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ORIGINAL ARTICLE

Innovative Roman Building: Geomaterials, Construction Technology and Architecture of the Roman Temple of Venus (Phlegraean Fields, Italy)

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Abstract

The aim of this research is to characterize the geomaterials used for the construction of the Temple of Venus, located in the Phlegraean Fields area (Southern Italy), through a multi-analytical approach involving petrographic and mineralogical analysis. The 9 samples characterized for this study are mortars, bricks, building stone, tuff, volcanic scoria and lava, along with efflorescence. This study highlighted the following main results: (a) mortars are lime-based, hydraulic, containing a volcanic aggregates linked to the Neapolitan Yellow Tuff formation of Phlegraean Fields; (b) bricks are characterized by both silico-clastic and volcanic fractions ascribable to sedimentary transport or artificial addition; (c) scoria has a Vesuvian provenance given the presence of leucite crystals; (d) tuff sample is genetically linked to the Neapolitan Yellow Tuff formation of Phlegraean Fields; (e) lava has a trachytic texture linked to Phlegraean Fields products, containing microlites of alkali feldspar in the groundmass; (f) efflorescence is made up of halite. The goal that has been set is to deepen the knowledge about the skills acquired by the Romans for the preparation and the use of geomaterials. This information may be useful for future restoration interventions of Temple of Venus.

Keywords Geomaterials characterization · Phlegraean fields · Ancient roman

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Introduction and Geological Background

The Romans founded one of the greatest empires in history, conquering the Mediterranean area and half of Europe. The sign of their passage can be seen through buildings, roads, aqueducts, temples and monuments. From an architectural perspective, the Romans inspired many populations, both past and present. Their ability to build monuments starting from simple geological materials and obtaining more complex ones that would last over time has been, and still is, object of interest for researchers. From a geological point of view, the high interest aroused by the study of Roman operas comes from their extraordinary preservation state (Miriello et al. 2010; De Luca et al. 2015; Rispoli et al. 2019; Rispoli et al. 2020; Rispoli et al. 2016; Columbu et al. 2022; Columbu et al. 2018; Columbu et al. 2019; Sitzia et al. 2020; Montesano et al. 2022), proving the important technical skills of the craftsmanship.

Named after the discovery in situ in 1595 of a statue attributed to the goddess Venus, the Temple of Venus is an important archaeological site located in the area of Baia of the Phlegraean Fields (Southern Italy; Fig. 1) which was the most important hall of the much larger thermal complex of Baia. The thermal complex of Baia consists of a series of mainly thermal and residential areas, dating between the 2nd century BC and the 4rd century AD, divided into five sectors: the Ambulatio Villa, the Mercury Complex, the Sosandra Sector, the Temple of Diana and the Venus sector. Unfortunately, most of the halls have been lost because of the bradyseism characterizing the Phlegraean area, and the same Temple of Venus is today about 6 m below the surface.

The Temple represents a wonderful example of Roman architecture of the imperial era, one of the landmarks of the city of Baia. The edifice, built in the 2nd century AD at the behest of Emperor Hadrian, is a thermal building, the *natatio* of the baths desired by the emperor himself. The plan is octagonal at the outside, circular on the inside, and its dome is called “umbrella” due to the shape of the different sections forming it. The niches that opened to the central hall, in turn giving access to other small halls, were probably the pools of a large bath, in continuity with the other complexes excavated in the Gulf of Baia. The thermal complex was intended for body care and, most probably, to cure the illness that Emperor Hadrian was suffering for. As was common in thermal complexes, several activities were carried out in the edifice, from political to social, from trade to culture spreading.

Research Aim

The aim of this research is to obtain information about geomaterials used for the Temple of Venus through a multi-analytical approach involving macroscopic analysis, petrographic and mineralogical techniques to examine thoroughly the features of the temple.

Sampling and Analytical Methods

For this work, 9 samples from the Temple of Venus were investigated (Table 1; Fig. 2):

The sampling activity was carried out in collaboration with the Archaeological Park of the Phlegraean Fields. The sampling strategy took into account (i) limited invasiveness (b) representativeness, (iii) limited sample size and (iv) limited visual impact.

Macroscopic, petrographic and mineralogical analyses were carried out at the Department of Earth, Environmental and Resources Sciences (DiSTAR) at the University of Naples Federico II.

