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THE JUDICIOUS SELECTION AND PRESERVATION OF TUFF AND TRAVERTINE BUILDING STONE IN ANCIENT ROME*

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The Republican and early Imperial monuments of Rome are, for the most part, built of tuffs quarried from at least seven pyroclastic deposits erupted from nearby Monti Sabatini and Alban Hills volcanoes. Remarks by Vitruvius (2.7.1–5), field observations of the monuments, and petrographic and rock testing studies of samples from Roman quarries demonstrate that Roman builders developed a good knowledge of the diverse material properties of the tuffs over centuries of use and exposure. Measurements of compressive strength, specific gravity, water absorption and adsorption of water vapour confirm that the petrographic characteristics of each tuff lithology strongly influence its strength and durability. Early construction utilized weakly durable, soft or vitric tuffs such as Tufo del Palatino or Tufo Giallo della Via Tiberina that are susceptible to decay, as at Temple C (290 BC) of the Largo Argentina Sacred Area. Late Republican structures, such as the Temple of Portunus (80–90 BC), employed somewhat durable, vitric–lithic Tufo Lionato reinforced with travertine, a durable limestone quarried near Tivoli. Roman builders selected the material properties of the tuffs to advantage for specific structural elements within large public monuments of the first century BC and the first century AD, as at the tabernae of the Forum of Caesar (46 BC), where an upper storey of lightweight Tufo Lionato is supported by robust, lithic–crystal Lapis Gabinus pillars and flat arches reinforced with travertine. The tuffs are not very durable building stones; Romans preserved them with protective stucco, and travertine and marble cladding. Their high water intake, coupled with direct exposure to rain, daily fluctuations in relative humidity and urban weathering at present makes them especially vulnerable to decay.

KEYWORDS: ANCIENT ROME, BUILDING STONES, TUFF, TRAVERTINE, PETROGRAPHIC CHARACTERISTICS, PHYSICAL PROPERTIES

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INTRODUCTION

The volcanic building stones of ancient Rome, primarily moderately well- to well-lithified tuffs with diverse material properties, were erupted from neighbouring Monti Sabatini and Alban Hills (Colli Albani) volcanoes (Fig. 1) between 561 and 36 ka (Karner *et al.* 2001a). The earliest existing stone construction in Rome (eighth to ninth centuries BC) used friable tuffs quarried *in situ* on the Palatine Hill (Steinby 1999, *LTUR* IV, 14–15). With acquisition of nearby lands and improved transportation routes, Romans procured more durable varieties of tuff quarried up to 26 km from the city (Fig. 2). During the late Republican period, they used a suite of moderately well- to well-lithified tuffs for ashlar or dimension stone construction (*opus quadratum*). Travertine, a durable limestone deposited by springs near Tivoli, provided keystones in tuff arches, capitals of tuff columns and decorative revetments for tuff walls. Lavas served mainly as road paving stones. By the end of the Republican period, Roman builders had developed an innovative transition in structural design, using the diverse properties of the tuffs to produce a highly refined architecture of ashlar masonry integrated with concrete construction (*opus incertum* or *opus reticulatum*) (Ward-Perkins 1977, 97–102). During the Imperial period, they created a revolutionary architecture of vaults and grandiose public monuments using brick-faced concrete (*opus testaceum*) composed primarily of local volcanic materials (Lechtman and Hobbs 1987) and clad with durable decorative stone, such as Carrara marble.

Much has been written about Roman methods of stone masonry construction (Frank 1924; Blake 1947; Adam 1999; Steinby 1993–9). Lugli (1957) placed the use of the tuff building stones within the epochs of Roman history. Tuff nomenclature presented in geological and archaeological publications (Table 1), however, is confusing and/or obsolete (e.g., De Rita *et al.* 1995; DeLaine 1995, 556–7; Coarelli 1997, 366–7; Claridge 1998, 37–8). In this paper and our geological mapping (Fig. 2), we follow the lithological nomenclature and volcanic chronostratigraphy proposed by Karner *et al.* (2001a). Furthermore, although Italian archaeological publications employ the geologically correct 'tufo' for the volcanic tuff building stones, archaeological publications in English consistently refer to them as 'tufa'. Deposits of hard travertine and soft tufa deposited by calcium carbonate-rich thermal springs abound within the Roman region; we distinguish these sedimentary rocks from tuffs produced by explosive volcanism.

As explained by Marcus Vitruvius Pollio (31–27 BC) in *De architectura*, the only surviving manual of Roman architecture, Roman builders acquired an excellent knowledge of their local stone building materials over many centuries of use (Vitruvius 2.1.7, 2.7.1–5). To describe the relative strength and durability of the tuffs and travertine, we measured modulus of rupture (R) and uniaxial compressive strength (q_u) under oven-dried, water-soaked and humid conditions, and determined water absorption (Ab), water adsorption at about 98% relative humidity (Ad) and bulk specific gravity (G) for samples from Roman quarries and outcrops. These data, field observations of the tuff building stones and statements by Vitruvius show how judiciously Romans employed the material properties of the tuffs and travertine in late Republican and early Imperial construction. We evaluate environmental factors in Rome that influence stone degradation and discuss how Romans protected the tuffs from decay.

LITHOLOGICAL DESCRIPTIONS OF ROMAN TUFF BUILDING STONE

The city of Rome occupies a strategic position along the Tiber River where pyroclastic deposits from the Monti Sabatini and Alban Hills volcanic districts interfinger (Figs 1 and 2). Volcanic

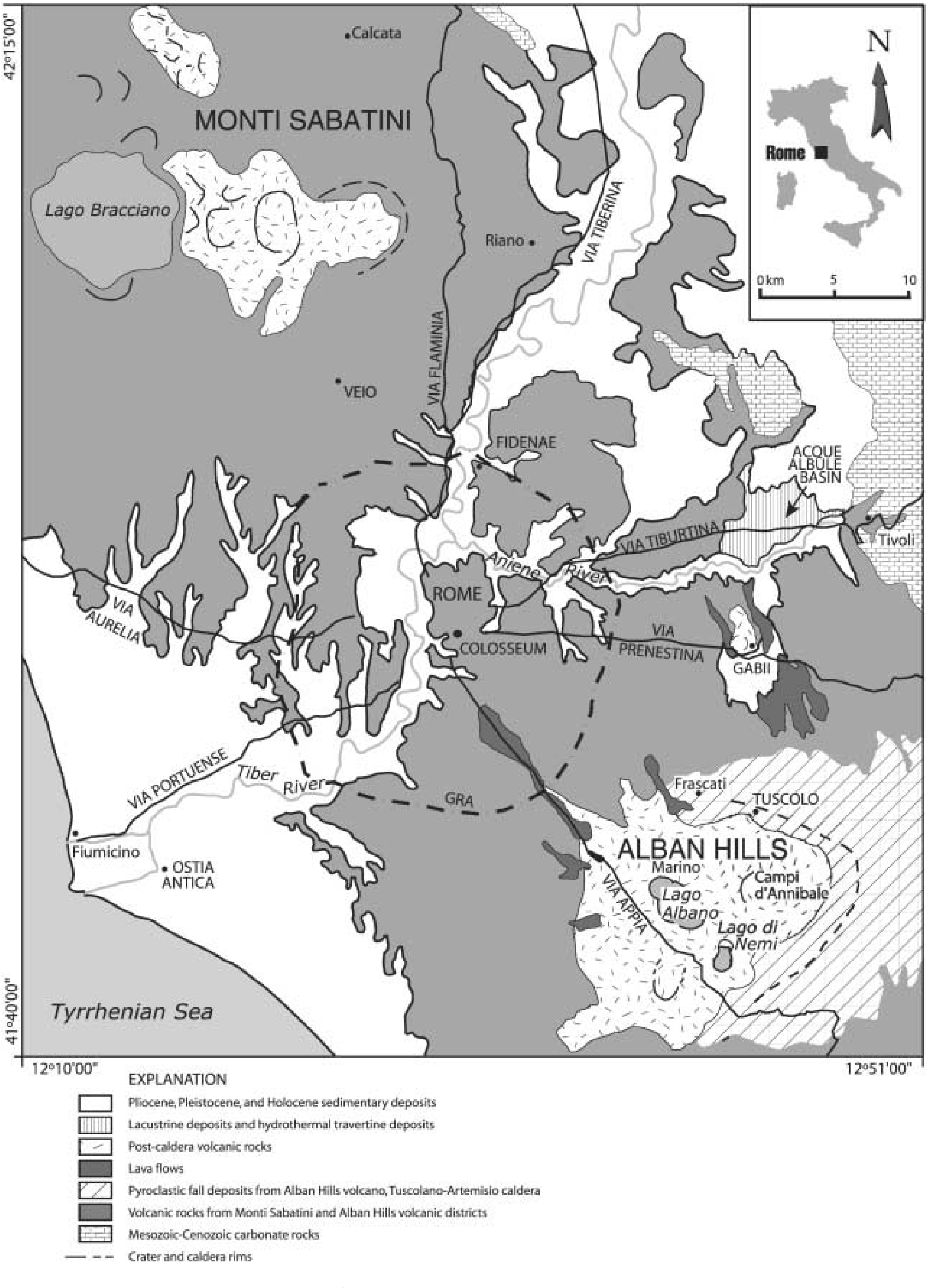
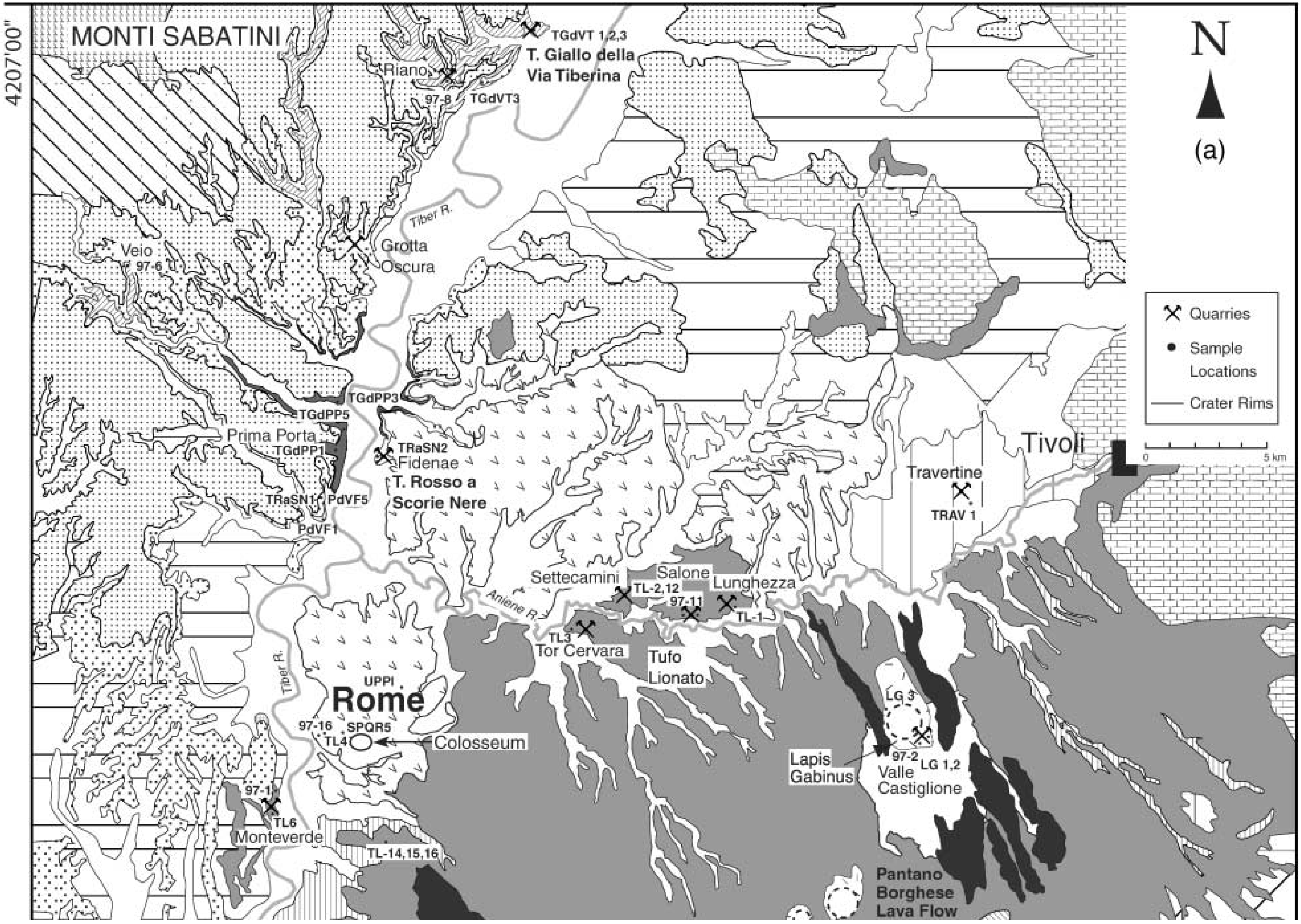


