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Leucite phonolite millstones from the Orvieto production centre: new data and insights into the Roman trade

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ABSTRACT. — The leucite phonolite lava from quarries located near Orvieto (about 100 km northward from Rome) has represented a volcanic rock in great demand and highly prized for manufacturing millstones in the Roman period. Good abrasive property and rough vescicular surface of this lithotype from the Roman Volcanic Province (Vulsini District) gave to the mills an excellent grinding capacity through the time. The quarries and production centre of Orvieto were located few kilometers from the Tiber River, an impressive natural waterway along which the Romans could transport millstones down to the Tyrrhenian Sea. Because of several findings of leucite phonolite millstones throughout the Mediterranean, we can suppose that from the port of Ostia Antica (located at the estuary of the Tiber River) these artefacts were shipped in large number (as cargoes) or used as ballasts until the localities of destination. This is supported by the presence, at the bakery (Mill Building) of Ostia Antica of several well-preserved Pompeian-style rotary millstones made of the Orvieto leucite phonolite (LP), as shown by petrographic and geochemical analyses. Moreover, in the same archaeological site, some containers for kneading the bread dough (kneading-machine) consist of less vesciculated leucite tephritic phonolites with lower porphyritic index (LTP1 and LTP2).

RIASSUNTO. — La lava fonolitica a leucite proveniente dalle cave localizzate vicino ad Orvieto (circa 100 km a nord di Roma) rappresenta uno dei litotipi di natura vulcanica più apprezzati e ricercati in epoca romana per la manifattura di macine. Questo litotipo della Provincia Vulcanica Romana (Distretto Vulsino), è caratterizzato da una buona resistenza all'abrasione e da una vescicolazione grossolana che conferivano alle macine un'ottima e duratura capacità di frantumazione. Le cave ed il centro di produzione di Orvieto erano localizzati a pochi km dal fiume Tevere, un'imponente via d'acqua naturale lungo la quale i Romani potevano trasportare le macine fino al Mar Tirreno. I numerosi ritrovamenti di macine in fonolite a leucite di Orvieto avvenuti in tutto il Mediterraneo lasciano supporre che dal porto di Ostia Antica (costruito all'estuario del Fiume Tevere) questi manufatti fossero imbarcati sistematicamente in grandi quantità in navi mercantili o usati saltuariamente come zavorre e poi scaricati nelle località di destinazione. Questa ipotesi è supportata dalla presenza, nei panifici di Ostia Antica (Edificio dei Mulini), di numerose macine rotatorie di stile Pompeiano ancora ben conservate e realizzate con la fonolite a leucite (LP) di Orvieto, come dimostrato dalle analisi petrografiche e

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geochimiche. Nella stessa area archeologica sono inoltre presenti alcuni contenitori in pietra lavica utilizzati per impastare il pane, realizzati con fonolititi tefritiche a leucite meno vescicolate e meno porfiriche (LTP1 e LTP2).

KEY WORDS: *Millstones, Ostia Antica, Roman trade, Leucite phonolite, Orvieto, Roman Volcanic Province.*

INTRODUCTION

Recent studies (Oliva *et al.*, 1999; Antonelli *et al.*, 2000, 2001; Renzulli *et al.*, 2002; Buffone *et al.*, 2003) have unequivocally shown that the leucite phonolite outcropping near Orvieto (between the localities of Sugano and Buonviaggio, Latium, Roman Volcanic Province, Vulsini District, Fig. 1), was one of the most widespread leucite-bearing lava for manufacturing millstones in the Roman period, as firstly suggested by Peacock (1980, 1986). It was also inferred that the Tiber River represented a natural fluvial waterway which allowed to transport the Orvieto artefacts down to the Tyrrhenian Sea (Pavolini, 1986; Antonelli *et al.*, 2001; Renzulli *et al.*, 2002). In this way the port of Ostia Antica, located at the estuary of the Tiber River, (Fig. 1), could represent the starting point of the leucite phonolite millstones towards the different Mediterranean routes. Artefacts found at the Ostia Antica bakery (Fig. 2a) are represented by leucite-bearing grey lavas worked both as (i) Pompeian-style rotary millstones (*molae versatiles*; Fig. 2b) and (ii) kneading-machines (*machinae quibus farinae iubiguntur*; for kneading the bread dough; Fig. 2c). In order to detect the provenance of these volcanic rock artefacts we carried out a comprehensive mineralogical, petrographic and geochemical investigation on 22 very small samples. In addition, the leucite phonolite millstone Roman trade within the Italian peninsula and the whole Mediterranean will be also reviewed.