Thin sections analysis through optical microscopy (OM) was performed by using a Leica Laborlux 12 Pol microscope Leica Camera, (Wetzlar, Germany). Mineralogical analyses was carried out by means of X-Ray powder diffraction (XRPD) with a Malvern Panalytical X’Pert Pro modular diffractometer (RTMS detector, X’Pert High Score Plus 3.0c software—Malvern PANalytical, Almelo, The Netherlands) were conducted for the identification of the crystal phases; the following conditions were used: CuKα radiation, 40 kV, 40 mA, 2θ range from 4° to 70°, step size 0.02 °2θ, equivalent counting time 120 s per step. Representative aliquots of the samples (grain size <10 μm) were obtained using a McCrone micronizing mill (agate cylinders and wet grinding time of 15 min; Retsch-Alle, Haan, Germany).

Fig. 1 (**a**) Maps of Phlegraean Fields area with location of the Temple of Venus (red star) and the other sectors of the Thermal Complex of Baia (Temple of Mercury: green star; Temple of Diana: white star; Sosandra Sector: yellow star); (**b**) Thermal Complex of Baia - general plan with identification of the five sectors (Di 1992); (**c**) East and (**d**) internal views of the Temple of Venus

Table 1 List of the investigated samples with location of sampling points (see also Fig. 2) and macroscopic characteristics

Samples	Type	Location	Colour *	Aggregate size	Cohesion**
S1.1	bedding mortar	internal part of eastern wall	light beige	0.5–1 cm	+++
S2	coating mortar	internal part of eastern wall	light yellow	0.5–1.5 cm	++
S6	bedding mortar	external part of eastern wall	light yellow	0.5–1.5 cm	++
S1.2	brick	internal part of eastern wall	red		+++
S5	brick	external part of eastern wall	red		+++
S4	volcanic scoria	coating	gray		+
S8	tuff	internal part of western wall	yellow		++
S9	lava as building stone	external part of northern wall	dark gray		+++
S7	efflorescence	access arc	white		

* colour: for mortar samples, colour refers to the binder;

**cohesion has been evaluated to the touch, depending on the crumbling of the material: +++ high; ++ medium; + low

Results

Optical Microscopy

Macroscopic observations revealed similarities among mortars in displaying cohesion from medium to high, light colours from beige to yellow and an aggregate size of 0.5–1.5 cm (Table 1). According to petrographic analysis, mortar samples (i.e., S.1.1 and S6 – bedding mortars and S2 – coating mortar) display a binder with a prevailing cryptocrystalline, and subordinately micritic, texture (Fig. 3a-f). Binder fraction also contains subrounded lime lumps (Fig. 3e-f). The aggregate abundance is around 50% as evaluated from comparative charts (Terry and Chilingar 1955) and is mainly represented by pumice and subordinate alkali feldspar and clinopyroxene (Fig. 3a-b). Pumice shows carbonation features and evident reaction rims (Fig. 3a-b).

Brick samples (i.e., S1.2 and S5) show a reddish color, with moderate optical activity of the ceramics body (Fig. 3g-j). Brick samples show a seriate distribution of grains and inclusions abundance around 15%. The main inclusions are represented by pumice, volcanic lithics, *lime* lumps, alkali feldspar, plagioclase, as well as tiny quartz and mica crystals, with subordinate clinopyroxene, biotite and sporadic amphibole (Fig. 3g-j).

Scoria sample (i.e., S4; Fig. 4a-d) shows a highly vesiculated porphyritic texture in which the irregularly shaped and sized vesicles make up more than 70% of the total. The glassy groundmass contains clinopyroxene and plagioclase (Fig. 4a-d).

Tuff sample (i.e., S8; Fig. 4e-h) is characterized by both pyrogenic and authigenic phases, containing phenocrysts of alkali feldspar, plagioclase, clinopyroxene and mica within a matrix consisting of pumice and glass shards.

Lava sample (i.e., S9; Fig. 4i-j) shows a trachytic texture, with the groundmass consisting mainly of minute tabular alkali feldspar microlites aligning sub-parallel, sometimes forming flow lines around the phenocrysts.

X-Ray Powder Diffraction

X-Ray Powder Diffraction (XRPD; Table 2) allows to confirm the occurrence of lime-based mortars (samples S1.1, S2 and S6; Fig. 5a), in which calcite is the most abundant phase of the binder fraction, together with subordinate gypsum and halite. Aggregates fraction contain analcime, phillipsite and chabazite, the latter detected only in sample S2, along with alkali feldspar.