Figure 1 *A generalized geological map of the Roman region, showing the Monti Sabatini and Alban Hills volcanic rocks, travertine deposits within the Acque Albule basin near Tivoli, and Roman roads through the region. Modified from Karner* et al. *(2001a).*


4207'00"
MONTI SABATINI
TGdVT 1,2,3
T. Giallo della Via Tiberina
Riano
97-8
TGdVT3
N
(a)
Tiber R.
Grotta Oscura
Veio
97-6
Quarries
Sample Locations
Crater Rims
0
5 km
TGdPP3
TGdPP5
Prima Porta
TGdPP1
TRaSN2
Fidenae
T. Rosso a Scorie Nere
TRaSN1
PdVF5
PdVF1
Tivoli
Travertine
TRAV 1
Settecamini
Salone
Lunghezza
TL-2,12
97-11
TL-1
Aniene R.
TL3
Tor Cervara
Tufo Lionato
Tiber R.
UPPI
Rome
97-16
SPQR5
TL4
Colosseum
LG 3
97-2
LG 1,2
Lapis Gabinus
Valle Castiglione
97-1
TL6
Monteverde
TL-14,15,16
Pantano Borghese Lava Flow

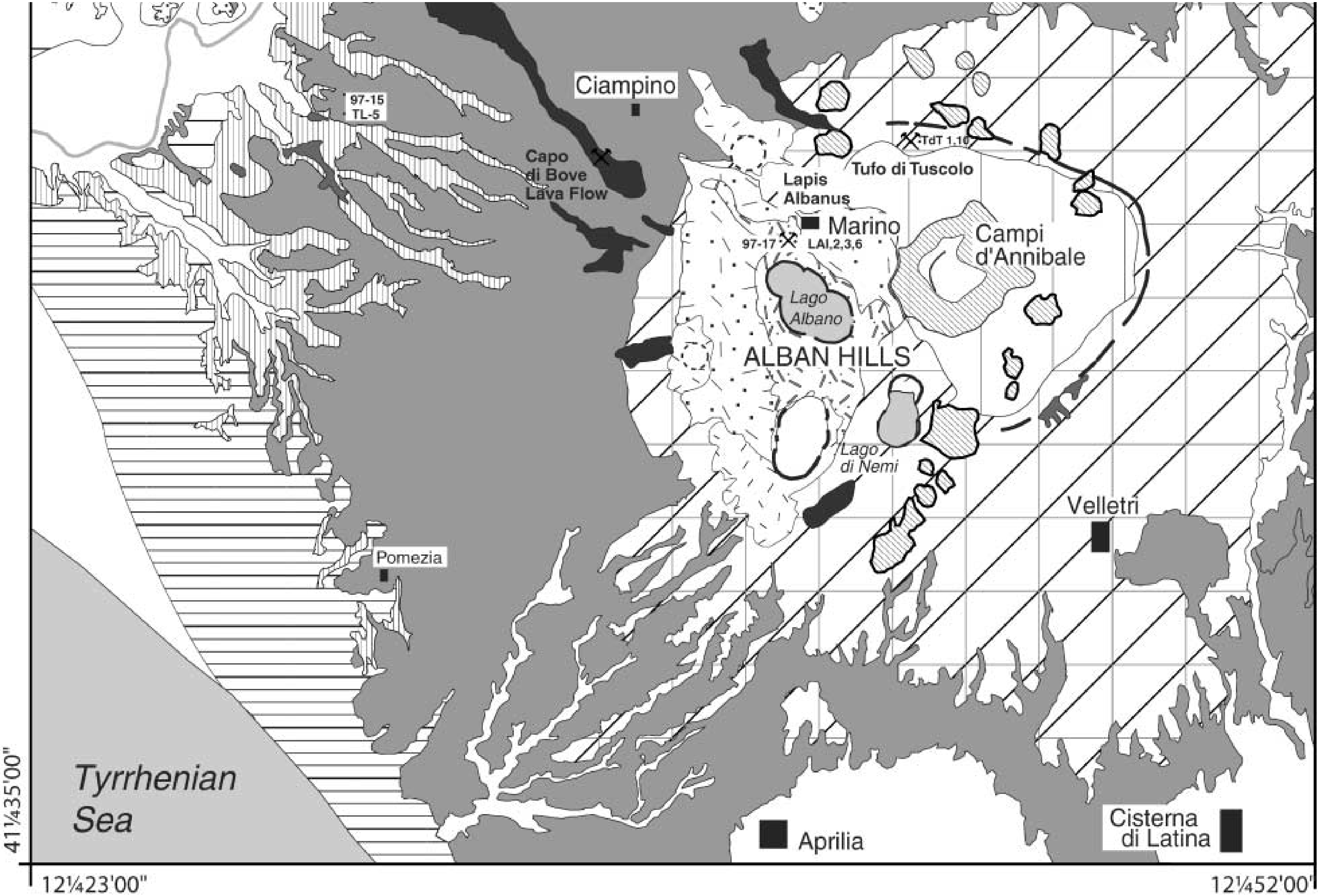


Figure 2 *Continued overleaf.*

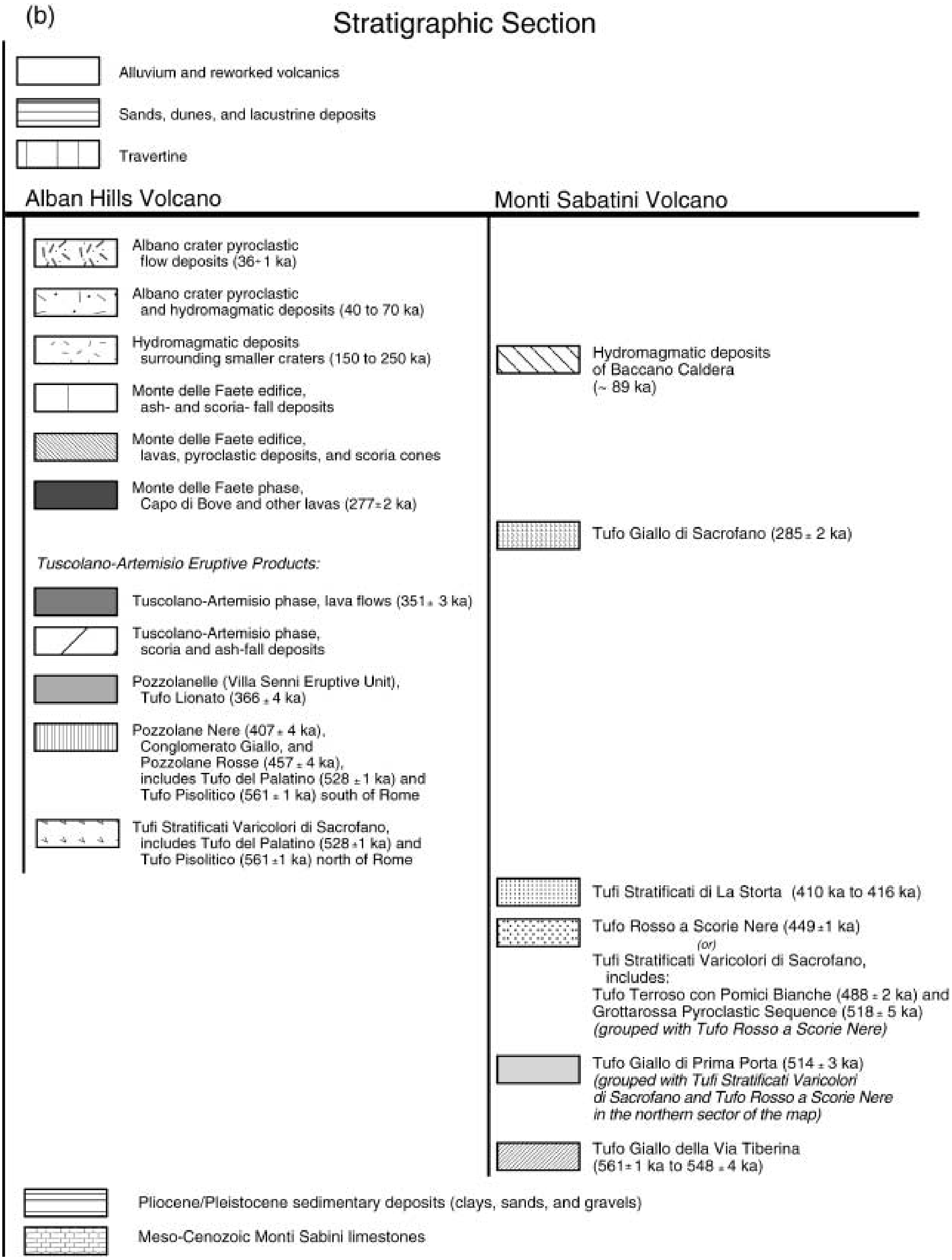


Figure 2 *A geological map of Rome and its surroundings (a) and a chronostratigraphic section (b) showing Roman quarries and sample locations: based on original geological mapping and adapted, in part, from De Rita* et al. *(1988, 1993). Following recent studies by Karner* et al. *(2001a) and Freda* et al. *(1997), we have grouped Pozzolane Nere with older Alban Hills volcanic rocks. The geological map of the Alban Hills volcano (De Rita* et al. *1988), however, groups Pozzolane Nere with Tufo Lionato.*