MILLSTONES IN THE ROMAN PERIOD

Most of the Roman millstones discovered in archaeological sites throughout the Mediterranean are made of volcanic rocks; some others, much less common, are made of limestones and sandstones. In fact, lavas are generally characterised by wear resistance and they are particularly suitable for milling because of their abrasive property and rough vescicular surface that provide a good grinding capacity. The most widespread mills used by the Romans were represented by volcanic-rock rotary millstones up to 1.5 meter high (Fig. 2b) typically consisting of an hourglass-shaped (double-cone) upper stone (*catillus*) resting on the conical lower stone (*meta*) (Moritz, 1958). The wheat was crushed to powder by the friction between the *meta* and *catillus*, being this latter turned by means of a bar pushed by slaves or a donkey (*mola asinaria* or *iumentaria*; donkey-mills). Rotary millstones are also known as Pompeian-style mills after the site where they occur so frequently and firstly discovered (i.e. *Pompeii*; Peacock, 1989; Buffone *et al.*, 2003). They were a very popular item, highly prized in Roman households and bakeries. Shipwrecked cargoes of millstones as that of Sec (Mallorca, Spain; Williams-Thorpe and Thorpe, 1990), testify both their importance in the Roman period and their east-west Mediterranean trade. Re-interpreting Varro (the Latin polygraph of the first century B.C.; Pliny the Elder, 1981: *Naturalis Historia*, $XXXVI_{135}$) rotary millstones (*molae versatiles*) were most probably invented in *Volsinii veteres* (at present Orvieto), the famous Etruscan village, and not simply in *Volsinii* (or *Volsinii novi*, at present Bolsena), the Roman city built in the first half of the third century B.C. close to the Bolsena Lake, *ca.* 8 km to SW from Orvieto (Fig. 1; Antonelli *et al.*, 2001). On the basis of fieldworks, thin section petrography and archaeological studies Peacock (1980; 1986) concluded that the main quarries and production center of leucite-bearing Roman millstones were located close to Orvieto (between Sugano and Buonviaggio; Fig. 1).

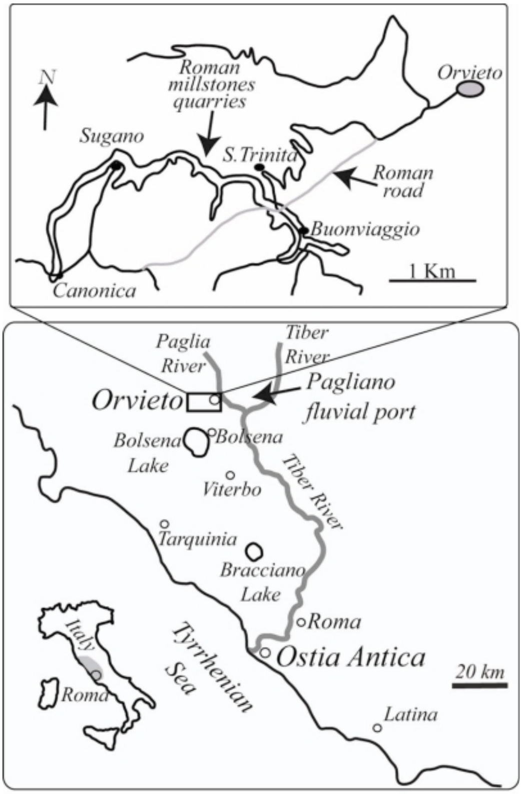

Fig. 1 – The location of the leucite phonolite quarries exploited by the Romans to produce rotary millstones (from Peacock, 1986, modified).

Volcanic rock artefacts from the Ostia Antica bakery

The archaeological site of Ostia Antica

Presently, the geomorphology around Ostia Antica differs from that during ancient (Roman) times because of the numerous changes in the Tiber River course and related fluvial deposits. The choice of this area for the first *castrum* was laid to commercial and political reasons, including the leadership of the lower valley of the Tiber River. In fact, this waterway represented the main communication channel from the coast inland and *viceversa*. Thus, since the 2nd century B.C., the colony of Ostia Antica turn into an important trade center. In this period, the primordial fortified built-up was replaced by numerous shops (*tabernae*) and *horreae* used for sale and storage of the goods respectively.

The samples analysed come from the millstones in the bakery in «Via dei Molini» (Fig. 2a), which was built in *opus mixtum* in the time of Emperor Hadrian. The bakery (also called Mill Building) was able to cover the entire wheat processing production cycle, from milling to making the dough, to baking and selling the bread. It was rectangular in shape and comprises five rooms, with the largest, central area housing the millstones. These areas communicate on the eastern side with a set of eight rooms that look out over «Via dei Molini» and that were probably used as *tabernae* where the bread might have been sold. The complete, definitive destruction of the building, based on the excavation dates, may have taken place in the last decades of the 3rd century A.D. and can certainly be attributed to a fire, of which we can see clear traces on the brickwork, on the paintings and on the objects found during the excavations. The fire did not, however, affect a number of both millstones and containers for the flour-dough (kneading-machines), made of volcanic rocks (*lapis molaris*).

The combination of milling and processing plants for the Ostia Antica wheat (*pistrina et panificia*) appears to be a kind of production factory, especially if we compare them with those in other areas of Italy (e.g. Pompeii, where the baker's shops are smaller and less numerous) or in other areas of the empire. In addition, we know that the bread produced in Ostia Antica was generally sold in Rome (*panis fiscalis ostiensis*), and it has been calculated that an Ostia Antica millstone could grind a quantity of wheat for the daily requirements of at least 150-300 people. If we consider that a population of the colony, during the 2nd century A.D. consisted of around forty thousand inhabitants, we can calculate that there must have been at least 180 millstones in the city, of the type described, shared among 20

