Roman Stone Masonry: Volcanic Foundations of the Ancient City

MARIE JACKSON AND FABRIZIO MARRA

Abstract

This article provides a geological framework for the study of the cut-stone and concrete masonry of ancient Rome that yields important new insights into the many uses of native volcanic rock—tuffs, pozzolane, and lavas—in the development of Roman architecture. Geological maps and field observations of building stones in existing monuments, along with experimental and petrographic measurements of the physical and material characteristics of the Roman tuffs and travertine, offer a scientific basis for the examination of descriptions of Roman stone construction by Vitruvius. The appendix gives a full geological description of each stone and a gazetteer of extant Roman buildings using that stone. These data form a thorough and precise foundation for tracing the provenance of various volcanic rocks and for appreciating the Romans' empirical understanding of their diverse and distinctive characteristics. Our geological reassessment corrects misconceptions in previous archaeological scholarship that depend on a faulty nomenclature for Roman stone building materials based, in part, on mistranslations of the original Latin terms used by Vitruvius. The updated geological maps included here will make possible accurate studies of the transport of stone from quarries and the economy of urban construction, with a view to documenting the human capacity to transform the landscape of Rome and its surroundings both geomorphologically and architecturally over many centuries. A better understanding of the geological characteristics of Roman stone masonry can guide us in the archaeological preservation of the ancient monuments.*

INTRODUCTION

A great variety of volcanic deposits underlies the city of Rome. Indeed, the Roman landscape is formed largely of rock erupted from nearby Monti Sabatini and Alban Hills volcanoes (fig. 1). Local volcanic rock was the primary stone building material of ancient Rome from its initial settlement through the Early Imperial age. This article provides a geological framework for understanding the provenance and material characteristics of these volcanic building stones. It offers new observations about Roman construction and the expertise of the Roman builders in the design and preservation of their stone monuments.

During the 1900s, many archaeologists described the native stone building materials of ancient Roman construction.[1] Scientific studies during the past decade have redefined the setting of Rome in geologic terms and established a modern nomenclature for Roman volcanic building stones (table 1).[2] As a result, many aspects of the long-accepted, comprehensive reviews of Roman building stone by Frank, Blake, and Lugli are now largely outdated. Although these scholars provided a valuable record of use of the various tuffs in Republican and Imperial age stone masonry, several of their geologic characterizations give a scientifically questionable picture of the role of volcanic rock in Roman construction. The traditional archaeological terminology for many of the Roman volcanic building stones is at odds with modern geologic nomenclature; therefore, it is time to reassess the actual provenance of some of the tuffs.[3] For instance, archaeological nomenclature for the tuffs, which uses terms such as "cappellaccio," "Grotta Oscura," "tufo litoide," "sperone," or "peperino," is either ambiguous and includes several different varieties of tuff or is not substantiated by strati-

*We thank the Soprintendenza Archeologica di Roma and the Sovraintendenza ai Beni Culturali del Comune di Roma for allowing us access to many Roman monuments over the years. In particular, we especially acknowledge Stefano Antonelli, Cinzia Conti, Irene Iacopi, Roberto Meneghini, Rossella Rea, Ida Sciortino, and Elisabetta Segala for their collaboration and assistance during field visits. We extend special thanks to the late Richard Hay and Cynthia Kosso for contributing their geological and archaeological expertise to this article. Leonardo Lombardi, Gianni Lombardi, and Erhard Winkler shared with us their various perspectives of Roman building stone. John Murray, Thomas Hoisch, and Bronze Black provided valuable field and technical support. Reviews by Lynne Lancaster, Thaïs Morgan, Carla Maria Amici, and three anonymous readers substantially improved the article. Nancy DeConciliis offered the original inspiration for this research.

[1] For archaeological perspectives of the volcanic building materials of Rome, see Frank 1924; Blake 1947; Lugli 1957; Corsi 1991; Coarelli 1997, 366–67; Claridge 1998, 37–8.

[2] Funiciello (1995) provides a modern context for understanding the geology of the city. Karner et al. (2001b) establish a comprehensive volcanic chronostratigraphy for the Roman volcanic districts.

[3] E.g., Frank 1924, 11–17; Blake 1947, 21–3; Lugli 1957, 194–333.

American Journal of Archaeology 110 (2006) ■■–■■

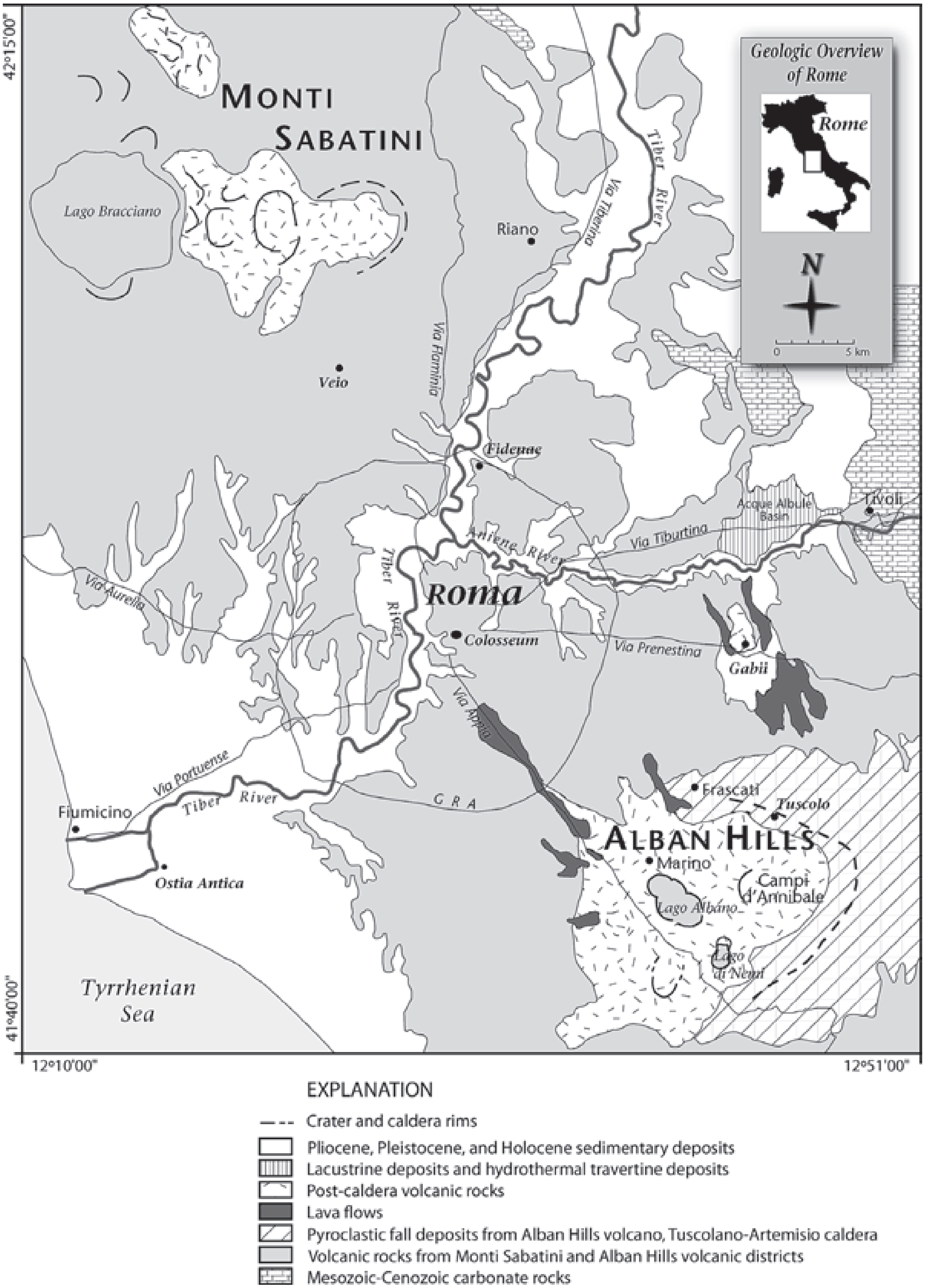


Fig. 1. Generalized geological map of Rome and its surroundings, showing Monti Sabatini and Alban Hills volcanic deposits, travertine deposits within the Acque Albule basin near Tivoli, and ancient Roman roads through the region (modified from Karner et al. 2001b).

graphic and petrographic data.[4] Similarly, earlier archaeologists had to rely on such vague terms as "friable," "flaky," "inconsistent," "firm," or "compact" to evaluate the relative strength and durability of Roman building stones. Recent, systematic measurement of the material and physical properties of these rocks sheds new light on Roman expertise in selection and preservation of cut-stone building materials and the development of concrete masonry.[5]

The earliest existing construction in Rome, which dates to sixth and fifth centuries B.C.E., used soft volcanic tuff blocks quarried in situ on the Palatine Hill.[6] Tuff is a pyroclastic rock (*pyro* = fire + *clastic* = broken in pieces) produced by volcanic explosions of hot gases, molten rock (magma), crystals, and fragments of host rock. In the region of Rome, this material erupted mainly as pyroclastic flows, or hot volcanic hurricanes composed of gases and incandescent fragments that flow swiftly down the ground surface of a volcano, sometimes for many kilometers away from the site of the eruption. Tuff forms when pyroclastic material composed of variably sized glass, crystal, and rock fragments—usually lava and limestone in the Roman tuffs—consolidates and develops mineral cements. (Volcanic glass is the amorphous product of rapidly cooled magma.) In general, tuff deposits within the city provided porous, weakly durable building stone.

Romans procured more durable varieties of tuff as they acquired nearby lands and extended transportation routes (figs. 1, 2).[7] They also developed quarries near Tivoli for travertine, a hard, light yellowish-gray, sedimentary rock precipitated from calcium carbonate-rich waters warmed by nearby volcanic activity.[8] Although deposits of hard, compact travertine and soft, porous, calcareous tufa abound within the region of Rome, these sedimentary rocks deposited by thermal springs are clearly distinguishable from tuffs produced by explosive volcanism. Archaeological publications in English, however, refer to the Roman tuff building stones as "tufa." In contrast, Italian archaeological publications employ the geologically correct "tufo" for the volcanic tuff building stones of ancient Rome. The geologically correct term in English is "tuff."

By the end of the Republican period (509–27 B.C.E.), Romans used seven different tuffs and travertine to develop an innovative architecture of cut-stone masonry integrated with small, functional elements of concrete construction.[9] Lavas provided paving stone and dense aggregate for concrete masonry. Geological field observations of the stone monuments, rock testing experiments, and remarks by Vitruvius demonstrate that by the late first century B.C.E., Roman builders recognized the diverse material characteristics of the various tuffs and travertine.[10] By the Early Imperial age, Romans selected coarse aggregate of light pumice, porous tuff, dense lava, or durable travertine lain in hydraulic pozzolan-lime mortar to formulate concretes with specific material properties.[11] With this expertise, Romans, during the Imperial age (27 B.C.E.–476 C.E.), created a revolutionary architecture of vaults and grandiose public monuments with immense interior spaces,[12] using brick-faced concrete composed primarily of local volcanic materials, which was clad with travertine, marble, and other decorative stone.

In this article, first, we offer an updated geological map of Rome (fig. 3) and describe the various stone building materials available to the early inhabitants

[4] Note that archaeological names for the Roman tuff building stones are in lower case (see table 1). In our effort to establish a straightforward, unambiguous terminology for the volcanic building stones of ancient Rome, we have relied on a geological nomenclature based upon lithostratigraphic units, or defined bodies of strata that are distinguished by petrographic characteristics and stratigraphic position. By definition, lithostratigraphic units are capitalized (e.g., Tufo Giallo della Via Tiberina), as are their type localities, such as Lapis Albanus from the Lago Albano pyroclastic debris flow, Lapis Gabinus from the Valle Castiglione ground surge deposit, and Tufo di Tuscolo from the Tuscolano-Artemisio scoria and ash fall deposits (see fig. 2).

[5] Jackson et al. 2005.

[6] *LTUR* 4:17–22.

[7] DeLaine (1995) provides a valuable investigation of the supply of stone building materials to Rome, excavation conditions, and probable means of transport to the city.

[8] Faccenna et al. 1994.

[9] In the engineering and materials science literature, cut-stone (or ashlar) masonry is called "dimension stone masonry." The faces of the squared building stone blocks are placed immediately adjacent to those of the other stones to permit very thin joints that may or may not contain mortar. Archaeologists classify this masonry in Rome as *opus quadratum*.

[10] Vitr. *De Arch.* 2.7.1–5. We use the Rowland and Howe (1999) translation of the *Ten Books of Architecture*. In many cases, however, we have adapted certain words and passages to more accurately portray the geological context of Vitruvius' descriptions of stone building materials.

[11] Lancaster 2005. Roman concrete is classified according to the facings used to contain a wall core of fist-sized chunks of coarse aggregate (*caementa*) that is laid in a mortar of lime and fine pozzolane aggregate. *Opus incertum* refers to an irregular facing of small stone chunks, usually tuff; *opus reticulatum* refers to a facing of small tuff pyramids with their square face laid diagonally; *opus testaceum* refers to brick or tile facing; *opus mixtum* refers to a facing with alternating panels of tuff *opus reticulatum* and brick (Sear 1989, 74; Claridge 1998, 44).

[12] Lechtman and Hobbs (1987) examine the social context for the adoption of concrete masonry for public construction during the Imperial age and review some of setting and curing reactions of ancient Roman and modern Portland cements.

Table 1. Stratigraphic and Chronologic Schemes and Historical Names for Roman Volcanic Rocks.

Monti Sabatini Volcano		Alban Hills Volcano	
Archaeological Term	Geological Nomenclature[a]	Geological Nomenclature[a]	Archaeological Term
	hydromagnetic activity	Lago Albano pyroclastic debris flow 36 +1 ka	Lapis Albanus, peperino di Marino, *Albanae*[b]
		Valle Castiglione ground surge deposit 260 ka	Lapis Gabinus, Gabine tufa, pietra Gabina, sperone
		Capo di Bove Lava and other leucititic lavas 277+2 ka	selce
	Tufo Giallo di Sacrofano 285+1 ka		
		Tuscolano–Artemisio scoria and ash deposits: Tufo di Tuscolo ca. 355 ka	sperone
		Villa Senni eruptive sequence: Pozzolanelle, Tufo Lionato 366+4 ka	Tufo Lionato, Anio, litoide, Monteverde, *lapidicinis Rubris*[b]
	Piroclastici Stratificate Varicolori di La Storta ca. 410 ka		
		Pozzolane Nere 407+4 ka	
		Conglomerato Giallo	
Fidenae tufa, tufo rosso litoide, *Fidenates*[b]	Tufo Rosso a Scorie Nere 449+1 ka	Pozzolane Rosse 457+4 ka	red- and black-colored pozzolane
		Vallerano Lava 460+4 ka	selce
	Tufo Terrosco con Pomici Bianche 488+2 ka		
cappellaccio	Grottarossa Pyroclastic Sequence 514+5; 518+5 ka		
		Tufo di Bagni Albule	
	Tufo Giallo di Prima Porta 514+3 ka		
		Tufo del Palatino 528+1 ka	cappellaccio, tufo granulare grigio, tufo pisolitico, peperino della Via Flaminia
Grotta Oscura, tufo giallo porosa, lapidicinis Pallensibus[b]	Tufo Giallo della Via Tiberina (upper eruptive subunits a–b–c) 548+4 ka		
	Tufo Giallo della Via Tiberina (lower eruptive subunits) 561+4 ka	Tufo Pisolitico di Trigoria 561+1 ka	
	First Ash Fall Sequence 800–580 ka		

[a] After Karner et al. 2001b
[b] Vitruvius' nomenclature of Roman tuff building stones

of the city. Next, we review the geologic setting of Rome and its surroundings (see fig. 2), which provided the diverse stone building materials Romans used to create their innovative architecture. Geologic data give important information about the stratigraphy of the deposits used for building stone and archaeological insights about the ease and depth of stone access, techniques for stone extraction, and a sense of the efforts Romans made to select, quarry, and transport their stone construction materials. The maps also show the broad distribution of ancient quarries, enabling us to record the provenance of the various stone building materials. When provenance is identified, archaeologists can determine transportation routes and, possibly, land ownership, leading ultimately to a fuller understanding of the economy of the Roman building industry. We then give concise geologic descriptions of the Roman volcanic building stones and explain the diverse eruptive processes through which these were deposited. Eruptive process greatly influences the physical and material properties of the various tuffs and, in many instances, defines the geological characteristics that are critical for distinguishing one type of tuff from another. With these geological descriptions, archaeologists can correctly identify the tuffs used in a Roman building. And, finally, to provide a more rigorous assessment of the relative strengths and durability of the Roman tuffs and travertine, we review results from rock testing experiments that approximate the behavior of these building stones within the environmental conditions of the city.

GEOLOGIC SETTING OF ROME

The city of Rome occupies a landscape dominated by rocks erupted from Rome's neighboring volcanoes, the Monti Sabatini and Alban Hills districts. The geological map (see fig. 3) provides a primary geologic framework for understanding the nature and distribution of building materials used in the early history of the city. Pyroclastic flow deposits from both volcanoes (colored green and pink on the map) interfinger within Rome and cap its hills with tuff. The tuffs rest on sands and gravels deposited by the Tiber River and its tributaries (blue) or on older deposits of claystone (brown) that form the bedrock of Rome.[13] The stratigraphic section provides a time line for the emplacement of these sedimentary and volcanic deposits. What follows is an outline of the geological history of the city, which corrects inaccurate accounts set forth in the influential archaeological works of the last century.

The subsurface geology of Rome is extremely complex; it is the result of a long series of modifications to the surface topography of the area that would become Rome. Marine claystones form the bedrock of the city (fig. 4). Deposited between 4 and 2 million years ago, when the area of Rome was submerged under the sea, these rocks crop out only along the slopes of the Monte Mario-Gianicolo ridge where they have been uplifted by recent movement along faults (see fig. 3).[14] About 1 million years ago, the region of Rome emerged from the sea after a period of slow and progressive uplift. From about 800,000 to 150,000 years ago, nine periods of glaciation raised and lowered sea level. During high stands, the ancient Tiber River and its tributaries deposited gravels, sands, and clays within streams, lakes, and swamps in the area that would become Rome. During lower sea-level stands, streams eroded deep valleys within these deposits. As a result, deposition of successive sedimentary rocks within Rome was mainly restricted to valleys and swamplands, such as the *Velabrum maius* (the site of the Roman Forum) and *Velabrum minus* (the site of Circus Maximus), the *Petronia Amni*s (leading from the Column of Marcus Aurelius to the Stadium of Domitian [now Piazza Navona]), and the *Palus Caprae* (leading from the Forum of Trajan to Largo Argentina) (see fig. 3). At present, the Tiber River floodplain continues to occupy much of the historic center of the city.[15] The natural relief of many low-lying areas has been extensively altered and improved for human habitation through the addition and leveling of landfills, as described by Ammerman for the Roman Forum.[16]

Beginning about 600,000 years ago, eruptive activity from the Monti Sabatini and Alban Hills volcanic districts deposited within the area that would become Rome large volumes of pyroclastic material, or tephra (derived from the Greek *téphra* [ashes]), the variably sized particles of glass, crystals, and rock fragments transported through the air or across the ground

[13] Faccenna et al. (1995) describe the geologic setting of the Roman area and the evolution of its landscape since the Pliocene epoch (about 5 million years ago).

[14] Marra and Rosa (1995) and Karner and Marra (1998) describe the marine claystone bedrock of the Monte Vaticano and Monte Mario Formations and correlate the Monte Ciocci and Paleo-Tiber Formations with climate events (see fig. 3).

[15] Amanti et al. (1995) provide a digital elevation model of the historic center of Rome, which shows ancient subsurface springs and stream drainages. Corazza and Lombardi (1995) and Bencivenga et al. (1995) review the history and magnitudes of Tiber River floods in Rome.

[16] Ammerman 1990.

