Mediterranean trade of the most widespread Roman volcanic millstones from Italy and petrochemical markers of their raw materials

Fabrizio Antonelli*, Lorenzo Lazzarini

Laboratorio di Analisi dei Materiali Antichi (LAMA) – Dip. Storia dell’Architettura, Università IUAV di Venezia, San Polo 2468, 30125 Venice, Italy

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**ABSTRACT**

The petrochemical study of millstones can contribute to improve the archaeological research into reconstruction of ancient communication routes and trade networks. Volcanic rocks are geographically restricted and rather rare in the Mediterranean regions, and during the Roman period Italian volcanoes were important sources of raw materials for millstones, so the task of determining their geological origin is relatively straightforward. The Italian vesicular volcanics most frequently employed for this purpose were: trachytes from Euganean Hills (Veneto), leucite-bearing lavas from the Vulsini Volcanic District (Latium), basic-intermediate leucite-bearing lavas from Somma-Vesuvius (Campania), silica undersaturated lavas from Monte Vulture Volcano (Basilicata), a rhyolitic ignimbrite from Sardinia and basic products from Mount Etna and the island of Pantelleria (Sicily). This paper contains a general outline of the trade network for each volcanic typology used for millstones during the Roman period — updated with data concerning the leucite-bearing lavic items discovered in the archaeological sites of the ancient Cuicul (now Djemila, Algeria) — together with a summary of their petrographic and geochemical features.

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1. Introduction

It is generally acknowledged that archaeometric research on mills and millstones found in the Mediterranean area is an important means for the identification of the production sites of these artefacts and for the rediscovery of important trade networks of protohistory and history. During the Roman age, hourglass-shaped or flat, cylindrical rotary millstones were exported to and imported from many provinces of the Empire, including Germany, France, Italy, Spain, Portugal, Morocco, Tunisia, Libya, Algeria, Cyprus and Turkey (cf. Williams-Thorpe, 1988; Antonelli et al., 2001, 2005 and bibliography therein). Most of these Roman millstones discovered in archaeological sites throughout the Mediterranean are made of volcanic rock. In fact, lavas are generally wear-resistant and they are particularly suitable for milling because of their abrasive property (hard enough not to contaminate the flour unduly) and rough vesicular surface that provides a good grinding capacity. The mills most commonly used by the Romans were up to 1.5 metres high (Fig. 1) and typically consisted of an hourglass-shaped (double-cone) upper stone (catillus) resting on the conical lower stone (meta) (Moriz, 1958). The catillus was turned on the meta by means of a bar pushed by slaves or a donkey (mola asinaria or iumentaria; donkeymills). As proposed by Antonelli et al., 2001, re-interpreting Varro (the Latin scholar of the first century BC) rotary millstones (molae versatiles) were most probably invented (no later than the fourth century BC) in Volsinii veteres (present-day Orvieto), the famous Etruscan village, and not simply in Volsinii (or Volsinii novi, now Bolsena), the Roman city built in the first half of the third century BC close to Bolsena Lake, ca 8 km NE of Orvieto. Rotary millstones hourglass-shaped are also known as Pompeian-style millstones after the site where they occur so frequently and were first discovered (i.e. Pompeii–Naples; Peacock, 1989; Buffone et al., 2003). Other famous Italian archaeological sites where well-preserved examples have been discovered include Ostia Antica (Rome) and Aquileia (Udine). They were a very popular item, highly prized in Roman bakeries and military settlements of the Imperial provinces. Shipwrecked cargoes of millstones such as that of Sec (Mallorca, Spain; Williams-Thorpe and Thorpe, 1989, 1991; Lorenzoni et al., 1999; Antonelli, 1993; Oliva et al., 2000a,b; Oliva et al., 1999; Antonelli, 2003). The petrochemical study of millstones can contribute to improve the archaeological research into reconstruction of ancient communication routes and trade networks. Old and recent works (Peacock, 1980, 1986, 1989; Ferla et al., 1984; Williams-Thorpe, 1988; Williams-Thorpe and Thorpe, 1989, 1990, 1991, 1993; Lorenzoni et al., 1996, 2000a,b; Oliva et al., 1999; Antonelli, 2003).
et al., 2000, 2001, 2004, 2005; Renzulli et al., 2002a; Santi et al., 2004; Buffone et al., 2003) have combined to establish a useful petrographic, geochemical and historical database on the source areas for the grinding tools used in Mediterranean countries from the Neolithic to the Roman periods.

The purpose of this paper is to give a concise overview of the main Italian volcanic rocks exploited by the Romans in the manufacture of exported millstones as well as of their trade network. The general outline is updated with new data referring to leucite phonolite mills discovered at the archaeological site of ancient Cuicul (now Djemila, Algeria) (cf. Figs. 4e–6 and Table 1).