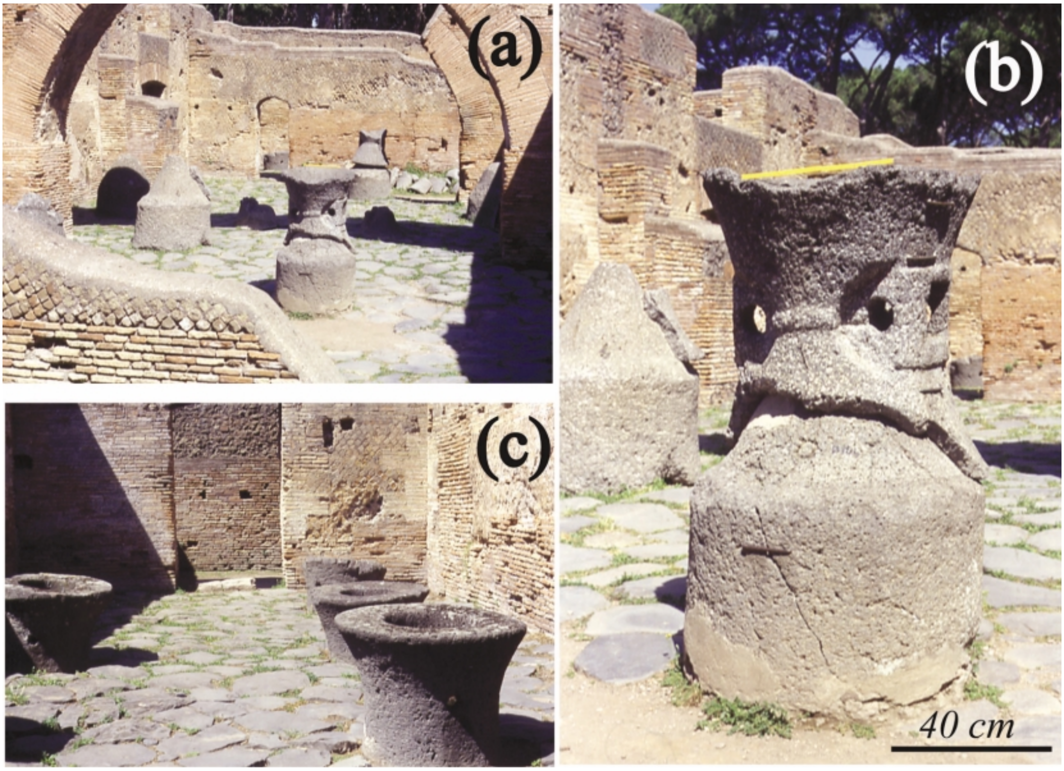

Fig. 2 – Archaeological site of Ostia Antica (Rome): (a) the Mills Building; (b) the Pompeian-style millstone; (c) the kneading-machines.

workshops, and only a very small number of these has been identified today. With regard to the chronology and the spatial distribution of the bakeries, more than half the installations in Ostia Antica must have been set up under Hadrian (117-138 A.D.), while others were carried out between the end of the 2nd and the first quarter of the 3rd century.

Sampling and analytical methods

In order to carry out petrography on thin section and geochemical analyses, 22 very small samples (few tens of grams, not crucial for any kind of possible future restoration) of Pompeian-style millstones (*catilli* and/or *metae*) and kneading-machines for making the dough were provided by one of the authors (P.P.).

Whole-rock major and trace elements contents were determined on selected powdering samples at the Activation Laboratories LTD (Ancaster, Canada) by ICP-OES (Inductively Coupled Plasma-Optical Emission Spectrometry) for major elements; and ICP-MS (Inductively Coupled Plasma-Mass Spectrometry) for trace elements. Samples for the ICP-OES-MS method were mixed with a flux of lithium metaborate and lithium tetraborate and fused in an induction furnace. The melts were poured directly into a solution of 5 vol.% nitric acid containing an internal standard, and stirred continuously until completely dissolved. The sample solutions were run for major oxide and trace elements on a «Thermo Jarrell-Ash ENVIRO II ICP» and a «Perkin Elmer SCIEX ELAN 6000 ICP-MS» respectively. Errors were ≤ 1 wt.% for major oxides and ≤ 3 wt.% for trace elements.

Petrography and Geochemistry

On a macroscopic scale all the samples consist of leucite-phyric lavas with a grey to pale-grey colour. According to the modal mineralogy (QAPF diagram; Streckeisen, 1978) and to the classification of volcanic rocks on a chemical basis (Total Alkali-Silica diagram; Fig. 3) these rocks are leucite phonolites (LP) and leucite tephritic phonolites (LTP).

On thin section (22 studied samples) the most abundant lithotype (LP) is represented by a vesciculated porphyritic rock (PI=25-30 vol.%) with large (up to 15 mm in size) euhedral leucite phenocrysts and a microcrystalline, pilotassitic (trachytic) groundmass mainly consisting of sanidine and leucite microlites with subordinate plagioclase, clinopyroxene and opaque minerals (Fig. 4). Phenocrysts and microphenocrysts of green clinopyroxene, plagioclase and sanidine are also present. Optical zoning is shown by both clinopyroxene and plagioclase phenocrysts. Among the accessory phases rare apatite crystals were detected in the groundmass. All the samples from the millstones are constituted by this leucite phonolite lithotype (LP).

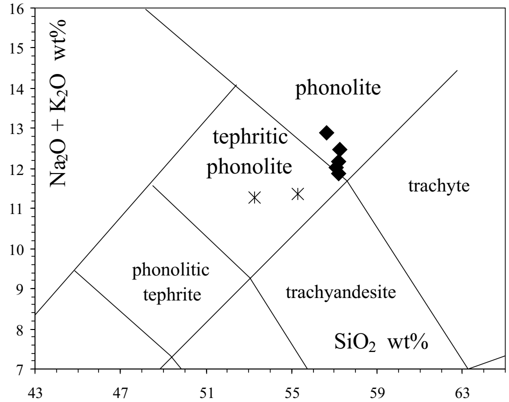

Fig. 3 – Total Alkali *vs* Silica (TAS) classification diagram (Le Bas *et al.*, 1986) for the volcanic rock artefacts of Ostia Antica. Symbols: full diamond = Pompeyan-style rotary millstones; asterisk = kneading-machines.

