

PROVENANCE ANALYSES OF THE VOLCANIC ROCK GRINDING STONES FROM THE GREEK COLONY OF SELINUNTE, SICILY (ITALY)—CONSTRAINTS AND POSSIBILITIES*

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The petrography as well as the major and trace element compositions of the Selinunte grinding stones, made of grey vesicular lava, were analysed. By comparison with geochemical data from volcanic rocks in the Mediterranean, we were able to determine that only a minor number of the tools were extracted from the nearest volcanics of Mount Etna and the Hyblean Mountains, while the majority of the grinding stones were most probably imported from the Aeolian Islands, although an origin from the Aegean cannot be excluded entirely. The results are important in order to scrutinize trading connections, especially for the earlier times of settlement during the sixth century BC.

KEYWORDS: MILLSTONE, GRINDING STONE, VOLCANIC ROCK, GEOCHEMISTRY, PROVENANCE, SICILY, AEOLIAN ISLANDS, XRF, LA-ICP-MS, PETROGRAPHY

INTRODUCTION

Selinunte, a Greek colony on Sicily (Fig. 1) was founded in 628/7 BC, according to the Greek historian Thucydides. Notably, the Agora excavations at Selinunte, recently conducted by the German Archaeological Institute (DAI), Rome Department, uncovered 31 grinding tools (Fig. 2), mainly grinding stones as well as a few pounders, 12 of them belonging to stratified contexts of the sixth century BC. The majority of the grinding stones can be related to a device composed of a boat-shaped upper stone (Fig. 3) and an approximately rectangular lower stone. A complete device was found during the 2012 campaign (Bentz *et al.* 2013). The rectangular lower parts of the grinding stones in particular show that these items represent a developed level of grinding technique, already resembling the later so-called ‘Olynthian’ or ‘Olynthus’ type millstones, which were composed of two rectangular-shaped stones, and where the grinding was performed with the help of a lever. Representing a ‘technical link’, the grinding stones of Selinunte provide an outstanding opportunity to study the development of millstones and milling techniques, which is still a matter of debate (see Wefers 2011, 2012a,b). At the latest in the fifth century BC, with rotary querns and the ‘Olynthus mills’, two different methods of advanced food preparation techniques are present in the Mediterranean alongside the comparatively simpler grinding stones. Whereas the earliest rotary querns, dating to the late sixth and the fifth centuries BC, seem to be

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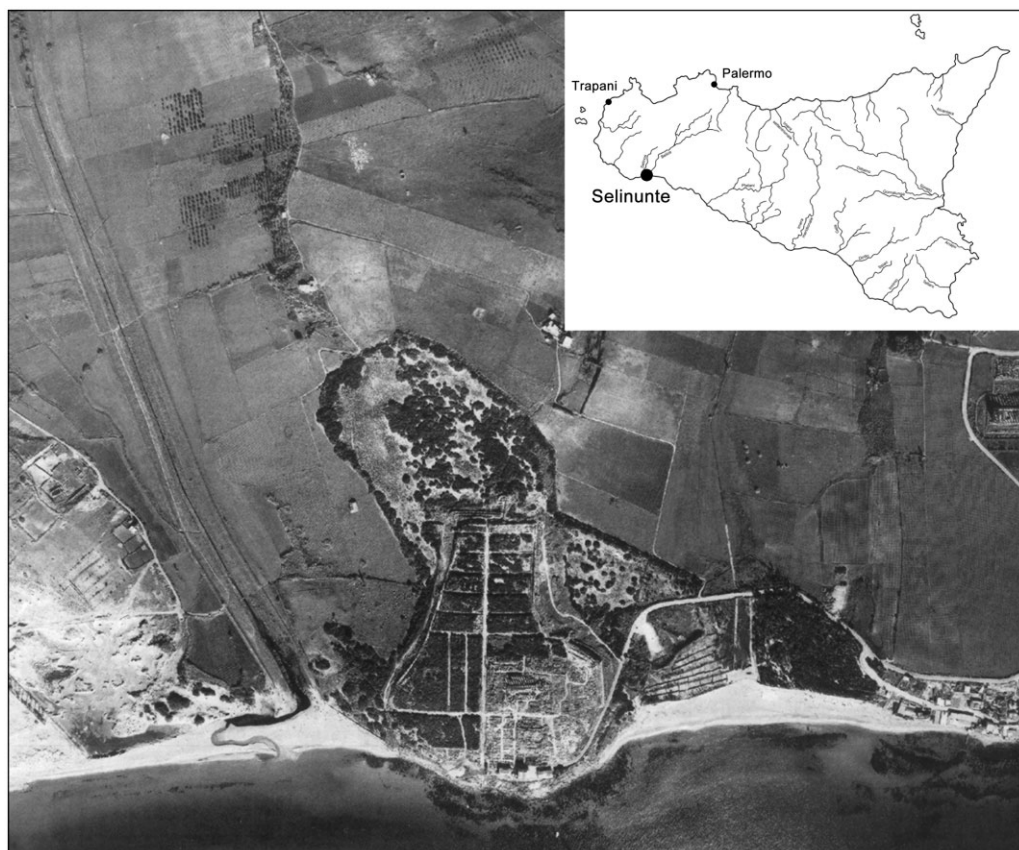


Figure 1 The ancient city of Selinunte (photograph, Mertens 2003; map basis, De Angelis 2003).

restricted to the western part of the Mediterranean—the north-eastern coast of Spain (see Alonso 1995, 1996, 1997) and Carthage, Tunisia (see Morel 2001)—in the eastern part of the Mediterranean the Olynthus mill was common. The earliest finds of the Olynthus type are dated to the fifth century BC, and perhaps even to the seventh century BC (Frankel 2003). In Selinunte, both technical developments—Olynthus mills as well as a rotary quern ('Morgantina-type'; e.g., White 1963)—have been discovered, but unfortunately without a secure context.

The majority of the grinding stones (22 finds), as well as three pounders, were produced from grey, vesicular lava, which does not occur in the region around Selinunte; only a few finds are made of local sedimentary rocks. Alongside issues regarding their technological development, the question of the provenance of the lithic material of the tools is essential. For the present study, we could sample 21 volcanic grinding stones, but could also include two volcanic rock pounders.

The potential to determine the provenance of tools produced from volcanic material is well known (see, e.g., Gluhak and Hofmeister 2009, 2011; Antonelli and Lazzarini 2010, 2012; Gluhak and Rosenberg 2013; Santi *et al.* 2013—or for obsidian, Chataigner *et al.* 2013; Darabi and Glascock 2013; Kuzmin *et al.* 2013—to list but a few of the most recent publications). The geographical situation of Selinunte, with direct access to the sea, and the geological background of Sicily, alongside the historical context of being a Greek colony, leads to the question of from