Both brick fragments (Fig. 5b) contain calcite, halite, alkali feldspar, plagioclase, quartz and hematite, while only sample S1.2 contain mica and phillipsite.

Scoria S4 (Fig. 5c) contains alkali feldspar, plagioclase, clinopyroxene and zeolites, analcime and phillipsite, together with leucite and hematite, whereas tuff sample S8 (Fig. 5c) contain alkali feldspar, mica, analcime, phillipsite and chabazite, and gypsum.

Efflorescence is made up entirely of halite (Fig. 5d).

Lava S7 (Fig. 5d) contains pyrogenic phases alkali feldspar, plagioclase, clinopyroxene, amphibole and mica, but also gypsum.

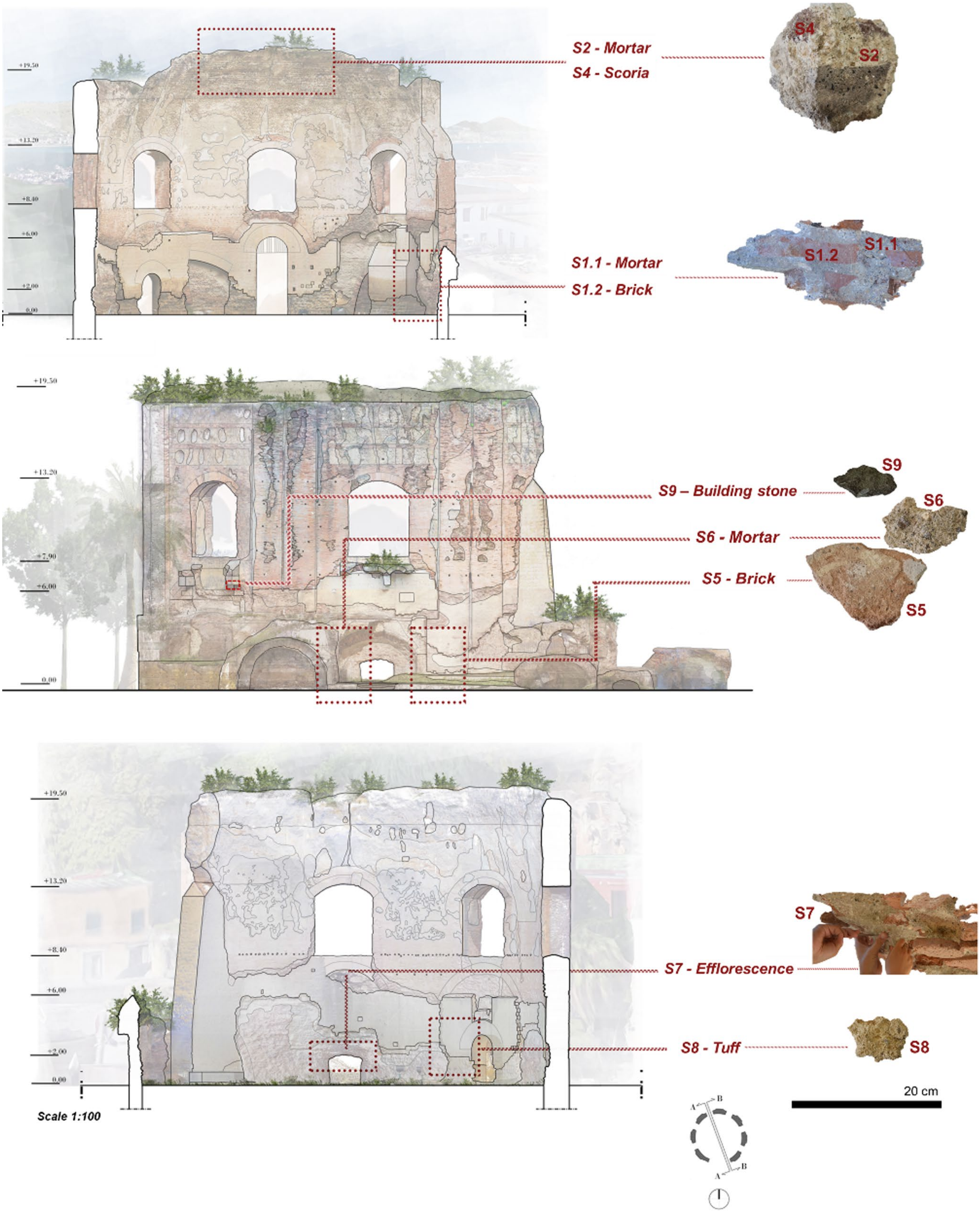


Fig. 2 Sketch of the Temple of Venus (Antonini 2021), with location of the 9 investigated samples