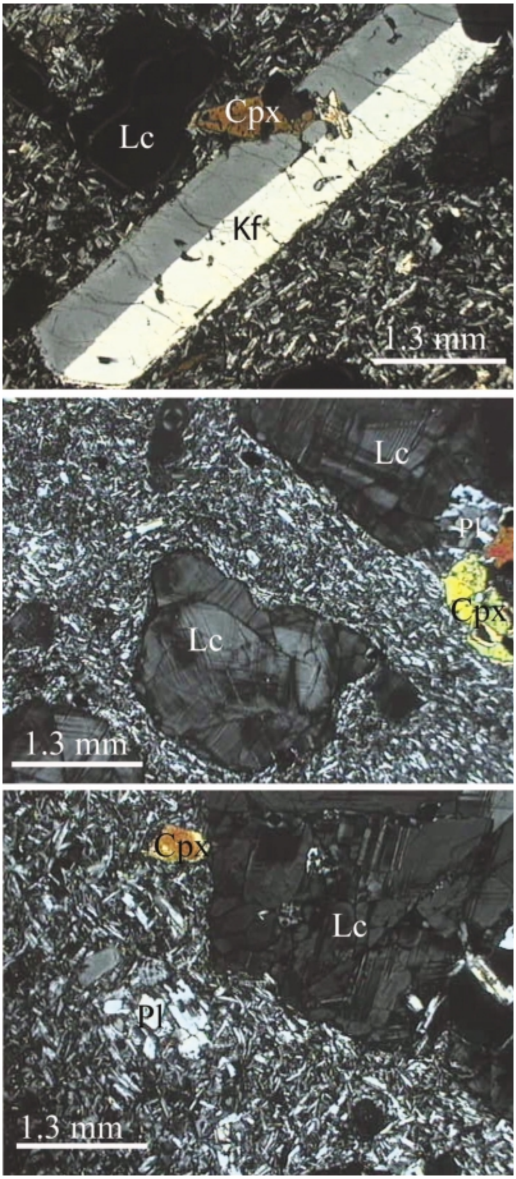

Fig. 4 – Thin section mineralogy and texture (crossed nicols) of Pompeian-style rotary millstones (leucite phonolite; LP rock-type). Abbreviation of minerals: Lc=leucite, Kf=K-feldspar, Pl=plagioclase, Cpx=clinopyroxene.

Kneading-machines for making the dough (all sampled in a different room from that housing the millstones) consist of two type of leucite tephritic phonolite (LTP). LTP1 rock-type is a slightly vesciculated lava, with finer grained leucite phenocrysts (up to 4 mm in size) and finer grained micro-cryptocrystalline feldspathic groundmass. In thin section, this rock-type shows a porphyritic index of about 20 vol.% with an intergranular groundmass (Fig. 5a,b). The phenocryst assemblage is represented by medium size leucite, green clinopyroxene and zoned plagioclase in decreasing order of abundance; sanidine and oxidized biotite microlites are also present in few amounts. The groundmass is mainly constituted by intergranular leucite, clinopyroxene and feldspar laths (sanidine = plagioclase). Opaque minerals and apatite are also present as accessory phases. The LTP2 rock-type is characterized by leucite phenocrysts up to 7 mm in size and a microcrystalline intergranular groundmass. This leucite tephritic phonolite has a porphyritic index of about 20 vol.% and shows a pseudo-doleritic microcrystalline groundmass (Fig. 5c,d). Among the phenocrysts, leucite and pale-green to colourless optically zoned clinopyroxene are prevailing whereas plagioclase is subordinate. The groundmass is constituted by sub-rounded leucite, clinopyroxene and opaque minerals within feldspar microlite laths (plagioclase > sanidine).

Whole rock geochemical analyses (major oxides and trace elements) of representative leucite phonolite samples were carried out (Tables 1 and 2; Fig. 3). LOI (loss on ignition) values are generally low, between 1.1 and 2.3%, supporting that the samples are relatively fresh; only OSM2 sample is more altered (LOI 3.1%). The leucite phonolites are *ne*-normative between 6.2 and 6.6% with the exception of sample OSM3 which shows higher *ne*- and *di*-normative contents (12.2 and 6.7% respectively). All the rotary millstones where manufactured with this LP lava. By contrast, the LTP samples, collected from kneading-machines for making the dough, consist of tephritic phonolites (Fig. 3). The LTP1 rock-type is *ne*-normative around 8%, whereas OSM9 sample (LTP2) is both *ne*- (13,2%) and

