The source of stone building materials from the Pompeii archaeological area and its surroundings

Pia Kastenmeier[1], Giovanni Di Maio[2], Giuseppina Balassone[3]*, Maria Boni[3], Michael Joachimski[4] and Nicola Mondillo[3]

[1]Deutsches archäologisches institut, Podbielski allee 69-71, D-14195 Berlin, Germany
[2]Geomed srl, via L. sicignano 41, i-84018 scafati (na), italy
[3]Dipartimento di scienze della terra, università di napoli "Federico ii" via mezzocannone 8, i-80134 napoli, italy
[4]Geozentrum nordbayern, university of Erlangen-nürnberg, schlossgarten 5, D-91054 Erlangen, Germany

Abstract - this work is part of a large-scale survey carried out by the Deutsches archäologisches institut (Dai) of Berlin, which aim to locate the sources of raw building materials employed throughout various archaeological sites on the sarno river plain (Pompeii, nuceria, stabiae, longola, etc.) while also reconstructing the paleo-environments of this area during the olocene. the present paper reports the preliminary results of a multidisciplinary project on the ancient stones used for construction in the town of Pompeii and other archaeological areas nearby (6th century B.C.- a.D.79). the building stones used in these areas (volcanic and sedimentary carbonate rocks) have been analysed for their geological, mineralogical, petrographic and geochemical features and have been compared to rocks cropping out on the sarno river plain - the possible provenances for these building material. our data indicate that most of the stones employed for the edifices in Pompeii and other related archaeological sites between 6th century B.C. and a.D. 79 originate from local quarries, mainly situated in several localities on the sarno river plain itself and in surrounding areas.

Riassunto - il presente lavoro fa parte di una più ampia ricerca condotta dall'istituto archeologico Germanico di Berlino (Dai), finalizzato alla ricostruzione dei paleo-ambienti della Piana del sarno risalenti all'olocene e delle provenienze dei materiali litoidi impiegati in vari siti archeologici (Pompei, nuceria, stabiae, longola, etc.). si riportano i dati preliminari di una ricerca multidisciplinare sui diversi materiali da costruzione (rocce vulcaniche e sedimentarie carbonatiche) utilizzati nell'antica Pompei e in siti archeologici vicini. le caratteristiche geologiche, mineralogiche, petrografiche e geochimiche di tali materiali sono confrontate con simili affioramenti, zone di possibile provenienza. i dati fin qui raccolti indicano che i materiali da costruzione dei siti studiati, databili tra il vi sec. a.C. e il 79 d.C., provengono da varie località poste nella stessa Piana del sarno o da zone immediatamente limitrofe.

Key words: *Sarno River plain; Ancient Pompeii; paleo-environment; building stones; volcanic rocks; travertine; limestone, provenances.*

Introduction

ancient Pompeii and its surroundings, located on the sarno river plain (Campania region, southern italy), is one of the most famous and complex areas of archaeological investigation in the world, partly due - at least for Pompeii - to a uniquely favorable state of preservation. Though many studies have been devoted over time to various archaeological aspects, large-scale and detailed studies aimed at characterizing mineralogy, petrography and isotope geo-chemistry of the stones used for construction are still lacking. Likewise, no ancient quarries for these building materials have been identified until now, mainly due to widespread anthropogenic modifications of the whole area. The first descriptions of stones building materials - and the related petrographic nomenclature widely used over time by archaeologists (i.e. "*pappamonte*", "*cruma*", *"Sarno limestone"*) - date back to the late nineteenth century (i.e. Fouqué, 1886; nissen, 1887). other studies on Pompeian artefacts or building materials are owed to nicotera (1950), Kawamoto and Tatsumi (1992), Lazzarini and Cancelliere (1999), Lorenzoni *et al.* (2001) and Buffone *et al.* (1999, 2003).

This work is part of a large-scale survey carried out by the Deutsches archäologisches institut (Dai) of Berlin, with the purposes of reconstructing the paleo-environments of the Sarno River plain during the Olocene and, consequently, locating the provenances of raw materials employed throughout various archaeological sites in this area (seiler, 2006, 2008; Kastenmeier and seiler, 2007; vogel and Märker, 2010). The present paper reports the preliminary results of a multidisciplinary project on the ancient building stones used in the town of Pompeii and other archaeological areas nearby (6th century B.C.- a.D. 79), with the scope of defining the provenance of the material used for ancient constructions in the city of Pompeii and the possible related trade routes (Balassone *et al.*, 2009). To reach our results, we have characterized the geological and mineralogical features of various stones found in the archaeological sites, and have compared them to rock specimens sampled in different localities on the Sarno River plain, where a pre-79 a.D. exploitation for building material (for both volcanic and carbonate rocks) is evident. The evidence is both visual (by far of still-existing historically active quarries), confined to old documents, and even in association with traditional tell-tale names (i.e. "*Tartarito*" and or "*Scafati Bagni*"), where some travertines (the so-called "*Sarno limestone*") have been detected (De spagnolis Conticello, 1994; Di vito *et al.*, 1998).

Geological outline and sampling procedure

The area investigated is located on the Sarno River plain (Cinque and Russo, 1986), and is surrounded by the Quaternary somma-vesuvius volcano (Rolandi *et al.*, 1993; Lirer *et al.*, 2005; Santacroce *et al.*, 2005), the Lattari Mountain ridge of the sorrento peninsula (Bonardi *et al.*, 1988) and the sarno mountains (Franza, 2005 and reference therein), which both consist of carbonates mainly of mesozoic age (Fig. 1). These carbonates also form the basement of the whole region at 2.5-3 km depth b.s.l.

For somma-vesuvius, the oldest period of volcanic activity is dated at 39-19 ka, with lava flow extrusions and low-energy explosive eruptions, building up the somma stratovolcano (*Pomici di base*, 18.3 ka). For the last 19 ka somma-vesuvius erupted 50 km^3 of magma with differing compositions, during three magmatic periods: the first with K-basalt (shoshonite) to K-latite lavas and K-latite to K-trachyte pyroclastic deposits (19-10 ka); the second with phonotephrite to phonolite magmas (10 ka - a.D. 79); the third with leucititic phonotephrite to phonolitic magmas (A.D. 79 - 1944) (Di Renzo *et al.*, 2007). in this area at least seven different tephra deposits are recognized as being due to somma-vesuvius eruptive activity, but other pyroclastic deposits are also attributed to the volcanic activities of the Phlegraean Fields (Campi Flegrei) district, northeast of Naples. The

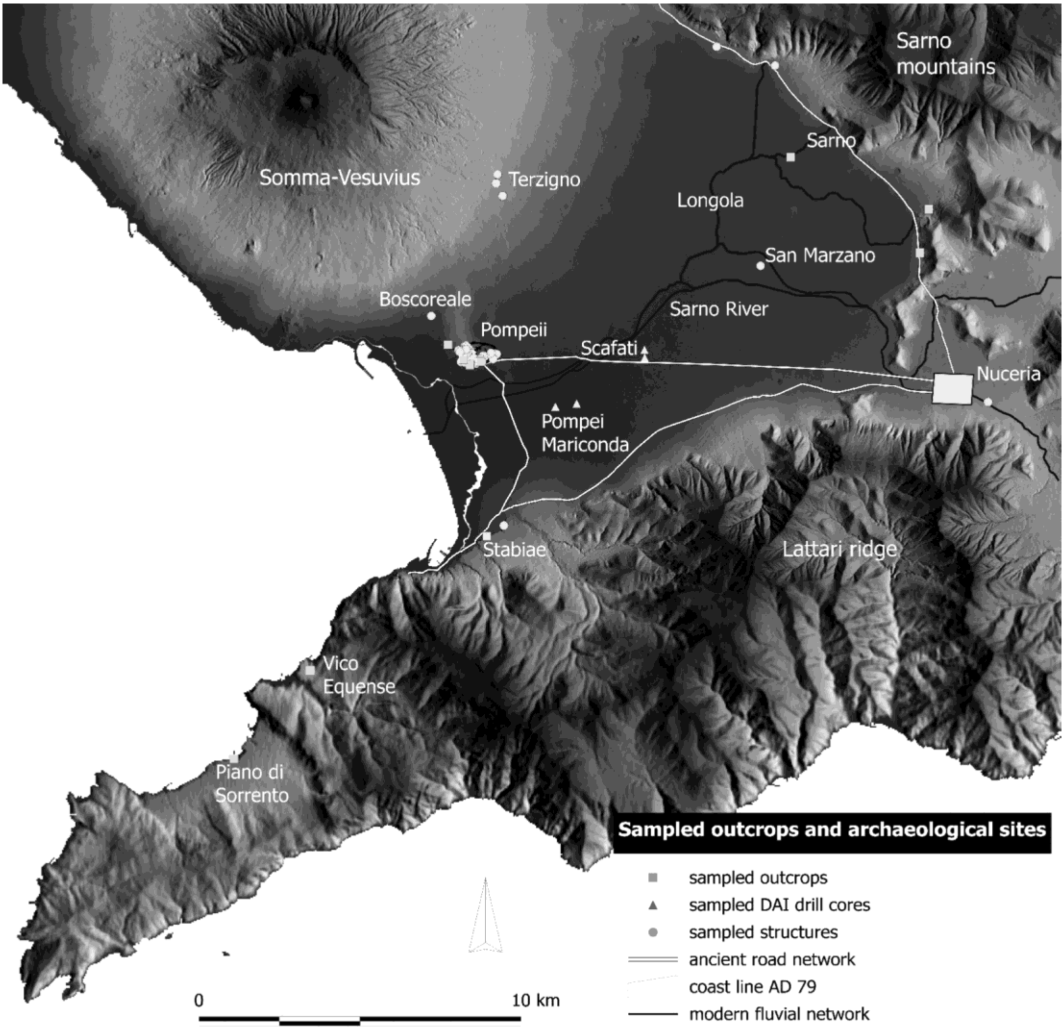


Fig. 1 - map (DEm) of the sarno river plain and the sorrento Peninsula.