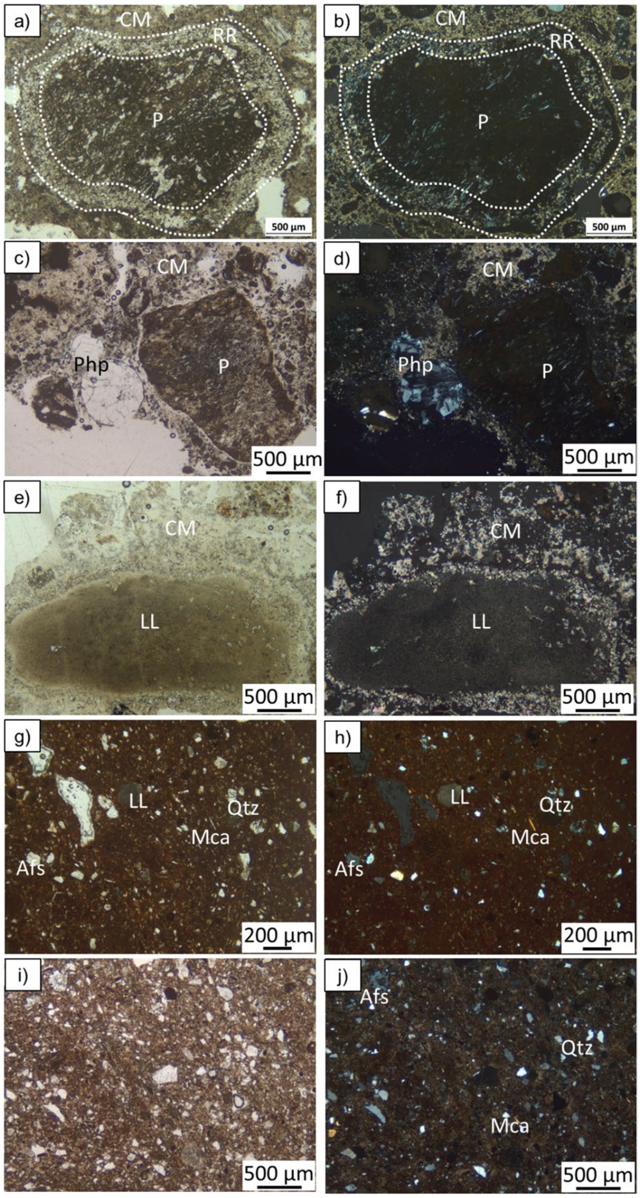


Fig. 3 Plane (**a**, **c**, **e**, **g**, **i**) and crossed (**b**, **d**, **f**, **h**, **j**) polarized light microphotographs. (**a**-**b**) S1.1 and (**c**-**d**) S6 bedding mortars, (**e**-**f**) S2 coating mortar; (**g**-**h**) S1.2 and (**i**-**j**) S5 brick samples. Mineral abbreviations: CM = cryptocrystalline matrix; RR = reaction rim; P = pumice; Php = phillipsite; LL = lime lump; Afs = alkali feldspar; Mca = mica; Qtz = quartz

Discussion and conclusions

The characterization of the geomaterials which made up the Temple of Venus allows to establish the provenance of the raw materials used for its construction and information about the production techniques. The provenance proved to be linked to the two main Campanian volcanic district: Phlegraean Fields and Somma Vesuvius.