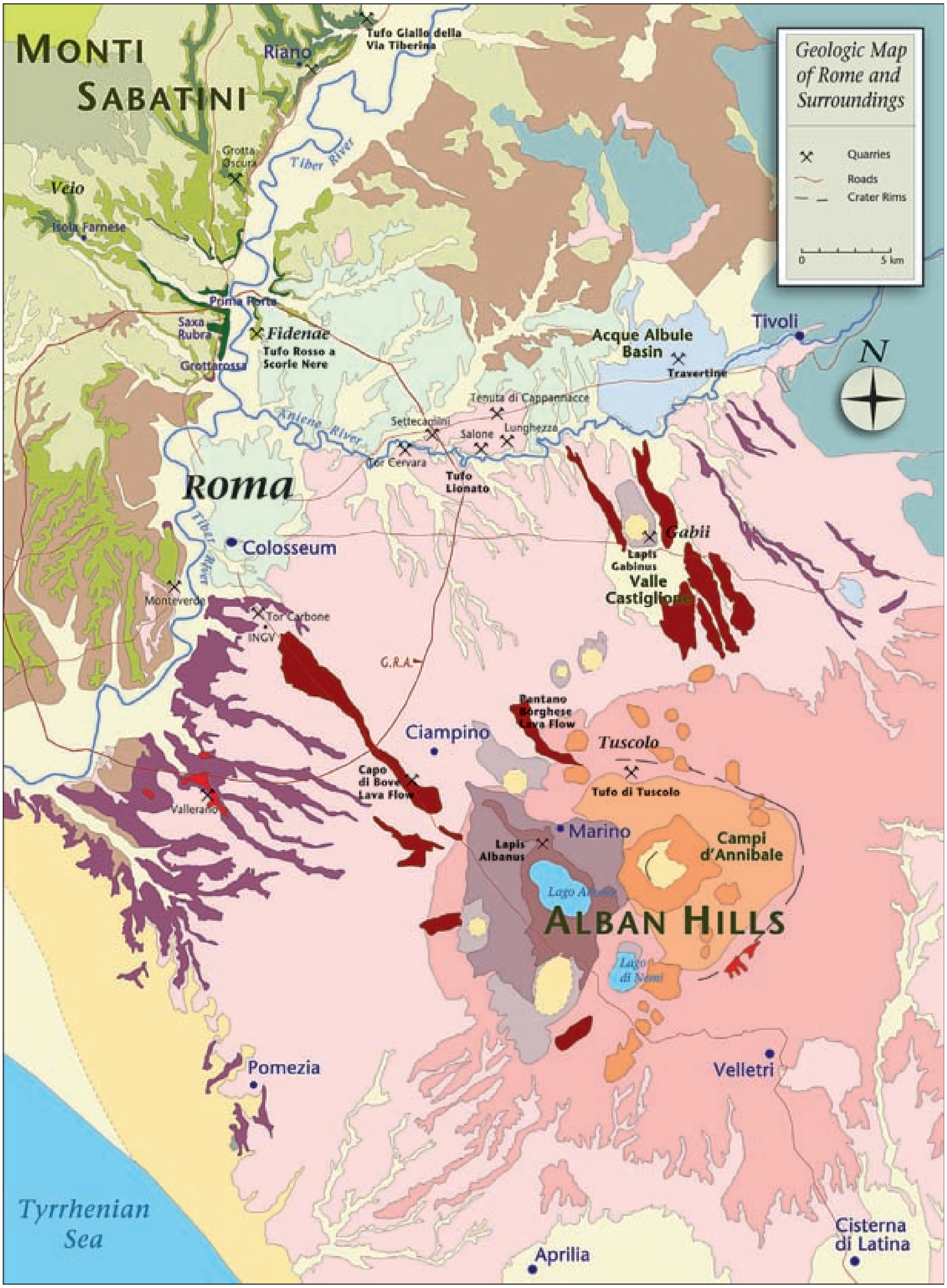


Fig. 2. Geological map and stratigraphic section of Rome and its surroundings, showing ancient Roman quarries. Deposits from Monti Sabatini volcano crop out north of Rome, extending west of the Tiber River and north of the Aniene River. Deposits from Alban Hills volcano crop out south and east of the city (based on the geologic nomenclature and volcanic chronology of Karner et al. 2001b; adapted from De Rita et al. 1988, 1993, 1995).

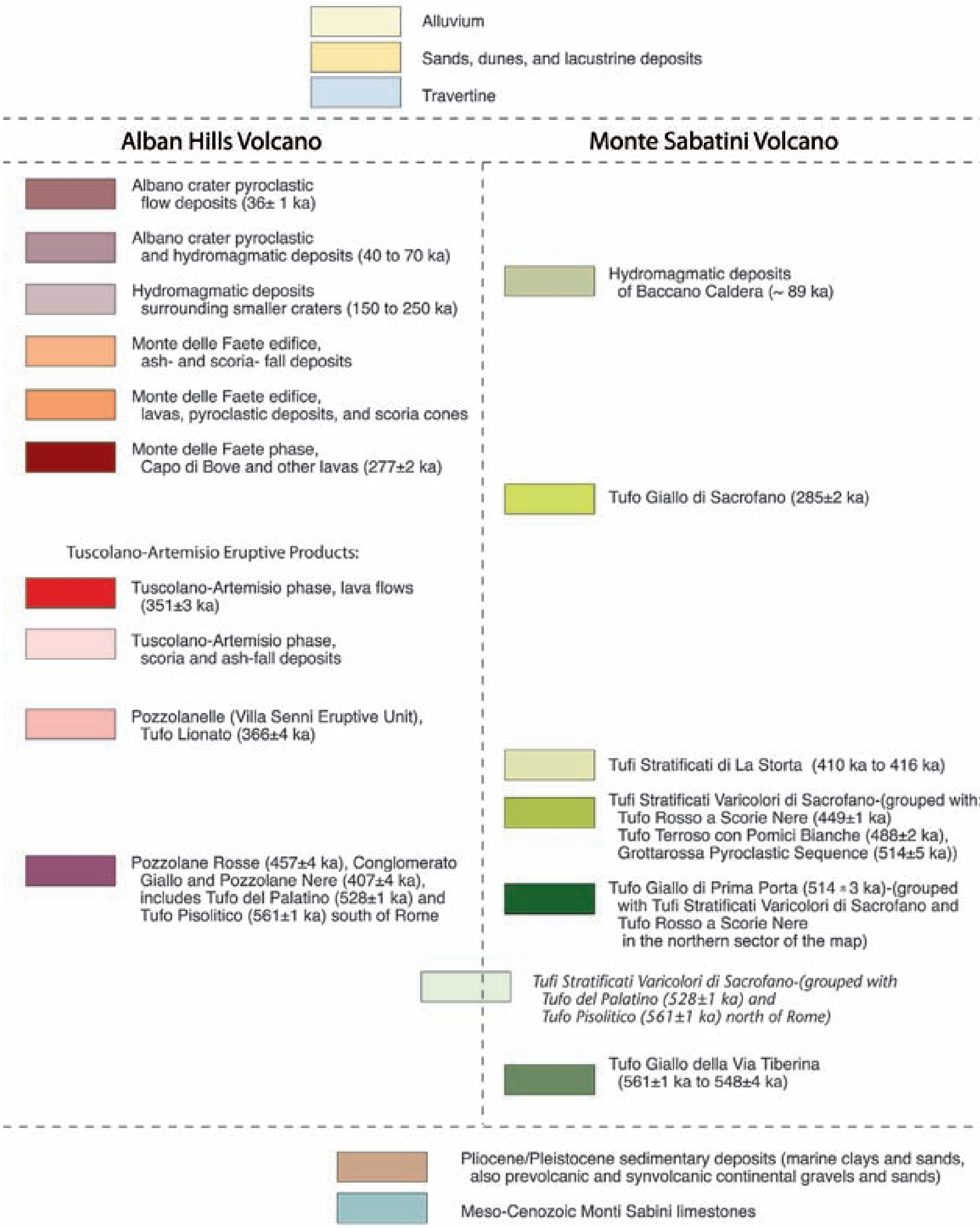


Fig. 2, continued.

surface during an explosive eruption. These deposits added a new element of complexity to the geological development of the city's landscape.[17] Most of the tephra was transported to Rome through pyroclastic flows, which lithified, or consolidated, to form tuff. (Lithification, derived from the Greek *lithos* [stone], is the conversion of a deposit of loose particles or fragments into coherent, solid rock through processes of cementation, compaction, and/or crystallization.) In contrast, Roman pozzolane are formed of rather loose, granular tephra deposited by pyroclastic flows that did not go through the same process of cementation to form consolidated rock. Interbedded with the tuffs and pozzolane are several fallout tephra deposits from Monti Sabatini volcano. These are composed of unconsolidated tephra, with an abundance of pumice and scoria. Winds carried the tephra to Rome, where they fell to the surface as a rain of volcanic particles. Over time, the Tiber River and its tributaries partially eroded and reworked, or redeposited, these various pyroclastic deposits.[18]

The stratigraphic diagram (see fig. 4) shows a typical vertical sequence of sedimentary and volcanic deposits within the center of the city. The sedimentary bedrock of Rome is overlain by pyroclastic deposits such as lithified tuffs, partially lithified tuffs, pozzolane, and fallout tephra, which are interleaved with loosely consolidated sediments, paleosols (ancient soil horizons), and pyroclastic deposits reworked by the Tiber River. The degree of lithification of deposits underlying the Roman monuments strongly influences the damaging impact of ground motion during earthquakes, as demonstrated by seismic studies of the Colosseum and Columns of Trajan and Marcus Aurelius.[19] The cross-section (see fig. 3) shows that the steep slopes of the Capitoline and Palatine Hills expose tuffs from both the Monti Sabatini and Alban Hills districts.

A SURVEY OF ROMAN VOLCANIC BUILDING STONE

In *De Architectura*, Vitruvius describes the various stone building materials that were quarried in the region of Rome during the late first century B.C.E.:

> 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[20] 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,[21] like the *Tibur* stones, the *Amiternae* stones, and the *Soracte* stones, and others of this type. Some are hard, like lavas.[22]

Do English translations of *De Architectura* reflect the careful distinctions that Vitruvius makes among rocks used in the buildings of Rome? The stones listed by Vitruvius as "yielding" in quality (*molles*) are volcanic tuffs quarried from Monti Sabatini and Alban Hills volcanoes; the *Fidenates* stones refer to Tufo Rosso a Scorie Nere quarried near Fidenae; the *Albanae* stones refer to Lapis Albanus, quarried from the Albano Crater pyroclastic deposit (see table 1, figs. 1, 2). Some question exists, however, about the locations of quarries for tuffs that Vitruvius terms *Rubrae* and *Pallenses*. Many archaeologists assume that *Rubrae* refers to red-colored tuff quarried along the Aniene River, that is, Tufo Lionato.[23] They also assume that *Pallenses* refers to pale yellow tuff quarried near Grotta Oscura, that is, Tufo Giallo della Via Tiberina (fig. 5a; see table 1, fig. 2). Strabo describes a trio of building stones, travertine, Lapis Gabinus, and Tufo Lionato (or red stone), that were quarried and trans-

---

[17] Alvarez et al. (1996) describe the complex internal stratigraphy of the Capitoline Hill, which records cycles of valley cutting and filling by the Tiber River, emplacement of pyroclastic deposits, and geological influences on ancient structures; see also Karner and Renne 1998.

[18] Karner and Marra (1998) show that the San Paolo Formation, e.g., contains eroded fragments of white pumice and gray and red scoria derived from Tufo Terroso con Pomici Bianchi and Pozzolane Rosse, respectively (see fig. 3).

[19] Boschi et al. (1995) and Funiciello et al. (1995) analyze the damaging effects of ground shaking of subsurface sediments on the amplification of seismic response of these monuments.

[20] Vitr. *De Arch.* 2.7.1. Rowland and Howe (1999) translate *molles* as soft; *mollis* has the additional meanings of pliant, flexible, and yielding. Yielding may most accurately describe Vitruvius' empirical understanding of the tendency of these rocks to rupture under heavy loads. In geological terms, this refers to the low yield strength (the force required to produce inelastic strains leading to rupture) of the tuff building stones, which is usually less than 40 MPa, based on rock testing experiments (ASTM 2002a, b) by Jackson et al. 2005. For further discussion of Vitruvius' observations of stone building materials, see Jackson et al. 2006.

[21] Rowland and Howe (1999) translate *temperatae* as neither hard nor soft. In geological terms, all of these limestones have moderate yield strengths, usually less than 100 MPa.

[22] Rowland and Howe (1999) translate *durae* as hard. This word has the additional meanings of strong (with high yield strength), enduring (with good durability when exposed to processes of geologic weathering), and difficult to work, as in *glebae*, of agricultural land, a clod of soil, or lump of stone. Rowland and Howe (1999) translate *siliceae* as silex. Although *siliceae* refers to any hard stone, we speculate that, in this instance, Vitruvius is referring specifically to lava flows that crop out near Rome. These have the highest yield strengths (in the range of 150–350 MPa for basalts [Goodman 1989, 61]) of all rocks that crop out in the Roman region.

[23] Lanciani 1897, 35; Frank 1924, 26–7; Blake 1947, 29.

ported along the Aniene River. This trio of stones played an important role in the Forum of Caesar and the Forum of Augustus, constructed in the late first century B.C.E. (figs. 5d, f, h, 6, appx.).[24] Oddly, however, Lugli refers to "tufo dell'Aniene" (Tufo Lionato) as *lapis Pallens* and to "tufo di Grotta Oscura" (Tufo Giallo della Via Tiberina) as *lapides Rubri*, which he suggests comes from quarries at Saxa Rubra.[25] Our geological fieldwork confirms: first, that there are no traces of important ancient quarries in Saxa Rubra (modern Grottarossa), which is located on the right bank of the Tiber River between miles 4 and 7 of Via Flaminia; and, second, that there are no outcrops of Tufo Giallo della Via Tiberina in the Prima Porta area (see figs. 1, 2).[26] Cicero, Livy, and Tacitus also refer to the locality of Saxa Rubra along Via Flaminia but make no mention of quarries for building stone there.[27] Based on this evidence, we conclude that the *lapidicinis Rubris* of Vitruvius refers to Tufo Lionato quarried along the Aniene River, and that *lapidicinis Pallensibus* refers to Tufo Giallo della Via Tiberina quarried near Grotta Oscura and northward along Via Tiberina (see table 1).

The stones that Vitruvius describes as "moderate" in quality (*temperatae*) are sedimentary rocks formed of calcite (crystalline calcium carbonate): the travertine deposits of Tivoli and the limestone bedrock of the Appennine Mountains quarried near Amiternum, 140 km northeast of Rome, and Monte Soratte, 40 km northeast of Rome. Note that Vitruvius differentiates travertine and limestone from silex (*siliceae*) in the passage cited above. Although there is some ambiguity regarding Vitruvius' use of this term,[28] we speculate that here *siliceae* does refer to "hard" stone quarried within leucititic lava flows. Following Vitruvius, Pliny the Elder makes a qualified statement that the best silex (*nigri silices optimi*) is the black variety.[29]

GEOLOGICAL CHARACTERISTICS OF THE ROMAN TUFFS

Tuff, pozzolane, and lava, the volcanic building materials of ancient Rome, have diverse physical and material properties; they played very different roles in Roman construction. Pyroclastic eruptions of gas and tephra that produced deposits of tuff and pozzolane dominate the history of Monti Sabatini and Alban Hills volcanic districts. As a point of reference, let us take Pliny the Younger's description of the explosive eruption of Mount Vesuvius in 79 C.E. and its eruptive column shaped like the tall trunk of an umbrella pine tree, whose crown was infused with earth (*terram*) and cinders (*cineremve*).[30] In geological terms, a Plinian eruption is violently explosive and produces a jet of hot gases filled with ash and pumice that may extend up to 50 km into the atmosphere. Collapse of the eruptive column produces pyroclastic flows that rush down the sides of the volcano and transport hot gases and tephra across the ground surface. In the region of Rome, these flows often filled valleys; therefore, they have a complicated outcrop pattern through both Rome and its surroundings. Many pyroclastic deposits lithified to form tuff through the development of mineral cements that bound tephra fragments together as rock. This process may have taken many thousands of years.

The Roman tuff building stones were quarried from at least seven different pyroclastic deposits (see table 1, figs. 2, 5). Each has its own distinctive geologic appearance. The primary components of the tuffs are fragments of glass, crystals contained within the magma, and fragments of rock, mainly lavas and

---

[24] Strabo *Geographica* 5.3.11: "Thence the [Aniene] river flows out through a very fruitful plain past the quarries of Tiburtine stone, and of the stone of Gabii, and of what is called the 'red-stone'; so that the delivery from the quarries and the transportation by water are perfectly easy" (Jones 1923).

[25] Lugli (1957, 253–57) contains a good deal of misinformation that we have attempted to correct in these and subsequent paragraphs.

[26] Karner et al. 2001b.

[27] Cic. *Phil.* 2.7; Livy, *Ab Urbe Condita* 2.49; Tac. *Hist.* 3.79.

[28] Vitruvius mentions *alba saxo* and *silice coquatur* (*De Arch.* 2.5.1) as sources for lime; these terms may refer to soft, porous, calcareous tufa and hard, compact marine limestone, respectively. *Saxis silicibus* (*De Arch.* 8.1.2) harboring aquifers may also refer to limestone, with water-bearing sinkholes and caves dissolved within the rock. The description of *saxa silicea* (*De Arch.* 8.1.2) as durable stone that fractures and dissolves when heated and treated with acid again suggests hard limestone. We infer, however, that *siliceae* (*De Arch.* 2.7.1) refers to lava (supra n. 22).

[29] Plin. *HN* 36.49.168. Pliny's related remarks concerning the durable and fire-resistant qualities of Anician tuff, quarried northwest of Rome at Lago Bolsena, seem to paraphrase more detailed and accurate commentary by Vitruvius (*De Arch.* 2.7.2–4) (Jackson et al. 2006).

[30] Plin. *Letters* 6.16: "A cloud, from which mountain was uncertain, at this distance (but it was found afterwards to come from Mount Vesuvius), was ascending, the appearance of which I cannot give you a more exact description of than by likening it to that of a pine-tree, for it shot up to a great height in the form of a very tall trunk, which spread itself out at the top into a sort of branches; occasioned, I imagine, either by a sudden gust of air that impelled it, the force of which decreased as it advanced upwards, or the cloud itself, being pressed back again by its own weight, expanded in the manner I have mentioned; it appeared sometimes bright and sometimes dark and spotted, according as it was either more or less impregnated with earth and cinders" (Melmoth 1909–1914; see De Carolis and Patricelli 2003).