Table 1 *Chronostratigraphic schemes and historical names for the Roman volcanic rocks (after Karner* et al. *2001a). Geochronological data from* ^{40}*Ar/*^{39}*Ar analyses were collected at the Berkeley Geochronology Center following procedures described in Karner and Renne (1998)*

Monti Sabatini		*Alban Hills*		
De Rita et al. *(1993)*	*Karner* et al. *(2001a)*		*De Rita* et al. *(1988)*	
Hydromagmatic phase	Hydromagmatic activity	Lago Albano pyroclastic flow, 36 ± 1 ka *Lapis Albanus*, *Peperino di Marino*	Final hydromagmatic phase	
		Valle Castiglione ground surge deposit, 260 ka* *Lapis Gabinus, Pietra Gabina, Sperone, Gabine Tufa*		
Pizza Prato, Bracciano and Vigna di Valle Pyroclastic Flow Units				
Sacrofano Upper Pyroclastic Flow Unit	Tufo Giallo di Sacrofano, 285 ± 1 ka			
Pyroclastic fall products from Sacrofano and local scoria cones	Piroclastici Stratificate Varicolori di La Storta, *c.* 410 ka	Capo di Bove and other leucititic lavas, 277 ± 2 ka *Selce*	Campi di Annibale edifice (= Faete) phase	
		Tufo di Tusculo, *c.* 355 ka *Sperone*		
		Villa Senni eruptive sequence: includes Pozzolanelle and Tufo Lionato, 366 ± 4 to 351 ± 3 ka *Tufo Lionato, Lapis Ruber, Anio, Litoide, Monteverde*	T.-A. 4th pyroclastic flow (Pozzolanelle; Tufo di Villa Senni)	Tuscolano–Artemesio Phase
		Pozzolane Nere, 407 ± 4 ka	T.-A. 3rd pyroclastic flow (Pozzolane Nere and Tufo Lionato)	
		Conglomerato Giallo		
‘Red Tuff with black Scoria’ Pyroclastic Flow Unit	Tufo Rosso a Scorie Nere, 449 ± 1 ka *Lapis Fidenae, Tufo Rosso Litoide, Fidenae Tufa*	Pozzolane Rosse, 457 ± 4 ka	T.-A. 2nd pyroclastic flow	
		Vallerano lava, 460 ± 4 ka	Lava dell’Acquacetosa	
	Tufo Terroso con Pomici Bianche, 488 ± 2 ka			
	Grottarossa Pyroclastic Sequence, 514 ± 5; 518 ± 5 ka *Cappellaccio*			
		Tufo di Bagni Albule, 526 ± 1 ka		
	Tufo Giallo di Prima Porta, 514 ± 3 ka			
		Tufo del Palatino, 528 ± 1 ka *Cappellaccio, Tufo Granulare Grigio, Peperino della Via Flaminia*		
Sacrofano Lower Pyroclastic Flow Unit	Tufo Giallo della Via Tiberina (upper a-b-c), 548 ± 4 ka *Grotta Oscura, Tufo Giallo Poroso, Lapis Pallens*			
	Tufo Giallo della Via Tiberina (lower), 561 ± 4 ka	Tufo Pisolitico di Trigoria, 561 ± 1 ka		
Pyroclastic fall deposits from Morlupo edifice	First Ash Fall Sequence, 800–580 ka		T.-A. 1st pyroclastic flow	

* Narcisi *et al.* (1992).

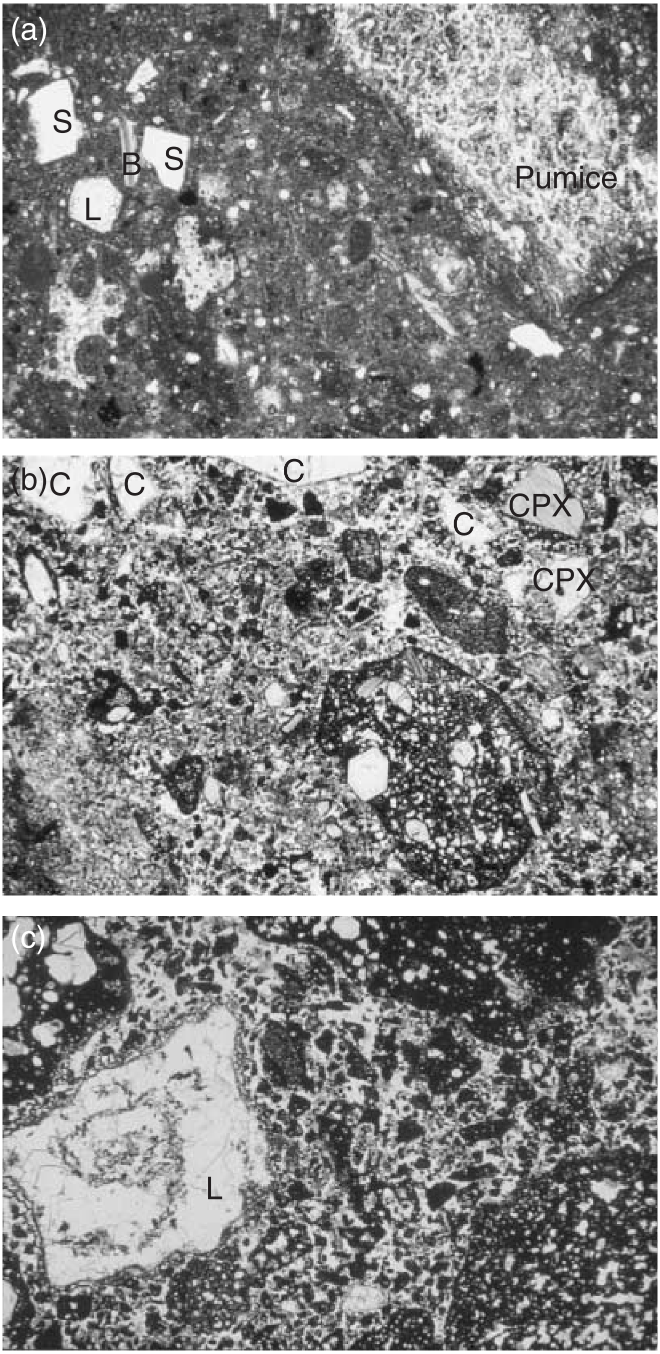


Figure 3 *Photomicrographs of thin sections of tuffs sampled from Roman quarries, showing characteristic textures. See Figure 2 for sample locations. All are plane light with 2.5 times magnification and a field of view 4 mm across.* (*a*) *Tufo Giallo della Via Tiberina (TGdVT 1b). Altered vitric matrix (mottled dull grey) and pumice fragments (lighter grey) dominate the tuff. Both contain small but pervasive amounts of clay. The tuff is nearly 50% chabazite, present mainly as cement within the vitric matrix. Note crystals of sanidine (S), leucite (L) and biotite (B).* (*b*) *Tufo Lionato,*

deposits from Monti Sabatini volcano crop out north of Rome, extending west of the Tiber River and north of the Aniene River. Volcanic deposits from Alban Hills volcano form the landscape of the Roman countryside south and east of the city. Volcanic rocks of the Alban Hills district (Trigila *et al.* 1995) have unique, rather uniform, low-silica, high-alkali compositions that are enriched in potassium and calcium and lie within the K-foidite to tephrite field of the TAS (total alkali silica) classification system (Le Bas *et al.* 1986). Leucite and augite crystals are common; plagioclase is generally absent. Volcanic rocks of the Monti Sabatini district (Scherillo 1944–6; De Rita *et al.* 1993) vary more in chemical composition, ranging from tephrite–phonolite to trachybasalt in the TAS system. They commonly contain sanidine, which distinguishes them from Alban Hills deposits.

Romans quarried tuffs from at least seven pyroclastic eruptive units including ignimbrites, ground surge, and debris flow deposits. In this paper, ignimbrite refers to the deposit of a pyroclastic flow, a density current of hot gases and particulate pyroclastic material (volcanic glass, crystals and rock fragments) that travels swiftly across the ground surface away from an eruptive vent. Ground surges are turbulent particulate flows that usually involve explosive magma–water interactions. A recently erupted pyroclastic deposit may avalanche to produce a volcanic debris flow. All of the Roman pyroclastic deposits used as building stone are unwelded but lithified by zeolite and lesser amounts of calcite cements. No airfall deposits were used as stone masonry. The tuff lithologies show substantial variations in the abundances of their constituent glass (vitric), rock (lithic) and crystal fragments, as well as differences in texture and sorting, cementation and clay alteration; they thus provided Romans with an exceptionally diverse suite of stone building materials.

To assist in explaining variations in the physical properties of the tuffs as well as their use in Roman construction, two of us (MDJ and RLH) determined the petrographic compositions of samples collected from Roman quarries and outcrops through Rome and its surroundings (Fig. 2 and Table 2). Through point count analysis of thin sections and studies of powders with immersion oils using a petrographic microscope, we identified the primary and secondary components of the tuffs. We counted more than 500 points per section and made duplicate counts of several samples, checking these results with X-ray diffraction analysis of random powders. Point counts were reproducible within a range of ±10%.