2. Quarrying areas and circulation of the artifacts

The Romans exploited several Italian lava sources (Fig. 2), generally vesicular and so relatively easy to work, to produce millstones and rotary querns; judging by the archaeological finds the most widespread were (from northern to southern Italy): (i) Na-trachytes from the Euganean Hills (Padua – Veneto); (ii) leucite phonolites from quarries in the Vulcini Volcanic District (near Orvieto – Latium); (iii) leucite basaltic trachyandesites of Somma-Vesuvius (Naples – Campania) and (iv) tephrites-foidites from Vulture (Potenza – Basilicata); (v) volcanic rocks from Sardinia, chiefly rhyolitic ignimbrite from Mulargia and, to a very minor extent, the grey vesicular subalkaline basalts from different parts of the island (not considered here); (vi) hawaiites, mugearites and basalts from Etna (Catania – Sicily) as well as, to a minor extent, some other Sicilian basic lavas from Hyblean Plateau and the islands of Pantelleria, Ustica and Lipari. However, according to the archaeological and archaeometric evidence, volcanics (iii), (v) and (vi) were generally preferred by Romans for export on a medium-large scale, (i) and (ii) were exported on a medium-to-small scale, whereas the lavas from Vulture (iv) were seldom transported far from the production centres and basically employed locally and on a small scale.

2.1. Trachytic rocks from the Euganean Hills – Venetian Volcanic Province

The Euganean Hills, located in North-Eastern Italy (province of Padua) within the Venetian Tertiary Volcanic Province, comprise 81 domes whose origin is related to the extensional tectonic regime of the South-Alpine foreland (De Pieri et al., 1983) and the extensive eruptive activity that took place from the late Paleocene to the late

<table>
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<th>Sample</th>
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<th>D3</th>
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| ppm     |    |    |    |       |     |
| V       | 143 | 120 | 114 | 125  | 19.45 |
| Cr      | <10 | <10 | <10 | 2.67  | 1.0  |
| Co      | 6.50 | 5.70 | 5.80 | 5.56  | 0.3  |
| Ni      | <5  | <5  | <5  | 4.00  | 0.9  |
| Rb      | 278 | 282 | 396 | 352  | 40.0 |
| Sr      | 2100 | 2170 | 1865 | 1947  | 61.0 |
| Y       | 39  | 35  | 30  | 39    | 1.6  |
| Zr      | 811 | 649 | 558 | 730   | 69.0 |
| Nb      | 54.1 | 48.0 | 36.6 | 45.0  | 1.9  |
| Ba      | 2300 | 2430 | 2120 | 2232  | 44.0 |
| La      | 204 | 183 | 144 | 183   | 7.0  |
| Ce      | 394 | 316 | 255 | 325   | 12.0 |
| Nd      | 121 | 108 | 87  | 107   | 4.0  |
| Sm      | 18.05 | 16.05 | 13.10 | 16.10 | 0.50 |
| Gd      | 17.00 | 15.00 | 12.15 | 11.30 | 0.60 |
| Dy      | 8.17 | 7.20 | 6.04 | 7.18  | 0.32 |
| Er      | 4.61 | 4.22 | 3.38 | 3.42  | 0.13 |
| Yb      | 4.05 | 3.64 | 2.96 | 3.35  | 0.12 |
| Lu      | 0.57 | 0.52 | 0.42 | 0.51  | 0.02 |
| Hf      | 13.10 | 11.60 | 9.50 | 10.80 | 0.40 |
| Th      | 144 | 126.5 | 95.6 | 180  | 9.0  |
Fig. 2. Geographic location of the main Italian volcanic rock source areas exploited by the Romans to manufacture millstones. 1. Euganean Hills: general map after Capedri et al., 2000. Letters and numbers in bold are related to the sites chemically analyzed by Capedri et al., 2000. 2. Roman Magmatic Province: draft of the outcrops and exploited sources of volcanic products (after Buffone et al., 2000, modified). 3. Sardinia: sketch map of showing the distribution of Oligocene–Miocene (diagonal lines) and Pliocene–Pleistocene (stippled areas) volcanic rocks (after Williams-Thorpe and Thorpe, 1989; modified). 4. Mt. Etna Volcano: sketch map showing the distribution of the main units (after Cristofolini et al., 1991, modified): (1) Sedimentary basal levels; (2) Tholeiites; (3) Ancient Na-alkalic deposits (basalts and hawaiites dating back to 225 ky before present); (4) Trifolieto Unit (mugearites); (5) Detrital alluvial fan originated from the Valle del Bove; (6) Elliptical volcano deposits (Mongibello Unit: hawaiites to trachytes); (7) Recent Mongibello (hawaiites and mugearites); (8) Edge of the Valle del Bove; (9) Major faults.
Oligocene. Volcanic and sub-volcanic products range from subordinated basalts to intermediate and acidic lithotypes, mostly trachytes and rhyolites with a moderate Na-alkaline magmatic affinity. The latter crop out in the central part and at the edge of the area respectively and testify to the change in magmatic activity in the Lower Oligocene (Zantedeschi, 1994). Euganean Trachytes have been among the most widely distributed stones of NE Italy since ancient times. They were already used by the Paleo-Venetian populations in the seventh century BC for stelae (preserved in the Archaeological Museums of Este and Padua) and mills (Antonelli et al., 2004). The Romans occupying the Po Valley from the second century BC used it much more abundantly for the same purposes and for architectural elements (columns, capitals, lintels, pillars, etc.), water pipes, bridges and to pave Venetian, Istrian and Emilian roads (several sections of the Via Aemilia were paved with polygonal trachytic blocks; Renzulli et al., 1999, 2002b). In Roman times the stone also reached distant towns such as Ticinum (Pavia) (Tozzi and Oxilia, 1981), Mediolanum (Milan), Tergeste (Trieste), Fano Fortunae (Fano; Renzulli et al., 1999) and Ankon (Ancora; Renzulli et al., 1999); these towns form a triangle within which trachyte is very often found. In the same period, Euganean trachytic millstones and rotary-millstones were manufactured and spread through in the Regio Augusta, Venetia et Histria (Antonelli et al., 2004; Antonelli and Lazzarini work in progress) also reaching some localities of ancient Aemilia and Picenum (Marche) regions (i.e., Fossomborone and Urbisaglia – Renzulli et al., 2002a; Santi and Renzulli, 2006). Among the 70 open-pit trachyte quarries identified in the field by Capedri et al. (2000), the sites where exploiting activity was particularly important were Monselice, Monte Rosso, Monte Oliveto, Monte Merlo, Monte Liscida, Monte Alto and Monte Altore (Fig. 2). The trade towards the south was quite easy to carry out (especially from the Monselice area) along the Mid-Adriatic coast and also throughout a system of drainage channels joining the hills to the paleo-Adige and the Brenta Rivers (Renzulli et al., 1999, 2002b), while the connections between Euganean sources and the regions to the east could be effected by using the fluvial and maritime routes that had operated in this part of Caput Adriae since protohistoric times.