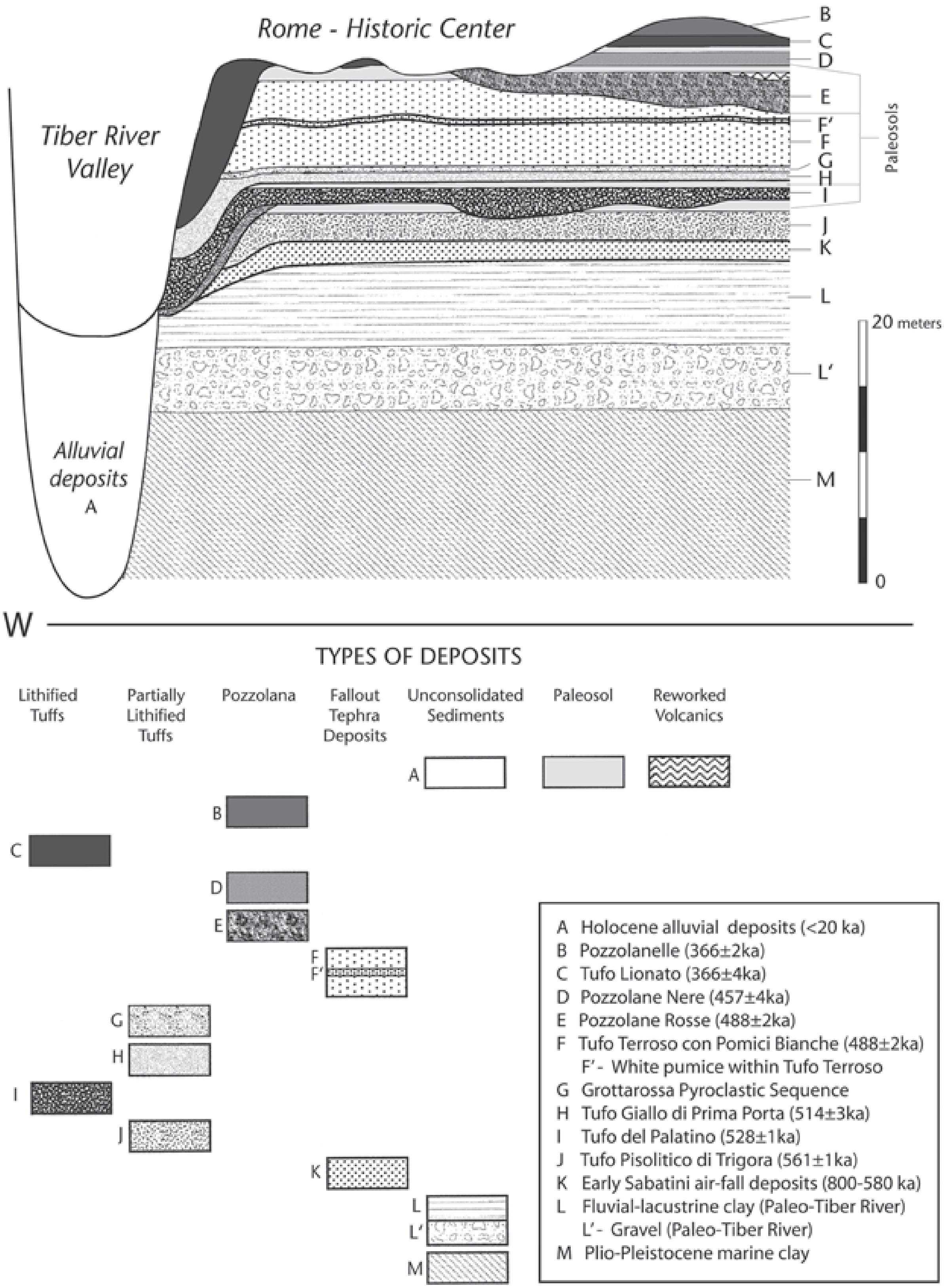


Fig. 4. Typical stratigraphic section of the sedimentary and volcanic deposits underlying downtown Rome.

limestone. The tephra are bound together by zeolite mineral cements as well as lesser amounts of calcite cements.[31] Overall, the tephra show a wide disparity in grain sizes ranging from fine ash (1/16 mm) to coarse ash (2 mm) to small lapilli (less than 64 mm). Significantly, the tuffs used as building stone are grain-supported rocks; that is, their coarse, ash-sized particles are so abundant that they touch one another and are in three-dimensional contact. The largest fragments are generally composed of pumice (frothy volcanic glass), lava or limestone, and, less commonly, pebbles swept into the pyroclastic flow as it traveled across the ground surface. Crystals are mainly leucite, clinopyroxene, and biotite; sanidine appears only in the Monti Sabatini tuffs. Rock fragments are chiefly leucititic lavas, although many tuffs contain bits of the limestone bedrock underlying the volcanic districts. Limestone and leucititic lava flows form the walls of conduits through which magma traveled to the earth's surface. During explosive eruption, fractured fragments of the conduit walls were entrained within the eruptive mixture.[32]

The relative abundance of glass, rock, and crystal fragments contained within a given Roman tuff is the main factor that determines its strength as a building stone.[33] Lots of glass fragments generally produce a porous, lightweight tuff that is poorly to moderately cemented. The photograph of Tufo Giallo della Via Tiberina (see fig. 5a) shows this characteristic glassy (vitric) texture.[34] The alteration of glass fragments, and in particular those of pumice, to clay minerals reduces the durability of glassy tuff building stones. However, an abundance of rock (lithic) and/or crystal fragments usually produces a durable, strongly grain-supported tuff that is fairly well cemented. The photographs of Tufo di Tuscolo, Lapis Gabinus, and Lapis Albanus (see figs. 5e–g) show this characteristic lithic-crystal texture. Modern Romans call these tuffs "peperino" (like black pepper) for their dark gray lava fragments and occasional light yellowish-gray limestone bits and pieces.

In the region of Rome, differing mechanisms of eruption and flow of pyroclastic material across the ground surface determined, in large part, the relative abundance of glass, crystal, and rock within the tuffs and, therefore, their strength and durability. In general, pyroclastic flow deposits are produced by dense, voluminous particulate flows that commonly move down valleys. They often contain large quantities of fine-grained glass fragments that solidified from the molten rock of the eruption. When this particulate material comes to rest, it forms a massive deposit called ignimbrite, with little internal structure or layering. Many of the Roman pyroclastic building materials, such as Tufo Giallo della Via Tiberina, Tufo del Palatino, and Tufo Lionato as well as Pozzolane Rosse, Pozzolane Nere, and Pozzolanelle, were quarried within ignimbrites (see table 1, figs. 2, 5a, c, d, appx.). In contrast, pyroclastic surge deposits in the Roman area are associated with very explosive, eruptive interactions between hot magma and ground and/or surface water, which fractured older rocks that lay beneath the volcanic vent. These include pyroclastic rocks and, more important, leucititic lavas and limestone. Such surge eruptions produced well-bedded deposits with most layers dominated by coarse-grained lava fragments derived from the fractured conduit walls; some layers show a predominance of bits of fine-grained glass derived from the magma itself. Lapis Gabinus tuff, for example, was quarried within a pyroclastic surge deposit erupted from Valle Castiglione crater (see figs. 2, 5f, appx.). A recently erupted pyroclastic surge deposit may avalanche to form a volcanic-debris flow under rain-soaked conditions or on steep slopes. Lapis Albanus tuff, which erupted from Lago Albano crater, is a volcanic-debris flow deposit with relatively homogeneous fabric and little internal layering that filled a narrow valley near Marino (see figs. 2, 5g, appx.).[35]

Lapis Gabinus, Lapis Albanus, and Tufo di Tuscolo come from pyroclastic deposits that are localized around their eruptive vents, so that it is possible to

---

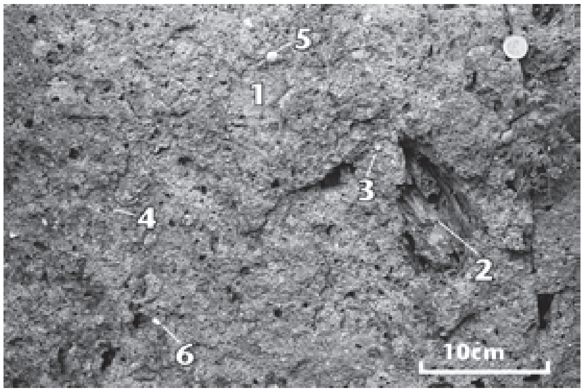
[31] As shown by Jackson et al. (2005) through petrographic and geochemical studies, the secondary components of the tuffs are zeolite, calcite, and clay minerals. These formed when glass and leucite crystals dissolved during low-temperature reactions with ground and surface water. Hay and Ijima (1968) describe the reaction geochemistry of volcanic glass with cold percolating water in tuffs to form zeolite and altered volcanic glass. Welded tuffs do not occur within Rome.

[32] Fisher and Schminke 1984, 128–32.

[33] Jackson et al. (2005) measured the abundances of glass, crystal, and rock fragments and mineral cements in thin sections of tuffs collected from ancient Roman quarries. They classified the tuffs according to the composition of their constituent fragments with the dominant particle type listed first. E.g., a coarse-grained Lapis Gabinus sample (LG-3) containing 36% rock fragments, 19% glass fragments, and 8% crystals and crystal fragments, or $L_{0.36}V_{0.19}C_{0.08}$, is a lithic-vitric-crystal tuff. In contrast, a glassy Tufo Lionato sample (TL-12) with 39% glass fragments, 12% crystals and crystal fragments, and 7% rock fragments, or $V_{0.39}C_{0.12}L_{0.07}$, is a vitric-crystal-lithic tuff.

[34] Fisher and Schminke (1984) give descriptions of pyroclastic fragments and deposits as well as the alteration of volcanic glass, which is yellow-colored sideromelane or orange-colored palagonite in Roman pyroclastic deposits.

[35] Villa et al. 1999; Giordano et al. 2002; Marra et al. 2003.

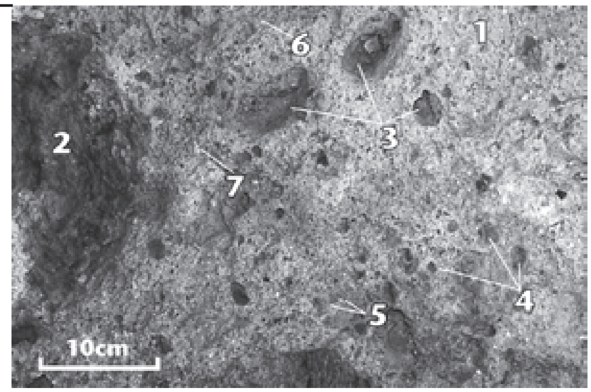


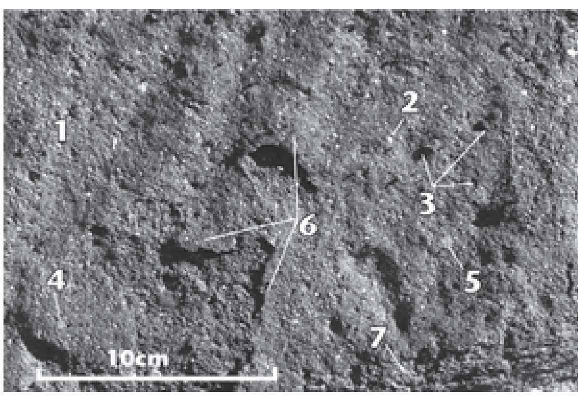
a. Tufo Giallo della Via Tiberina, Republican Wall, fourth century B.C.E., Aventine Hill:

1 = porous, yellowish-gray, altered glass matrix (with zeolite cement)
2 = large, grayish yellow pumice fragment
3 = leucite and analcime crystal fragments (hexagonal shapes)
4 = sanidine crystal fragment (rectangular shape)
5 = round accretionary lapillus
6 = limestone rock fragment; eroded pumice fragments give a porous, deeply pitted stone surface

b. Tufo Rosso a Scorie Nere, Temple of Juno Moneta, mid Republican period, Capitoline Hill:

1 = porous, light brown, altered glass matrix (with zeolite cement)
2 = large, dark gray scoria fragment
3 = smaller scoria fragments
4 = lava rock fragments
5 = leucite and analcime crystal fragments (hexagonal shapes)
6 = sanidine crystal fragment (rectangular shape)
7 = limestone rock fragment





c. Tufo del Palatino, Temple of Jupiter Capitolinus, 509 B.C.E., Capitoline Hill:

1 = compact, olive-gray, altered glass matrix
2 = leucite or analcime crystal fragments (hexagonal shapes)
3 = lava rock fragments
4 = limestone rock fragment
5 = mudstone pebble
6 = exfoliation (flaking) of weathered stone surface
7 = fissility (splitting) at edges of block

d. Tufo Lionato (Aniene River quarries), Temple of Apollo Medicus Sosianus, late first century B.C.E., Velabrum Valley:

1 = porous, moderate light brown, altered glass matrix with zeolite cement)
2 = strong, white zeolite cement
3 = light brown glass fragments
4 = pumice fragment
5 = leucite and analcime crystal fragments (hexagonal shapes)
6 = lava rock fragments (in white outlines)
7 = limestone rock fragment
8 = chisel marks on soft stone surface

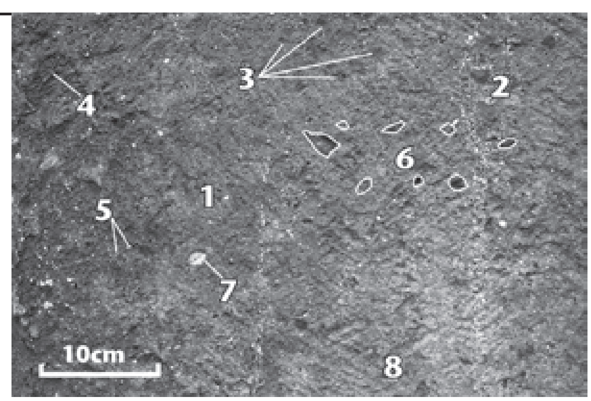
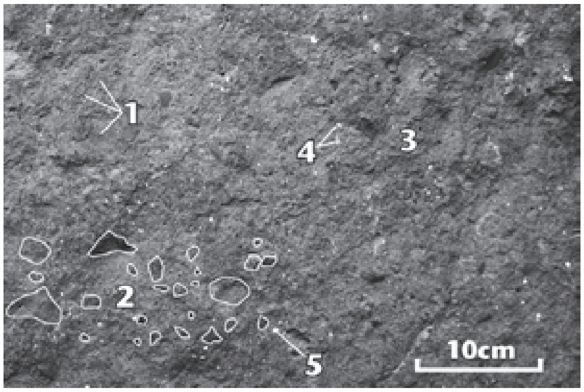


Fig. 5. Roman tuff and travertine building stones (for photomicrographs of thin sections of these rocks, see Jackson et al. 2005).

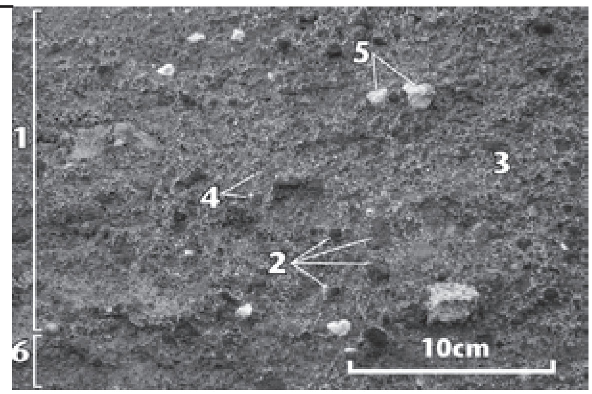


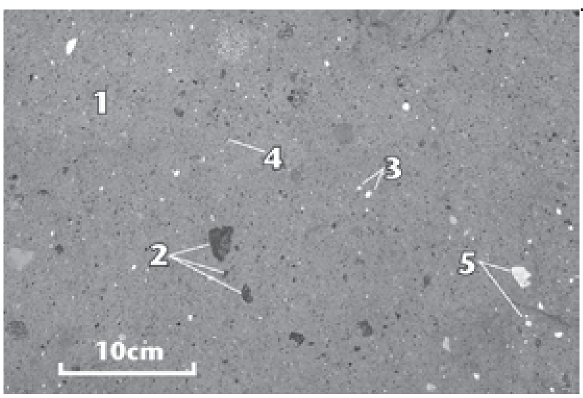
e. Tufo di Tuscolo, Colosseum, 79 C.E.:

1 = fine to coarse ash-sized lava and glass fragments (with strong zeolite cement)
2 = abundant coarse lava fragments (in white outlines)
3 = glass fragment
4 = leucite and analcime crystal fragments (hexagonal shapes)
5 = limestone rock fragment; hard, compact stone surface has rough lava fragments and variable amounts of light brown glass fragments

f. Lapis Gabinus, Tabularium, 78 B.C.E., Capitoline Hill:

1 = compact, coarse-grained layer
2 = abundant lava fragments throughout
3 = strong, pervasive, white zeolite cement
4 = leucite and analcime crystal fragments
5 = limestone rock fragments
6 = thin layer of fine-grained glass fragments; hard lava and limestone fragments protrude from stone surface





g. Lapis Albanus, Temples at San Nicola in Carcere, third century B.C.E., Velabrum Valley:

1 = lighter, olive-gray glass matrix (with zeolite cement)
2 = numerous lava rock fragments
3 = leucite and analcime crystal fragments (hexagonal shapes)
4 = biotite (mica) crystal fragment
5 = limestone rock fragments; smooth, fairly durable stone surface

h. travertine (modern block):

1 = stromatolite, a small, domed structure built of layers of bacterially precipitated calcium carbonate
2 = layer of compact, calcium carbonate mud
3 = mat of irregular, shrublike calcareous growths with lens-shaped cavities

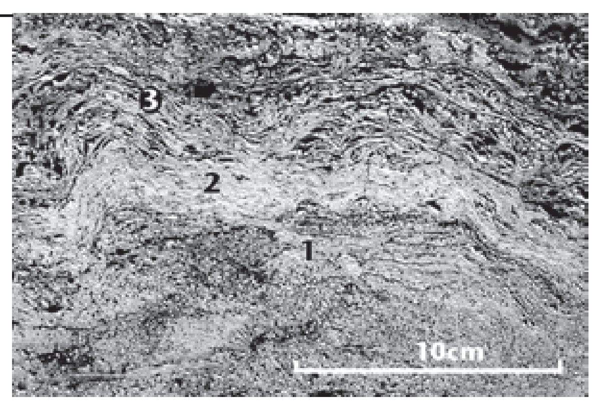


Fig. 5, continued.

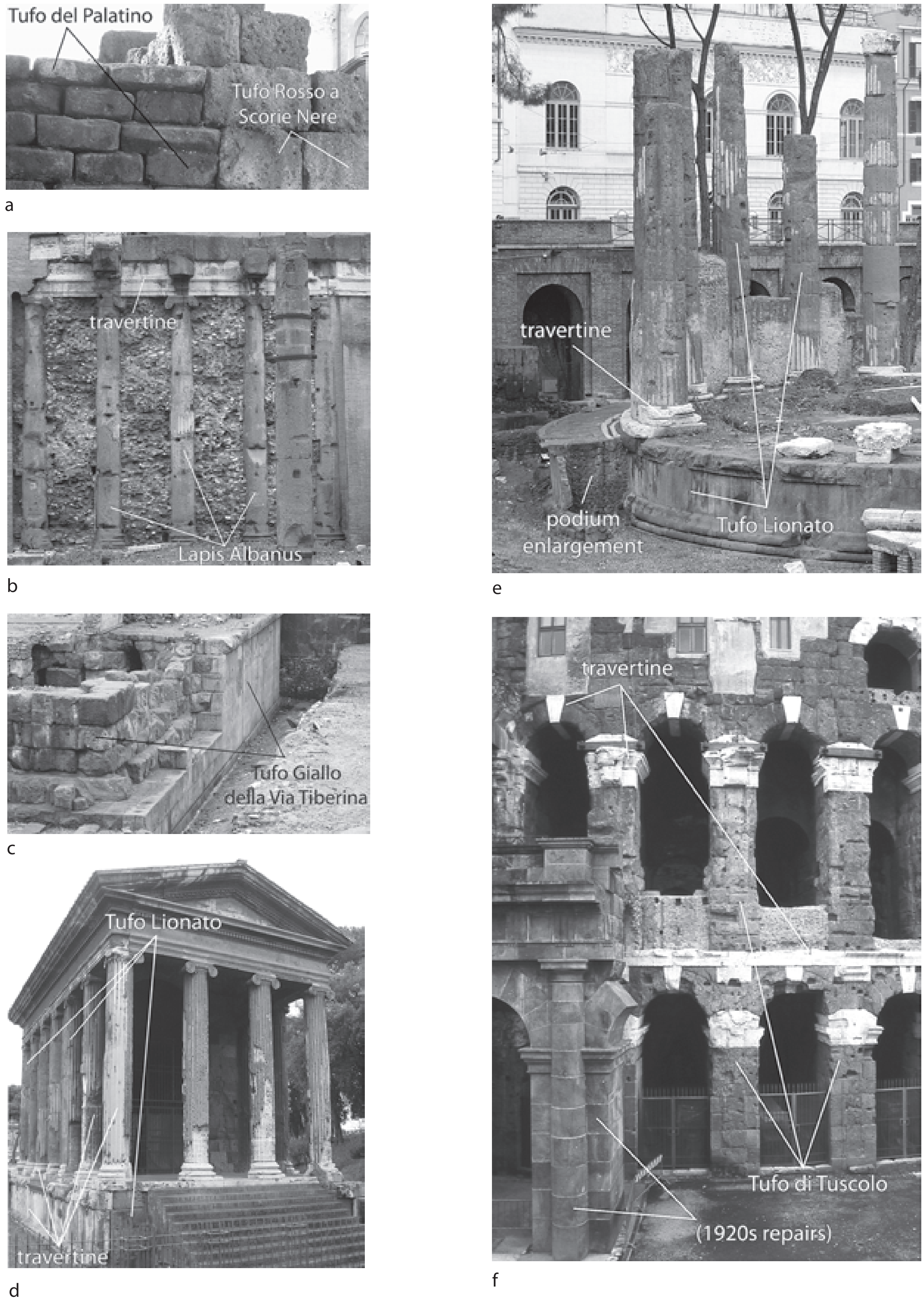
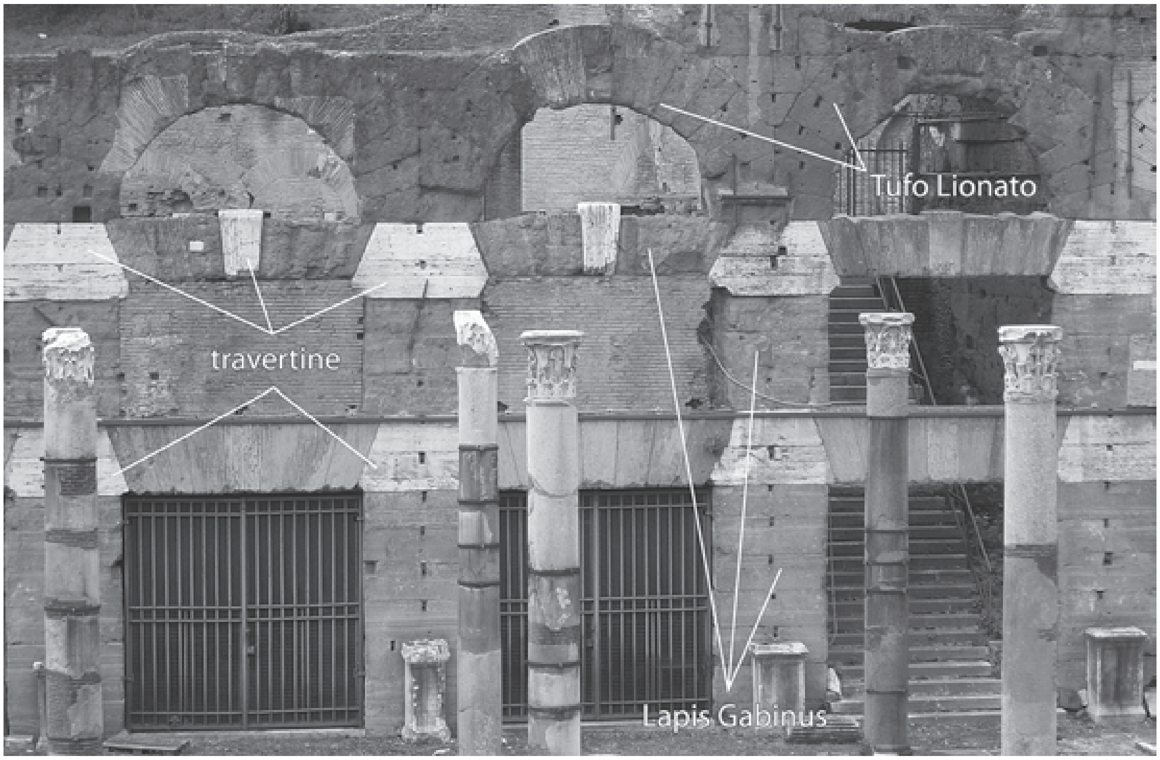
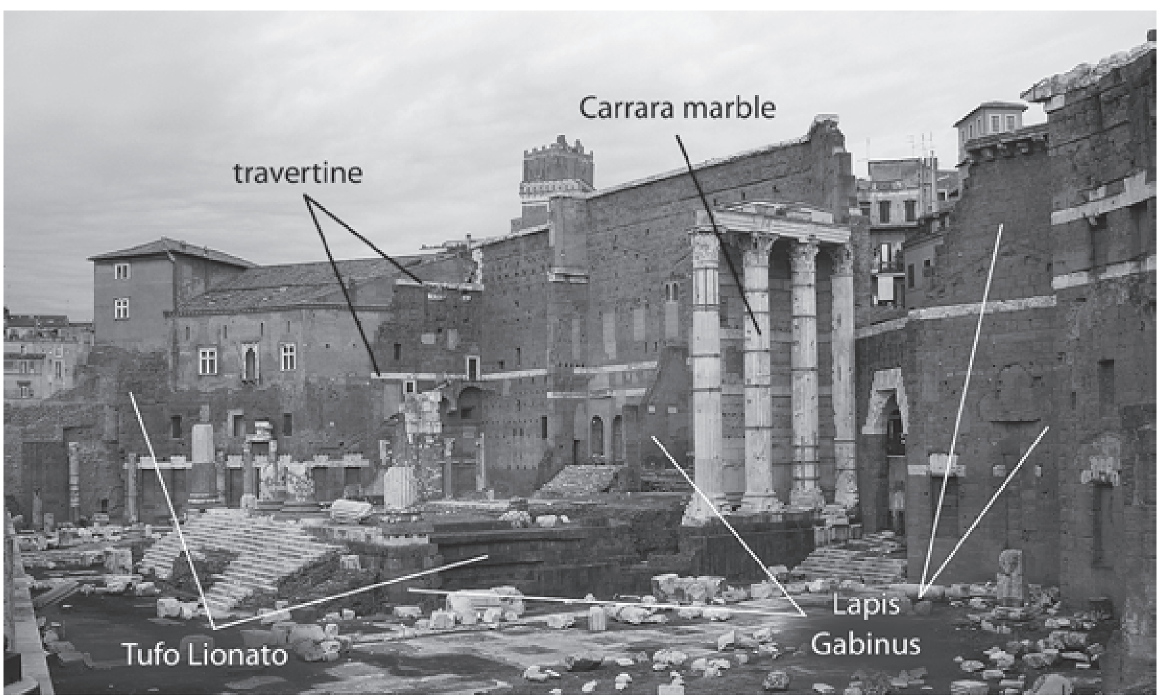