In the mortar samples S1.1, S2 and S6 the binding matrix is characterized by calcite whereas the aggregate fraction contains pumice. It is possible to infer that these mortars became hydraulic by addition of aggregates (volcanic materials) which produced a pozzolanic reaction reacting with the lime of the binder fraction (calcite) (Artioli and Secco 2019). This is testified by the intensive carbonation feature showing up by pumice as evident reaction rims (Fig. 3a-f; (Graziano et al. 2018). Lime lumps usually indicate unreacted lime and their presence is likely to be attributed to a lack of accuracy or failure during the slaking process of lime (UNI-EN 2009; UNI 2019; Bakolas et al. 1995) and in the mixing of materials. The presence of gypsum in samples S1.1 and S6 (bedding mortars) is related to the calcite sulphation process, likely due to a pH decrease because of the atmospheric SO_2dissolution (de Gennaro et al. 2000; Ricca et al. 2023). The absence of gypsum in sample S2 (coating mortar) indicates that the weathering is more extensive in the area in contact with the ground due to the rising damp to which the walls of the Temple of Venus are subjected.

The aggregate fraction of the mortar samples is mainly made of pumice, scoriae, alkali feldspar, plagioclase, clinopyroxene and mica. The presence of zeolites (analcime, phillipsite and chabazite).

allows to establish a local origin of the aggregate, attributed to the Phlegraean Fields Neapolitan Yellow Tuff (Morra et al. 2010). As regards the origin of the lime, it is reasonable to hypothesize that it was prepared by using raw materials found in situ, probably from the relief that borders the Piana Campana (Orsi et al. 1996).

Brick samples S1.2 and S5 show almost the same composition, except for the presence of mica and phillipsite in sample S1.2. Moreover, the presence of calcite residual grains in sample 1.2 indicates that calcite dissolution