2.2. Leucite phonolite from Orvieto – Vulsini Volcanic District

In the Mediterranean area, the use of leucite-bearing lavas was particularly widespread. Millstones and rotary querns produced from these lavas have been discovered in Italian archaeological sites (e.g., Aquileia – unpublished data – Luni, Veio, Ostia, Ercoleano, Pompeii, Paestum and in Sicily; Antonelli et al., 2001; Santi et al., 2004 and bibliography therein) as well as in other Mediterranean regions such as Iberia, France, Cyprus, Tunisia, Tripolitania, Cyrenaica (Peacock, 1980, 1986; Williams-Thorpe, 1988; Oliva et al., 1999; Antonelli et al., 2001, 2005) and Algeria (Djemila, ancient Cuicul; new data included in this work). On the basis of fieldworks and archaeological studies Peacock (1980, 1986) concluded that the main quarry and production centre of leucite-bearing Roman millstones was located close to Orvieto (between Sugano and Buonviaggio; Fig. 2) in the Vulsini Volcanic District (0.6–0.125 Ma; Nappi et al., 1998; Peccerillo, 2005). The first detailed petrographic and geochemical database on this quarry with a clear archaeanographic goal was created by Antonelli et al. (2000, 2001). The data confirmed Peacock’s suggestion and revealed the local use of this rock for some oval saddle-querns already in the ninth century BC. Later on, several petro-archaeometric works (Renzulli et al., 2002a; Buffone et al., 2003; Santi et al., 2004; Antonelli et al., 2005) showed unequivocally that the leucite phonolite quarried near Orvieto is the most widely used lava for manufacturing millstones in the Roman period. It was also inferred (Antonelli et al., 2001) that at ca 10 km ESE of the Orvieto quarries, at the confluence of the Tiber and Paglia Rivers, the fluvial port of Pagliano was the main collecting point for the millstone trade (they were probably shipped as ballast with wheat loads) along the River Tiber. This latter was a natural fluvial waterway which enabled the Orvieto artefacts to be transported down to the Tyrrhenian Sea (Pavolini, 1986; Antonelli et al., 2001; Renzulli et al., 2002a). Similarly, the port of Ostia Antica, located at the estuary of the River Tiber, probably represented the starting point of the leucite phonolite millstones for their journeys along the different Mediterranean routes.1 The strategic position of the quarries and the high grinding performance of these rotary millstones (due to the high vesiculation and intrinsic abrasive capacity of the mineralogical assemblage of the rock as well as to its durability) only partially explains why they were so frequently exported to faraway provinces of the Roman Empire, also to places where fairly similar lavas outcrop and were used to produce the same items most likely cheaply because of lower transportation costs (i.e. Pompeii). Probably, apart from commercial reasons, this important trade involving the pistrina of all the western Mediterranean (Fig. 3a) depended on historical and symbolic aspects related to the renown of the place where this kind of millstone was invented.

2.3. Leucite basaltic trachyandesites from Castello di Cisterna quarry – Somma-Vesuvius Complex

The leucite-bearing lavas from the Somma-Vesuvius, specifically those outcropping and exploited close to Castello di Cisterna (Naples; Fig. 2), were indicated as the probable rock used for the hourglass millstones of ancient Pompeii from the end of the nineteenth century (Tenore, 1883). One century later, Peacock (1980, 1989), basing his opinions both on hand specimens and typological comparison with volcanic millstones from Orvieto found at Ostia, was the first to suggest that only a part of those discovered at Pompeii were made from the Vesuvius raw materials. More recently, Buffone et al. (2000, 2003), in the first detailed archaeometric studies of this topic, stated that more than 60% of the Pompeian hourglass millstones were produced at Orvieto (infra) while fewer than 40% are made of local leucite basaltic trachyandesites belonging to the oldest eruptions of Somma-Vesuvius (30 ka ago; Peccerillo, 2005; these products are almost wholly covered by the younger volcanic formations) and cropping out at Castello di Cisterna (near the Circumvesuvius railway station) and outside the walls of Pompeii, east of the Amphitheatre. They also pointed out that these volcanic rocks correspond to the so-called ottaviani of Johansen (1937), a name nowadays no longer used. Working from the suggestion of Sebesta (1974) on the presence at Aquileia of Somma-Vesuvius rock millstones, Buffone et al. (2003), on the basis of a morphological examination of the mills conducted simply on the pictures annexed to the Sebesta paper, stated both that Vesuvius must have been an export area for millstones and that there must have been a trade route for these items from Naples to Aquileia (UD – Friuli). We are currently carrying out a detailed petrographic and geochemical study on the Aquileia millstones. However, there is so far no significant archaeological-archaeometric evidence to support this conclusion or to suppose the existence of trade on a large or medium scale. In fact, hourglass millstones from this region have been found only in Campania and at Grumentum (Basilicata; Lorenzoni et al., 2000a,b).