CF caldera results from two main collapses related to the Campanian ignimbrite (Ci, 39 ka; Pappalardo *et al.*, 1999, 2008) and the neapolitan yellow tuff (nyt, 15 ka; Deino *et al.*, 2004) - both powerful phlegraean eruptions. the Ci deposits covered about 30,000 km^2 and occur extensively in this area (rolandi *et al.*, 2003), whereas the nyt covered about 1000 km^2 and mostly outcrops in CF (Pozzuoli bay) and in the city of napoli area.

the ridge of the lattari mountains is comprised in the stratigraphic unit *Monti Picentini - Monti Lattari* and is characterized by limestones and dolostones ranging from upper triassic to upper Cretaceous , as well as miocene flysch and terrigenous sediments which range in age from miocene to Pliocene (Bonardi *et al.*, 1988).

the sarno mountains consist of limestones, dolomitic limestones, limestones with requieniae and hippurites, and conglomeratic marly limestones with orbitolinae, spanning from lower to upper Cretaceous and belonging to the *Alburno-Cervati* stratigraphic unit (D'argenio, 1973).

the ash-fall deposits, mainly derived from the explosive activity of mount somma-vesuvius, were varyingly distributed among the lattari and sarno carbonate reliefs, according to the dispersion axes of each eruption, reaching a total thickness ranging from 4 to 7 metres on the lattari mountains and values ranging around 2 metres on the sarno mountains (De vita and Celico, 2006). after rolandi *et al.* (2000), in this

taBlE 1

Distinction of rock type, functional categories, date of construction and number of sampled collected from fifty archaeological monuments.

rock type	functional categories	date of construction	number of samples
lava	town walls - public buildings - public functional architecture - temples - houses (Pompeii) villae rusticae (terzigno)	6th century b.C. - 1st century a.D.	15
grey tuff	town walls - public buildings - public functional architecture - temples - houses (Pompeii) public buildings (sarno) public functional architecture (Palma Campania) tombs (nocera) villae rusticae (terzigno)	6th - 1st century b.C.	15
yellow tuff	public functional architecture - temples - tombs (Pompeii) villa rustica (Boscoreale)	1st century b.C. - 1st century a.D.	4
"pappamonte"	town walls - houses (Pompeii)	6th century b.C.	2
travertine	town walls - houses - workshops (Pompeii) public buildings (sarno) public functional architecture (Palma Campania) tombs (nocera) villae rusticae (terzigno) luxury villas (stabiae)	5th - 1st century b.C.	24
limestone	public buildings - temples (Pompeii) public buildings (sarno) tombs (nocera, sarno) villae rusticae (terzigno)	7th -1st century b.C.	10

area the older tephra correspond to the so-called *Complesso Piroclastico Antico* (CPa), formed by Ci and ischia island deposits, whereas younger tephra correspond to the *Complesso Piroclastico Recente* (CPr) which mainly comprises, as aforementioned, seven volcanic deposits from somma-vesuvius eruptions, i.e. *Codola* (25 ka), *Pomici di base-Sarno* (18.3 ka), *Mercato-Ottaviano* (8 ka), *Avellino* (3.8 ka), *Pompeii* (a.D. 79), *Pollena* (a.D. 473) and a.D. 1631 (rolandi *et al*., 2003).

locally, in several zones of the plain outcrops of travertines and travertine-like rocks occur; Pleistocene to recent fossil encrustations of travertines also outcrop in various localities in the nearby salerno province (sele river valley), e.g. at Pontecagnano, Paestum, Faiano (anzalone *et al*., 2007).

For this research, an extensive sampling work has led to the collection of about ninety samples, which come from different archaeological monuments from within the Pompeii excavations, and also from the towns of Pompei, Boscoreale, nuceria, Palma Campania, san marzano, sarno, stabiae and terzigno. we have also sampled in nine different locations, where still partly outcropping rock types may have been quarried for building materials during out time-frame of the 6th century b.C. to the 1st century a.D. in Piano di sorrento, the Pompeii excavations, sarno, scafati and vico Equense the specimens originate from outcrops, whereas in the Pompei-mariconda and the scafati-Bagni localities we drilled in october 2008. the drill cores were necessary, because portions of the travertines are unable to be seen on the geological maps, having been covered by the volcanic products of the a.D. 79 and following eruptions and paleosoils.

in taBlE 1 we report a selection of seventy samples from a total of fifty monuments, with the different lithological cathegories, the main functions of the original building and the supposed age. taBlE 2 reports the main characteristics of sixteen volcanic specimens sampled from manufacts (13 samples from archaeological monuments) and outcrops (3 samples from different lava outcrops distributed over the Pompeian town hill) selected for the present study. taBlE 4 shows locations, sampling sites, ages and petrographic characteristics of representative twenty-eight travertine and limestone samples, coming both from manufacts and drill cores.

analytiCal mEthoDs

the volcanic samples have been first described macroscopically, and then optical microscopy (om) has been used for their petrographic description in thin sections. the identification of various phases of the mineral assemblages has been determined by means of combined om and X-ray diffraction (XrD, seifert–GE mZvi diffractometer (Federico ii naples university).

whole rock major and selected trace elements of the lava samples have been analyzed on powder pellets by a Philips Pw1400 XrF spectrometer at CisaG (Centro interdipartimentale di servizio per analisi Geomineralogiche of Federico ii naples university). the data have been then reduced following the method described by melluso *et al*. (1997). Precision is better than 3% for major elements, 5% for Zn, sr, Zr and Ba and better than 10% for the other trace elements. the different lava typologies have been classified on a chemical basis following the iuGs criteria, with the use of the total alkali-silica (tas) and K_2O vs. na_2O diagrams (le maitre *et al.*, 1989; middlemost, 1975; le Bas and streckeisen, 1991).

Quantitative chemical analyses of glass fractions on selected pyroclastic samples have been performed at CisaG, on a sEm JEol-Jsm 5310 instrument, equipped with a link EDs and using natural and synthetic standards. operating conditions were 15kv accelerating voltage and 10µm spot size. the data have been

Table 2

Sample number, sampling location and specific site, date of construction of the building and petrographic features of the igneous rocks.

sample #	location	sampling site	date of construction	rock type	rock composition
1	Pompeii	house VII 6, 3.4.	2nd century b.C. (?)	soft lava	shoshonite
4	Pompeii	town walls near to Porta Ercolano (*opus incertum*)	2nd - 1st century b.C.	lava	shoshonite
6	Pompeii	town walls tower X	2nd - 1st century b.C.	lava	shoshonite
11	Pompeii	lava outcrop insula meridionalis		soft lava	shoshonite
12	Pompeii	Doric Temple (*cella*)	6th century b.C.	soft lava	phonotephrite
14	Pompeii	lava outcrop insula I 2, 2-4		lava	shoshonite
15	Pompeii	house VII 14, 14	3rd century b.C. (?)	soft lava	shoshonite
17	Pompeii	Temple of Venus (blocks in front of the north wall)	1st century a.D.	lava	trachyte
18	Pompeii	Temple of Jupiter	2nd century b.C.	soft lava	shoshonite
21	Pompeii	road pavement	1st century b.C.	lava	latite/tephriphonolite
27	Pompeii	public fountain	1st century b.C.	lava	latite/tephriphonolite
31	Pompeii	amphitheatre	1st century b.C.	lava	shoshonite
48	Pompeii	lava outcrop villa dei misteri		soft lava	shoshonite
71	Terzigno	villa rustica, Cava Ranieri	1st century b.C.	lava	shoshonite
72	Terzigno	villa rustica, Cava Ranieri	1st century b.C.	lava	shoshonite
73	Terzigno	villa rustica, Cava Ranieri	1st century b.C.	lava	latite

processed by the software Link An10000 and INCA version 4.08 (Oxford Instrument, 2006).