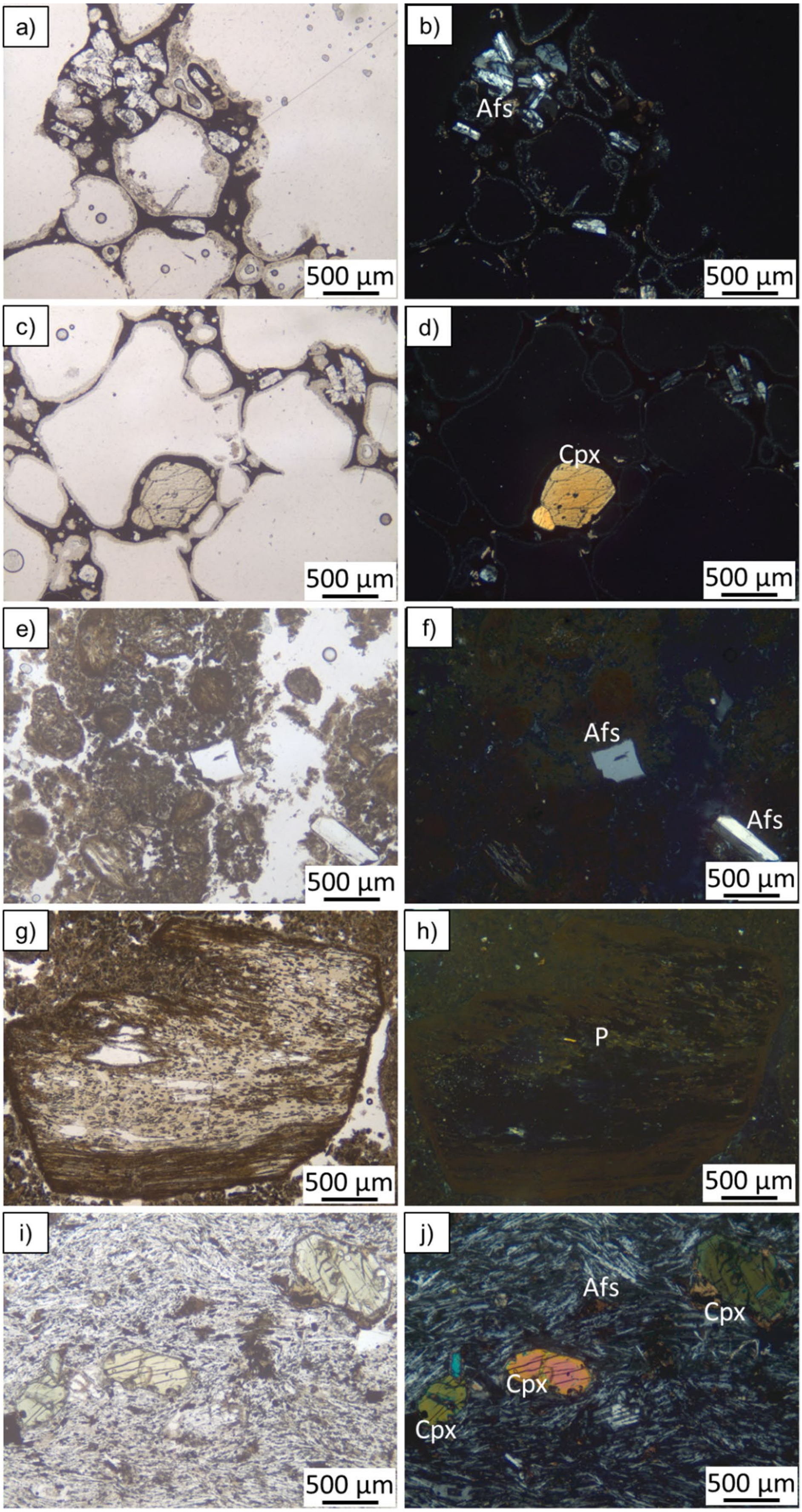


Fig. 4 Plane (**a**, **c**, **e**, **g**, **i**) and crossed (**b**, **d**, **f**, **h**, **j**) polarized light microphotographs. (**a-d**) S4 scoria sample, (**e-h**) S8 tuff sample and (**i-j**) S9 lava sample. Mineral abbreviations: Afs = alkali feldspar; Cpx = clinopyroxene; P = pumice

Table 2 Mineralogical composition of the investigated mortar samples

Sample	Type	Cal	Hl	Gp	Kfs	Pl	Cpx	Amp	Mca	Anl	Php	Cbz	Lct	Qz	Hem
S1.1	bedding mortar	X	X	X	X					X	X				
S2	coating mortar	X	X		X					X	X	X			
S6	bedding mortar	X	X	X	X					X	X				
S1.2	brick	X	X		X	X			X		X			X	X
S5	brick	X	X		X	X								X	X
S4	scoria				X	X	X			X			X		X
S8	tuff			X	X				X	X	X	X			
S7	lava			X	X	X	X	X	X						
S9	efflorescence		X												

Mineral abbreviations from (Warr 2021): Cal: calcite; Hl: halite; Gp: gypsum; Kfs: alkali feldspar; Pl: plagioclase; Cpx: clinopyroxene; Amp: amphibole; Mca: mica; Anl: analcime; Php: phillipsite; Cbz: chabazite; Lct: leucite; Qz: quartz; Hem: hematite

temperatures (about 800 °C) were exceeded but the fact that the matrix is still moderately active suggests that total decomposition of the clay fraction was not achieved. Regarding the composition of the temper, a predominantly silico-clastic fraction is associated with a moderate volcanic fraction. Since this is a naturally and genetically incompatible association of materials, it is likely that sedimentary transport has occurred or that volcanic material has been added artificially.

The highly vesiculated scoria S4 was used in the upper part of the Temple of Venus (Fig. 2). This suggests that Romans used this type of material to support the weight avoiding collapsing, giving lightness to the coating mortar S2 with which is in contact. The presence of leucite identified through mineralogical analysis is indicative of a Vesuvian provenance (Ricca et al. 2023). Therefore, even though this Temple is located in the Phlegraean Fields area, it was necessary to import material from the Vesuvian area for structural purposes. This construction technique allowed to build structures still perfectly preserved nowadays.