1 We underline that all the rotary-millstones present in the big bakery of Ostia Antica come from Orvieto (Santi et al., 2004).
2.4. Tephrites-foidites from Vulture (Potenza – Basilicata)

The Mount Vulture is an extinct volcano, mid-Pleistocene in age (De Fino et al., 1986), rising on the southern Appennine Chain (northern Basilicata; Fig. 2) and representing the easternmost magmatic event occurring during the Quaternary in central-southern Italy. It was an active millstone producing area from the Bronze Age to Roman times and beyond, but use and export of these items were just regional (Lorenzenzi et al., 1996, 2000a,b). Roman millstones made of tephrite-foiditic lavas from Vulture have been detected in a few Roman sites of the southern Italian mainland, e.g., Basilicata, Molise and Apulia regions (i.e., Egnatia, S. Giovanni di Ruoti, Biferno Valley, Cannae, Altamura Gravina di Puglia; Volterra and Hancock, 1994; Lorenzenzi et al., 2000a,b; Williams-Thorpe, 1988; Volterra, 1997). They are only of the Olynthian hopper-rubber type and, following Lorenzenzi et al. (1996), were manufactured in several (unknown) localities scattered on the outcropping area of the small flows of the vesicular lavas, particularly on the north-eastern and south-eastern slopes of the volcano. The same authors found excavation signs on tephrite blocks between the villages of Melfi and Rapolla.

2.5. Rhyolitic ignimbrite from Mulargia (Sardinia)

Sardinia was an important millstone production centre and a source of millstone trade during the period of Roman settlement. Studies of Roman millstones on the island showed that the Pompeian type is the most common, whereas cylindrical hand querns occur more rarely (Peacock, 1980; Williams-Thorpe and Thorpe, 1989). The great majority of these items are made of a distinctive reddish rhyolitic ignimbrite and, to a very minor extent, of grey vesicular lavas of basic-intermediate composition. Following Williams-Thorpe and Thorpe (1989), there are several areas on the island where archaeological, historical and local tradition indicate a possible millstone production in the past. In particular, the rhyolitic millstones are from a single source of Olignocene-Miocene ignimbrite cropping out at Mulargia (called Molaria in Roman times; Meloni, 1975), a village near Macomer (west-central Sardinia; Fig. 2), while the millstones made of intermediate-basic lavas have varied sources within Tertiary and, above all, Pliocene–Pleistocene volcanics, i.e.: Monte Arci (west Sardinia), ca 30 km south of Oristano; Monte Teccu, in the south-eastern sectors of the island; Montiferro and Punte Luzzanas (west-central Sardinia), southwest of Macomer; Orroli and Nurri (southern Sardinia), ca 50 km north of Cagliari and some others. However, on the basis of the archaeometric studies (Peacock, 1980; Williams-Thorpe, 1988; Williams-Thorpe and Thorpe, 1989) we can conclude that, starting from the 1st century AD, only the Mulargia millstone production area is clearly proven as a major source and shows clear evidence of significant Roman trade, whereas millstones from all the other Sardinian localities (e.g., the subalkaline basalts from Monte Arci) were merely exploited locally or regionally during the Roman period. Mulargia millstones, almost exclusively hourglass-shaped, were widely exported in the western Mediterranean (particularly towards North-Africa) from Morocco (Volubilis – unpublished data – and Tetouan; Williams-Thorpe, 1988; Williams-Thorpe and Thorpe, 1989) to Sicily (Segesta, Solunto, Selinunte and Megara Iblea) passing through Spain (Ampurias and Mallorca), Algeria (Djemia – unpublished data), and Tunisia (Utica, Carthage, Musti, Sousse and Gightis; Williams-Thorpe and Thorpe, 1989). Peacock (1980) first supposed a trade in millstones between Sardinia and North Africa from the Roman to Byzantine periods remembering also that the island was under the control of Carthage during the Vandal period. This trade (partially and indirectly confirmed also by the presence of columns made of Sardinian pink granite in many of the above-mentioned sites) generally shows a steep fall in the frequency of occurrences as the distance from Sardinia increases (Williams-Thorpe and Thorpe, 1989); since this assumption does not appear to apply to Carthage, where a significant number of Pompeian millstones made of Sardinian red-brown ignimbrite were found, Williams-Thorpe (1988) suggested that the town had a role as importer.
and secondary distributor of Mulargia millstones in north Africa. The fact that Mulargia millstones (like those from Orvieto) were exported to parts of the Mediterranean where local lavas were present and used is an indication of their good reputation (Fig. 3b).