The primary components of the tuffs are glass fragments, mainly yellow sideromelane (mafic glass) and orange palagonite (the alteration product of sideromelane); rock fragments, mainly leucititic lavas; and crystal fragments, mainly leucite, clinopyroxene, sanidine, biotite, melanite garnet and melilite (Fig. 3). Although most rock fragments are lavas, some tuff lithologies contain limestone fragments that were entrained as xenoliths within the erupting magma. The secondary, or authigenic, components of the tuffs are zeolite, calcite and clay, which formed diagenetically through a solution–precipitation process during low temperature reaction of interstitial water with glass, leucite and, rarely, the glassy groundmass of some lava fragments (Hay and Ijima 1968).

Salone quarry (TL 12). Small palagonite fragments (medium grey) ranging from fine to coarse ash in size and pumice fragments (lighter grey) form about 40% of the tuff. A vesicular lava fragment (darker grey) occupies the lower right quadrant of the field of view. All colourless pore space is phillipsite cement, which forms nearly 30% of the tuff. Note crystals of augite (CPX) and limestone (calcite) fragments (C). Clay is absent. (*c*) *Lapis Gabinus, Torre Castiglione quarry (97-2B). This grain-supported horizon contains about 50% fine- to coarse-ash sized lava fragments (darker grey) strongly cemented by chabazite, which forms about 25% of the layer. Note the absence of vitric matrix. The large clear and transparent area is a leucite crystal (L) partially altered to zeolite and calcite, not distinguishable in the photomicrograph.*

Table 2 *Petrographic data showing primary and secondary components of the tuffs determined through point counts of thin sections*

Sample name	*Type of tuff*	*Clast compositions*			*Whole-rock compositions*			*Authigenic minerals*						*Pumice*
		Vitric fragments	*Lithic fragments*	*Crystal fragments*	*Vitrics and clay*	*Lithics and crystals*	*Zeolites and calcite*	*Analcime*	*Phillipsite*	*Chabazite*	*Total zeolite*	*Calcite*	*Clay*	
MONTI SABATINI VOLCANICS														
Tufo Giallo della Via Tiberina														
TGdVT1a	Vitric–lithic/crystal	0.43	0.08	0.07	0.5	0.14	0.37	0.01	0	0.35	0.35	0.01	0.06	0.17
TGdVT1b*	Vitric–crystal	0.43	0.04	0.08	0.5	0.12	0.38	0	0	0.37	0.37	0.01	0.07	0.17
TGdVT2	Vitric–lithic/crystal	0.44	0.03	0.03	0.54	0.06	0.4	0.02	0	0.37	0.39	0.02	0.1	0.2
97-08	Vitric–crystal–lithic	0.3	0.07	0.05	0.42	0.12	0.48	0	0.16	0.28	0.44	0.03	0.12	0.25
Tufo Giallo di Prima Porta														
TGdPP1	Vitric–crystal	0.33	0.03	0.08	0.36	0.11	0.52	0	0.05	0.47	0.52	0	0.03	0.1
TGdPP5*	Vitric–crystal	0.32	0.01	0.12	0.32	0.13	0.57	0	0.03	0.54	0.57	0	0.01	0.15
TGdPP3	Vitric–crystal	0.34	0	0.14	0.38	0.14	0.48	0	0.06	0.42	0.48	0	0.04	0.12
Grottarossa pyroclastics														
SPQR-5*	Vitric/lithic–crystal	0.13	0.12	0.1	0.28	0.29	0.43	0.25	0.02	0	0.27	0.16	0.15	0.03
Tufo Rosso a Scorie Nere														
TRaSN-1	Vitric–lithic	0.33	0.15	0.03	0.36	0.19	0.49	0	0.31	0	0.31	0.17	0.01	0.13
ALBAN HILLS VOLCANICS														
Tufo del Palatino														
97-16	Vitric–lithic–crystal	0.28	0.15	0.13	0.56	0.28	0.17	0.07	0	0	0.07	0.09	0.29	0
UPP1	Vitric–crystal–lithic	0.26	0.09	0.14	0.28	0.23	0.5	0.5	0	0	0.5	0	0.02	0
PdVF-5f	Lithic–vitric–crystal	0.2	0.32	0.09	0.33	0.41	0.27	0	0.28	0.01	0.28	0.03	0.12	0.04
PdVF-5f	Lithic–vitric–crystal	0.2	0.24	0.07	0.38	0.31	0.31	0	0.27	0.01	0.27	0.04	0.19	0.03
PdVF-1a*	Vitric–lithic–crystal	0.22	0.19	0.16	0.35	0.35	0.31	0.12	0.16	0	0.28	0.03	0.13	0

TL-12*	Vitric–lithic–crystal	0.39	0.12	0.07	0.39	0.19	0.43	0	0.27	0.05	0.32	0.1	0	0.2
97-11B (Aniene, Salone)	Vitric–crystal–lithic	0.36	0.06	0.11	0.44	0.17	0.39	0	0.35	0.04	0.39	0	0.08	0.21
TL-1 (Aniene, Lunghezza)	Vitric–crystal–lithic	0.41	0.08	0.1	0.49	0.18	0.33	0	†	†	0.33	0	0.08	0.27
TL-3 (Aniene, Tor Cervara)	Vitric–lithic/crystal	0.35	0.06	0.06	0.4	0.12	0.49	0	†	†	0.49	0.02	0.05	0.24
TL-14 (Largo Martiri)	Vitric–lithic	0.25	0.05	0.04	0.37	0.1	0.55	0	†	†	0.55	0	0.12	0.15
TL-15 (Largo Martiri)	Vitric–lithic	0.49	0.05	0.04	0.5	0.09	0.41	0	†	†	0.41	0	0.02	0.3
Tufo di Tusculo														
TdT-10*	Lithic–crystal–vitric	0.18	0.3	0.22	0.18	0.52	0.3	0.01	0.23	0.06	0.3	0	0	0
Lapis Gabinus														
LG-3*	Lithic–crystal–vitric	0.19	0.36	0.08	0.2	0.44	0.34	0	†	†	0.33	0.01	0.01	0
97-2B	Lithic–vitric	0.12	0.52	0.04	0.12	0.56	0.32	0	0.02	0.26	0.28	0.07	0	0
97-2B	Lithic–vitric–crystal	0.15	0.45	0.05	0.15	0.51	0.35	0.01	0.03	0.26	0.29	0.06	0	0
97-2Da	Vitric–lithic–crystal	0.3	0.2	0.08	0.36	0.285	0.36	0.01	†	†	0.33	0.03	0	0
97-2Db	Vitric–lithic–crystal	0.38	0.17	0.07	0.38	0.232	0.38	0.01	†	†	0.35	0.03	0	0
Lapis Albanus														
LA-6*	Crystal/lithic–vitric	0.14	0.3	0.3	0.14	0.6	0.27	0.01	0.07	0.15	0.21	0.06	0	0
97-17A	Vitric–crystal–lithic	0.26	0.12	0.15	0.26	0.27	0.48	0	0.09	0.25	0.34	0.15	0	0.05
97-17B	Crystal–lithic/vitric	0.14	0.14	0.35	0.16	0.5	0.36	0	†	†	0.32	0.04	0.02	0

* For compressive strength data, see Table 4.

† In these samples, it was not possible to distinguish phillipsite and chabazite in thin section.

Analcime commonly replaces leucite (Giampaolo and Lombardi 1994). Table 2 gives the proportions of vitric, lithic and crystal fragments determined through point counts and classifies the various tuffs according to the composition of their constituent clasts following Pettijohn (1975, 306), with the dominant particle type (greater than 5% of the whole rock composition) listed first. For example, sample TGdVT 1a, containing 43% vitrics, 8% lithics and 7% crystals, or $V_{0.43}$ $L_{0.08}$ $C_{0.07}$, is a vitric–lithic–crystal tuff. In contrast, sample TGdVT 2, with $V_{0.44}$ $L_{0.03}$ $C_{0.03}$, is a vitric tuff (Fig. 3 (a)). These measurements provide a guide for determining tuff composition in hand sample and in the building stone of the Roman monuments. We use the Geological Society of America Rock-Color Chart to describe the tuffs with Munsell colour notation.

The tuff lithologies are, overall, texturally similar. They are poorly sorted with a wide disparity in grain sizes, ranging from fine ash (< 1/16 mm) to lapilli-sized fragments (< 64 mm). The coarsest fraction, forming 5% to 10% of the clasts, ranges from 0.5 cm to 1 cm in diameter and rarely exceeds 2–3 cm. These particles are lava, pumice or limestone fragments or pebbles entrained during the emplacement of certain pyroclastic flows. Some lithologies, such as Tufo Giallo della Via Tiberina and Tufo Lionato, contain lapilli-sized pumice fragments, sub-angular, non-vesicular glass fragments or bubble-wall glass shards with cuspate margins. These and smaller, sand-sized, glass fragments are sideromelane or palagonite; there is little fresh glass. The Tufo Giallos, Tufo Lionato from south of Rome and some horizons within the Valle Castiglione ground surge deposit (Lapis Gabinus) and the Lago Albano pyroclastic debris flow deposit (Lapis Albanus) (Table 1) are loosely grain supported tuffs with 20–50% very fine grained, altered vitric matrix containing zeolite, calcite and/or clay.

The Monti Sabatini volcanic deposits

Two major ignimbrites from Monti Sabatini volcano (Karner *et al.* 2001a), the upper eruptive unit of Tufo Giallo della Via Tiberina (548 ± 4 ka), and Tufo Rosso a Scorie Nere (449 ± 1 ka), were used as building stones in Rome. The geological map (Fig. 2) shows some of the Roman quarries for these tuffs that lie along Via Flaminia and Via Tiberina (Fig. 1).

Tufo Giallo della Via Tiberina The vitric tuff of the lower two subunits 'a' and 'b' of the upper eruptive unit of Tufo Giallo della Via Tiberina (Karner *et al.* 2001b) is a massive, moderately well-lithified, yellowish grey to greyish orange (5Y 8/2 to 10YR 7/4) ignimbrite. The tuff is loosely grain supported with abundant greyish yellow to moderate yellow orange (5Y 8/4 to 10YR 7/6) partly altered pumice fragments, fewer accretionary lapilli and < 15% lava, crystal and limestone fragments (Fig. 3 (a)). Yellowish grey (5Y 8/1 and 5Y 7/2) and greyish orange (10YR 7/4) altered vitric matrix forms about 40–50% of the rock and contains abundant chabazite. Leucite crystals are partially replaced by analcime, phillipsite, chabazite and calcite. Pumice fragments, which range up to 5 cm across, crumble easily. When rubbed briskly with the thumb, the tuff disaggregates readily into fine powder. Karner *et al.* (2001b) note that all outcrops of yellow vitric tuff along the southward continuation of Via Tiberina, including those at Prima Porta and along Via Flaminia (Figs 1 and 2) are Tufo Giallo di Prima Porta (514 ± 3 ka) ignimbrite. The yellowish grey (5Y 8/1) upper facies that crops out north of the city is a porous, vitric–crystal tuff cut by irregular joints. Greyish orange (10YR 7/4), altered pumice fragments are generally < 0.5 cm in diameter. The yellowish grey (5Y 8/1), altered vitric matrix contains abundant chabazite but is weakly cemented (Table 2). Lava fragments, crystals, dark grey scoriae, sedimentary lithic fragments and distinctive volcanic italite clasts form < 15% of the tuff. We suspect that Romans may have occasionally employed this facies as aggregate in concrete masonry; we have, in fact, identified fragments of Tufo Giallo di Prima Porta in concrete work on the eastern and western sides of the tabernae of the Forum of Caesar (54 BC to 29 BC) (Steinby 1995, *LTUR* II, 304–5).

