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PROVENANCING OF LIGHTWEIGHT VOLCANIC STONES USED IN ANCIENT ROMAN CONCRETE VAULTING: EVIDENCE FROM ROME*

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This paper presents the geochemical analysis of lightweight scoria and pumice used in concrete vaults from ancient Rome. The geochemical signatures of dark scoria indicates a provenance of the 36–18 ka lavas of Vesuvius, as opposed to the more recent events on which Pompeii was built, as previously thought. The light-coloured pumices analysed, which were originally thought to belong to the Sabatini volcanic system (north of Rome), corresponded instead to products from Campi Flegrei. These results provoke re-evaluation of the trade and acquisition of these specialized materials destined for imperial projects in the capital city.

KEYWORDS: CONCRETE VAULT, CAMPI FLEGREI, ICP–MS, PUMICE, POMPEII, ROME, SCORIA, TRADE ROUTES, VESUVIUS, XRF

INTRODUCTION

Some of the most structurally innovative concrete vaults built in imperial Rome employed lightweight volcanic rocks to reduce the lateral thrust on the supporting walls, the most famous being the Pantheon. Roman concrete (*opus caementicium*) was made up of mortar binding together pieces of large aggregate (*caementa*) usually ranging from 10 to 20 cm long, which were hand laid in the mortar (as opposed to being poured as is typical in modern concrete), so that it resembles mortared rubble. A key aspect of the development of large-scale concrete vaulting was the ability to regulate the weight of the ingredients in order to reduce the weight of the vaults and to control the forces within the structure. The volcanic environment along the west coast of Italy provided numerous stones of different weights and physical properties from which the builders could choose (Fig. 1), including pumice and scoria, which were the most common choices for the lightweight *caementa* of the most innovative vaulted structures. Because these materials were produced by many of the Italian volcanoes, our goal was to establish the provenance of those used in vaults in Rome in order to understand better the supply network. We first used thin sections to narrow the potential sources and then we submitted selected samples to X-ray fluorescence spectroscopy (XRF) and laser ablation inductively coupled plasma mass spectrometry (LA–ICP–

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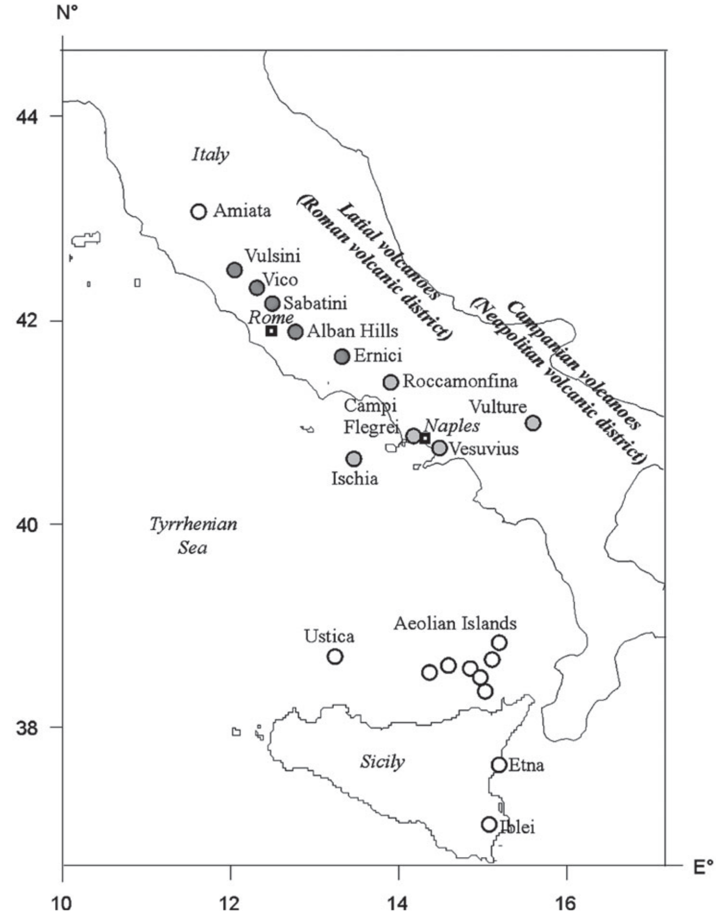

Figure 1 *A map showing the location of the Italian volcanoes and volcanic districts.*

MS) to determine the concentration of major and selected trace elements in an attempt to isolate further the volcano and, when possible, the event that produced the materials.

PREVIOUS STUDIES

The use of scoria and pumice in Roman concrete vaults has been recognized for centuries, but only in the 20th century were scientific analyses routinely employed to identify their provenance. The geologist Gioacchino De Angelis D'Ossat was one of the first to take a scientific interest in these rocks. In 1929, he was able to make thin sections of the dark reddish brown vesicular scoria taken from the Pantheon dome during restorations, and in his 1930 publication he argued that it was from Vesuvius, on the basis of the size and rounded shape of the vesicles ('lava bollosa'), on its mineralogical assemblage—which led him to define it as leucitic tephrite bordering on basanite due to the presence of olivine—and on its visual similarity to materials found in walls at Pompeii (De Angelis d'Ossat 1930). In 1945, he published the results of his examination of the pumice in the dome of the 'Temple of Minerva Medica', arguing that it was from the Sabatini or perhaps Cimini volcanic district (north of Rome), on the basis of the abundant presence of sanidine (prominent in the products of these volcanoes), the high acidity and the texture of the vesicles (De Angelis d'Ossat 1945). He did not provide a complete report of the mineralogical assemblage in either article, and geochemical techniques were not yet available in his day.

The work of Gioacchino De Angelis d'Ossat also affected the identification of pumice in the vaults of the Baths of Diocletian, albeit indirectly. His son, the renowned architectural historian Guglielmo De Angelis d'Ossat, writing at the same time as his father was working at 'Minerva Medica', noted the presence of a light-coloured pumice (yellowish or white) from the tepidarium of the Baths of Diocletian and suggested that it was a product from the scoria deposits of volcanoes in Lazio ('dai depositi di scorie dei vulcani laziali') (De Angelis d'Ossat 1940, 245; De Angelis d'Ossat 1946, 20–1), but no geological evidence for this identification was presented.

Only recently has there been renewed interest in identifying the provenance of lightweight rocks in Roman structures using scientific methods. The studies most relevant for the present investigation are those identifying the use of pumice as fine aggregate within the mortar of the vaults at the Forum of Caesar, the Basilica Ulpia, the Sala Trisegmentata of the Forum of Trajan and the Grande Aula at Trajan's Markets (Jackson *et al*. 2009, 2010, forthcoming; Bianchi *et al*. forthcoming). Thin sections of samples from all these monuments indicate the presence of different types of pumices in the mortar (Jackson *et al*. 2010, 65). One type of the Forum of Caesar sanidine-bearing pumice has been hypothesized to be consistent with the deposits of the bank into which the forum was excavated (Jackson *et al*. 2010, 65–6; Jackson *et al*. forthcoming). The provenance of the other types of pumice, as well as of the pumice at the Markets of Trajan, has not yet been determined (Jackson *et al*. 2009, 2487).