2.6. Hawaiitites and mugearites from Mongibello – Etna (and basalts from Pantelleria)

As recognized by Williams-Thorpe (1988), Etnean hawaiitites, mugearites and, to very minor extent, basalts were widely employed in the production of millstones in antiquity (locally begun in the Bronze Age; Ferla et al., 1984). We can assume — as also revealed by the finds of grinding tools dating back to the sixth century BC both in the Apulia region (Lorenzoni et al., 2000a,b) and Istria and Italian-Slovenian Karst (Antonelli et al., 2004) — that their trade was already well organized during protohistory. Old and recent studies (Williams-Thorpe, 1988; Volterra and Hancock, 1994; Lorenzoni et al., 1996; Buffone et al., 2000, 2003; Renzulli et al., 2002a; Antonelli et al., 2005) documented the presence of Roman millstones made of these rocks not only within Sicily but also in central southern Italy (Marche, Apulia and Campania regions), Spain (Ampurias), Tunisia (i.e., Carthage, Thuburbo Muta, Utica, El Maklouba, Thapsus), Tripolitanian and Cyrenaica (Cyba). Williams-Thorpe (1988) noted the presence in North Africa (Tunisia) of artefacts both from Mt. Etna and the Sicilian Na alkaline volcanic islands traditionally considered as the historical sources of basaltic s.l. millstones (i.e., Pantelleria and, to a very minor extent, Ustica) but unfortunately the paper does not present the complete chemical data for all of the numerous millstones considered. Antonelli et al. (2005) clearly identified Roman millstones manufactured with Pantellerian basalt and Etnean mugearite in the provinces of Tripolitania (at Leptis Magna) and Cyrenaica (at Cyrene) which are among the southernmost production areas of grain in the Roman Empire. Sicily and the adjacent small islands provided both obvious stop-over sites and important millstone sources on the traditional north-south axis of the wheat trade (as mentioned by Strabo, VI.2.3: Etna). All the above-mentioned research papers indicate the Mongibello stratovolcano lava flows as the source of the Etnean raw material exploited by Romans (Fig. 2). More specifically, it was ascertained that the most widely worked rocks were mugearites and hawaiites belonging to the Mongibello Recente activity (Cristofolini et al., 1991), dating from 14 ka to the present (Peccherio, 2005). Williams-Thorpe (1988) first and Renzulli et al. (2002a) later suggested that the Fratelli Piti quarry (on the outskirts of Catania and dating from 693 BC) was another of the Roman sites regularly exploited to work hawaiitic millstones. Following Buffone et al. (2003), who detected four Etnean rotary-millstones at Pompeii, an additional possible Roman site for the production of mugearitic millstones may be found within the outcropping area of the Pizzi Deneri formation (Older Mongibello; Coltelli et al., 1994).

3. Useful petrographic and geochemical markers for archaeometric purposes

Petrographic and geochemical features here summarised have been generally taken from the recent literature considering at least six samples (more often ten or tens) for each kind of lava. To avoid analytical bias, most of chemical data considered refer to the XRF analytical method for major and trace elements. In the case of the leucite-bearing lavas from the Orvieto region we used the current database which was produced by ICP-OES-MS methods (Antonelli et al., 2001). Anyway, a comparison between these data and those produced through XRF on few samples of the same rock-type (Buffone et al., 2000) proved a satisfactory analytical compatibility for the most discriminant elements.

3.1. Euganean trachytes from the Venetian Volcanic Province — They are mildly vesicular and of a colour that varies through the different shades of grey

According to the usual TAS classification diagram (Fig. 5a) these rocks are principally transitional trachytes, seldom rhyolites or trachyanidesites. Capedri et al. (2000) outlined mineralogical-petrographic, and chemical parameters characterising the trachytes of the most important historical quarries of the district. From a compositional and textural point of view Euganean trachytes are always porphyritic lavas (PI mainly from 20 vol.% to 40 vol.%), frequently not seriate and with glomerophyre aggregates. Anorthoclase (+Na-sanidine) > plagioclase > biotite + Mg-kaersutitic amphibole ± clinopyroxene are the main phases in phenocrysts (Fig. 4d); titanomagnetite, apatite and zircon are ubiquitous accessory minerals, whereas titanite only crystallises in a few trachytes (Monselice, Monte Merlo, Monte Trevisan). Phenocrysts of allotriomorphic to euhedral anorthoclase, with crystals varying from 2 to 10 mm in size, frequently show evidence of internal melting (spongy texture) and very thin rims of new anorthoclase overgrowths. Euhedral to subhedral plagioclase phenocrysts are often zoned and may also be rimmed by anorthoclase or Na-sanidine. Biotite and, when it occurs (Monselice, Monte Merlo and not many others), amphibole are frequently oxidised and embayed-re-absorbed. Fabrics are characterised by a holo-microcrystalline groundmass containing feldspar microlites (mainly of anorthoclase) which sometimes show sub-parallel orientation due to magmatic flow (pilotaxitic/trachytic textures; e.g. lavas from the Monselice and Monte Oliveto areas) as well as no fluidal orientation (feltty texture; e.g. trachytes from Monte Cero, Monte Altore, Monte Rosso, Monte Merlo, Monte Lispida and many other areas; Capedri et al., 2000); small amounts of interstitial quartz and, occasionally, minute interstitial brownish glass may also be present in the groundmass. It is very common to see grey-black inclusions with porphyric/granitoid/very weakly schistous fabric normally referring to trachyandesitic, gabbroic and cornubianitic composition, respectively (Lazzarini et al., 2008 and reference therein), that contain a larger amount of biotite, amphibole, pyroxene and magnetite than ordinary trachyte, and sometimes small amounts of calcite; more rare are white-grey xenoliths of alkaline-rhyolites or granitoid rocks.