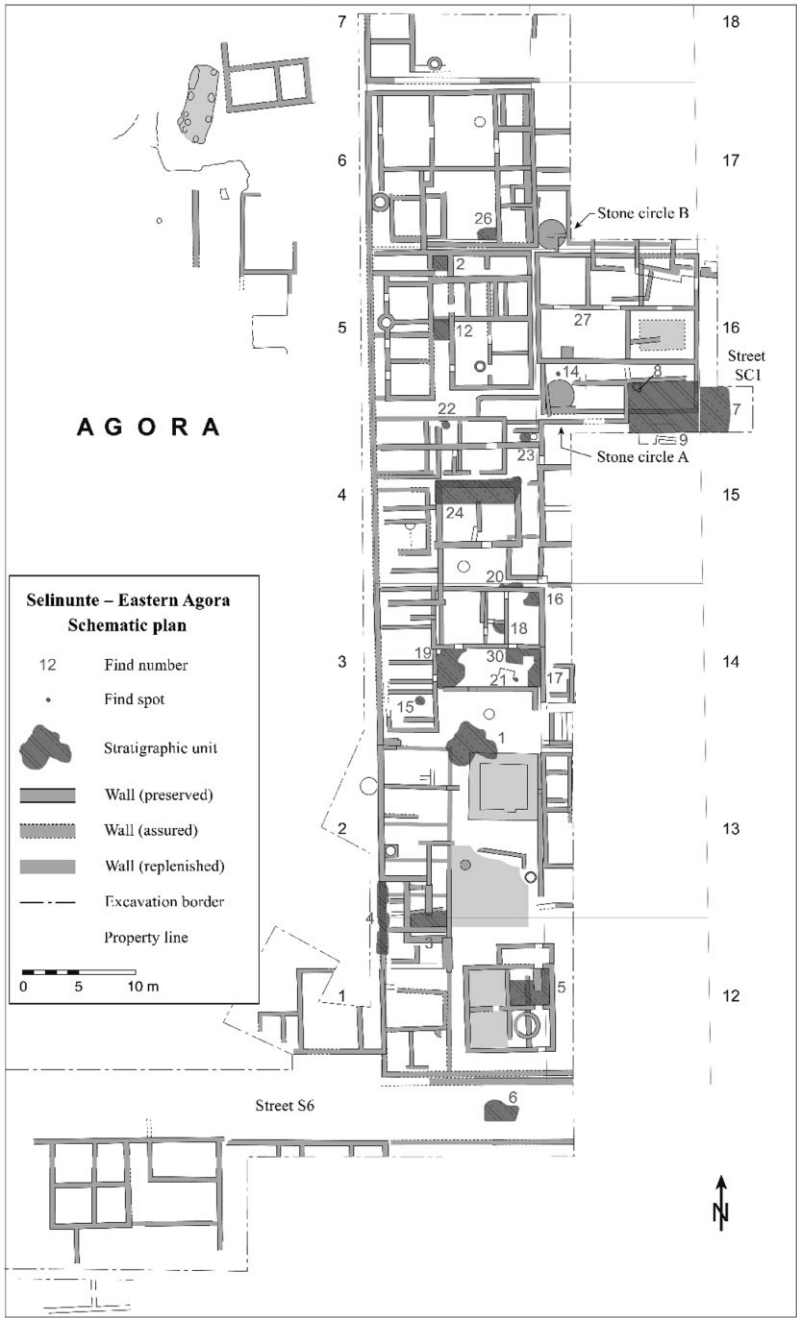


Figure 2 The excavation plan of the eastern Agora, with mapped find spots of the grinding stones and pounders (map basis, German Archaeological Institute, Rome Department, Excavation Selinunte).

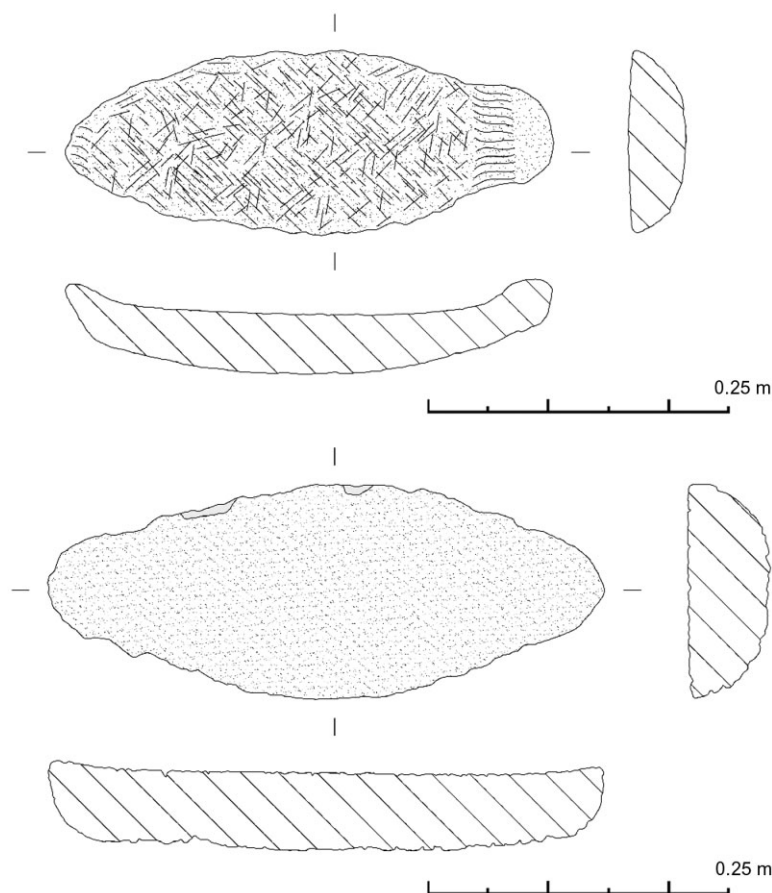


Figure 3 Boat-shaped upper parts of grinding stones found in the area of the eastern Agora.

where the grinding stones were imported. Several sources have to be taken into account. On Sicily itself and in its close surroundings, volcanic rocks are abundant (Mount Etna, the Hyblean Mountains and the Aeolian Islands) and the access to the sea easily allows the importation of volcanic rocks from outside Sicily. The Greek background also draws attention to the Aegean Islands as potential sources. Williams-Thorpe and Thorpe (1990) have stated in their provenance study on the millstones found in a Greek shipwreck close to Mallorca Island that in the fourth century BC, these items were already being transported from the Aegean Sea to the western Mediterranean. In the present study, the finds are dated about 200 years earlier, so that the determination of the origin of the grinding stones of Selinunte, as a case study for a Greek colony on Sicily, allows us to estimate the extent of the rock procurement systems in and around the island that already existed in the sixth century BC. Thus, in addition to archaeological ceramic studies of the Agora excavation (Dehl-von Kaenel 2003), the grinding stones provide us with new information regarding the provenance of imported goods for Selinunte.

Up to now, provenance studies on Sicilian grinding stones, Olynthian mills and rotary querns made from volcanic rocks have been done for finds from *Rocca di Entella* (Daniele 1997, 1999) and *Monte Castellazzo di Poggioreale* (Ferla *et al.* 1984). The *Rocca di Entella* finds were

affiliated to Mulargia/Sardinia, Etruria, Mount Etna, Pantelleria and to the Aeolian Islands of Lipari, Stromboli and Vulcano (Daniele 1997, 1999). Some grinding stones from *Monte Castellazzo di Poggioreale*, an indigenous site in the hinterland of Selinunte, were assigned to Mount Etna, the Hyblean Mountains and central Italy; others to the Aeolian Islands, the Aegean Islands or Sardinia (Ferla *et al.* 1984; Spatafora 1993).

In the present paper, we aim to determine the provenance of the Selinunte grinding tools based on their major and trace element composition. We want to outline the possibilities that we have when no analytical data from our own 'in-house' measurements of potential source rocks of the stone tools are available as comparative data, but also show the limits with which we are confronted when provenance analyses are placed on a broad database. Additionally, we use thin-section petrographic analyses, which are an essential tool to exactly characterize the raw material and to determine from how many different sites it was eventually extracted.

A NOTE ON THE GEOLOGICAL BACKGROUND

Since the Palaeocene, the Tyrrhenian Sea has been the setting for intensive volcanism. The volcanic activity is linked to the complicated subduction system of three major plates (African, European and Adriatic) and an undetermined number of smaller plates, basins and terranes. To describe the complex tectonic setting of this region is clearly beyond the scope of this paper; for further details on the geodynamic evolution, we would recommend the most recent publication by Carminati *et al.* (2012). However, the majority of the volcanic rocks surrounding the Tyrrhenian Sea (Sardinia, the Aeolian Islands, the Tuscan and Roman magmatic provinces, and Mount Vulture) display geochemical patterns that are typical for orogenic settings. Magmatic rocks with anorogenic geochemical features occur on the islands of Sicily, Ustica, Pantelleria and Linosa, and in some cases on Sardinia. The extent to which the volcanism of these islands is triggered by a plume or the subduction zones is still a matter of discussion; additionally, an extension-related setting is suggested for the Hyblean Mountains magmatic rocks. An overview of the various orogenic and anorogenic volcanic rocks, their assumed tectonic setting, the state of the discussion and further literature is given by Lustrino and Wilson (2007) and Lustrino *et al.* (2011).

METHODS

The grinding stones and two pounders were sampled with a diamond driller. A slice was cut off from every core to produce a thin section. The rest of the sample was cleaned in an ultrasonic bath, dried, crushed in a jaw crusher and ground to powder in an agate mill. For X-ray fluorescence (XRF) major element measurements, 0.4 g of powder was used to produce the glass beads, the loss on ignition was determined on ~1 g. Lead was measured on powder pellets. The major and trace element measurements were conducted routinely in a 2002 model Philips MagXPRO wavelength-dispersive X-ray spectrometer with a rhodium (Rh) X-ray tube, and a maximum excitation of 3.2 kW for major and 3.6 kW for trace elements.