THE SAMPLES AND THEIR CONTEXTS

Our project initially began as an attempt to identify the provenance of scoria similar in appearance to that in Pantheon dome but which was found in vaults of other buildings in Rome: the Forum of Caesar, the Basilica Ulpia, the Baths of Trajan, the Baths of Caracalla and the Basilica Julia. Thin sections revealed that the mineral phases of the scorias were all consistent with that of Vesuvius (Table 1) (Lancaster 2005a, 222–3), but in order to establish the event that produced the scoria and narrow down the possible locations of the Vesuvian quarries, geochemical analysis was necessary. We then added a sample of light-coloured sanidine-rich pumice (Table 1) that was used as a fine aggregate mixed into the mortar (as opposed to being used as *caementa*) of some vaults at the Colosseum and of a sanidine-rich pumiceous scoria used as *caementa* in vaults at the Baths of Diocletian. Given the abundance of sanidine in both samples, we initially thought that they probably belonged to one of the volcanic districts north of Rome, as suggested by the De Angelis d'Ossats. However, the mineral phases revealed by thin sections were too general to associate with a particular volcanic district and required trace element analysis to narrow down the possible provenance. Recently, Peccerillo (2005) provided a large reference database for the compositions of the products of the volcanic districts of Italy, and showed that the relative abundances of immobile elements such as Zr/Y and Nb/Y ratios, among others, may represent geochemical signatures that discriminate among different volcanic products. The comparison of these ratios appears to give an accurate representation of provenance to a specific volcanic area and, sometimes, to a single eruption unit. The five samples from monuments in Rome that we chose for geochemical analysis represent a broad chronological range from the mid-first century BC to the early fourth century AD, which should provide data for the supply network for lightweight vaulting stones at key points during the economic history of the capital city.

Table 1 *The mineral phases of the original sample set. Symbols: ++, prevailing phenocrystals; +, less abundant phenocrystals; –, poorly abundant phenocrystals (<5 vol%); *, microcrystal occurring only in the groundmass. Samples with numbers correspond to samples listed in Table 2. Those without numbers were not submitted for geochemical analysis*

Sample		*Scoria*								*Pumice*
		021 Forum Caesar	*Trajan's Baths E*	*022 Basilica Ulpia*	*Baths Caracalla A*	*Baths Caracalla B*	*Basilica Julia A*	*023 Basilica Julia B*	*Pompeii*	*011 Colosseum*
	Colour	*Dark brown 10YR 3/3*	*Dark reddish brown 2.5YR 3/2*	*Dark reddish brown 2.5YR 3/2*	*Dark brown 10YR 3/3*	*Reddish brown 2.5 YR 4/4*	*Brown 7.5YR 4/2*	*Weak red 10R 4/4*	*Dusky red 10R 3/2*	*Light grey 10YR 7/1*
Phenocrysts	Pyroxene	+	++	++	++	++	++	+	++	–
	Plagioclase	++	++	++	+	+	+	++	+	+
	Leucite				+	+	+		+	
	Olivine relicts		+	+	+	+	+	+	+	
	Magnetite				–	–	–			–
	Phlogopite		+	+						
	Sanidine									++
	Mica									–
Groundmass	Pyroxene		*	*						
	Plagioclase	*	*	*	*	*	*		*	
	Leucite	*	*	*	*	*	*	*	*	*
	Magnetite		*	*	*	*	*		*	
	Sanidine	*	*	*	*	*	*	*	*	*
	Glass	Zeotilized	Zeotilized	Zeotilized	Zeotilized	Zeotilized	Zeotilized	Zeotilized	Zeotilized	Zeotilized

Figure 2 *A photograph of scoria in the vault of a room facing on to the Forum of Caesar.*

The earliest of our scoria samples (021), from the Forum of Caesar, was taken from one of the vaults of the rooms (46–44 BC) that were built against the Capitoline Hill and faced on to the portico surrounding the forum. C. M. Amici (1991, 52, 162) first noted the use of the dark scoria *caementa* (Fig. 2). This is the earliest example of its use in Roman vaults, and it is the only one of our samples to date before the AD 79 eruption of Vesuvius. The mortar in these vaults also contains pumice (Jackson *et al*. 2010, forthcoming), which is not included in our study.

Next in the chronological sequence is a sample of light grey pumice (011) from the level 2 vaults of the Colosseum (AD 80). The use of the lightweight stone in this example is different from the other samples because it was added to the mortar mixture in lapilli-sized pieces

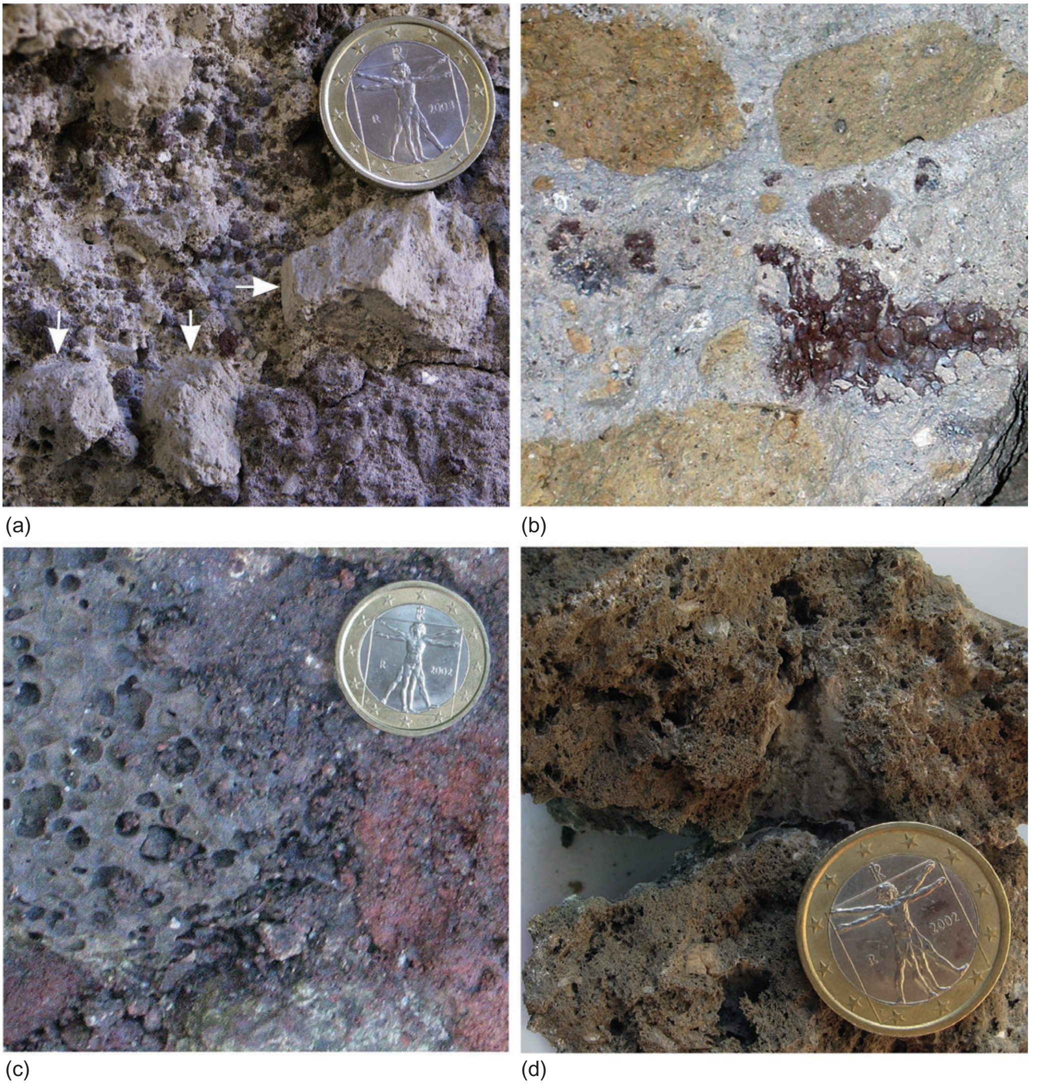

Figure 3 *(a) Colosseum mortar containing small pieces of light grey pumice (indicated by arrows). (b) The Basilica Ulpia vaulting, with alternating layers of Tufo Giallo della Via Tiberina and dark scoria. (c) The Basilica Julia vaulting, with scoria detail. (d) Pumice sample 05 from the Baths of Diocletian (euro = 2.3 cm dia.)*

(<1.5 cm) rather than used as *caementa* (Fig. 3 (a)), which in this case was Tufo Giallo della via Tiberina from the Sabatini volcanic district. The Colosseum represents the beginning of the systematic use of Tufo Giallo della Via Tiberina (1270–1520 kg m^{-3}) to lighten vaults as opposed to the more commonly used but heavier Tufo Lionato (1679 kg m^{-3}; average weights from Jackson *et al*. 2009, 2483). Due to the Colosseum's location on top of the lake once adjoining Nero's Golden House, and the difficult geological and drainage conditions in which the foundation trenches were excavated (Funiciello *et al*. 2002; Rea *et al*. 2002, 346–8), the builders went to considerable efforts to control the forces within the structure by using different types of stone in different parts of the building (Lancaster 2005b). The use of the pumice in the mortar and Tufo Giallo as *caementa* is therefore part of a larger programme of judicious stone selection. One goal of the analysis of the Colosseum pumice was to determine if it could have been local material from the excavation of the foundation trenches. Furthermore, it dates before the regular use of the dark scoria as *caementa* for structurally innovative vaulting in Rome, which begins in the Trajanic period (Lancaster 2005a, 65–6), and thus represents an intermediate stage in the development of the use of lightweight stones.