With regard to the chemical composition, general common features are K2O/Na2O ratio around 1, the absence of Nb-Ta negative anomalies and the presence of Q and Hy in the CIPW norm (Milani et al., 1999). As described by Capedri et al. (2000), trachytes of individual quarrying areas are chemically quite homogeneous, but there is a rather wide chemical variability among the different sites, which allows a good differentiation within the main Roman sources. The authors consider TiO2, Zr, Nb, Y, V, Rb, Sr and Pb particularly useful for discriminating and propose some valuable binary plots able to reduce all the main quarried trachytes to five fields (Th vs Sr; Fig. 8a) and to separate the stone varieties belonging to the fourth and fifth field groups (i.e., TiO2, Rb and Zr vs K2O; Y vs Nb and V; TiO2 vs Th and Zr; Fig. 8b).

3.2. Leucite phonolite from Orvieto

From a petrographic point of view these rocks can be described as grey to light-grey vesicular (vesicles around 10–15 vol.%) leucite-bearing lavas, characterised by large euhedral leucite phenocrysts (mainly 8–18 mm in size) which show complex zoning and frequent inclusions of pyroxene + plagioclase ± opaque minerals. Among the most common micro- and phenocrysts (Porphyritic Index 25–30 vol.%) are also green clinopyroxene (Fig. 4a), sanidine, plagioclase (as strongly zoned single crystals, or as aggregates), at
times rimmed by sanidine, and Fe–Ti oxides. The microcrystalline
pilotassitic to intergranular groundmass consists of sanidine,
leucite and plagioclase microlites with subordinate clinopyroxene
and ore minerals (Fig. 4a). As regards geochemistry, these lavas are
evolved members, strongly undersaturated in silica, belonging to
the Roman-type high potassium series (HKS; Peccerillo, 2005;
average K₂O/Na₂O > 2.5) of the Roman Magmatic Province
(Appleton, 1972). According to the modal mineralogy and Total
Alkali-Silica classification diagram (TAS; Le Maitre et al., 1989),
they are essentially phonolites (Fig. 5a). More specifically, they show
appreciable enrichment in light rare earths (LREE), La, Sr, Th and,
Ba, together with Nb and Ti negative anomalies, which are all
typical features of the subduction-related Quaternary potassic
rocks from the north-west sector of the Roman Volcanic Province
(Serri, 1990). As verified first by Antonelli et al. (2000, 2001), in
the case of the rocks from the Orvieto quarries, their highest abundance
of La (172–228 ppm), Sr (1823–2167 ppm), Th (136–178 ppm) and
Ba (1957–2340 ppm) are very useful chemical fingerprints for
differentiating these leucite phonolites from the other similar rocks
outcropping within the Roman Volcanic Province. La, Th, Sr versus
Ba binary diagrams proved to be the most efficient for this purpose
(Antonelli et al., 2000, 2001; Renzulli et al., 2002a; Santi et al.,
2004; Fig. 6a). The possible overlapping of the Vulture and
Orvieto fields in the diagram Ba vs Sr can be easily resolved through
the petrography (discriminant presence of haüyne in the lavas from
Vulture; infra).

Similar petrographic (Fig. 4b) and geochemical (Figs. 5 and 6a)
features have been found for two catillus (Fig. 6a). The possible overlapping of the Vulture and Orvieto fields in the diagram Ba vs Sr can be easily resolved through the petrography (discriminant presence of haüyne in the lavas from Vulture; infra).

3.3. Somma-Vesuvius leucite basaltic trachyandesites from Castello
di Cisterna

They are highly porphyritic lavas (PI ca 50–65vol.%) with porphyritic
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idiomorphic leucite ($Q_{max}$ 4–5 mm), labradoritic-biotonitic plagioclase ($Q_{max}$ 2 mm) and olivine ($Q_{max}$ 1.5 mm) are the most abundant phenocrysts respectively (Fig. 4e); occasionally rare sanidine may also be present. Pyroxene, leucite and plagioclase may each form polycrystalline aggregates. The microcrystalline groundmass consists (in decreasing order of abundance) of feldspar, pyroxene, leucite, Fe–Ti oxides, phlogopite and apatite.

In the TAS diagram (Le Maitre et al., 1989; Fig. 5a) they fall essentially in the basaltic trachyandesites field, seldom in that of the phonolitic tephrites. These rocks, as always for the potassic series (KS; Peccerillo, 2005) of the Roman Magmatic Province, are characterised by $K_2O/Na_2O$ ratios varying from 1.5 to 2.5 (often < 1.8; Joron et al., 1987), absence of Ba and P negative anomalies (Serri, 1990), La 43–48 ppm, Sr 673–696 ppm and Ba 1449–1502 ppm (Buffone et al., 2000, 2003). Their mineralogical and chemical compositions suggest to classify them as shoshonites and allow these leucite-bearing lavas to be readily differentiated from the others outcropping within the Roman Volcanic Province (Fig. 6a).

