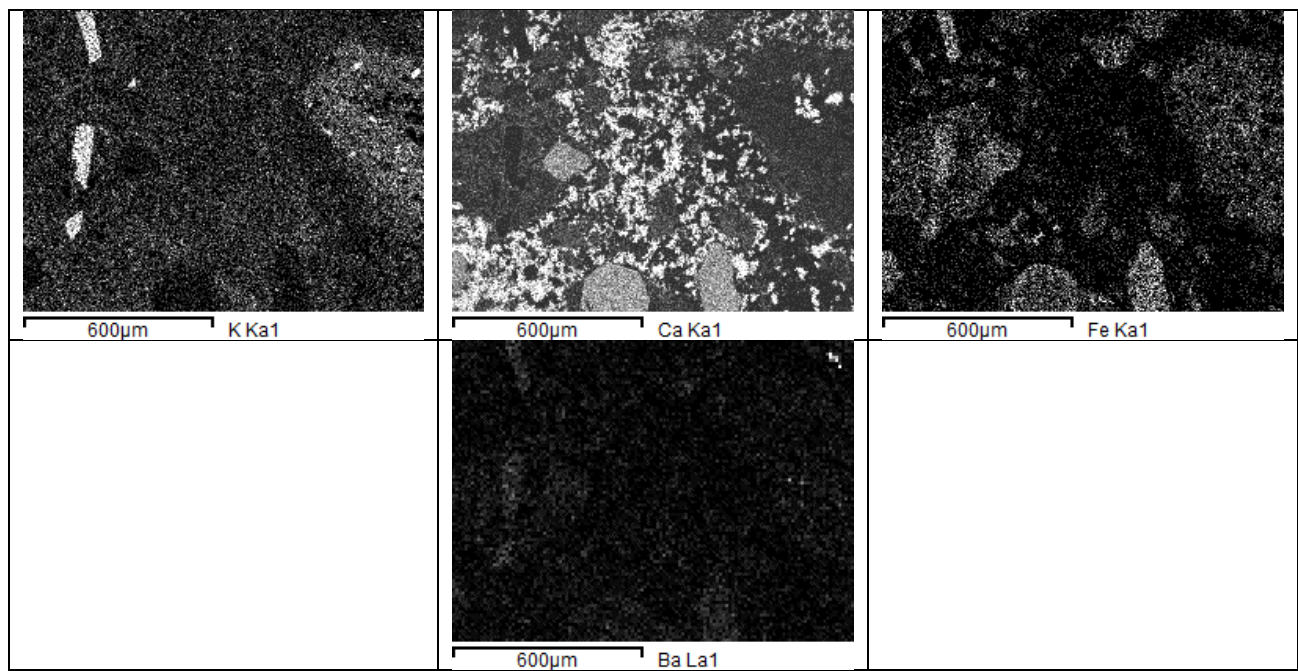


Figure 10 Site 6 elemental maps

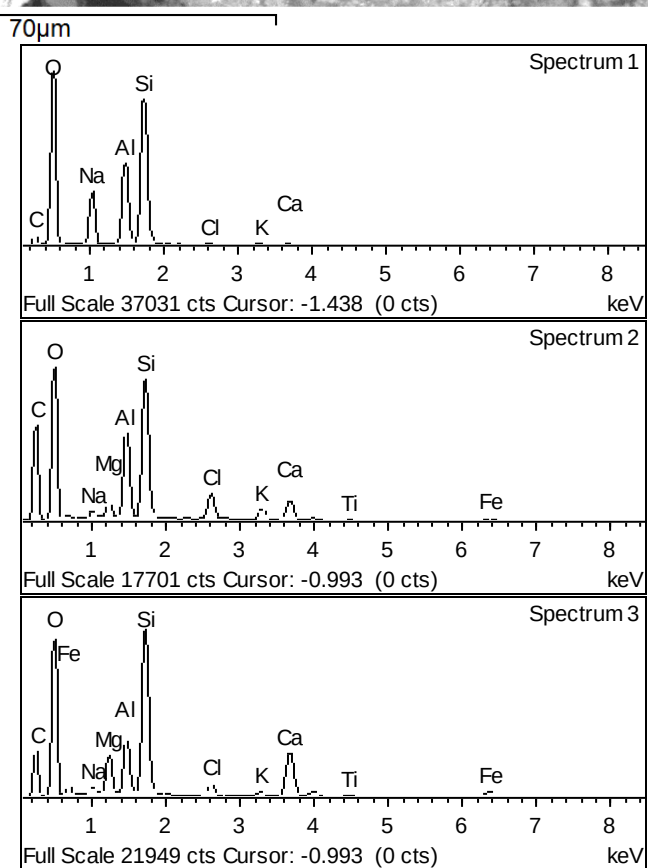
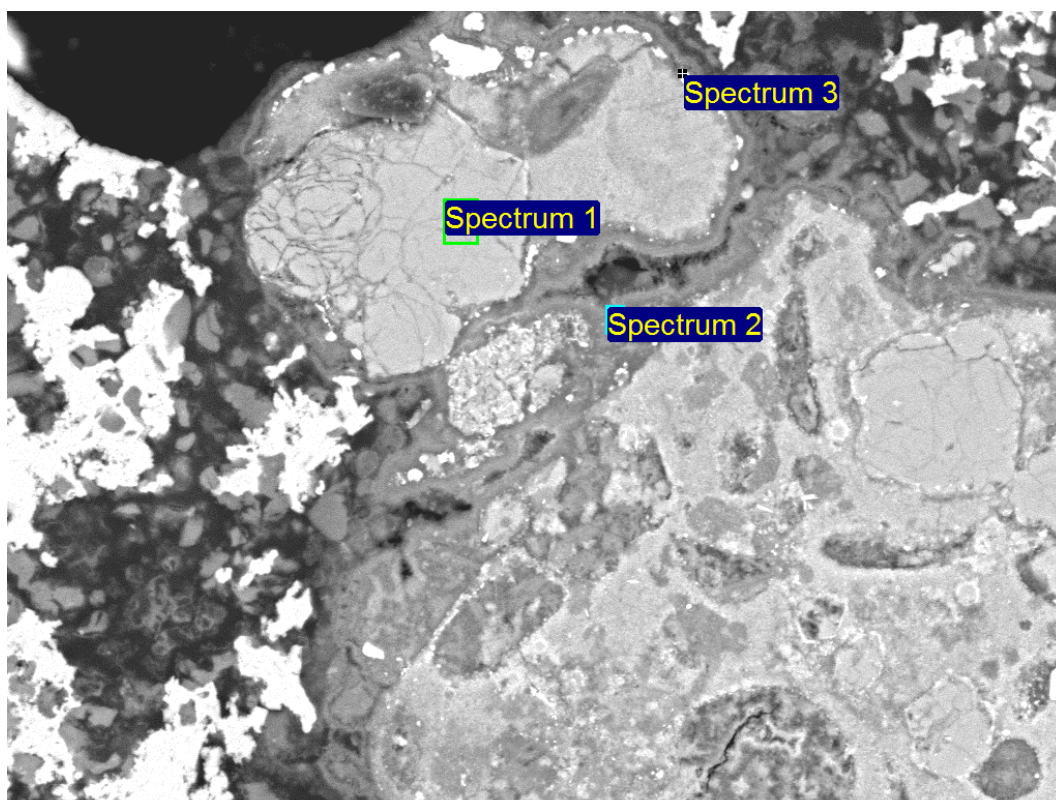


Figure 11 Site 7

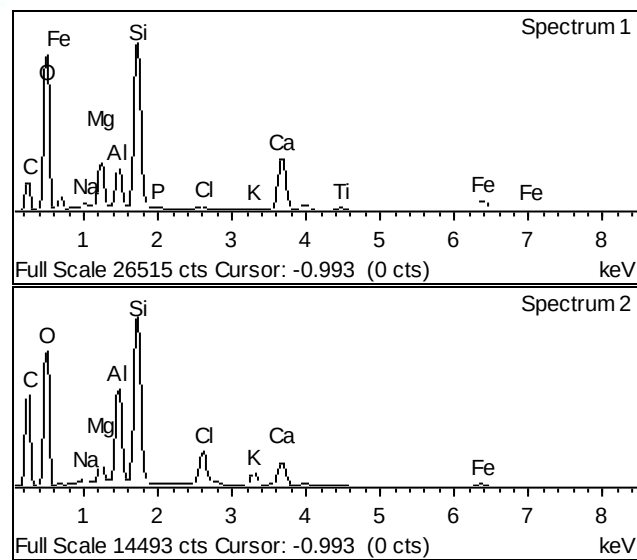
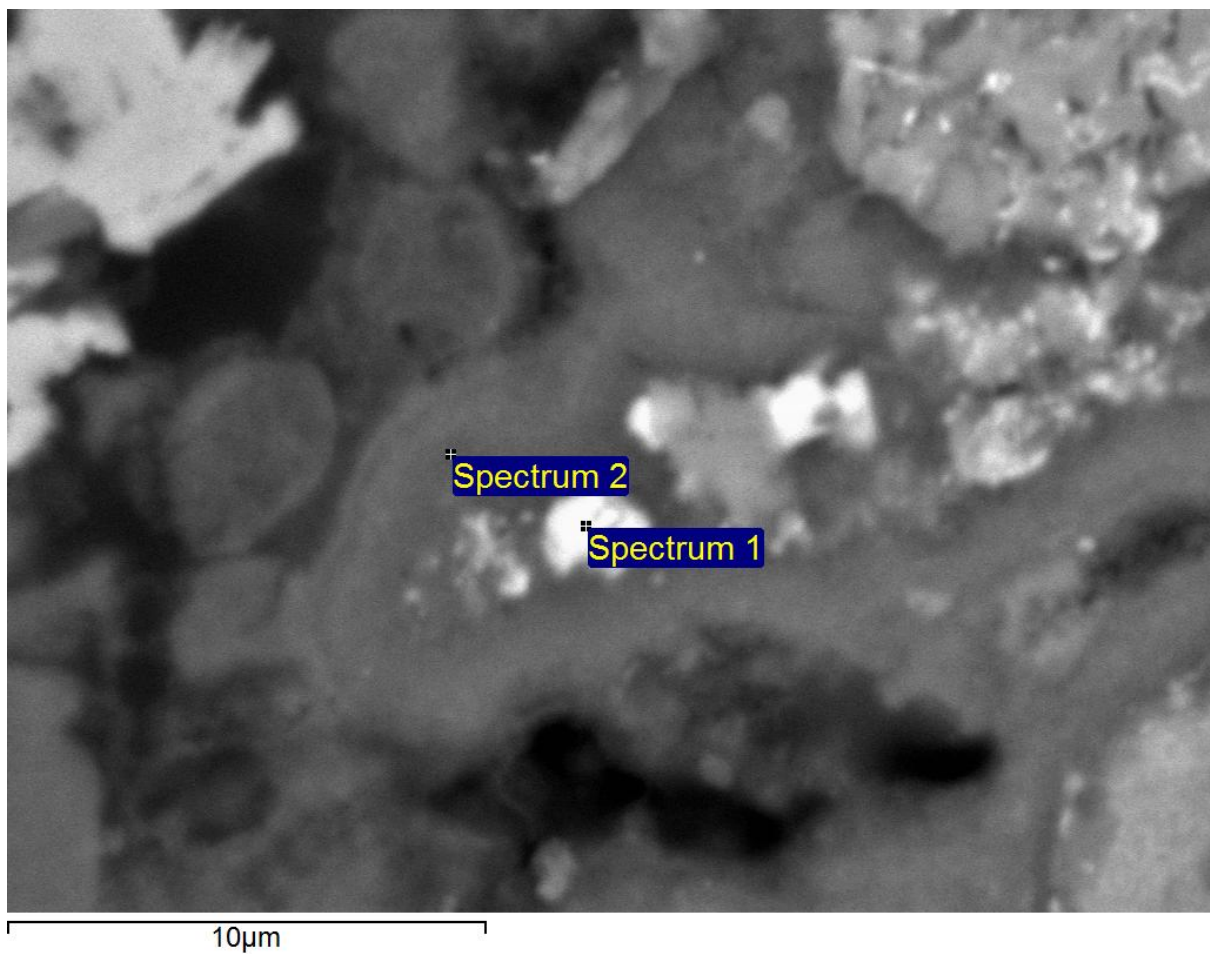