Tufo Rosso a Scorie Nere The red tuff with black scoriae, or Tufo Rosso a Scorie Nere, is a moderately well-lithified ignimbrite that contains prominent, lapilli-sized dark grey (N2) scoriae and smaller, medium dark grey (N5) lava fragments in a light brown (5YR 5/6) altered vesicular ash matrix (Lenzi and Passaglia 1974; Alvarez *et al*. 1975). Brisk rubbing produces a fine powder that lightly coats the thumb. Near Rome, Tufo Rosso a Scorie Nere crops out along Via Flaminia and on the eastern bank of the Tiber River near Fidenae and its Etruscan quarries (Figs 1 and 2).

The Alban Hills volcanic deposits

Early construction in Rome utilized soft Alban Hills tuffs quarried within the city centre (Frank 1924). From the fourth to the first century BC, Romans developed quarries for Alban Hills tuffs more than 20 km distant from the city along the Aniene River and within the steep slopes of the volcano (Fig. 2; and see DeLaine 1995). By the late Republic, in the second to first centuries BC, they utilized specific lithologies for ashlar masonry, and for mortar and coarse aggregate (*caementa*) in concrete masonry.

Tufo del Palatino In Rome, Tufo del Palatino (528 ± 1 ka) ignimbrite is a soft, moderate olive grey (5Y 5/1) vitric–crystal–lithic tuff containing 10–15% lava fragments, fewer limestone fragments and pebbles of mudstone, sandstone and chert (Alvarez *et al*. 1996; Karner and Renne 1998; Karner *et al*. 2001b). There is little or no pumice. Leucite is partially or wholly replaced by analcime, and analcime cements the tuff, which may contain abundant clay (Table 2). North of Rome, Tufo del Palatino corresponds to Peperino della Via Flaminia (Karner *et al*. 2001b), an olive grey to dark yellowish brown (5Y 4/1 to 10YR 4/2), lithic–vitric tuff with abundant lava fragments, moderate brown (5YR 3/4) palagonite fragments, variable amounts of sedimentary rock fragments and strong phillipsite cement. We have not identified this highly lithified facies in the monuments; we suspect it could be confused with Lapis Albanus or Lapis Gabinus (Karner *et al*. 2001b).

Tufo Lionato Romans quarried Tufo Lionato (366 ± 4 ka), the palagonitic tuff used extensively in Republican and early Imperial period construction, from deposits south and west of Rome (Fig. 2) as well as within the city (Marra and Rosa 1995; Karner *et al*. 2001b). Romans first quarried soft Tufo Lionato from the Capitoline Hill and the Monteverde area, on the west bank of the Tiber River (Frank 1924). By the second century BC, they quarried more durable, moderately well-lithified Tufo Lionato along the Aniene River at Tor Cervara, Settecamini, Salone and Lunghezza (Quilici 1974). From the first century AD onwards, Romans employed soft Tufo Lionato rubble quarried south of the city as *caementa* in concrete masonry (DeLaine 1997). De Casa *et al*. (1999) describe substantial variations in the physical and petrographic characteristics of Tufo Lionato; our data corroborate these results. Moderate to light brown (5YR 4/4 to 5YR 5/6) Tufo Lionato quarried from deposits > 10 m thick along the Aniene River is a fairly well cemented vitric tuff, termed 'Litoide' or stone-like by modern Italians (Corsi 1828). It contains about 35–40% palagonitic glass, about 12–20% lava, crystal and limestone fragments, and predominantly phillipsite cement (Fig. 3 (b)). Leucite crystals are partially or wholly altered to phillipsite, chabazite and calcite. Pumice fragments remain remarkably intact; the pumice and the tuff as a whole contain little or no clay. When rubbed briskly, a fine film of light brown powder coats the thumb. Tufo Lionato from thin deposits south of Rome, on the other hand, is a soft vitric tuff, ranging from light brown (5YR 5/6 and 5YR 6/4) to greyish orange (10YR 7/4) and cut by irregular joints. It contains, in general, < 10% lava and crystal fragments, 20–50% palagonitic ash matrix and small pumice fragments, as well as variable amounts of clay (Table 2). Brisk rubbing with the thumb dislodges lava and crystal fragments and generates a coarse powder of glass.

Tufo di Tusculo Lugli (1957, 198) identified as Tufo di Tusculo a dense, moderate brownish grey (5YR 5/1), compact, lithic–crystal–vitric tuff quarried near the Roman town of Tusculum on the rim of the central caldera of Alban Hills volcano (Fig. 2). Fornaseri (1963, 136–8) describes quarries and outcrops extending along the caldera rim up to 5 km east of Tusculum. Commonly called Sperone (De Rita and Giampaolo 1996), Tufo di Tuscolo contains > 50% lava and crystal fragments, about 20% light brown (5YR 6/4) palagonite fragments, phillipsite cement and little pumice or clay. Leucite crystal fragments are partially or wholly replaced by analcime. Brisk rubbing with the thumb produces no visible disaggregation.

Lapis Gabinus Quarried from ground surge deposits at Valle Castiglione crater (Fig. 2; and see Narcisi *et al*. 1992; Karner and Renne 1998), Lapis Gabinus (~260 ka) is a hard, well-lithified, thin- to thick-bedded building stone. The lithic–vitric tuff of coarse-grained, strongly grain-supported beds contains about 50% lava fragments and crystals with well-developed chabazite cement, little vitric matrix and no clay (Fig. 3 (c) and Table 2). The vitric–lithic tuff of finer-grained beds is loosely grain-supported and contains accretionary lapilli, occasional pumice fragments and sparse clay with 20–40% moderate yellow grey (5Y 8/1) altered vitric matrix containing predominantly phillipsite cement.

Lapis Albanus Romans quarried Lapis Albanus (37 ka), an olive grey (5Y 4/1), well-lithified tuff, from the 12 m thick deposit of an ignimbrite that formed a debris flow north of Lago Albano crater (Karner *et al*. 2001b; Marra *et al*. 2003; Giordano *et al*. 2002; and see Fig. 2). The lithic–vitric tuff of coarser-grained horizons contains about 50% lava fragments and crystals with predominantly chabazite cement (Table 2). The vitric–lithic tuff of finer-grained horizons contains about 15% yellowish grey (5Y 7/2) altered vitric ash matrix, and both phillipsite and chabazite cement. There is a general absence of clay and pumice in all samples.

TRAVERTINE

Horizontally stratified, light yellowish grey (5Y 8/1) travertine deposits more than 60 m thick near Tivoli (Fig. 1) provided Romans with an important source of hard, dense building stone with very different material properties than the tuffs. The travertine accumulated between 160 and 40 ka within the spring-fed, shallow lake of Acque Albule basin (Faccenna *et al*. 1994). Living clumps of bacteria surrounded themselves with a continuously precipitating corona of calcite; the bacteria readily decayed, leaving calcite crystals riddled with micropores (Chafetz and Folk 1984). Aggregates of these crystals formed shrub-like growths 2–8 cm high, the result of flourishing growth of summer bacteria. These horizons were intercalated with finely and crudely laminated muds deposited during winter. Cyclic repetitions of these

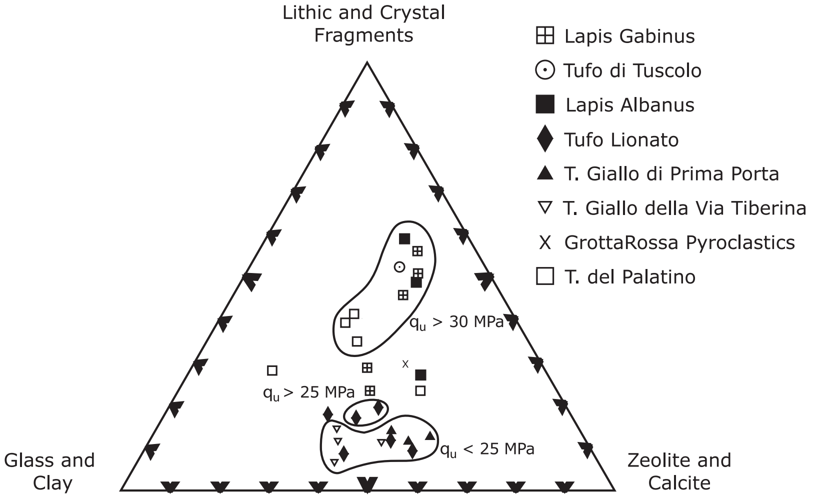


Figure 4 *The ternary diagram of tuff components determined by point counts of thin sections. The upper apex shows the percentage of lava and limestone rock fragments, crystals and crystal fragments, mainly leucite, clinopyroxene, sanidine, biotite, melanite garnet and melilite. The lower left apex shows glass and secondary clay. The lower right apex shows secondary zeolite and calcite, which occur mainly as cement. The outlined areas show the uniaxial compressive strength* ($q_{u\ dry}$) *of selected samples. See Tables 2 and 4 for data.*

structures give the travertine a complex but durable texture, where calcitic mudstone strongly cements the remains of small stromatolites and bioherms. In contrast, thin, localized incrustations of tufa that form around the mouth of a calcareous spring, such as those within the middle Pleistocene Valle Giulia Formation in Rome (Marra *et al.* 1998), have a porous, spongy, semi-friable texture that is unsuitable for building stone.