The third sample (022), from the Basilica Ulpia (AD 112), represents the first use of the dark vesicular scoria as *caementa* in vaults as a means of dealing with a difficult structural situation. The Basilica Ulpia was unusual in having its side aisles vaulted rather than covered with wooden trusses, as had been done in earlier basilicas. The precise nature of the vaulting and its support structure is controversial because there are few remains (Lancaster 2005a, 121–5), but at least some of the vaults were clearly supported by a series of columns, which would have presented an inherently unstable situation that prompted the builders to employ the lightweight scoria to reduce the load and the thrust on the columns. Our sample was taken from a surviving chunk of the fallen vaulting from the north aisle that is now located in the underground storerooms on the west side of the Basilica Ulpia excavation zone (Meneghini 1989). The *caementa* of the vault consist of alternating layers of dark reddish brown scoria and Tufo Giallo della Via Tiberina (Fig. 3 (b)), the same combination found in the crown of the Pantheon dome. The mortar also contains small pieces of sanidine-bearing pumice (Jackson *et al*. 2010; Bianchi *et al*. forthcoming). This use of the dark scoria is the first attested use in Rome after the AD 79 eruption of Vesuvius and therefore provides useful comparanda for the earlier Forum of Caesar sample.

The fourth sample (023), from the Basilica Julia, is dark scoria from the vaults reconstructed after a fire under Diocletian in AD 283 destroyed the earlier structure. It was rebuilt with vaulted aisles on the model of the Basilica Ulpia, some of which lie partially buried at the south-east corner of the building (Canina 1860, 187). The *caementa* of the visible remains consist entirely of the dark scoria (Fig. 3 (c)). This reconstruction occurred during the economic recovery under Diocletian, after the instability of the mid-third century when very little was built. The sample, therefore, was chosen for its potential to provide insight into the continuity or disruption of material supply at this crucial time of economic change.

The fifth sample (05) is pumiceous scoria from the Baths of Diocletian (AD 298–305). Numerous examples of ‘pomice’ have been reported in the vaults throughout the complex. It has been described as yellowish-white, white and black (Rivoira 1925, 206; De Angelis d’Ossat 1946, 21–2). In the excavation of the west palaestra, D. Candilio (1985, 528) reported grey ‘pomice’ in the fallen portico vaults. The examples of pumice *caementa* still visible today range from a dark grey in the east palaestra vaults to a mid-grey (our sample) in the buttressing arches of the frigidarium (Fig. 3 (d)). This represents the first time a lightweight rock different from the dark vesicular scoria was used as *caementa* in a major structure in Rome. It was also built just after Diocletian’s restructuring of the tax system in AD 298, which affected the way in which building materials were acquired and thus represents a new economic context.

We also added reference samples to the geochemical analysis for both the dark scoria and the pumices. For scoria, we included a sample from remnants of fallen wall near the House of Meleager (VI.9.2) in Pompeii (Fig. 4 (a)) and one from a second- to third-century AD bath building on the north flank of Vesuvius at Pollena Trocchia (De Simone 2008, 340–2; De Simone *et al*. 2009, 232–5) (Fig. 4 (b)). The vaults of the bath employed *caementa* consisting of a roughly equal mix of Neapolitan Yellow Tuff and dark vesicular scoria. In addition, we took quarry samples (L1 and L2) from the 36–18 ka lavas accessible at Cava Traianello (40°51′26.6″N,

Figure 4 *(a) Scoria in a (generic) wall at Pompeii. White inclusions are leucite crystals. (b) Scoria in a bath at Pollena Trocchia. (c) Cava Traianello lava sample L1. Large white inclusions are leucite crystals; black inclusions are pyroxene crystals. (d) Cava Traianello lava sample L2 (euro = 2.3 cm dia.).*

14°26′58.3″E) on the north slopes of Vesuvius (Figs 4 (c) and 4 (d)). We found that none of the scoria visually matched our other samples, but whatever quarries the Romans were using may well be long buried by more recent events.

For the pumices, we included reference samples (08, 09, 010) from three different outcrops in the Monti Sabatini volcanic district. Indeed, while a large data set of geochemical analyses is provided by Peccerillo (2005) as a reference for the Campanian volcanics, very scanty data are available for the Sabatini volcanic district. We have thus incorporated samples from two major pumice horizons: Isola Farnese Fall A (Fig. 5 (a)) and Riano Fall B (Sottili *et al*. 2004)

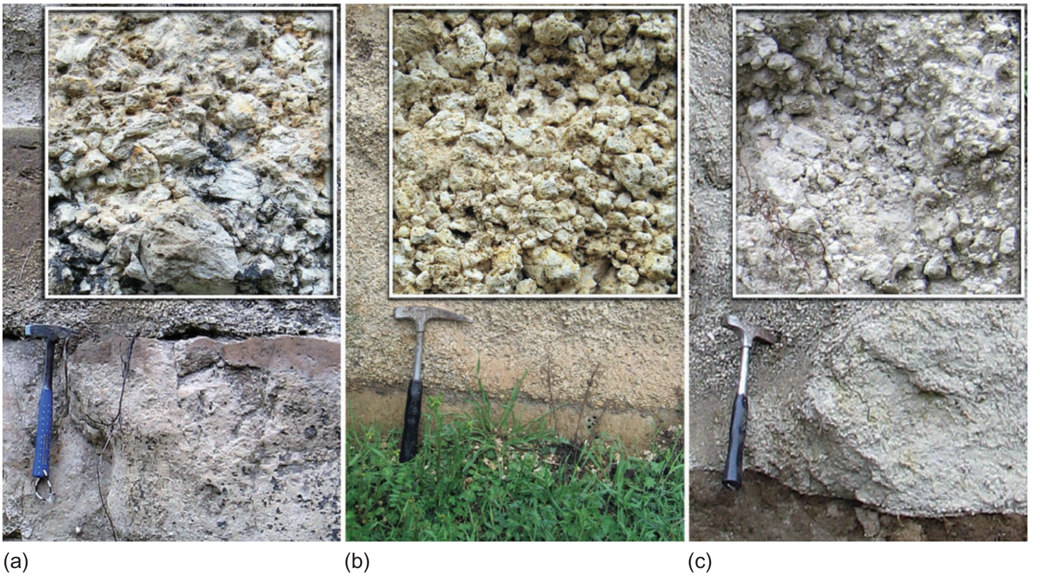

Figure 5 *(a) The sampling location (42°01′05.9″N, 12°23′40.0″E) of Isola Farnese Unit A (08). (b) The sampling location (42°05′43.5″N, 12°30′52.8″E) of Riano Fall B (09). (c) The sampling location (42°09′44.6″N, 12°29′19.3″E) of Tufo Giallo di Prima Porta pumice at Valle Reale (010).*

(Fig. 5 (b)), both of which occur within the Tufi Terrosi con Pomici Bianche (Karner *et al*. 2001). Despite not exceeding 60 cm in thickness, these are the thickest pumice horizons emplaced within the area of Rome. The third sample is taken from a 1.7 m thick basal fallout deposit of Tufo Giallo di Prima Porta at Valle Reale (Fig. 5 (c)). The distal portion of the pyroclastic-flow deposit of Tufo Giallo di Prima Porta crops out along the banks of the Tiber River Valley within the city of Rome (Jackson and Marra 2006), and reworked pumice clasts eroded from this unit occur within the sedimentary deposits of the Valle Giulia Formation cropping out on the southern flanks of the Capitoline Hill (Jackson *et al*. 2007).