For whole-rock trace element determination by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), ~40 mg of sample powder was melted to glass beads on an iridium strip heater for 10 s at 1200°C (Nehring *et al.* 2008). The measurements were carried out in an Agilent 7500 CE quadrupole ICP-MS, coupled to an ESI New Wave Research NWR193 (ArF-excimer) laser ablation system with 193 nm wavelength. Three spots, each with a diameter of 100 µm, were measured on every glass bead using a pulse rate of 10 Hz and laser energy densities

of 6 J cm^{-2} . The carrier gas was Argon. ^{43}Ca served as the internal standard, its values being taken from the XRF measurements. Reference material NIST SRM 610 served as the external standard, its values being taken from the GeoReM Database (<http://georem.mpch-mainz.gwdg.de/>). The USGS-BCR-2G was measured for quality control purposes after every ninth sample spot and is in accordance with literature data. Data reduction was carried out on GLITTER 4.4.2 software (Macquarie University, Sydney, Australia).

In the first step, the geochemical composition of the artefacts was used to determine how many different types of volcanic rocks were used to produce the stone tools. To constrain the tools' provenance, the geochemical values of the individual geochemical groups were compared to the available data of geochemically similar igneous rocks in the Mediterranean. We used the principal of exclusion: at the beginning, we checked if certain provenances could already be rejected based on general rock classification and the geodynamic setting, as implied by the artefacts' geochemical composition. In the following steps, we went further into detail: we excluded or confirmed possible provenances first based on major elements; if this gave ambiguous results, we included trace elements. In general, this study applies the recommendations of Antonelli and Lazzarini (2010), who presented useful geochemical markers for the raw material of the most widespread Roman volcanic millstones. In contrast to Antonelli and Lazzarini (2010), in the present case we are dealing with artefacts from an earlier period, which means that additional potential raw material sources have to be taken into account. The data used in this study from the central and western Mediterranean region and the Aegean Islands were compiled from the GEOROC database (<http://georoc.mpch-mainz.gwdg.de/georoc/>). Thus, the geochemical compositions of about 3400 volcanic rock samples, chemically comparable to the grinding tools, were assembled to serve as the database for the provenance analysis.¹

Furthermore, to support the geochemical studies, thin sections of the grinding stones were analysed and petrographic groups were defined. Without any of our own field samples, a direct petrographic comparison with potential source rocks is impossible. However, the petrographic studies help us to determine whether, and how many, different extraction sites might be 'hidden' within a previously defined geochemical cluster.²

RESULTS

Geochemical rock classification

The results of the major and trace element measurements are presented in Table 1. Table 2 summarizes the rock classification. The fine-grained volcanic rocks are classified using the 'total alkali silica' (TAS) diagram (Le Bas *et al.* 1986; see Fig. 4), a standard tool to discriminate volcanic rocks based on their SiO_2 content and the sum of $\text{Na}_2\text{O} + \text{K}_2\text{O}$, especially when they are too fine-grained for them to be classified reliably by their modal mineral content. In general, the grinding stones and pounders can be subdivided into an alkaline group and a sub-alkaline/tholeiitic group. Most of the alkaline samples (nos. 2, 9, 14 and 27) plot in the field of basaltic trachyandesites and can be further defined as mugearites, whereas sample 29, which plots in the trachybasalt field, is a K-trachybasalt. The majority of all artefacts lie in the sub-alkaline/tholeiitic field, with a basaltic andesitic to andesitic composition. The sub-alkaline/tholeiitic stone tools can be further subdivided. One cluster of basaltic andesite samples can be

¹The single references are given as supplementary data.

²The thin-section images of the various petrographic groups are presented as supplementary data (Fig. S1–Fig. S10).

Table 1 Major (LOI-free) and trace element composition of the Selinunte grinding stones and pounders

	Sample number										
	2	4	6	7	8	9	10	11	12	14	16
SiO ₂ (wt%)	50.96	61.58	58.75	62.91	61.51	51.28	54.15	55.22	59.41	51.94	55.95
Al ₂ O ₃	20.14	19.25	15.22	17.95	19.34	18.61	18.72	18.07	17.42	17.03	18.11
Fe ₂ O ₃ (t)	8.76	4.64	8.77	5.81	4.74	9.77	7.98	7.38	5.31	10.48	7.84
MnO	0.16	0.08	0.10	0.11	0.08	0.16	0.13	0.12	0.11	0.19	0.15
MgO	2.99	0.96	2.17	1.92	1.03	3.08	4.45	4.95	3.35	3.08	3.90
CaO	8.84	5.85	4.75	5.43	5.90	8.40	9.19	9.08	8.68	7.55	8.47
Na ₂ O	4.28	3.14	3.77	3.07	2.96	4.32	2.92	2.85	3.01	4.56	2.59
K ₂ O	1.74	3.70	3.74	2.03	3.60	2.02	1.54	1.48	2.08	2.46	2.04
TiO ₂	1.42	0.59	1.95	0.55	0.60	1.64	0.80	0.72	0.50	1.85	0.69
P ₂ O ₅	0.72	0.21	0.76	0.06	0.22	0.68	0.12	0.11	0.10	0.85	0.24
LOI	0.09	1.21	0.39	2.50	1.14	-0.30	0.08	1.58	2.67	-0.05	0.56
Sc (ppm)	23.9	24.5	21.0	27.2	32.1	27.6	36.4	41.4	30.2	32.1	32.7
V	193.7	65.7	116.1	102.9	56.0	264.4	250.0	225.7	136.5	209.0	230.6
Cr	3.0	15.0	1.6	19.0	11.0	8.8	15.5	62.7	65.4	2.8	15.1
Co	25.4	10.3	20.7	11.4	12.1	27.2	25.3	24.4	18.1	26.1	21.4
Ni	6.6	3.1	3.3	5.1	4.5	9.1	13.9	20.9	32.2	4.7	11.5
Cu	150.7	43.9	17.7	20.4	37.3	58.3	86.8	77.1	53.4	38.8	52.8
Zn	104.6	73.8	108.3	59.3	75.7	87.6	71.7	68.0	60.6	36.5	83.6
Ga	62.9	55.1	83.5	46.6	69.1	69.1	31.9	35.5	40.7	84.4	36.1
Rb	38.5	121.4	95.5	96.0	108.4	43.2	26.7	35.6	75.5	47.3	47.6
Sr	1532.2	867.7	787.7	389.9	724.8	1283.1	668.4	670.7	370.3	1092.1	630.4
Y	31.3	22.2	26.7	22.1	25.2	28.2	16.2	15.1	15.8	33.8	17.3
Zr	231.4	158.8	267.0	72.2	181.6	273.3	107.1	90.6	103.0	330.4	74.3
Nb	75.7	13.4	40.5	9.5	14.3	85.1	3.5	4.1	6.7	99.4	7.0
Ba	919.6	774.6	1504.3	653.7	772.6	915.0	275.1	324.1	569.4	1034.1	449.3
La	103.0	46.2	59.2	24.3	50.8	99.4	15.7	17.4	19.7	119.0	26.3
Ce	168.6	80.3	111.2	43.3	84.8	169.5	30.6	32.4	32.3	200.5	42.8
Pr	18.1	8.9	13.3	4.8	9.5	18.1	3.7	3.9	3.4	21.4	4.8
Nd	70.8	34.9	57.2	19.2	38.1	69.1	16.6	16.5	13.4	81.9	19.8
Sm	11.9	6.5	11.2	4.0	7.2	11.6	3.6	3.7	2.8	13.9	4.0
Eu	3.6	1.7	3.1	1.2	1.8	3.4	1.1	1.1	0.9	3.9	1.2
Gd	9.6	5.3	8.8	3.8	6.3	9.0	3.4	3.4	2.8	10.9	3.7
Tb	1.2	0.7	1.1	0.6	0.9	1.1	0.5	0.5	0.4	1.4	0.5
Dy	6.3	4.1	5.9	3.8	4.7	5.9	3.0	2.9	2.7	7.1	3.2
Ho	1.2	0.8	1.1	0.8	0.9	1.1	0.6	0.6	0.6	1.3	0.7
Er	3.0	2.3	2.5	2.4	2.6	2.8	1.7	1.6	1.7	3.3	1.8
Tm	0.4	0.3	0.3	0.4	0.4	0.4	0.2	0.2	0.3	0.4	0.3
Yb	2.7	2.2	2.1	2.6	2.5	2.4	1.7	1.6	1.8	2.9	1.9
Lu	0.4	0.3	0.3	0.4	0.4	0.4	0.3	0.2	0.3	0.4	0.3
Hf	4.9	4.1	6.8	2.3	4.7	6.0	2.8	2.6		7.2	2.0
Ta	3.4	0.8	2.4	0.6	0.9	3.9	0.2	0.3	0.6	4.5	0.3
Pb	9	19	25	16	21	12	12	14	17	14	8
Th	15.2	11.8	13.1	9.0	12.9	15.8	6.7	6.8	10.7	18.8	5.4
U	3.8	3.4	2.0	2.5	3.1	3.7	1.6	1.9	3.3	4.1	1.7