### 3.4. Tephrites-foidites from Vulture (Potenza, Basilicata)

Unlike the volcanic complexes aligned from Vulcini to Vesuvius along the Tyrrhenian margin of Italy, Mount Vulture is located near the easternmost border of the Appennine compressive front. This peculiar structural setting is accompanied by a unique composition of magmas and derived alkaline rocks, which are characterised by both K and Na enrichment (Beccaluva et al., 2002) as well as by common presence of haüyne in all the volcanic products (De Fino et al., 1986; Beccaluva et al., 2002; Peccerillo, 2005).

Tephrite-foidite vesicular lavas (vesicles ca 35 vol%) used for millstones show evident porphyritic texture (Pl ca 30–35 vol%) and are composed of phenocrysts mainly of green pyroxene and haüyne >> leucite and nepheline ± biotite and apatite (Fig. 4f). They are embedded in a very fine-grained groundmass in which opaque minerals, plagioclase, pyroxene, feldspathoids and occasionally K-feldspar may be recognizable. Pyroxene phenocrysts, generally abundant and zoned, have fairly irregular form and inclusions of haüyne, opaques and nepheline. Those of haüyne are common or abundant and usually appear smaller and more rounded than pyroxene. Their colour is typically blue at the rim. Finally nepheline, leucite and biotite (which may be altered) phenocrysts are commonly small in size. Using the TAS diagram (Fig. 5a) these lavas fall in the tephrite, tephrphonolite and foidite fields in agreement with the petrographic classification (De Fino et al., 1986; Caggianelli et al., 1990; Beccaluva et al., 2002; De Astis et al., 2006). Geochemistry reveals that they belong to the potassic alkaline series (De Fino et al., 1982, 1986) of the Roman Magmatic Province, with $K_2O/Na_2O$ variable, but frequently high (always > 1) although haüyne is the dominant feldspathoid (Lorenzoni et al., 2000a). In these basic lavas the K/Na ratio is similar to those of KS basic magmas (Fig. 5b), but the enrichment of most incompatible elements and the degree of silica undersaturation are close to those of HKS magmas (De Fino et al., 1986). CaO and TiO$_2$ vol% are mainly 8.1–12.4 and 0.8–1.4, respectively, while, with regard to trace elements, the Zr values are generally between 305 and 570 ppm, V varies roughly from 180 to 270 ppm, Sr approximately from 1600 to 2850 ppm, Rb from 70 to 170 ppm, Ba from 1700 to 2800 ppm and Y roughly from 40 to 60 ppm (De Fino et al., 1986; Lorenzoni et al., 2000a; Beccaluva et al., 2002; De Astis et al., 2006). In the Mediterranean basin as a whole these mineralogical and geochemical compositions (cf. Figs. 6a and 7) are peculiar just to Mt. Vulture, the only volcano to have such abundant haüyne in the emitted products (among all the volcanoes of the Roman Magmatic Province negligible amounts of haüyne are present only in the Roccamonfina lavas) (Lorenzoni et al., 2000a).

### 3.5. Rhylotic ignimbrite from Mulargia (Sardinia)

This ignimbrite has a distinctive red colour with paler flammé and contains many sharp edged vesicles (usually about 1–3 mm in size), very often lined with a typical green mineral, supposed to be celadonite (Williams-Thorpe and Thorpe, 1989) probably mixed with some kind of zeolite. In thin-section it exhibits a brown-red
glassy (often devitrified glass) groundmass, showing traces of flow structure (Peacock, 1980), embedding very rare phenocrysts of quartz and andesine feldspar/C6 biotite/C6 opx. This rock outcrops in the north-west of Sardinia and belongs to the relatively high K calc-alkaline dacite-rhyolite lava series erupted during the Oligocene-Miocene (30–13 ka) subduction of lithospheric plate in the Sardinian–Corsican microplate environment, so it shows chemical characteristics common to island-arc related rocks (Dostal et al., 1982; Peccerillo, 2005). Following data reported by Williams-Thorpe (1988) and Williams-Thorpe and Thorpe (1989) the Mulargia ignimbrite exhibits low concentrations of Cr (ca 2–20 ppm); Rb ca 140–165 ppm; Sr ca 150–190 ppm, Y ca 30–53 ppm; V ca 20–43 ppm; Zr ca 200–230 ppm, TiO2 around 0.60%, SiO2 ca 67–69%; Al2O3 ca 14.9–16%; K2O/Na2O ratio roughly 1 (frequently slightly < 1) and K2O + Na2O > 8%. Obviously, to prove univocally a provenance from Mulargia, petrochemical analyses should be always necessary for a scientific validation of the origin of this high-silica rock (Figs. 6a and 7). Unfortunately, due to its general macroscopic aspect, supposed to be sufficiently distinctive to identify it in hand specimens directly with the naked eye by most of the archaeologists, archaeometric analyses concerning this kind of volcanic millstones are very rare (few analyzed samples are reported just in Williams-Thorpe, 1988 and Williams-Thorpe and Thorpe, 1989).