Fig. 6. Roman tuff and travertine building stones of the Roman monuments: *a*, Temple of Juno Moneta (345 B.C.E.); *b*, temple at San Nicola in Carcere (mid third century B.C.E.); *c*, Temple C (290 B.C.E.), Largo Argentina; *d* Temple of Portunus (80 to 70 B.C.E.); *e*, Temple B (101 B.C.E.), Largo Argentina; *f*, Theater of Marcellus (23 to 11 B.C.E.).



g



h

Fig. 6, continued: *g,* Forum of Caesar (42 B.C.E.); *h*, Forum of Augustus (2 C.E.).

establish the general quarry location of a given building stone (see fig. 2). In contrast, the pyroclastic flows from which the Tufo Giallo della Via Tiberina and Tufo Lionato ignimbrites were quarried traveled for many kilometers from their eruptive vents; they are, therefore, widespread throughout the Roman landscape. These deposits exhibit a fair amount of internal variability, and it is difficult, if not impossible, to identify the exact provenance of a specific building stone.

Eruptions of molten, fluid rock produce lavas that flow down the slopes of a volcano. The Capo di Bove and Pantano Borghese lavas (see fig. 2) provided paving stone for roads such as Via Appia and Via Prenestina near Castiglione crater, as well as dense aggregate for the concrete foundations of large imperial monuments, such as the Colosseum.[36] The Roman lavas usually contain conspicuous white or translucent, often hexagonally shaped, leucite crystals, greenish-black tablets of clinopyroxene crystals, and small amounts of honey-colored melilite crystals. Archaeologists describe these as leucititic lavas; there are no lavas with basalt compositions.[37]

SOURCES OF ROMAN STONE BUILDING MATERIALS

The geological map (see fig. 2) shows important Roman quarries that were most likely active when Vitruvius wrote his manual of Roman architecture. The accompanying stratigraphic section gives the relative ages of the volcanic and sedimentary deposits that crop out through the Roman region. Pyroclastic deposits used as building materials from Monti Sabatini and Alban Hills volcanic districts usually overlie older deposits of unconsolidated sand and gravel laid down by the Tiber River and its tributaries, which, in turn, overlie thick deposits of marine claystone that form the bedrock of Rome.[38] These latter deposits, which crop out northeast of the city, provided clay for Roman brick. A thick sequence of Mesozoic–Cenozoic limestone crops out within the foothills of the Appennine Mountains, about 35 km east of Rome. Burning limestone in kilns produced the lime that was essential for Roman pozzolanic mortar.[39] In addition, travertine deposits more than 60 m thick accumulated in a shallow lake environment fed by thermal springs near Tivoli.[40] This unique suite of volcanic and sedimentary rocks provided Roman builders with an abundant and diverse supply of stone building materials including tuff and travertine for cut-stone masonry, pozzolane and lime for mortars, and tuff, lava, and travertine coarse aggregate for brick-faced concrete masonry.

Monti Sabatini Tuffs

The two main pyroclastic flow deposits from Monti Sabatini volcano used as building stone in Rome crop out within the Tiber River valley several kilometers north of the city (see fig. 2). Archaeologists recognize these as the "Grotta Oscura" building stone, quarried from the upper part of Tufo Giallo della Via Tiberina ignimbrite,[41] a yellowish-gray to grayish-orange, glassy tuff with large grayish-yellow pumice fragments, and the "Fidenae" building stone, quarried from Tufo Rosso a Scorie Nere ignimbrite,[42] a light brown, porous, glassy tuff with prominent, dark gray scorie and lava fragments (see table 1). Scorie are vesicular or frothy fragments of lavas that are heavier, darker, and more crystalline than pumice. Photographs (see fig. 5), geological descriptions (see appx.), and a hand lens can be used to identify these features in the field. The geological map (see fig. 2) shows Roman quarries for Tufo Giallo della Via Tiberina at km 13 of Via Tiberina and at Grotta Oscura.[43] The extensive ancient quarries for Tufo Giallo della Via Tiberina between km 13 and 15 of Via Tiberina occur as chambers and corridors within hillsides and as surficial excavations (fig. 7a). In the fourth-century B.C.E. Republican Wall[44] on the Aventine Hill at Via San Anselmo and the podium of Temple C (290 B.C.E.)[45] at Largo Argentina are porous, strongly weathered Tufo Giallo della Via Tiberina blocks with large, crumbling, pumice fragments (see figs. 5a, 6a). By contrast, walls of moderately well-lithified Tufo Giallo della Via Tiberina blocks protected within the Theater and Crypta of Balbus (13 B.C.E.)[46] remain fresh and unaltered. During the Imperial age, Ro-

[36] Rea et al. 2002, 346–49.

[37] Roman lavas have unusual compositions that are high in potassium and low in silica (Scherillo 1944–1946; Trigila et al. 1995, 33–7). Their compositions are best described as tephrites (for Alban Hills) or tephritic phonolites and trachybasalts (for Monti Sabatini).

[38] Faccenna et al. 1995.

[39] Adam (1999, 66–73) describes the manufacture of lime for Roman mortar.

[40] Supra n. 8.

[41] Scherillo (1941), Lenzi and Passaglia (1974), Nappi et al. (1979), and Karner et al. (2001b) describe Tufo Giallo della Via Tiberina in further detail.

[42] Alvarez et al. (1975) describes Tufo Rosso a Scorie Nere in further detail.

[43] Frank (1924, 19–20) described quarries for "Grotta Oscura" tuff 4 km north of Prima Porta along Via Tiberina, but this area is not easily accessible at present.

[44] Corazza et al. 1987; *LTUR* 4:322.

[45] Richardson 1992, 33–5; Coarelli 1997, 274–76.

[46] *LTUR* 1:326–29; 5:30–1.

mans made extensive use of Tufo Giallo della Via Tiberina as coarse aggregate in concrete work; the original vaults of the upper stories of the Colosseum (70 to 80 C.E.) provide a good example.[47]

Interestingly, all the outcrops along the southward continuation of Via Tiberina, including those at Prima Porta and along Via Flaminia, are Tufo Giallo di Prima Porta ignimbrite, a yellow-gray, glassy tuff with small, grayish-orange pumice fragments (see figs. 1, 2, appx.).[48] It seems the Romans did not employ this tuff, which has abundant joints or fractures, as cut-stone blocks; we have positively identified it as occasional coarse aggregate in concrete work of the Forum of Caesar. Although archaeologists might assume this yellow tuff to be Grotta Oscura,[49] its geological characteristics distinguish it as Tufo Giallo di Prima Porta and provide a way to significantly narrow its area of provenance as compared with Tufo Giallo della Via Tiberina.

Roman quarries for Tufo Rosso a Scorie Nere are not well preserved within the Fidenae area. Nevertheless, the soft tuff was used for block work throughout the Republican age. Weathered Tufo Rosso a Scorie Nere blocks form an enlargement of the podium of the Temple of Juno Moneta, inaugurated in 345 B.C.E. on the Capitoline Hill (see figs. 5b, 6a).[50] Within the Tabularium,[51] the state archive office constructed in about 78 B.C.E., interior walls of Tufo Rosso a Scorie Nere block work retain their light red-brown color and glassy texture.

Alban Hills Tuffs

Archaeologists refer to the soft tuff building stones of the oldest structures on the Palatine and Capitoline Hills and in the Roman Forum as "cappellaccio" (see table 1). Geologically speaking, the term "cappellaccio" includes two distinct ignimbrites, each from a different volcanic district.[52] Tufo del Palatino erupted from Alban Hills volcano; it crops out at the base of the Palatine and Capitoline Hills (see figs. 3, 5c, appx.). Grottarossa Pyroclastic Sequence subunit a erupted from Monti Sabatini volcano; it is exposed at the top of the Palatine Hill (see fig. 3, appx.). The tuff seems to have been employed only in Archaic structures on the hilltop.[53] In hand samples, both tuffs are olive gray, are relatively poorly lithified, and have abundant dull-white leucite fragments, which have been partially or wholly replaced by analcime. Tufo del Palatino, however, contains more lava fragments, little biotite, and no sanidine. The Temple of Juno Moneta shows the characteristic soft, friable appearance of this tuff (see fig. 6a). Romans used

Fig. 7. Examples of ancient Roman quarries (see fig. 2 for locations): *a*, Tufo Giallo della Via Tiberina, quarry at km 13; *b*, Tufo Lionato, Salone quarry along the Aniene River; *c*, Lapis Gabinus, quarry within the Valle Castiglione tuff ring.

[47] Lancaster 1998.

[48] Karner et al. (2001b) used age dating and geologic field relationships to distinguish between Tufo Giallo della Via Tiberina (548±4 ka) and Tufo Giallo di Prima Porta (514±3 ka).

[49] Frank 1924, 19–21; Blake 1947, 27–9; Lugli 1957, 253–66.

[50] *LTUR* 3:123–25, 279–80.

[51] *LTUR* 5:17–20.

[52] Marra and Rosa 1995; Karner et al. 2001b.

[53] Supra n. 6.

Tufo del Palatino, typically cut into flat blocks about 30 cm thick, mainly during the seventh through fifth centuries B.C.E.[54]

The term "cappellaccio" has given rise to some confusion in the archaeological literature about the buildings of Rome. Blake describes true cappellaccio as the "thin layer of peppery, gray, friable tufa which caps all the hills of Rome," but then states that "the term as generally applied refers to the lowest stratum of every hill of the Roman group." Blake adds that the term "peperino" was used for cappellaccio in some older archaeological books. She suggests that the term "cappellaccio" be employed "in a modern attempt to make a distinction between this ugly friable tufa and the more fine-grained peperino [i.e., Lapis Albanus] or the coarser Gabine stone."[55] Some varieties of Tufo del Palatino that crop out within the city do contain a great deal of lava fragments, about 20–30% of the rock volume;[56] further work is needed to identify this special aspect of the tuff within the monuments. Even so, the use of modern geologic nomenclature (see table 1, fig. 5) and mapping of the tuffs (see fig. 3) immediately clarify much of the longstanding confusion over the term "cappellaccio": Grottarossa Pyroclastic Sequence subunit a crops out only at the top of the Palatino Hill; Tufo del Palatino crops out at the base of the Palatine and Capitoline Hills; Lapis Albanus and Lapis Gabinus are readily distinguishable. All four tuffs can be clearly identified in the monuments by their proper geological names. In addition, archaeologists should be aware that a very well-lithified variety of Tufo del Palatino crops out north of the city and near the Vatican (see figs. 2, 3). Called "peperino della Via Flaminia," it bears some resemblance to Lapis Albanus; we have not, however, identified this facies in monuments in Rome.[57]

Tufo Lionato, the tawny-orange, glassy tuff that was used extensively in Roman Republican cut-stone construction, is an ignimbrite that was quarried west and south of Rome as well as in the city (see figs. 2, 3). The Romans first quarried soft Tufo Lionato from the Capitoline Hill and the Monteverde area, on the west bank of the Tiber River, for use in cut-stone masonry (see fig. 3).[58] These quarries are now largely obliterated by ancient and modern construction. Tufo Lionato from outcrops in the Monteverde area and at the base of the Capitoline Hill is quite similar; it is soft and porous, with abundant small pumice fragments and less than 10% lava fragments. White zeolite cement stands out against the moderate brown glass matrix (see appx.). Frank identifies "Monteverde tufa" in several second-century B.C.E. and early first-century C.E. Roman monuments, stating that it was used in Ostia through the Augustan period.[59] In our view, however, further work is needed to identify the petrographic characteristics of Tufo Lionato that might have been quarried from the Monteverde area.

By the second century B.C.E., the Romans had created extensive quarries for firm, moderately durable, vitric-lithic/crystal Tufo Lionato (see figs. 2, 5d, appx.) within ignimbrite deposits more than 10 m thick along the Aniene River at Tor Cervara, Settecamini, Salone (fig. 7b), and Lunghezza.[60] Sometimes termed "litoide" (stonelike) by modern Italians, Tufo Lionato from these quarries contains up to 20% lava and crystal fragments, which enhance its strength in cut-stone construction. The podium of the Temple of Apollo Medicus Sosianus,[61] rebuilt in late first century B.C.E. (see fig. 5d), provides good exposures of this Tufo Lionato cut-stone masonry, as do many other Late Republican structures (see figs. 6d, e, g, h). Tufo Lionato obtained from thin deposits south of Rome, however, is a much softer, glassy tuff, which ranges from light brown to grayish-orange to pale yellowish-orange in color, and is cut by irregular and frequent fractures. The walls of the Baths of Caracalla constructed in 211–216 C.E., for example, are brick-faced concrete with a wall core of this Tufo Lionato coarse aggregate.[62]

Three strong, durable tuffs containing abundant lava and crystal fragments—Tufo di Tuscolo, Lapis Gabinus, and Lapis Albanus—played an important structural role in Late Republican and Early Imperial construction. Tufo di Tuscolo is a dense, moderate brownish-gray, compact tuff that commonly contains up to 50% lava fragments (see fig. 5e, appx.); some blocks, however, have abundant light brown glass. Quarries for the tuff exist near the Roman town of Tuscolo along the northern rim of the central caldera of Alban Hills volcano (see fig. 2). Lugli men-

[54] Frank 1924, 17–19; Blake 1947, 23–6; Coarelli 1997, 364–67.

[55] Blake 1947, 23.

[56] Jackson et al. 2006.

[57] Karner et al. 2001a.

[58] Frank 1924, 28–32.

[59] Frank 1924, 29–30; Blake 1947, 30–1.

[60] Quilici (1974) presents comprehensive descriptions, maps, and photographs of these quarries.

[61] *LTUR* 1:49–54.

[62] DeLaine (1995, 87) describes the soft, yellowish to red Tufo Lionato coarse aggregate of concrete of the Baths of Caracalla and suggests the tuff could have been quarried from the San Saba area near the Aventine Hill or the Fosse Ardeatina. Petrographic characteristics of Tufo Lionato sampled near these areas by Jackson et al. (2005) support this hypothesis.

tions in passing the building stone used in Tuscolo but never cites its use in Rome.[63] De Rita, however, identifies the tuff building stones of the Colosseum as "sperone" quarried near Tuscolo; she describes sperone as the product of scoria eruptive fountains.[64] Based on our petrographic studies, however, pyroclastic surge eruptions might better account for the variable abundances of lava and glass fragments in the tuff. We have identified as Tufo di Tuscolo the robust block work of the radial piers and ambulatory walls of the Theater of Marcellus (23–11 B.C.E.) (see fig. 6f),[65] along with some internal walls and supporting pillars of the Tabularium. Lapis Gabinus is a hard, moderately well-lithified, thin- to thick-bedded tuff composed of coarse- to fine-grained layers that was quarried at Valle Castiglione (see figs. 2, 7c). Coarse-grained layers contain about 50% dark gray lava fragments and crystals, while finer-grained, glassy layers contain accretionary lapilli, occasional pumice fragments, and sparse clay (see fig. 5f, appx.). (Accretionary lapilli are spheroidal pellets usually less than 1 cm in diameter formed during eruption by accretion of wet glass particles around a central nucleus, such as a glass or rock fragment.) These variations are particularly visible within the foundation of the Tabularium and the boundary wall of the Forum of Augustus (see fig. 6h).[66] Romans quarried Lapis Albanus, an olive-gray, comparatively well-lithified tuff rich in crystals as well as lava and limestone rock fragments (see fig. 5g, appx.) from a 12 m thick pyroclastic surge deposit that avalanched within an ancient valley near Marino (see fig. 2).[67] The podium and cella walls of the Temple of Antoninus and Faustina (141 C.E.) provide good examples of variations in the tuff.[68]

Modern Italians commonly refer to both Lapis Gabinus and Tufo di Tuscolo as "sperone." Distinguishing between the tuffs geologically, however, is straightforward. Tufo di Tuscolo has a compact texture with rough surfaces defined by pitted lava fragments surrounded by light to moderate brown glass fragments; Lapis Gabinus has a distinctive layered appearance with olive-gray, coarse- and fine-grained beds; and Lapis Albanus has a homogeneous fabric with scattered lava and limestone fragments that stand out against a light olive-gray matrix (see figs. 5f–h, appx.).[69]

Pozzolane

The Roman pozzolane are deposits of partially lithified, granular tephra; they can be easily excavated with a shovel. Three pozzolane deposits, Pozzolane Rosse, Pozzolane Nere, and Pozzolanelle, crop out through the Alban Hills volcanic district (see fig. 2). Pozzolane Rosse is composed primarily of pale red (10R 6/2 on the Munsell Color Notation chart of the Geological Society of America), grayish-red (10R 4/2), and blackish-red (5R 1/2) altered microscoria and opal-cemented aggregates of fine ash-sized microscoria that resist crushing when pressed between the fingers (fig. 8); Pozzolane Nere contains generally both fine and coarse, pale brown (5YR 5/2), altered glass and lava fragments; and Pozzolanelle contains soft, crumbly, moderate yellow-brown (10YR 5/4) altered glass and pumice. A common misconception is that the Roman pozzolane are composed largely of fresh volcanic glass or vitreous components.[70] Our petrographic and geochemical analyses indicate that all glass of Pozzolane Rosse, Pozzolane Nere, and Pozzolanelle has been altered through diagenetic processes, mainly low-temperature alteration of interstitial groundwater with volcanic glass and leucite, which occurred over hundreds of millennia after the emplacement of the pyroclastic flows. Nondispersive

[63] Lugli 1957, 198. Curiously, Frank (1924), Blake (1947), Coarelli (1997), and Claridge (1998), e.g., make no mention of Tufo di Tuscolo building stones in Rome.