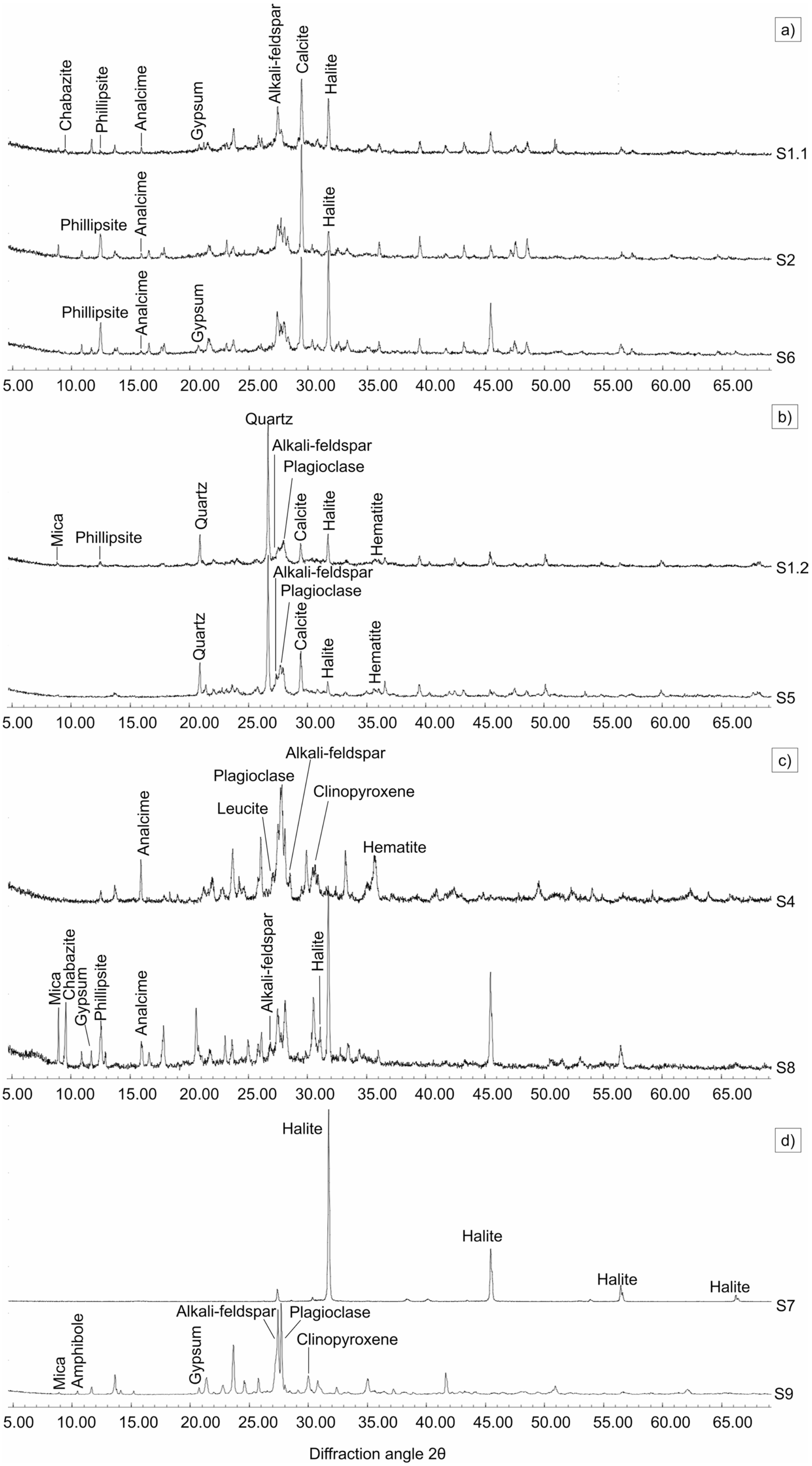
Tuff sample S8 shows typical mineralogical association of Phlegraean Fields area, with the presence of phillipsite, chabazite and alkali feldspar. Therefore, it could be associated to Neapolitan Yellow Tuff formation or to the yellow facies of the Campanian Ignimbrite (Orsi et al. 1996).

The lava sample S9 can be associated with the alkaline-potassium series characteristics of the Phlegraean Fields products given the trachytic texture and the presence of clinopyroxene, plagioclase, alkali feldspar and mica (Morra et al. 2010). For this sample, a Vesuvian provenance can be ruled out given the absence of leucite, the index mineral of Somma Vesuvius products (Morra et al. 2010).

The presence of efflorescence S7 (halite, NaCl) is widespread on the internal and external surfaces of the walls and highlights a weathering phenomenon.

This study highlights mineralogical, petrographic and structural characteristics of the materials used for the construction of the Temple of Venus and provided further insights into the technical skills achieved by the ancient Romans, and how their production technology was aimed at innovation, quality, sustainability, durability and, not least, beauty.

Fig. 5 XRPD patterns of the analyzed samples (**a**) S1.1, S2 and S6, (**b**) S1.2 and S5, (**c**) S4 and S8, (**d**) S7 and S9



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Data Availability All data derived from this research are presented in the enclosed figures and tables.

Declarations

Conflict of interest The authors declare no conflict of interest.

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