Table 1 (Continued)

	Sample number										
	17	18	19	20	21	23	24a/b	25	26	27	29
SiO ₂ (wt%)	53.47	61.90	60.98	53.80	62.32	54.87	54.95	61.64	52.59	51.57	50.01
Al ₂ O ₃	15.02	18.11	17.55	15.27	17.57	18.25	18.25	19.10	14.59	18.15	17.72
Fe ₂ O ₃ (t)	11.00	5.34	5.27	10.86	5.42	7.19	7.61	4.83	11.26	10.03	10.06
MnO	0.14	0.12	0.10	0.12	0.11	0.13	0.13	0.08	0.15	0.18	0.16
MgO	6.69	2.30	2.92	5.90	2.25	4.19	4.42	1.00	7.23	3.02	4.54
CaO	8.92	6.18	6.93	9.10	6.20	8.61	9.25	5.65	9.29	7.98	8.80
Na ₂ O	2.75	3.10	3.19	2.81	3.18	2.68	2.95	3.19	2.78	4.31	4.08
K ₂ O	0.19	2.24	2.39	0.22	2.22	2.85	1.56	3.65	0.17	2.22	2.16
TiO ₂	1.62	0.53	0.53	1.70	0.62	0.81	0.75	0.62	1.70	1.73	1.67
P ₂ O ₅	0.14	0.16	0.13	0.15	0.11	0.32	0.12	0.22	0.18	0.80	0.76
LOI	0.35	2.02	0.76	0.69	1.45	0.59	-0.14	0.54	-0.01	-0.13	0.33
Sc (ppm)	30.7	26.0	32.3	36.6	33.6	33.2	41.4	28.1	33.9	31.9	28.0
V	141.0	130.3	146.9	155.0	106.0	215.5	216.9	52.6	157.7	213.7	219.1
Cr	273.0	16.0	24.9	276.6	14.0	22.1	17.4	3.1	273.3	5.4	45.7
Co	45.5	13.8	15.3	45.9	14.1	25.3	24.2	9.2	45.9	26.2	33.6
Ni	218.7	8.7	10.5	203.4	5.2	24.2	13.9	3.0	222.6	6.7	26.8
Cu	102.0	24.0	51.0	113.5	25.9	77.6	94.2	35.3	92.0	57.2	149.0
Zn	117.8	60.0	52.8	116.3	61.0	71.7	75.7	59.5	103.5	121.6	97.6
Ga	22.2	45.9	49.9	23.4	53.4	52.6	34.3	62.1	22.7	76.9	55.4
Rb	2.2	84.7	89.0	2.0	93.0	110.3	31.8	118.1	1.4	46.0	48.5
Sr	213.6	388.1	595.2	217.2	329.3	499.0	669.8	724.5	248.4	1153.3	1175.3
Y	21.4	18.8	15.8	20.9	16.0	21.6	16.4	19.8	19.5	28.6	28.7
Zr	86.5	88.7	74.3	89.1	61.9	175.1	92.5	161.7	96.7	278.2	264.5
Nb	9.9	8.8	7.6	9.8	10.5	23.5	4.6	13.3	14.5	88.2	82.5
Ba	67.3	654.2	627.5	69.7	586.1	848.2	289.1	728.4	88.8	941.1	879.9
La	9.6	22.4	21.5	7.8	21.1	40.8	17.0	42.9	10.2	101.7	98.6
Ce	18.1	40.2	35.8	15.6	37.0	73.5	33.3	74.8	20.8	181.7	165.5
Pr	2.4	4.2	3.9	2.1	4.0	8.0	4.0	8.1	2.7	18.8	17.5
Nd	12.0	16.7	15.7	10.6	15.3	31.6	17.5	31.2	13.0	72.2	68.0
Sm	3.7	3.5	3.2	3.4	3.1	6.3	3.8	5.8	3.8	12.1	11.5
Eu	1.5	1.0	1.0	1.4	0.9	1.6	1.1	1.5	1.5	3.5	3.4
Gd	4.5	3.3	3.1	4.3	3.0	5.2	3.3	4.7	4.4	9.5	8.9
Tb	0.7	0.5	0.5	0.7	0.4	0.7	0.5	0.6	0.7	1.2	1.1
Dy	4.3	3.2	2.7	4.2	2.8	4.1	3.1	3.6	4.1	6.1	6.0
Ho	0.8	0.7	0.6	0.8	0.7	0.8	0.6	0.8	0.8	1.1	1.1
Er	2.1	2.0	1.6	2.0	1.7	2.2	1.8	2.0	2.0	2.8	2.8
Tm	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4
Yb	1.7	2.2	1.8	1.7	1.8	2.2	1.7	2.1	1.6	2.5	2.5
Lu	0.2	0.4	0.3	0.2	0.3	0.3	0.3	0.3	0.2	0.4	0.4
Hf	2.5	2.8	2.6	2.5	2.0	4.2	2.8	4.2	2.8	6.1	5.8
Ta	0.5	0.6	0.5	0.5	0.7	1.2	0.3	0.8	0.7	3.9	3.7
Pb	2	15	17	1	18	21	11	15	n.d.	10	12
Th	0.7	8.8	9.1	0.7	8.6	19.2	6.4	11.9	0.9	15.9	15.8
U	0.2	2.4	3.1	0.2	2.7	5.1	2.1	3.2	0.2	4.2	4.3

Table 2 *A summary of the rock classification and the connection to a geodynamic setting*

<i>Sample number(s)</i>	<i>Rock type</i>	<i>Setting</i>
2, 9, 14, 27 (alkaline)	Mugearite	Anorogenic/no subduction relation
29 (alkaline)	K-trachybasalt	Anorogenic/no subduction relation
17, 20, 26 (tholeiitic)	Basaltic andesite	Anorogenic/no subduction relation
10, 11, 16, 24a/b (sub-alkaline)	'High'-alkali basaltic andesite	Subduction relation
7, 12, 18, 19, 21 (sub-alkaline)	Andesite	Subduction relation
4, 8, 25 (sub-alkaline)	Latite	Subduction relation
23 (sub-alkaline)	Shoshonite	Subduction relation
6 (alkaline-sub-alkaline)	Latite	Subduction relation

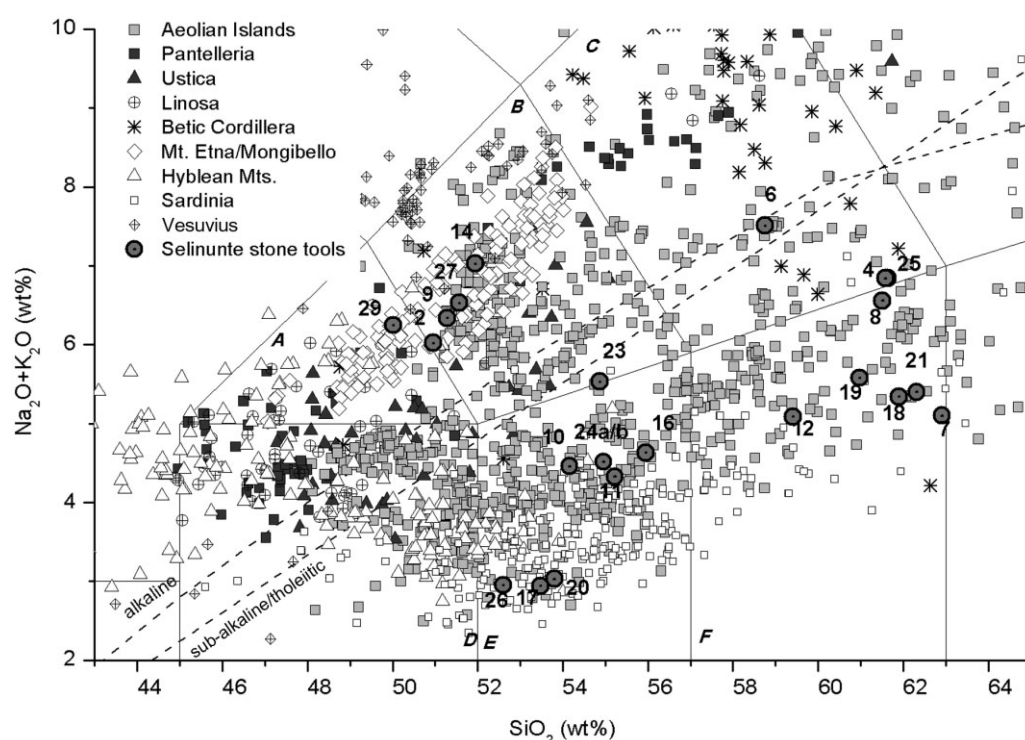


Figure 4 The classification of the grinding stones and pounders in the TAS diagram (Le Bas et al. 1986). Data for comparison are from the Aeolian Islands, Pantelleria, Ustica, Linosa, the Betic Cordillera, Mount Etna/Mongibello, the Hyblean Mountains, Sardinia, Vesuvius and Alboran, compiled from the GEOROC database.³ A, trachybasalt; B, basaltic trachyandesite; C, trachyandesite; D, basalt; E, basaltic andesite; F, andesite.

constrained by its very low content in Na₂O and K₂O (nos. 17, 20 and 26). A second basaltic andesite group with a higher alkali content is composed of samples 10, 11, 16 and 24a/b. The andesitic group comprises samples 7, 12, 18, 19 and 21. One group at the border of the andesite to trachyandesite field comprises samples 4, 8 and 25, which can be specified as latites. One

³For references, see the supplementary data.

individual sample lying at the border of the basaltic andesite to basaltic trachyandesite is shoshonitic (no. 23). Sample 6, which can also be defined as a latite, lies at the transition from sub-alkaline to alkaline rocks in the trachyandesite field.