Figure 12 Site 8

Sample OS-C15

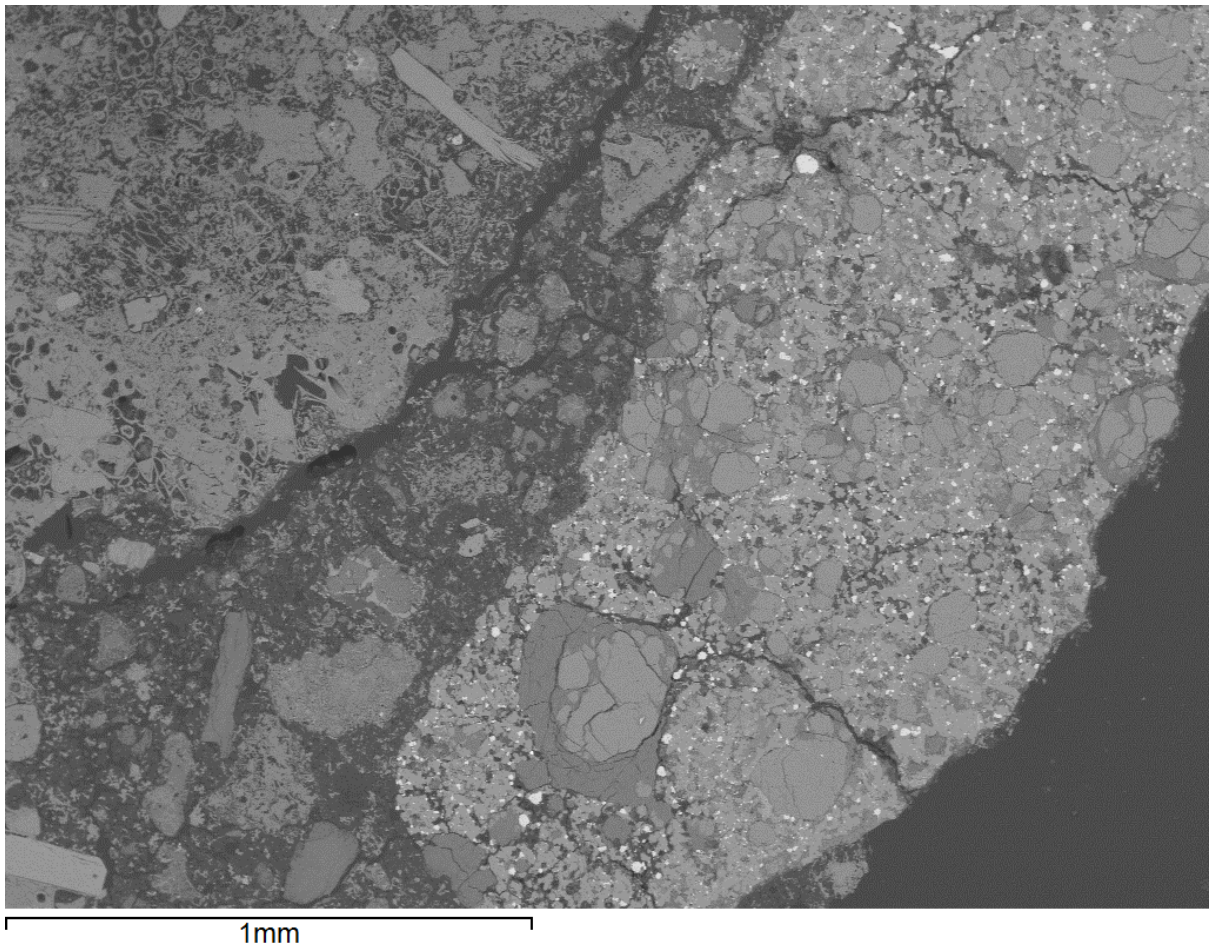


Figure 1 Site 1

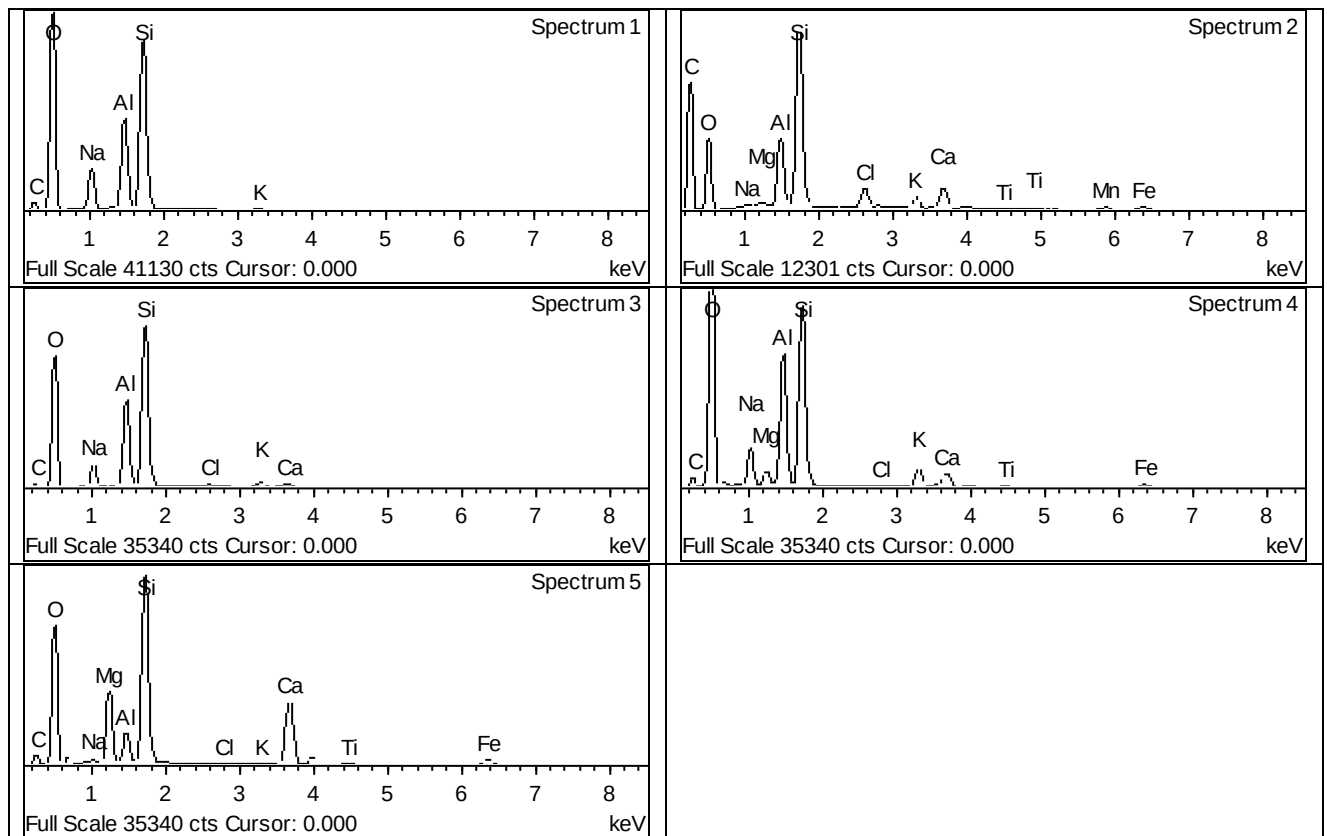
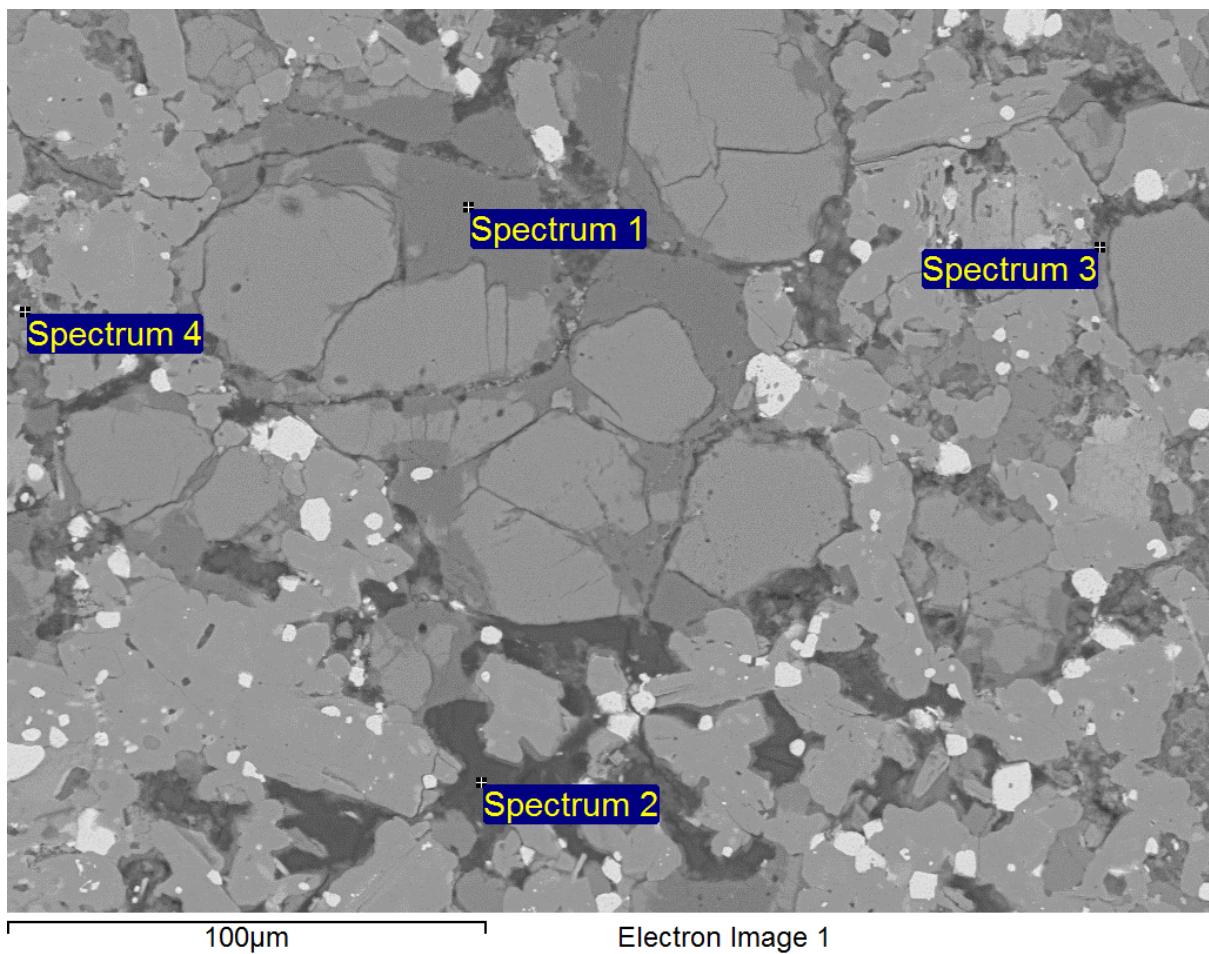
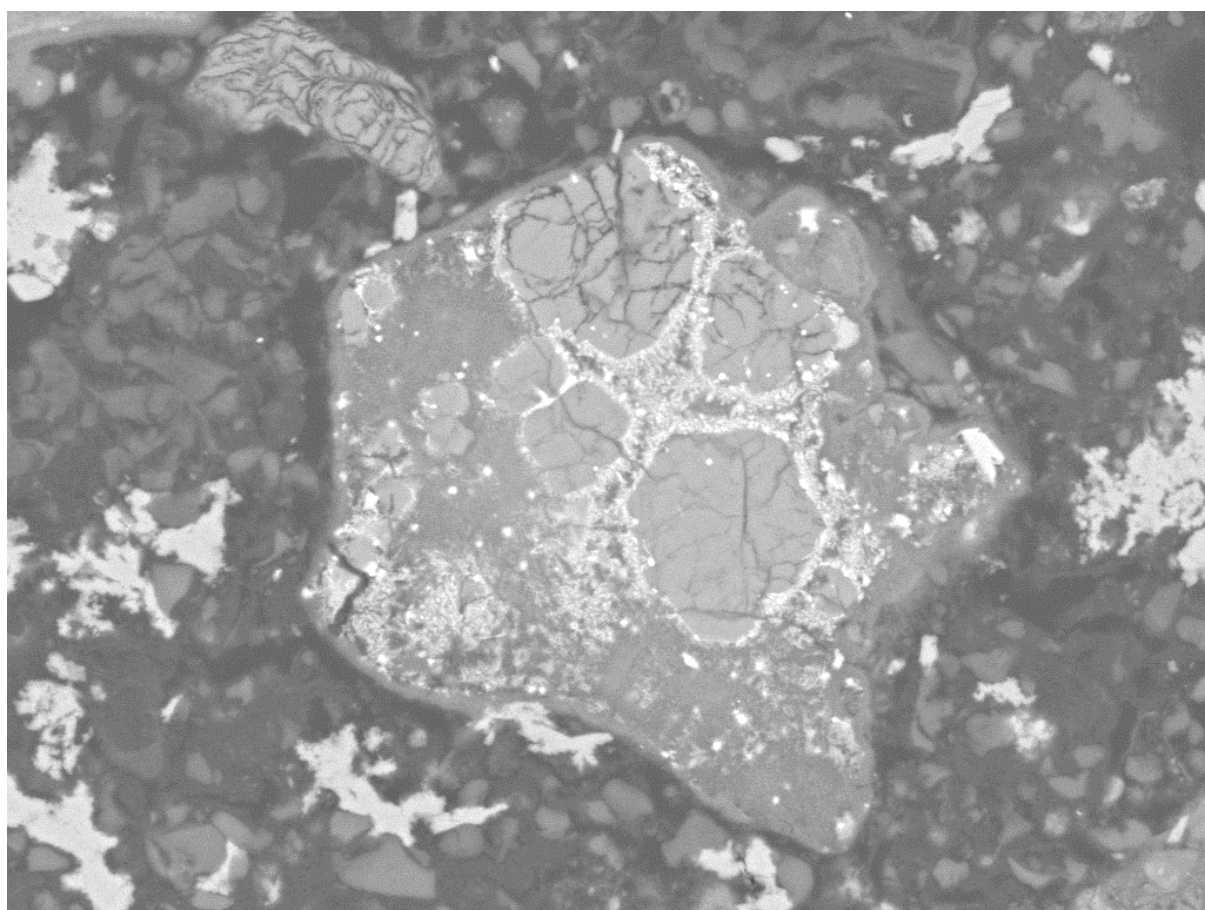
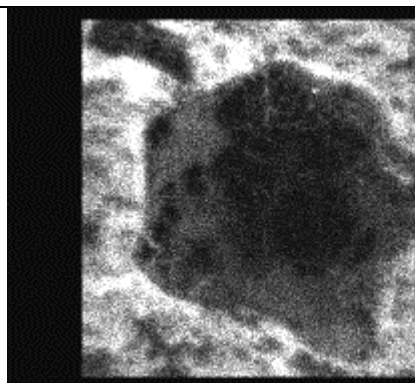


Figure 2 Site 2

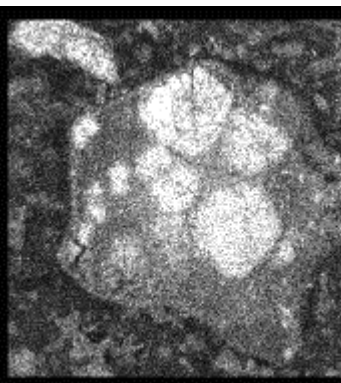


50µm



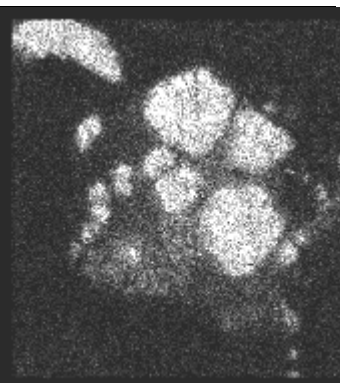
50µm

C Ka1_2



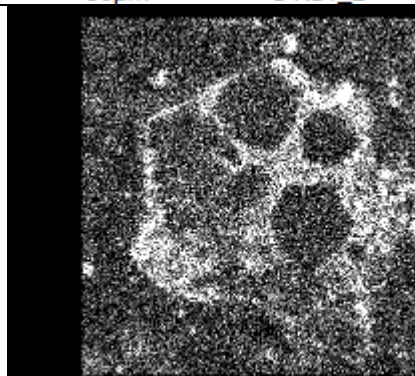
50µm

O Ka1



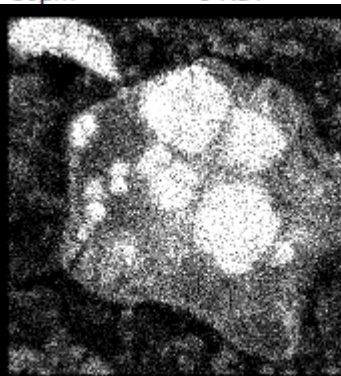
50µm

Na Ka1_2



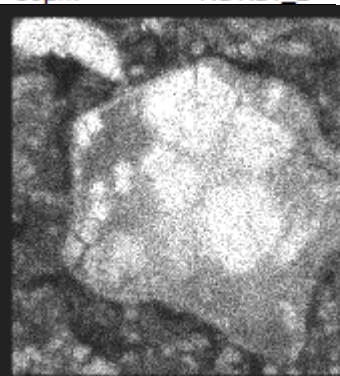
50µm

Mg Ka1_2



50µm

Al Ka1



50µm

Si Ka1

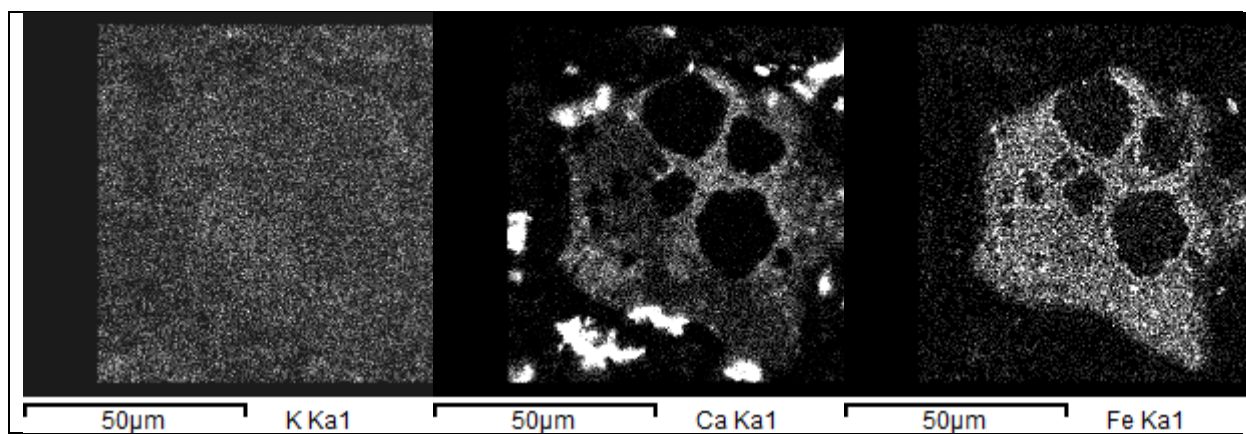


Figure 3 Site 3

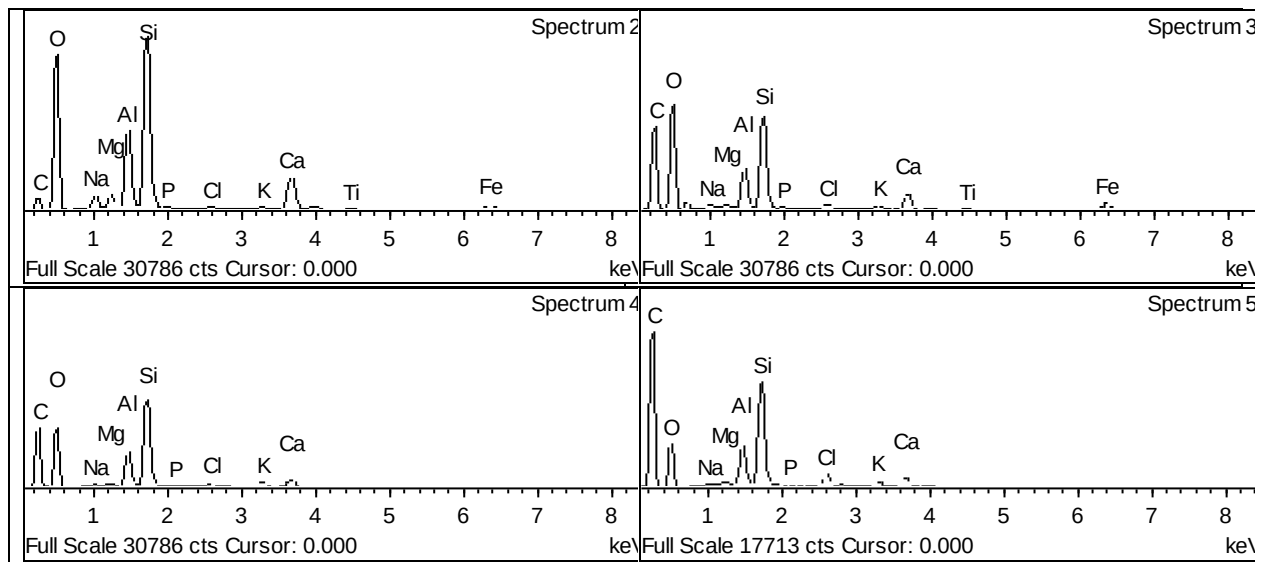
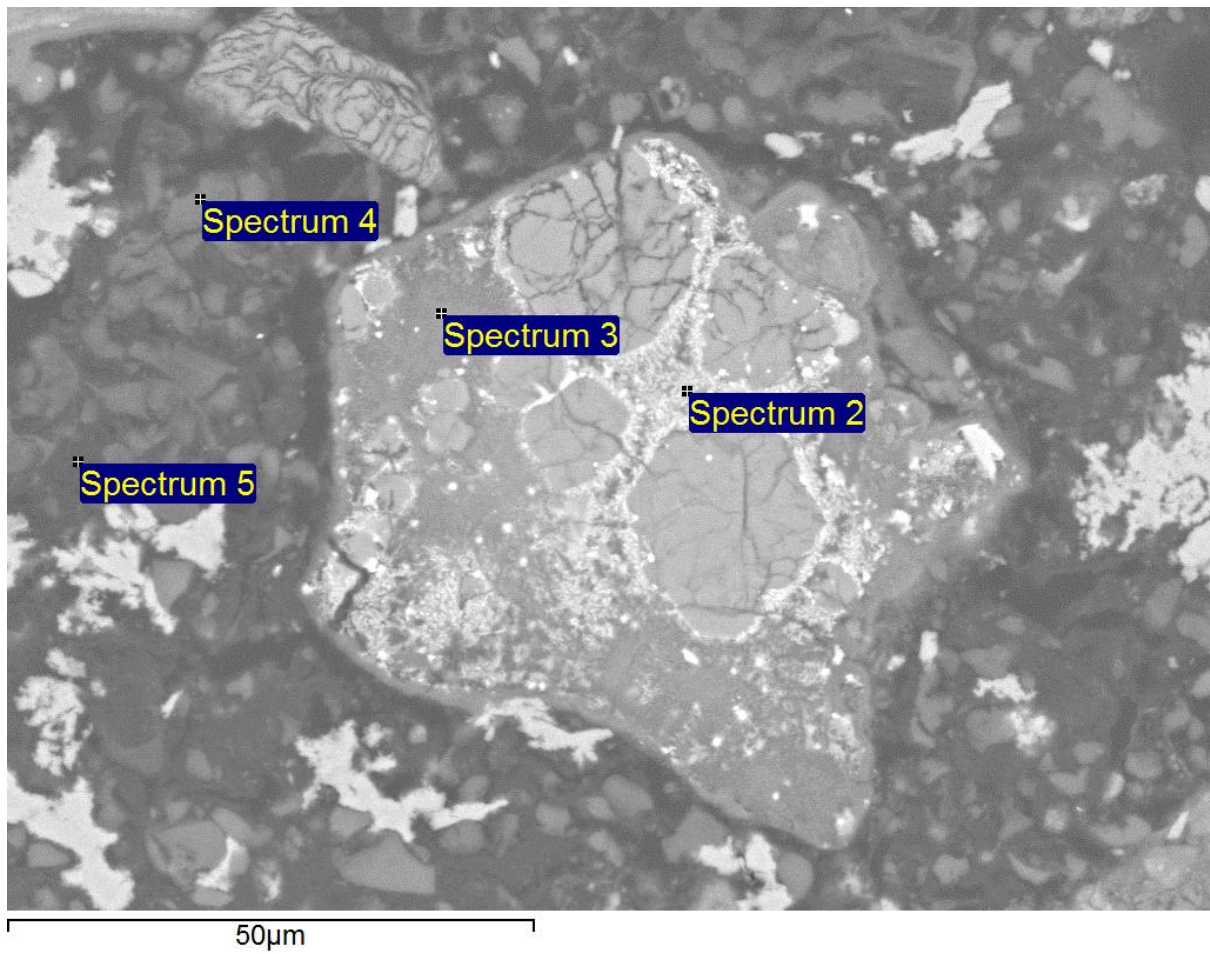
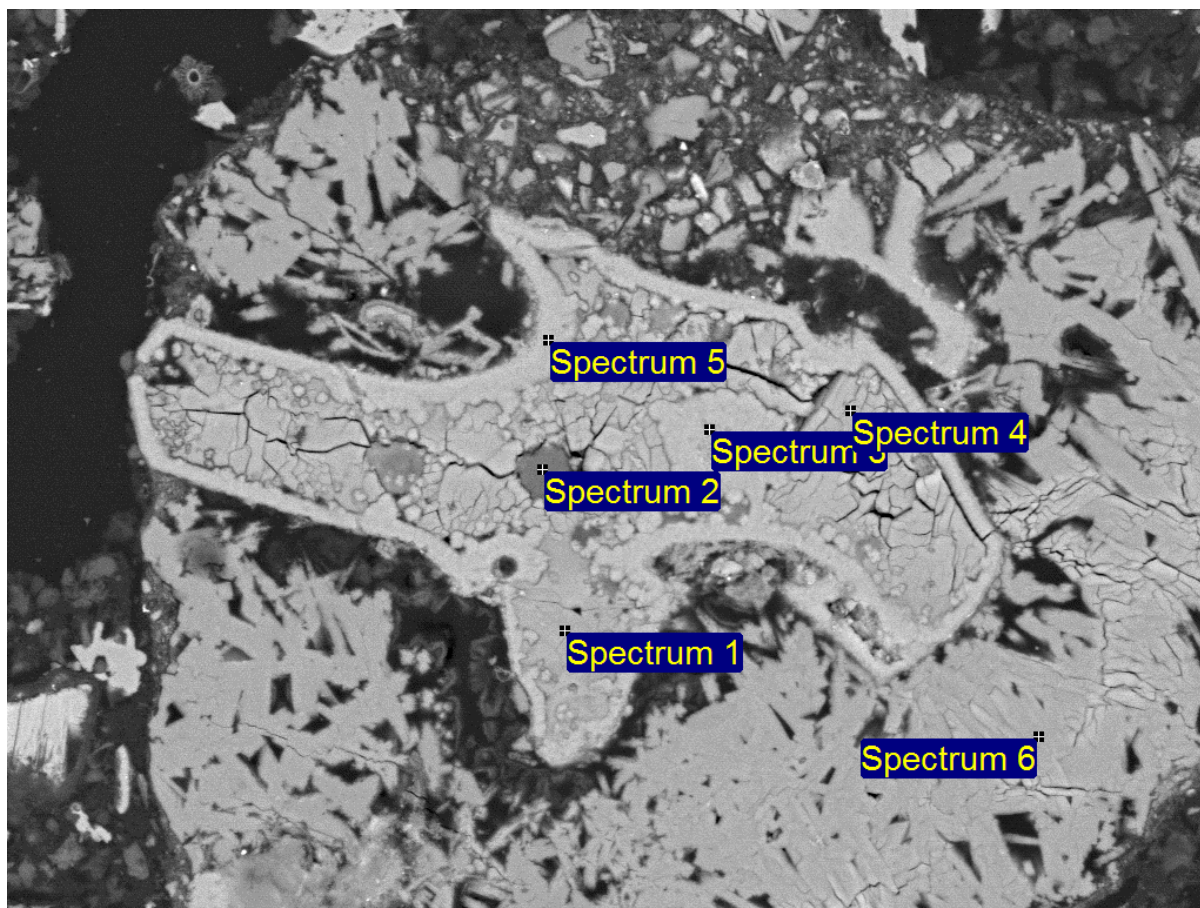