[64] De Rita and Giampaolo 2005. Fornaseri et al. (1963, 136–38) describe modern and ancient quarries for sperone near Tuscolo but do not discuss use of Tufo di Tuscolo as building stone.

[65] *LTUR* 5:31–5. Claridge (1998, 243–44) describes repairs made in the 1920s to the arcades of the northeastern outer ambulatory; we identify these as Tufo di Tuscolo. The fresh, olive-gray (5Y 3/2) blocks give a sense of the robust quality of the stone with which Roman builders were familiar. Decay over 2,000 years has altered the glassy constituents of the tuff; the ancient blocks range in color from light brown (5YR 4/6) to moderate brown (5YR 3/4).

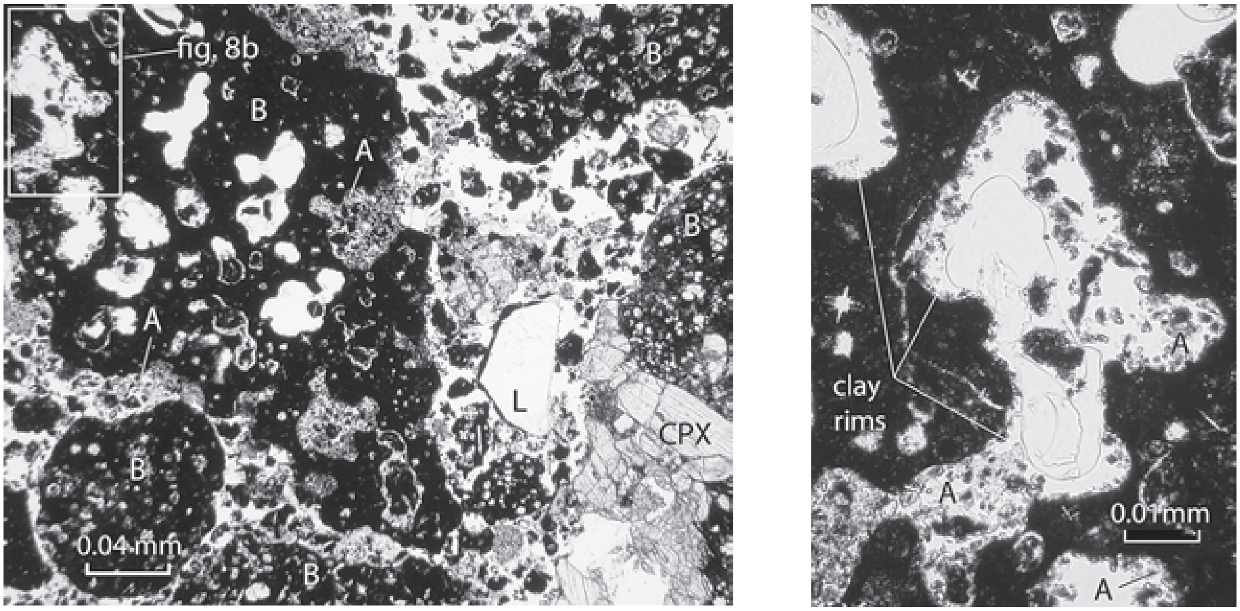
[66] *LTUR* 2:289–95.

[67] Lago Albano pyroclastic deposits (supra n. 35).

[68] *LTUR* 1:46–7.

[69] Lugli (1957, 245–334) introduced a great deal of confusion into the identification of the tuffs with his catalogues of building stones of the Republican and Imperial monuments. He did not recognize Tufo di Tuscolo as a building stone in Rome; rather, he describes the tuff of the Theater of Marcellus and the Colosseum as both "tufo litoide" (329, 333) and "tufo dell'Aniene" (311, 329). One might then consider that his tufo litoide refers to Tufo Lionato and that he has mistakenly identified Tufo di Tuscolo as Tufo Lionato. It is perplexing, therefore, that Lugli refers to the Lapis Albanus building stones at the Forum of Nerva and Temple of Divine Hadrian as both "tufo litoide" and "peperino" (305, 333). In other instances he refers to both Lapis Albanus and Lapis Gabinus by their proper names as well as "peperino" and "tufo litoide." These and other contradictions in terminology (supra n. 25) demonstrate the need for reidentification of the tuff building stones using systematic geological nomenclature.

[70] Torracca 1988, 71; Roy and Langton 1989, 7.



a b

Fig. 8. Photomicrographs of a thin section of Pozzolane Rosse from a drill core beneath Istituto Nazionale di Geofisica e Vulcanologia (see fig. 2) showing characteristic volcanic and alteration textures (sample INGV-PR-06), plane polarized light: *a,* note opal and clay cemented accretions of fine ash-sized microscoria (A) around the perimeters of sand-sized altered microscoria (B) and within vesicles (cavities) in microscoria, poorly crystalline clay coatings fill vesicles and surround volcanic fragments, ash accretions, and ash aggregates (L = leucite, CPX = clinopyroxene); *b,* detail of microscoria vesicle.

clay mineral, which does not remain suspended in water, is the principal alteration product.[71] The pozzolane, therefore, have material characteristics that are very different from the Roman tuffs.

In the modern cement industry, "pozzolan" refers to all inorganic materials that harden in water when mixed with lime or materials that release lime.[72] The pyroclastic pozzolane deposits that occur near Pozzuoli (near Naples) or Rome are specific types of pozzolan that generate hydraulic mortars that harden in water. By the early second century B.C.E., Romans had developed hydraulic, pozzolan-lime mortars with fine aggregate of Roman pozzolane, rather than pyroclastic deposits from Pozzuoli, for functional concrete work within the city.[73] We have identified Pozzolanelle as friable aggregate within early mortars (fig. 9a), as in the early second century B.C.E. Porticus Aemilia,[74] and within functional structures, such as a segment of the Aurelian Wall at Via Giotto, constructed in third century C.E. over an outcrop of Pozzolanelle. Mortars of monuments constructed from the late first century B.C.E. onward employ Pozzolane Rosse predominantly as pozzolan (see fig. 8, appx.) and retain volcanic and alteration textures of the pozzolane within their internal structure (fig. 9b, c).

Vitruvius describes the fine aggregate of Roman mortars as *harena fossiceae*, or excavated sand.[75] Granulometric measurements substantiate Vitruvius' observations; they show that natural Roman pozzolane contained within Roman mortars are composed chiefly of sand-sized grains.[76] Note that the only ma-

[71] Fornaseri et al. (1963) identified the clay mineral in Pozzolane Rosse as halloysite ($Al_2O_3\ 2SiO_2\ 4H_20$), which consists of the hydrated and nonhydrated forms. Altered microscoria compose about 45–65% by volume of Pozzolane Rosse (see fig. 8); crystals of leucite and/or analcime, clinopyroxene, and biotite form about 5–15%; and coatings or natural cements of opal (amorphous silica with no crystalline structure), clay, or opal-clay mixtures form up to 30%.

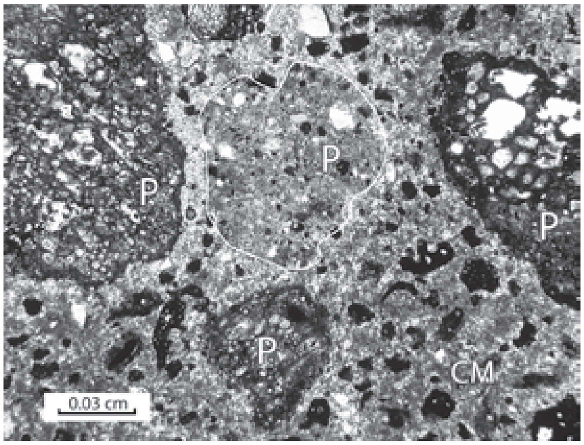
[72] Massazza 1998.

[73] Lechtman and Hobbs 1987, 88–93.

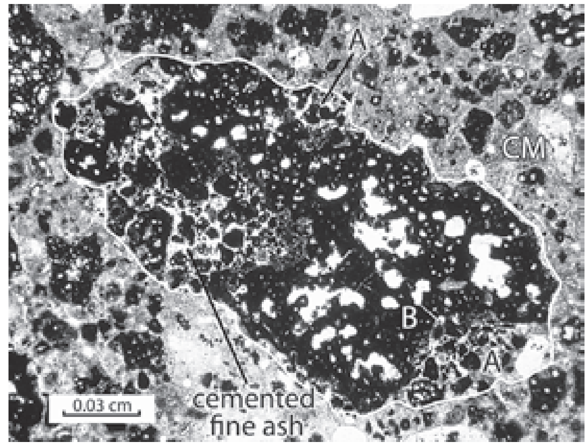
[74] *LTUR* 4:116–17.

[75] Vitr. *De Arch.* 2.4.1–3.

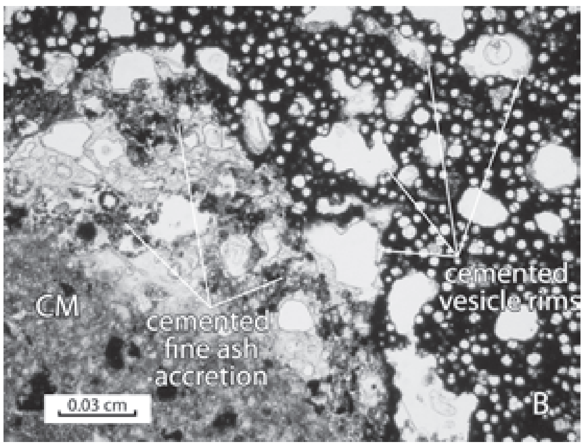
[76] Jackson et al. 2006. Our initial measurements of particle-size distributions (we measured the long and short axes of 500 grains per thin-section and computed a corrected sieved-size distribution through the method determined by Friedman 1957) show that sand-sized grains form about 70–75% of natural Pozzolane Rosse and the fine aggregate of Roman mortar samples from the Basilica Argentaria (113 C.E.) and the Baths of Caracalla (217 C.E.), and the Pozzolanelle fine aggregate from a segment of the Aurelian city wall (third century C.E.).



a



b



c

Fig. 9. Photomicrographs of thin sections of Roman mortars, plane polarized light: *a,* oldest mortar of Porticus Aemilia (sample 2004–PA-C1), with pumicelike altered glass fragments of Pozzolanelle (P) surrounded by friable cementitious matrix (CM) containing fine sand-sized altered glass fragments; *b,* Basilica Argentaria mortar with Pozzolane Rosse fine aggregate (sample 2004–FC-C4), with a hard ash aggregate, as described by Vitruvius (*De Arch.* 2.4.1), overgrown by cementitious materials; *c,* Basilica Argentaria mortar with Pozzolane Rosse fine aggregate (sample 2004–FC-C4), with a sand-sized, altered microscoria with an accretion of fine ash-sized microscoria and vesicle rims (see fig. 8b) overgrown by cementitious materials (A = cemented accretion of fine ash-sized microscoria; B = sand-sized altered microscoria; CM = strong cementitious matrix containing fine sand-sized altered microscoria).

terials that Vitruvius recommended be sieved were gravels from the riverbed or seashore. The sand of these sedimentary deposits, the "*fossicia fluviatili aut marinae*" of Pliny the Elder, is composed chiefly of quartz, or chemically stable, silicon-dioxide crystals that have little reactivity with lime.[77] Vitruvius recommends 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.[78] We observe that when thus rubbed, Pozzolanelle crumbles into a fine, earthy powder that adheres to the fingers. Pozzolane Rosse, however, makes a crackling sound and retains a largely pellet-like structure formed of altered microscoria and opal and/or clay cemented ash aggregations (see figs. 8, 9). Apparently, the abundance of soluble clay and opal within Pozzolane Rosse, coupled with the high porosity and reactive surface area of its altered tephra, enhanced its capacity to react with hydrated lime (portlandite, Ca $[OH]_2$) to form enduring cementitious compounds that have remained robust and durable over two millennia.

Travertine

Deposits of light yellowish-gray travertine within the Acque Albule basin, about 30 km east of Rome (see fig. 2), provided the Romans with an important source of hard, dense, durable building stone. The deposits are associated with faults that produced conduits along which sulphurous and calcium carbonate–rich groundwater traveled to the surface and filled shallow lakes within the basin.[79] Living clumps of bacteria on the lake bottoms continuously precipitated coronas, or rings, of calcite; the bacteria then decayed seasonally, leaving calcite crystals riddled with micropores.[80] During flourishing growth of bacteria during the summer, aggregates of these crystals

[77] Vitr. *De Arch.* 2.4.2–3; Plin. *HN* 36.175.
[78] Supra n. 77

[79] Faccenna et al. 1994.
[80] Chafetz and Folk 1984.

formed laterally extensive, shrublike growths 2–8 cm high. During the winter, these were covered with thin deposits of mud transported by winter storm water; this calcite mud helps to cement the travertine. Cyclic repetitions of these structures give the travertine a complicated, hummocky internal texture with abundant small voids (see fig. 5h). The travertine accumulations are more than 60 m thick and contain many active quarries. In contrast, thin, localized deposits of tufa that form around the mouth of a calcareous seep or spring have a porous, spongy, crumbly texture unsuitable for building stone.[81]

Limestone

Romans burned limestone to obtain lime for pozzolan-lime mortar.[82] The marine limestone that forms the deep bedrock of Rome was deposited during the Mesozoic-Cenozoic eras. In the city, these deposits remain buried under much younger sedimentary and volcanic deposits (see figs. 3, 4). Uplift of the Appennine Mountains brought extensive limestone deposits to the earth's surface, such as those that form the Monti Tiburtini about 35 km east of Rome above Tivoli (see fig. 2). Hard limestone also forms the isolated peaks of Monte Cornicolani and Monte Soracte, 25 and 40 km northeast of Rome, which existed as islands within the Middle Pleistocene–age sea that deposited the claystone bedrock of Rome and its surroundings.[83] These various localities provided important sources of lime, which would be transported to Rome along the Aniene River.[84]

Clay

Within Rome, the Monte Vaticano formation, which crops out on the west bank of the Tiber River (see fig. 3), provided the principal source of clay for brick.[85] There are extensive surficial exposures of the Monte Vaticano formation (see fig. 2) along the Tiber River north of Rome and near Monte Cornicolani. During the Imperial age, many brickyards existed within this area and, in particular, near the confluence of the Farfa River with the Tiber.[86] Wood fuel was readily available to fire the brick and would be transported down the Tiber River into Rome.

PHYSICAL CHARACTERISTICS OF THE ROMAN TUFFS AND TRAVERTINE

A description of the relative strengths and durability of the volcanic building stones leads to a deeper archaeological understanding of Roman structural design and construction, as well as to an appreciation of the expertise of Roman builders. Geologic assessment with petrographic studies and rock testing experiments demonstrates that the Roman tuffs and travertine have a wide range of physical and material properties.[87] Overall, the weight-bearing strengths of the tuffs are much lower than that of travertine (fig. 10). The most durable tuffs, Lapis Albanus, Lapis Gabinus, and Tufo di Tuscolo, contain more than 40% lava and crystals (see figs. 5e–g). These tuffs have greater bulk specific gravity (G= 1.81–1.87) and, therefore, a greater capacity to withstand weight-bearing loads without fracturing.[88] The lava fragments provide a strongly grain-supported framework of hard, dense, relatively inert particles to which mineral cements in the tuff may firmly adhere. In contrast, Tufo Giallo della Via Tiberina and soft Tufo Lionato from the south of Rome contain less than 15% lava and crystals, more than 20% altered glass matrix, and/or more than 5% pumice fragments. (Matrix is fine-grained ash that encloses larger particles within the tuff.) Accordingly, pumice-rich Tufo Giallo della Via Tiberina has low bulk specific gravity (G=1.52) and low compressive strength (see fig. 10). During weathering, pumice glass commonly alters to clay and crumbles (see fig. 5a). In addition, the altered glass matrix of Tufo Giallo della Via Tiberina, porous Tufo Lionato from the south of Rome, and some Tufo del Palatino samples contains small but pervasive amounts of clay. Mineral cements

[81] Marra et al. (1998), e.g., describe calcareous tufa incrustrations within the Middle Pleistocene Valle Giulia Formation in Rome (see fig. 3).

[82] Cato *Agr. Orig.* 38; see also Rapp 2002, 255–58.

[83] Facenna et al. 1995, fig. 10.

[84] DeLaine 1997, 88–9.

[85] A late 18th-century drawing by F. Becker (Keaveney 1988) shows an ancient claystone quarry within the Monte Mario Formation along the south flank of Saint Peter's basilica.

[86] DeLaine 1997, 89–91; Lancaster 2005, 17.

[87] Jackson et al. (2005) determined uniaxial compressive strength (ASTM D695 [C170–90] [ASTM 2002b]) under oven-dried, water-soaked, and humid (90–98% relative humidity) conditions for seven Roman tuffs and travertine sampled from the important Roman quarries; absorption of liquid water, computed as $weight_{water\text{-}soaked} – weight_{oven\text{-}dried}/weight_{water\text{-}soaked}$ (ASTM D570 [C97–96] [ASTM 2002a]); adsorption of water vapor, computed as $weight_{humid} – weight_{oven\text{-}dried}/weight_{humid}$; and bulk specific gravity, computed as $weight_{oven\text{-}dried}/weight_{water\text{-}soaked, in air} – weight_{water\text{-}soaked, in water}$ (ASTM D792 [C97–96] [ASTM 2002a]). Additional data are presented in Ventriglia 1971, 187–225; Nappi et al. 1979; Bianchetti et al. 1994; De Casa et al. 1994, 1999; Laurenzi-Tabasso et al., 1994; Sappa et al. 1995.

[88] Bulk specific gravity is the ratio of the mass of one substance (such as rock) to the mass of an equal volume of water at a specified temperature. It provides a standardized measure of the unit weight per volume for building stone.