A further subdivision of the sub-alkaline rocks exclusively is given by the ratio of SiO_2 and K_2O (Fig. 5). Apart from the three tholeiitic samples 17, 20 and 26, the sub-alkaline samples lie at the transition from the calc-alkaline series to the high-K calc-alkaline series and to the shoshonite series, respectively. The calc-alkaline and shoshonitic compositions strongly indicate a subduction-related origin of these rocks. The plot confirms the grouping of the samples within the TAS diagram (Fig. 4), with sample 16 being an exception: Obviously, it is an individual sample and does not belong to the basaltic andesite group of samples 10, 11 and 24a/b.

The trace element concentration (Fig. 6) supports the grouping based on the major elements so far. The alkaline group shows the highest trace element concentrations. Apart from Ba to U and Ta, the pattern is, in comparison to the other samples, rather more related to typical ocean island basalts (OIB). In contrast, the tholeiite group possesses significantly lower trace element concentrations and shows similarities to enriched mid-ocean ridge basalts (E-MORB), apart from the strong depletion in Rb and a Pb and slight Sr enrichment. All other stone tools show patterns that are typical for subduction-zone-related volcanism: elements such as Ba, Rb, Th and U are enriched and Nb, Ta, and Ti show negative anomalies. In comparison to the other subduction-

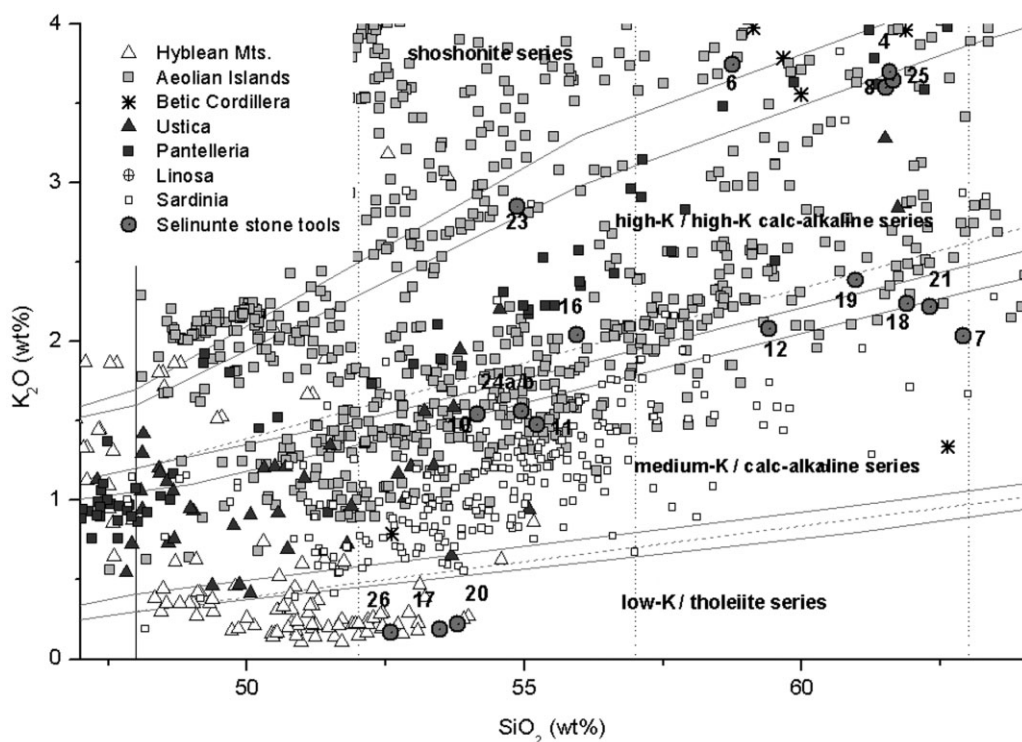


Figure 5 The SiO_2 – K_2O diagram of the sub-alkaline grinding stones and pounders in comparison to the Hyblean Mountains, the Aeolian Islands, the Betic Cordillera, Ustica, Pantelleria, Linosa, Sardinia and Mount Etna/Mongibello. (data compiled from the GEOROC database; for references see the supplementary data).

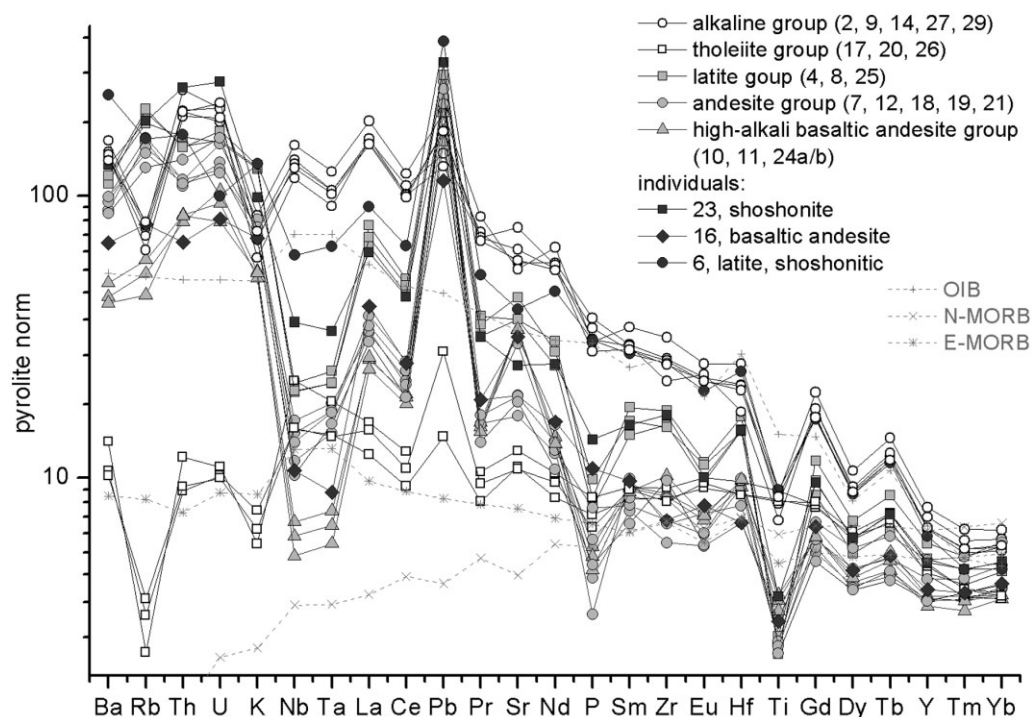


Figure 6 The pyrolite-normalized trace element concentration of the grinding stones and pounders. Pyrolite values from McDonough and Sun (1995); for Pb, OIB, N-MORB and E-MORB, see Sun and McDonough (1989).

related rocks, the latite group is marked by higher contents in Ta, La, Ce, Pr, Sr, Nd, Sm and Zr. The andesite group displays a medium Nb, Ta and La content and the lowest Sr content among the subduction-related rocks. The high-alkali basaltic andesite group is especially marked by the lowest contents in Nb and Ta of all tested artefacts. All three individual samples (nos. 6 and 16, and poulder 23) show subduction-related patterns, but none of them is compatible with the patterns of the other artefacts.