Figure 4 Site 3 Spectra



80µm

Electron Image 1

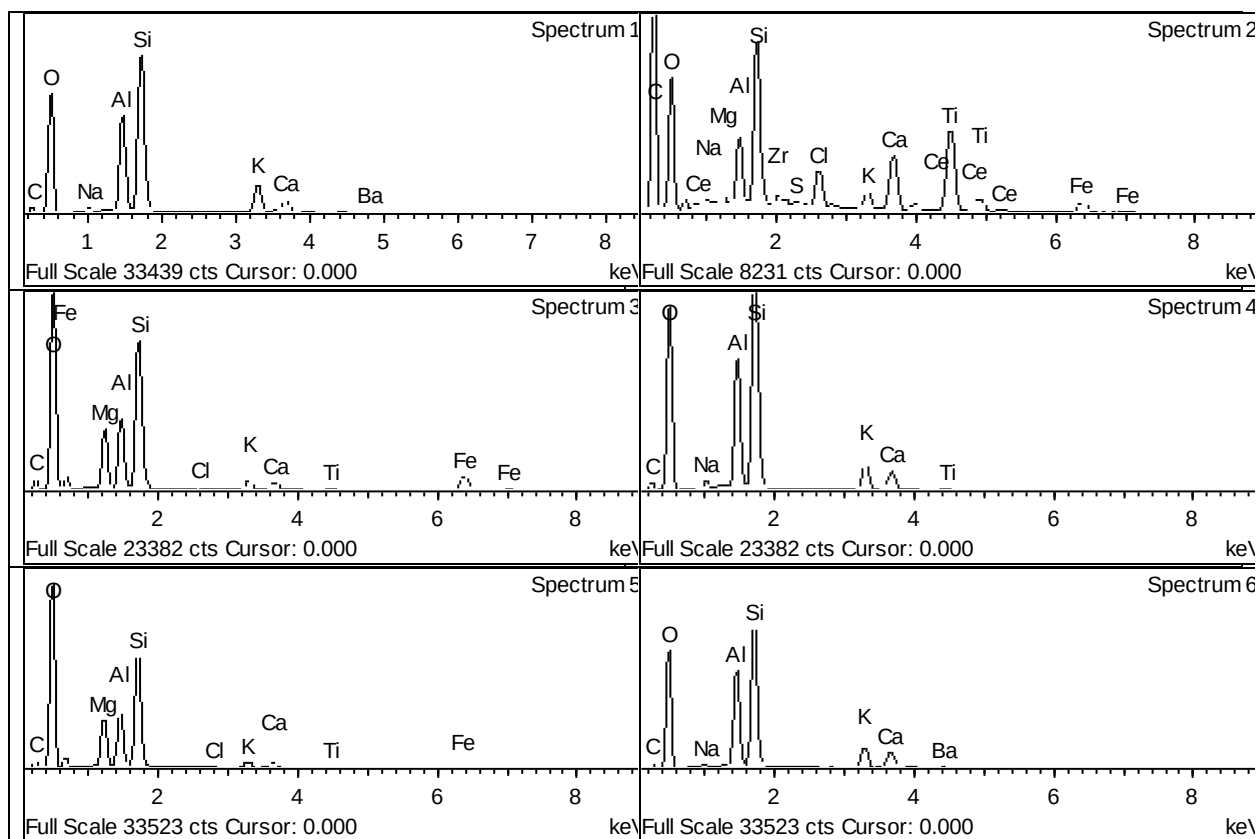
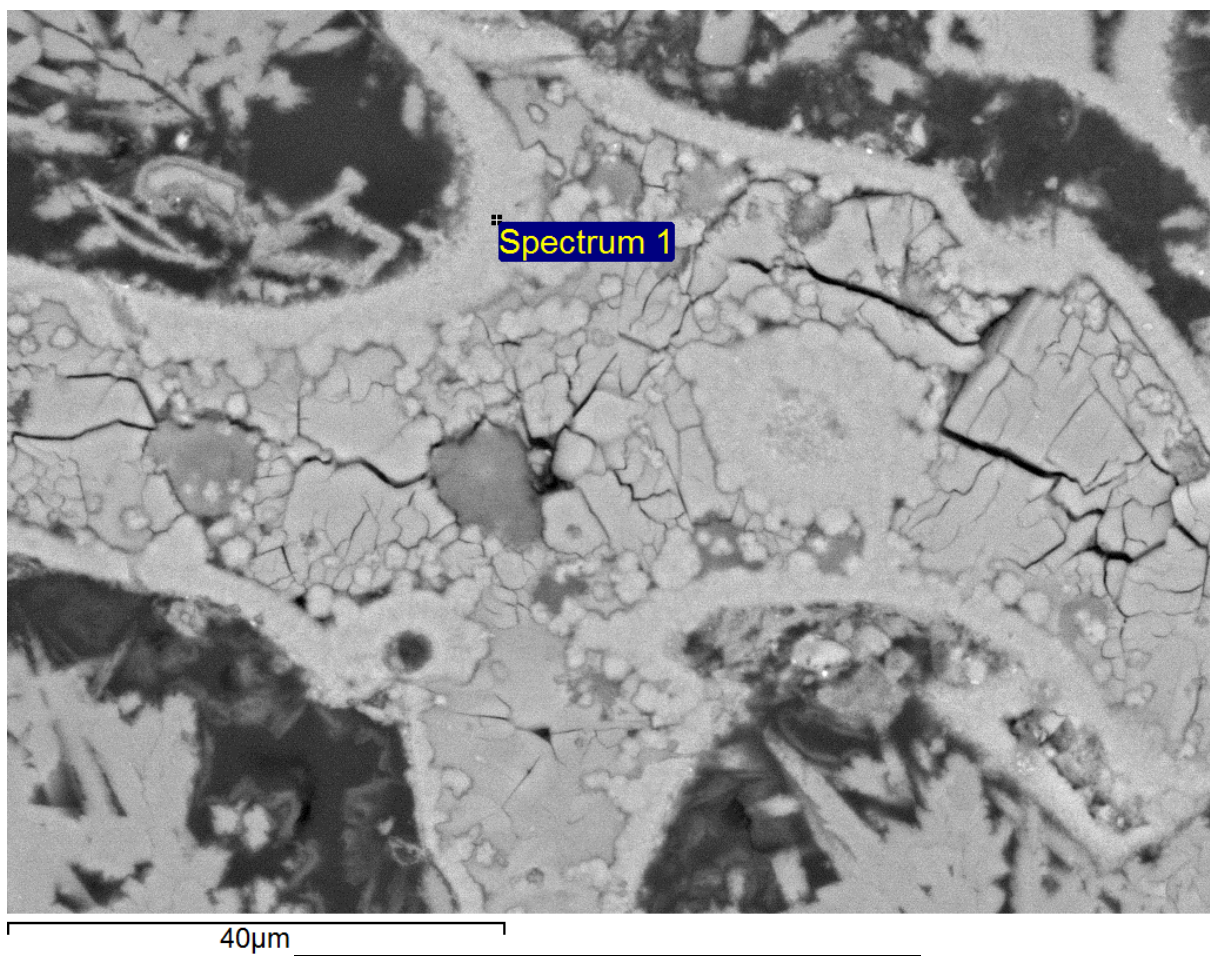


Figure 5 Site 4



40µm

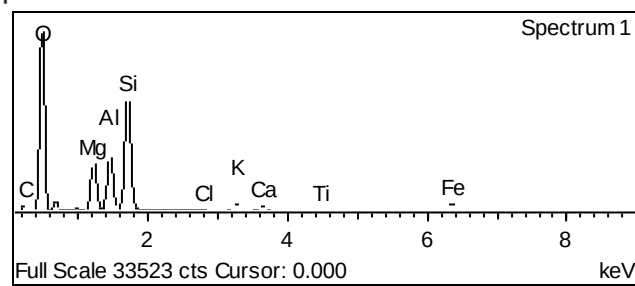


Figure 6 Site 6

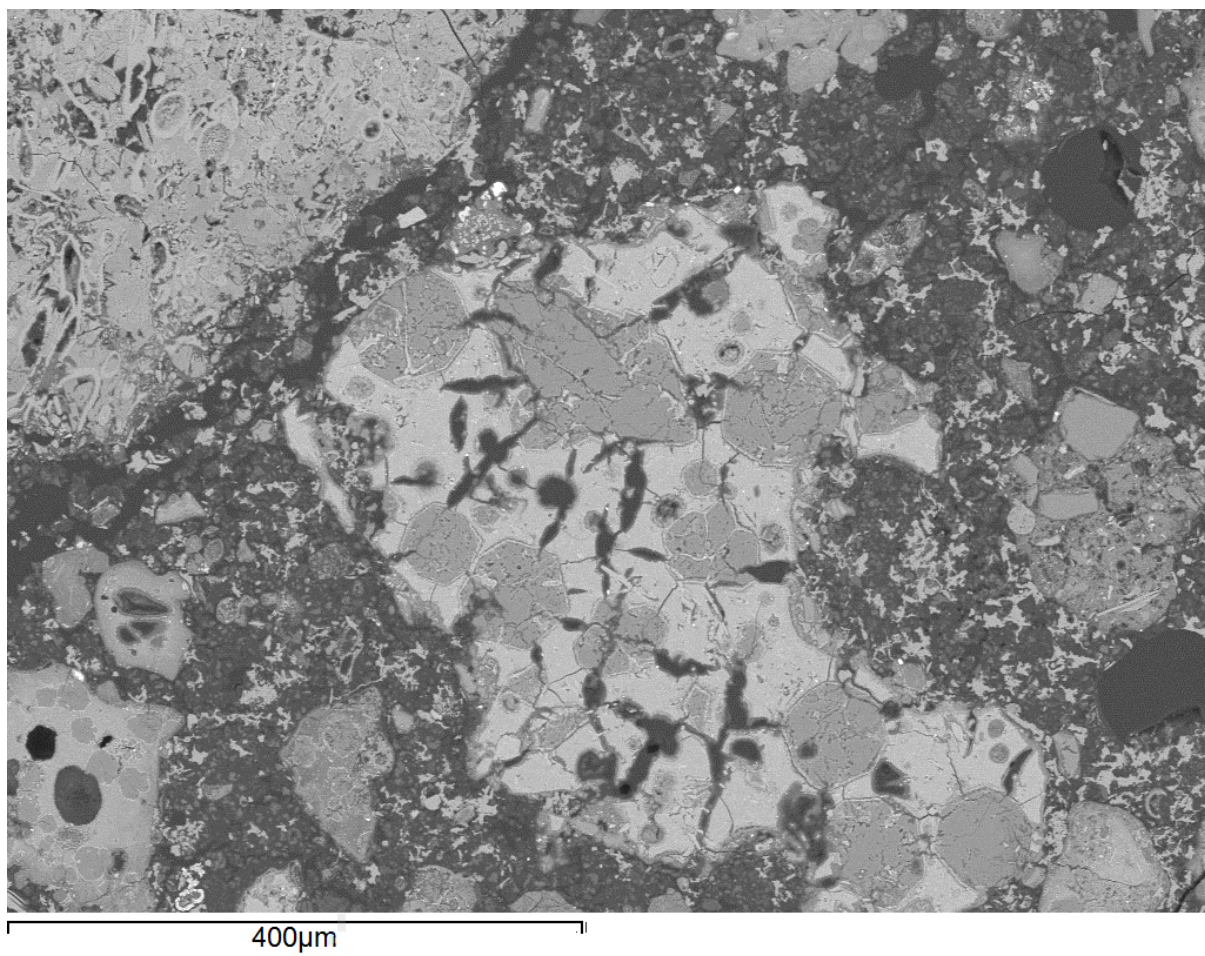
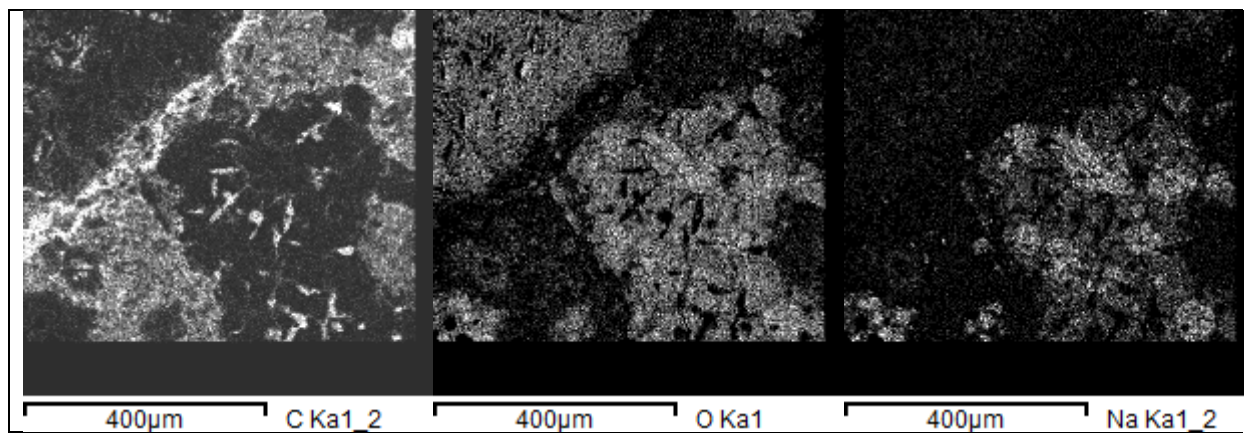