The carbonate (mainly travertine) samples have been firstly examined manually, and from 20 of them thin sections have been made for petrographic examination. Stable isotopes (O-C) geochemical analysis has been performed on 38 samples at the Stable Isotope Laboratory of Erlangen-Nürnberg University. Carbonate powders were collected with a dental drill and made to react with 100% phosphoric acid at 75°C using a Kiel III carbonate preparation line connected online to a Thermo Fisher 252 mass spectrometer. All values are reported in permil relative to V-PDB by assigning a $\delta^{13}C$ value of +1.95‰ and a $\delta^{18}O$ value of -2.20‰ to NBS19. Reproducibility was

TABLE 3

Major (wt%) and selected trace element (ppm) composition of lava samples.

sample #	1	4	6	11	12	14	15	17	18	21	27	31	48	71	72	73
SiO_2	50.69	49.82	51.64	50.34	51.44	51.72	51.37	64.09	51.34	52.98	52.81	51.42	50.94	52.26	52.51	56.43
TiO_2	0.87	1.06	0.92	0.92	0.93	0.86	0.88	0.47	0.89	0.88	0.85	0.87	1.07	0.90	0.84	0.92
Al_2O_3	15.59	15.21	16.99	15.01	16.11	16.40	15.04	16.66	16.14	17.65	16.89	17.03	15.29	16.04	16.49	17.17
Fe_2O_3tot	8.01	8.69	7.37	8.49	7.97	7.36	7.90	2.60	7.96	6.88	6.64	7.03	9.00	8.05	7.33	7.96
MnO	0.14	0.14	0.13	0.15	0.13	0.13	0.14	0.11	0.14	0.11	0.11	0.12	0.15	0.14	0.13	0.11
MgO	5.29	5.98	4.17	5.89	4.42	4.48	5.99	0.61	4.82	3.49	3.72	4.20	5.93	5.11	4.15	3.88
CaO	10.26	10.26	8.89	10.72	8.98	9.34	10.49	1.78	9.63	8.04	8.41	9.55	10.37	8.96	8.39	3.48
Na_2O	3.61	3.66	3.48	2.32	3.16	2.91	2.58	4.92	3.88	2.50	2.42	2.83	4.08	2.83	2.64	1.54
K_2O	4.35	3.89	5.08	5.07	5.44	5.32	5.03	7.78	4.02	6.75	6.83	5.37	2.37	5.23	6.22	7.84
P_2O_5	0.62	0.54	0.71	0.58	0.68	0.61	0.50	0.11	0.57	0.65	0.63	0.65	0.54	0.39	0.47	0.32
LOI	0.57	0.76	0.63	0.50	0.74	0.88	0.08	0.88	0.62	0.07	0.69	0.94	0.24	0.09	0.84	0.34
Ni	49	56	44	53	45	49	51	4	56	32	36	41	61	50	35	20
Rb	249	265	240	242	345	242	288	303	306	287	283	224	260	270	348	348
Sr	870	955	862	866	970	821	784	157	930	853	794	895	933	938	834	1083
Y	17	22	18	18	17	17	18	34	18	18	18	16	21	16	14	19
Zr	162	187	194	171	175	162	157	368	165	196	213	193	174	170	154	219
Nb	17	21	25	19	20	17	15	61	17	25	29	25	19	19	17	32
Sc	27	25	20	31	22	23	29	5	27	15	15	16	28	24	23	9
Cr	122	117	81	164	80	113	159	-	197	39	69	63	136	105	76	34
Ba	2090	2157	2139	2077	2329	2197	1932	330	2192	2229	2246	2179	2138	2213	1781	2221
La	39	46	42	53	55	32	39	70	46	35	40	42	62	44	29	51
Ce	88	79	85	100	110	93	74	131	98	98	83	85	96	91	67	136

- : below detection limit

taBlE 4
Sample number, location, monument type and age, and petrographic features of the travertine specimens.

sample #	location	sampling site	date of construction	main petrographic features
24	Pompeii	Casa del Fauno (vi 12, 1-8)	2nd century B.C.	n.a.
26	Pompeii	Casa di orfeo (vi 14, 18-19)	5th century B.C.	pisoidal fabric, fragments of gastropodes and concretions around plant remnants, traces of some fine volcanic detritus
28	Pompeii	town walls, Porta vesuvio	4th- 3rd century B.C.	alteration by volcanic(?) fluids, porosity with new minerals and Fe(hydr)oxides have been deposited
34	sarno	theatre	2nd century B.C.	well crystallized travertine, with evidences of fresh-water radial cements and cyanobacteria
40	nocera superiore	tomb, Pizzone necropolis	1st century B.C.	crystals of carbonate minerals (probable aragonite), plant filaments and cavities.
44	sarno	modern surface near tartarito	-	crystals of carbonate minerals, porosity filled by fine detrital sediment (probably volcanic)
50	Palma Campania	aqueduct near torricelle	1st century B.C.	fibro-radial fabric, cyanobacterial(?) remnants and plants, ome detritus of volcanic and glassy material
54	Boscoreale	villa regina	1st century B.C.	travertine with a pelletoidal structure
57	san marzano	tomb, protohistoric necropolis	7th century B.C.	n.a.
59	Pompeii	Casa del Chirurgo (vi 1, 9.10.23)	3rd - 2nd century B.C.	well-diagenized travertine with concretions and neoformed crystals in the porosity
60	Pompeii	house vi 11, 11. 12	3rd century B.C.	n.a.
61	Pompeii	house vi 11, 6. 13	3rd century B.C.	n.a.
62	Pompeii	town walls near to Porta vesuvio	5th-4th century B.C.	travertine with micropeloids some thin-shelled gastropods and non-carbonate sediments (ashes?) as cavity filling
63	Pompeii	Casa del Granduca michele (vi 5, 5.6.21)	3rd century B.C.	n.a.
64	Pompeii	house i 5, 1. 2	3rd century B.C.	travertine with a cavernous fabric and cavities left from dissolution of plant material. locally volcanic fragments
65	Pompeii	house i 3, 25	4th century B.C.	n.a.
66	Pompeii	house i 8, 8. 9	4th century B.C.	n.a.
67	Pompeii	Casa di amarantus (i 9, 11. 12), atrium	4th century B.C.	travertine with fine sediment material and cavities derived from the dissolution of plants material and/or ostracods; filaments encrusted with Ca-carbonate and cyanobacterial concentrations
68	Pompeii	Casa di amarantus (i 9, 11. 12), facade	4th century B.C.	n.a.
70	Pompeii	caupona ii 3, 7-9	3rd - 2nd century B.C.	n.a.
74	terzigno	villa rustica, Cava ranieri	1st century B.C.	n.a.
76	terzigno	villa rustica, Cava ranieri	1st century B.C.	travertine with peloidal fabric and cavities derived from plants and/or ostracods
77	terzigno	villa rustica, Cava ranieri	1st century B.C.	n.a.
83	Pompei	mariconda, drill core Dai 24 (-7.90 m)	-	travertine (calcareous tufa) with micropellets and cyanobacteria(?) and with thin-shelled gastropods
84	scafati	industrial area, drill core Dai 21 (-7.80 m)	-	poorly cemented travertine (calcareous tufa) with micropellets (ostracods? insect remains?)
85	scafati	industrial area, drill core Dai 21 (-8.90 m)	-	n.a.
86	scafati	Bagni, drill core Dai 22 (-4.50 m)	-	fine calcareous sediment, well cemented with fragments of carbonate crusts, cyanobacterial remnants, radial cements and peloids
87	scafati	Bagni, drill core Dai 22 (-5.50 m)	-	similar to #84, traces of possible diatomaee

n.a. = not analyzed in thin section by om

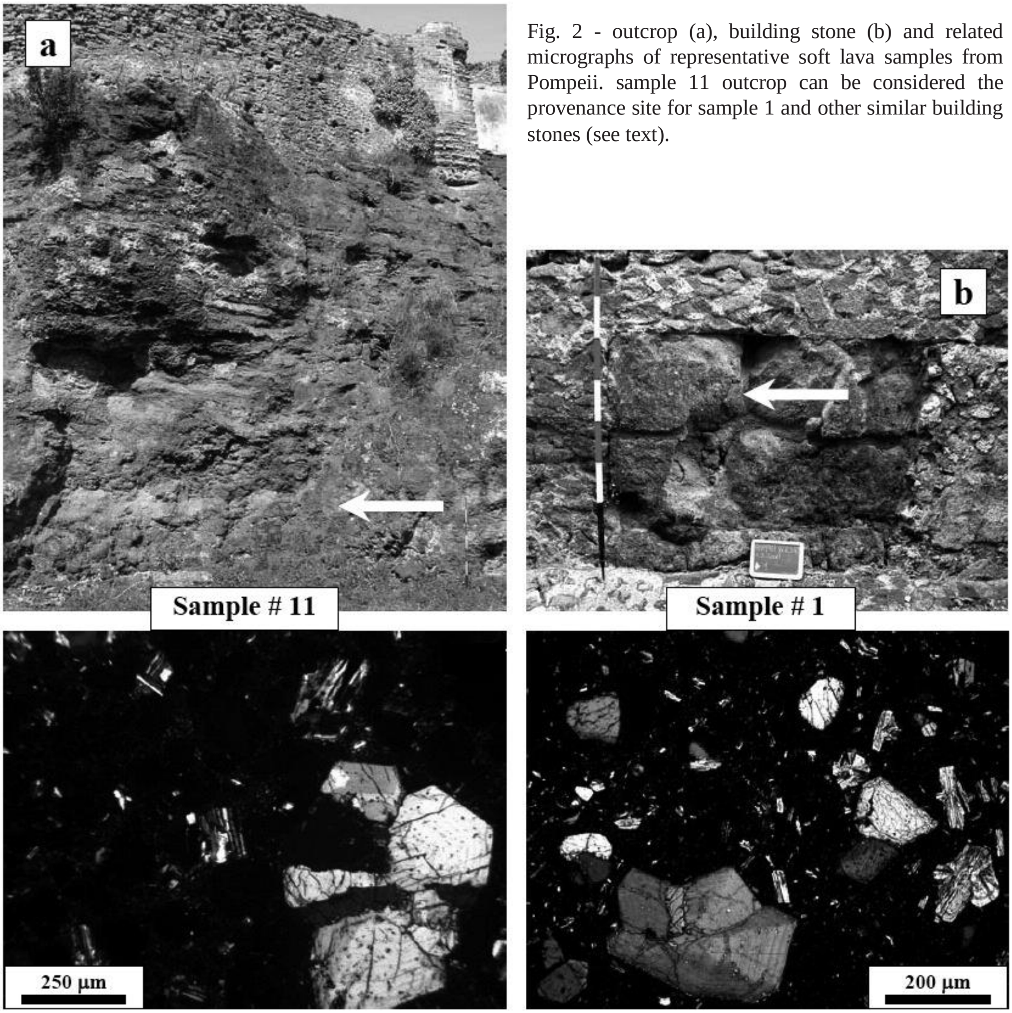


Fig. 2 - outcrop (a), building stone (b) and related micrographs of representative soft lava samples from Pompeii. sample 11 outcrop can be considered the provenance site for sample 1 and other similar building stones (see text).

