

# Geological Basis of Vitruvius's Empirical Observations of Material Characteristics of Rock Utilized in Roman Masonry

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## INTRODUCTION

Marcus Vitruvius Pollio began his career as an architect and engineer in the late republican age, during the rule of Julius Caesar. At some point between 31 and 27 BCE he wrote an account of architecture, construction methods, and Roman technology entitled *De Architectura*, and dedicated his work to the new emperor Augustus (fig.1). *De Architectura* is the only major work on architecture to survive from classical antiquity; it was used as a textbook on architecture from ancient Roman times to the Renaissance (for example, Alberti 1988; Palladio 1997). Indeed, until about two centuries ago, it was the foundational text upon which all other architectural treatises depended (McEwen 2004). While many of the ten books of *De Architectura* explicitly consider architectural styles, the text is vastly more comprehensive than that. Vitruvius described building materials, city planning and architecture; astronomy, medicine, temple construction; public buildings; and private buildings; pumps, water clocks and sundials, hydraulics; and civil and military engines, even music and the arts.

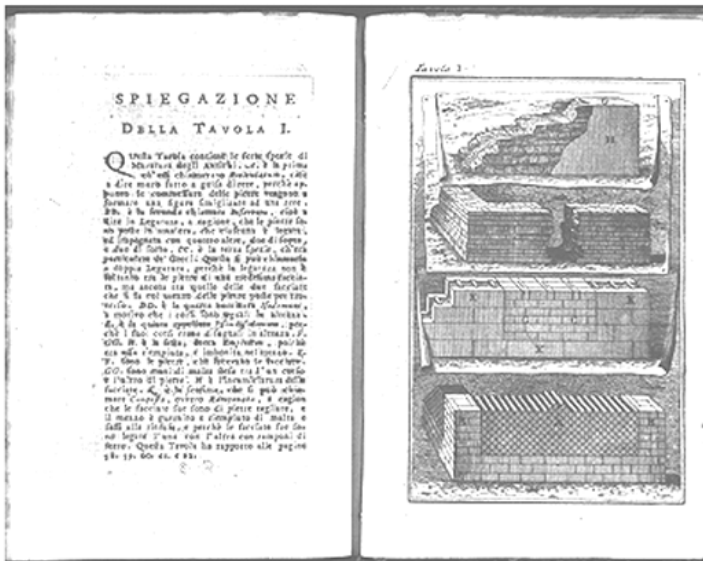


Figure 1. Reproduction from the L. B. Alberti (1570) transcription of *De Architectura*.

Like most ancient texts, Vitruvius’s work came down through medieval transcriptions. Copyists and especially medieval engineers saw these texts as technical manuals and not as immutable manuscripts to be preserved in their original form. As a result, we have been left with a variety of transcriptions and translations and the task of separating Vitruvius’s observations and intent from later commentary and interpolations. Several translations of *The Ten Books of Architecture* are currently in print; the most recent English translation (Rowland and Howe 1999) keeps closely to the Latin text and Vitruvius emerges as an inventive and creative thinker. We have, ourselves, returned to the Latin text of *De Architectura* and freshly translated certain passages to portray more accurately the geological basis of Vitruvius’s empirical observations of stone building materials (table 1). All translations in this paper are our own, unless otherwise stated. They contain no terms derived from Newtonian mechanics, such as force, weight, stress, and strain. The translations reflect, as objectively and faithfully as possible, Vitruvius’s stated purpose, “I shall now explain the nature and use of materials that we have” (*in hoc de naturalibus materiae rebus, quae habeant usum*) (*De Architectura* 2.1.8).

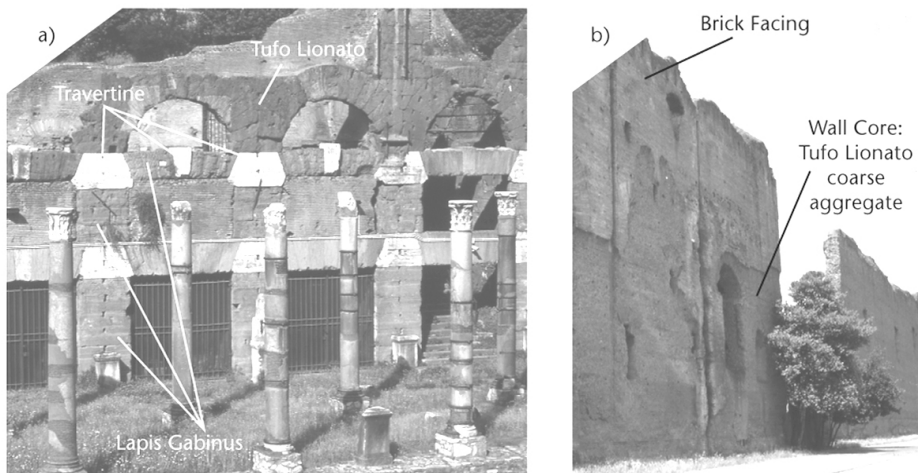


Figure 2. Roman masonry. a) Forum of Caesar (46 BCE): tuff and travertine dimension stone, b) Baths of Caracalla (217 CE): Brick facing a concrete wall core of Tufo Lionato coarse aggregate and mortar with Pozzolane Rosse.

Vitruvius described the transitional Roman architecture of first century BCE, which combined cut stone masonry with concrete construction (fig.2) (*De Architectura*, 2.8.1-10). Through integrative analysis of ancient texts, geological field observations, and rock testing experiments we have documented Roman builders’ discriminating knowledge and understanding of the diverse material properties of their locally quarried tuff and travertine building stones (Jackson et al. 2005). With these analyses and new petrographic and chemical data for Roman pozzolane (Jackson et al. 2005; Jackson et al. 2004; Jackson and Marra in press), we have gained an

unconventional perspective of the varied material characteristics of volcanic rock as understood and utilized by the Romans. Thus, our analyses provide a means to gain new insights into Roman technical expertise for selection and preservation of dimension stone masonry and for enhancing the strength and durability of cementitious materials in concrete work. Focused concentration on Vitruvius's remarks on architectural styles (MacDonald 1982; McEwen 2003; Smith 2003) has led scholars to neglect these important aspects of Roman technology.

Table 1. Translations of Latin texts of *De Architectura* 2.4.1-3 and 2.7.1-5.

DE ARCHITECTURA 2.4.1 to 2.4.3

1. in *caementiciis autem structuris* primum est de harena quaerendum, ut ea sit idonea ad *materiam miscendam* neque habeat terram commixtam. genera autem *harenae fossiciae* sunt haec, nigra, cana, rubra, *carbunculus*. ex his quae in manu confricata fecerit stridore m erit optima, quae autem terrosa fuerit non habebit asperitatem. item si in vestimentum candidum ea coniecta fuerit, postea excussa vel lota id non inquinat neque ibi terra subsiderit, erit idonea.