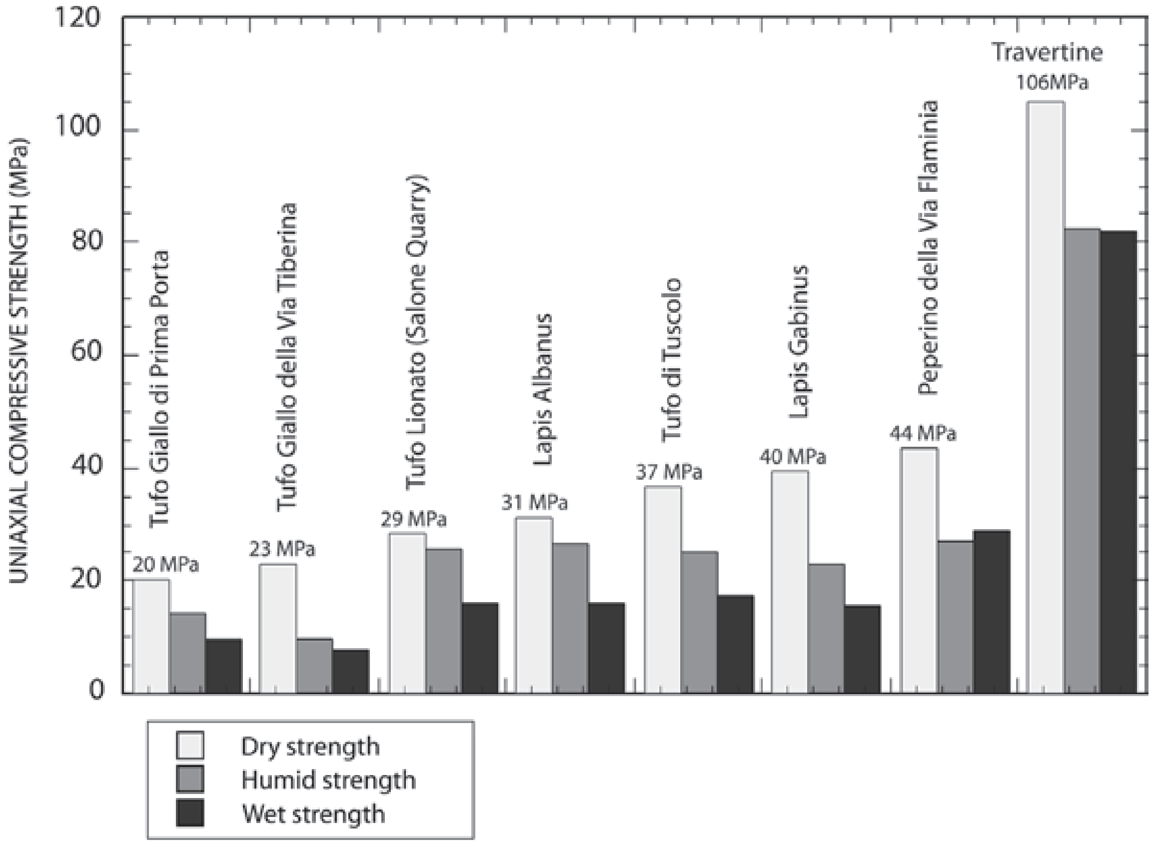


Fig. 10. Uniaxial compressive strengths of the Roman tuffs and travertine under oven-dried, humid, and water-soaked experimental conditions (modified from Jackson et al. 2005).

bind poorly to clay-bearing pumice fragments and matrix, reducing the durability of the stone.

The Roman tuff building stones are, at best, only moderately well-lithified, porous rocks. Vitruvius states that "so long as they are sheltered in covered places [*locis tectis*] they will hold up and sustain loads [*sustineant laborem*], but if they are laid bare or exposed in the open air, ice and frost accumulate within them and they crumble and dissolve apart."[89] Comparison of disaggregating, crumbling Tufo Giallo della Via Tiberina exposed for centuries in the Republican Wall on the Aventino Hill (see fig. 5a) with the fresh, intact tuff protected within the Theater and Crypta of Balbus strongly supports Vitruvius' statement. Similarly, Tufo Rosso a Scorie Nere exposed within the podium of the Temple of Juno Moneta is worn, lichen covered, and altered (see fig. 6a), while the glassy tuff blocks that form interior walls within the Tabularium retain their sharp corners and edges.

Vitruvius' contrasting observations on the differential decay of tuff building stones in covered and exposed settings can be explained by the fact that all Roman tuffs readily take in significant quantities of water as liquid and/or vapor. With this intake of moisture they lose about 15–40% of their dry strength (see fig. 10) and are exposed to processes of stone degradation. The tuff building stones of many ancient foundations are periodically saturated with groundwater, thereby lessening their weight-bearing strength. Absorption or penetration of rainwater into porous stone masonry may soften the surface of the building stone, causing it to swell and corrode.[90] Absorption of droplets of acid rain at present accelerates the dissolution of mineral cements within the

[89] Vitr. *De Arch.* 2.7.2. Vitruvius seems to imply with the term "*locis tectis*" a plaster covering or *opere tectorio* (*De Arch.* 7.5.8) over the tuff stonework. In Lewis and Short (1879), one can find *tectōrĭus* (*a, um*; adj.) defined as "of or belonging to covering or to a cover . . . that belongs to or serves for covering or overlaying walls, ceilings, floors, etc.; of or belonging to staining, painting, stuccoing, plastering, etc." Vitruvius mentions such plasterwork no less than 30 times in *De Architectura*; in addition to its decorative function, it seems to have had great importance for protecting soft masonry walls from degradation and decay.

[90] Torracca 1988, 97–9.

tuffs.[91] Adsorption of water vapor into building stone occurs during the day when warm, humid air condensates on cool masonry walls. In the evening, when temperatures decline, the air releases water vapor, which settles on the exposed surfaces of cool building stones. Free water molecules then penetrate into the porous stone and attach to the surfaces of narrow capillaries.[92] Moisture traveling through pores and capillaries may dissolve grain cements and cause microcracking and disaggregation of the tuff as clay minerals expand and contract. When tuff masonry—or any other soft, porous, stone masonry—is protected from direct contact with rainwater and daily fluctuations of atmospheric humidity through, for example, a roof and overhanging eaves, applications of plaster (fig. 11a), or decorative stone facings, it retains much of its strength and durability.

Vitruvius states, "Travertine, on the other hand, and all stones of the same type, withstands heavy loads [*oneribus*] and damage incurred during stormy, wet seasons [*tempestatibus inurias*]."[93] Field observations and experimental data support Vitruvius' observations. Travertine resists decay far better than the tuffs; it has low water intake and retains 80% of its strength when water soaked (see fig. 10). Vitruvius continues, "but [travertine and all stones of the same type] cannot be safeguarded against fire. As soon as they come into contact with it, they crack apart and fall to pieces."[94] Travertine, marine limestone, and marble (metamorphosed, recrystallized limestone) are composed of calcite crystals. When heated, calcite lengthens 0.189% along one crystallographic axis but contracts 0.042% perpendicular to it.[95] This irregular change in shape generates strains within the grain mosaic of the stone. At the high temperatures of urban fires (800ÚC–1200ÚC), grain contacts among calcite crystals rupture and the stone eventually fractures, as Vitruvius describes. In addition, experimental heating of certain marbles to 900ÚK (627ÚC) causes them to undergo an overall thermal linear expansion (or lengthening) of about 2%, while certain tuffs expand only about 0.25%.[96] Carrara marble, in particular, experiences an average thermal linear expansion of 6 x 10^{-6} cm/cm/ÚC, while the few measurements performed on lithified tuffs give lower values, 4–4.65 x 10^{-6} cm/cm/ÚC.[97] The interlocking texture of calcite crystals in travertine and marble accommodates thermal expansion far less readily than the porous, weakly cemented texture of the tuffs.

ELEMENTS OF ROMAN VOLCANIC STONE CONSTRUCTION

In *De Architectura*, Vitruvius describes the development and progress of human expertise in building and the arts:

> 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 of what quality they are and which quality they have.[98]

He discusses "the supplies of material that are assembled to bring buildings to completion, both with regard to their construction and to the correct treatment of materials, . . . of what particular functional qualities they possessed, and . . . of what natural elements they are composed."[99] We now give examples of volcanic rock in Roman construction that offer new insights into certain monuments, as well as provide instructive, easily accessible localities where others may examine the geologic characteristics of the various stone building materials. These geological observations of the monuments illustrate a continual development of Roman skill and ingenuity in using the diverse material properties of local stone to execute and perfect an architecture that, in Vitruvius' words, "exhibits the principles of durability, utility, and grace [*firmitatis, utilitatis,* and *venutatis*]."[100]

Cut-Stone Tuff and Travertine Masonry

The geological map (see fig. 3) shows exposures of the relatively poorly lithified tuffs, mainly the Tufo del Palatino, Grottarossa Pyroclastic Sequence subunit a, and Tufo Lionato ignimbrites, first available to the inhabitants of Rome. Early Romans developed quarries for these tuffs along hillsides and in underground galleries beneath the Palatine and Capitoline Hills.[101] Sixth- and fifth-century B.C.E. use of these tuffs for cut-stone masonry (see appx.) include two largely intact, circular, Archaic cisterns or granaries of Grottarossa Pyroclastic Sequence on the Palatine Hill, the original Tufo del Palatino podium (see fig. 5c) of the Temple of Jupiter Capitolinus (509 B.C.E.),[102] and the Tufo del Palatino foundation of

[91] De Gennaro et al. 1992; Colantuono et al. 1993.

[92] Torracca 1988, 13–16; Pearce and Smith 1990; Winkler 1994, 142–55.

[93] Vitr. *De Arch.* 2.7.2.

[94] Supra n. 95

[95] Logan et al. 1993; Winkler 1994, fig. 10.3.

[96] Touloukian et al. 1981.

[97] Bauleke and Hugh 1968; Logan 1993.

[98] Vitr. *De Arch.* 2.1.7

[99] Vitr. *De Arch.* 2.preface 5.

[100] Vitr. *De Arch.* 1.3.2.

[101] Frank 1924, 11–32; Blake 1947, 23–6; Cifani 1995.

[102] *LTUR* 3:148–53.

the Regia (sixth century B.C.E.).[103] Further petrographic work is needed to unambiguously identify Tufo Lionato quarried from the Capitoline Hill and Monteverde areas (see fig. 3) in Republican-age construction. These three rather poorly consolidated, predominantly glassy tuffs have low strengths and readily absorb rain and groundwater and adsorb atmospheric moisture in Rome's often humid climate.[104] They are particularly susceptible to corrosion and decay when exposed to winter rains, daily fluctuations in relative humidity, and the freezing temperatures that occur sporadically within the city. Regular inundations of floodwater in the Tiber River floodplain (see fig. 3) and groundwater flow exacerbated deterioration of tuff walls and foundations. Still, the soft tuff masonry was far more durable than mudbrick walls and foundations that disintegrated when saturated with floodwater, as described by Dio Cassius regarding the 54 B.C.E. Tiber River flood.[105]

After their conquest of the nearby Etruscan cities of Fidenae and Veio in 426 B.C.E. and 396 B.C.E., Romans began using glassy tuffs quarried from Monti Sabatini volcano for cut-stone masonry (see fig. 2, appx.). Porous Tufo Rosso a Scorie Nere (see figs. 5b, 6a) has very low weight-bearing strength and was used sparingly in Late Republican construction.[106] By contrast, Tufo Giallo della Via Tiberina (see figs. 5a, 6c) has somewhat greater weight-bearing strength (see fig. 10), and is more durable than the clay-bearing Tufo del Palatino quarried within Rome.[107] For much of the sixth through fourth centuries B.C.E., Roman architecture strongly reflected Etruscan architectural influences based on fine cut-stone tuff masonry. Temple C at Largo Argentina, for example, has a high podium (see fig. 6c) of Tufo Giallo della Via Tiberina block work, and a frontal staircase and entrance with a deep pronaos.[108] The 4 m tall podium, constructed on the marshy ground of the Campus Martius in the Tiber River floodplain, elevated the interior of the temple above the level of most floodwaters, while alae along the sidewalls and wide eaves probably protected the rather porous, pumice-rich tuff cella walls from direct exposure to moisture. At a later date, Romans constructed an outer, corniced perimeter wall of fairly well-lithified, more durable Tufo Giallo della Via Tiberina around the original temple podium.

Construction of the Via Appia in 312 B.C.E. gave Romans access to quarries for moderately well-

a

b

Fig. 11. Example of Roman techniques for preservation of tuff cut-stone masonry and concrete: *a*, plaster-coated Lapis Albanus columns, first century B.C.E., Via delle Botteghe Oscure; *b*, marble facings, Augustan Rostra and Arch of Septimus Severus, 203 C.E., Roman Forum..

cemented Lapis Albanus from Alban Hills volcano, 20 km southeast of Rome. The weight-bearing strength

[103] *LTUR* 4:189–92.

[104] Bianchetti et al. (1994) describe alteration of exposed tuffs within the Roman Forum.

[105] Dio Cass. 39.61.

[106] About 2–5 MPa under ambient conditions; Frank 1924, 21–2; Blake 1947, 26–7; Lugli 1957, 256–58; Laurenzi-Tabasso et al. 1994.

[107] Supra n. 6.

[108] Boethius 1978, 121–23, 130–31, 156; Coarelli 2001, 331–39.

and durability of this solid, lithic-crystal tuff is far greater than the more porous, glassy tuffs previously available in Rome (see fig. 10). During the third and second centuries B.C.E., Romans used Lapis Albanus mainly for column bases, drums, and capitals (see appx.), such as those forming the Ionic colonnade of the northernmost of the Republican victory temples of Janus, Spes, and Juno Sospita (mid third century B.C.E.) at San Nicola in Carcere in the Forum Holitorium (see fig. 6b). An intricately carved Lapis Albanus frieze, now in broken blocks on the grounds south of the church, apparently formed a decorative element of the temple.[109]

During the late second century B.C.E., quarries along the Aniene River produced an abundant supply of moderately durable, glassy lithic-crystal Tufo Lionato with moderate weight-bearing strength (see figs. 5d, 10) that could be transported by barge 6 to 8 km to the city center.[110] This Tufo Lionato became the ubiquitous building stone of Late Republican and Early Imperial construction. Temple B (101 B.C.E.) at Largo Argentina sacred area,[111] with its round podium and 16 fluted Tufo Lionato columns with travertine pedestals, bases, and capitals, provides a good example of early construction with Tufo Lionato from the Aniene quarries (see fig. 6e). With the increasingly sophisticated architecture of first century B.C.E., which combined Roman and Etruscan traditions with foreign influences from the growing Roman commonwealth,[112] Romans continued to make extensive use of Tufo Lionato but integrated this less durable tuff masonry with travertine and more robust lithic-crystal tuffs. The Temple of Portunus, rebuilt in 80–70 B.C.E. on the banks of the Tiber River, is a well-preserved example of the refined Tufo Lionato and travertine stonework of the Late Republican age (see fig. 6d).[113] The tabernae of the Forum of Caesar, inaugurated in 42 B.C.E., show the sophisticated construction design and careful selection of tuff and travertine for specific structural elements employed by Roman builders in a fascinating example of the integration of cut-stone and concrete masonry (see fig. 6g). An upper facade of Tufo Lionato with low bulk specific gravity (G= 1.73) is supported by robust, lithic-crystal Lapis Gabinus (G=1.81) pillars and flat arches, reinforced with travertine (G= 2.58) keystone voussoirs. Conversely, concrete barrel vault walls have lightweight Tufo Giallo della Via Tiberina as coarse aggregate (G=1.52) and overarches of dark brown Vesuvian scoria as coarse aggregate.[114] Again, at the Forum of Augustus, dedicated in 2 C.E., durable Lapis Gabinus block work and flat arches of travertine voussoirs give weight-bearing support in lower-level piers and statutory niches; lighter weight, moderately durable Tufo Lio-nato block work forms the upper story of the western hemicycle (see fig. 6h).[115] The Tufo Lionato podium of the Temple of Mars Ultor is reinforced with blocks of Lapis Gabinus at its corners, and fire-resistant Lapis Gabinus block work forms the boundary wall of the Forum; large travertine voussoirs support the gateway arch in the firewall. Strabo describes this trio of building stones quarried along the Aniene River as the source of "most of the works of art in Rome being constructed of stone."[116]

During the first century C.E., Romans continued to develop their expertise in using the material properties of their local tuffs and travertine to advantage in the structural design of public monuments. The Colosseum demonstrates the uniquely Roman empirical understanding of volcanic materials.[117] Tufo di Tuscolo forms the massive, cut-stone radial piers that support the upper stories of the amphitheater; large travertine blocks provide weight-bearing strength to the piers.[118] Tufo di Tuscolo was, perhaps, the most robust lithic-crystal tuff building stone available in Rome. Abundant lava fragments within the tuff produce its good compressive strength and higher specific gravity (G=1.83) (see figs. 5e, 10).[119] The Tufo di Tuscolo and travertine piers rest on a 13 m thick

[109] *LTUR* 3:90–1.

[110] Frank 1924, 14.

[111] *LTUR* 2:269–71.

[112] Boethius 1978, 136–37.

[113] Richardson 1992, 320; *LTUR* 4:153–54.

[114] *LTUR* 2:299–307. Lancaster (2005, 59–67) identifies Vesuvian scoria in concrete vaults of several Imperial-age structures.

[115] *LTUR* 2:289–95. The northeastern segment of the wall, which bounds the Forum of Nerva, was constructed in about 81–96 C.E. of Lapis Albanus.

[116] Supra n. 24.

[117] *LTUR* 1:30–5.

[118] Lancaster 2002, 361.

[119] We are currently investigating the petrographic characteristics of Tufo di Tuscolo within the Colosseum, in collaboration with Conti, to determine its source localities and variations in durability influenced, in part, by the relative abundance of light brown glass fragments within the tuff. At first glance, glassy blocks of Tufo di Tuscolo could be confused with Tufo Lionato. Initial petrographic studies, however, show that they contain more leucite than Tufo Lionato; strong phillipsite cement, with wide, clear, crystal rods characteristic of Tufo di Tuscolo quarried at Tuscolo; and well-developed calcite cements. When integrated with studies by Lancaster (2005, 60) on the provenance of pumice in concrete mortar of the Colosseum, and Beste (2002, 354–61) on Domitian renovations to the *ipogei* of the Colosseum, these analyses will provide a geological framework for evaluating the economy of construction of the amphitheater.

concrete ring composed of pozzolanic mortar and fist-sized leucititic lava coarse aggregate.[120] Like the lava fragments that lend compressive strength to Tufo di Tuscolo, the lava aggregate gives good weight-bearing strength, high specific gravity, and lasting durability to the concrete foundation. The concrete cross vaults and inner ambulatory vaults, however, contain coarse aggregate of porous, glassy Tufo Giallo della Via Tiberina; the low specific gravity of the aggregate reduces loads born by the underlying Tufo di Tuscolo and travertine piers and walls.[121] Travertine semi-columns supporting horizontal entablatures form the outer trabeated arcade of the Colosseum; with its low moisture sorption (see fig. 10), the travertine provided a decorative and highly durable facing for the amphitheater.

Remarkably, the stone builders of the Republican era coated most tuff masonry with a protective layer of plaster, which had a dual purpose: pragmatic, to remove the soft, porous stone from direct contact with rain and atmospheric humidity; and aesthetic, to provide a decorative surface that gave the appearance of the marble of ancient Greece.[122] Vitruvius emphasizes the importance of protecting soft tuff masonry with plaster and gives lengthy instructions for the mixing, application, and finishing of these coatings.[123] The broad, colonnaded porticus of fluted Lapis Albanus semi-columns exposed at the Temple of Janus, the Tufo Lionato columns at Temple B of Largo Argentina, and the Tufo Lionato semi-columns at the Temple of Portunus (see figs. 6b, d, e) retain original coatings of plaster, as do Lapis Albanus columns of the temple exposed at Via delle Botteghe Oscure (see fig. 11b).[124] During the first century B.C.E., Romans used panels of travertine as durable facings for tuff masonry. The cut-stone podium of the Temple of Portunus, for example, is Tufo Lionato faced with travertine nearly 50 cm thick (see fig. 6d). The facade of the outer ambulatory of the Theater of Marcellus is a highly decorative trabeated travertine arcade; there, travertine also reinforces the Tufo di Tuscolo cut-stone masonry (see fig. 6f).

With the development of quarries for Carrara marble in the late first century B.C.E. near Luni in Liguria,[125] Romans began to use marble more extensively as durable cladding for cut-stone tuff and concrete masonry. In the Forum of Augustus, for example, white Carrara marble faced the Tufo Lionato podium and cella walls of the Temple of Mars Ultor, while 24 Carrara marble columns supported its coffered ceiling; Italian and imported marble revetments hid the complexity of tuff and travertine cut-stone masonry entirely from view (see fig. 6h). Suetonius, writing in late first century C.E., comments: "Since the city was not adorned as the dignity of the empire demanded, and was exposed to flood and fire, [Augustus] so beautified it that he could justly boast that he had found it built of brick and left it in marble. He made it safe, too, so far as human foresight could provide for this."[126] Augustus remarks that he extensively rebuilt and refurbished numerous public buildings, temples, and bridges.[127] New construction and renovations of older structures involved the installation of marble or other ornamental stone revetments over tuff block work, usually moderately durable Tufo Lionato, more robust Lapis Gabinus, or concrete masonry.[128] For example, the concrete podium of the Late Republican rostra in the Roman Forum, which was initiated by Julius Caesar and refitted by Augustus, was faced with panels and bands of pink-gray Chios and red Teos marble that protected its porous Tufo Lionato coarse aggregate from decay (see fig. 11b).[129] In transforming the often plaster-covered tuff monuments of Rome into

[120]Rea 2002, 348–50.

[121]Lancaster 2002, 363.

[122]Boethius 1978, 139.

[123]Vitr. *De Arch.* 7.3.8, 7.4.1.

[124]*LTUR* 4:132–37.