The analysis of both the scorias and the pumices produced unanticipated results (reported below), which further emphasized the importance of reassessing pre-1950 attributions based on thin sections alone, and of using both thin-section and geochemical methods to confirm provenance attributions.

PETROGRAPHIC AND GEOCHEMICAL FEATURES

The collected samples were analysed first using thin sections under an optical microscope for the detection of the mineral phases and textural features. They were then analysed by X-ray fluorescence spectroscopy (XRF), which is based on the emission of characteristic (fluorescent) X-rays from a material that has been excited by bombarding with high-energy rays, and laser ablation inductively coupled plasma mass spectrometry (LA–ICP–MS) to determine the concentration of major and selected trace elements. ICP–MS is based on pairing together an inductively coupled plasma as a method of producing ions (ionization) with a mass spectrometer as a method of separating and detecting the ions. For the XRF analyses, the samples were powdered and pressed into a wafer. SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O,

P_2O_5, Ni, Cu, Zn, Rb, Sr and Zr were determined with a Bruker S4 PIONEER X-ray fluorescence 4 kW wavelength-dispersive spectrometer. Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb,Y, Dy, Ho, Er, Yb, Lu, V, Cr, Nb, Hf, Ta, Pb, Th and U (Table 2) were determined with a Micromass Platform Inductively Coupled Plasma-Mass Spectrometer. Wet chemical techniques were used to measure the loss on ignition (LOI). International rock standards have been used for curve calibration. Precision is better than 5% for Rb and Sr, better than 10% for Ni, Zr, Nb, Ba, Ce and La, and better than 15% for the other elements. As will be specified in the following sections, we will not use some major elements (e.g., Na, K, Ca and Fe) to classify the samples with microscopic (e.g., zeolites) or geochemical (e.g., high LOI) evidence of alteration, because the concentration of these elements may change significantly during weathering (Duzgoren-Aydin *et al*. 2002). In particular, leaching of cations prevails in the early stages of weathering, whereas chemical exchange and adsorption on to clay dominate in the advanced stages. We use trace elements (e.g., Nb, Zr and Y) whose concentration does not vary during water-dominated and/or low-metamorphism processes (Floyd and Winchester 1978). Therefore, on the basis of the above considerations, standard classification and/or discrimination diagrams (e.g., SiO_2 versus Na_2O + K_2O; Le Bas *et al*. 1986) cannot be used for altered and/or contaminated volcanic rocks.

The scorias from monuments in Rome (021, Forum of Caesar; 022, Basilica Ulpia; 023, Basilica Julia)

The samples are scorias ranging from dark brown (10YR 3/3) to weak red (10R 4/4) and are characterized by a low phenocryst content (10 vol%). Phenocrysts include clinopyroxene, plagioclase, olivine and leucite (023 (BasJul)), and phlogopite (022 (BasUlp)). The groundmass consists of the above-reported phases and leucite, Fe–Ti oxides, plagioclase and sanidine. Zeolites sometimes occur in the glassy groundmass. With the exception of 021 (ForCaes), which shows a high LOI (3.92 wt%) and microscopic evidence of alteration (zeolites), the other samples are relatively fresh (LOI content, <2.34 wt%), with poor microscopic evidence of zeolitization (Table 2). The samples are vesiculated (20–30 vol%). Vesicles of the sample 021 (ForCaes) are coalescing, subrounded to slightly elliptical, with a size of 1–3 mm. The sample 022 (BasUlp) is characterized by non-coalescing, subrounded to slightly elliptical vesicles of size 1–2 mm. The vesicles in the sample 023 (BasJul) are stretched and elongated with a size of 0.2–0.5 mm.

The mineral association of these samples is consistent with that of the Plio-Quaternary Italian volcanic rocks of the undersaturated potassic association, which, in the Mediterranean area, characterize the Latial and Campanian volcanoes (Peccerillo 2005). In particular, the Nb/Y and Zr/Y values of the samples (Fig. 6 and Table 2) overlap those of the potassic rocks from the Campanian volcanoes, which are represented by Campi Flegrei and Vesuvius (Peccerillo 2005). All three samples can be attributed to Vesuvius due to the presence of leucite, which characterizes the products of Vesuvius but is virtually lacking in those of Campi Flegrei (Peccerillo 2005; Piochi *et al*. 2005 and references therein). Furthermore, in the Total Alkali Silica (TAS) classification diagram (Le Bas *et al*. 1986), the unaltered samples 022 (BasUlp) and 023 (BasJul) fall at the phonotephrite/basaltic trachyandesite boundary and overlap the field of Vesuvius rocks dating between 18 and 36 ka (Fig. 7) (Santacroce *et al*. 2005), which diffusely outcrop on the northern flank of the edifice (Santacroce and Sbrana 2003). Sample 021 (ForCaes) falls within the field of basanites and tephrites, but due to its alteration (LOI 3.92%, and occurrence of zeolites in the groundmass), it cannot unequivocally be attributed an age on the basis of its petrographic and geochemical features.

Table 2 *Chemical analysis of the samples discussed in the text (LOI = loss on ignition)*