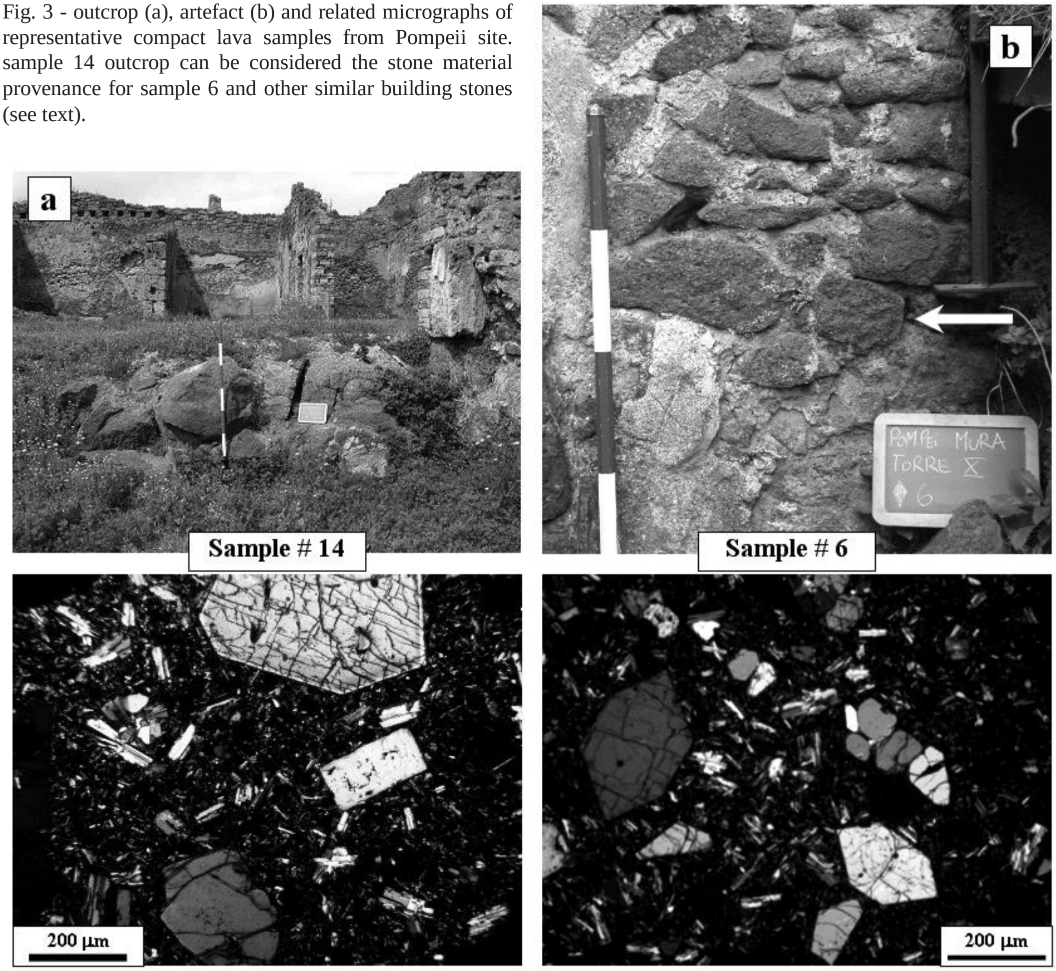
checked by replicate analyses of laboratory standards and was better than ± 0.05 ‰ (1 σ) for both carbon and oxygen isotopes.

VolCaniC BuilDinG stonEs

Combined hand-specimen examination and optical microscopy study of lava samples have led to the distinction between two main lithologies, i.e. compact lavas (simply indicated as "lava" in taBlE 2) and scoriaceous, glass-rich lavas (the "soft lava" of taBlE 2). Examples of compact and soft lava are shown in Fig. 2 and 3, respectively.

the chemical analyses of the studied lava specimens are presented in taBlE 3. they are characterized by potassic to high potassic affinity (Fig.4a). Plotted in the tas diagram, the majority of the lavas correspond compositionally to basaltic trachyandesites with leucite (shoshonites), whereas some samples plot between the phonotephrite and phonolite fields

Fig. 3 - outcrop (a), artefact (b) and related micrographs of representative compact lava samples from Pompeii site. sample 14 outcrop can be considered the stone material provenance for sample 6 and other similar building stones (see text).



(Fig. 4b). in particular, samples 1, 4, 6, 12, 15, 18, 21, 27 and 31 fall very close to samples 11 (soft lava) and 14 (compact lava), these last two corresponding to *in situ* rock specimens. most of the lavas plot in the field of 19-10 ka of somma-vesuvius activity after santacroce *et al.* (2005), and also fit very well with the somma lavas field reported by solone (2006). samples 48 (i.e. a shoshsonite from a lava outcrop close to villa dei misteri) and 73 (i.e. a latite from a *villa rustica* of terzigno) sligtly differ from the others. sample 17 - the Pompeiian temple of venus (table 2) - shows a trachytic compostion, and plots fairly far away from the majority of the Pompeiian lava samples.

with regards to the pyroclastic samples (table 1), a complete petrographic-geochemical characterization is still in progress. hand specimen and microscopic observations and preliminary EDs analyses of the three lithologies, i.e. grey and yellow tuffs and the so-called *pappamonte*, indicate that the first two tephra types can be similar to Ci and CF deposits, respectively. *Pappamonte* corresponds