MATERIAL PROPERTIES OF ROMAN BUILDING STONE

The petrographic characteristics of the Roman tuffs

The petrographic diversity of the tuff building stones becomes clear when point count data are plotted on the ternary diagram of Figure 4, with the abundance of lava and sedimentary rock fragments plus crystals and crystal fragments on the upper apex; glass plus authigenic clay on the lower left apex; and authigenic zeolite plus calcite on the lower right apex. Tufo di Tusculo, coarse-grained Lapis Albanus and Lapis Gabinus, and Peperino della Via Flaminia (or well-lithified Tufo del Palatino) contain, in general, about 50% lithic and crystal fragments (Table 2). Fine-grained, vitric layers of Lapis Albanus and Lapis Gabinus and soft Tufo del Palatino sampled within Rome contain lesser amounts of lava and crystal fragments, about 23–35%. Modern Romans call these lithologies ‘peperino’, or black pepper-like, for their dark grey lava fragments. The Tufo Giallos and soft Tufo Lionato from south of Rome contain the smallest amounts of lava and crystal fragments, < 15%, and variable amounts of glass, and zeolite, calcite and clay. Tufo Lionato from the Aniene River quarries contains more lava and crystal fragments, about 12–20%. The tuffs exhibit a fairly wide range of petrographic variability within a single lithology. For Tufo Giallo della Via Tiberina and Tufo Lionato, which have widespread source localities, it is difficult to identify even generally the provenance of a specific building stone. Lapis Gabinus, Lapis Albanus and Tufo di Tusculo come from volumetrically smaller eruptive deposits (Fig. 2), so that quarry locations are constrained within a smaller area.

The physical properties of the tuffs and travertine

To assess systematically the physical properties of the Roman tuffs and travertine, we measured their strength and durability under oven-dried, water soaked and humid conditions (Winkler 1994, 142–55). In a preliminary study, two of us (MDJ and EMW) determined the dry-to-wet strength ratio as modulus of rupture (R) using 3 mm thick discs sliced from 35 mm cores with tests of five or more discs for each run (Winkler 1986). Tufo del Palatino crumbled in water; Tufo Rosso a Scorie Nere and Tufo Lionato collected from the south of Rome were too weak to be tested when water-soaked (Table 3). The Tufo Giallos gave low R and dry-to-wet strength ratios of about 33–51%. Tufo Lionato from three Aniene River quarries gave moderate R and dry-to-wet strength ratios of 65–84%. Lapis Albanus gave high R with dry-to-wet strength ratios of 66–89%, while Lapis Gabinus and Peperino della Via Flaminia gave highest R but had lower dry-to-wet strength ratios. In general, low water absorption (Ab) has a positive correlation with increased durability, measured as the dry-to-wet strength ratio. Travertine from Tivoli and Carrara marble gave significantly greater R and dry-to-wet strength ratios of 90–97%, with $Ab < 1$ wt% (ASTM C97-96: see ASTM 2000a).

To further describe the physical properties of the tuffs and travertine, two of us (MDJ and CC) determined uniaxial compressive strength (ASTM C170-90: see ASTM 2000b) for travertine and seven tuff lithologies that best represent the petrographic characteristics of the important Roman quarries (Table 4). We used a Tinius–Olsen universal tension-testing device in which the certified calibration was within 1% of the range of loads in which we were working. For each lithology we ran between six and eight tests on cores 2 cm in diameter and height, reading horizontal and vertical strains at 200 lb (890 N) increments of vertical load at a constant rate of 20–50 lb s^{-1} (4.4–11 N s^{-1}). We dried oven-dried tests at 60°C for 24 h prior to testing; we dried water-soaked tests at 60°C for 24 h and then soaked them in distilled water for 48 h prior to testing. Similarly, we dried humid tests at 60°C for 24 h and then kept them at RH 90–98% at 19–21°C for 48 h; we constructed a humidity chamber to maintain high moisture over the testing apparatus in a dry ambient atmosphere.

The oven-dried compressive strengths ($q_{u\ \mathrm{dry}}$) of the tuffs increase from low values of 20 MPa for Tufo Giallo di Prima Porta, sampled at Via Flaminia, and 23 MPa for Tufo Giallo della Via Tiberina, sampled at the Roman quarry at km 13 of Via Tiberina, to a moderate value of 29 MPa for Tufo Lionato, sampled from the Roman quarry at Salone along the Aniene River (Figs 2 and 5, and Table 4). Lapis Albanus, Tufo di Tusculo and Lapis Gabinus have higher values of 31 MPa, 37 MPa and 40 MPa, respectively. At 44 MPa, Peperino della Via Flaminia appears to have the greatest $q_{u\ \mathrm{dry}}$, but we have not yet found this highly lithified facies of Tufo del Palatino used as building stone. The tuffs show a strong tendency to absorb liquid water and adsorb water vapour (Fig. 5 and Table 4). The water-soaked Tufo Giallos absorbed between 20 wt% and 23 wt% water; Tufo Lionato absorbed about 15 wt%; and the well-lithified, lithic–crystal tuffs absorbed between 11 wt% and 15 wt%. Tufo Giallo della Via Tiberina performed most poorly when water-soaked. Most of the tuffs adsorbed between about 3 wt% and 7 wt% water vapour. With this intake of humidity they retained between 60% and 85% of their dry strength, with the exception of pumice-rich Tufo Giallo della Via Tiberina, which retained only 40%. Travertine has low Ab, 0.6–0.8 wt%, and

Table 3 *Modulus of rupture data for the Roman tuffs, travertine and Carrara marble, determined following the methodology described by Winkler (1986)*

Sample name	*Modulus of rupture, dry (MPa)*	*Modulus of rupture, wet (MPa)*	*Ratio of wet/dry modulus of rupture (%)*	*Water absorption, soaked (%)*	*Water adsorption, at 98% RH (%)*
Tufo del Palatino					
UPP1A				33	
Tufo Rosso a Scorie Nere					
TRaSN-1	0.97			28	4.45
TRaSN-2	1.72			28	4.53
Tufo Giallo della Via Tiberina					
TGdVT-1	3.27	1.28	39	24	
TGdVT-2	3.49	1.16	33	10	1.85
TGdVT-3	2.75	1.34	51	23	3.81
Tufo Giallo di Prima Porta					
TGdPP-1	2.59	1.11	51	20	4.38
Tufo Lionato					
TL-1 (Aniene, Lunghezza)	3.72	3.14	84	25	
TL-1B (Aniene, Lunghezza	4.16	2.61	68	26	3.76
TL-2 (Aniene, Salone)	2.62	2.84	1.08	19	4.09
TL-2B (Aniene, Salone)	3.74	2.98	80	18	
TL-3 (Aniene, Tor Cervara)	2.56	2.02	65	31	
TL-4 (Rupe Tarpea)	1.77	1.15	65	31	
TL-5 (Monteverde, Via Sapori)	4.34			26	
TL-6 (Monteverde, Via Portuense)				27	
Lapis Albanus					
97-17B	4.03	2.67	66	10	1.85
LA-1	5.87	5.24	89	12	
LA-2	8.25	6.66	81	12	
LA-2B	8.71	5.8	67	10	2.85
LA-3	5.04	3.89	77	13	2.37
Lapis Gabinus					
LG-1	10.93	5.07	47	12	3.13
LG-2	8.97	3.72	42	12	2.84
Peperino della Via Flaminia					
PdVF-1	9.09	4.88	54	20	4.47
Travertine, Tivoli					
TRAV-1	15.2	14.7	97	0.76	0.08
Carrara marble					
CARRARA-1	12.33	11.18	91	0.29	0.03

Ad, 0.07–0.08 wt%, and retains about 80% of its dry strength under these conditions (Tables 3 and 4).

These data corroborate, in general, rock testing results reported by Nappi *et al.* (1979), Bianchetti *et al.* (1994), Sappa *et al.* (1995) and De Casa *et al.* (1994, 1999) for the Roman tuffs. For Tufo Rosso a Scorie Nere, Laurenzi Tabasso *et al.* (1990) and Sappa *et al.* (1995)

Table 4 *Uniaxial compressive strength and related physical properties of the Roman tuffs and travertine (ASTM C170-90 (ASTM 2000b)). The absorption of liquid water, Ab, is computed as* [$\text{weight}_{\text{water-soaked}} - \text{weight}_{\text{oven-dried}}/\text{weight}_{\text{water-soaked}}$] *(ASTM C97-96 (ASTM 2000a)). The adsorption of water vapour, Ad, is computed as* [$\text{weight}_{\text{humid}} - \text{weight}_{\text{oven-dried}}/\text{weight}_{\text{humid}}$]*. Bulk specific gravity, G, is computed as* [$\text{weight}_{\text{oven-dried}}/(\text{weight}_{\text{water-soaked in air}} - \text{weight}_{\text{water-soaked in water}}$] *(ASTM C97-96 (ASTM 2000a))*

Sample name	*Uniaxial compressive strength (MPa) (oven-dried)*	*Standard deviation*	*Uniaxial compressive strength (MPa) (water-soaked)*	*Standard deviation*	*Uniaxial compressive strength (MPa) (RH 90–98%)*	*Standard deviation*	*Water absorption, Ab (%)*	*Water adsorption, Ad (%)*	*Bulk specific gravity, G*
Tufo Giallo di Prima Porta									
TGdPP5	20.4	1.7	9.8	1.1	14.1	2.3	22.7	6.8	1.44
Tufo Giallo della Via Tiberina									
TGdVT 1b	22.9	4.1	7.6	0.7	9.8	0.8	20.1	6.6	1.52
Tufo Lionato, Salone Quarry									
TL 12	28.5	2.4	15.9	2.5	25.8	6.6	15.3	5.1	1.73
Lapis Albanus									
LA 6	31.3	0.8	16.3	2.4	26.6	0.9	10.7	2.9	1.87
Tufo di Tusculo									
TdT10	36.7	4.9	17.3	2.8	25.1	3.2	15.3	3.2	1.83
Lapis Gabinus									
LG 3	39.5	10.5	15.5	3.4	23	6.3	13.8	5.7	1.81
Tufo del Palatino (Peperino della Via Flaminia)									
PdVF 1a	43.4	14.3	28.8	12.1	27.2	6	13.4	6.6	1.89
Travertine, Tivoli									
T 1	104.8	9.5	81.8	11.2	82.6	13	0.6	0.07	2.58