Sample	*O21 Forum Caesar Scoria*	*O22 Basilica Ulpia Scoria*	*O23 Basilica Julia Scoria*	*O24 Casa Meleager Pompeii Scoria*	*05 Baths Diocletian Rome Pumice*	*011 Colosseum Pumice*	*L-1 Cava Traianello Scoria*	*L-2 Cava Traianello Scoria*	*032 PolTroc Scoria*	*08 Isola Farnese Fall A Pumice*	*09 Riano Fall B Pumice*	*010 Valle Reale Tufo Giallo Prima Porta Pumice*
wt%												
SiO_2	48.45	51.70	50.78	51.12	57.12	53.03	50.63	51.90	50.88	55.47	54.41	52.95
TiO_2	0.92	0.89	0.94	0.96	0.45	0.41	0.88	0.95	0.89	0.48	0.52	0.41
Al_2O_3	17.93	17.65	18.70	18.36	17.77	15.97	16.87	18.76	17.87	18.82	19.31	19.49
Fe_2O_3	7.25	7.78	7.45	7.22	3.62	3.58	7.31	7.44	7.89	4.14	4.03	3.02
MnO	0.12	0.14	0.12	0.12	0.13	0.14	0.12	0.12	0.15	0.47	0.11	0.15
MgO	3.26	3.32	3.19	3.24	0.64	0.64	5.64	3.36	3.47	0.73	0.80	0.35
CaO	9.78	8.76	7.22	7.59	2.75	6.01	9.22	7.20	8.46	2.59	2.84	3.63
Na_2O	3.41	2.97	2.79	2.46	4.47	4.94	2.22	3.72	2.80	2.00	1.93	3.52
K_2O	3.79	4.62	5.32	5.75	7.84	6.93	5.34	4.22	4.25	8.73	6.82	9.51
P_2O_5	0.73	0.58	0.77	1.10	0.11	0.08	0.58	0.72	0.58	0.13	0.13	0.04
Total	95.64	98.41	97.28	97.92	94.90	91.73	98.81	98.39	97.24	93.56	90.90	93.07
LOI	3.92	1.24	2.34	1.71	4.89	8.14	0.82	1.23	2.37	6.24	8.75	6.48
ppm												
Ni	31	35	30	29	–	–	40	–	–	–	–	–
Cu	87	57	63	121	–	–	57	44	30	–	–	–
Zn	66	60	66	63	–	–	57	66	76	–	–	–
Rb	227	158	243	213	376	355	243	250	252	420	392	276
Sr	963	954	884	849	339	286	789	880	1475	1080	987	1931
Zr	203	242	213	228	563	596	156	200	215	539	677	818
Ba	2288.23	1454.93	1967.18	1831.70	549.28	406.12	1893.89	1910.88	1444.52	1267	948.91	971.72
La	45.45	51.93	47.10	46.30	94.53	99.46	37.35	44.52	52.51	166.94	167.76	237.12
Ce	92.76	105.72	96.60	96.79	186.03	177.26	80.05	90.66	103.86	281.15	301.48	420.44
Pr	10.78	12.47	11.09	11.14	18.19	18.97	9.51	10.66	12.90	32.78	33.44	42.04
Nd	40.21	47.95	41.95	42.09	59.59	65.31	35.66	40.03	49.42	115.89	111.52	135.43
Sm	9.12	10.36	9.39	9.46	10.43	11.17	7.32	7.97	9.90	18.87	17.39	20.66
Eu	2.14	2.33	2.16	2.15	1.86	1.65	1.89	1.99	2.38	3.13	3.18	3.81
Gd	6.59	7.60	6.80	6.75	9.79	10.30	6.02	6.45	8.06	15.14	15.43	18.10
Tb	0.86	0.99	0.90	0.88	1.29	1.34	0.78	0.84	1.03	1.73	1.67	2.02
Y	22.58	29.53	23.78	23.44	36.59	39.77	20.09	22.02	28.97	40.70	38.66	48.69
Dy	4.22	5.32	4.45	4.35	5.92	6.38	3.88	4.14	5.39	7.14	6.97	8.02
Ho	0.82	1.03	0.87	0.83	1.12	1.23	0.70	0.73	0.97	1.23	1.18	1.35
Er	2.12	2.64	2.23	2.13	3.38	3.68	1.79	1.98	2.63	3.23	3.16	3.71
Yb	2.05	2.57	2.15	2.10	3.54	3.79	1.70	1.93	2.55	3.20	3.18	3.90
Lu	0.30	0.38	0.31	0.30	0.51	0.56	0.25	0.28	0.36	0.48	0.46	0.54
V	190.01	167.08	197.34	194.38	62.83	42.54	254.69	242.34	1.24	102.34	102.64	91.87
Cr	10.86	43.50	9.72	13.34	7.39	11.05	121.86	7.89	0.22	9.65	12.29	3.67
Nb	31.46	35.86	33.73	37.90	72.72	66.29	26.76	39.00	0.57	32.76	44.59	53.29
Hf	4.42	5.18	4.55	4.61	9.74	10.97	3.54	4.64	0.03	12.21	13.29	13.62
Ta	1.74	2.01	1.82	2.00	3.96	3.94	1.51	2.21	0.02	2.54	2.96	2.77
Pb	30.20	20.50	31.90	23.30	102.43	107.25	24.91	40.37	0.44	223.50	265.32	373.15
Th	15.43	16.48	17.00	17.78	48.38	52.13	11.89	17.89	0.22	124.95	132.47	172.59
U	5.17	4.60	6.08	6.12	17.61	17.67	3.79	6.25	0.12	27.33	32.05	43.32

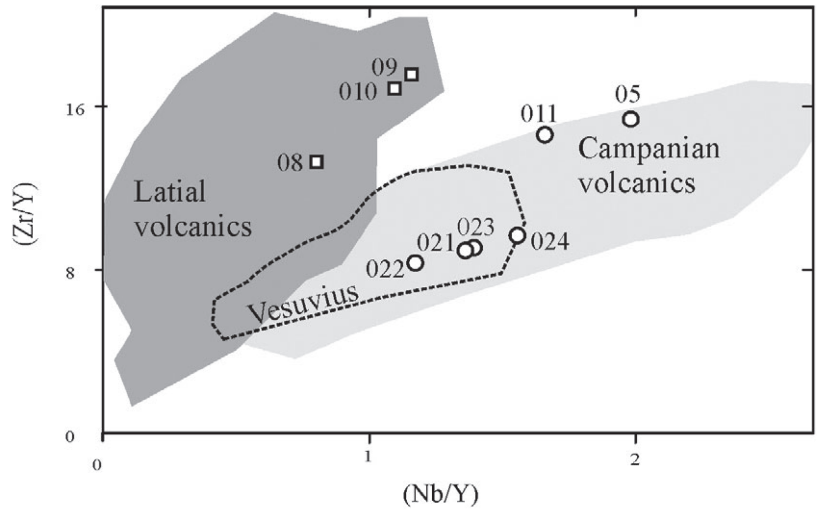

Figure 6 *An Nb/Y and Zr/Y diagram, showing the fields of the Latial and Campanian volcanics in relation to the scoria and pumice samples (data from Table 2).*

The scorias from monuments in Campania (024, Pompeii; 032, Pollena Trocchia Bath)

Sample 024 (Pomp) is dusky red (10R 3/2) and characterized by a low phenocryst content (10 vol%). Phenocrysts include clinopyroxene, plagioclase, olivine and leucite. The groundmass consists of the above-reported phases and Fe–Ti oxides, plagioclase and sanidine. Zeolites sometimes occur in the glassy portion of the groundmass. Vesicles are 20–30 vol%; they are subrounded to elongated, with a size of 6–8 mm. Sample 032 (PolTroc) is a weak red (10R 4/2) pumiceous scoria and is characterized by about 20 vol% of phenocrysts, including clinopyroxene, plagioclase, brown mica (phlogopite), leucite and nefeline. Vesicles are 30–40 vol%; they are subrounded and some are coalescing. The vesicle size does not exceed 1 mm. The matrix consists of a reddish glass with minor Fe–Ti oxides. From a geochemical point of view, sample 024 (Pomp) falls at the phonotephrite/basaltic trachyandesite boundary and 032 (PolTroch) falls at the boundary between the basaltic trachyandesites and trachybasalts. Both samples fall within the field of Vesuvius rocks dating between 18 and 36 ka (Fig. 7).

The scorias sampled from the Cava Traianello Quarry at Vesuvius (L1 and L2)

The samples L1 and L2 represent two scorias characterized by distinct textural features. Sample L1 is dark grey (N 4/0) and shows a porphyritic texture with 40 vol% of phenocrysts immersed in an almost totally crystalline groundmass constituted by plagioclase, leucite, clinopyroxene and Fe–Ti oxides. The phenocrysts, which reach 3–4 mm in size, are leucite, clinopyroxene, plagioclase, olivine and Fe–Ti oxides. Vesicles are generally subrounded and do not exceed 15–20 vol%. Sample L2 is grey (N 5/0) and is characterized by a 25–30 vol% of phenocrysts immersed in a microlite-rich groundmass consisting of plagioclase, clinopyroxene, leucite and Fe–Ti oxides. The phenocrysts are plagioclase, clinopyroxene, olivine, brown mica (phlogopite) and Fe–Ti oxides. Vesicles are <0.5 mm in size and show elliptical shapes with rounded to angular margins. The samples L1 and L2 have a phonotephritic composition and, like the