[125]Strabo *Geographica* 5.2.5.

[126]Suet. *Aug.* 2.28.3. Here, brick (*lateres*) is strictly "of sun-dried brick." Marble (*marmor*) is either "of marble, or stone, in general" (Rolfe 1914).

[127]Augustus *Res Gestae,* 20–1: "The Capitolium and the theatre of Pompey, both works involving great expense, I rebuilt without any inscription of my own name. I restored the channels of the aqueducts . . . I completed the Julian Forum and the basilica which was between the temple of Castor and the temple of Saturn . . . I rebuilt in the city eighty-two temples of the gods, omitting none which at that time stood in need of repair . . . I reconstructed all the bridges except the Mulvian and the Minucian. On my own ground I built the temple of Mars Ultor and the Augustan Forum from the spoils of war. On ground purchased for the most part from private owners I built the theatre near the temple of Apollo which was to bear the name of my son-in-law Marcus Marcellus" (Shipley 1924).

[128]Favro 1996, 182–89. E.g., the Forum of Caesar and Forum of Augustus were constructed of marble-clad tuff and travertine block work (see figs. 6a, b); the tuff block work of the Theater of Marcellus has travertine cladding (see fig. 6h). Augustan repairs to the Lapis Gabinus block work of the Pons Fabricius have travertine cladding; a few fragments of the marble restoration of the Tufo del Palatino block work of the Temple of Jupiter Capitolinus survive in the Capitoline Museum; see also Boethius 1978, 208.

[129]Claridge 1998, 81–4; *LTUR* 4:212–17. By contrast, the imposing travertine podium of the Arch of Septimus Severus (*LTUR* 1:103–5) constructed next to the rostra in 203 C.E. has a gray-white Proconnesian marble facing (Claridge 1998, 75–6) that served a purely decorative function (see fig. 11b).

elegant, marble-clad structures, Augustus elevated the urban landscape of Rome to imperial stature and, at the same time, preserved the soft tuff masonry foundation of the city from decay for generations to come.

Concrete Masonry

Our geological framework for understanding the role of volcanic rock in Roman stone masonry would not be complete without a brief comment about the development of Roman concrete. Although cut-stone tuff and travertine masonry were used in construction in Rome through the second century C.E.,[130] concrete masonry had been present in the city since the second century B.C.E.; Porticus Aemilius, the large, riverfront warehouse reconstructed in 174 B.C.E. along the Tiber River, seems to be the earliest example of concrete construction in Rome. There, *opus incertum* concrete walls and barrel vaults contain rough chunks of Tufo Giallo della Via Tiberina coarse aggregate in the wall core and wall facings. Petrographic analyses suggest that its oldest pozzolan-lime mortars contain crumbly, light brown to grayish-orange Pozzolanelle fine aggregate (see fig. 9). Frank describes early functional concrete work of a 117 B.C.E. reconstruction of the podium of the Temple of Castor that employed Tufo del Palatino coarse aggregate taken from the older cut-stone temple walls.[131] Romans also used concrete rubble as fill between sections of tuff cut-stone masonry.[132] The enlargement of the circular podium of Temple B at Largo Argentina in about 19–12 B.C.E., for example, consists of a thin pavement of Lapis Albanus supported by vertical panels of Tufo Lionato from the Aniene quarries (see fig. 6e). The space between the original, corniced Tufo Lionato podium and the outer enlargement is filled with concrete composed of rough Tufo Lionato aggregate; perhaps the rubble was obtained from broken or rejected tuff blocks from the Aniene River quarries. *Opus incertum* walls of the barrel vaults over the latrines of the Forum of Caesar provide another good example of utilitarian concrete work; these have mainly Tufo Giallo della Via Tiberina coarse aggregate and mortar with Pozzolane Rosse fine aggregate. During the early first century C.E., Romans used Tufo Lionato from the Aniene River quarries to perfect *opus reticulatum* and *opus mixtum* facings for concrete work, such as those well preserved within the Auditorium of Maecenas on the Esquiline Hill.[133] The well-cemented tuff could be easily hewn into small, precise pyramids yet still remain coherent on the exterior of the wall, if protected from moisture.

Lancaster discusses the grading of coarse aggregate within concrete vaulted structures of the Imperial period.[134] Roman builders preferred lightweight Tufo Giallo della Via Tiberina in concrete vaults, as at the Colosseum and the Pantheon. They employed heavier Tufo Lionato coarse aggregate for wall cores, as at Trajan's Markets, again reserving Tufo Giallo della Via Tiberina for specific cross vaults. Early third-century Severan construction, however, adopted Tufo Lionato for wall cores, as at the Baths of Caracalla, but this Tufo Lionato seems to have been quarried from south of Rome rather than the Aniene River quarries.[135] Tufo Giallo della Via Tiberina is generally absent in these structures; Vesuvian scoria provided coarse aggregate for some concrete vaults.[136] A systematic investigation of the Tufo Lionato of various imperial monuments using the geological methodologies described here would help to identify its changing provenance and architectural and/or economic factors influencing its use over time.

CONCLUSION

An integration of geological and archaeological concepts is critical to understanding the central role of volcanic rock in the ancient Romans' development of their monumental architecture. Geological field observations, petrographic and rock testing data, and analysis of Latin texts show that by the late first century B.C.E., Roman builders had acquired a good understanding of the material characteristics of seven distinctive volcanic tuffs. They employed these to best advantage in the sophisticated cut-stone and concrete construction of the monuments of this period through the second century C.E. Strong, durable travertine played the most important role as a structural reinforcement to the soft tuff, cut-stone masonry and, with decorative marble cladding, protected the porous tuffs from decay. The Roman invention of robust concretes composed primarily of volcanic rock freed builders from the limitations of working with inconsistent and less durable cut-stone tuff masonry, eventually leading them to a truly innovative architecture of complex, molded interior spaces.

The volcanic rocks that form the basis of Roman construction—tuffs, pozzolane, and lavas—have diverse physical properties that depend on the mecha-

[130] Massive block work of Lapis Albanus cut-stone masonry was employed extensively in imperial monuments constructed by Vespasian (69–79 C.E.), Nerva (96–8 C.E.), Hadrian (117–134 C.E.), and Antoninus Pius (138–61 C.E.) (see appx.)

[131] Frank 1924, 79–80; *LTUR* 1:242–45.

[132] Ward-Perkins 1977, 97–100.

[133] *LTUR* 3:74–5.

[134] Lancaster 2005, 59–67, 213–14.

[135] Supra n. 62.

[136] Supra n. 134.

nisms through which they were erupted and transported away from the volcanic vent as well as their subsequent alteration on the ground surface. The strength and durability of the tuff building stones, for example, are defined by the relative abundances of their primary components—glass and pumice, crystals, and lava and limestone rock fragments—that were determined in large part by eruptive process. The secondary components of the tuffs and pozzolane, mainly zeolite cements for the tuffs and zeolite, opal, and clay mineral coatings and cements for the pozzolane, developed during alteration after eruption. This mineralogical assemblage enhanced the durability of Roman concrete; it augmented the reactivity of Roman pozzolane with lime and increased the bonding strength of coarse tuff aggregate with robust pozzolanic mortar. The volcanic landscape of Rome thus provided Roman builders with a unique and varied palette of stone building materials with which they made extraordinary technological innovations over many centuries.

The techniques of geological analysis described in this article provide a scientific basis for making new archaeological findings about ancient Roman construction. Our new geological maps are essential to establishing an archaeological understanding of the volcanic foundations of Rome and the human capacity to transform an urban environment from both geomorphological and architectural points of view. The use of modern geological maps and stratigraphy clarifies the nomenclature of the tuff and pozzolanic building materials and lays the foundation for accurate studies of transport of stone from quarries and economy of construction. In practice, identification of the petrographic characteristics of a given tuff or pozzolane through simple observation of thin sections with a petrographic microscope may obviate the need for far more expensive techniques, such as isotopic analysis or age dating, to establish provenance. Ultimately, integration of petrographic and rock testing data with systematic observations of the structural elements of volcanic stone construction in the Roman monuments gives us new insights about Roman builders' empirical understanding of stone material properties and the evolution of their architecture.

Many questions about ancient Roman stone construction and provenance remain unanswered. For example, where and when did Romans first obtain the more durable Tufo Giallo della Via Tiberina employed in the perimeter wall of the podium of Temple C at Largo Argentina and the Theater and Crypta of Balbus (13 B.C.E.)? This building stone is far more firm and robust than the more widespread soft and porous Tufo Giallo della Tiberina used in the Republican walls of fourth century B.C.E. or as coarse aggregate in Late Republican and Early Imperial concrete work. A future study might compare the petrographic features of Tufo Lionato from the Monteverde area and the Aniene River quarries to establish the provenance of early Tufo Lionato construction in the city. Why, after the early first century B.C.E. and the construction of the Forum of Augustus, does the once ubiquitous Tufo Lionato block work from the Aniene River quarries rarely appear as cut-stone masonry?[137] What might have precipitated its sudden withdrawal from use, and how does this relate to the popularity of concrete work with Tufo Lionato *opus reticulatum*? When did porous Tufo Lionato from south of Rome first come into widespread use in Imperial-age concrete work? What of Tufo di Tuscolo, an important component of Late Republican and Early Imperial construction, about whose quarries little is known? Answers to these and other questions would give new archaeological insights into how the ancient builders' dissatisfaction with the strength limitations and relatively low durability of the Roman tuffs shaped and hastened the development of robust concrete masonry. An archaeological reassessment of Roman construction based on the systematic geological framework described here would reveal a great deal about the intelligence of Roman builders in the design, construction, and preservation of the stone monuments that are the glory of Rome.

DEPARTMENT OF HISTORY
P.O. BOX 6023
NORTHERN ARIZONA UNIVERSITY
FLAGSTAFF, ARIZONA 86011
MARIE.JACKSON@NAU.EDU

ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA
VIA DI VIGNA MURATA 605
00143 ROME
ITALY
MARRA@INGV.IT

[137] Blake 1947, 33–4.

Appendix: Geologic Descriptions of Roman Volcanic Tuffs Used as Building Stone and Examples in Roman Construction

MONTE SABATINI VOLCANIC DISTRICT

Volcanic Tuff: Tufo Giallo della Via Tiberina.
Age: 561±1 ka to 548±4 ka.
Eruptive Unit: Upper eruptive unit (subunits a, b).[138]
Type of Deposit: Ignimbrite.
Geological Description: Porous, moderately well-consolidated, yellowish-gray (5Y 8/2) to grayish-orange (10YR 7/4), vitric tuff. Loosely grain supported: contains <15% lava, crystal, and limestone fragments. Yellowish-gray (5Y 8/1 and 5Y 7/2) and grayish-orange (10YR 7/4), altered glass matrix forms 40–50% of the rock. Contains mainly chabazite cement. Large, lapilli-sized,[139] grayish-yellow to moderate yellow-orange (5Y 8/4 to 10YR 7/6), altered pumice fragments crumble easily (see fig. 5a).
Easily Accessible Examples in Roman Construction:
Republican Walls: Termini Station forecourt; Aventine Hill at Via di San Anselmo (see fig. 5a); Esquiline Hill, cut-stone walls (reworked in opus reticulatum at Auditorium of Maecenas).
Campus Martius: Largo Argentina, Temple C (290 B.C.E.), original cut-stone podium and second-century B.C.E. corniced perimeter wall (see fig. 6c); Theater and Crypta of Balbus (13 B.C.E.), cut-stone interior walls; Pantheon (118–125 C.E.), coarse aggregate (with Vesuvian scoria) of concrete dome; Pozzolane Rosse fine aggregate.
Velabrum Valley: San Omobono, parts of cut-stone walls of Republican era temples; Round Temple by the Tiber River (late second century or early first century B.C.E.), cut-stone podium and cella walls.
Porticus Aemilia (174 B.C.E.): coarse aggregate of concrete walls; early walls have Pozzolanelle fine aggregate (see fig. 9a).
Forum of Caesar (54–29 B.C.E.): coarse aggregate of concrete walls of tabernae vaults; Pozzolane Rosse fine aggregate.
Colosseum (70–80 C.E.): coarse aggregate of all original concrete vaults; Pozzolane Rosse fine aggregate.

Volcanic Tuff: Tufo Giallo di Prima Porta.
Age: 514±3 ka.
Eruptive Unit: Upper eruptive unit.[140]
Type of Deposit: Ignimbrite.
Geological Description: Porous, moderately well-consolidated, yellowish-gray (5Y 8/1), vitric-crystal tuff. Loosely grain supported: yellowish-gray (5Y 8/1), poorly cemented, altered glass matrix foms up to 50% of the rock. Contains mainly chabazite cement. Grayish-orange (10YR 7/4), altered pumice fragments are generally <0.5 cm in diam.
Easily Accessible Examples in Roman Construction:
F*orum of Caesar (54-29 B.C.E.):* concrete walls of barrel vaults contain occasional Tufo Giallo di Prima Porta coarse aggregate. Otherwise, not identified at present in the Roman monuments.

Volcanic Tuff: Grottarossa Pyroclastic Sequence.
Age: 514±5 ka.
Eruptive Unit: Eruptive subunit a.[141]
Type of Deposit: Ignimbrite.
Geological Description: Poorly consolidated, olive-gray (5Y 5/1), vitric-lithic-crystal tuff. Grain supported: contains about 30% lava and crystal fragments. Abundant dull-white leucite crystals are partially or wholly replaced by analcime. Contains analcime and calcite cement, variable amounts of clay, sparse sanidine.
Easily Accessible Examples in Roman Construction:
Palatine Hill: traces of Early Iron Age hut village (eighth and ninth centuries B.C.E.) are etched into Grottarossa Pyroclastic Sequence bedrock; circular Archaic cisterns or granaries (fifth or sixth centuries B.C.E.), corbelled cut-stone walls.

Volcanic Tuff: Tufo Rosso a Scorie Nere.
Age: 449±1 ka.
Type of Deposit: Ignimbrite.
Geological Description: Porous, moderately well-consolidated, vitric-lithic tuff. Loosely grain supported: light brown (5YR 5/6) altered glass matrix contains abundant, predominately phillipsite cement. Contains prominent, large lapilli-sized, dark gray scorie and lava fragments (see fig. 5b).
Easily Accessible Examples in Roman Construction:
Velabrum Valley: San Omobono, Archaic temple (fourth century B.C.E.), cut-stone cella walls.
Campus Martius: Largo Argentina, Temple A (third century B.C.E.), cut-stone of early cella walls.
Capitoline Hill: cut-stone enlargement of the original Tufo del Palatino podium of the Temple of Juno Moneta (Mid to Late Republic) (see figs. 5b, 6a); Tabularium (78 B.C.E.), some internal walls.

ALBAN HILLS VOLCANIC DISTRICT

Volcanic Tuff: Tufo del Palatino.
Age: 528±1 ka.

[138] Karner et al. 2001b
[139] Lapilli-sized fragments are about 2–4.6 cm in diam.
[140] Karner et al. 2001b
[141] Karner et al. 2001b

Type of Deposit: Ignimbrite.
Geological Description: Poorly to moderately well-consolidated, olive-gray (5Y 5/1), vitric-crystal/lithic tuff. Grain supported: contains 10–15% lava and limestone fragments as well as river pebbles entrained during emplacement. Abundant leucite crystals are partially to wholly replaced by analcime. Contains analcime and calcite cement. Poorly consolidated samples have about 20% altered glass matrix and up to 30% clay (see fig. 5c).
Easily Accessible Examples in Roman Construction:
Velabrum Valley: San Omobono, Archaic temple(s) (sixth century B.C.E.), cut-stone podia.
Roman Forum: original cut-stone podium of the Regia (sixth and seventh centuries B.C.E.).
Capitoline Hill: original cut-stone podia of the Temple of Jupiter Capitolinus (sixth century B.C.E.) (see fig. 5c); Auguraculum (sixth century B.C.E.); Temple of Juno Moneta (345 B.C.E.) (see fig. 6a).

Volcanic Tuff: Tufo Lionato.
Age: 366±4 ka.
Type of Deposit: Ignimbrite.
Geological Description: Poorly to well-consolidated vitric tuff with a distinctive tawny-orange color. Tufo Lionato from the Aniene River quarries is moderate to light brown (5YR 4/4 to 5YR 5/6), well consolidated, and grain supported. It contains about 12–20% lava, crystal fragments, a small percentage of limestone fragments, and predominantly phillipsite cement. Lapilli-sized, moderate yellowish-brown (10YR 4/2) to dark yellowish-orange (10YR 7/6) pumice fragments are largely intact (see fig. 5d). Tufo Lionato from south of Rome is light brown (5YR 5/6 and 5YR 6/4) to grayish orange (10YR 7/4), poorly to moderately well consolidated, and loosely grain supported. It contains <10% lava and crystal fragments, fewer limestone fragments than Tufo Lionato from the Aniene River, small, altered pumice fragments ranging from light brown (5YR 5/6) to dark yellowish-orange (10YR 6/6), both phillipsite and chabazite cement, and variable amounts of clay. In the Monteverde area, on the west bank of the Tiber River in Rome, the tuff varies in color, has predominantly milky-white phillipsite cement, and contains little or no clay.
Easily Accessible Examples in Roman Construction (Aniene River):
Campus Martius: Largo Argentina, Temple A (mid to late first century B.C.E. reconstruction), cut-stone podium and plaster-clad, fluted column drums and bases; Temple B (101 B.C.E.), original cut-stone, corniced, circular podium and plaster-clad, fluted column drums (see fig. 6e); podium enlargement (ca. 50 B.C.E.), Lapis Albanus pavement and vertical, Tufo Lionato slabs, Tufo Lionato coarse aggregate in concrete fill.
Velabrum Valley: Temple of Portunus (70–80 B.C.E.), cut-stone podium, cella walls, and half columns (see fig. 6d); Temple of Apollo Medicus Sosianus (late first century B.C.E.), cut-stone podium (see fig. 5d).
Capitoline Hill: Tabularium (78 B.C.E.), some cut-stone interior walls.
Forum of Caesar (54–29 B.C.E.): cut-stone facades and round arches of upper story (see fig. 6g).
Forum of Augustus (2 C.E.): cut-stone podium of the Temple of Mars Ultor, upper story walls above western exedra (see fig. 6h).
Esquiline Hill: Auditorium of Maecenas (early first century C.E.), walls of opus mixtum.
Easily Accessible Examples in Roman Construction (South of Rome):
Baths of Caracalla (211–216 C.E.): coarse aggregate of concrete walls and vaults, Pozzolane Rosse fine aggregate.
Colosseum (after 217 C.E. fire): coarse aggregate of repairs to concrete vaults, Pozzolane Rosse fine aggregate. Further investigation is needed to identify this Tufo Lionato in Roman concretes.

Volcanic Tuff: Tufo di Tuscolo.
Age: ca. 355 ka.
Type of Deposit: Pyroclastic surge deposit(?).
Geological Description: Very well-consolidated, massive, moderate brownish-gray (5YR 5/1), lithic/crystal-vitric tuff. Strongly grain-supported blocks contain >50% lava and crystal fragments (with abundant leucite), well-developed phillipsite cement, intergranular calcite cements, and calcite replacement of leucite, and little pumice or clay. Less durable blocks of Tufo di Tuscolo contain greater proportions of light brown (5YR 4/6) to moderate brown (5YR 3/4) altered glass (see fig. 5e).
Easily Accessible Examples in Roman Construction:
Capitoline Hill: Tabularium (78 B.C.E.), massive, corniced, internal pillars.
Velabrum Valley: Theater of Marcellus (23–11 B.C.E.), cut-stone walls, radial piers, voussoirs of round arches (see fig. 6f); reconstruction (1920s), outer arcade.
Colosseum (70–80 C.E.): radial piers of first and second story (reinforced with travertine) (see fig. 5e); reconstruction of arena substructure by Domitian (80s–90s C.E.), walls and rough voussoirs of flat arches.
San Clemente: Mithraeum and Horrea (first century C.E.), cut-stone walls(?).

Volcanic Tuff: Lapis Gabinus
Age: ca. 260 ka

Type of Deposit: Valle Castiglione ground surge deposit.
Geological Description: Thin- to thick-bedded, well-consolidated, darker olive-gray (5Y 3/1), lithic tuff. Strongly grain-supported, coarse-grained, lithic-crystal beds contain 50% lava and crystal fragments, and predominantly chabazite cement. Loosely grain-supported, fine-grained, vitric-lithic beds contain 20–40% moderate yellow-gray (5Y 8/1), altered glass matrix, predominantly phillipsite cement, accretionary lapilli, and sparse clay (see fig. 5f).
Easily Accessible Examples in Roman Construction:
Velabrum Valley: Cloaca Maxima (first century B.C.E.), reconstruction of drain into Tiber River.
Capitoline Hill: Tabularium (78 B.C.E.), cut-stone foundation and second-story pillared arcade (see fig. 5f).
Forum of Caesar (54–29 B.C.E.): piers and voussoirs of flat arches of tabernae (see fig. 6g).
Forum of Augustus (2 C.E.): forum boundary wall and statuary niches (reinforced with travertine); reinforcing blocks at corners of podium of Temple of Mars Ultor (see fig. 6h).