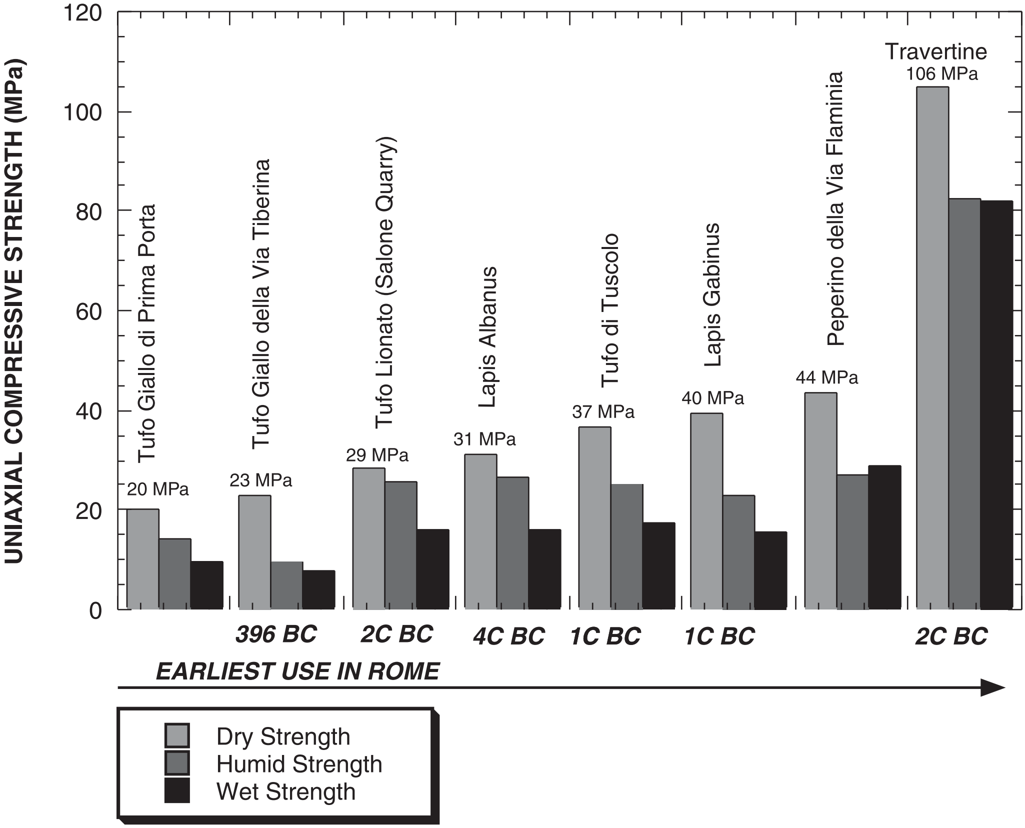


Figure 5 *The uniaxial compressive strengths* (q_u) *of samples of tuffs and travertine collected from Roman quarries and measured under oven-dried, water-soaked and humid (RH 90–98%) conditions.*

provide low values of compressive strength of about 2–5 MPa under ambient conditions. For the upper eruptive unit of Tufo Giallo della Via Tiberina, Nappi *et al.* (1979) report low values of tensile strength, T_o, that vary from about 1/6 to 1/10 of q_u under ambient conditions. De Casa *et al.* (1999) report values of T_o for Tufo Lionato that vary from 1/10 to 1/3 of ambient q_u.

Correlation of the physical and petrographic characteristics of the tuffs

The relative abundance of glass, crystal and rock fragments is the most diagnostic feature in defining the weight-bearing strength and durability of the Roman tuffs. Vesicular, loosely grain-supported, vitric tuffs, such as Tufo Giallo della Via Tiberina and Tufo Rosso a Scorie Nere, have low compressive strengths, high water sorption and low durability (Figs 4 and 5, and Tables 2 and 4; see also Laurenzi Tabasso *et al.* 1990). Coarse-grained, lithic–crystal Tufo di Tuscolo, Lapis Albanus and Lapis Gabinus have the greatest compressive strength and durability. Bulk specific gravity, *G*, increases regularly from the pumice-rich Tufo Giallos to Tufo Lionato to lithic–crystal Lapis Albanus, Tufo di Tusculo and Lapis Gabinus (Table 4). Lava and crystal fragments provide hard, strong particles to which zeolite cements may strongly adhere. They give dense, weight-bearing support to the stone in much the same way that inert granular materials such as sand and gravel add strength to modern-day concrete. Tufo di Tusculo contains > 50% lava and crystal fragments fairly uniformly. Lapis Albanus and Lapis Gabinus, however, are stratified deposits; they may perform less predictably than Tufo di Tusculo.

Pumice fragments commonly alter to clay within porous, vitric tuffs, such as Tufo Giallo della Via Tiberina and Tufo Lionato from south of Rome (Figs 3 (a) and 3 (b), and Table 2). The altered vitric matrix of these tuffs and the analcimic cement of some Tufo del Palatino samples also contain small but pervasive amounts of clay. The presence of clay reduces the adherence of zeolite cements to the binding surfaces of lithic and vitric particles and decreases compressive strength (Figs 4 and 5; see also Torracca 1988, 97–9). During repeated wetting and drying cycles, expansion and contraction of hydrophilic minerals such as clay and zeolite exacerbates stone decay (Torracca 1988, 30; Colantuano *et al.* 1993; Winkler 1994, 151).

ANCIENT EXPERTISE IN STONE SELECTION AND PRESERVATION

To illustrate the evolution of Roman expertise in design and preservation of tuff masonry, two of us (MDJ and FM) made geological field observations of stone monuments in Rome. Early in the history of the city, from the sixth century BC to the second century BC, Romans constructed relatively modest structures of soft Tufo del Palatino and Tufo Lionato quarried within Rome (Blake 1947). After the conquest of Etruscan cities in 426 BC and 396 BC, they also utilized porous, weakly durable Tufo Giallo della Via Tiberina and Tufo Rosso a Scorie Nere, quarried within the Monti Sabatini volcanic district (Figs 3 (a) and 6 (a)). By the mid-second century BC, Romans made extensive use of moderately durable vitric–lithic and vitric–crystal Tufo Lionato from the Aniene River quarries (Figs 3 (b) and 6 (b)). During the late Republic and early Imperial periods, Romans employed well-lithified, more durable, lithic–crystal Lapis Albanus, Tufo di Tuscolo and Lapis Gabinus in the weight-bearing foundations and walls of large monuments (Figs 3 (c) and 6 (c)). Tufo Giallo della Via Tiberina served mainly as *caementa* in concrete masonry. The earliest datable use of travertine as building stone in Rome occurs in the Temple of Concord, dedicated in 121 BC (Steinby 1993, *LTUR* I, 316–20). Field observations, systematic measurement of material properties of the tuffs (Figs 4 and 5) and descriptions by Vitruvius of the diverse material characteristics of Roman building stone (2.7.1–5), processes of absorption of liquid water (6.1.8) and adsorption of water vapour (8.1.4–5, 8.2.3–4), application of protective stucco (7.3.8) and distribution of loads within structures (6.8.1–4) demonstrate that by the late first century BC Roman builders had gained an extensive practical knowledge of the material properties of the tuffs and travertine.

The selection of tuff building stone

The podium of Temple C (Fig. 6 (a)), constructed in 290 BC within the Largo Argentina Sacred Area (Richardson 1992, 33–5; Coarelli 1997, 274–6), provides an example of decay of the porous, vitric Tufo Giallo della Via Tiberina that was utilized extensively during the early and mid-Republic. The massive, pumiceous, tuff blocks, exposed since excavation in the 1920s, are currently disaggregating in places. A perimeter wall of more durable Tufo Giallo della Via Tiberina, which predates a pavement of Tufo Lionato installed in about 100 BC, surrounds parts of the podium and still stands strong and secure. Romans used Tufo Giallo della Via Tiberina as ashlar masonry throughout the first century BC. At the Theatre and Crypta of Balbus

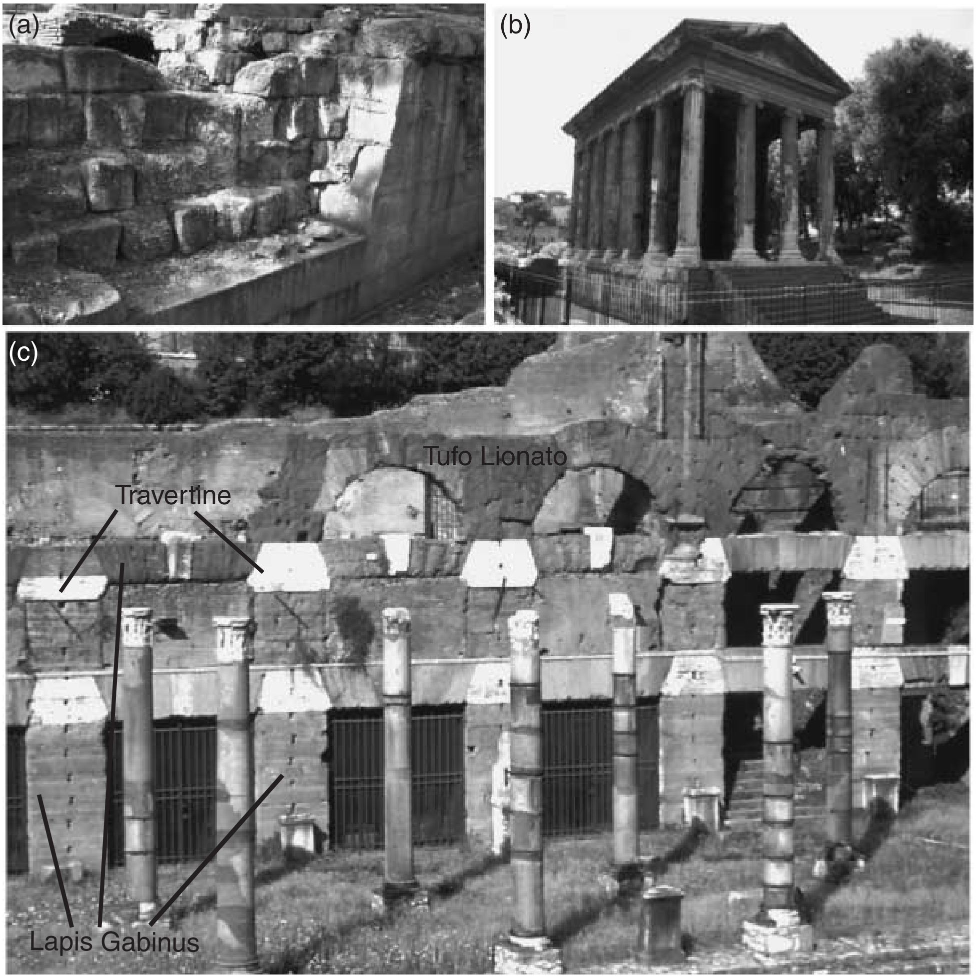


Figure 6 *Photographs of tuff and travertine building stone in some Republican age monuments of ancient Rome.* (*a*) *Temple C, Largo Argentina Sacred Area. The rectangular temple podium, constructed in 290* BC *of vitric, pumice-rich Tufo Giallo della Via Tiberina ashlar masonry, is badly decayed. An outer wall of more durable Tufo Giallo della Via Tiberina, constructed during the second century* BC*, surrounds the older podium.* (*b*) *The Temple of Portunus. Reconstructed during the late first century* BC*, this rectangular temple remained protected within a Christian church for many centuries. Vitric–lithic Tufo Lionato ashlar masonry from the Aniene River quarries forms the temple podium and cella walls. Fluted Tufo Lionato half-columns of the cella and travertine columns of the portico partially retain coatings of stucco. Travertine blocks reinforce the corners of the tuff cella; travertine revetments protect the Tufo Lionato temple podium.* (*c*) *The Forum of Caesar. Coarse-grained, lithic–vitric Lapis Gabinus pillars support the tabernae of the forum, dedicated in 46* BC*. The flat arches have Lapis Gabinus voussoirs, or wedge-shaped blocks, with travertine keystones. Durable travertine blocks at the top of the Lapis Gabinus pillars relieve compressive stresses from the arches. The upper-storey round arches are lightweight Tufo Lionato from the Aniene River quarries.*

(Steinby 1999, *LTUR* IV, 133), for example, it was combined in walls with more durable Tufo Lionato and travertine, and protected with stucco or travertine facings.