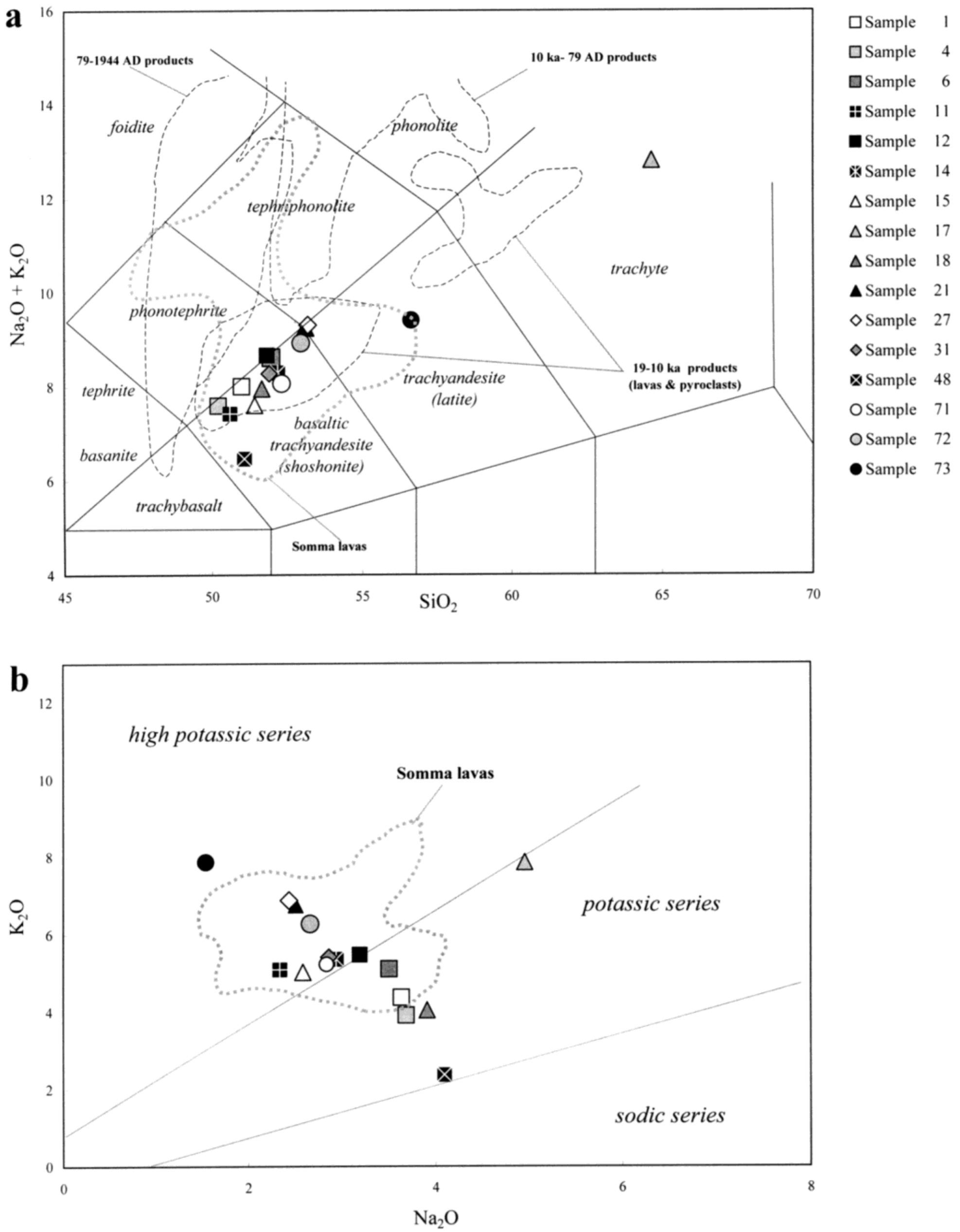


Fig. 4 - (a) Classification diagram (tas) of lava samples: specimens no. 1 to 31 are from building stones of the Pompeii monuments, no. 71, 72 and 73 are from terzigno edifices, whereas samples 11, 12 and 48 are lava outcrops at Pompeii (see also taBle 2). Dashed black line fields are related to somma-vesuvius rocks of different ages after santacroce et al. (2005); dotted grey line field is related to somma lavas reported by solone (2006 and reference therein). (b) K_2o *vs* na_2o diagram (middelmost, 1975), with the grey dotted line field of somma lavas after solone (2006) (symbols as in a).

to a welded, lithic tuff rich in scoriae, lava and intrusive rocks fragments. Geological evidence *in situ* seems to indicate that this lithology can belong to grey-greenish pyroclastic deposits younger than Ci, currently outcropping at a very low depth, in the south-western part of the Pompeii archaeological site. Fig. 5 shows the representative building stones of the pyroclastic type at Pompeii.

Travertine and limestone building stones

The main petrographic characteristics of selected travertine samples in thin section are given in Table 4. The majority of the building material samples taken into account for this study consist both of "calcareous tufa", soft and brittle, and of real hard "travertines" - less porous and with strong evidence of diagenetic crystallization. Both were called *Sarno limestone* in the old (Fouqué, 1886) and new (Santoro, 2007) literature. Today, the names "travertine" and "calcareous tufa" are applied to a wide range of freshwater fluvial and lacustrine carbonates. Most people use the term calcareous tufa for the softer varieties, which would be unsuitable for building. The need to distinguish between travertines, tufas and deposits such as calcretes and stromatolites has been recognized for many years and a number of schemes have been proposed, but there is still much confusion on the nomenclature (Pentecost and Viles, 1994). The distinction between travertine and calcareous tufa is based mainly on the degree of cementation, which is neither easy to define in terms of its limits nor its measure (Flügel, 1982;

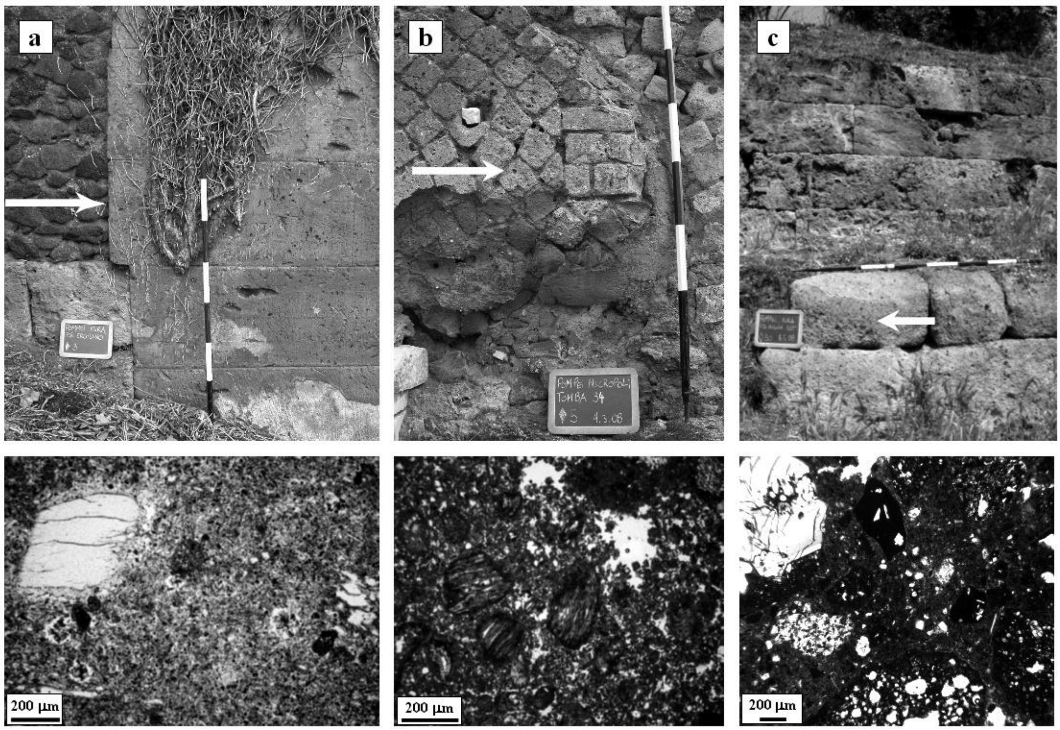


Fig. 5 - some building stone of pyroclastic type at Pompeii: (a) grey tuff, (b) yellow tuff and (c) "*pappamonte*".

Folk *et al.*, 1985). a distinction has also been made on a genetic basis: only those derived from hot waters in former volcanic areas should be called travertines (Bagni di tivoli type), while all the others are calcareous tufas. this kind of classification, though, requires an isotopic geochemical characterization (i.e. stable isotopes. Deines, 1980; anzalone *et al.*, 2007).

the petrographical observation of the travertine samples from the sarno river plain has enabled the recognition of several sedimentary structures, as well as fossil remains (plants and ostracods), micritic peloids and several types of cyanobacterial (microbic) structures. it has been possible to distinguish at least two travertine facies, related to different diagenetic stages, which seem to have been used in distinct parts of the buildings at the archaeological sites. the two facies are a porous travertine or calcareous tufa, and a lithoid travertine, which is possibly the only one that can keep the traditional name (travertine).

stable isotopic analysis was enlarged to thirty-eight specimens of carbonate building materials (travertine and some limestone), sampled in several areas of the archaeological area of Pompeii (Fig. 6a), as well as in some *villae rusticae* of terzigno and Boscoreale and tombs of nuceria and san marzano. to compare the possible provenances of the materials used in the archaeological sites, we have analyzed five specimens coming from shallow cores (depth -4.50 to -8.90, samples 83, 84, 85, 86 and 87 of taBlE 4), drilled during 2009 in the southern suburbs of Pompeii, at the localities of Pompei-mariconda, scafati-industrial site, and scafati -Bagni. an example of specimen from a drill core is given in Fig. 6b. taBlE 5 lists the stable isotope data resulting from the analyses of the archaeological and drill core samples, and in Fig. 7 the same data together with the results of the analysis of some carbonate rocks are organized in a δ^{18}o - δ^{13}C diagram. a relatively small range in δ^{13}C and δ^{18}o characterizes all the calcareous tufa and travertine samples from Pompeii and the other archaeological areas nearby. oxygen isotope ratios are between -6.01 and -7.29‰. Carbon isotopic ratios vary between -2.69 and -0.22‰, with two samples bearing more negative values. oxygen isotope ratios of the travertines from sarno, san marzano and nuceria are slightly heavier (around -5.50‰), and the carbon isotopes are generally strongly positive (>1‰). the travertine samples from the drill cores (Pompei-mariconda, scafati-Bagni and scafati-industrial area) show isotope values with δ^{13}C and δ^{18}o varying between -0.74 and -1.69‰ and -6.03 and - 6.32‰, respectively. the carbon and oxygen isotope ratios of the Pompeii travertines and those of surrounding areas are comparable with those of the drill core samples, thus suggesting that the travertines occurring in the subsurface of the scafati and mariconda areas may have been used as building material for many of the archaeological buildings in the ancient town of Pompeii and nearby suburban villas. it must be observed, though, that the lithotypes sampled in the drill cores are more comparable to the soft and brittle calcareous tufa, than to real travertines.

DisCussion anD ConClusions

mineralogical and petrographic data indicate that most of the shoshonite samples used as building stones could derive from the same lavas that constitute the bedrock of ancient Pompeii (Figg. 2 and 3). indeed, for at least some of the millstones from Pompeii Buffone *et al.* (2003) have already hypothesized a provenance from the basaltic trachyandesites cropping out in the Pompeian area itself, or at Castello di Cisterna (naples). Even if the composition of these lavas fits well with the literature's data on the somma lavas, it has to be considered that according to Cinque and irollo (2004), on the basis of geomorphological and volcano-stratigraphic evidence, Pompeii does not lie on lavas directly originated from the somma volcano, but is located on a hill representing the relic of an independent volcanic edifice. Consequently, the shoshonitic lavas used for construction at Pompeii could derive from an *in situ* volcano, compositionally similar to somma deposits. after Cinque and irollo (2004), this edifice would have an age ranging from slightly older than 19 ka to olocene: this age should also be assigned to the majority of the lava samples of this study. only for the trachyte sample 17, a quite different provenance could be hypothesized (ischia island?).