Volcanic Tuff: Lapis Albanus.
Age: 36±1 ka.
Type of Deposit: Lago Albano volcanic debris flow deposit.
Geological Description: Well-consolidated, lighter olive-gray (5Y 4/1), crystal-lithic tuff. Coarse-grained zones contain about 50% lava and crystal fragments. Fine-grained zones contain about 15% yellowish-gray (5Y 7/2), altered-glass matrix. Phillipsite and chabazite cement occur throughout. Pumice and clay are generally sparse (see fig. 5g).
Easily Accessible Examples in Roman Construction:
Velabrum Valley: San Nicola in Carcere Temples (third and second centuries B.C.E.), plaster-clad Ionic column drums, capitals, and bases (see figs. 5g, 6b); unidentified temple at Via delle Botteghe Oscure (mid first century B.C.E.?), plaster-coated column drums (with travertine capitals and bases) (see fig. 11a); Foro Holitorio (first century B.C.E.?), cut-stone arcade of Triumphal Way.
Tullianum (fourth century B.C.E.?): cut-stone foundation and walls.
Palatine Hill: Temple of Magna Mater (rebuilt in 111 B.C.E.), massive plaster-clad column drums.
Forum of Nerva (69–70 C.E., inaugurated 97 C.E.): cut-stone boundary wall (adjacent to eastern exedra of Forum of Augustus), pavement, temple podium.
Colosseum (90s C.E.?): cut-stone repairs to Domitian's reconstruction of arena substructure.
Mausoleum of Hadrian (139 C.E.): cut-stone exterior and internal walls.
Temple of Hadrian (145 C.E.): cut-stone cella.
Roman Forum: Temple of Antoninus and Faustina (146 C.E.), cut-stone podium and cella.

Works Cited

Adam, J.P. 1999. *Roman Building*. London: Routledge.

Alvarez, W., A.J. Ammerman, P.R. Renne, D.B. Karner, N. Terrenato, and A. Montanari. 1996. "Quaternary Fluvial-Volcanic Stratigraphy and Geochronology of the Capitoline Hill in Rome." *Geology* 24:751–54.

Alvarez, W., A. Gordon, and E.P. Rashak. 1975. "Eruptive Source of the 'Tufo Rosso a Scorie Nere,' a Pleistocene Ignimbrite North of Rome." *Geologica Romana* 14:141–54.

Amanti, M., P. Cara, and M. Pecci. 1995. "Modello digitale della superficie reale del centro storico della citta di Roma." In *Memorie Descrittive della Carta Geologica d'Italia 50: La Geologia di Roma I*, edited by R. Funiciello, 217–48. Rome: Istituto Poligrafico e Zecca dello Stato.

Ammerman, A.J. 1990. "On the Origins of the Forum Romanum." *AJA* 94(4):627–45.

ASTM. 2002a. "Absorption and Bulk Specific Gravity of Dimension Stone (C97–96)." *ASTM 2002 Annual Book of ASTM Standards* 04.07, 1–3. Philadelphia: American Society for Testing and Materials.

———. 2002b. "Standard Test Method for Compressive Strength of Dimension Stone (C170–90)." *ASTM 2002 Annual Book of ASTM Standards* 04.07, 17–19. Philadelphia: American Society for Testing and Materials.

Bauleke, M.P., and J.M. Hugh. 1968. "Thermal Expansion of Kansas Volcanic Ash." *State Geological Survey of Kansas Bulletin* 194:15–16.

Bencivenga, M., E. Di Loreto, and L. Liperi. 1995. "Il regime idrologico del Tevere, con particolare riguardo alle piene nella citta di Roma." In *Memorie Descrittive della Carta Geologica d'Italia 50: La Geologia di Roma I*, edited by R. Funiciello, 125–72. Rome: Istituto Poligrafico e Zecca dello Stato.

Beste, H.-J. 2002. "Il cantiere del Colosseo: Osservazioni tecniche sugli ipogei del Colosseo." *Romische Mitteilungen* 109:354–61.

Bianchetti, P.L., G. Lombardi, S. Marini, and C. Meucci. 1994. "The Volcanic Rocks of the Forum and Palatine (Rome): Characterization, Alterations, Results of Chemical Treatments." In *Lavas y Tobas Volcanicas*, edited by A.E. Charola, R.J. Koestler, and G.R. Lombardi, 83–105. Proceedings of the International Meeting on Lavas and Volcanic Tuffs, Easter Island, Chile, 25–31 October.

Blake, M.E. 1947. *Ancient Roman Construction in Italy from the Prehistoric Period to Augustus*. Washington, D.C.: Carnegie Institute.

Boethius, A. 1978. *Etruscan and Early Roman Architecture*. New Haven: Yale University Press.

Boschi, E., C. Caserta, C. Conti, M. Di Bona, R. Funiciello, L. Malagnini, F. Marra, G. Martines, A. Rovelli, and S. Salvi. 1995. "Resonance of Subsurface Sediments: Unforeseen Complication for Designers of Roman Columns." *Bulletin of the Seismological Society of America* 85:320–24.

Cifani, G. 1995. "Aspetti dell'edilizia Romana Arcaica." *Studi Etruschi* 60:185–226.

Chafetz, H.S., and R. Folk. 1984. "Travertines: Depositional Morphology and the Bacterially Constructed Constituents." *Journal of Sedimentary Petrology* 54:289–316.

Claridge, A. 1998. *Rome*. Oxford: Oxford University Press.

Coarelli, F. 1997. *Roma*. Milan: Mondadori.

———. 2001. "Roma." In *Guide Archeologiche Laterza*, edited by F. Coarelli. Rome and Bari: G. Laterza and Figli Spa.

Colantuono, A., S. Dal Vecchio, O. Marino, and G. Mascholo. 1993. "Accurate Measurement of Expansion and Shrinkage in Porous Stones Caused by Moisture Absorption." In *Conservation of Stone and Other Materials I*, edited by M.J. Thiel, 204–11. London: E. and F.N. Spon.

Corazza, A., and L. Lombardi. 1995. "Idrogeologia dell' area del centro storico di Roma." In *Memorie Descrittive della Carta Geologica d'Italia: La Geologia di Roma I*, edited by R. Funiciello, 179–211. Rome: Istituto Poligrafico e Zecca dello Stato.

Corazza, A., C. Conti, M.G. Filetici, L. Lombardi, A. Rava, and G. Torraca. 1987. "Sulla Conservazione dei Tufi: Studi per una Metodologia di Intervento." In *Conoscenze e Sviluppi Teorici per la Conservazione di Sistemi Costruttivi Tradizional Muratura*, edited by G. Biscontin and R. Angeletti, 222–37. Atti del Convegno di Studi, Bressanone, Italy, 23–26 June. Padua: Libreria Progetto Editore.

Corsi, F. 1991. Reprint. *Delle Pietri Antiche*. Verona: Giorgio Zusi Editore. Original edition, 1828.

De Carolis, E., and G. Patricelli. 2003. *Vesuvius, A.D. 79*. Los Angeles: Getty Publications.

De Casa, G., G. Giglio, L. Lombardi, and M. Mariottini. 1994. "Characterization and State of Decay of the Volcanic Tuff of the Tabularium in the Roman Forum, Italy." In *Lavas y Tobas Volcanicas*, edited by A.E. Charola, R.J. Koestler, and G.R. Lombardi, 107–27. Proceedings of the International Meeting on Lavas and Volcanic Tuffs, Easter Island, Chile, 25–31 October.

De Casa, G., G. Lombardi, C. Meucci, R. Galloni, and P. Vitali. 1999. "Il Tufo Lionato dei Monumenti Romani: Caratteri Petrografici, Geomeccanici, e Trattamenti Conservativi." *Geologia Romana* 35:1–25.

De'Gennaro, M., S. Arzillo, M. Gargiulo, and M.D. Fuscaldo. 1992. "Il Degrado del Tufo Grigio Campano." *Arkos* 19:12–18.

DeLaine, J. 1995. "The Supply of Building Materials to the City of Rome." In *Settlement and Economy in Italy 1500 B.C. to A.D. 1500*, edited by N. Christie. Papers of the Fifth Conference in Italian Archaeology. *Oxbow Monograph* 41:555–62.

———. 1997. *The Baths of Caracalla*. *JRA* Suppl. Ser. 25. Portsmouth, R.I.: Journal of Roman Archaeology.

De Rita, D., and Giampaolo, C. 2005. "Local Volcanic Building Stones Used in the Construction of Ancient Rome." In *Cultural Responses to the Volcanic Landscape: The Mediterranean and Beyond*, edited by M. Balmuth, D. Chester, and P. Johnston, 165–84. Colloquia and Conference Papers 8. Boston: Archaeological Institute of America.

De Rita, D., C. Faccenna, R. Funiciello, and C. Rosa. 1995. "Stratigraphy and Volcano-Tectonics." In *The Volcano of the Alban Hills*, edited by R. Trigila, 33–71. Rome: Tipografia S.G.S.

De Rita, D., R. Funiciello, L. Corda, A. Sposato, and U. Rossi. 1993. "Carta Geologica del Complesso Vulcanico Sabatino (1:50,000)." *Quaderni de La Ricerca Scientifica* 114:11. Rome: Consiglio Nazionale delle Ricerche.

De Rita, D., R. Funiciello, and M. Parotto. 1988. *Carta Geologica del Complesso Vulcanico dei Colli Albani (1:50,000)*. Rome: Consiglio Nazionale della Ricerche.

Faccenna, C., R. Funiciello, and F. Marra. 1995. "Inquadramento geologico strutturale dell'area Romana." In *Memorie Descrittive della Carta Geologica d'Italia 50: La Geologia di Roma I*, edited by R. Funi-ciello, 31–47. Rome: Istituto Poligrafico e Zecca dello Stato.

Faccenna, C., R. Funiciello, P. Montone, M. Parotto, and M. Voltaggio. 1994. "Late Pleistocene Strike-Slip Tectonics in the Acque Albule Basin (Tivoli, Latium)." *Memorie Descrittive della Carta Geologica d'Italia* 49:37–50.

Favro, D. 1996. *The Urban Image of Augustan Rome*. Cambridge: Cambridge University Press.

Fisher, R.V., and H.V. Schmincke. 1984. *Pyroclastic Rocks*. New York: Springer Verlag.

Fornaseri, M., A. Scherillo, and U. Ventriglia. 1963. *La regione vulcanica dei Colli Albani, Vulcano Laziale*. Rome: Consiglio Nazionale delle Ricerche Scientifica.

Frank, F. 1924. *Roman Buildings of the Republic: An Attempt to Date Them from Their Materials*. Rome: American Academy in Rome.

Friedman, G. 1957. "Determination of Sieve-Size Distribution from Thin Section Data for Sedimentary Petrological Studies." *Journal of Geology* 66:394–416.

Funiciello, R., ed. 1995. *La Geologia di Roma, Il Centro Storico. Memorie Descrittive della Carta Geologica d'Italia 50*. Rome: Istituto Poligraphico e Zecco della Stato.

Funiciello, R., L. Lombardi, F. Marra, and M. Parotto. 1995. "Seismic Damage and Geological Heterogeneity in Rome's Colosseum Area: Are They Related?" *Annali di Geofisica* 38:927–37.

Giordano G., D. De Rita, R. Cas, and S. Rodani. 2002. "Valley Pond and Ignimbrite Veneer Deposits in a Small Volume Phreatomagmatic Basic Ignimbrite, Lago Albano Maar, Colli Albani Volcano, Italy: Influence of Topography." *Journal of Volcanology and Geothermal Research* 118:131–44.

Goodman, R.E. 1989. *Introduction to Rock Mechanics*. New York: John Wiley.

Hay, R.L., and A. Ijima. 1968. "Nature and Origin of Palagonite Tuffs of the Honolulu Group on Oahu, Hawaii." *Geological Society of America Memoir* 116:331–76.

Jackson, M.D., C. Kosso, F. Marra, and R. Hay. 2006. "Geological Basis of Vitruvius' Empirical Observations of Material Characteristics of Rock Utilized in Roman Masonry." In *Proceedings of the Second International Congress of Construction History. Queens' College, University of Cambridge, 29 March–2 April 2006,* edited by M. Dunkeld, J. Campbell, H. Louw, M. Tutton, B. Addis, and R. Thorne, 1685–702. London: The Construction History Society.

Jackson, M.D., F. Marra, R.L. Hay, C. Cawood, and E.M. Winkler. 2005. "The Judicious Selection and Preservation of Tuff and Travertine Building Stone in Ancient Rome." *Archaeometry* 47:485–510.

Jones, H.L., trans. 1923. *Geographica,* by Strabo. Loeb Classical Library. Cambridge, Mass.: Harvard University Press.

Karner, D.B., and F. Marra. 1998. "Correlation of Fluviodeltaic Aggradational Sections with Glacial Climate History: A Revision of the Classical Pleistocene Stratigraphy of Rome." *Geological Society of America Bulletin* 110:748–58.

Karner, D.B., and P.R. Renne. 1998. "40Ar/39Ar Geochronology of Roman Volcanic Province Tephra in the Tiber River Valley: Age Calibration of Middle Pleistocene Sea-Level Changes." *Geological Society of America Bulletin* 110:740–47.

Karner, D.B., L. Lombardi, F. Marra, P. Fortini, and P. Renne. 2001a. "Age of Ancient Monuments by Means of Building Stone Provenance: A Case Study of the Tullianum, Rome, Italy." *JAS* 28:387–93.

Karner, D.B., F. Marra, and P.R. Renne. 2001b. "The History of the Monti Sabatini and Alban Hills Volcanoes: Groundwork for Assessing Volcanic-Tectonic Hazards for Rome." *Journal of Volcanology and Geothermal Research* 107:185–219.

Keaveney, R. 1988. *Views of Rome*. London: Scala Publications.

Lancaster, L.C. 1998. "Reconstructing the Restorations of the Colosseum After the Fire of 217." *JRA* 11:146–74.

———. 2002. "Il Cantiere del Colosseo: The Organization of Construction for the Superstructure of the Colosseum." *Romische Mitteilungen* 109:361–75.

———. 2005. *Concrete Vaulted Construction in Imperial Rome: Innovations in Context*. Cambridge: Cambridge University Press.

Lanciani, R. 1897. *The Ruins and Excavation of Ancient Rome*. London: MacMillan.

Laurenzi-Tabasso, M., A.M. Mecchi, and U. Santamaria. 1994. "Interaction Between Volcanic Tuff and Products Used for Consolidation and Water Proofing Treatment." In *Lavas y Tobas Volcanicas*, edited by A.E. Charola, R.J. Koestler, and G.R. Lombardi, 245–67. Proceedings of the International Meeting on Lavas and Volcanic Tuffs, Easter Island, Chile, 25–31 October.

Lechtman, H.N., and H.W. Hobbs. 1987. "Roman Concrete and the Roman Architectural Revolution." *Ceramics and Civilization* 3:81–128.

Lenzi, G., and E. Passaglia. 1974. "Fenomeni di zeolitizzazione nella formazione vulcaniche della regione Sabatina." *Bolletino Societa Geologica Italia* 93:623–45.

Lewis, C., C. Short, and W. Freund. 1879. *A Latin Dictionary*. Founded on Andrews' edition of Freund's Latin dictionary. Revised and enlarged by C.T. Lewis and C. Short. Oxford: Clarendon Press.

Logan, J.M., M. Hastedt, D. Lehnert, and M. Denton. 1993. "A Case Study of the Properties of Marble as Building Veneer." *International Journal of Rock Mechanics and Mineral Science* 30:1531–37.

Lugli, G. 1957. *La Tecnica Edilizia*. Rome: G. Bardi.

Marra, F., and C. Rosa. 1995. "Statigrafia e assetto geologico dell'area Romana." In *Memorie Descrittive della Carta Geologica d'Italia 50: La Geologia di Roma I,* edited by R. Funiciello, 50–118. Rome: Istituto Poligrafico e Zecca dello Stato.

Marra, F., F. Florindo, and D.B. Karner. 1998. "Paleomagnetism and Geochronology of Early Middle Pleistocene Depositional Sequences Near Rome: Comparison with Deep Sea $\delta^{18}O$ Climate Record." *Earth and Planetary Letters* 159:147–64.

Marra, F., C. Freda, P. Scarlato, J. Taddeucci, D.B. Karner, P.R. Renne, M. Gaeta, D.M. Palladino, R. Trigila, and G. Cavarretta. 2003. "40Ar/39Ar Geochronology and Compositional Features of Young Volcanic Rocks from the Alban Hills Volcanic District (Rome, Italy): Evidence of Rejuvenation Volcanism." *Bulletin of Volcanology* 65:227–47.

Massazza, F. 1998. "Pozzolana and Pozzolanic Cements." In *Lea's Chemistry of Cement and Concrete*, edited by P.C. Hewlett. New York: Arnold.

Melmoth, W., trans. 1909–1914. *Letters,* by Pliny. Revised by F.C.T. Bosanquet. The Harvard Classics. New York: P.F. Collier & Son.

Nappi, G., G. De Casa, and E. Volponi. 1979. "Geologia e caratteristiche tecniche del 'Tufo Giallo della Via Tiberina.'" *Bolletino Societa Geologica Italiano* 98:431–45.

Pearce, E.A., and G. Smith. 1990. *The Times Books World Weather Guide*. New York: Times Books.

Quilici, L. 1974. "Collatia." *Forma Italia* 1:x.

Rapp, G. 2002. *Archaeomineralogy*. New York: Springer-Verlag.

Rea, R. 2002. "Il cantiere del Colosseo: La cantieristica e le opere fondali degli ipogei e della cavea." *Romische Mitteilungen* 109:341–54.

Richardson, L. 1992. *A New Topographical Dictionary of Ancient Rome*. Baltimore: Johns Hopkins University.

Rolfe, J.C., trans. 1914. *Divus Augustus*, by Suetonius. Loeb Classical Library. Cambridge, Mass.: Harvard University Press.

Rowland, I.D., and T.N. Howe, trans. 1999. *De Architectura*, by Vitruvius. In *Vitruvius, Ten Books on Architecture*. Cambridge: Cambridge University Press.

Roy, D.M., and C.A. Langton. 1989. *Studies of Ancient Concrete as Analogs of Cementitious Sealing Materials for a Repository in Tuff*. Report LA-11527–MS, UC-721, prepared by the Materials Research Laboratory, Pennsylvania State University, for Los Alamos National Laboratory, Los Alamos, N.M.

Sappa, G., G. Giglio, and G. De Casa. 1995. "Mechanical Characteristics of Some Volcanic Tuffs Used in the Buildings of Ancient Rome." *Material Research Society Symposium Proceedings* 352:733–43.

Scherillo, A. 1941. "Studi su alcuni tufi gialli della regione Sabazia orientale." *Periodico di Mineralogia* 12:381–417.

———. 1944–1946. "I vulcani Sabatini." *Bolletino Societa Naturalisti* 55:125–30.

Sear, F. 1989. *Roman Architecture*. Ithaca, N.Y.: Cornell University Press.

Shipley, F.W., trans. 1924. *Res Gestae,* by Augustus. Loeb Classical Library, Cambridge, Mass.: Harvard University Press.

Torracca, G. 1988. *Porous Building Materials*. Rome: ICCROM.

Touloukian, Y.S., W.R. Judd, and R.F. Roy. 1981. *Physical Properties of Rocks and Minerals*. New York: McGraw-Hill.

Trigila, R., E. Agosta, C. Currado, A.A. De Benedetti, C. Freda, M. Gaeta, D.M. Palladino, and C. Rosa. 1995. "Petrology." In *The Volcano of the Alban Hills*, edited by R. Trigila, 33–71. Rome: Tipografia S.G.S.

Ventriglia, U. 1971. *La Geologica della città di Roma*. Rome: Amministrazione Provinciale.

Villa, I.M., N. Calanchi, E. Dinelli, and F. Lucchini. 1999. "Age and Evolution of the Albano Crater Lake (Roman Volcanic Province)." *Acta Vulcanologica* 11:305–10.

Ward-Perkins, J.B. 1977. *Roman Architecture*. New York: Harry N. Abrams.

Winkler, E.M. 1994. *Stone in Architecture*. New York: Springer-Verlag.