Figure 7 Site 7 Image



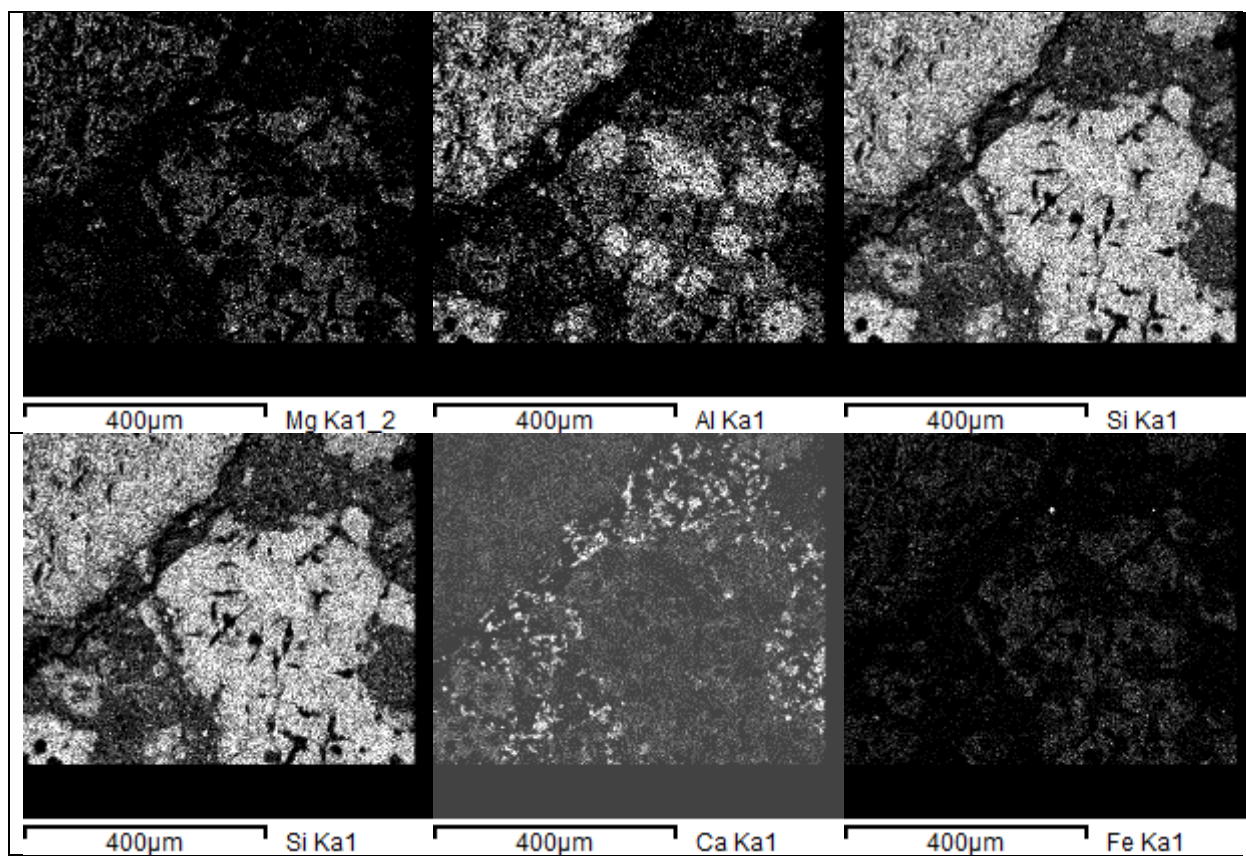


Figure 8 Site 7 maps

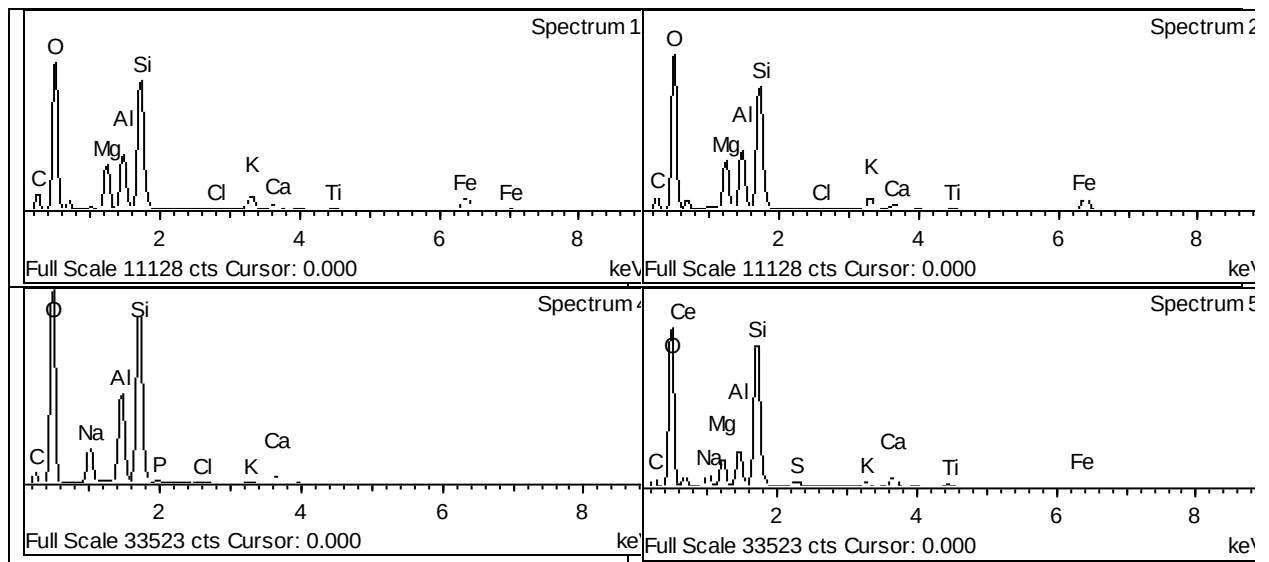
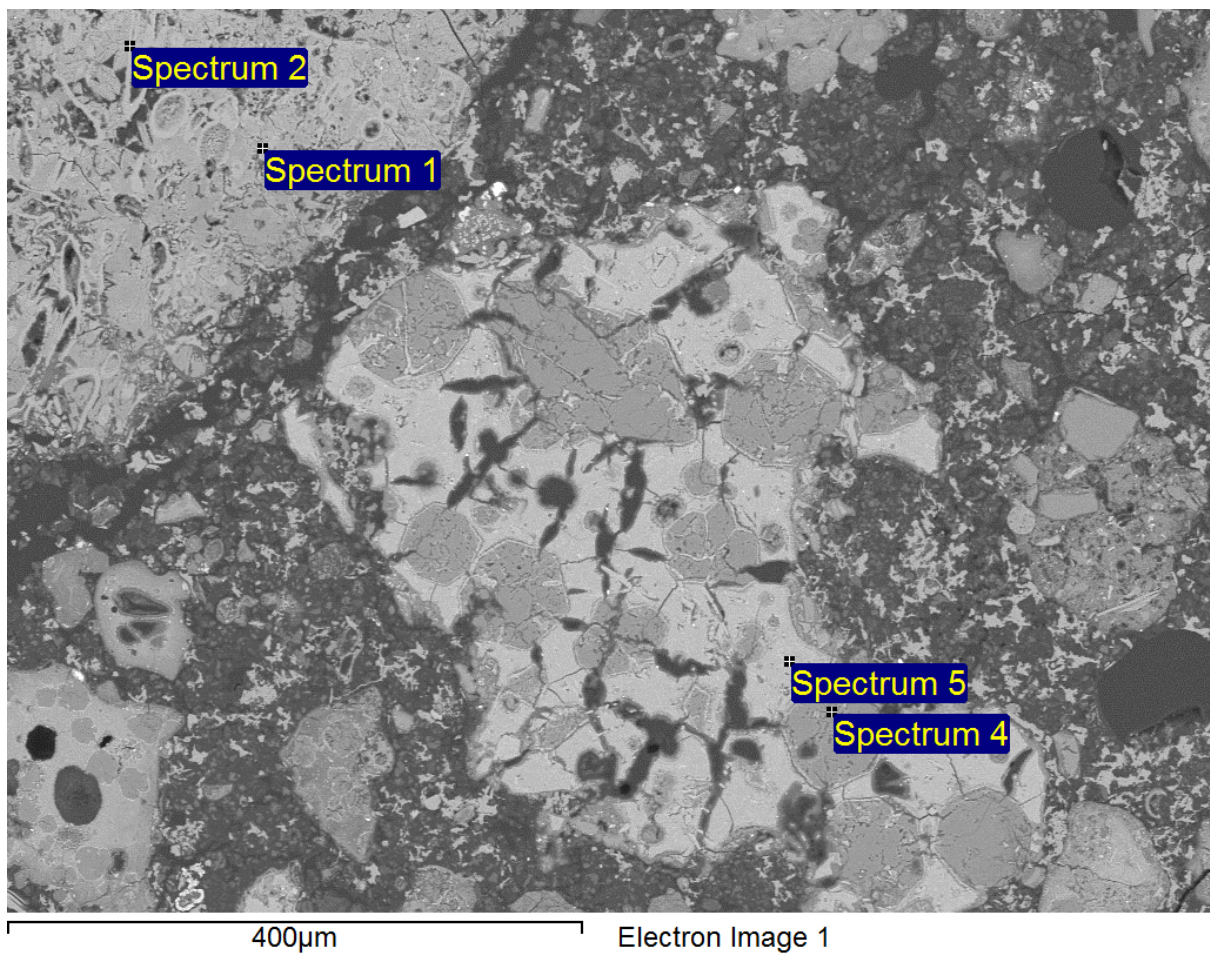


Figure 9 Site 7 Spectra

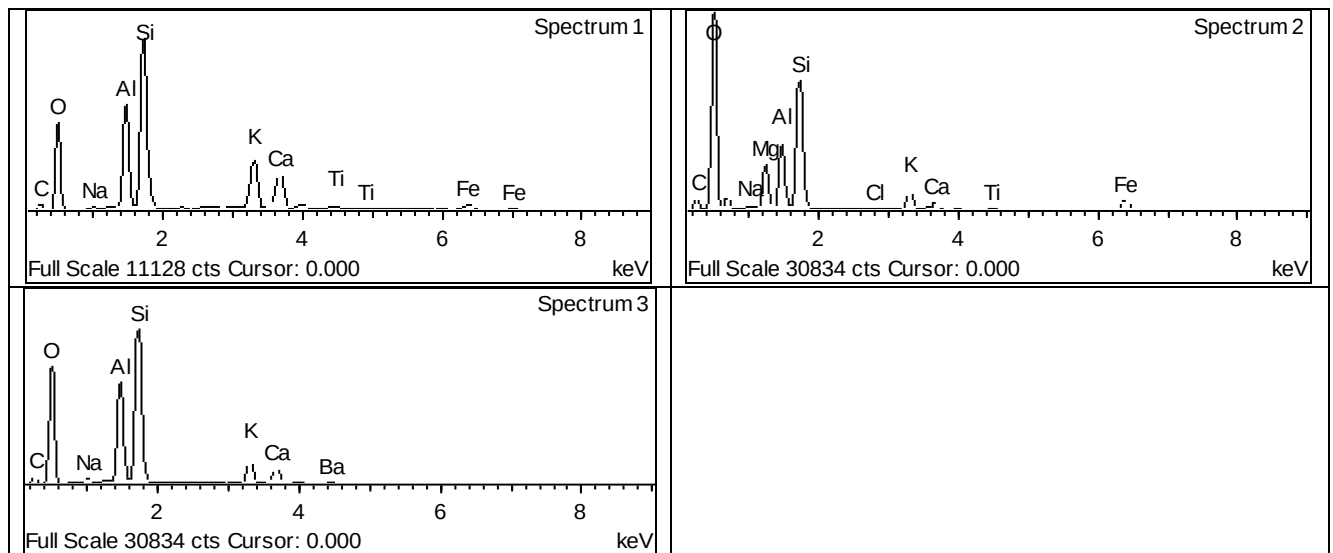
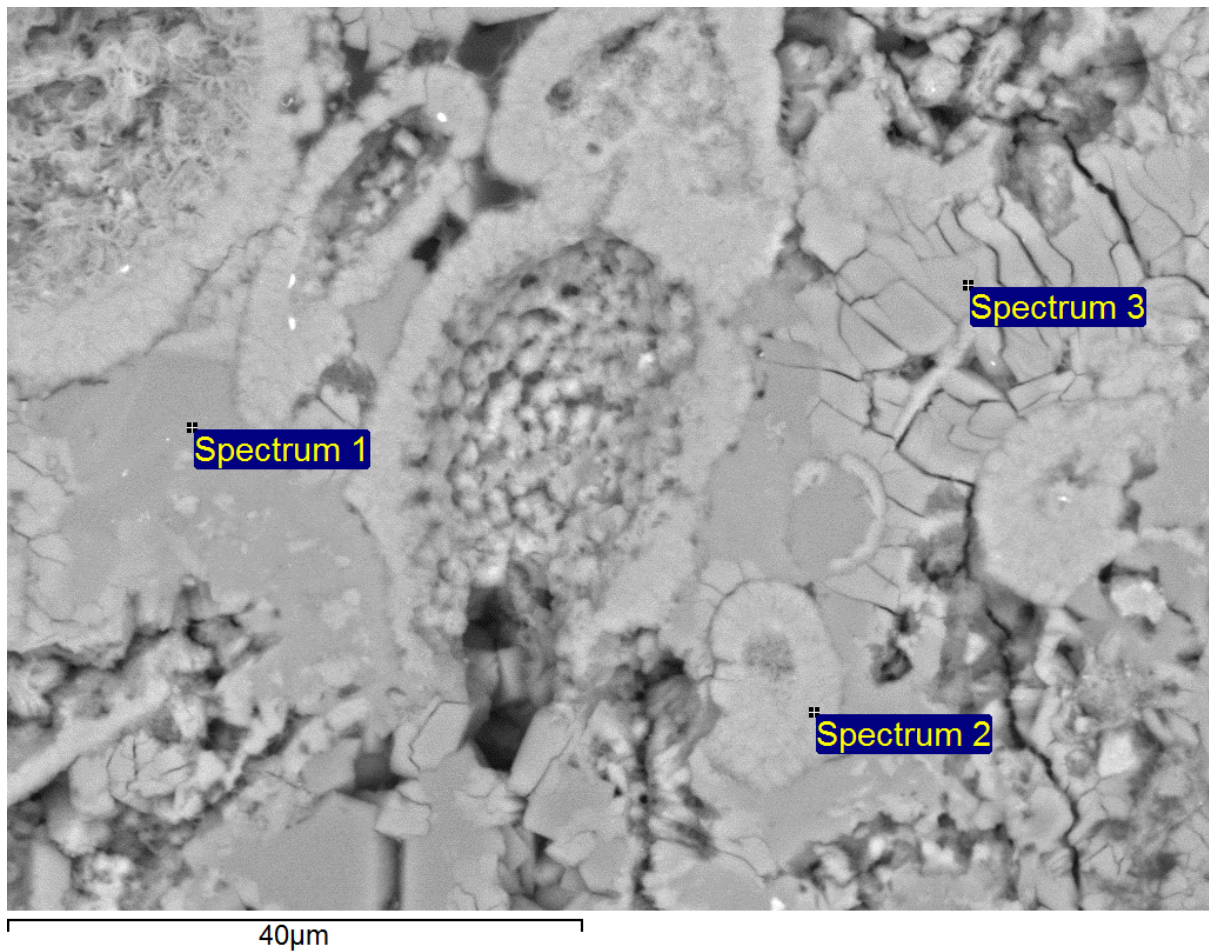
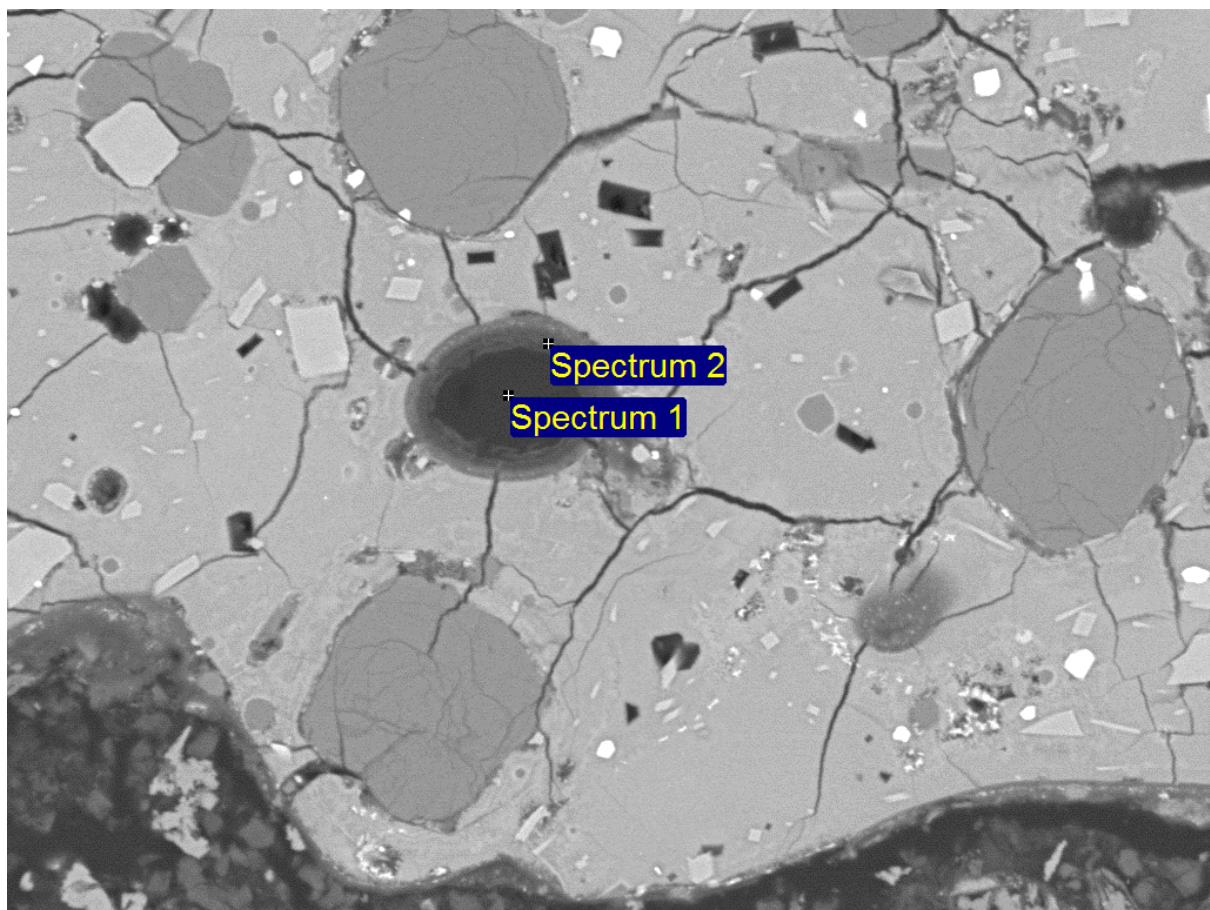


Figure 10 Site 8



90μm

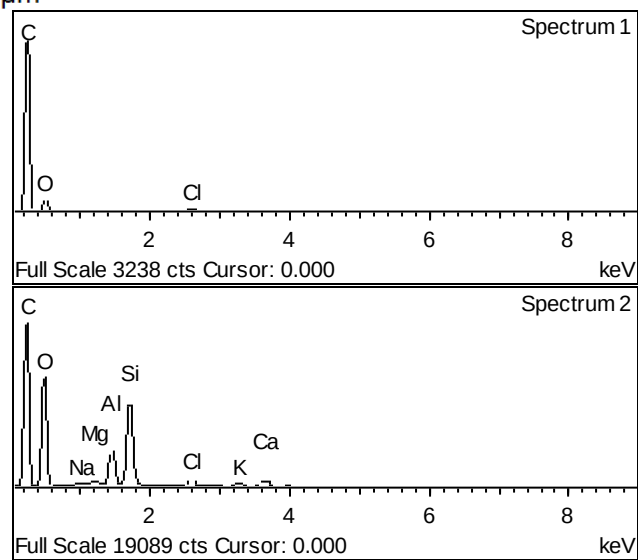
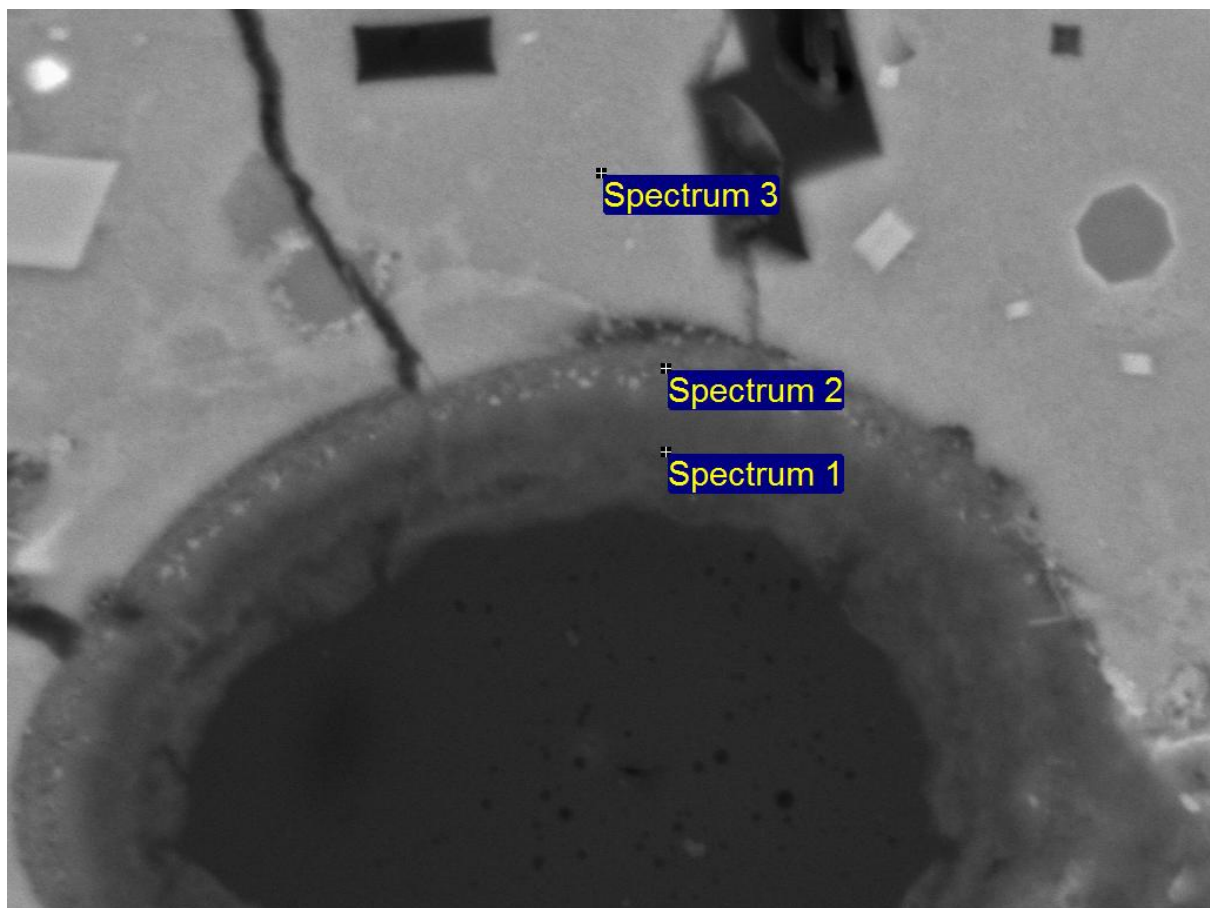