Before we discuss the possible origin of the travertines, which are the most abundant lithology among those sampled for this study, we

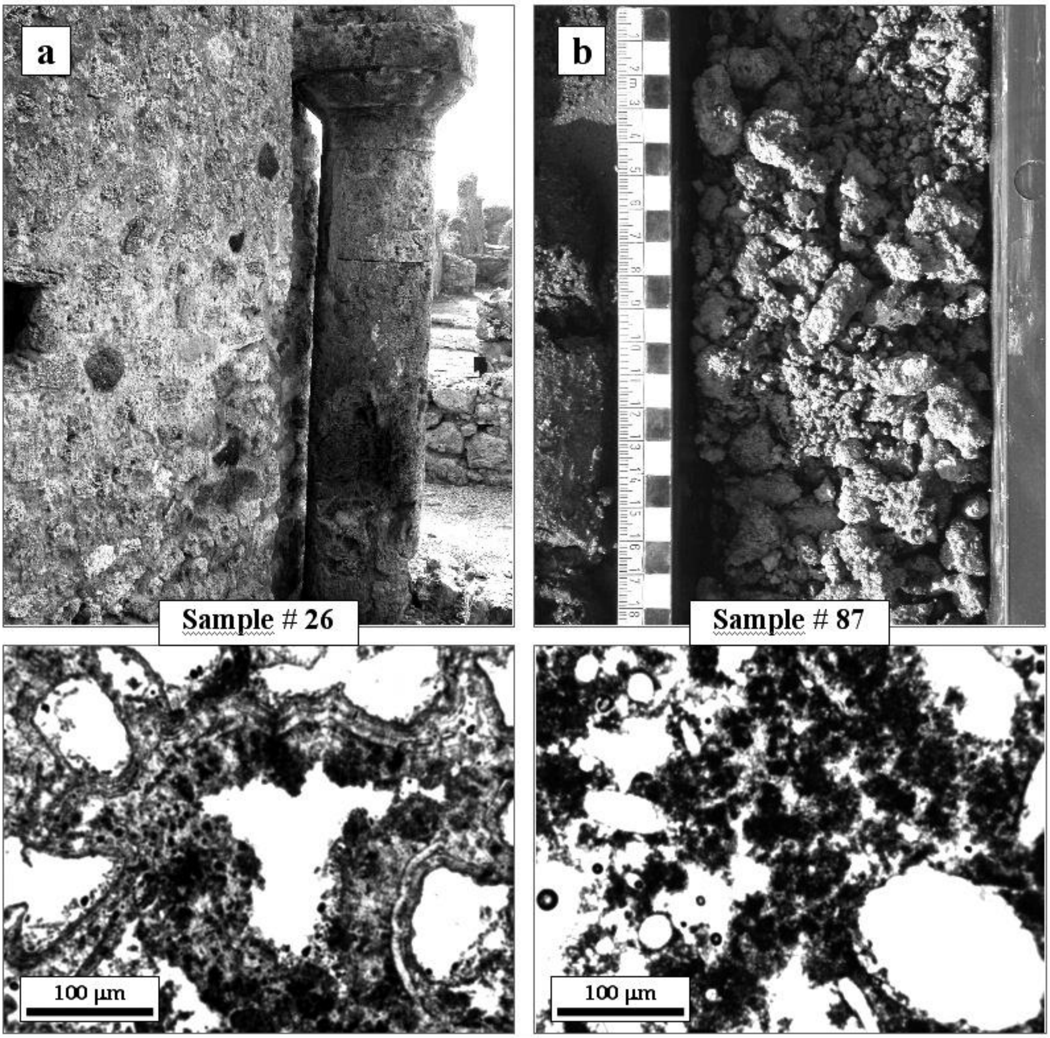


Fig. 6 - travertine samples and micrographs at polarizing microscope of samples 26 from building stones at Pompeii site (a) and 87 from a drill core at scafati-Bagni (b).

TABLE 5
Stable isotope data of travertine and compact limestone samples.

sample #	rock type	δ^{13}cV-PdB	std.dev.	δ^{18}oV-PdB	std.dev.
24	travertine	-1.67	0.02	-6.22	0.01
25	compact limestone	0.61	0.01	1.85	0.01
26	travertine	-0.87	0.01	-6.13	0.03
28	travertine	-1.10	0.01	-6.01	0.03
32	compact limestone	0.09	0.01	-0.89	0.01
34	travertine	2.80	0.01	-5.89	0.01
36	compact limestone	0.30	0.01	-2.41	0.03
38	compact limestone	0.09	0.01	-0.80	0.01
40	travertine	4.08	0.01	-5.82	0.02
42	compact limestone	2.05	0.01	-4.17	0.01
44	travertine	4.89	0.01	-6.01	0.01
49	compact limestone	-2.66	0.02	-3.57	0.02
50	travertine-encrustations	-7.88	0.01	-5.59	0.02
53	compact limestone	-2.69	0.01	-1.21	0.01
54	travertine	-0.52	0.41	-6.52	0.03
57	travertine	-3.50	0.01	-4.17	0.03
58	compact limestone	3.77	0.02	-2.86	0.02
59	travertine	-2.69	0.01	-7.29	0.02
60	travertine	-0.68	0.01	-6.59	0.02
61	travertine	-1.02	0.02	-6.23	0.01
62	travertine	-1.72	0.01	-6.25	0.03
63	travertine	-0.22	0.01	-6.59	0.03
64	travertine	-1.74	0.01	-6.29	0.03
65	travertine	-0.92	0.01	-6.93	0.01
66	travertine	-1.06	0.02	-6.12	0.03
67	travertine	-2.45	0.01	-6.63	0.02
68	travertine	-0.60	0.01	-6.92	0.01
70	travertine	-0.97	0.02	-6.67	0.01
74	travertine	-1.14	0.01	-6.90	0.01
75	compact limestone	0.01	0.01	-3.00	0.01
76	travertine	-1.50	0.01	-6.47	0.01
77	travertine	4.70	0.01	-6.03	0.01
78	compact limestone	-14.25	0.02	-4.98	0.02
83	travertine	-0.74	0.01	-6.28	0.01
84	travertine	-1.36	0.01	-6.09	0.02
85	travertine	-1.40	0.01	-6.32	0.02
86	travertine	-1.69	0.01	-6.03	0.02
87	travertine	-1.69	0.01	-6.27	0.01

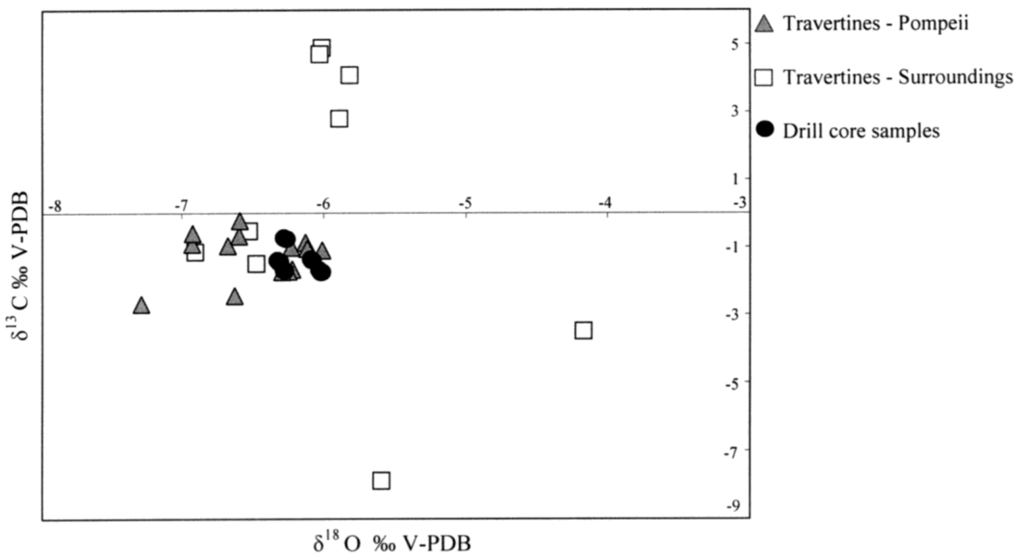


Fig. 7 - δ^{13}C *vs* δ^{18}o isotopic diagram of the archaeological and drill core travertine samples.

should review some recent ideas on the genesis of this rock type (Pentecost and viles, 1994).