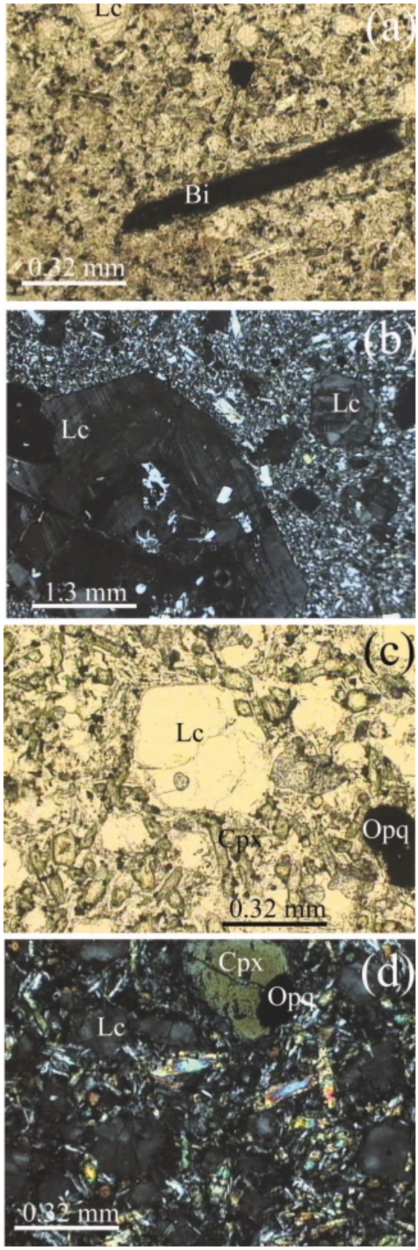

Fig. 5 – Thin section mineralogy and texture of kneading-machines: (a) and (b) leucite tephritic phonolite 1 (LTP1) rock-type; (c) and (d) leucite tephritic phonolite 2 (LTP2) rock-type. Abbreviation of minerals: Lc=leucite, Kf=K-feldspar, Pl=plagioclase, Cpx=clinopyroxene, Bi=biotite, Opq=opaques. (a) and (c) plane polarized light; (b) and (d) crossed nicols.

TABLE 1
Representative whole rock major oxides (wt%) and CIPW Norm calculations; LP = leucite phonolite, LTP = leucite tephritic phonolite. Average of 11 analyses of leucite phonolite lavas from Orvieto quarries (Antonelli et al., 2001) is reported as comparison.

	Pompeian-style millstones					Kneading-machines			Orvieto quarries (LP)	
Sample	LP OSM1	LP OSM2	LP OSM3	LP OSM4	LP OSM7	LTP1 OSM8	LTP1 OSM10	LTP2 OSM9	Av. of 11 analyses	σ
SiO_2	55.51	55.03	55.44	56.21	56.31	53.82	54.16	52.79	56.35	0.36
Al_2O_3	20.04	19.97	20.01	20.37	20.28	20.06	20.08	18.24	21.42	0.13
Fe_2O_3	4.19	4.08	4.13	3.92	4.18	5.13	5.26	5.55	4.37	0.15
MnO	0.14	0.15	0.15	0.15	0.16	0.15	0.15	0.15	0.13	0.01
MgO	0.77	0.82	0.82	0.82	0.81	1.10	1.15	2.85	0.81	0.03
CaO	3.81	3.66	3.84	3.66	3.84	4.93	5.03	7.39	3.57	0.09
Na_2O	3.42	2.83	3.89	2.69	3.07	2.89	2.97	2.84	2.79	0.42
K_2O	8.46	9.18	9.01	9.78	9.11	8.48	8.39	8.43	9.95	0.30
TiO_2	0.53	0.51	0.51	0.49	0.52	0.54	0.56	0.63	0.50	0.02
P_2O_5	0.13	0.13	0.11	0.13	0.13	0.22	0.20	0.24	0.10	0.01
LOI	2.34	3.05	1.32	1.93	1.75	2.15	1.89	1.14	-	-
Total	99.35	99.41	99.24	100.14	100.16	0.00	99.47	99.85	100.24	99.99
K_2O/Na_2O	2.47	3.24	2.32	3.64	2.97	2.93	2.82	2.97	3.57	
					C.I.P.W. Norm					
q	-	-	-	-	-	-	-	-	-	
or	51.7	56.5	54.5	59.0	54.9	51.7	50.8	46.4	59.0	
ab	17.7	13.4	11.2	11.4	14.9	10.5	11.0	-	9.2	
an	14.8	15.3	10.8	14.9	14.9	17.3	17.1	12.3	16.6	
ne	6.6	6.2	12.2	6.4	6.3	8.0	8.0	13.2	7.9	
lc	-	-	-	-	-	-	-	3.2	-	
di	3.2	2.3	6.7	2.3	3.0	5.5	6.0	19.0	0.4	
ol	2.6	3.1	1.4	2.9	2.8	3.5	3.4	2.0	3.8	
mt	2.0	1.9	1.9	1.8	1.9	2.0	2.1	2.2	2.0	
il	1.0	1.0	1.0	1.0	1.0	1.1	1.1	1.2	1.0	
ap	0.3	0.3	0.3	0.3	0.3	0.5	0.5	0.6	0.2	

lc-normative (3.2%) and shows a high *di*-normative value (19%).

According to modal mineralogy and K_2O/Na_2O ratios >2 all the investigated volcanic rock artefacts belong to the leucite-bearing high-K series of the Roman Volcanic Province (Appleton, 1972; Peccerillo and Manetti, 1985). In particular, in the trace-element spiderdiagram of Fig. 6 the samples show significant Ba, Nb, Ta, P, and Ti negative anomalies which are fingerprint of the subduction-related Quaternary potassic rocks of the north-west Roman Volcanic Province (Serri, 1990). High Sr contents (1900-2150 ppm; Table 2) among the investigated manufacts strongly confirm this hypothesis. The LP millstones are characterized by higher Th (161-194 ppm vs. 124-149) and Ba (2330-2670 ppm vs. 1740-2100 ppm) with respect the LTP samples (Table 2).

TABLE 2

Representative whole rock trace elements (ppm); LP = leucite phonolite, LTP = leucite tephritic phonolite. Average of 11 analyses of leucite phonolite lavas from Orvieto quarries (Antonelli et al., 2001) is reported as comparison.