Figure 11 Site 9



10μm

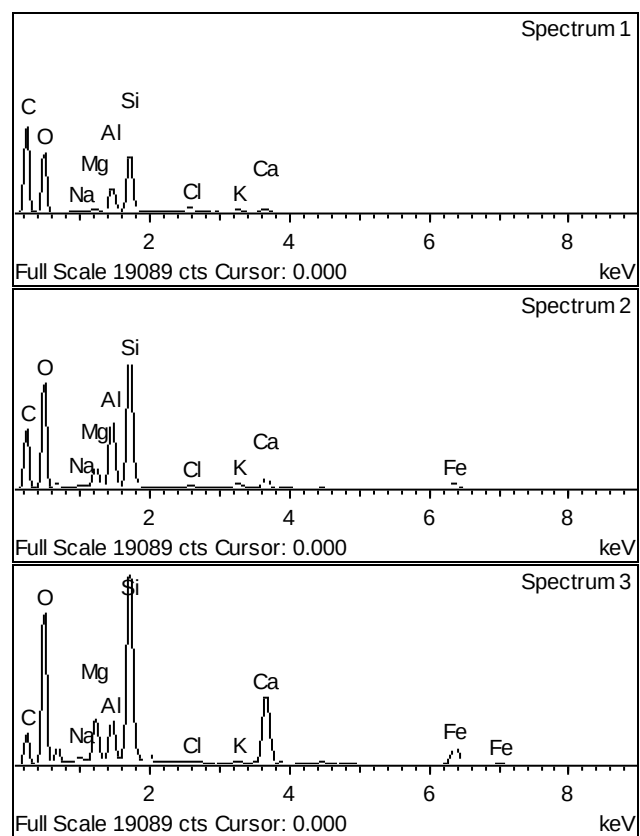


Figure 12 Site 10

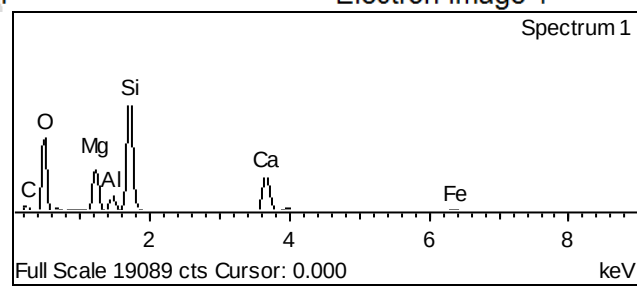
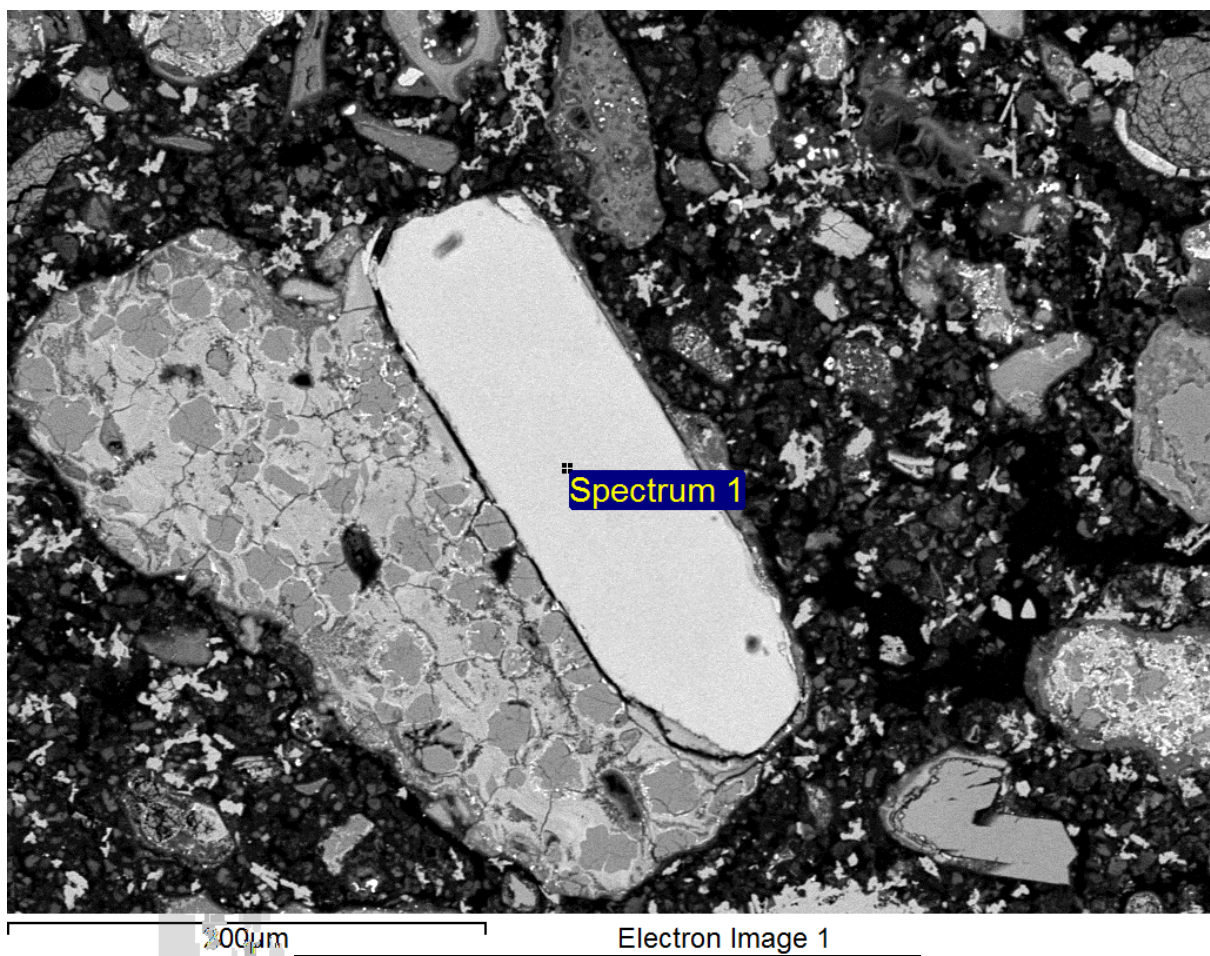


Figure 13 Site 11

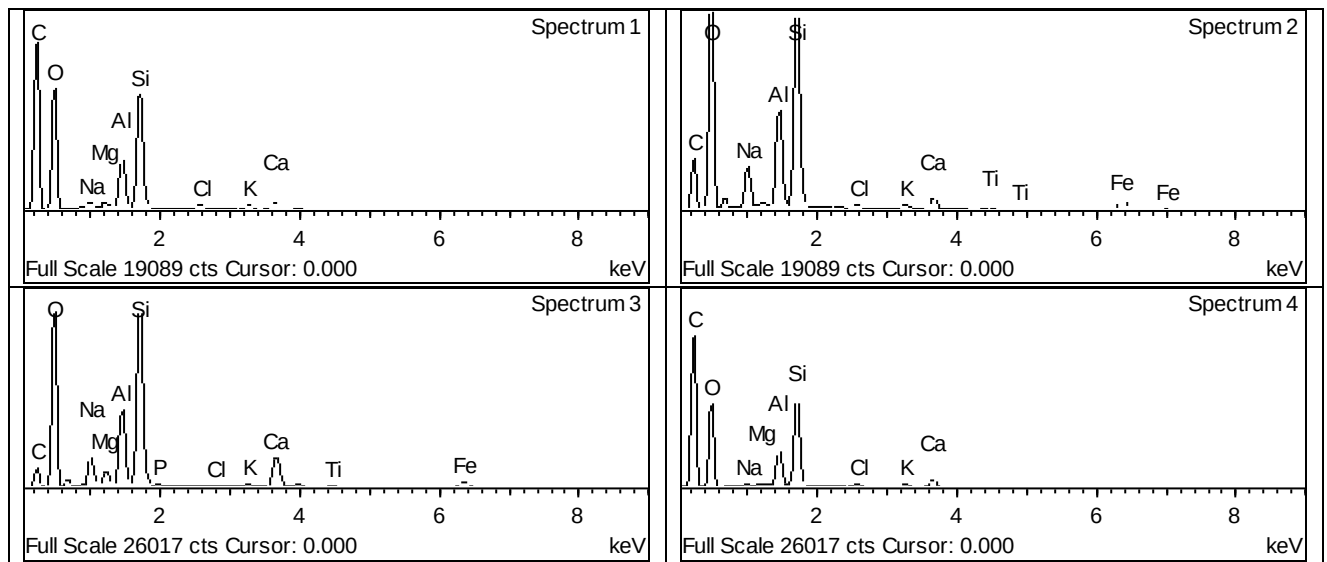
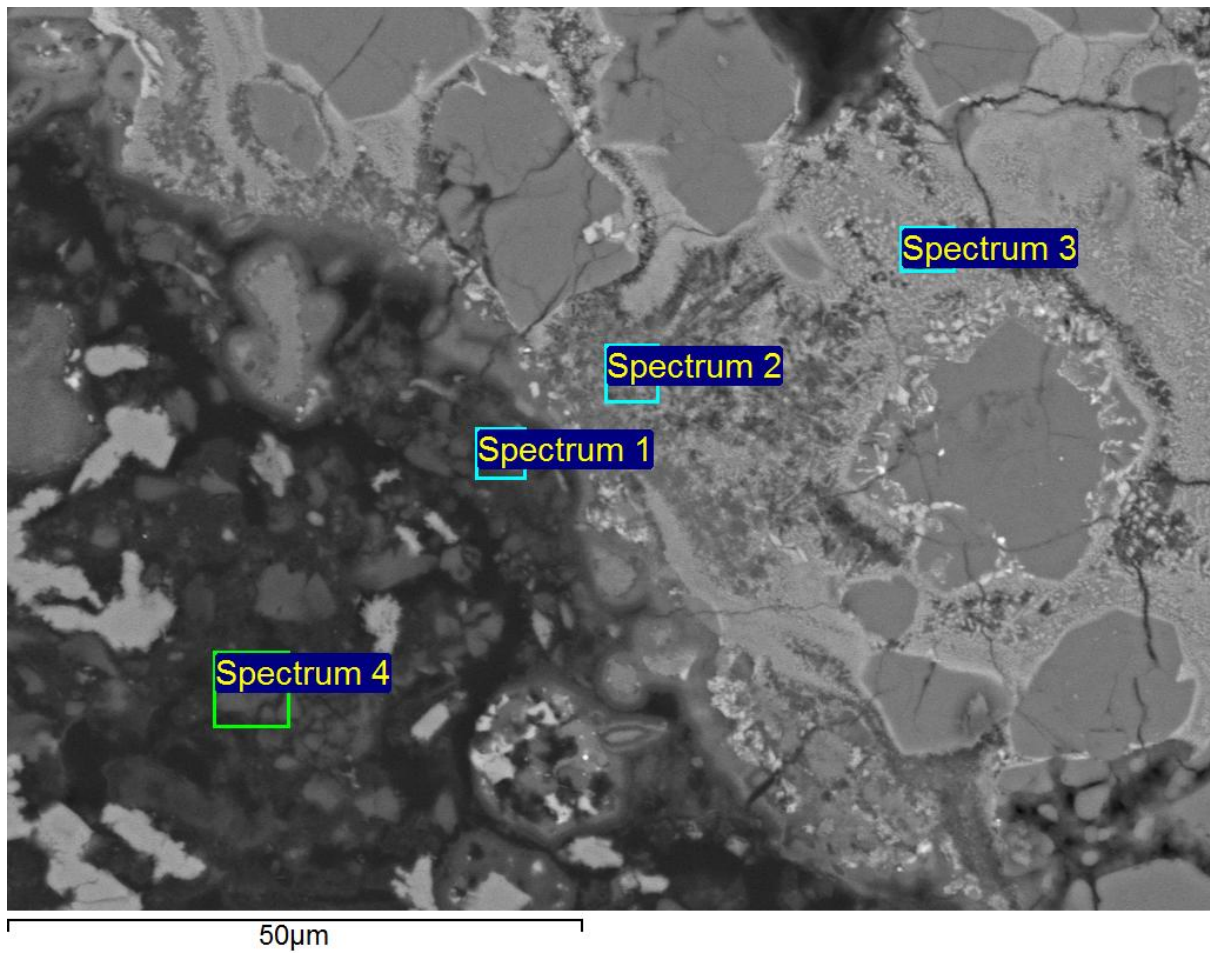


Figure 14 Site 12

Appendix E - XRD Peak data

OS-A-C24 – Case a Giardino					
2Theta	d (Å)	Height	Area	FWHM	Relative Peak Height
11.720	7.5449	2096.9	29317.8	0.1837	14.4794
15.891	5.5726	5526.5	66313.6	0.1575	38.1612
18.357	4.8290	3121.8	37460.8	0.1575	21.5564
18.974	4.6734	2469.7	29636.4	0.1575	17.0536
19.989	4.4385	2647.1	39561.6	0.1968	18.2786
20.836	4.2598	2672.6	42750.7	0.2099	18.4546
23.148	3.8394	3412.7	47774.8	0.1837	23.5651
24.335	3.6546	3170.5	41168.4	0.1706	21.8927
24.999	3.5591	3043.2	48687.6	0.2099	21.0137
26.036	3.4197	12952.7	168150.7	0.1706	89.4400
26.272	3.3894	3896.5	22538.5	0.0787	26.9058
26.696	3.3366	3340.1	43398.6	0.1706	23.0638
27.117	3.2857	3502.5	45507.0	0.1706	24.1852
27.286	3.2657	3411.4	33928.1	0.1312	23.5561
27.672	3.2211	3796.9	60749.2	0.2099	26.2181
28.017	3.1822	3233.5	35565.4	0.1443	22.3277
29.483	3.0272	14482.0	217215.0	0.1968	100.0000
29.884	2.9875	8724.0	112985.3	0.1706	60.2403
30.304	2.9470	5716.2	68499.1	0.1575	39.4711
30.612	2.9181	7765.5	100952.0	0.1706	53.6217
30.863	2.8949	4574.6	45072.7	0.1312	31.5882
31.962	2.7978	3729.9	55946.5	0.1968	25.7554
32.848	2.7244	3518.5	45534.7	0.1706	24.2957
33.332	2.6859	4629.8	73923.1	0.2099	31.9693
34.054	2.6306	3067.6	33712.1	0.1443	21.1822
35.067	2.5569	4912.3	77218.4	0.2099	33.9200
35.653	2.5162	8133.2	121959.2	0.1968	56.1608
36.073	2.4879	5161.5	71672.6	0.1837	35.6408
37.106	2.4209	3663.2	58521.3	0.2099	25.2948
37.978	2.3673	3288.4	46026.8	0.1837	22.7068
38.487	2.3372	3267.9	35893.2	0.1443	22.5653
39.039	2.3054	3821.4	57314.9	0.1968	26.3872
39.513	2.2788	5479.0	93098.1	0.2231	37.8332
40.572	2.2218	4247.3	72049.1	0.2231	29.3281
41.241	2.1872	3159.9	28403.7	0.1181	21.8195
42.009	2.1490	3582.1	46541.7	0.1706	24.7348
42.414	2.1294	4310.2	68922.6	0.2099	29.7625
42.894	2.1067	4103.6	65612.3	0.2099	28.3359
43.279	2.0889	5930.7	100763.7	0.2231	40.9522
43.895	2.0609	3489.5	45124.0	0.1706	24.0954
44.514	2.0337	3916.7	69715.4	0.2362	27.0453
44.852	2.0192	4075.8	80846.2	0.2624	28.1439
45.521	1.9911	3202.7	25620.5	0.1050	22.1150

OS-A-C24 – Case a Giardino					
2Theta	d (Å)	Height	Area	FWHM	Relative Peak Height
45.948	1.9735	4112.1	81482.7	0.2624	28.3946
46.510	1.9510	3275.9	29477.1	0.1181	22.6205
46.861	1.9372	3470.4	41640.8	0.1575	23.9635
47.240	1.9226	4156.2	57584.8	0.1837	28.6991
47.554	1.9106	5566.6	93608.5	0.2231	38.4381
47.796	1.9015	5222.4	72053.0	0.1837	36.0613
48.585	1.8724	6117.0	157946.0	0.3412	42.2386
49.624	1.8356	3937.3	62996.5	0.2099	27.1875
50.265	1.8137	3856.7	96378.0	0.3280	26.6310
51.426	1.7754	3463.1	79608.9	0.3018	23.9131
52.524	1.7409	5921.7	123949.7	0.2756	40.8901
53.105	1.7232	3779.6	45353.8	0.1575	26.0986
53.443	1.7131	4161.2	49820.9	0.1575	28.7336
53.551	1.7099	3980.3	35442.1	0.1181	27.4845
54.332	1.6871	4186.7	95830.7	0.3018	28.9097
54.823	1.6732	4016.9	63860.4	0.2099	27.7372
55.232	1.6618	3882.3	62026.6	0.2099	26.8078
55.864	1.6445	3830.0	79608.2	0.2624	26.4466
56.605	1.6247	5250.3	99652.0	0.2493	36.2540
57.505	1.6014	5245.4	68126.1	0.1706	36.2201
57.727	1.5957	4636.5	45729.4	0.1312	32.0156
59.033	1.5635	3765.7	59940.6	0.2099	26.0026
59.863	1.5438	3885.8	42724.7	0.1443	26.8319
60.773	1.5228	4770.5	57210.9	0.1575	32.9409
61.234	1.5125	4537.6	36189.4	0.1050	31.3327
61.413	1.5085	4649.6	97417.9	0.2756	32.1061
61.965	1.4964	4094.1	57311.6	0.1837	28.2703
62.884	1.4767	5251.0	190727.9	0.4855	36.2588
62.946	1.4754	5296.1	194087.7	0.4855	36.5702
63.628	1.4612	4010.6	40104.2	0.1312	27.6937
64.403	1.4455	4116.4	53464.2	0.1706	28.4243
64.797	1.4377	4634.6	69305.7	0.1968	32.0025
65.536	1.4232	5180.2	128245.1	0.3280	35.7699
66.010	1.4141	4790.3	52532.8	0.1443	33.0776
66.214	1.4103	4928.0	88299.5	0.2362	34.0284
66.799	1.3994	4041.7	36349.4	0.1181	27.9084
68.349	1.3713	4122.3	70023.9	0.2231	28.4650
69.139	1.3576	4949.4	69075.3	0.1837	34.1762
69.261	1.3555	4727.7	55820.6	0.1575	32.6454
70.072	1.3418	4073.2	32584.0	0.1050	28.1259
70.883	1.3284	4443.3	53320.8	0.1575	30.6815
71.475	1.3188	4146.7	45464.8	0.1443	28.6335
72.208	1.3073	4211.2	41973.8	0.1312	29.0789