In *caementiciis autem structuris*, one must first inquire into the sand so that it will be suitable for *materiam miscendam* and not have any earth mixed in it. These are the types of *harenae fossiciae*: black, white, red, and *carbunculus*. Of these, the type that makes a harsh, grating, rasping noise when rubbed vigorously in the hand is best; that which is earthy in texture will not be rough enough. Likewise, if it is wrapped in a white cloth that is afterwards shaken out, then if it neither stains the cloth nor has [fine] earthy particles that settle within it, then it is suitable.

2. sin autem non erunt *harenaria* unde fodiatur, tum de fluminibus aut e glare erit excernenda, non minus etiam de litore marino. sed ea in *structuris* haec habet vitia, difficulter siccescit, neque onerari se continenter paries paritur nisi intermissionibus requiescat, neque concamarationes recipit. marina autem hoc amplius quod etiam parietes, cum in is tectoria facta fuerint, remittentes salsuginem corium dissolvunt.

But if there are no *harenaria* from which it may be dug, then it will have to be sieved either from gravel out of the riverbed or even the seashore. But this [sieved] sand has [the following] defects in construction. It is difficult to dry, the wall cannot be burdened without interruptions for rest, nor does it accept arches (or vaults). But in the case of sea sands, when stuccos will have been applied, these walls will release salty rinds [from which the stuccos] separate.

3. *fossiciae* vero celeriter in *structuris* siccescunt, et tectoria permanent, et concamarationes patiuntur, sed eae quae sunt de harenariis recentes. si enim exemptae diutius iacent, ab sole et luna et pruina concoctae resolvuntur et fiunt terrosae. ita cum in *structuram* coiciuntur, non possunt continere *caementa*, sed ea ruunt et labuntur onera quae parietes non possunt sustinere. recentes autem *fossiciae* cum in *structuris* tantas habeant virtutes, eae in tectorio ideo non sunt utiles quod pinguitudine eius calx palea<sup>1</sup> commixta propter vehementiam non potest sine rimis inarescere. fluviatica vero, propter macritatem inutilis *signino*, liaculorum subactionibus in tectorio recipit soliditatem.

No doubt, *fossiciae* dry quickly in *structuris*, and they will bear permanent stucco coverings and arches, but only those which come from recently excavated sands. For after being taken out if they lay out for a long time exposed to the effects of day and night and frost, they break down and become earthy. Thus when they are thrown in with the *structuram* they cannot bind together the *caementa*. Instead the *caementa* comes loose, and the load of the masonry, which the walls can no longer sustain, collapses. However, although the newly excavated materials have so many virtues in construction they are not, for that reason, useful in plaster or stucco. Because of the mixture's richness when mixed with calx [and] palea<sup>1</sup> [and] because of its violent energy it is not able to dry without cracks. In fact, river sand because of its leanness is useless in *signinum* construction [but] when polished thoroughly it regains its firmness for plaster.

DE ARCHITECTURA 2.7.1 to 2.7.5

1. de calce et harena quibus varietatibus sint et quas habeant virtutes dixi. sequitur ordo de lapidicinis explicare, de quibus et quadrata saxa et caementorum ad aedificia eximuntur copiae et comparantur. haec autem inveniuntur esse disparibus et dissimilibus virtutibus. sunt enim aliae molles, uti sunt circa urbem Rubrae Pallenses Fidenates Albanae, aliae temperatae, uti Tiburtinae Amiterninae Soractinae et quae sunt his generibus, nonnullae durae, uti siliceae. sunt etiam alia genera plura, uti in Campani rubri et nigri tofi, in Umbria et Piceno et in Venetia albus, qui etiam serra dentata uti lignum secatur.

For lime and sand I have stated what their varieties are and what particular qualities they have. Now order demands that I explain about quarries, from which both squared stone and supplies of rough, unhewn stone are obtained and made ready for the buildings. Now these are found to have unequal and dissimilar qualities. Some are soft and yielding, around the city itself, in the manner of the Red stones, the Pale-Yellow stones, the Fidenae stones, and the Albanae stones. Some are of moderate quality like the Tibur stones, the Ameriternae stones, the Soracte stones, and others if this type; others are hard, enduring, and difficult to work, like lavas. There are also many other kinds, such as red and black tuff in Campania, [and] in Umbria, Piceno and in Venetia white, which, indeed, can be cut like wood by means of a serrated or toothed saw.

2. sed haec omnia quae mollia sunt hanc habent utilitatem quod ex is saxa cum sunt exempta in opere faciliter tractantur. et si sunt in locis tectis, sustinent laborem, si autem in apertis et patentibus, gelicidiis et pruina contacta friantur et dissolvuntur. item secundum oram maritimam ab salsugine exesa diffluunt neque perferunt aestus. Tiburtina vero et quae eodem genere sunt omnia sufferunt et ab oneribus et a tempestatibus iniurias, sed ab igni non possunt esse tuta, simulque sunt ab eo tacta dissiliunt et dissipantur, ideo quod temperatura naturali parvo sunt umore itemque non multum habent terreni sed aeris plurimum et ignis. igitur cum et umor et terrenum in his minus inest, tum etiam ignis, tactu et vi vaporis ex is aere fugato, penitus insequens et interueniorum vacuitates occupans ferverescit et efficit ea suis ardentia corporibus similia.

So long as these soft stones are sheltered under plaster they will hold up and do their work but if they are laid bare or exposed in the open air, ice and frost accumulate within them and they crumble apart and dissolve. Also along the sea coast salt eats at them and they dissolve apart; neither do they endure sea tides and spray. True travertine from Tivoli and all stones of the same type withstand heavy loads and harsh weather but from fire they cannot be safeguarded. And similarly, when they touch fire they crack apart and fall to pieces because they have a natural proportion with a little water and not much earth but plenty of air and fire.

3. sunt vero item lapidicinae complures in finibus Tarquiniensium, quae dicuntur Anicianae, colore quemadmodum Albanae, quarum officinae maxime sunt circa lacum Volsiniensem, item praefectura Statonensi. haec autem habent infinitas virtutes. neque enim is gelicidiorum tempestas neque ignis tactus potest nocere, sed sunt firmae et ad vetustatem ideo permanentes quod parum habent e naturae mixtionis aeris et ignis, umoris autem temperate plurimumque terreni. ita spissis comparationibus solidatae neque ab tempestatibus neque ab ignis vehementia nocentur.

There are also several quarries in the territory of Tarquinii called Anician, of about the same color as the Albanian stones, whose workshops are mostly around Lacus Volsiniensis and the prefecture of Statonia. Now these have endless virtues. Neither icy weather nor the touch of fire can damage them; they are strong and last to a very old age [because the four elements are combined in the manner that] they have little air and fire in their natural mixture and much of the earth. Because of their compact and solid texture they are harmed neither by the weather nor by strong, violent fires.

4. id autem maxime iudicare licet e monumentis quae sunt circa municipium Ferenti ex his facta lapidicinis. namque habent et status amplas factas egregie et minora sigilla floresque et acanthos eleganter scalptos. quae cum sint vetusta, sic apparent recentia uti si sint modo facta. non minus etiam fabri aerarii de his lapidicinis in aeris flatura formis comparatis habent ex is ad aes fundendum maximas utilitates. quae si prope urbem essent, dignum esset ut ex his officinis omnia opera perficerentur.