	Pompeian-style millstones					Kneading-machines			Orvieto quarries (LP)	
Sample	LP OSM1	LP OSM2	LP OSM3	LP OSM4	LP OSM7	LTP1 OSM8	LTP1 OSM10	LTP2 OSM9	Av. of 11 analyses	σ
V	131	130	129	121	129	168	177	177	-	-
Cr	< 20	< 20	< 20	< 20	< 20	< 20	41	92	2.67	0.98
Co	6	6	6	6	6	10	10	15	5.56	0.25
Ni	< 20	< 20	< 20	< 20	< 20	< 20	30	30	4.00	0.87
Rb	298	395	292	350	294	354	368	362	352	40
Sr	2130	1900	2140	2020	2150	1910	1980	2140	1947	61
Y	47.5	42.4	43.8	40.1	45.1	38.7	40.6	44.7	39.1	1.6
Zr	677	610	626	584	657	528	478	512	730	69
Nb	49.5	46.6	47.9	45.8	51.4	41.6	42.0	43.3	45.0	1.9
Ba	2430	2330	2670	2540	2520	1880	2100	1740	2232	44
La	173	182	189	176	169	160	163	156	183	7
Ce	345	312	317	304	336	276	286	274	325	12
Pr	37.3	34.0	34.6	32.2	36.3	30.6	31.6	31.2	-	-
Nd	124	112	114	106	116	106	109	108	107	4
Sm	18.4	16.7	16.9	15.7	17.5	16.5	16.7	17.7	16.1	0.5
Eu	3.67	3.33	3.52	3.26	3.54	3.29	3.36	3.53	3.44	0.10
Gd	12.3	11.2	11.7	10.8	11.9	11.5	11.7	12.8	11.3	0.6
Tb	1.56	1.43	1.45	1.37	1.50	1.38	1.43	1.58	-	-
Dy	8.01	7.28	7.35	6.89	7.62	6.92	7.09	7.83	7.18	0.32
Ho	1.47	1.34	1.35	1.26	1.38	1.27	1.29	1.38	-	-
Er	4.22	3.74	3.77	3.55	3.93	3.52	3.58	3.77	3.42	0.13
Tm	0.62	0.55	0.57	0.51	0.57	0.49	0.51	0.54	-	-
Yb	4.00	3.66	3.60	3.32	3.74	3.16	3.30	3.40	3.35	0.12
Lu	0.60	0.53	0.54	0.50	0.55	0.47	0.48	0.49	0.51	0.02
Hf	12.3	10.9	11.2	10.4	11.7	9.6	9.8	10.2	10.8	0.4
Ta	2.79	2.44	2.53	2.35	2.62	2.04	2.09	2.10	-	-
Pb	183	157	200	217	192	102	170	104	-	-
Th	194	170	173	161	180	147	149	124	160	9
U	38.4	36.6	34.6	35.3	39.4	31.8	30.9	27.1	-	-

DISCUSSION AND FINAL REMARKS

In the Roman period millstones were a very common item with a flourishing trade. This is supported by numerous findings of these stone artefacts in both the archaeological sites and the shipwrecked cargoes recovered in the Mediterranean Sea. The high performance of the rotary millstones manufactured with the Orvieto leucite phonolite was mainly due to workability, wear resistance and grinding capacity. It is worth to note that the rocks generally show a close relation between their mineralogy (and fabric) and Cerchar Abrasivity Index (CAI) which is «the abrasion of a metal pin after scratching over the freshly broken rock surface» (Suana and Peters, 1982). The good abrasive property of the leucite phonolite

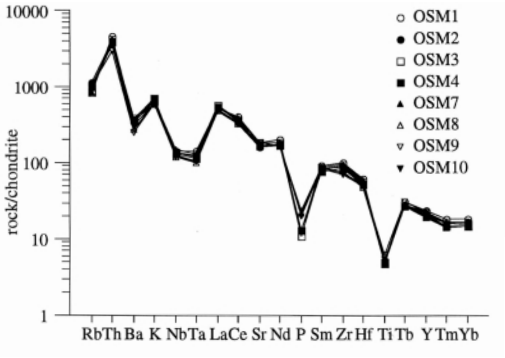

Fig. 6 – Incompatible trace-elements spiderdiagram, normalized to chondrites (Thompson *et al.,* 1984) for the volcanic rock artefacts of Ostia Antica (millstones and kneading-machines).

millstones can be attributed to the abundance of feldspars which are minerals slightly below the quartz (the most abrasive) in the CAI scale. Due to the small sizes of the available samples (archaeological findings) it was impossible to provide some physical properties by laboratory tests. Literature data on the abrasive wear strength (relative abrasion coefficient calculated with respect to the «San Fedelino» granite) is only provided for present-day exploited rocks (used as building material or decorative stones). We can extrapolate a good abrasive wear strength for the Orvieto leucite phonolite since a relative abrasion coefficient of 0.54 is reported by Giampaolo *et al.*, (2000) for a leucite-bearing trachyte (the so-called «basaltina») also outcropping in the Vulsini Volcanic District and having modal mineralogy and texture highly comparable with those of the millstones. We can infer that the Romans made an arrangement between good workability and abrasive wear strenght in choosing the lithotype to produce millstones. In addition, the high vesciculation of the leucite phonolite gave to the rotary mills the required grinding capacity through the time.