OS-A-C24 – Case a Giardino					
2Theta	d (Å)	Height	Area	FWHM	Relative Peak Height
72.330	1.3053	4217.9	37833.5	0.1181	29.1251
72.936	1.2960	4437.3	100827.2	0.3018	30.6401
73.751	1.2837	4874.3	67677.4	0.1837	33.6576
73.948	1.2807	4895.2	63632.8	0.1706	33.8020
74.371	1.2745	4418.7	39705.9	0.1181	30.5117
75.213	1.2623	4667.5	60433.1	0.1706	32.2297
75.308	1.2609	4612.5	63715.6	0.1837	31.8499
76.200	1.2484	4534.9	76889.5	0.2231	31.3140
77.191	1.2348	4412.8	52816.6	0.1575	30.4709
78.183	1.2216	4836.8	82202.5	0.2231	33.3987
78.340	1.2196	4571.4	63380.5	0.1837	31.5661
79.424	1.2056	4179.2	45850.6	0.1443	28.8579

OS-B-C30 – Caseggiato del Serapide					
2Theta	d (Å)	Height	Area	FWHM	Relative Peak Height
8.885	9.9441	2384.4	26212.7	0.1444	10.1414
13.780	6.4210	2247.6	24629.1	0.1444	9.5596
15.893	5.5718	10160.7	121667	0.1576	43.2159
18.357	4.8293	4152.5	49826.6	0.1576	17.6616
18.963	4.6763	2478	27258.3	0.1444	10.5395
20.088	4.4168	3082.3	40065.5	0.1707	13.1098
23.167	3.8362	3043.4	39519.5	0.1707	12.9443
24.335	3.6547	3778.8	45335.6	0.1576	16.0721
26.035	3.4198	23511.5	280821.7	0.1576	100.0000
26.670	3.3398	3811	49545.2	0.1707	16.2091
27.684	3.2197	3728.6	52191.2	0.1838	15.8586
29.513	3.0242	7809.2	124835.1	0.2101	33.2144
29.879	2.9880	8037.2	96107.2	0.1576	34.1841
30.331	2.9445	5206.5	61919.5	0.1576	22.1445
30.612	2.9181	13736.4	178380.8	0.1707	58.4242
32.005	2.7942	4058.7	60856.9	0.1970	17.2626
33.343	2.6851	6136.4	85888.7	0.1838	26.0996
35.095	2.5549	6096.8	103463.2	0.2232	25.9311
35.636	2.5173	6561.4	85084	0.1707	27.9072
35.887	2.5004	6735.3	80819.3	0.1576	28.6468
37.105	2.4210	4586.8	64051.7	0.1838	19.5088
39.010	2.3070	3584.2	82365.6	0.3020	15.2445
39.542	2.2772	4142.5	78542.8	0.2495	17.6190
40.566	2.2221	5031.8	85508.1	0.2232	21.4014
41.652	2.1666	3325	33250.1	0.1313	14.1420
42.034	2.1478	3539	53009.1	0.1970	15.0522
42.437	2.1283	4213.6	63077.5	0.1970	17.9214
42.874	2.1077	3947	70920.6	0.2364	16.7875
43.337	2.0862	4285.5	76734.6	0.2364	18.2273
44.575	2.0311	4113.3	73834.2	0.2364	17.4948
44.797	2.0215	4196.9	50195.6	0.1576	17.8504
45.906	1.9753	3494	41927.7	0.1576	14.8608
47.825	1.9004	6748.3	128212.6	0.2495	28.7021
48.780	1.8654	5762	115221.8	0.2626	24.5072
52.532	1.7406	8198.5	171821.8	0.2757	34.8702
53.436	1.7133	4735.3	94641.5	0.2626	20.1404
54.334	1.6871	5060.7	80849.3	0.2101	21.5244
54.773	1.6746	4140.5	74520.6	0.2364	17.6105
55.207	1.6625	4018.5	80300.1	0.2626	17.0916
56.017	1.6403	4083	77463.4	0.2495	17.3660
56.635	1.6239	4595	64189	0.1838	19.5436

OS-B-C30 – Caseggiato del Serapide					
2Theta	d (Å)	Height	Area	FWHM	Relative Peak Height
56.952	1.6156	4548.2	40932.3	0.1182	19.3446
57.144	1.6106	4401.3	39507.8	0.1182	18.7198
57.811	1.5936	5360.3	64223.5	0.1576	22.7986
57.887	1.5917	4748.4	31587.9	0.0919	20.1961
59.829	1.5446	4196.5	37755.3	0.1182	17.8487
59.988	1.5409	4170.4	33336.5	0.1050	17.7377
61.128	1.5149	4558	109391.1	0.3151	19.3863
61.993	1.4958	4542.1	63447	0.1838	19.3186
62.822	1.4780	5378.6	132648.7	0.3283	22.8765
62.908	1.4762	5243.3	127798.7	0.3283	22.3010
63.614	1.4615	4186	41840.1	0.1313	17.8041
64.400	1.4456	4103.8	57441.1	0.1838	17.4544
65.529	1.4234	4609.9	92182.8	0.2626	19.6070
66.006	1.4142	5684.4	68087.4	0.1576	24.1771
66.030	1.4138	5249.1	41328.7	0.1050	22.3257
67.552	1.3856	3842.7	45863.6	0.1576	16.3439
68.353	1.3713	4349.4	65218.8	0.1970	18.4990
69.134	1.3577	6058.3	78480.1	0.1707	25.7674
69.253	1.3556	5335	51403.1	0.1313	22.6910
70.442	1.3356	4110.6	36981.3	0.1182	17.4834
71.058	1.3256	4268.4	38367.3	0.1182	18.1545
72.164	1.3079	4430.9	57550.3	0.1707	18.8457
73.707	1.2843	5190.2	72476.9	0.1838	22.0752
73.902	1.2814	5030	94791.4	0.2495	21.3938
75.209	1.2624	4896	73153.7	0.1970	20.8239
76.238	1.2479	4373	74273.9	0.2232	18.5994
78.171	1.2218	5707.7	79406.8	0.1838	24.2762
78.481	1.2177	4826.9	57731.5	0.1576	20.5300

OS-C-C33 – Caseggiato del Larario					
2Theta	d (Å)	Height	Area	FWHM	Relative Peak Height
8.876	9.9551	3013.8	33120.9	0.1444	12.4906
15.882	5.5757	4894.7	58451.6	0.1575	20.2860
18.346	4.8319	2704.4	32447.6	0.1575	11.2083
20.016	4.4324	2250.4	24749.8	0.1444	9.3267
21.831	4.0680	2275.6	27301.3	0.1576	9.4312
23.145	3.8398	3671.3	47684.2	0.1707	15.2156
24.335	3.6547	2819.8	36569.1	0.1707	11.6866
26.020	3.4217	10696.1	138566	0.1707	44.3297
26.622	3.3457	13844.7	157821.8	0.1575	57.3790
27.362	3.2569	3382.9	40463.4	0.1575	14.0203
27.677	3.2205	3724	44675.4	0.1575	15.4340
27.966	3.1878	2871.3	28589.5	0.1313	11.9000
29.473	3.0282	24128.5	312452.8	0.1707	100.0000
29.871	2.9888	5651.3	67319.9	0.1576	23.4217
30.305	2.9470	4241	42222.4	0.1313	17.5767
30.599	2.9193	7238.7	93703.3	0.1707	30.0006
30.975	2.8847	3395	27487	0.1050	14.0705
31.538	2.8345	4008.2	59922.3	0.1969	16.6119
31.896	2.8035	3279.4	58860.9	0.2363	13.5914
33.328	2.6862	3692.8	51688.5	0.1838	15.3047
35.059	2.5575	3523	52845.7	0.1969	14.6010
35.725	2.5113	6198.9	104699.7	0.2232	25.6912
36.079	2.4875	5632.6	78819.1	0.1838	23.3442
37.095	2.4217	2911.1	40754.4	0.1838	12.0650
37.984	2.3670	2484.1	27323.1	0.1444	10.2953
38.652	2.3276	2543.3	27950	0.1444	10.5406
39.026	2.3061	2744.2	27229.6	0.1313	11.3733
39.509	2.2790	6618	105889.8	0.2101	27.4281
40.555	2.2226	3246.1	58336.5	0.2363	13.4534
42.007	2.1491	3032.9	39416.2	0.1707	12.5698
42.419	2.1292	3265.6	42367.2	0.1707	13.5342
43.278	2.0889	6484.2	109380.2	0.2232	26.8736
44.425	2.0376	3250.9	57850.5	0.2363	13.4733
45.067	2.0101	6801	128798.3	0.2495	28.1866
45.176	2.0055	6636.4	125473.4	0.2495	27.5044
45.491	1.9923	2694.6	21496.7	0.1050	11.1677
47.284	1.9208	4517.2	55379	0.1707	18.7214
47.554	1.9106	6779.4	101431.3	0.1969	28.0971
47.916	1.8970	4541.8	27945.9	0.0788	18.8234
48.577	1.8727	7279.7	159848.6	0.2888	30.1705
49.660	1.8344	2907.2	31976.7	0.1444	12.0488
50.180	1.8166	2682.3	32183.9	0.1576	11.1167
52.172	1.7518	3255.9	22960.7	0.0919	13.4940

OS-C-C33 – Caseggiato del Larario					
2Theta	d (Å)	Height	Area	FWHM	Relative Peak Height
52.515	1.7412	4392.1	52619.9	0.1576	18.2030
53.421	1.7138	3042.6	36467.9	0.1576	12.6100
54.336	1.6870	3083.8	61360.8	0.2626	12.7807
54.742	1.6755	3678	29118.9	0.1050	15.2434
54.875	1.6717	3816.9	34235.1	0.1182	15.8191
55.189	1.6630	2953.1	26567.3	0.1182	12.2391
56.662	1.6232	3924.9	66691.2	0.2232	16.2667
57.530	1.6007	4811.8	72120.9	0.1969	19.9424
58.125	1.5857	3174	31669.5	0.1313	13.1546
59.075	1.5625	3358.2	33549.5	0.1313	13.9180
59.244	1.5584	2923.2	23273.7	0.1050	12.1151
59.784	1.5457	2839.3	30966.4	0.1444	11.7674
60.785	1.5226	4198.8	62955.8	0.1969	17.4018
61.389	1.5090	3575.5	39302.7	0.1444	14.8186
61.958	1.4965	2979.2	32768.7	0.1444	12.3472
62.830	1.4778	3372.3	40223.9	0.1576	13.9764
64.840	1.4368	5040.6	55397	0.1444	20.8906
65.007	1.4335	4564.1	40869.3	0.1182	18.9158
65.571	1.4226	3914	42931.5	0.1444	16.2215
65.732	1.4194	3761	33804.2	0.1182	15.5874
65.999	1.4144	3601.6	43203.1	0.1576	14.9267
68.357	1.3712	3024.3	48385.7	0.2101	12.5341
69.141	1.3575	3647	54421.8	0.1969	15.1149
69.290	1.3550	3531.5	35010.5	0.1313	14.6362
70.698	1.3314	3214	35255.6	0.1444	13.3203
70.905	1.3280	3134.8	28181	0.1182	12.9921
71.084	1.3251	2997	26892.2	0.1182	12.4210
72.967	1.2955	3503.9	52368.7	0.1970	14.5218
73.690	1.2846	3403.1	37268.7	0.1444	14.1041
75.211	1.2623	3197.3	41159.1	0.1707	13.2511
75.562	1.2573	4008	40080.5	0.1313	16.6111
75.770	1.2544	4007.8	40070.5	0.1313	16.6102
75.984	1.2514	3285.1	29536.3	0.1182	13.6150
78.153	1.2220	3420.6	54575.9	0.2101	14.1766
78.926	1.2120	2887.3	28840.4	0.1313	11.9663

OS-D-C37 – Casa Basilicale					
2Theta	d (Å)	Height	Area	FWHM	Relative Peak Height
8.873	9.9582	2282.5	36463.9	0.2101	10.3554
15.884	5.5750	5518.5	88078.2	0.2101	25.0367
18.350	4.8310	3181.5	50878.7	0.2101	14.4341
20.024	4.4307	2691.5	42815.3	0.2101	12.2110
20.905	4.2459	2549	43315.3	0.2232	11.5645
23.142	3.8403	3786.1	60561.8	0.2101	17.1771
24.326	3.6561	2968.1	47423.2	0.2101	13.4659
26.028	3.4207	11382.1	182109	0.2101	51.6392
26.674	3.3393	4047.4	80661.2	0.2626	18.3626
27.347	3.2587	3258	42342.6	0.1707	14.7811
27.659	3.2226	4060.5	64958.4	0.2101	18.4220
29.481	3.0275	22041.6	359391.3	0.2232	100.0000
29.880	2.9879	10091.3	160541.4	0.2101	45.7830
30.293	2.9480	5796	80721.8	0.1838	26.2957
30.611	2.9182	7422	111328.1	0.1970	33.6727
30.866	2.8947	4752.8	50833.3	0.1444	21.5629
31.513	2.8367	3296.9	52737.5	0.2101	14.9576
31.946	2.7992	3489.6	66254.6	0.2495	15.8319
33.334	2.6858	4327.2	82061.7	0.2495	19.6320
35.047	2.5583	5091.3	86323.9	0.2232	23.0986
35.637	2.5173	8159.6	130515.8	0.2101	37.0191
36.055	2.4891	5615.6	94420.5	0.2232	25.4773
37.107	2.4209	3575.9	60433.5	0.2232	16.2234
38.024	2.3646	3106.7	55909.4	0.2364	14.0947
39.034	2.3057	3813.4	64788.8	0.2232	17.3009
39.501	2.2795	6489.5	116205.3	0.2363	29.4421
40.554	2.2227	4233.2	80294.7	0.2495	19.2055
40.885	2.2055	3390.9	46982.7	0.1838	15.3841
42.008	2.1491	3737	63306.5	0.2232	16.9543
42.404	2.1299	4496.9	80728.1	0.2363	20.4019
42.884	2.1072	4026.7	56362.4	0.1838	18.2686
43.254	2.0900	6603.1	118005.3	0.2363	29.9574
44.494	2.0346	3980.8	70039.8	0.2364	18.0604
44.950	2.0150	4147	99264.5	0.3151	18.8144
45.953	1.9733	3549.3	67128.6	0.2495	16.1027
47.207	1.9238	4176	58466	0.1838	18.9460
47.580	1.9096	6571.9	137762.8	0.2757	29.8159
48.589	1.8723	7077.3	148599	0.2757	32.1088
49.593	1.8367	3675.7	84480.5	0.3020	16.6762
50.191	1.8162	3324.3	69739.5	0.2757	15.0819
51.373	1.7772	3232.4	60364.4	0.2495	14.6650
52.243	1.7496	3843.3	37669.7	0.1313	17.4366
52.524	1.7409	5289.2	105777.7	0.2626	23.9964

OS-D-C37 – Casa Basilicale					
2Theta	d (Å)	Height	Area	FWHM	Relative Peak Height
53.466	1.7124	3774.6	71686.5	0.2495	17.1249
54.338	1.6870	3869	73512.7	0.2495	17.5532
54.806	1.6737	3955.8	75143.3	0.2495	17.9470
55.208	1.6624	3763.7	63561.5	0.2232	17.0754
56.234	1.6345	3904.6	57478.5	0.1969	17.7147
56.611	1.6245	5491.5	98583.7	0.2363	24.9143
57.085	1.6122	4615.7	69013.2	0.1969	20.9409
57.480	1.6020	5427	97562.5	0.2364	24.6216
58.163	1.5848	3659.6	54883.5	0.1969	16.6032
58.998	1.5644	3550	70758.5	0.2626	16.1059
59.819	1.5448	3639.1	94588.4	0.3414	16.5101
60.747	1.5234	4838.4	87086.2	0.2364	21.9512
61.422	1.5083	4763.5	113229.8	0.3151	21.6114
62.020	1.4952	3841.1	57614.6	0.1970	17.4266
62.830	1.4778	4909.3	152179.3	0.4070	22.2729
64.757	1.4385	4719.5	117921.4	0.3282	21.4118
65.530	1.4233	5202.4	148188.9	0.3808	23.6026
65.983	1.4147	4531	36205.1	0.1050	20.5566
66.294	1.4088	4938.1	98679.3	0.2626	22.4035
67.031	1.3951	3794.2	60655.6	0.2101	17.2138
67.798	1.3811	3749.2	48736.7	0.1707	17.0097
68.367	1.3710	3912.5	73213.2	0.2495	17.7505
69.133	1.3577	4627.1	133952.7	0.3808	20.9926
70.376	1.3367	4031.5	44002	0.1444	18.2904
70.544	1.3340	4242.5	67183.5	0.2101	19.2477
70.831	1.3292	4293.2	81207.9	0.2495	19.4777
72.194	1.3075	3892	77719.4	0.2626	17.6575
73.002	1.2950	4316.8	133606.5	0.4070	19.5848
73.878	1.2818	4632.1	152227.9	0.4333	21.0153
75.238	1.2619	4252.1	88301.9	0.2757	19.2912
75.385	1.2599	4210	61934.6	0.1970	19.1002
76.186	1.2486	4333	146981	0.4464	19.6583
77.233	1.2343	4130.3	139061.4	0.4464	18.7387
78.163	1.2219	4415.1	74099.9	0.2232	20.0308
78.366	1.2192	4235	58704	0.1838	19.2137

OS-E-C41 – <i>Piccolo Mercato</i>					
2Theta	d (Å)	Height	Area	FWHM	Relative Peak Height
15.887	5.5739	4054.6	60584.7	0.1968	18.6514
18.357	4.8292	2593.7	41378.9	0.2099	11.9311
18.968	4.6749	2161.9	30261.9	0.1837	9.9448
19.991	4.4381	2293.6	38716.5	0.2230	10.5507
20.941	4.2387	2277.8	36338.4	0.2099	10.4780
23.150	3.8391	3592.2	57474.4	0.2099	16.5243
24.338	3.6542	2610.2	46966.7	0.2362	12.0070
26.032	3.4202	8212.3	131272.2	0.2099	37.7770
26.717	3.3340	3988.7	59830.2	0.1968	18.3482
27.661	3.2223	3504.9	56078.3	0.2099	16.1227
28.033	3.1804	2888.9	37527.3	0.1706	13.2891
29.492	3.0263	21738.9	345027.6	0.2099	100.0000
29.885	2.9874	8118.5	113302.8	0.1837	37.3455
30.304	2.9470	4849.9	62987.8	0.1706	22.3098
30.611	2.9181	5919.3	82844.5	0.1837	27.2291
30.863	2.8950	4035.2	46780	0.1574	18.5621
31.782	2.8133	4437.2	70563.9	0.2099	20.4113
31.856	2.8069	3290.9	24877.1	0.1050	15.1383
33.334	2.6858	3705.6	62847.6	0.2230	17.0459
35.061	2.5573	4362.7	78361.8	0.2362	20.0686
35.643	2.5169	6814.6	108710.5	0.2099	31.3475
36.056	2.4890	5448.3	86299.5	0.2099	25.0624
36.601	2.4532	2815.6	39209.4	0.1837	12.9519
37.098	2.4215	3099.5	55671.2	0.2362	14.2579
39.043	2.3052	3301.3	52784.6	0.2099	15.1861
39.508	2.2791	6598	112161.6	0.2230	30.3511
40.557	2.2226	3631	65354.8	0.2362	16.7028
40.922	2.2036	3042.6	42111.2	0.1837	13.9961
41.999	2.1495	3220.7	54282.5	0.2230	14.8154
42.410	2.1296	4074.2	68981	0.2230	18.7415
42.888	2.1070	3529.5	42073.8	0.1574	16.2359
43.256	2.0899	6715.8	114010.8	0.2230	30.8930
44.511	2.0339	3437.4	58210.2	0.2230	15.8122
44.865	2.0187	3612.9	75598	0.2755	16.6195
45.510	1.9915	3791.8	68148.2	0.2362	17.4425
45.991	1.9718	3161	60059.8	0.2493	14.5408
47.216	1.9235	4163.4	62422	0.1968	19.1518
47.602	1.9088	7028.6	154614.8	0.2886	32.3319
48.602	1.8718	7210.7	151421.3	0.2755	33.1696
49.601	1.8364	3344.8	80069.5	0.3149	15.3862
50.193	1.8161	3229.3	54881.2	0.2230	14.8549
51.405	1.7761	2891.2	54833	0.2493	13.2997
52.522	1.7410	4423.6	88466.3	0.2624	20.3488