Provenance determination

Anorogenic/no subduction relation: the alkaline and tholeiitic stone tools Within the TAS diagram (Fig. 4), the alkaline group (samples 2, 9, 14, 27 and 29) plots within a field that is mainly covered by Mount Etna/Mongibello and Aeolian Island rocks. Some samples from Vesuvius, Pantelleria, Ustica and Linosa also lie in close vicinity to the alkaline artefacts. Additionally, samples 9, 2 and 29 cannot be clearly discriminated from Hyblean Mountains rocks. However, the $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios of rocks from Ustica and Pantelleria, which are lower in comparison to the alkaline artefact group, show that an origin from these two islands is rather improbable. A Vesuvian provenance can also be excluded for the alkaline artefacts, as Vesuvian rocks with similar SiO_2 concentrations are, in general, marked by an explicitly higher potassium content (>4%). The tholeiitic group (samples 17, 20 and 26) lies in Figure 4 within the same range as rocks from the Aeolian Islands, the Hyblean Mountains and Sardinia. In

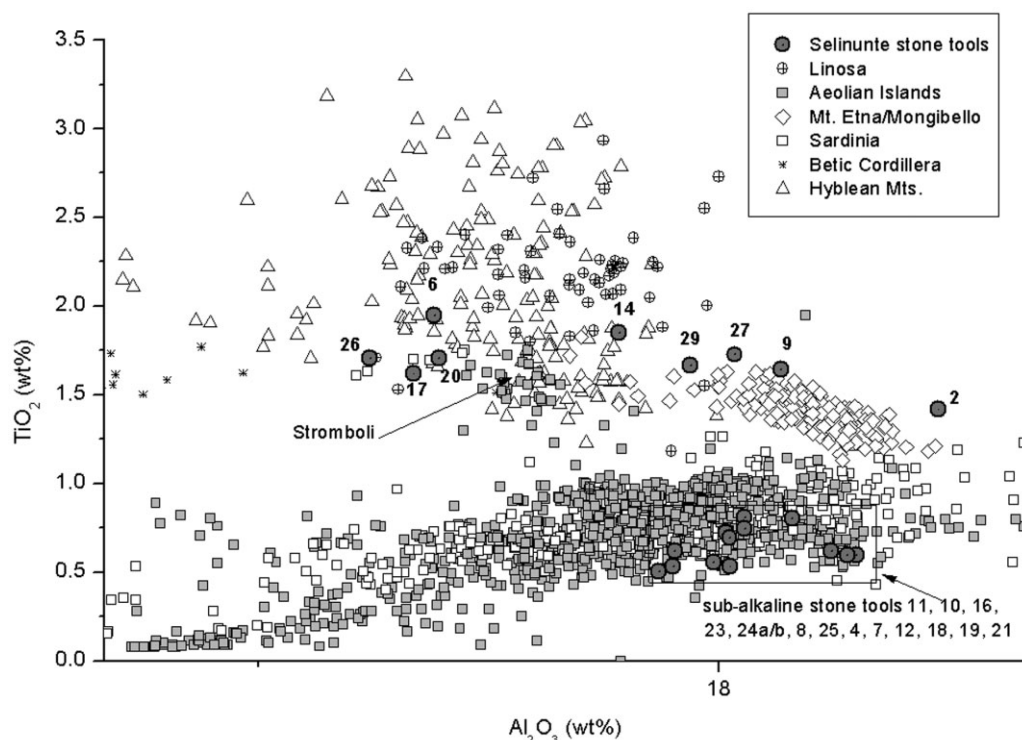


Figure 7 The Al_2O_3 – TiO_2 diagram of the grinding stones and pounders in comparison to Linosa, the Aeolian Islands, Mount Etna/Mongibello, Sardinia, the Betic Cordillera and the Hyblean Mountains. For key, see Figure 4. The arrow indicates the group of the 'high'- TiO_2 rocks of the Aeolian Island Stromboli.

particular, the tholeiitic group covers a range in its SiO_2 – K_2O composition that otherwise only comprises Hyblean Mountains rocks (Fig. 5). The major element composition helps to exclude importation from the Aeolian Islands for all alkaline and tholeiitic samples. Figure 7 shows that apart from some cases (Stromboli), the TiO_2 contents of the Aeolian Island lavas are significantly lower than those of the alkaline and tholeiitic stone tools (samples 2, 9, 14, 27 and 29, and 17, 20 and 26). At a given TiO_2 content, the alkaline grinding stones show higher concentrations in Al_2O_3 than the Stromboli rocks, whereas the tholeiitic finds display lower Al_2O_3 concentrations. Additionally, based on their higher P_2O_5 content (0.68–0.85% P_2O_5), the alkaline artefacts can be discriminated from Linosa Island (0.24–0.66% P_2O_5). So far, the major element compositions of the alkaline and tholeiitic stone tools strongly suggest a provenance from Mount Etna/Mongibello and the Hyblean Mountains. However, while a provenance from the Hyblean Mountains seems obvious for the tholeiitic rocks, the affiliation of the alkaline rocks to either Mount Etna/Mongibello or the Hyblean Mountains still has to be checked.

Antonelli and Lazzarini (2010) suggest the use of the Sr–Ba (Fig. 8) and TiO_2 –Sr concentrations (Fig. 9) to discriminate between Mount Etna/Mongibello and the Hyblean Mountains. Their reference data are supplemented by the data applied in this study. Figure 8, as well as Figure 9, confirms a Hyblean Mountains provenance for the tholeiitic samples. In both cases, the alkaline

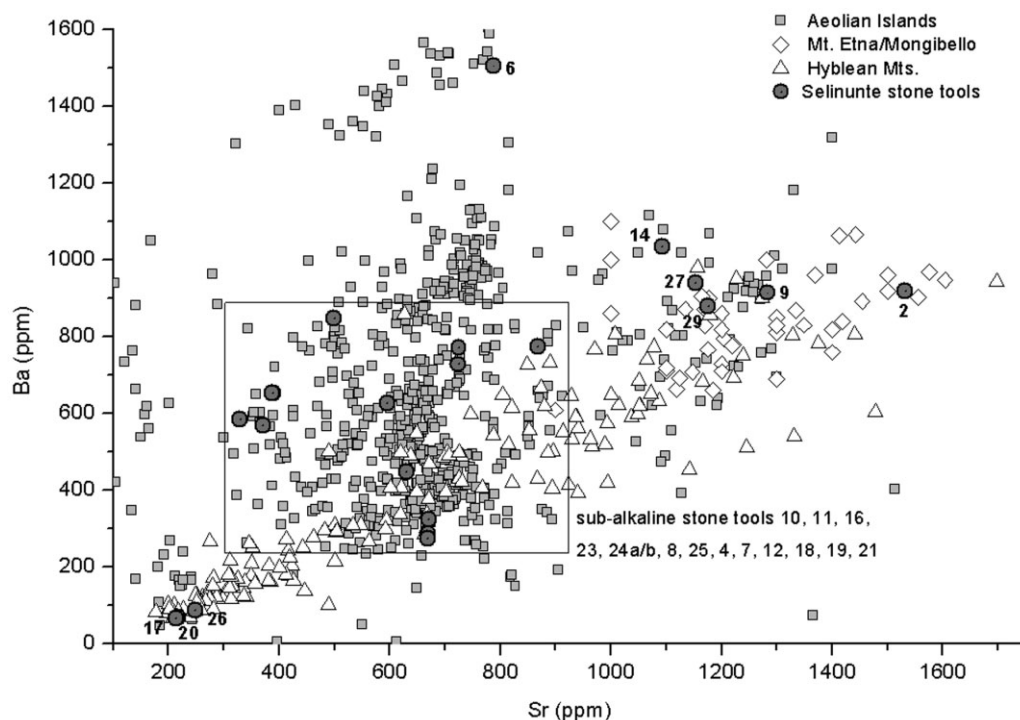


Figure 8 The Sr and Ba contents of the grinding stones and pounders in comparison to the Aeolian Islands, Mount Etna/Mongibello and the Hyblean Mountains. For key, see Figure 4.

artefacts lie within the Mount Etna/Mongibello range of Antonelli and Lazzarini (2010), but the additional reference data show that some rocks from the Hyblean Mountains also plot within the Ba–Sr concentration of the Mount Etna/Mongibello rocks (Fig. 8). The TiO_2 –Sr concentration of the alkaline stone tools also lies exactly in the transition from the Hyblean Mountains to Mount Etna/Mongibello (Fig. 9). Antonelli and Lazzarini (2010) also recommend the V–Zr composition as an appropriate tool for source discrimination. However, when further data from the Hyblean Mountains and Mount Etna/Mongibello are added to the V–Zr plot (not shown), the two locations overlap strongly, and the alkaline stone tools plot directly within this overlap. Nevertheless, for the alkaline as well as for the tholeiitic finds, Figure 9 proves helpful to exclude an origin from Sardinia.