This can be judged especially from the monuments of Ferentum, which are made of stone from these quarries. There are large statues outstandingly crafted, and smaller statues, and flowers and acanthus plants elegantly carved, which though they are old look newly finished. Moreover, bronze workers make molds for the casting of bronze out of stone from these quarries and find it very useful in bronze casting.<sup>2</sup> If these quarries [and/or] workshops were nearer the city it would be fitting that all work be performed out of these workshops.

5. cum ergo propter propinquitatem necessitas cogat ex Rubris lapidicinis et Pallensibus et quae sunt urbi proximae copiosius uti, si qui voluerit sine vitis perficere, ita erit praeparandum. cum aedificandum fuerit, ante biennium ea saxa non hieme sed aestate eximantur, et iacentia permaneat in locis patentibus. quae autem eo biennio a tempestatibus tacta laesa fuerint, ea in fundamenta coiciantur. cetera quae non erunt vitata, ab natura rerum probata durare poterunt supra terram aedificata. nec solum ea in quadratis lapidibus sunt observanda sed etiam in *caementiciis structuris*.

So, therefore, because of the proximity of their quarries necessity compels the use of the Red stones and the Pale-Yellow stones and those resources that are near to the city. If one wishes to complete his work without [serious] defects he will thus want to be prepared in this way. When it is time to build, the stones should be extracted two years before, not in winter but in summer, then toss them down and leave them in an open place. Whichever of these stones, in two years, is affected or damaged by weather should be thrown in with the foundations. The other ones that are not damaged by means of the trials of nature will be able to endure building above ground. Not only should these precautions be observed for squared stone but also for *caementiciis structuris*.

<sup>1</sup> "palea" is absent from Perseus text.

<sup>2</sup> Following M.H. Morgan translation, 1960, Dover Publications, New York.

## ROMAN VOLCANIC BUILDING STONE

Tuff dimension stone masonry was primary stone construction material of the republican age monuments (509 BCE – 27 BCE) of ancient Rome. The Roman tuffs were erupted from nearby Monti Sabatini and Alban Hills volcanoes (fig.3) between 560 – 37 ka as pyroclastic flows (*pyro*=fire and *clastic*=broken in pieces) composed of hot gases, molten rock (or magma), crystals, and fragments of surrounding host rock and fragments. This material commonly flowed

across the ground surface for many kilometres away from eruption sites; pyroclastic flow deposits form much of the landscape of the Roman region (fig.3). The lithified tuffs of Rome and its surroundings formed over many thousands of years as pyroclastic material consolidated and developed mineral cements.

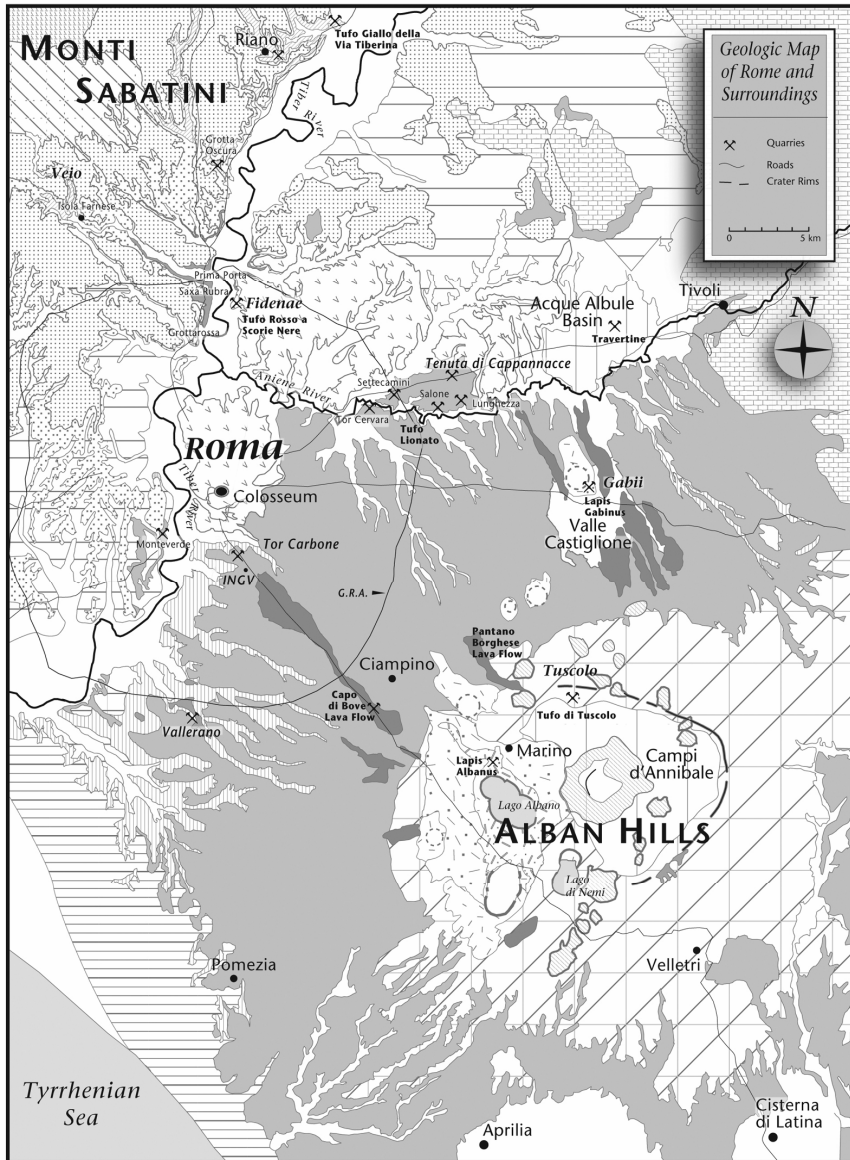


Figure 3a. Geological map of Rome and its surroundings (after Jackson et al. 2005). Based on data from Karner et al., 2001; De Rita et al. 1988, 1993.