From the geochemical point of view, two classes of travertines have been described:

a) meteogene travertines,

b) thermogene travertines.

in the former, the carrier Co_2 originates in the soil and in the epigean atmosphere forming deposits primarily in limestone terrains. these travertines are the most widely distributed and often display characteristic fabrics. their stable carbon isotope compositions range mainly from about 0 to -11‰, reflecting the depleted ^{13}C of soil Co_2.

the second group consists of thermal travertines. waters responsible for these deposits are normally hot and the carrier Co_2 results primarily from the interaction between hot rocks and Co_2- rich fluids. the carbon dioxide is also due to the processes of hydrolysis and the oxidation of reduced carbon, decarbonation of limestone or directly from the upper mantle - this occurring mainly in areas of volcanic activity. here, the high concentrations of carbon dioxide are capable of dissolving large volumes of carbonate. rate of degassing and deposition from these hot waters tends to be rapid, providing distinctive fabrics and a stable carbon isotope composition usually spanning the interval -4 to +8‰. this ^{13}C enrichment often reflects the heavier carbon released from decomposing marine limestones, but significant contributions from mantle Co_2 can result in the deposition of travertines depleted in ^{13}C. these travertines have a more restricted distribution, being located primarily in regions of recent volcanic activity. the most typical examples are the classical travertines of the tivoli region, near rome. it is important to distinguish between the above-mentioned travertines, and those formed from hot meteogene waters resulting from deep circulation. the latter possess low Co_2 levels derived from soils, and are invariably depleted in ^{13}C, with no thermal source of Co_2.

the combined (δ^{18}o - δ^{13}C) isotopic analyses on our samples have shown a range of values typical for a Co_2 of both magmatic-hydrothermal (samples 34, 40, 44, 77) and karstic-supergene origin (all the other samples). moreover, the relatively constant $\delta^{18}o$ data point to depositional conditions in atmospheric temperatures similar to those recent for most travertines.

the karstic-supergene travertines are in our case more similar to the calcareous tufa lithology - very porous and brittle - and in some specimens contain detrital fragments of magmatic minerals and volcanic glass. a similar lithology, complemented by rare volcanic fragments, has also been found in the samples taken from the drill cores at Pompeii mariconda and around the town of scafati. moreover, the isotopic data measured from scafati and mariconda calcareous tufa are in the same interval of values as the karstic travertines from the archaeological sites. therefore, it can be safely considered that at least some of the stones used for building in Pompeii were extracted from quarries set in the above-mentioned areas or in any other outcrop located in the southern suburbs of Pompeii (Fig. 8).

the high $\delta^{13}C$ values (between +2.80 and +4.89), detected in a few samples, can be derived from the cinetic fractionation of Co_2 in a solution rich in ^{13}C, due to the dissolution of marine carbonates. these carbonates can be located in the calcareous-dolomitic mountain ranges of sarno and/or nuceria, behind the possible (?) travertine quarries (see samples 34, 40, 44 and 77). another alternative is that these travertines have a completely different geographical origin, far from the town of Pompeii and the villages

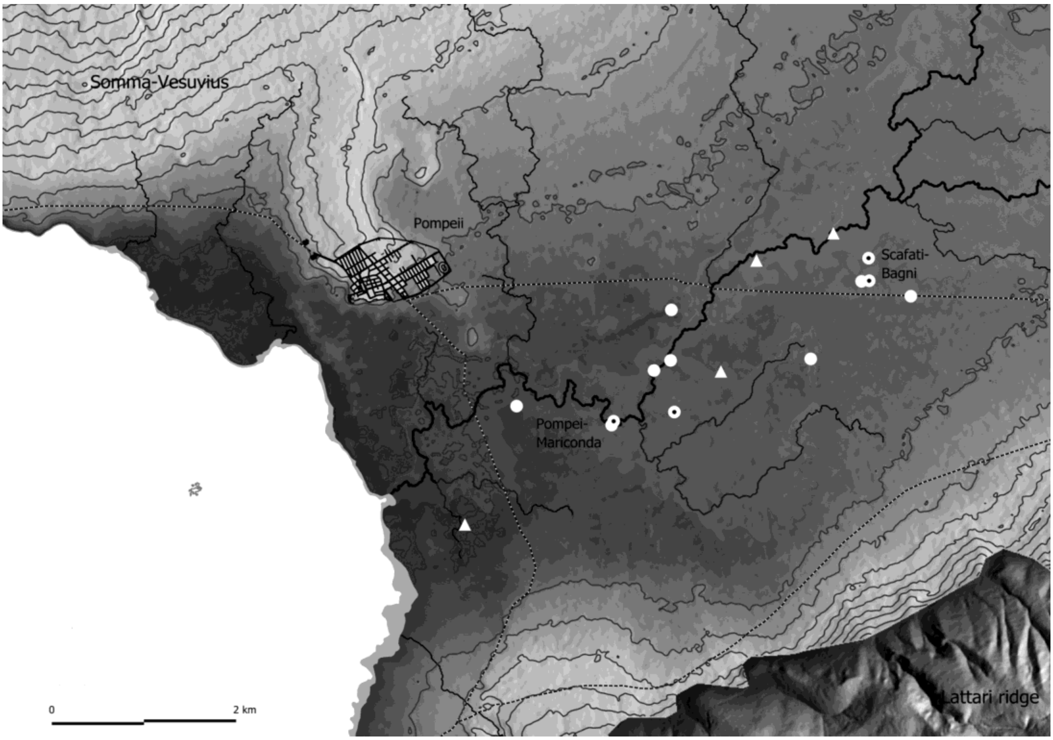


Fig. 8 - Evidence of travertine (circles and circled dots) and travertine concretions (triangles) in drilling cores located south and east of Pompeii projected on the aD 79 DEm, as generated by vogel and märker, 2010. Circled dots indicate current Dai drillings.

around it. such high δ^{13}C values have been found in the travertines of tivoli in latium (thermogene, associated with fluid circulation in a volcanic area) and also in the Pontecagnano (salerno) travertines (meteogene, derived from the dissolution of limestone chains nearby).

the δ^{18}O - δ^{13}C isotopic values detected in sample 57 (san marzano iron age necropolis) are fairly different from each of the above-mentioned clusters, and may point to a completely different source of building material for this much older archaeological find.

in conclusion, most of the stones used for the construction of edifices in Pompeii and other surrounding archaeological sites between vi century b.C. and 79 a.D. originate from local quarries, mainly situated in various localities on the sarno river plain itself or in surrounding areas (Fig. 9). Dimension stones of higher quality, however, were imported either from other areas along the italian peninsula (i.e. limestone/marble), or from variable sites throughout the mediterranean realm (i.e. granite/porphyry/serpentinite), in order to obtain pricey polishable slabs, to be used for embellishment of many private and public edifices.

aCKnowlEDGEmEnts

this work was financially supported by research funds of Deutsches archäologisches institut of Berlin, and G. Balassone. we would like to thank the collaborators of the soprintendenza speciale per i Beni archaeologici di napoli e Pompei and the soprintendenza per i Beni archaeologici di salerno, Benevento, avellino e Caserta for their support. a special thank is due to F. seiler, Dai Berlin, for his continuous scientific support and s. vogel fruitful discussions. l. melluso and l. Franciosi, università Federico ii napoli, and m. Piochi, inGv osservatorio vesuviano napoli, are warmly thanked for useful suggestions. the authors are also indebted

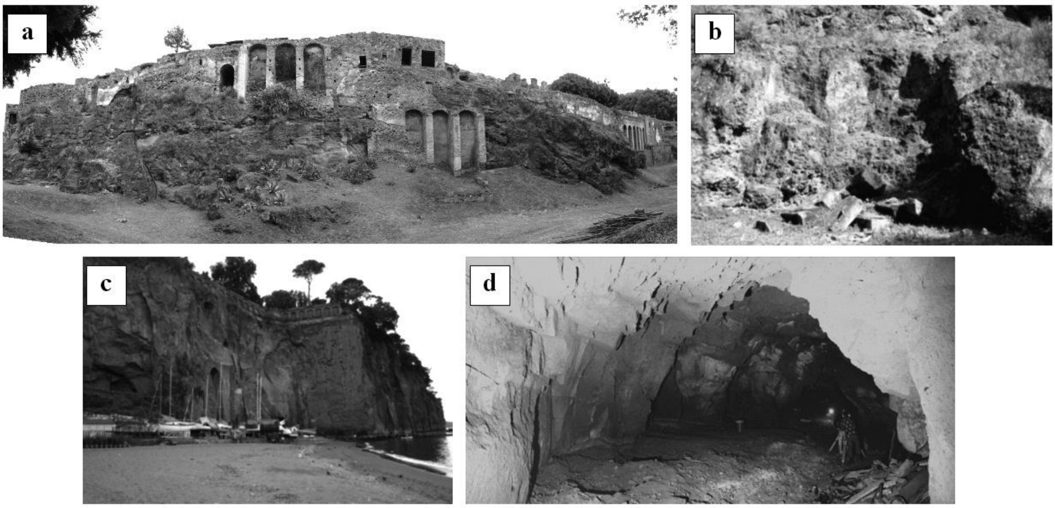


Fig. 9 - Examples of old quarries in volcanic rocks from the sarno river plain and the sorrento Peninsula. Pompeii, *Insula meridionalis*, scoriaceous lava to scoriae deposits (a) with evidences of quarrying activity (b). Piano di sorrento, remnants of an old Ci grey tuff quarry (c). stabiae, old underground excavations in Ci grey tuff (d).

to the two referees, v. Kockel, Klassische archäologie universität augsburg, and D. Barca, università della Calabria rende, for their helpful comments on the draft manuscript. the editing assistance of a.m. De Francesco, G. saviano and a. Gianfagna is gratefully acknowledged.

rEFErEnCEs

anZalonE E., FErrEri v., sProviEri m. and D'arGEnio B. (2007) - *Travertines as hydrologic archives: the case of the Pontecagnano deposits (southern Italy).* advances in water resources, **30**(10), 2159-2175.

BalassonE G., KastEnmEiEr P., Di maio G., mormonE a. and JoaChimsKi m. (2009) - *Characterization and provenance of the building stones from Pompeii's archaeological site (southern Italy).* Geophysical research abstracts, **11**, EGu General assembly wien, 3489.