In the present case, a spider diagram (Fig. 10) is a helpful tool to affiliate the grinding stones and pounder 2 with the Hyblean Mountains and/or Mount Etna/Mongibello. In general, the Mount Etna/Mongibello rocks have higher concentrations in most of the trace elements. Th, U, Ta, La, Ce and Nd in particular are remarkably higher in Mount Etna/Mongibello than in the Hyblean Mountains rocks. The alkaline stone tools clearly display the Mount Etna/Mongibello pattern, while the tholeiitic rocks, as already expected from the previous comparisons, coincide with the trace element patterns of the Hyblean Mountains volcanics.

Besides a compatible geochemistry, the tholeiitic Hyblean Mountains grinding stones all show the same petrography, so obviously they are all extracted from the same site. The holocrystalline rock displays an equigranular grain size distribution. It is composed mainly of plagioclase,

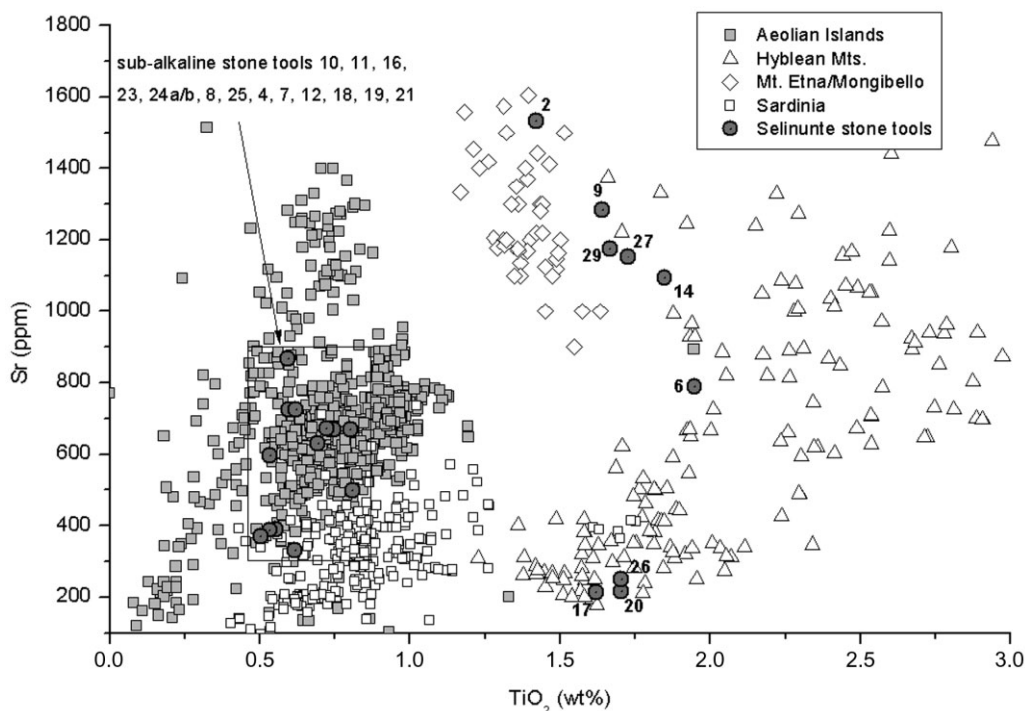


Figure 9 The TiO_2 and Sr contents of the grinding stones and pounders in comparison to the Aeolian Islands, the Hyblean Mountains, Mount Etna/Mongibello and Sardinia. For key, see Figure 4.

followed by clinopyroxene, sanidine, opaque grains, a few orthopyroxenes and olivines, probably xenocrysts, which are strongly altered to iddingsite (see grinding stone 26 in Fig. S1).

All alkaline (mugearitic/K-trachybasaltic) grinding stones and pounder 2, which are affiliated with Mount Etna/Mongibello, have a comparable modal mineral content. The matrix is composed of opaque grains, plagioclase, sanidine, clinopyroxene and a few olivines, in parts altered to iddingsite. The phenocrysts are plagioclase with a spongy texture, in some cases with small clinopyroxene inclusions, sanidine, clinopyroxene and olivines. However, the texture of the stone tools shows a considerable difference between the K-trachybasalt sample 29 (Fig. S2) and the mugearite samples 2, 9, 14 and 27 (see sample 9 in Fig. S3). While the matrix of the mugearites is nearly holocrystalline, the matrix of the K-trachybasalt sample is extremely fine-grained to opaque, glass-bearing, with micro-phenocrysts. Olivine is more abundant among the phenocrysts than in the mugearites. Furthermore, in contrast to the mugearites, more opaque phenocrysts occur in the K-trachybasalt. Thus, we assume that sample 29 is derived from another extraction site at Mount Etna/Mongibello, although we cannot ultimately exclude the possibility that the geochemical and petrographic range among the alkaline stone tools simply displays the geochemical and petrographic heterogeneity within one volcanic site. The petrography of the mugearitic Mount Etna/Mongibello rocks matches the petrography of the Etnean hawaiites as described by Antonelli and Lazzarini (2010).

Subduction relation: the sub-alkaline stone tools The TAS diagram (Fig. 4) implicates a provenance from the Aeolian Islands, Sardinia or, in the case of grinding stones 4, 8 and 25, a

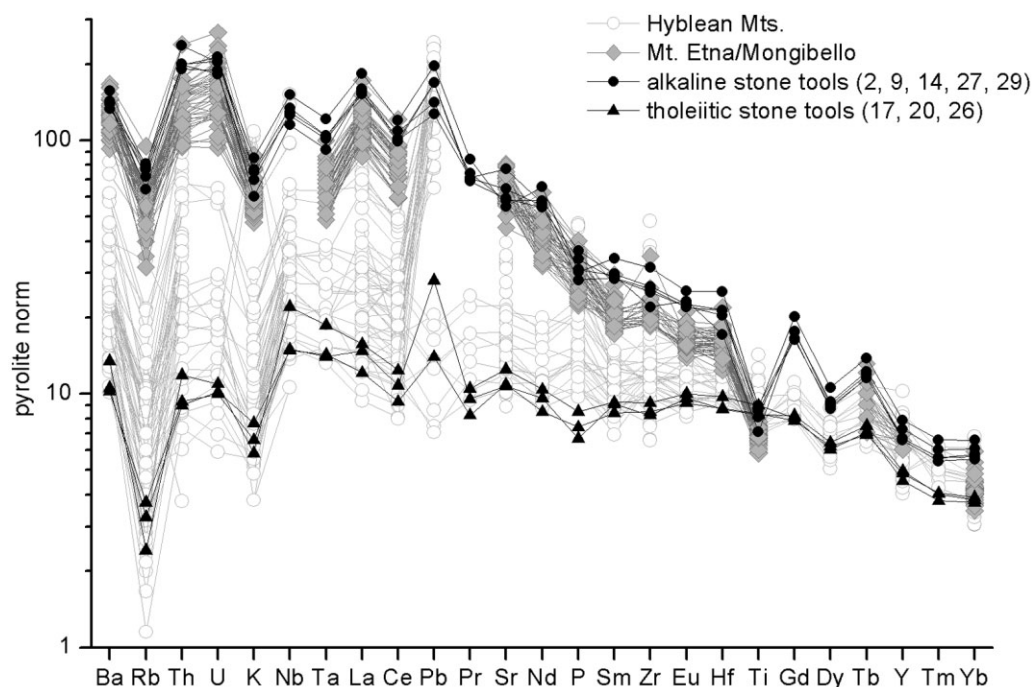


Figure 10 The pyrolite-normalized trace element diagram of the alkaline and tholeiitic grinding stones and pounder 2 in comparison to rocks from the Hyblean Mountains and Mount Etna/Mongibello. For key for pyrolite values, see Figure 6.⁴

provenance from Betic Cordillera volcanics in south-eastern Spain. The provenance from Betic Cordillera volcanics can be easily excluded for all tested grinding stones based on their Al_2O_3 and TiO_2 compositions (Fig. 7). Their high Sr content is a useful characteristic of the grinding stones to distinguish them from Sardinian volcanic rocks. Figure 11 shows that, in general, the Aeolian Island rocks display a higher Sr concentration than those from Sardinia, a characteristic that is especially obvious in connection with the total iron content. All sub-alkaline artefacts plot in the field that is clearly dominated by the Aeolian Island rocks.

To further constrain the provenance within the Aeolian Islands proves to be a difficult task. In general, the Aeolian Island volcanics show very similar geochemical characteristics, in major as well as in trace elements. Based on the available data, it is not possible to constrain single islands unambiguously from each other. Furthermore, the possibility cannot be excluded that the subduction-related artefacts, or at least some of them, were instead imported from the Aegean region. Neither based on major nor on trace element composition can the Aeolian Island volcanic rocks be clearly discriminated from the Aegean volcanics (see Fig. 12, which is exemplary for major elements, and Fig. 13 for trace elements).