Source identification of the volcanic rocks used for millstones provides valuable information on the routes undertaken by these artefacts before reaching the destinations. In this framework, the «Orvieto quarries» (Fig. 1) were documented as some of the most important production centres of millstones both in the Etruscan (Santi *et al.*, 2000; Renzulli *et al.*, 2002) and the Roman period (Peacock, 1986; Oliva *et al.*, 1999; Antonelli *et al.*, 2000, 2001; Buffone *et al.*, 2003).

Peacock (1980) firstly pointed out the rock-type similarity between the rotary millstones of Pompeii and Ostia Antica. He stated that there was absolutely no evidence that the lava used for manufacturing Roman mills (called «leucitophyre» in his work) was quarried at Somma-Vesuvius (neighbourhood of Pompeii) where leucite-bearing rocks outcrop. Peacock (1980) suggested for the Pompeii and Ostia Antica millstones a possible source in central Italy (Etruria) where Washington (1896) in his pioneer petrographic work on the Bolsena region describe, with a straightforward thin section report, an outcrop of vescicular, leucite-phyric phonolite lava with trachytic groundmass, located about 3 km SW of Orvieto (i.e. between Sugano and Buonviaggio; Fig. 1). Pavolini (1983) in the archaeological guide of Ostia Antica, erroneously interpreted Peacock's work and, as the millstones source, reported the «Rupe di Orvieto» (Cliff of Orvieto made of an ignimbrite), instead of the lava quarries. Recently, through a detailed petrological study, Buffone *et al.,* (2003) emphasized that 60% of the rotary millstones found at Pompeii come from the leucite phonolite quarries and production centre of Orvieto whereas 40% are made of a leucite-bearing basaltic trachyandesite belonging to the oldest eruptions of Somma-Vesuvius. Rocks from Somma-Vesuvius (Joron *et al.*, 1987) are characterized by K_2O/Na_2O ratios <1.8 and absence of Ba and P negative anomalies (Serri, 1990) and thus they are not compatible as the sources for the LP millstones of Ostia Antica. These latter and samples from the Orvieto quarries, match very well concerning modal mineralogy, texture and whole rock major-trace elements geochemistry (Tables 1 and 2, Figs. 4 and 7). Sr, La and Th *vs* Ba diagrams (Fig. 8) are reported as geochemical parameters to identify the volcanic area of provenance of the leucite

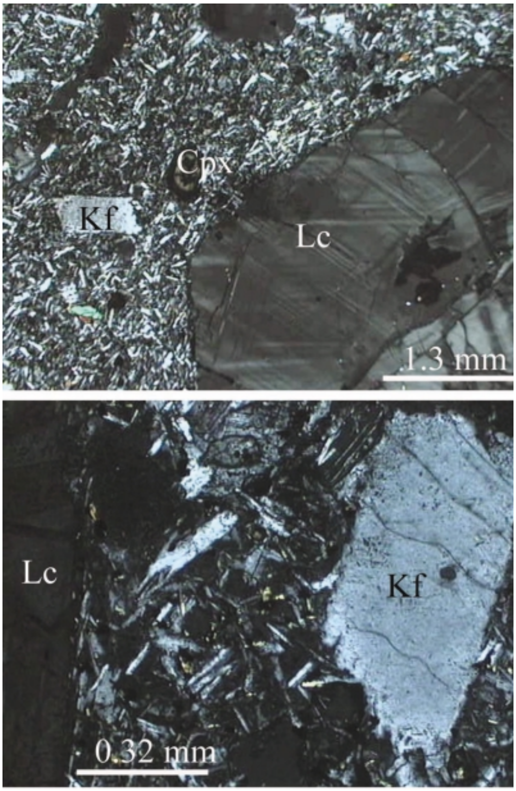

Fig. 7 – Thin section mineralogy and texture (crossed nicols) of leucite phonolite lavas from the Orvieto quarries. Abbreviation of minerals as in Fig. 5.

phonolite millstones. These plots support an Orvieto provenance for the LP millstones of Ostia Antica due to higher Sr, La, Th and Ba contents with respect to other leucite phonolites from the Roman Volcanic Province (*i.e.* Vico and Sabatini Volcanic Complexes; Fig. 8).

At the confluence of the Tiber and Paglia rivers, about 10 km ESE of the ancient leucite phonolite quarries (Fig. 1), the fluvial port of Pagliano (Morelli, 1957; Bruschetti, 2004), should have been an important crossroads of most of the commerce of central Italy in the Roman period. This port may have represented the main collecting point for the Orvieto millstone trade along the Tiber River (Antonelli *et al.,* 2001) which was the natural waterway to reach the Tyrrhenian Sea (Renzulli *et al.*,