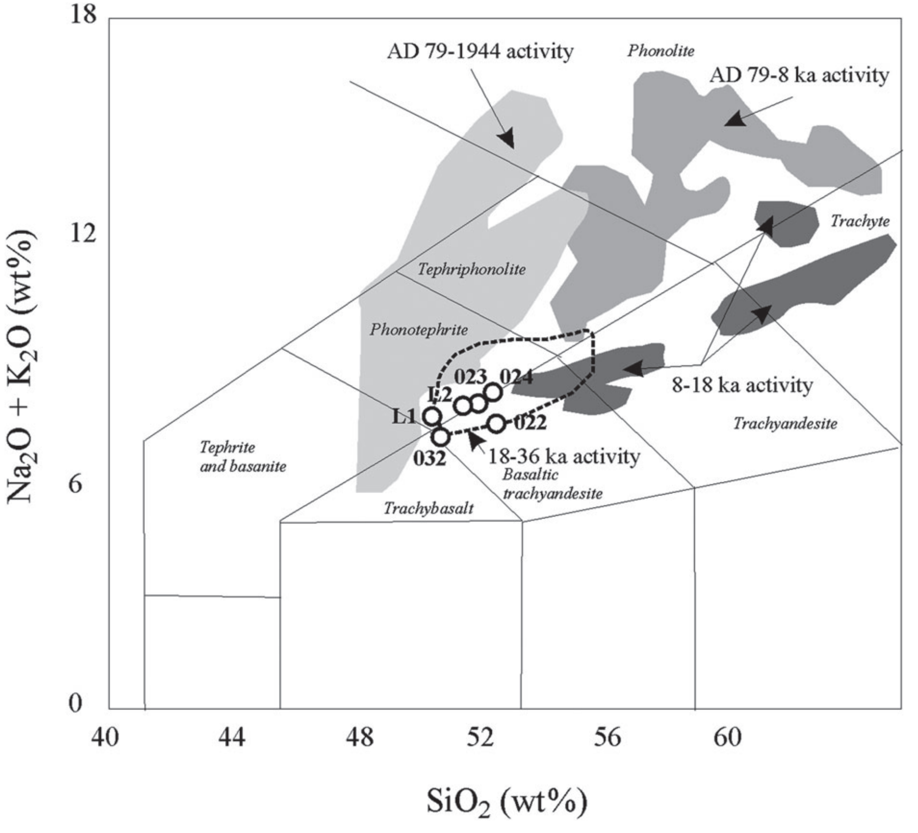

Figure 7 *A TAS diagram of the Vesuvius rocks, with fields depicting the composition of the products as a function of their age (from Santacroce and Sbrana 2003; Santacroce* et al. *2005) in relation to the scoria samples.*

previous samples, fall in the field of the Vesuvius rocks erupted between 36 and 18 ka; that is, the rocks belonging to the early stage of activity of the volcano (Fig. 7).

The pumices from monuments in Rome (05, Baths of Diocletian; 011, Colosseum)

Samples 05 (BathsDio) and 011 (Col) are distinctly different in colour and texture from the scoria samples above. Sample 05 (BathsDio) is a grey (10YR 5/1) pomiceous scoria fragment characterized by a glassy, partly altered (zeolites) matrix. The mineral phases are plagioclase, K-feldspar, clinopyroxene, phlogopite and Fe–Ti oxides. Vesicles reach 40–50 vol% and crystals are 15 vol%. Two main populations of vesicles are present: subrounded, 0.1–0.8 mm large vesicles and larger, 5–7 mm large vesicles with irregular shape. Sample 011 (Col) is a light grey (10YR 7/1) pumice with altered glass (zeolites) and 12 vol% of crystals. Crystals are K-feldspar, plagioclase with minor amounts of clinopyroxene, phlogopite and Fe–Ti oxides. Two populations of subrounded vesicles occur: a population with 0.1–0.3 mm large vesicles and another with 1.0–1.5 mm vesicles. The Nb/Y and Zr/Y values of samples 05 (Baths Dio) and 011 (Col) (Fig. 6 and Table 2) overlap those of the potassic rocks from the Campanian volcanoes. However, they have Zr/Y ≥ 14, which is well above those of Vesuvius, which have 4 < Zr/Y < 12, and of Ischia Island (Zr/Y ≤ 15 but mostly <10). Therefore, the provenance of the samples 05 (BathsDio) and 011 (Col) is from the Campi Flegrei.

The pumices from Monti Sabatini (08, Isola Farnese Fall A; 09, Riano Fall B; 010, Tufo Giallo Prima Porta (Valle Reale))

Sample 08 (IsFar A) is pale yellow (2.5Y 8/2) and has a density of 700 kg m^{-3}. The mineral phases are leucite, clinopyroxene, biotite and Fe–Ti oxides. Composition, as determined from XRF bulk analyses is trachyphonolite (Sottili *et al*. 2004), but the LOI value is high (6.24 wt%), suggesting that the glass is altered. It has a vesicularity between 65 and 80 vol%. The shape of the vesicles is heterogeneous with dominant coalescing, subrounded shapes and subordinate elongated shapes (tube vesicles). Sample 09 (Riano B) is very pale brown (10YR 8/3) and has a density of about 600 kg m^{-3}. The mineral phases are sanidine, biotite, clinopyroxene and Fe–Ti oxides. Composition, as determined from XRF bulk analyses (Sottili *et al*. 2004), is trachyandesite, but the LOI value is high (8.75 wt%), so it is probably altered at a micrometric scale. It has a vesicularity up to ~85 vol%. The shape of vesicles is dominantly subrounded. Sample 010 (TufGial) is a white (10YR 8/1) pumice with a density ~700 kg m^{-3}. The mineral phases are leucite, biotite, rare sanidine, clinopyroxene and Fe–Ti oxides. As with the previous two samples, the LOI is high (6.48 wt%), suggesting that it has been altered (Table 2). Its vesicularity is up to 70 vol%. The Nb/Y and Zr/Y values of samples 08, 09 and 010 are consistent with those of the rocks belonging to the Latial volcanites, and are distinctly different from those of the samples taken from the vaults of the Colosseum and the Baths of Diocletian (Fig. 6).

DISCUSSION

The scorias from Rome are very similar in appearance to the scoria used in walls in Pompeii (Fig. 4 (a)), so a primary goal of our analysis was to determine if the materials at Pompeii and Rome are the same and, then, if possible, where they were quarried. The location of the quarries could then provide some indication of the nature of the export trade in this building material. P. Nicotera, in his 1950 study of the geology at Pompeii, identified the scoria in the walls at Pompeii as coming from the upper part of the lava flow on which the city was built (Nicotera 1950, 415) and proposed that it was the refuse from trenches as the builders dug down to find a more compact surface on which to build their foundations. More recently, this lava flow has been dated to the inter-Plinian activity from the tenth to ninth centuries BC (Ranieri and Yokoyama 1997). Nicotera's interpretation has been the standard in the archaeological literature on Pompeii and its building materials (La Rocca *et al*. 1994, 37).

Contrary to Nicotera's assertion, our geochemical results indicate that all the samples, including 024 from Pompeii, belong to the 36–18 ka lava flows that outcrop on the north side of the volcano; that is, on the opposite side from Pompeii. Deposits also exist along the south flank, but they are located about 60 m below the ground in the southwestern sector and 12 m in the southern sector of the volcano (Di Vito *et al*. 1998) and would have been difficult to access even in the period prior to AD 79. Figures 8 and 9 show the geometric relationships between the deposits of the northeastern and southwestern flanks of Vesuvius. Near the coast (e.g., at Herculaneum), the 36–18 ka old products are below the sea level, whereas at Cava Traianello, on the opposite side of the volcano, they outcrop on the surface or are covered by a few meters (less than 10 m) of younger deposits, most of which date after AD 79. So, the builders were evidently not acquiring