OS-E-C41 – <i>Piccolo Mercato</i>					
2Theta	d (Å)	Height	Area	FWHM	Relative Peak Height
53.428	1.7135	3331.3	49831.8	0.1968	15.3241
54.346	1.6867	3385.5	60505.9	0.2362	15.5735
54.791	1.6741	3456.8	75334.4	0.2886	15.9014
55.203	1.6626	3295.2	75711.3	0.3018	15.1581
56.080	1.6386	3466.5	38011.9	0.1443	15.9461
56.616	1.6244	5234.4	104438.9	0.2624	24.0785
57.485	1.6019	5355.5	101746.3	0.2493	24.6356
58.153	1.5851	3368.6	43743.9	0.1706	15.4957
59.010	1.5641	3260.1	81375.6	0.3280	14.9966
60.750	1.5234	4727	75631.6	0.2099	21.7444
61.457	1.5075	4348.8	130224.7	0.3936	20.0047
61.961	1.4965	3486.5	69715.4	0.2624	16.0381
62.833	1.4778	4326.2	172650.1	0.5248	19.9007
63.187	1.4704	3977.5	159649.2	0.5248	18.2967
64.759	1.4384	4514.3	116489.3	0.3411	20.7660
65.541	1.4231	4507.2	128202.8	0.3805	20.7333
65.664	1.4208	4664	135222	0.3805	21.4546
66.305	1.4086	4316.2	86317	0.2624	19.8547
68.352	1.3713	3638.1	54362.1	0.1968	16.7354
68.535	1.3681	3407.5	26817.9	0.1050	15.6747
69.151	1.3574	4046.4	108028.6	0.3542	18.6136
70.492	1.3348	3805.5	89173.9	0.3149	17.5055
72.191	1.3075	3477.2	76390.3	0.2886	15.9953
73.049	1.2943	4025	127839.9	0.4198	18.5152
73.783	1.2832	4055.5	126936.2	0.4198	18.6555
73.942	1.2808	4171.5	133441.3	0.4198	19.1891
75.323	1.2607	4062.9	113575.4	0.3673	18.6895
76.265	1.2475	4106.8	89581.7	0.2886	18.8915
77.257	1.2339	3825.2	64839.6	0.2230	17.5961
78.149	1.2221	3922	66475.7	0.2230	18.0414
79.481	1.2049	3444.3	48031.4	0.1837	15.8439

OS-F-C45 – Terme del Foro					
2Theta	d (Å)	Height	Area	FWHM	Relative Peak Height
8.855	9.9784	2140.0	34176.5	0.2101	8.7537
12.431	7.1149	2160.2	32369.3	0.1970	8.8364
13.800	6.4118	2112.1	35859.3	0.2232	8.6396
15.888	5.5737	4908.4	78046.1	0.2101	20.0780
18.351	4.8308	2792.2	44658.5	0.2101	11.4216
18.927	4.6849	2220.6	28867.4	0.1707	9.0834
20.943	4.2382	2572.8	40914.2	0.2101	10.5241
23.159	3.8375	3944.4	63006.4	0.2101	16.1347
23.574	3.7709	2521.0	35274.6	0.1838	10.3122
24.326	3.6560	2787.3	47374.7	0.2232	11.4015
26.031	3.4202	9764.2	165913.1	0.2232	39.9408
26.715	3.3343	4623.7	78573.2	0.2232	18.9134
27.297	3.2645	3139.8	46911.1	0.1970	12.8435
27.691	3.2189	3632.9	54381.2	0.1970	14.8605
27.965	3.1880	3134.0	40703.9	0.1707	12.8197
28.531	3.1260	2850.7	42751.6	0.1970	11.6609
29.494	3.0261	24446.7	390957.0	0.2101	100.0000
29.872	2.9886	5868.9	75417.5	0.1707	24.0069
30.331	2.9445	4218.9	40890.4	0.1313	17.2575
30.606	2.9186	6593.0	111959.8	0.2232	26.9689
31.518	2.8363	2983.1	50280.5	0.2232	12.2025
32.011	2.7937	3047.5	60904.3	0.2626	12.4659
33.323	2.6867	4098.4	85933.0	0.2758	16.7646
35.078	2.5561	4348.1	82610.9	0.2495	17.7860
35.645	2.5168	4790.8	80996.9	0.2232	19.5969
36.088	2.4869	6211.4	111076.6	0.2364	25.4079
36.638	2.4508	2957.1	41274.4	0.1838	12.0961
37.101	2.4213	3130.2	56296.3	0.2364	12.8042
37.969	2.3679	2899.6	52186.4	0.2364	11.8609
39.050	2.3048	2904.1	40297.8	0.1838	11.8793
39.518	2.2785	7259.2	129869.4	0.2364	29.6940
40.580	2.2214	3445.7	68912.8	0.2626	14.0947
41.693	2.1646	2760.9	33122.9	0.1576	11.2935
42.001	2.1494	3065.0	48587.5	0.2101	12.5375
42.439	2.1282	3327.0	63133.8	0.2495	13.6092
42.913	2.1058	3246.6	35564.5	0.1444	13.2803
43.278	2.0889	6973.4	123550.2	0.2364	28.5249
44.438	2.0371	3231.1	79909.6	0.3283	13.2169
44.793	2.0217	3236.1	81521.6	0.3414	13.2374
45.927	1.9744	3476.7	66043.4	0.2495	14.2216
47.242	1.9225	4437.1	66033.1	0.1970	18.1501
47.602	1.9088	7173.4	150631.3	0.2758	29.3430
48.605	1.8717	7948.7	166356.7	0.2758	32.5144

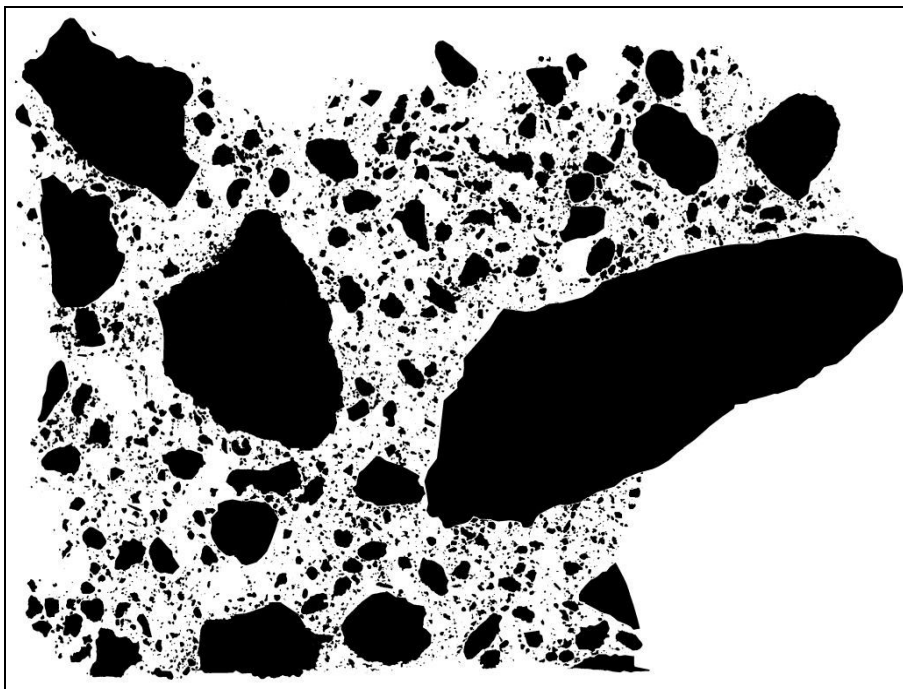
OS-F-C45 – Terme del Foro					
2Theta	d (Å)	Height	Area	FWHM	Relative Peak Height
49.599	1.8365	2992.9	50796.7	0.2232	12.2426
50.226	1.8150	3096.0	65007.8	0.2758	12.6643
52.523	1.7409	4662.7	111872.4	0.3152	19.0729
53.427	1.7136	3269.7	71544.3	0.2889	13.3748
54.897	1.6711	3576.1	72891.1	0.2889	14.6282
56.118	1.6376	3295.7	55710.0	0.2232	13.4812
56.684	1.6226	4450.9	88949.9	0.2626	18.2065
57.521	1.6010	5711.9	125631.9	0.2889	23.3647
58.155	1.5850	3338.6	40050.4	0.1576	13.6566
60.792	1.5224	4712.4	80087.0	0.2232	19.2762
61.435	1.5080	4032.5	96042.3	0.3152	16.4951
61.917	1.4974	3479.8	41380.1	0.1576	14.2342
62.910	1.4762	3840.2	87278.4	0.3020	15.7085
63.123	1.4717	3832.2	68978.0	0.2364	15.6757
64.296	1.4476	3288.3	42652.1	0.1707	13.4509
64.794	1.4377	4859.3	116619.2	0.3151	19.8771
65.704	1.4200	4166.2	119965.7	0.3808	17.0420
66.259	1.4094	3848.2	72637.3	0.2495	15.7412
67.802	1.3811	3345.8	50052.7	0.1970	13.6861
68.383	1.3707	3566.5	67515.1	0.2495	14.5889
69.278	1.3552	4027.8	131753.7	0.4333	16.4758
69.365	1.3537	4106.2	128973.4	0.4333	16.7965
70.339	1.3373	3681.8	102873.9	0.3677	15.0605
72.995	1.2951	4010.9	80175.0	0.2626	16.4067
73.849	1.2822	3955.2	66199.4	0.2232	16.1789
74.003	1.2799	3920.4	62696.8	0.2101	16.0365
75.327	1.2607	3640.4	129161.5	0.4727	14.8912
75.370	1.2601	3609.6	128671.4	0.4727	14.7652
76.402	1.2456	3689.9	99537.6	0.3546	15.0937
77.218	1.2345	3768.1	105195.7	0.3677	15.4135
78.112	1.2225	3728.3	125547.2	0.4465	15.2507
78.370	1.2192	3626.3	124421.5	0.4465	14.8335

OS-G-C50 – <i>Insula dell'Ercole Bambino</i>					
2Theta	d (Å)	Height	Area	FWHM	Relative Peak Height
8.654	10.2098	2253.4	31172.8	0.1800	14.0811
8.860	9.9723	2108.1	22782.4	0.1444	13.1732
13.800	6.4118	2164.4	27787.5	0.1707	13.5250
15.884	5.5749	5715.2	91366.7	0.2101	35.7133
18.351	4.8308	3108.2	49729.9	0.2101	19.4226
18.962	4.6765	2314.0	36989.9	0.2101	14.4598
20.020	4.4316	2464.7	39416.9	0.2101	15.4015
20.945	4.2380	2429.7	38862.6	0.2101	15.1828
23.164	3.8367	3337.3	56635.5	0.2232	20.8542
23.589	3.7685	2549.9	35555.8	0.1838	15.9339
24.336	3.6546	2980.3	50517.3	0.2232	18.6234
25.326	3.5139	2755.4	43684.8	0.2101	17.2180
26.031	3.4203	11507.5	184114.5	0.2101	71.9084
26.701	3.3360	4039.9	68187.8	0.2232	25.2446
27.345	3.2589	3378.3	47178.7	0.1838	21.1104
27.717	3.2160	6366.1	100212.5	0.2101	39.7807
28.002	3.1839	3016.2	29903.9	0.1313	18.8477
29.524	3.0231	16003.0	256015.8	0.2101	100.0000
29.876	2.9883	8118.5	111923.3	0.1838	50.7311
30.305	2.9470	5335.0	69223.5	0.1707	33.3375
30.606	2.9187	7450.2	111389.9	0.1969	46.5550
30.832	2.8977	4492.1	33512	0.1050	28.0704
31.776	2.8138	4509.3	76582.4	0.2232	28.1778
33.330	2.6861	4292.7	76917.8	0.2363	26.8243
35.076	2.5563	4768.4	95181.3	0.2626	29.7969
35.654	2.5161	6804.2	115669.8	0.2232	42.5183
36.092	2.4866	4872.7	77104.4	0.2101	30.4487
37.112	2.4206	3425.4	68508.1	0.2626	21.4047
37.956	2.3686	2998.9	50737.2	0.2232	18.7396
38.465	2.3385	2987.7	50285.1	0.2232	18.6696
39.059	2.3043	3426.1	58236.3	0.2232	21.4091
39.544	2.2771	5437.7	102959.3	0.2495	33.9793
40.539	2.2235	3959.0	82904.6	0.2757	24.7391
40.941	2.2026	3179.8	31718.3	0.1313	19.8700
42.024	2.1483	3472.0	55459.1	0.2101	21.6959
42.415	2.1294	4172.2	70538.1	0.2232	26.0714
42.904	2.1062	3737.7	56063.9	0.1969	23.3562
43.299	2.0879	5617.1	100813.7	0.2363	35.1003
44.541	2.0326	3671.1	79163.1	0.2888	22.9401
44.849	2.0193	3742.6	78581.1	0.2757	23.3869
45.502	1.9918	3966.4	71141.7	0.2363	24.7854
45.930	1.9743	3655.5	65324.1	0.2363	22.8426
47.278	1.9211	3836.3	53397.5	0.1838	23.9724

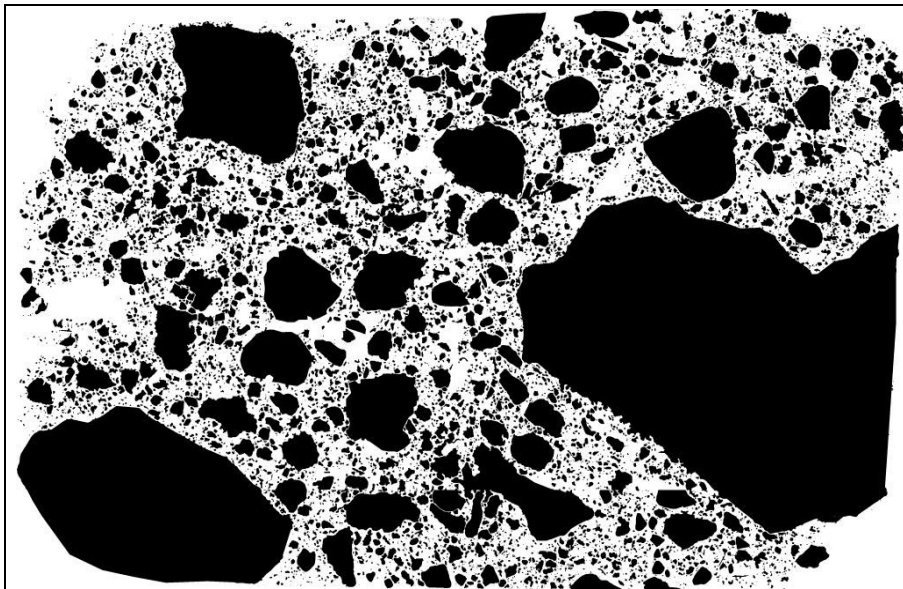
OS-G-C50 – <i>Insula dell'Ercole Bambino</i>					
2Theta	d (Å)	Height	Area	FWHM	Relative Peak Height
47.748	1.9033	5766.5	155570.4	0.3545	36.0339
48.662	1.8696	5928.5	147658.9	0.3282	37.0462
49.547	1.8383	3530.6	82838.6	0.3151	22.0621
50.251	1.8142	3362.6	67151.6	0.2626	21.0123
50.729	1.7982	3086.4	52318.1	0.2232	19.2864
52.522	1.7409	5204.0	104057.5	0.2626	32.5189
53.446	1.7130	3658.2	72969.5	0.2626	22.8595
54.344	1.6868	3716.8	74096.6	0.2626	23.2256
54.803	1.6738	3676.0	75932.5	0.2757	22.9707
55.190	1.6629	3476.1	48599	0.1838	21.7216
56.166	1.6363	3737.8	55738.3	0.1969	23.3569
56.624	1.6242	4842.1	101681.3	0.2757	30.2575
57.053	1.6130	4151.2	45658.3	0.1444	25.9401
57.552	1.6002	4700.1	145570.6	0.4070	29.3701
58.225	1.5833	3456.3	44347.1	0.1707	21.5978
58.966	1.5651	3417.5	95654	0.3676	21.3554
60.021	1.5401	3595.7	96301.5	0.3545	22.4689
60.709	1.5243	4191.1	78753.5	0.2626	26.1895
60.837	1.5214	4276.2	72438.7	0.2232	26.7212
61.217	1.5129	4261.4	173879.3	0.5383	26.6288
61.500	1.5066	4120.0	167102	0.5383	25.7452
61.942	1.4969	3789.6	52777.8	0.1838	23.6806
62.811	1.4783	4489.9	143267.5	0.4201	28.0566
63.517	1.4635	3660.6	46592.1	0.1707	22.8745
64.417	1.4452	3679.9	47833.9	0.1707	22.9951
64.832	1.4370	4326.7	107791.7	0.3282	27.0368
65.810	1.4179	4545.1	107899.8	0.3151	28.4015
65.998	1.4144	4463.8	53490.7	0.1576	27.8935
66.270	1.4092	4573.4	86716.6	0.2495	28.5784
68.352	1.3713	3815.0	79790.8	0.2757	23.8393
69.126	1.3578	4382.3	135826.8	0.4070	27.3842
70.542	1.3340	4018.2	96333.7	0.3151	25.1090
71.493	1.3186	3683.0	51553.8	0.1838	23.0144
72.207	1.3073	3773.0	67416	0.2363	23.5768
73.076	1.2939	4055.0	76944.8	0.2495	25.3390
73.760	1.2835	4273.4	150504.6	0.4727	26.7037
73.961	1.2805	4397.6	158249.1	0.4727	27.4798
75.327	1.2607	4441.2	97246.8	0.2888	27.7523
76.188	1.2486	4038.5	72608.6	0.2363	25.2359
77.376	1.2323	3947.1	67099.8	0.2232	24.6648
78.150	1.2220	4276.5	136436.1	0.4202	26.7231