## Geologic Map of Rome - Stratigraphic Section

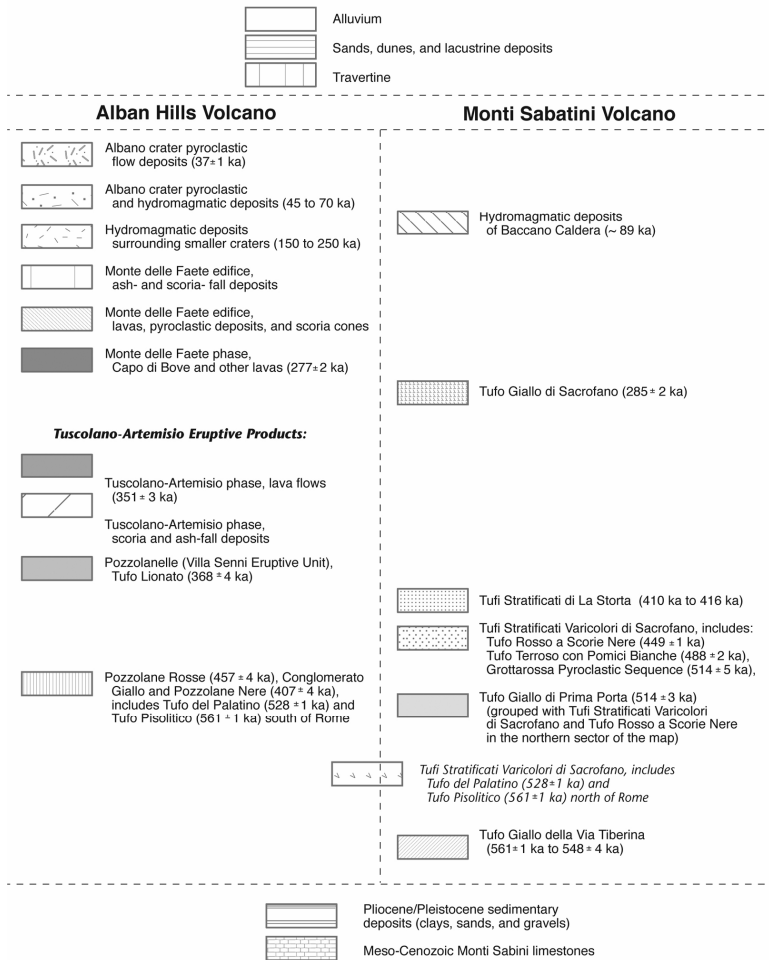


Figure 3b. Chrono-stratigraphic section of Rome and its surroundings (after Jackson et al. 2005).

Based on data from Karner et al., 2001; De Rita et al. 1988, 1993.

Early stone construction in Rome, dating to sixth and fifth centuries BCE, consists of soft volcanic tuff quarried within the city. As Romans expanded their influence over nearby lands (fig.3), they quarried more durable varieties of tuff from Monti Sabatini volcano and, later, from Alban Hills deposits (DeLaine 1995). During the late republican age Romans utilized seven different tuffs and travertine, a hard sedimentary rock formed of calcite that was quarried near Tivoli (Faccenna et al. 1994; Chafetz and Folk 1984), to create a transitional architecture of dimension stone masonry integrated with concrete construction, as exemplified by the Forum of Caesar, 46 BCE (fig.2a) (Jackson et al. 2005). They utilized lavas as paving stone and as coarse

aggregate in concrete masonry. During the early imperial age (27 BCE – 476 CE) Romans formulated more durable hydraulic, pozzolanic mortars and created a complex, concrete architecture of vaults and enormous interior spaces (MacDonald 1982; Lechtman and Hobbs 1987). Robust concretes eventually supplanted soft, cut stone tuff masonry, as at the Baths of Caracalla (217 CE) (DeLaine 1997) (fig.2b).

Within the Roman region, there are numerous accumulations of hard travertine and soft tufa deposited by calcium carbonate-rich thermal springs (fig.3). These sedimentary rocks are readily distinguishable from volcanic tuffs. Archaeological publications in English, however, refer incorrectly to the Roman volcanic tuff building stones as *tufa*. Archaeological publications in Italian employ the correct geological term, *tuffo*, for the tuff building stones.

### **MATERIAL CHARACTERISTICS OF ROMAN CUT STONE MASONRY: *DE ARCHITECTURA* 2.7.1 TO 2.7.5**

In Book Two of *De Architectura*, Vitruvius relates the processes through which Romans gained progressively greater expertise in using the diverse materials of their surroundings for building construction (*De Architectura* 2.1.1–9). He begins,

cum essent autem homines imitabili docilique natura, cotidie inventionibus gloriantes alius alii ostendebant aedificiorum effectus, et ita exercentes ingenia certationibus in dies melioribus iudiciis efficiebantur.

(*De Architectura* 2.1.3)

“Since people are by nature imitative and teachable, daily [or regularly] they would show each other the effect of their buildings and their glorious inventions and so, they brought about better effects by means of their natural qualities”.

He explains, expansively:

posteaquam animadverterunt profusos esse partus naturae et abundantem materiae copiam ad aedificationes ab ea comparatam, tractando nutrierunt et auctam per artes ornaverunt voluptatibus elegantiam vitae. igitur de his rebus, quae sunt in aedificiis ad usum idoneae, quibusque sunt qualitibus et quas habeant virtutes, ut potuero, dicam.

(*De Architectura* 2.1.7)

“After that, they understood rich material for building to be a lavish and abundant part of nature from which they drew; they nourished and increased [it] through skill, [and] they equipped life with a delightful elegance. Therefore, I will discuss, as far as I am able, the things which are of best use in building and which are the [highest] quality and which have excellence”.

Vitruvius then describes the varied material characteristics of local rock – tuffs, travertine, and lavas – quarried within the Roman region during late first century BCE (table 1), as follows:

Now order demands that I explain about quarries, from which both squared blocks and the supplies of rough unhewn stone for building are obtained and readied. These, in turn, will be found to have unequal and dissimilar qualities. Some are soft and yielding around the City itself, in the manners of the *Rubrae* stones, the *Pallenses* stones, the *Fidenates* stones, and the *Albanae* stones. Some are of moderate strength, like the *Tibur* stones, the *Amiternae* stones, and the *Soracte* stones, and others of this type. Some are hard, enduring, and difficult to work, like lavas.