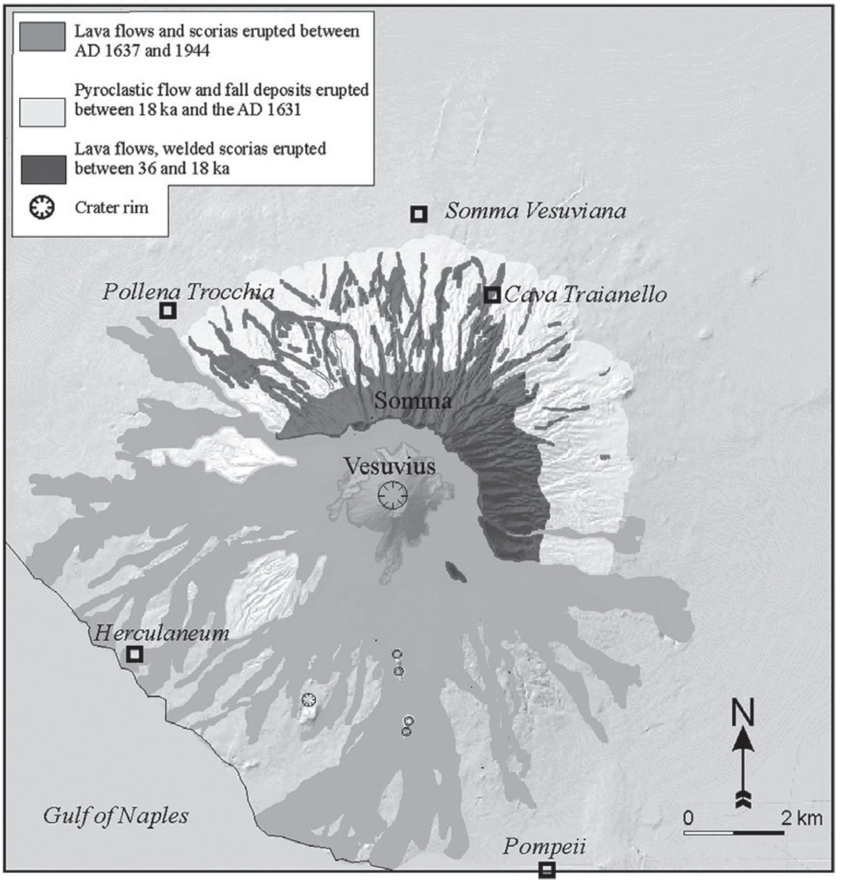

Figure 8 *A map of Vesuvius, showing the location of the 36–18 ka outcrops, Pompeii, Herculaneum, Cava Traianello, Pollena Trocchia and Somma Vesuviana (modified from Santacroce* et al. *2003).*

their material from foundation trenches as previously thought (Nicotera 1950, 415). However, a provenance of this material from trenches located within the Campanian Plain east of the Vesuvius volcano cannot be ruled out *a priori*. In fact, lavas belonging to the pre-18 ka activity were found in modern trenches in quarries located 10 km east of the Vesuvius crater. Here, the 36–18 ka old scoriaceous lavas were found 6–12 m below the deposits of the AD 79 eruption (IAVCEI 1996).

Aside from the appearance of the dark Vesuvian scoria in the walls at Pompeii, it has been associated with that city due to a comment by Vitruvius (*De arch.* 2.6.2–3). He says: 'Antiquity records that fires cropped up in great abundance under Mount Vesuvius and that flames vomited forth from thence into the surrounding countryside. Thus that *spongia* or *pumex pompeianus* seems to have been reduced to its present type of consistency by the burning (*excoctio*) of some other type of stone' (translation by Rowland and Howe 1999). His description of it as being sponge-like and burnt, as well as his association of it with Pompeii, implies that he had in mind the dark vesicular scoria found in the walls at Pompeii. However, when Vitruvius referred to it as *pumex pompeianus*, he may well have associated it with the river port at Pompeii rather than with

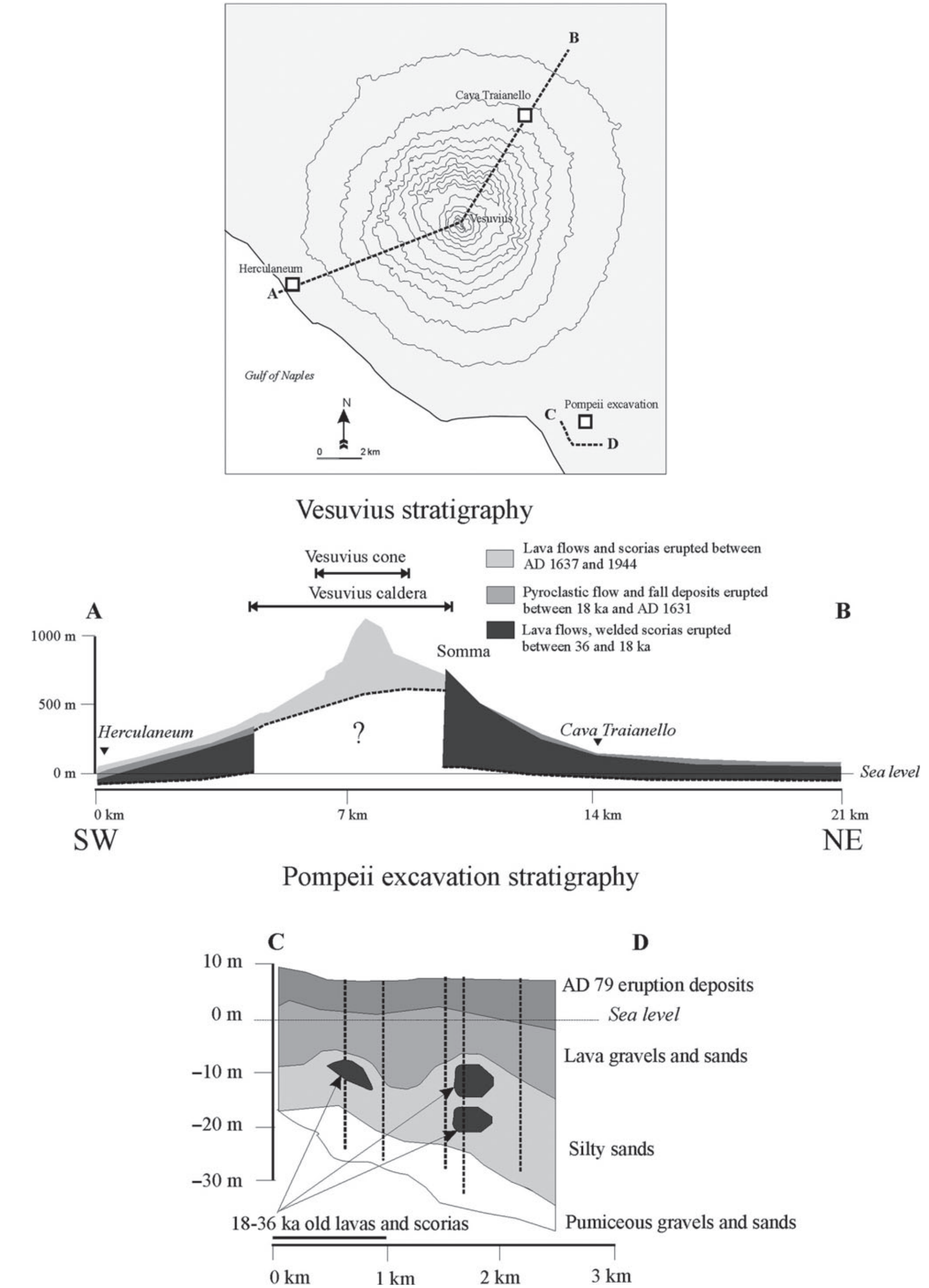

Figure 9 *The general stratigraphy of Vesuvius, showing the depth of the 38–18 ka lavas and scorias (after Di Vito* et al. *1998*; *Ventura* et al. *1999).*