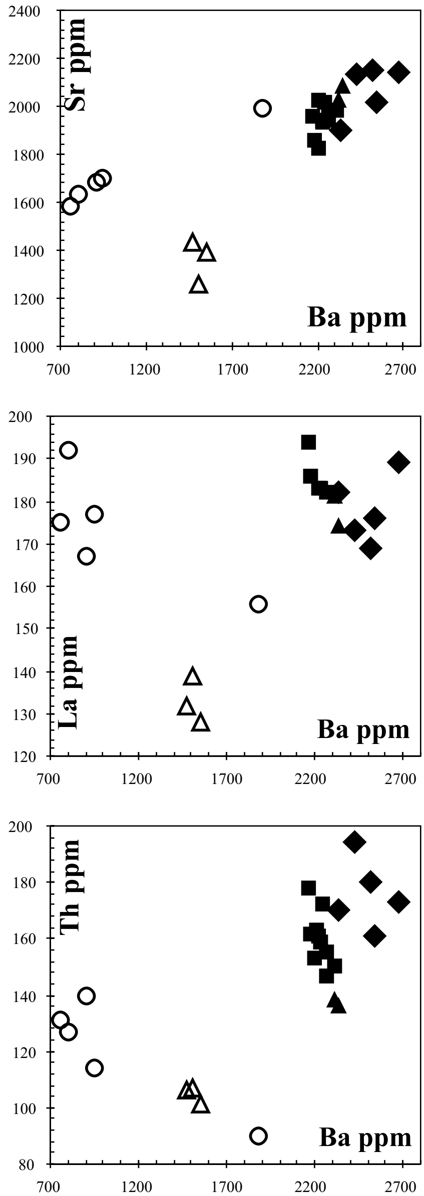

Fig. 8 – Trace elements variation diagrams for the Pompeian-style millstones of Ostia Antica (full diamond) compared with the leucite phonolites from Orvieto quarries, Vulsini District (full square = data from Antonelli *et al.*, 2001; full triangle = data from Oliva *et al.*, 1999), leucite phonolite lavas from Vico Volcano (open triangle = data from Antonelli *et al.*, 2001) and leucite phonolite lavas from Sabatini Volcanic Complex (open circle = data from Conticelli *et al.*, 1989, 1997).

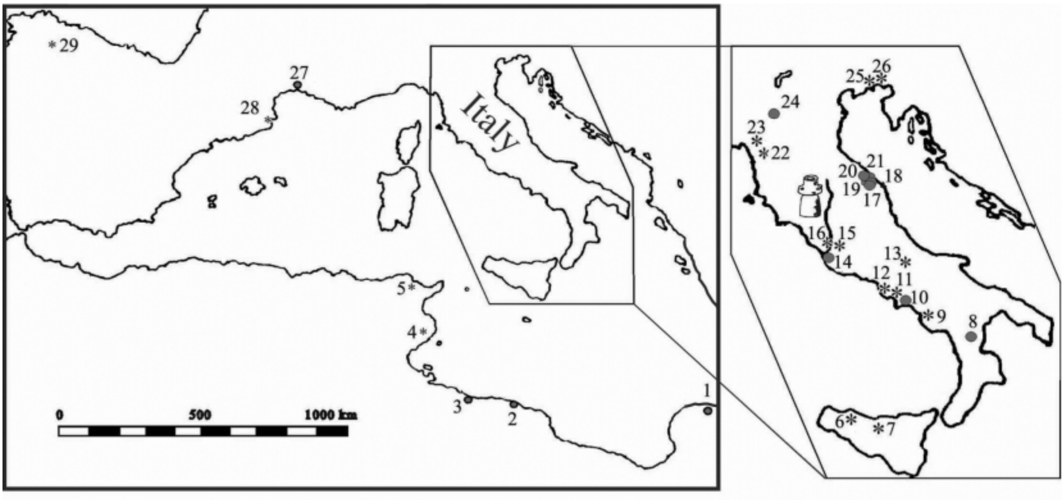

Fig. 9 – Geographic distribution of the leucite phonolite millstones from Orvieto, inferred through detailed petrological studies (full circles) or hand specimen/thin section petrography (asterisks). The Orvieto production centre (here located as a stylized rotary millstone) and the Tiber River (bold line in central Italy) are also reported.
1. Cyrene and 2. Leptis Magna (Libya; Antonelli *et al.*, unpublished data); 3. Sabratha (Libya; Antonelli *et al.*, unpublished data); 4. El Djem and 5. Carthage (Tunisie, Peacock, 1980); 6. Palermo (Williams-Thorpe, 1988); 7. Halaesa (Peacock, 1980); 8. Grumentum (Lorenzoni *et al.*, 2000); 9. Paestum (Peacock, 1980, 1989); 10. Pompeii (Peacock, 1989; Buffone *et al.*, 2003); 11. Herculaneum (Peacock, 1980, 1989); 12. Mondragone (Williams-Thorpe, 1988); 13. Biferno Valley (Williams-Thorpe and Peacock, 1995); 14. Ostia Antica (present study); 15. Anguillara (Peacock, 1986); 16. Veii (Peacock, 1980); 17. Suasa (Renzulli, unpublished data); 18. Fossombrone (Renzulli *et al.*, 2002); 19. S.Angelo in Vado (Antonelli *et al.*, 2001); 20. Colombarone (Renzulli, unpublished data); 21. Pesaro (Antonelli *et al.*, 2001); 22. Lucca (Peacock, 1989); 23. Luni (Peacock, 1980); 24. Cannetolo di Fontanellato (Renzulli, unpublished data); 25. Concordia (Donner, 1993); 26. Aquileia (Antonelli, unpublished data); 27. Les Martys (France; Oliva *et al.*, 1999); 28. Ampurias and 29. Astorga (Spain; Peacock, 1986, 1989).

2002). From the port of Ostia Antica, which was built at the estuary of the Tiber River, some of the Orvieto millstones could be easily shipped (as cargoes or often used as ballasts) by different routes throughout the Mediterranean, including far-away provinces of the Roman Empire such as Gallia, Iberia, Tunisia, Tripolitania and Cirenaica (Fig. 9).

The tephritic phonolite (LTP1 and LTP2) composition of the kneading-machines do not match that of the LP Orvieto rock-type. Although in the NE sector of the Vulsini Volcanic District mineralogy and chemistry of some leucite tephritic phonolites are compatible with those of the LTP used for the keading-machines, work is still in progress to determine the provenance of these much less common lithotypes.

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