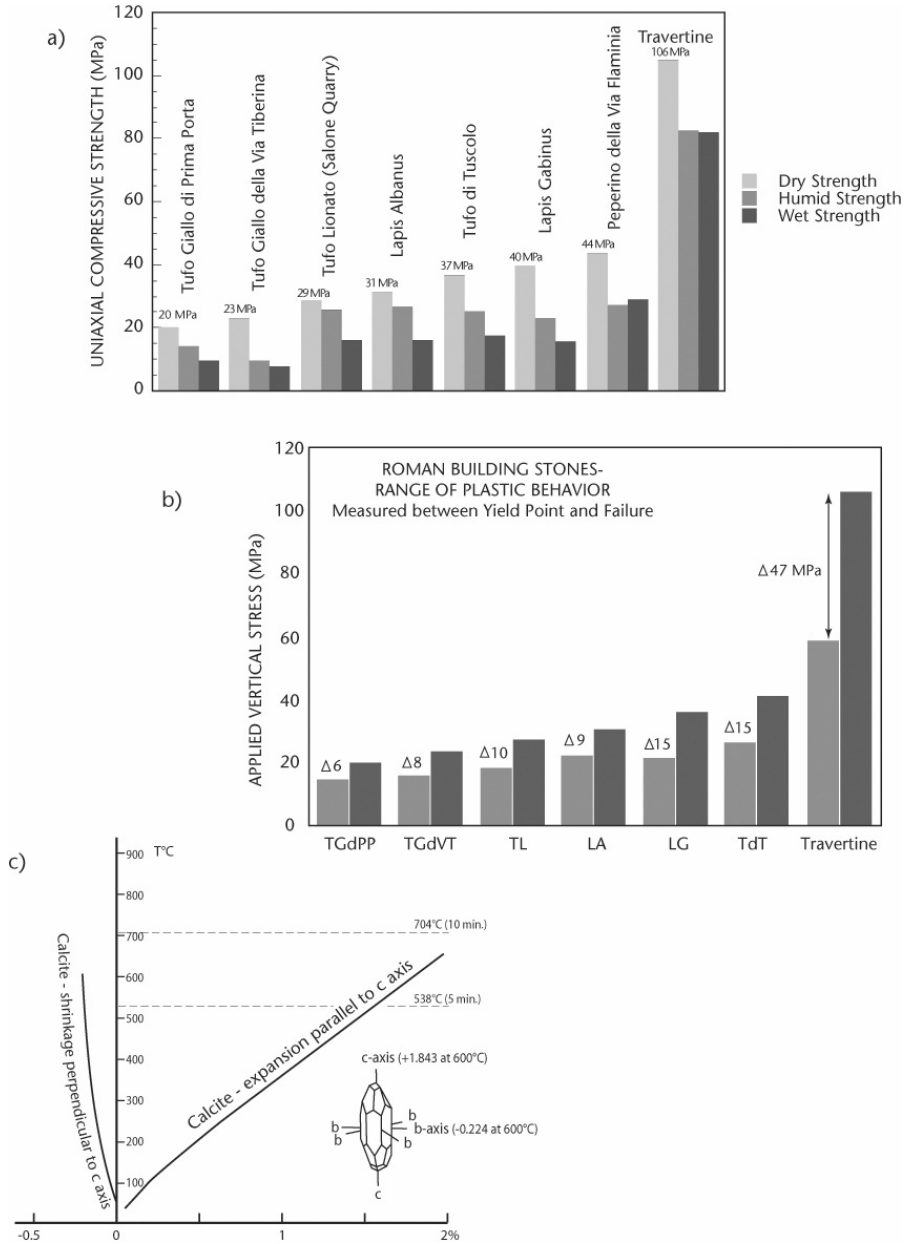
(*De Architectura* 2.7.1)

Stones that are “soft and yielding” (*molles*) are tuffs quarried from Monti Sabatini and Alban Hills volcanoes: the *Fidenates* stones refer to Tufo Rosso a Scorie Nere quarried near Fidenae (fig.2) and the *Albanae* stones refer to Lapis Albanus, quarried from the Albano Crater pyroclastic deposit (fig.2). Our geological field work and examination of the Latin texts of Strabo (*Geographica* 5.3.11), Cicero (*Phillippicae Orationes* 2.7), Livy (*Ab urbe condita* 2.49), and Tacitus (*Historiae* 3.79) demonstrate that the *Rubrae lapidicinus* of Vitruvius refers to red colored Tufo Lionato quarried along the Aniene River and that *Pallenses* refers to pale yellow Tufo Giallo della Via Tiberina quarried near Grotta Oscura and northwards along Via Tiberina (Jackson and Marra in press) (fig.2). Although “*molles*” has usually been translated in this passage as “soft” (Rowland and Howe 1999; Morgan 1960; Granger 1931), it may also mean pliant, flexible, and yielding. It is possible that “yielding” may represent Vitruvius’s empirical perception of the propensity of these rocks to rupture under heavy loads. Rock testing experiments and stress/strain relationships (Jackson et al. 2005) demonstrate that the Roman tuffs have low yield strengths (the force required to produce inelastic strains leading to rupture), which are generally less than 18 MPa for porous Tufo Giallo della Via Tiberina (Fig. 5a) and Tufo Lionato (figs.4a, b).

Stones that are “moderate” (*temperate*) in quality are the travertine deposits of Tivoli and the limestone bedrock of the Appennine Mountains quarried near Amiternum, 140 kilometers northeast of Rome, and Monte Soratte, 40 kilometers northeast of Rome. These are sedimentary rocks formed of calcite, or crystalline calcium carbonate, which have moderate compressive strengths, usually between 50 MPa and 100 MPa (Goodman 1989, p. 61).

Rocks that are “hard” (*durae*) are, most likely, lavas. The term “*siliceae*” may refer, generally, to any hard stone. Here, we suggest that Vitruvius describes lavas from flows that crop out near Rome (Jackson and Marra in press). “*Siliceae*” has the additional meanings of strong, enduring, and difficult to work. Lavas have the highest compressive strengths (in the range of 150 MPa to 350 MPa for basalts (Goodman 1989, p. 61)) of all rocks of the Roman region.





Vitruvius's remark that refers to "*profusos*" (lavish, rich) and "*abundatem*" (abundant) material drawn from nature for building (*De Architectura* 2.1.7) comes alive when one examines the diverse physical properties of tuffs and travertine selected by Roman builders in the structural design of the *tabernae* of the Forum of Caesar, 46 BCE (figs.2a; 4a, b). An upper facade of vitric-lithic Tufo Lionato with low bulk specific gravity (G) and uniaxial compressive strength ( $q_u$ ) ( $G = 1.73$ ;  $q_{u \text{ dry}} = 29 \text{ MPa}$ ) is supported by robust, lithic-crystal Lapis Gabinus ( $G = 1.81$ ;  $q_{u \text{ dry}} = 29 \text{ MPa}$ ) pillars and flat arches, which are reinforced with travertine ( $G = 2.58$ ,  $q_{u \text{ dry}} = 105 \text{ MPa}$ ) keystone voussoirs (Jackson et al. 2005). On either side of the *tabernae*, the concrete walls of barrel vaults have porous, lightweight Tufo Giallo della Via Tiberina ( $G = 1.44$ ) coarse aggregate (fig.5a). The concrete vaults themselves contain dark-red pumice coarse aggregate (Amici 1991) imported from Mount Vesuvius (Lancaster 2005, pp. 59-64); the pumice has a low density ( $\rho = 0.75\text{-}0.85 \text{ g/cm}^3$ ) (Lancaster in press) that is about half that of the Tufo Giallo della Tiberina coarse aggregate ( $\rho = 1.43\text{-}1.91 \text{ g/cm}^3$ ) of the supporting walls. Clearly, Roman builders had an astute empirical understanding of the material characteristics of density, specific gravity, and compressive strength as regards the volcanic rock of their surrounding landscape.

### **Durability of the Roman Tuffs**

Although Vitruvius describes the Roman tuffs as "*molles*" (soft and yielding), he states (table 1), "So long as these soft stones are sheltered under plaster they will hold up and do their work but if they are laid bare or exposed in the open air, ice and frost accumulate within them and they crumble apart and dissolve" (*De Architectura* 2.7.2). In Rome, tuff masonry was seldom left exposed. Columns throughout Rome, such as the fluted Lapis Albanus semi-columns exposed at the Temple of Janus at San Omobono, mid-third century BCE (Steinby 1996, *LTUR* III, pp. 90-1), and the fluted Tufo Lionato columns at Temple B of Largo Argentina Sacred Area, 101 BCE (Steinby 1995, *LTUR* II, p. 269), retain layers of "*tectoria*" (plaster or stucco), permeable to both rainwater and water vapor, that protected the porous tuff (fig.1, uppermost diagram). Vitruvius gives specific instructions for mixing, applying, and polishing stucco and improving its protective qualities (*De Architectura* 2.5.1; 7.3.3-11, 7.4.1-3, 2.3.2). Durable, decorative travertine and marble cladding also shielded tuff walls (Torracca 1988, pp. 111-4), as at Temple of Portunus, 80 to 70 BCE (Richardson 1992, p. 320; Steinby 1999, *LTUR* IV, p. 153; Jackson et al. 2005).