The Temple of Portunus (Fig. 6 (b)), rebuilt between 80 BC and 70 BC on the banks of the Tiber River near Tiber Island, exemplifies the refined, well-preserved Tufo Lionato and travertine masonry of the late Republic (Richardson 1992, 320; Steinby 1999, *LTUR* IV, 153). Tufo Lionato blockwork forms the temple podium, the cella walls and their half-columns. Travertine columns still partially coated with stucco support the portico; travertine blocks alternating with blocks of Tufo Lionato support the corners of the cella; and travertine revetments face the Tufo Lionato podium. Stucco and travertine facings protected the tuff from direct contact with atmospheric humidity, rain and floodwater, and provided a decorative surface that gave the appearance of the marble of ancient Greece. From AD 872 to the early 20th century, the temple was incorporated within the church of Santa Maria Egiziaca (Claridge 1998, 253).

The Forum of Caesar (Fig. 6 (c)), dedicated in 46 BC, provides a valuable illustration of how carefully Romans employed the diverse properties of the tuffs and of travertine in structural design (Steinby 1995, *LTUR* II, 299–306). The front walls of the lower level of tabernae consist of well-preserved, lithic–vitric Lapis Gabinus (Fig. 3 (c)) ashlar pillars that support flat arches of wedge-shaped Lapis Gabinus and travertine voussoirs cut with bedding subparallel to their inclined joints. Here, Roman builders demonstrated their knowledge of the relative strength and durability of the two stones. They minimized the weight of the flat arches with Lapis Gabinus voussoirs ($G = 1.81$, $q_{u\ \mathrm{dry}} = 40$ MPa) that direct compressive stress on to travertine blocks at the top of the tuff pillars, and maximized their strength with travertine keystones that could withstand high compressive stresses ($G = 2.58$, $q_{u\ \mathrm{dry}} = 105$ MPa). The second-storey wall and round arches are weathered Tufo Lionato from the Aniene River quarries. With its lower bulk specific gravity ($G = 1.73$) and intermediate compressive strength ($q_{u\ \mathrm{dry}} = 29$ MPa), vitric–lithic Tufo Lionato (Fig. 3 (b)) provided moderately durable stone for the upper storey and yet minimized the weight-bearing load supported by the underlying Lapis Gabinus and travertine masonry. Tuff and travertine blocks bear the traces of dowel holes where metal clips fastened marble revetments to their exterior surfaces. The concrete barrel vaults on either side of the tabernae have lightweight Tufo Giallo della Via Tiberina *caementa* ($G = 1.44$); the porous, vitric tuff (Fig. 3 (a)) has an abundant surface area with which to bond with pozzolanic mortar (Lechtman and Hobbs 1987).

The thermal expansion of tuff and travertine Writing at the time of Emperor Augustus, Vitruvius states, ‘Travertine, on the other hand, and all stones of that type, endure every strain, whether it be stress or the injuries inflicted by harsh weather, but they cannot be safeguarded against fire. As soon as they make contact with it, they crack apart and fall to pieces’ (Vitruvius, 2.7.2). Modern experimental data fully support Vitruvius’ statement: travertine (Table 4) and Carrara marble (J. Logan pers. comm., 2003) have far greater compressive strengths, in the range of 105 MPa and 130 MPa, than the Roman tuffs. They are far more durable under water-soaked and humid conditions. When heated, however, calcite undergoes anisotropic expansion, lengthening 0.189% parallel to the *c*-axis and contracting 0.042% perpendicular to it (Rayleigh 1934; Logan *et al.* 1993; Winkler 1994, fig. 10–3). The change in shape of individual crystals strains the original grain mosaic, eventually rupturing grain contacts and leading to fracture of the stone at high temperatures. Furthermore, experimental data demonstrate that Carrara marble experiences an average thermal linear expansion of 6×10^{-6} cm cm^{-1} °C^{-1} (Logan *et al.* 1993; pers. comm., 2003), while the few measurements performed on lithified tuffs give lower values, ranging from 4×10^{-6} to 4.65×10^{-6} cm cm^{-1} °C^{-1} (Bauleke and Hugh 1969). When heated to 900 K (627°C) certain marbles undergo a linear expansion of about 2%, while the tuffs only expand by about 0.25% (Touloukian *et al.* 1981).

At the Forum of Augustus, dedicated in AD 2, Lapis Gabinus ashlar masonry forms the northwestern segment of the boundary wall, constructed to protect the forum from fires on the

Quirinal Hill. The southeastern extension of the wall, constructed in the late first century AD against the Forum Transitorium, is Lapis Albanus blockwork. During fires the tuffs may have sustained temperatures in the range of 800–1200°C without fracturing (Winkler 1994, fig. 10–1; C. McHugh pers. comm., 2003). The porous, pyroclastic texture of the Roman tuffs thus accommodates thermal expansion far more readily than the interlocking crystalline calcite texture of travertine or marble.

The preservation of tuff building stone

Vitruvius describes the Roman tuffs as ‘soft stones’ and states that ‘as long as they are used in covered areas, they will sustain stress, but if they are put in open uncovered places, then, once they have been saturated with ice and frost they crumble apart and dissolve’ (Vitruvius, 2.7.1–2). In Rome, tuff masonry was seldom left exposed. Applications of stucco, impermeable to both rainwater and water vapour, protected tuff surfaces from decay and prevented moisture accumulation within the porous stone (Vitruvius 7.2–7.4). Durable, decorative travertine and marble cladding also shielded tuff walls (Torracca 1988, 111–14; Manaresi 1993), as exemplified by the Temple of Portunus (Fig. 6 (b)).

Water sorption seems to be the most influential factor in decay of the Roman tuff building stones. Absorption of liquid water occurs mainly through saturation of tuff foundations and walls with groundwater in low-lying areas (Corazza and Lombardi 1995) and with regular inundations of floodwater from the Tiber River (Bencivenga *et al.* 1995). Direct penetration of rainwater softens the surface layer of the tuff building stone, causing it to swell and corrode as water remains in contact with hydrophilic minerals (Torracca 1988, 9–12, 97–9). Absorption of acid rain or water droplets accelerates dissolution of zeolite and calcite cements (De’Gennaro *et al.* 1992).

Rome has humid, warm summers and rainy, cool winters; freezing temperatures occur only sporadically within the city. In fall and winter, relative humidity (RH) falls from about 85% in the morning to about 60–70% at midday as temperatures rise (Pearce and Smith 1990). During the day, adsorption of water vapour into building stone occurs when warm, humid air condensates on cool masonry walls (Winkler 1994, 142–5). In the evening, as temperatures decline, water vapour released from the cooling air settles on their exposed surfaces. Free water molecules adsorbed into the porous stone attach as ordered water to the surfaces of narrow capillaries (Torracca 1988, 13–16; Winkler 1994, 142–55), where they may dissolve grain cements and cause microcracking and disaggregation of the tuff as hydrophilic minerals expand and contract (Colantuano *et al.* 1993). In the summer, sun and wind evaporate moisture from the tuffs, depositing dissolved constituents as surface efflorescence and indurated crusts that may overlay incoherent material (Torracca 1988, 41–4). Exfoliation and alveolar erosion further degrade the surfaces of the tuff blocks so that they may develop convex-outward shapes as the stone disaggregates and erodes along corners. Decay is most pronounced in porous Tufo Giallo della Via Tiberina (Corazza *et al.* 1987) and friable Tufo del Palatino (Bianchetti *et al.* 1982), the building stones containing the greatest amounts of altered pumice and/or clay (Table 2).

CONCLUSIONS

Petrographic studies and rock testing data provide a scientific framework to explain Roman expertise in employing the diverse physical and material properties of tuff building stones in late Republican and early Imperial architecture. Tuff lithologies with an abundance of lava and crystal fragments have the greatest compressive strengths and durability. Pumice, clay and/or significant percentages of altered vitric matrix decrease compressive strength as well as the adherence of zeolite cements to vitric and lithic fragments. Field observations of building stones as well as statements by Vitruvius in *De architectura* (31–27 BC) demonstrate that Romans understood the material properties of the various tuffs and used these to advantage in the construction of specific structural elements within large, public monuments of the first century BC and the first century AD. For example, Tufo di Tuscolo, a hard, lithic–crystal tuff, provided blocks for piers and weight-bearing walls; Lapis Gabinus, a well-cemented predominantly lithic–vitric tuff, served as ashlar masonry in foundations and as voussoirs in flat arches; Tufo Giallo della Via Tiberina, a pumice-bearing vitric tuff, furnished *caementa* for concrete work in vaults. Durable travertine provided keystones for arches and pavements at the base of weight-bearing tuff columns. The Roman tuffs absorb and adsorb significant quantities of water and water vapour; with this intake of moisture, they lose about 15–40% of their dry strength. Roman builders preserved porous tuff building stone with stucco coatings or travertine or marble cladding, whose water sorption is far less than that of the tuffs. Although burial and enclosure protected the tuff building stone of many ancient monuments for centuries, modern archaeological excavations have exposed the tuffs to accelerated decay. The tuff building stones of many of Rome's most precious monuments are in the process of active disintegration. To prevent further deterioration and eventual corrosion of the monuments, the tuffs should be placed under protective cover, as Vitruvius recommended more than 2000 years ago.

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