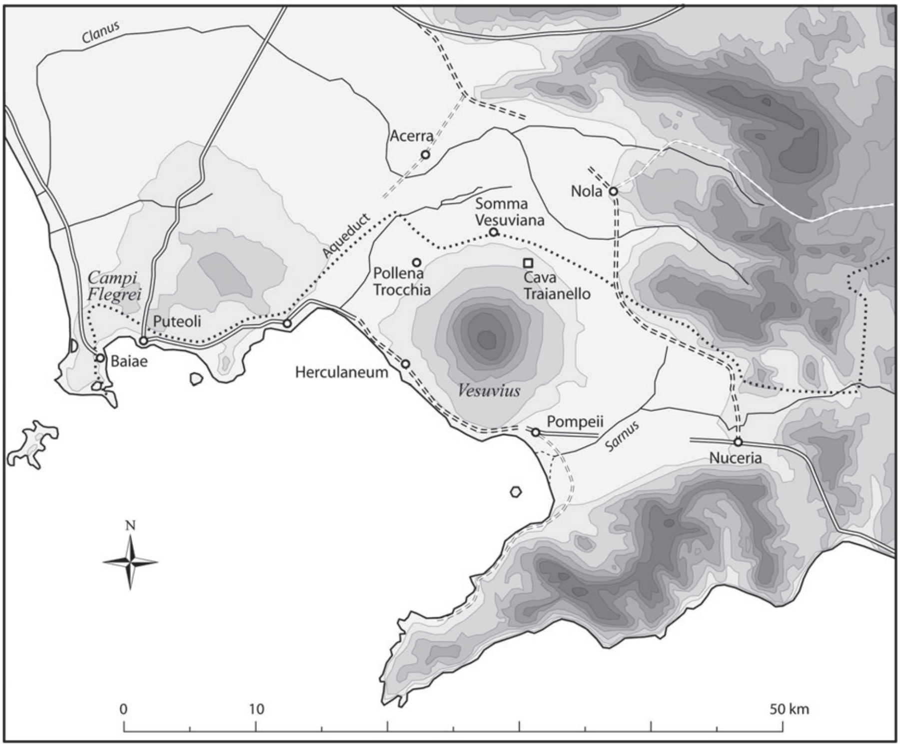

Figure 10 *A map of the Bay of Naples with the sites mentioned in the text (elevations and ancient road locations after Talbert 2000). Solid double lines are known roads. Broken double lines are approximate routes. The single dotted line is an aqueduct.*

any quarries at Pompeii. In fact, Strabo (5.4.8) emphasizes Pompeii's role as a node of connection to the hinterland when he notes that it is 'on the river Sarnus—a river which both takes the cargoes inland and sends them out to sea' and that it is 'the port-town of Nola, Nuceria, and Acherrae'. Moreover, close connection between the river port at Pompeii and the main port city of Puteoli is also suggested by the set of wax tablets called the Sulpicii archive. These documents record extensive commercial activity taking place in Puteoli, but they were found outside Pompeii's Stabian gate (near the river) (Camodeca 1999). The term *pumex pompeianus* may, therefore, imply an extensive road and river transport network reaching into the hinterland from the port of Pompeii (Fig. 10).

The exploitation of materials from the north flank of Vesuvius after AD 79 makes sense given the distribution pattern of the AD 79 eruption. As Pliny (*Ep*. 6.17) notes, the wind was blowing from the north, which resulted in most of the fallout and the collapse of the explosive column covering the southern and eastern areas. The river port at Pompeii could no longer have been a point of export, and Hadrianic milestones suggest that the road system was still being rebuilt some 40 years later (Pagano 1998 [1995–6], 37–8). The northern flank of the volcano, on the other hand, received very little fallout and few pyroclastic flows. Excavations at the 'Villa d'Augusto' at Somma Vesuviana revealed no AD 79 deposits within the structure (Perrotta *et al*. 2006, 460–2). The quarries and transport system to the north would have been little affected. Sample 032 from the vaults of the second- to third-century bath at Pollena Trocchia on the north flank of Vesuvius is the same material as that found in Pompeii and Rome. Its use in this fairly small structure is probably due to its proximity to the quarries and the transport route to the sea. Elsewhere in the Bay of Naples, a similar-looking (but unanalysed) scoria can also be seen in the barrel vaults along the main entryways of the amphitheatre (*c.* AD 80) at Pozzuoli (ancient Puteoli) and in the upper part of the dome of the 'Temple of Venus' at Baiae (first half of second century AD), both of which were easily accessed by sea.

The role of land transportation has played a critical role in discussions on the Roman economy. The view put forth by M. I. Finley in his 'primitivist' model of the ancient economy emphasized the high costs of land transport over those of sea/river transport as a major factor in what he saw as the lack of economic growth and technological development inherent in the ancient Mediterranean (Finley 1985, 126–7). In contrast, recent investigations incorporating a broad array of evidence including papyrus documents, iconographic and epigraphical sources, and even excavated harness systems, have shown that land transport played a greater role in the economy than assumed in the primitivist approach (Raepsaet 2008). For example, K. Hopkins (2002, 221–2) stressed the integrated nature of land and sea transport; rather than seeing them as opposing options, he proposed a 'network of feeder towns' in which the two methods formed a symbiotic relationship. C. Adams (2007, 7–8, 289–90), in his recent analysis of land transport in Egypt, has built on this observation and stressed that land and sea transport together form a system that should be examined as a whole.

The idea of an integrated system of land, sea and river transport is useful for understanding the implications of our geochemical analysis of the scoria, which implies a greater role for land transport of building stones around Vesuvius than previously thought. Moreover, the results suggest that the activities along the north flank of the volcano have been unfairly neglected in the past, as studies have tended to focus on the better-preserved sites to the south, such as Pompeii and Herculaneum. As Adams (2007, 205–10, 83–91) points out, much of the land transport in Egypt was stimulated by imperial desire for grain and decorative stone to be exported. Our scoria is not so desirable as wheat or coloured stone, but it nevertheless was associated largely with grand imperially sponsored monuments in Rome; thus an imperial interest in the scoria quarries is likely. Moreover, recent excavations of the impressive 'Villa di Augusto' at Somma Vesuviana near outcrops of the old lava provides new evidence for the continuation of lavish living on this side of the edifice after the AD 79 eruption (Aoyagi *et al.* 2010).

The two other analysed pumice samples from monuments in Rome, one from the Colosseum and one from the Baths of Diocletian, also yielded unexpected results. Both rocks were previously assumed to have come from one of the volcanic districts north of Rome, yet the trace element results (Nb/Y and Nb/Zr; Fig. 6) indicate that both are from the Campi Flegrei district, and our geochemical data on the Sabatini samples (08, 09 and 010) exclude a provenance from the Sabatini district. The pumice lapilli in the mortar of the upper level Colosseum vaults are very similar in appearance and size to those in the strata of pumice fallout visible at Monte Procida and other outcrops around Bacoli in the Campi Flegrei where much of the pozzolana (*pulvis puteolanis*) was quarried, so it could have been a subsidiary product of pozzolana quarrying. Unfortunately, the chemical profiles of the various strata in this part of the Campi Flegrei are very similar and do not allow for further isolation of provenance of either sample.

CONCLUSIONS

For both the scorias and the pumices, the original identifications were made before the advent of geochemical analysis, which occurred only after the atomic advances during the Second World

War, with the commercialization of neutron activation analysis (NAA) in the 1950s. On the basis of the earlier reports and thin-section data, the suggestion was made that the change in Rome at the end of the third century AD from Vesuvian scoria to pumice local to Rome could have been the result of the changes to the taxation system, which was revised under Diocletian (Lancaster 2005a, 67), but the new geochemical results indicate that, in fact, all of the lightweight stones analysed were imported from the Bay of Naples over a broad chronological range. The question remains as to why there was a change in *caementa* from the Vesuvian scoria at the Basilica Julia in AD 284 to the Phlegrean pumice in AD 298–305. Further geochemical analysis of the lightweight volcanic stones used as *caementa* in other late antique structures in Rome, such as 'Minerva Medica' (De Angelis d'Ossat 1945) and the Basilica of Maxentius (Amici 2005, 136–7) could clarify whether the change to Phlegrean pumice was part of a wider phenomenon. One possibility is that land transport around the Vesuvian quarries became difficult in the hard economic times of the mid-third century and that the Phlegrean material was easier to access. Further research on the development of the infrastructure along the north slopes of Vesuvius (currently being conducted by G. F. De Simone) should help provide answers to such questions in the future.

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