### **Thermal Linear Expansion of Travertine**

In his concise statement regarding the strength and durability of travertine building stone and its propensity to crack and split apart when exposed to urban fires, Vitruvius makes the following observations (table 1):

True travertine from Tivoli and all stones of the same type withstand heavy loads and harsh weather but from fire they cannot be safeguarded. And similarly, when they touch fire they crack apart and fall to pieces...

(*De Architectura* 2.7.2)

Results from rock testing experiments (fig.4a) demonstrate that travertine has far greater compressive strength, in the range of 105 MPa, than any of the Roman tuffs (Jackson et al. 2005). Stress/strain relationships indicate that it has a greater range of elastic behavior than the tuffs; yield strengths are in the range of 60 MPa (fig.4b), confirming Vitruvius's statement that compared to the tuffs, travertine has the capacity to withstand heavy loads. In addition, absorption of water and adsorption of water vapor are low, in the range of <1 weight percent, so that under rain- or water-soaked conditions or periods of high relative humidity, travertine retains about 80% of its compressive strength (fig.4a). Vitruvius's observation that "travertine and all stones of the same type ... crack apart and fall to pieces" (*dissiliunt et dissipantur*) when exposed to fire is based on the fact that all stone formed of calcite – travertine, limestone, and marble – undergoes an anisotropic volume change at elevated temperatures (fig.4c). When heated, calcite expands 0.189% along the long c-axis and but shrinks 0.042% perpendicular to it, along the short or b-axes of the crystal (Rayleigh 1925; Logan 1993; Winkler 1994, pp. 241-247). This uneven change in the shape of individual crystals strains the grain mosaic of the stone so that the spontaneous, intense heat of urban fires, at 600°C for example, may generate a percentage volume change of 1.843% along calcite c-axes and -0.224 perpendicular to them (Winkler 1994, table 10.2). Grain contacts eventually rupture and the stone fractures.

The porous, pyroclastic texture of the Roman tuffs accommodates thermal expansion far more readily than travertine or marble; certain marbles experience a linear expansion of about 2% when heated to 900 °K (627 °C), while tuffs expand only about 0.25% (Touloukian et al. 1981). Indeed, the 30 metre tall boundary wall designed to protect the Forum of Augustus (Steinby 1995, *LTUR* II, p. 289-295) from fires on the Quirinal Hill is constructed of robust Lapis Gabinus tuff, with only two single courses of stabilizing travertine (Jackson and Marra in press). Although the Forum was dedicated in 2 CE, construction began twenty years earlier, soon after Vitruvius completed *De Architectura*. When designing the firewall, Roman builders may have heeded Vitruvius's cautionary remarks over travertine's lack of resistance to fire. Furthermore, Tacitus states that in the reconstruction of Rome after the fire of 64 CE, "a certain part of the buildings themselves were to be solidly constructed without wood [beams], [and] of stone from Gabii or Alba because that stone is impervious to fire" (*aedificiaque ipsa certa sui parte sine trabibus saxo Gabino Albanove solidarentur, quod is lapis ignibus impervius est*) (*Annals* 15.43). Lithic-crystal tuffs from *Gabii* and *Alba*, Lapis Gabinus and Lapis Albanus, are stronger and more durable than glassy, porous Tufo Giallo della Via Tiberina and Tufo Lionato (fig.4a), which were used rarely in dimension stone masonry after first century BCE.

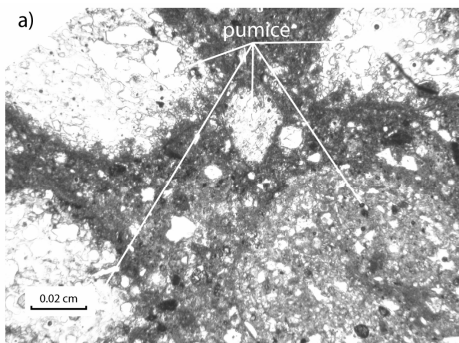
### **Volcanic Building Stone from Lago Bolsena**

Vitruvius departs from his somewhat dispassionate descriptions of the material characteristics of the native tuff and travertine building stones of Rome to extol the "*infinitas virtutes*" (endless virtues) of a building stone quarried near the volcanic crater of Lago Bolsena 80 kilometres northwest of Rome and the modern city of Viterbo (table 1):

There are also several quarries in the territory of Tarquinii called Anician, of about the same color as the Albanae stones, whose workshops are mostly around Lacus Volsiniensis and the prefecture of Statonia. Now these have endless virtues. Neither icy weather nor the touch of fire can damage them; they are strong and last to a very old age... Because of their compact and solid texture they are harmed neither by the weather nor by strong, violent fires.

(*De Architectura* 2.7.3)

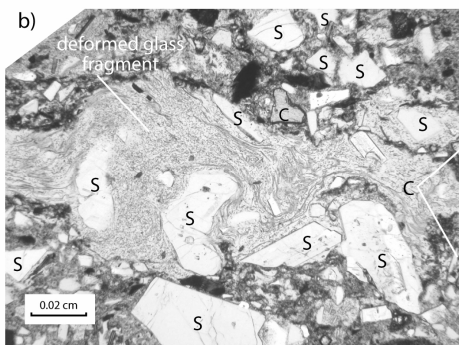
Petrographic examination of this volcanic rock, "*lapidicinae Anicianae*", which is commonly called Peperino di Viterbo by modern Italians, reveals that it is a welded tuff formed of lenticular-shaped glass fragments that were hot and soft enough to change shape and deform with transport across the ground surface (fig.5b). The glass fragments incorporated fine ash during flow; the masses of glass eventually fused and hardened, producing a texture that Vitruvius describes as "*spissis comparationibus solidatae*" (solid and compact). This building stone is, indeed, far less porous than the soft, pumice-bearing Roman tuffs, such as Tufo Giallo della Via Tiberina (Fig. 5a), which are weakly durable lithified tuffs bound by zeolite (and calcite) mineral cements.



Tufo Giallo della Via Tiberina  
*Pallensibus lapidicinis*

Abundant pumice fragments give this tuff a porous texture that Vitruvius describes as "soft and yielding" (*molles*) and cause it to readily "crumble apart and dissolve" (*friantur et dissolvuntur*).

(*De Architectura* 2.7.1, 2)



Peperino di Viterbo  
*lapidicinae Anicianae*

Abundant sanidine (S) and clinopyroxene (C) crystals and once malleable glass fragments give this complex lava a texture that Vitruvius describes as "compact and solid" (*spissis comparationibus solidatae*).

(*De Architectura* 2.7.3)

Figure 5. Photomicrographs of Roman volcanic building stone (*quadrata saxa*) (*De Architectura* 2.7.1-2).