BonarDi G., D'arGEnio B. and PErronE v. (1988) - *Carta geologica dell'Appennino meridionale (1:250 000).* atti del 74° Cong. soc. Geol. d'it., 13-17 settembre 1988, sorrento (na).

BuFFonE l., lorEnZoni s., Pallara m. and ZanEttin E. (1999) - *Le macine rotatorie in rocce vulcaniche di Pompei.* riv. st. Pomp., **10**, 117-130.

BuFFonE l., lorEnZoni s., Pallara m. and ZanEttin E. (2003) - *The Millstones of ancient Pompeii: a petro-archaeometric study*. Eur. J. mineral., **15**, 207-215.

CinQuE a. and irollo G. (2004) - *Il "Vulcano di Pompei": nuovi dati geomorfologici e stratigrafici*. il Quaternario, **17**, 1, 101-116.

CinQuE a. and russo F. (1986) - *La linea di costa del 79 d.C. tra Oplonti e Stabia nel quadro dell'evoluzioni Olocenica della Piana del Sarno (Campania).* Boll. soc. Geol. it., **105**, 111-121.

D'arGEnio B., PEsCatorE t. and sCanDonE P. (1973) - *Schema geologico dell'Appennino meridionale (Campania e Lucania).* atti acc. naz. lincei. Quad. **183**, 49-72.

DEinEs P. (1980) - *The isotopic composition of reduced carbon.* in P. Fritz, and J.C. Fontes, eds., Environmental isotope Geochemistry. Elsevier, amsterdam, 600 p.

DEino a.l., orsi G., DE vita s. and PioChi m. (2004) - *The age of the Neapolitan Yellow Tuff caldera-forming eruption (Campi Flegrei caldera - Italy) assessed by $^{40}Ar/^{39}Ar$ dating method.* Journ. volc. Geoth. res., **133**, 157-170.

DE sPaGnolis ContiCEllo m. (1994) - *Il pons Sarni di Scafati e la via Nuceria-Pompeios*. soprint. archeol. Pompei, monografie, 8, roma.

DE vita P. and CEliCo P. (2006) - *Distribuzione delle coltri piroclastiche sui versanti carbonatici perivesuviani e suscettibilità a franare*. Giorn. Geol. appl., **3**, 145-151.

Di rEnZo v., Di vito m. a., ariEnZo i., CaranDEntE a., CivEtta l., D'antonio m., GiorDano F., orsi G. and tonarini F. (2007) - *Magmatic history of Somma-Vesuvius on the basis of new geochemical and isotopic data from a deep borehole (Camaldoli della Torre).* Journ. Petrol., **48**-4, 753-784.

Di vito m.a., SulPiZio r., ZanChEtta G. and CalDEroni G. (1998) - *The geology of the South Western Slopes of Somma-Vesuvius, Italy, as inferred by borehole stratigraphies and cores*. acta vulcanologica **10**, 383-393.

FlüGEl E. (1982) - *Microfacies analysis of limestones.* springer verlag, Berlin, 575 p.

FolK r.l., ChaFEtZ h.s. and tiEZZi P.a. (1985) - *Bizarre forms of depositional and diagenetic calcite in hot-spring travertines, central Italy, p. 349-369.* in: n. sChEiDEmann anD P. harris, eds., Carbonate Cements. society of Economic Paleontologists and mineralogists, special Publication 36, tulsa, oklahoma, 349-369.

FouQué F. (1886) - *Sur les materiaux de construction employés à Pompéi*. in: association Française pour l'avancement des sciences, Comptes rendus, 15e session, nancy.

Franza a. (2005) - *L'evoluzione tardo-quaternaria del glacis basale dei Monti di Sarno (Campania) ed il ruolo degli input piroclastici*. unpublished PhD Dissertation, university "Federico ii", 287 pp.

KastEnmEiEr P. and sEilEr F. (2007) - *La ricostruzione dei paleo-paesaggi nella piana del Sarno*. Quaderni autorità di Bacino del sarno. studi, documentazione e ricerca, **1**, 24-26.

Kawamoto t. and tatsumi y. (1992) - *Classification and regional distribution of lava blocks in Pompeii*. op. Pomp., **2**, 92-97.

laZZarini l. and CanCElliErE s. (1999) - *Note sui marmi e le pietre d'importazione e la loro lavorazione a Pompei*. in: a. Ciarallo - E. DE Carolis eds., homo faber. natura, scienza e tecnica nell'antica Pompei, milano.

Le Bas M.J. and Streckeisen A. (1991) - *The IUGS systematics of igneous rocks*. Journ. Geol. soc., **148**(5), 825-833.

Le Maitre R.W., Bateman P., Dudek A., Keller J., Lameyre J., Le Bas M.J., Sabine P.A., Schmid R., Sorensen H., Streckeisen A., Woolley A.R. and Zanettin B. (1989) - *A classification of igneous rocks and glossary terms: recommendations of the International Union of Geological Sciences, Subcommssion on the systematics of Igneous Rocks*. oxford, 193 pp.

Lirer L., Chirosca M.C., Munno R., Petrosino P. and Grimaldi M. (2005) - *Il Vesuvio. Ieri, Oggi, Domani.* Regione Campania, Napoli, 150 pp.

Lorenzoni S., Casella A.C., Zanettin E. (2001) - *La più antica cinta muraria di Pompei. Studio petro-archeometrico,* Rass. Archeol. Class. Postclass., **18** B, 35-49.

Melluso L., Morra V., Brotzu P., Razafiniparany A., Ratrimo V. and Razafimahatratra D. (1997) - *Geochemistry and Sr-isotopic composition of the Cretaceous flood basalt sequence of northern Madagascar: petrogenetic and geodynamic implications*. J. afr. Earth sci., **24**, 371-390.

Middlemost E.A.K. (1975) - *The basalt clan.* Earth Science Reviews **11**, 337-364.

Nicotera P. (1950) - *Sulle rocce laviche adoperate nell'antica Pompei.* in: Pompeiana. Raccolta di studi per il secondo Centenario degli scavi di Pompei, 4. suppl. PP, a cura di a. maiuri, napoli, 396-424.

Nissen h. (1877) - *Pompeianische Studien zur Städtekunde des Altertums.* Leipzig, 5-22.

Pappalardo L., Civetta L., D'Antonio M., Deino A., Di Vito M., Orsi G., Carandente A., De Vita S., Isaia R. and Piochi M. (1999) - *Chemical and isotopical evolution of the Phlegraean magmatic system before the Campanian Ignimbrite (37 ka) and the Neapolitan Yellow Tuff (12 ka) eruptions*. J. Volcanol. Geotherm. Res., **91**(2-4), 141-166.

Pappalardo L., Ottolini L. and Mastrolorenzo G. (2008) - *The Campanian Ignimbrite (southern Italy) geochemical zoning: insight on the generation of a super-eruption from catastrophic differentiation and fast withdrawal.* Contr. min. Petr., **156**-1, 1-26.

Pentecost A. and Viles H. (1994) - *A review and reassessment of travertine classification*. Géograph. Phys. Quatern., **48**(3), 305-314.

Rolandi G., Barrella A.M. and Borrelli A. (1993) - *The 1631 Eruption of Vesuvius.* J.volcanol. Geotherm. Res., **58**, 183-201.

Rolandi G., Bartolini F., Cozzolino G., Esposito n. and Sannino D. (2000) - *Sull'origine delle coltri piroclastiche presenti sul versante occidentale del Pizzo d'Alvano*. Quad. Geol. appl., **7**-1, 213-235.

Rolandi G., Bellucci F., Heizler M.T., Belkin H.E. and De Vivo B. (2003) - *Tectonic controls on the genesis of ignimbrites from the Campanian Volcanic Zone, S. Italy*. min. Petr., **79**, 3-31.

Santacroce R., Cioni R., Marianelli P. and Sbrana a. (2007) - *Understanding Vesuvius and preparing for its next eruption.* in: Balmuth M.S., Chester D.K., Johnston, P.A., eds., Cultural responses to the volcanic landscape: the mediterranean and beyond. archaeological institute of america, Coll. Conf. Papers Boston, **8**, 27-55.

Santoro S. (2007) - *Pompei: Insula del Centenario (IX, 8). Studi e scavi*. università di Bologna, n.s., 16.

Seiler F. (2006) - *Current research projects*. in: aktuelle Forschungsprojekte, Deutsches archäologisches institut Zentrale, 34-35.

Seiler F. (2008) - *Rekonstruktion der antiken Kulturlandschaften des Sarno-Beckens. Ein multidisziplinäres Kooperationsprojekt mit Partnern aus Naturwissenschaften und Altertumswissenschaften in Deutschland, Italien und England.* in: P.G. Guzzo - M.P. Guidobaldi eds, nuove ricerche archeologiche nell'area vesuviana (scavi 2003-2006). Conv. int. Roma 1-3 febbraio, 485-490.

Solone R. (2006) - *Petrogenesi delle lave potassiche e ultrapotassiche del Monte Somma (Italy).* unpublished PhD Dissertation, university "Federico ii", naples, 134 pp.

Vogel S. and Märker M. (2010) - *Reconstructing the Roman topography and environmental features of the Sarno River Plain (Italy) before the AD 79 eruption of Somma-Vesuvius.* Geomorphology, **115**, 67-77.