Appendix F – Image Analysis

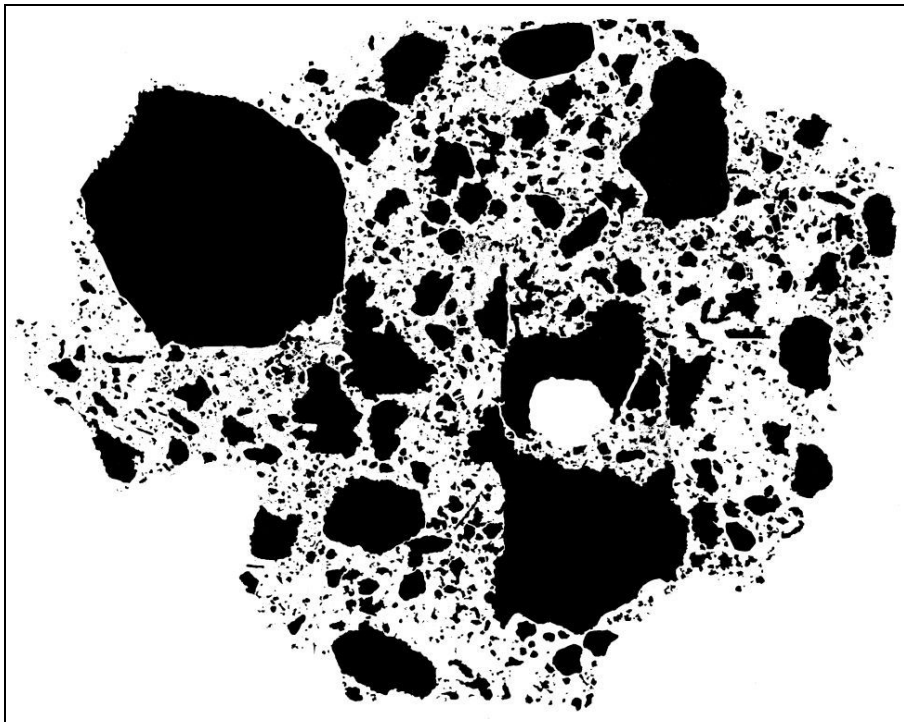
OS-C15 – Case a Giardino



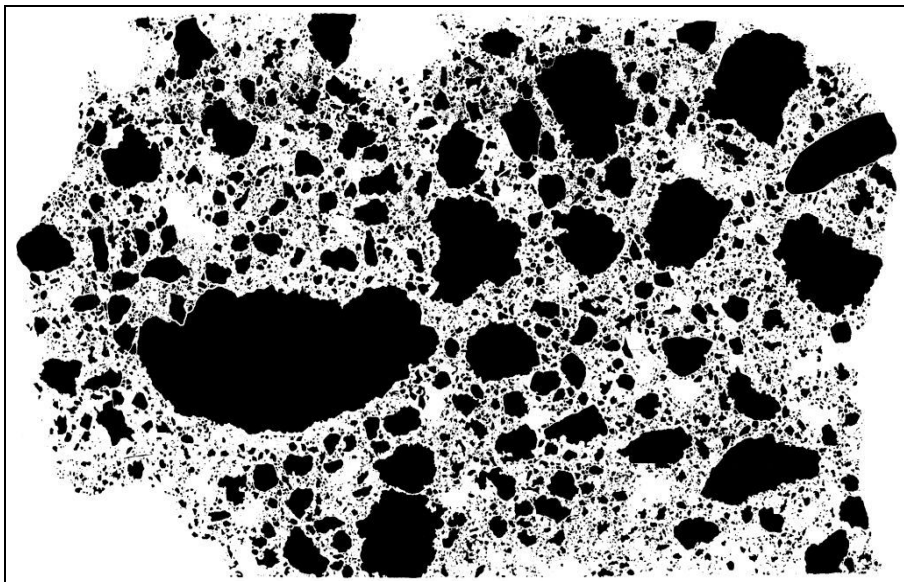
OS-C16 – Caseggiato del Serapide



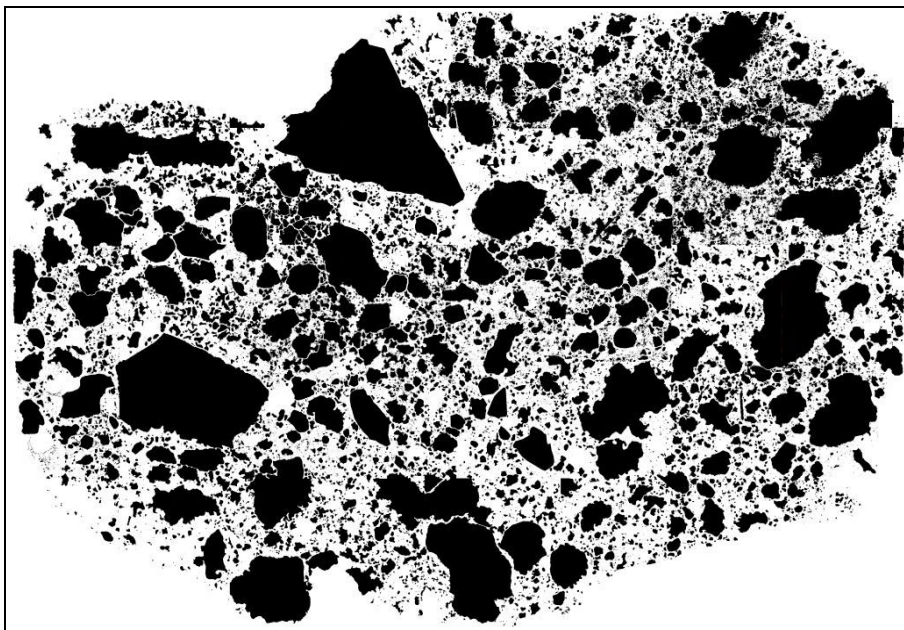
OS-C5 -Caseggiato del Larario



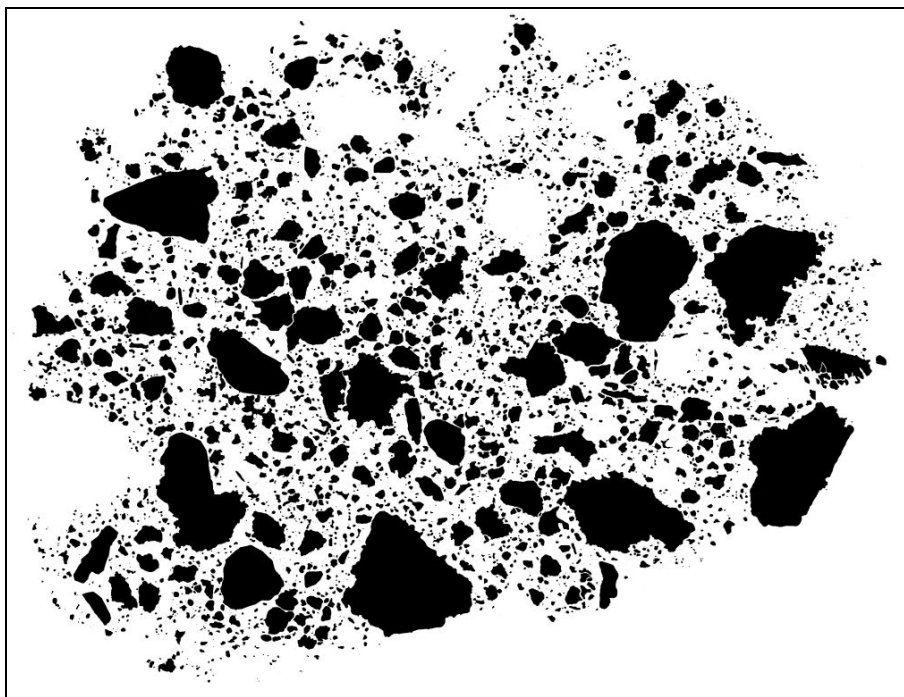
OS-C3 – Casa Basilicale



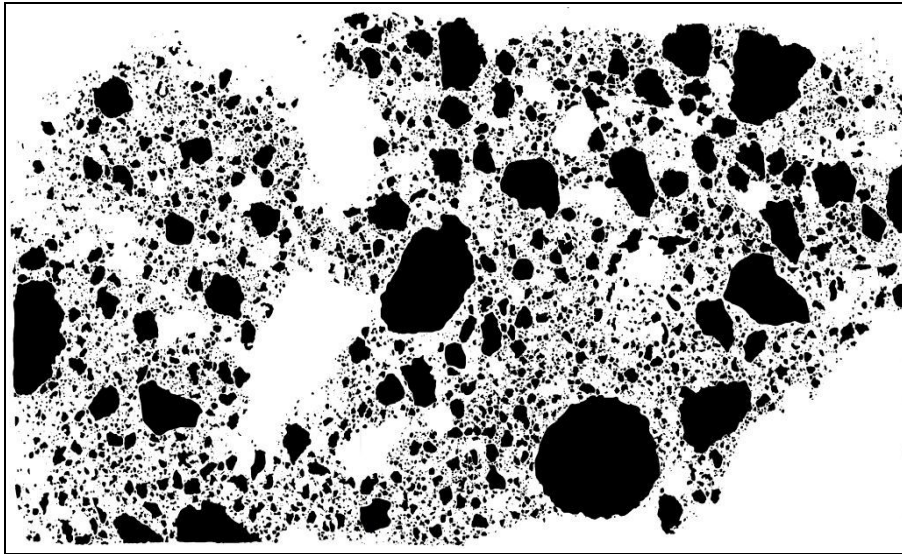
OS-C1 – Piccolo Mercato



OS-C9 – Terme del Foro



OS-C21 – Insula del'Ercole Bambino



Descriptive statistics of grey scale colour data from SEM backscatter images of binder areas of mortars from all structures.

Structure	Image	Mean	Std Dev	Median	Skew	Result
Casa a Giardino	15P_Paste 8	99.0	41.3	119.0	left	Si > Ca
Casa a Giardino	15_Paste7	76.4	51.7	96.0	left	Si > Ca
Casa a Giardino	15-paste6	44.5	50.0	21.0	right	Ca > Si
Casa a Giardino	15-paste5	71.3	54.1	82.0	left	Si > Ca
Casa a Giardino	15-Paste 4	62.9	50.4	71.0	left	Si > Ca
Casa a Giardino	Average	70.8	49.5	77.8	left	Si > Ca
Caseggiato del Serapide	16Q-Paste4	78.7	50.8	72.0	right	Ca > Si
Caseggiato del Serapide	16P-Paste6	57.4	44.1	48.0	right	Ca > Si
Caseggiato del Serapide	16O_Paste5	54.9	46.9	41.0	right	Ca > Si
Caseggiato del Serapide	16N_Paste4	69.4	45.9	66.0	right	Ca > Si
Caseggiato del Serapide	16E_Paste7	56.7	46.7	48.0	right	Ca > Si
Caseggiato del Serapide	Average	63.4	46.9	55.0	right	Ca > Si
Caseggiato del Larario	5O_Paste8	30.4	36.1	18.0	right	Ca > Si
Caseggiato del Larario	5N_Paste7	61.2	41.7	59.0	right	Ca > Si
Caseggiato del Larario	5J_Paste3	66.2	47.6	55.0	right	Ca > Si
Caseggiato del Larario	5K_Paste4	47.6	39.3	40.0	right	Ca > Si
Caseggiato del Larario	5m-paste6	63.1	48.9	53.0	right	Ca > Si
Caseggiato del Larario	Average	53.7	42.7	45.0	right	Ca > Si

Structure	Image	Mean	Std Dev	Median	Skew	Result
Casa Basilicale	3O_paste6	30.5	41.1	9.0	right	Ca > Si
Casa Basilicale	3n-paste5	41.6	40.9	32.0	right	Ca > Si
Casa Basilicale	3k-paste4	58.7	48.1	51.0	right	Ca > Si
Casa Basilicale	3j-paste	42.7	44.0	29.0	right	Ca > Si
Casa Basilicale	3i-paste2	45.0	45.2	32.0	right	Ca > Si
Casa Basilicale	Average	43.7	43.9	30.6	right	Ca > Si
Piccolo Mercato	1m-paste6	30.2	37.0	16.0	right	Ca > Si
Piccolo Mercato	1h-paste2	88.3	44.3	94.0	left	Ca > Si
Piccolo Mercato	1L-paste5	66.4	50.0	60.0	right	Ca > Si
Piccolo Mercato	1J-paste4	82.9	46.2	89.0	left	Ca > Si
Piccolo Mercato	1I-paste3	75.5	50.2	72.0	right	Ca > Si
Piccolo Mercato	Average	68.7	45.5	66.2	right	Ca > Si
Terme del Foro	9z-paste4	34.8	42.5	16.0	right	Ca > Si
Terme del Foro	9y-paste3	33.5	43.1	12.0	right	Ca > Si
Terme del Foro	9v-paste2	64.5	48.5	57.0	right	Ca > Si
Terme del Foro	9bb-paste6	38.0	45.5	14.0	right	Ca > Si
Terme del Foro	9aa-paste5	52.4	47.4	41.0	right	Ca > Si
Terme del Foro	Average	44.6	45.4	28.0	right	Ca > Si
Insula dell'Ercole Bambino	21t-paste8	62.3	53.2	53.0	right	Ca > Si
Insula dell'Ercole Bambino	21s-paste7	76.1	50.0	83.0	left	Ca > Si
Insula dell'Ercole Bambino	21r-paste6	50.2	51.0	32.0	right	Ca > Si
Insula dell'Ercole Bambino	21p-paste5	58.1	53.1	44.0	right	Ca > Si
Insula dell'Ercole Bambino	21n-paste4	66.0	52.6	58.0	right	Ca > Si
Insula dell'Ercole Bambino	Average	62.5	52.0	54.0	right	Ca > Si

Descriptive Statistics of Point count data for key measured parameters

Area mm2

	Mean	Std Dev	Min	Max	Median	Mode	IQR
Casa a							
Giardino	0.0856	1.8116	0.0004	97.0239	0.0040	0.0006	0.0099
Caseggiato del							
Serapide	0.0746	2.0791	0.0004	160.8511	0.0050	0.0004	0.0123
Caseggiato del							
Larario	0.0951	1.2519	0.0004	48.6433	0.0055	0.0005	0.0173
Casa Basilicale	0.0534	0.8588	0.0004	69.0624	0.0043	0.0005	0.0113
Piccolo							
Mercato	0.0499	0.5530	0.0004	31.6676	0.0027	0.0004	0.0090
Termo del Foro	0.0496	0.3755	0.0004	9.7312	0.0054	0.0009	0.0131
Insula							
dell'Ercole							
Bambino	0.0328	0.3357	0.0004	19.3950	0.0042	0.1103	0.3020

Perimeter							
	Mean	Std Dev	Min	Max	Median	Mode	IQR
Casa a							
Giardino	0.5321	1.5038	0.0674	48.6100	0.2524	0.1103	0.3178
Caseggiato del							
Serapide	0.5482	1.3714	0.0674	71.5506	0.2935	0.1216	0.3589
Caseggiato del							
Larario	0.7139	1.9163	0.0674	47.0519	0.3225	0.1103	0.4788
Casa Basilicale							
Piccolo	0.5399	1.2505	0.0674	50.8624	0.2795	0.1103	0.3655
Mercato	0.6106	1.7673	0.0670	64.6695	0.2439	0.1098	0.3768
Termo del Foro							
Insula	0.5496	1.0207	0.0674	18.4139	0.2954	0.1216	0.3608
dell'Ercole							
Bambino	0.4511	0.7521	0.0674	20.7067	0.2636	0.1103	0.3020
Circularity							
	Mean	Std Dev	Min	Max	Median	Mode	IQR
Casa a							
Giardino	0.7490	0.1875	0.1131	1.0000	0.7920	1.0000	0.2623
Caseggiato del							
Serapide	0.7094	0.1797	0.1106	1.0000	0.7327	1.0000	0.2538
Caseggiato del							
Larario	0.6469	0.2027	0.0589	1.0000	0.6583	1.0000	0.2981
Casa Basilicale							
Piccolo	0.6803	0.2025	0.0540	1.0000	0.6996	1.0000	0.3096
Mercato	0.5827	0.2327	0.0288	1.0000	0.5779	1.0000	0.3678
Termo del Foro							
Insula	0.7502	0.1688	0.1457	1.0000	0.7778	1.0000	0.2393
dell'Ercole							
Bambino	0.7427	0.1640	0.1412	1.0000	0.7642	1.0000	0.2235
Aspect Ratio							
	Mean	Std Dev	Min	Max	Median	Mode	IQR
Casa a							
Giardino	1.6506	0.5670	1.0000	8.0000	1.4853	1.2878	0.5403
Caseggiato del							
Serapide	1.6837	0.6022	1.0000	8.0000	1.5243	1.2878	0.5807
Caseggiato del							
Larario	1.7878	0.7895	1.0000	12.3737	1.5825	1.3721	0.6771
Casa Basilicale							
Piccolo	1.7137	0.6169	1.0000	21.6285	1.5530	1.9357	0.6159
Mercato	1.8452	0.7545	1.0000	12.0000	1.6407	1.9357	0.7347
Termo del Foro							
Insula	1.5953	0.5262	1.0000	5.9847	1.4411	1.9357	0.5115
dell'Ercole							
Bambino	1.5765	0.4751	1.0000	8.0000	1.4568	1.2878	0.4905
Roundness							
	Mean	Std Dev	Min	Max	Median	Mode	IQR
Casa a							
Giardino	0.6570	0.1640	0.1250	1.0000	0.6733	0.7765	0.2295
Caseggiato del							
Serapide	0.6469	0.1652	0.1250	1.0000	0.6560	0.7765	0.2387
Caseggiato del							
Larario	0.6249	0.1757	0.0808	1.0000	0.6319	0.5166	0.2582
Casa Basilicale							
Piccolo	0.6353	0.1642	0.0462	1.0000	0.6439	0.5166	0.2419
Mercato	0.6055	0.1764	0.0833	1.0000	0.6095	0.5166	0.2615
Termo del Foro							
Insula	0.6756	0.1612	0.1671	1.0000	0.6939	0.5166	0.2295
dell'Ercole							
Bambino	0.6766	0.1530	0.1250	1.0000	0.6864	0.7765	0.2217

Feret Diameter

	Mean	Std Dev	Min	Max	Median	Mode	IQR
Casa a Giardino	0.1819	0.4647	0.0286	19.0453	0.0969	0.0397	0.1097
Caseggiato del Serapide	0.1866	0.3824	0.0286	18.7052	0.1103	0.0397	0.1255
Caseggiato del Larario	0.2231	0.4265	0.0337	8.9180	0.1191	0.0463	0.1631
Casa Basilicale Piccolo	0.1769	0.3275	0.0286	14.6647	0.1035	0.0463	0.1218
Mercato	0.1732	0.3330	0.0285	8.8407	0.0894	0.0395	0.1147
Termo del Foro	0.1886	0.2924	0.0286	4.3963	0.1106	0.0463	0.1255
Insula dell'Ercole Bambino	0.1579	0.2292	0.0286	5.6478	0.1004	0.0397	0.1048

Minimum Feret Diameter

	Mean	Std Dev	Min	Max	Median	Mode	IQR
Casa a Giardino	0.1128	0.2513	0.0079	7.2361	0.0635	0.0318	0.0670
Caseggiato del Serapide	0.1171	0.2544	0.0079	13.4616	0.0714	0.0318	0.0742
Caseggiato del Larario	0.1398	0.3112	0.0079	7.6679	0.0774	0.0238	0.1008
Casa Basilicale Piccolo	0.1114	0.2041	0.0079	6.6333	0.0665	0.0318	0.0749
Mercato	0.1074	0.2130	0.0079	6.0703	0.0553	0.0237	0.0727
Termo del Foro	0.1224	0.1943	0.0159	3.3649	0.0715	0.0318	0.0745
Insula dell'Ercole Bambino	0.1029	0.1544	0.0079	4.7826	0.0635	0.0318	0.0687