### **Quarrying of Soft Tuff Building Stone near Rome**

Vitruvius returns, pragmatically, to instructions for handling soft “*Rubris lapidicinis*” (Tufo Lionato) and “*Pallensibus*” (Tufo Giallo della Via Tiberina) quarried near Rome to improve their durability for dimension stone and concrete masonry (table 1):

So, therefore, because of the proximity of their quarries necessity compels the use of the Red stones and the Pale-Yellow stones and those resources that are near to the city. If one wishes to complete his work without [serious] defects he will thus want to be prepared in this way. When it is time to build, the stones should be extracted two years before, not in winter but in summer, then toss them down and leave them in an open place. Whichever of these stones, in two years, is affected or damaged by weather should be thrown in with the foundations. The other ones that are not damaged by means of the trials of nature will be able to endure building above ground. Not only should these precautions be observed for squared stone but also for *caementiciis structuris*.

(*De Architectura* 2.7.5)

Modern quarries for Tufo Giallo della Via Tiberina (*Pallensibus lapidicinis*) and for Tufo Lionato (*Rubris lapidicinis*) commonly extract water-saturated stone from below the ground water table (G. Lombardi pers. comm. 2002). These porous tuffs absorb 15 to 23% of their weight in water; when water saturated they retain only about 35 to 55% of their compressive strength and, therefore, have little durability (figs.4a; 5a). Vitruvius recommends they be extracted in the dry summer season when rainfall is low, about 1 to 4 cm per month (Pearce and Smith 1990), and left in the open air for two years so that their absorbed moisture would evaporate. Those blocks that remained intact at the end of the culling process might still retain about 5 weight percent moisture from adsorbed humidity (fig.4a), but they would have regained a large percentage of their dry compressive strength.

### **MATERIAL CHARACTERISTICS OF ROMAN VOLCANIC SANDS:**

#### ***DE ARCHITECTURA* 2.4.1 TO 2.4.3**

During second and first century BCE, Romans developed concretes that utilized granular volcanic ash, or pozzolane, as fine aggregate in pozzolan-lime mortar and chunks of tuff as coarse aggregate. Three pozzolane deposits, Pozzolane Rosse, Pozzolane Nere, and Pozzolanelle, crop out through the Alban Hills volcanic district (fig.3). Vitruvius specifies that the best excavated sand (*harena fossiciae*) for concrete work should make a hissing, rasping sound (*stridorem*) and retain a harsh, grating, roughness (*asperitatem*) when rubbed forcefully between the hands (table 1):

Of these, the type that makes a harsh, grating, rasping noise when rubbed vigorously in the hand is best; that which is earthy in texture will not be rough enough. Likewise, if

it is wrapped in a white cloth that is afterwards shaken out, then if it neither stains the cloth nor has [fine] earthy particles that settle within it, then it is suitable.

(*De Architectura* 2.4.1)

Vitruvius cautions that excavated sand that has earthy (*terrosa*) texture or has softened or disintegrated (*concoctae resolvuntur*) through daily exposure to weather and frost is unsuitable for mortar (*De Architectura* 2.4.1-3). We observe that when rubbed between the hands, Pozzolanelle crumbles into a fine, soil-like powder that adheres to the fingers. Pozzolane Rosse, on the other hand, makes a crackling sound and retains a largely pellet-like structure formed of altered microscoria and opal and/or clay cemented ash aggregations (fig.6a, b); these characteristics correlate with Vitruvius’s recommendations for pozzolane that is best (*optima*) for mortar (*materiem miscendam*). Vitruvius describes the Roman pozzolane as sand-sized, excavated materials or *harena fossiciae* (*De Architectura* 2.4.1-3). Our initial measurements of particle size distributions (we measured the long and short axes of 500 grains per thin-section and computed a corrected sieved-size distribution through the method determined by Friedman (1957)) (fig.7), substantiate Vitruvius’s observations and demonstrate that sand-sized grains, mainly vesicular microscoria, form about 70-75% of natural Pozzolane Rosse and the fine aggregate of Roman mortar samples from the Basilica Argentaria (113 CE) and the Baths of Caracalla (217 CE), and the Pozzolanelle fine aggregate from a segment of the Aurelian city wall (third century CE).

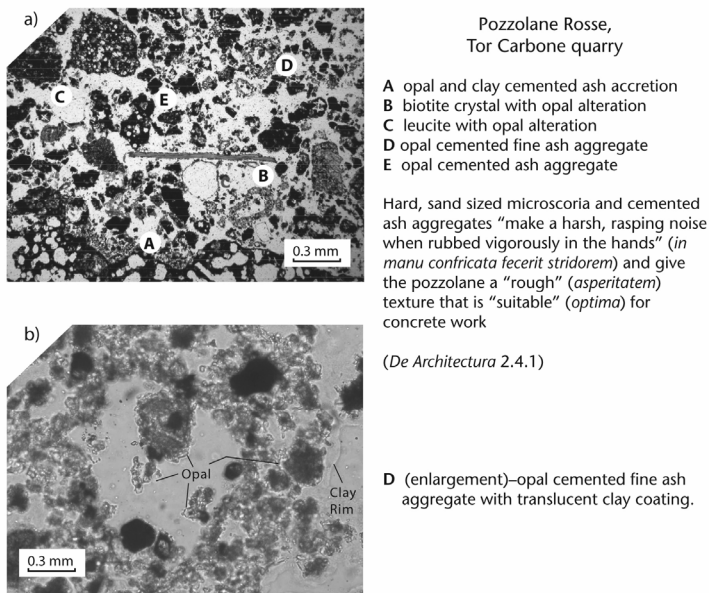


Figure 6. Photomicrographs of Roman granular volcanic ash (*harena fossiciae*) (*De Architectura* 2.4.1; 2.4.3).

Field observations, petrographic studies, and X-ray diffraction analyses demonstrate that the glassy components of granular ash particles of Roman pozzolane have been diagenetically altered, chiefly to non-dispersive, siliceous clay (Jackson et al. 2004). Within Pozzolane Rosse, clay, opal (amorphous silica), and opal/clay mixtures coat volcanic clasts, fill vesicles, and replace zeolites (fig.6a, b). The principal clay mineral is halloysite (Fornaseri et al. 1963). Clay mineral and opal within the Roman pozzolane apparently reacted with lime and water (portlandite) to form enduring cementitious phases within ancient mortars. It should be noted here that the only materials that Vitruvius recommended be sieved were gravels from the riverbed or seashore (*De Architectura* 2.4.2-3). The sand of these sedimentary deposits is composed chiefly of quartz crystals that have little or no reactivity with lime.