3.6. Etnean hawaiites and mugearites from Mongibello (and basalts from Pantelleria)

Mugearites and hawaiites are generally grey to dark-grey slightly vesicular (vesicles < 10%) seriate lavas often characterised by evident porphyritic texture (Pl: 20–60 vol.% ca for mugearites; 30–50 vol.% ca for hawaiites). Mugearites have microcrystalline-intergranular groundmass made up of plagioclase, opaque minerals and less abundant pale-green or colourless clinoxyroxene. Phenocrysts and microphenocrysts are represented by plagioclase > clinoxyroxene > olivine > Fe–Ti oxides (Fig. 4c). Euhedral (labradoritic)-bytownitic plagioclases are the largest ones (4–5 mm in size) and often feature sponge texture, deep embayments, glass and opaque inclusions. Augitic pale-green pyroxene is normally small in size (mainly 0.5 mm, sometimes up
to 3.5 mm), whereas olivine phenocrysts are smaller (mainly ≤ 0.5 mm in size) and show a rounded habit.

Hawaiitic lavas have microcrystalline-intergranular groundmass composed of plagioclase, clinopyroxene, olivine and Fe–Ti oxides. They include euhedral-plagioclase sieved plagioclase (up to 3 mm in size, with opaque and glass inclusions) > augitic green to brownish pyroxene (up to 2 mm in size and including oxides) ≥ sub-rounded olivine (around 1 mm in size; on occasion in glomerophytic associations with clinopyroxene).

As concerns the geochemical characters of mugearite, hawaiites from Mongibello Recente, they refer to original magmas related to an extensional within-plate regime and with a weak Na-alkaline affinity; This is shown, for example, by the Th/Nb (see, e.g., Fig. 8 of Beccaluva et al., 1991) and K2O/Na2O ratios (¼ 0.5; Peccerillo, 2005). In particular, useful fingerprints are represented by TiO2 < 2 wt. %, high Sr values (>1000 ppm) and Ba (>700 ppm) (Cristofolini and Romano, 1982; Cristofolini et al., 1991; Peccerillo, 2005). Furthermore, Sr vs Ba (Fig. 6a), Nd, Sr vs TiO2 (Antonelli et al., 2004, 2005; Fig. 6b) or Zr vs V (Fig. 7; after Williams-Thorpe, 1988, modified) diagrams can be quite valuable for discrimination between our basic lavas and those from other Etnean areas (tholeiitic basalts), Hyblean Plateau (alkaline and transitional basalts), Ustica (alkali-basalts, hawaiites and mugearites), and Pantelleria (alkaline and transitional basalts); these are virtually all possible sources for Roman volcanic millstones. In particular, as reported by Williams-Thorpe and Thorpe (1990), Pantelleria was a producer of small, relatively simple millstones from at least the Bronze Age to the Roman period. Basaltic lavas outcropping as far as the coast in the northern (at San Leonardo and Murcia; Civetta et al., 1984) and north-east parts of the island (at Le Balate; Villari, 1974; Civetta et al., 1984) were the most probable flow sources. Specifically, the dark-grey vesicular, olivine-basalts of San Leonardo, which are
characterised by a seriate porphyritic texture (Pl 25–30 vol %; phenocrysts: labradoritic-biotwtinic plagioclase > augite clinopyroxene > olivine), microcrystalline-intergranular groundmass (plagioclase + clinopyroxene + Fe–Ti oxides + olivine), chemical transitional/sofic affinity (K₂O/Na₂O ratio ≤ 0.3, TiO₂ > 2 wt. % and Sr < 550 ppm; Villari, 1974; Civetta et al., 1984, 1998), were the raw material used to obtain some Roman millstones discovered in North Africa, specifically in Tunisia and Libya (Peacock, 1985; Williams-Thorpe, 1988; Antonelli et al., 2005).

As regards other possible Sicilian lava sources, the use of alkaline and transitional basalts from Ustica and Hyblean Plateau, as well as of andesites from the Aeolian island of Lipari is very rare outside the Sicilian district; very few Roman mills and grindstones made of these lavas have been identified on the Italian mainland (for example one possible grinding tool of Hyblean origin at Fossombrone, Marches; Renzulli et al., 2002a) and in North Africa (a quern made of trachybasalt from Ustica is mentioned at Carthage by Williams-Thorpe, 1988).

4. Conclusions

The petrographic and geochemical features summarised above, when used together (possibly integrated by critical historical-archaeological data too) may produce reliable results concerning the origin of the Italian raw material of the Roman volcanic millstones. This approach enables most millstones to be attributed to a geological source, if not ever with absolute certainty then surely with a fully acceptable degree of reliability. For three decades at least, the petrochemical study of millstones (and all of the geomaterials) has made substantial contributions to archaeological research into the reconstruction of ancient communication routes, trade networks and cultural links in different periods. Volcanic rocks outcrop in limited areas within the Mediterranean basin as a whole and Italian volcanics played a primary role in the production and trade in millstones during the Roman period. This paper brings together the petrography and major-trace elements geochemistry of the most exploited and widespread Italian volcanic rocks worked as millstones during the Roman period as well as a general evaluation of the amount and geographical extent of the trade for millstones of each stone typology within the Mediterranean.

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