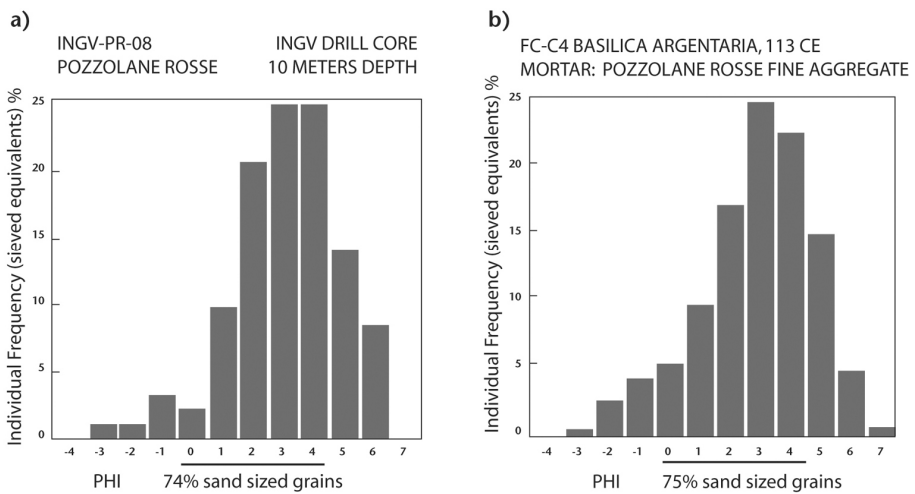


Figure 7. Histograms showing sand-sized particle size distribution of natural Pozzolane Rosse and pozzolana within Roman mortar. a) INGV-PR-8; b) Basilica Argentaria (113 CE).

## DISCUSSION

Our linguistic analyses suggest that Roman builders developed a precise vocabulary to describe the diverse characteristics of geological building materials. For example, Romans apparently developed a keen awareness for the potential decay of soft tuff building stones over centuries of experience. Vitruvius employs the terms “*friantur*” (*frio, friare, v.*, to break up small, to crumble, to pulverize, to fall into fragments), “*dissolvuntur*” (*dissoluo, dissolvere, v.*, to break up into component parts; to disintegrate; to undo, dismantle, take to pieces), and “*diffluunt*” (*diffluo, diffluere, v.*, to flow away in all directions; to waste or wear away, to melt away, disappear) (*De Architectura* 2.7.2) to describe the processes through which soft, weakly cemented Roman tuff building stone disaggregated and eroded into its constituent glass, crystal, and rock fragments.

In re-reading *De Architectura* in light of the geological evidence presented above we find numerous inaccuracies in English translations and interpretations of Vitruvius's empirical observations of the characteristics of stone building materials. For example, the translation by F. Granger (1931) of Vitruvius's description of the texture of Roman excavated sand (*harena fossiciae*), "*ex his quae in manu confricata fecerit stridorem erit optima, quae autem terrosa fuerit non habebit asperitatem*", states, "that which makes a noise when rubbed in the hand will be best; but that which is earthy will not have a like roughness" (*De Architectura* 2.4.1). In the Lewis and Short dictionary one can find *stridorem* as "*strīdor, ōris, m. [strideo], I. any harsh, shrill, hissing, grating, or creaking sound; a creaking, hissing, rattling, buzzing, whizzing, whistling, etc. (class.; esp. freq. in the poets)*" and *confricata* as "*con-frīco, āvi, ātum, I, I. v. a., to rub vigorously, to rub in*". Granger has flattened the meanings of both "*stridorem*" and "*confricata*". On the other hand, the translation by M. H. Morgan (1914), "Of these the best will be found to be that which crackles when rubbed in the hand, while *that which has much dirt in it* will not be sharp enough" portrays the rasping sense of "*stridorem*". Nevertheless, it muddles Vitruvius's description with an interpretative reference to an abundance of "dirt" (*terrosa*), which is misleading from a geological point view and does not represent Vitruvius's concept of earthy texture (*De Architectura* 2.4.3). I. D. Rowland and T. N. Howe (1999) have compiled a cogent and comprehensive English edition of *De Architectura*. Their translation, "Of these the type that crackles *when a few grains* are rubbed together in the hand will be the best for earthy sand will not be rough enough", however, introduces new text in its valiant effort to penetrate Vitruvius's description. Insufficient geological background and interdisciplinary expertise has caused these various translators to misconstrue Vitruvius's actual observation. As previously stated, our petrographic and geochemical analyses indicate that hard, sand-sized, altered microscoria and cemented ash aggregates of Pozzolane Rosse (figs.2, 6), which crackle when abraded, resist crushing, and generally maintain a coarse and rugged texture after handling, produce a "harsh, grating, rasping noise when rubbed vigorously in the hand". Significantly, our field and petrographic observations of Roman mortars suggest that Pozzolane Rosse was the most common fine aggregate utilized within concretes from late first century BCE through the imperial age (Jackson and Marra, in press).

We are presently engaged in chemical and granulometric analyses of Roman pozzolane to identify their microstructures, fine-scale chemical variations, and sequence of alteration reactions. These data coupled with further analyses of *De Architectura* and the compilation of a glossary of construction terms utilized by Vitruvius, with its basis in geological and materials science and new geochemical analyses, will provide a scientific foundation for further refining our understanding of Vitruvius's empirical observations.

## CONCLUSIONS

Geological field observations, rock testing experiments, and petrographic analyses demonstrate that the Roman architect, Vitruvius, possessed a remarkably acute sense of empirical observation and a



well-versed, practical understanding of stone building materials. Measurements of uniaxial compressive strength under oven-dry, water-soaked, and humid conditions (fig.4a) validate the accuracy of Vitruvius's remarks regarding the strengths and relative durability of the Roman tuff, travertine, and lava building stones (*De Architectura* 2.7.1-2). They confirm the importance of his instructions for allowing porous tuffs with high water sorption, Tufo Lionato (*Rubris lapidicinis*) and Tufo Giallo della Via Tiberina (*Pallensibus*) (figs.4a; 5a), to dry for two years after quarrying (*De Architectura* 2.7.5). Measurements of yield strength, or range of inelastic behavior (fig.4b), support Vitruvius's description of various Roman tuffs as "soft and yielding" (*molles*) (*De Architectura* 2.7.1). Experimental data measuring the thermal anisotropic expansion of calcite (fig.4c) give a scientific explanation for Vitruvius's description of the fracture of travertine (*Tiburtina*) at urban fire temperatures (*De Architectura* 2.7.2). Petrographic examination of Peperino di Viterbo (*lapidicinae Anicianae*), a complex, crystal-rich welded tuff from Lago Bolsena (fig.5b), reveal its "compact and solid texture" (*spissis comparationibus solidatae*) and "endless virtues" (*infinitas virtutes*) as strong and durable building stone (*De Architectura* 2.7.3-4). Petrographic examination and granulometric analyses of Roman pozzolane substantiate Vitruvius's observation that the excavated, granular volcanic ash (*harena fossiciae*) of Roman mortar is composed predominantly of sand-sized grains, mainly altered, vesicular microscoria and cemented ash aggregates. In *De Architectura*, Vitruvius recorded an exceptionally inventive period in the development of Roman construction when, after centuries of experimentation, Roman builders acquired the technical expertise to use volcanic rock to its best advantage in creating a innovative architecture of cut stone and concrete masonry. Based on the geological data presented within this paper we can state without hesitation that Vitruvius's empirical observations of Roman stone building materials and his instructions for creating a sustainable architecture of cut stone and concrete construction are fully substantiated by careful scientific observation and analysis.

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