However, the petrographic features of the samples help us to define at least the number of different extraction sites on the islands.

⁴For references for the Hyblean Mountains and Mount Etna/Mongibello values, see the supplementary data.

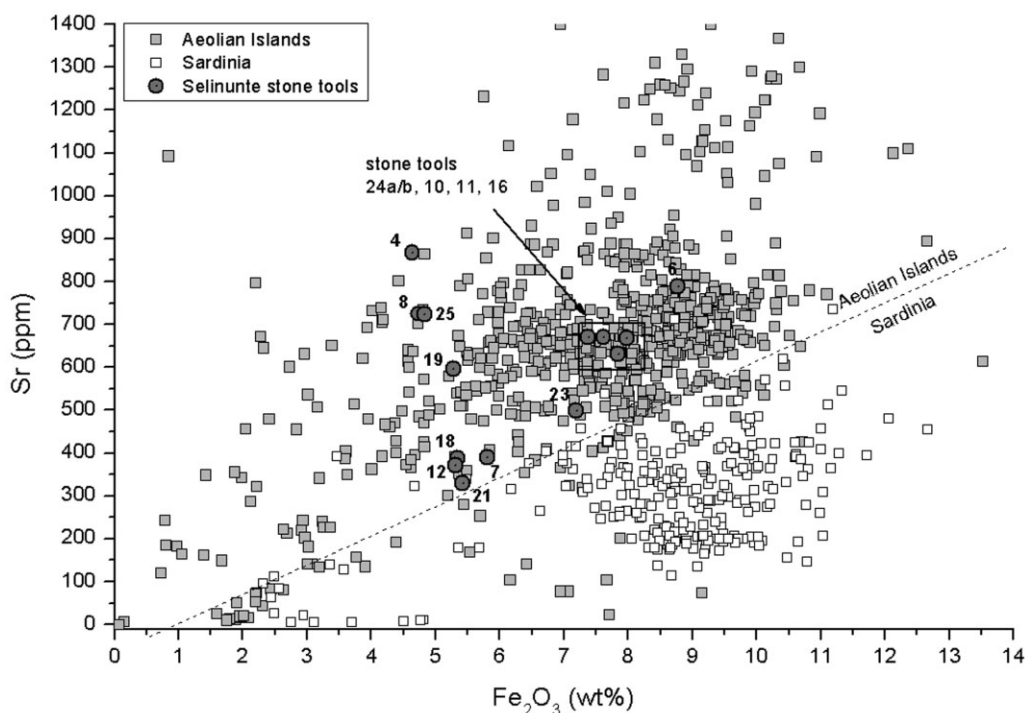


Figure 11 The sub-alkaline stone tools in comparison to rocks from the Aeolian Islands and Sardinia. The dashed line separates the Aeolian Islands-dominated field from the Sardinian rocks.⁵

As already indicated by their geochemical composition, the petrography confirms that the latite samples 4, 8 and 25 are derived from one extraction site (see sample 4 in Fig. S4). The very fine-grained matrix of the porphyritic rock is composed of opaque minerals, sanidine, quartz and a few orthopyroxenes, while the embedded phenocrysts with a serial grain size distribution are mainly plagioclase, some intergrown with orthopyroxene, followed by sanidine, orthopyroxene and a few quartz grains.

The andesite grinding stones 7, 12, 18, 19 and 21 cover a geochemical range that makes it difficult to decide whether or not they are all extracted from the same lava. The petrographic features of all andesites show that they are indeed derived from a common source. The fine-grained matrix is composed of glass, sanidine, quartz, plagioclase, opaque minerals, orthopyroxene and a few clinopyroxenes. The serially distributed phenocrysts are mainly plagioclase, followed by amphibole and mica, and furthermore sanidine and quartz, as well as rare clinopyroxene phenocrysts in samples 12, 18, 19 and 21 (see sample 19 in Fig. S5).

In spite of the geochemical homogeneity among the basaltic andesites (grinding stones 10, 11 and 24a/b) the petrographic features and modal mineralogy of sample 11 show that its source is different from that of samples 10 and 24a/b. The rock of grinding stone 11 is porphyritic; the phenocrysts show serial grain size distribution. The fine-grained matrix contains glass and opaques, plagioclase, sanidine and ortho- and clinopyroxene; the phenocrysts are

⁵For references for Sardinian and Aeolian rocks, see the supplementary data.

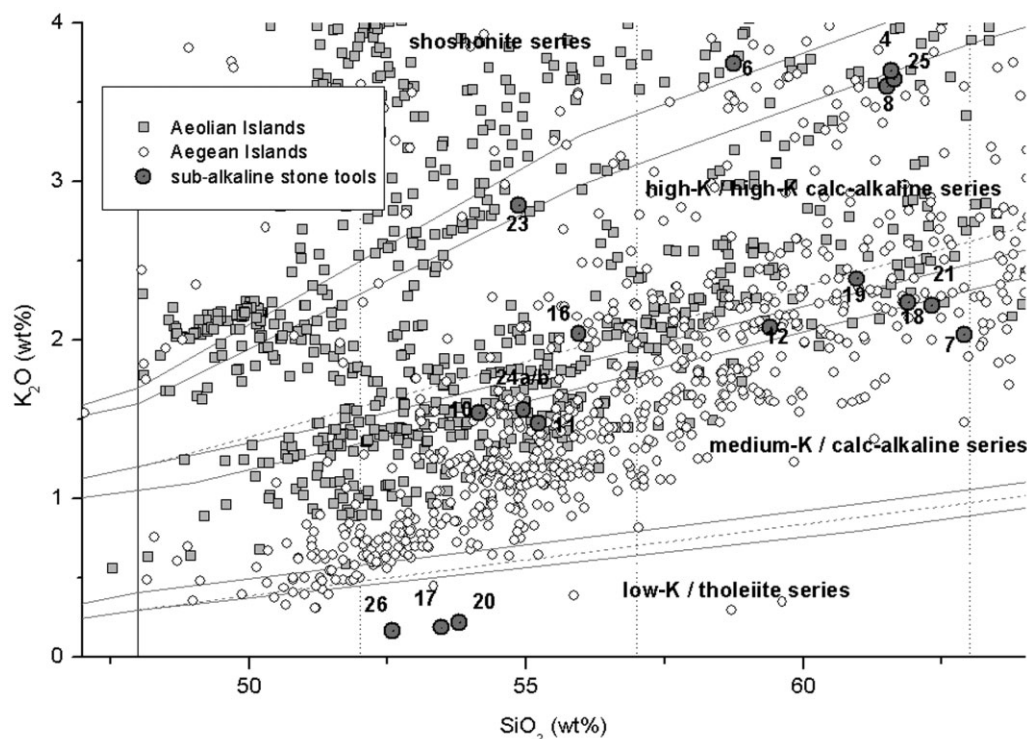


Figure 12 A comparison of the SiO_2 - K_2O diagram of the subduction-related rock stone tools with rocks from the Aeolian and Aegean Islands.⁶

amphiboles with oxidized rims, clinopyroxenes, plagioclase, mica and orthopyroxenes, which in some cases are intergrown with mica, and a few quartz and sanidine minerals (Fig. S6). In contrast to that, grinding stones 10 and 24a/b are holocrystalline with a serial grain size distribution and do not contain any amphiboles. They are composed of mainly plagioclase, sanidine, quartz and clino- and orthopyroxene. The phenocrysts are ortho- and clinopyroxenes with opaque grain inclusions (see sample 10 in Fig. S7). According to these petrographic characteristics, we can state that these grinding stones are extracted from two distinct extraction sites of basaltic andesites.

Three geochemically individual samples among the artefacts that were probably derived from the Aeolian Islands are the latite sample 6, the basaltic andesite sample 16 and the shoshonite sample 23. Their petrographic features do not match any of the other grinding stones. Sample 6 is porphyritic, with very few (~3%) phenocrysts of clinopyroxene and rare plagioclase and sanidine. The matrix contains glass and equigranular microcrysts of mainly sanidine, followed by plagioclase, opaque grains, clino- and orthopyroxene and little quartz (Fig. S8). Grinding stone 16 also shows porphyritic texture; the very fine-grained matrix is composed mainly of plagioclase, as well as sanidine, opaque grains, a few clinopyroxenes and rare quartz. The

⁶For references for Aegean and Aeolian rocks, see the supplementary data.

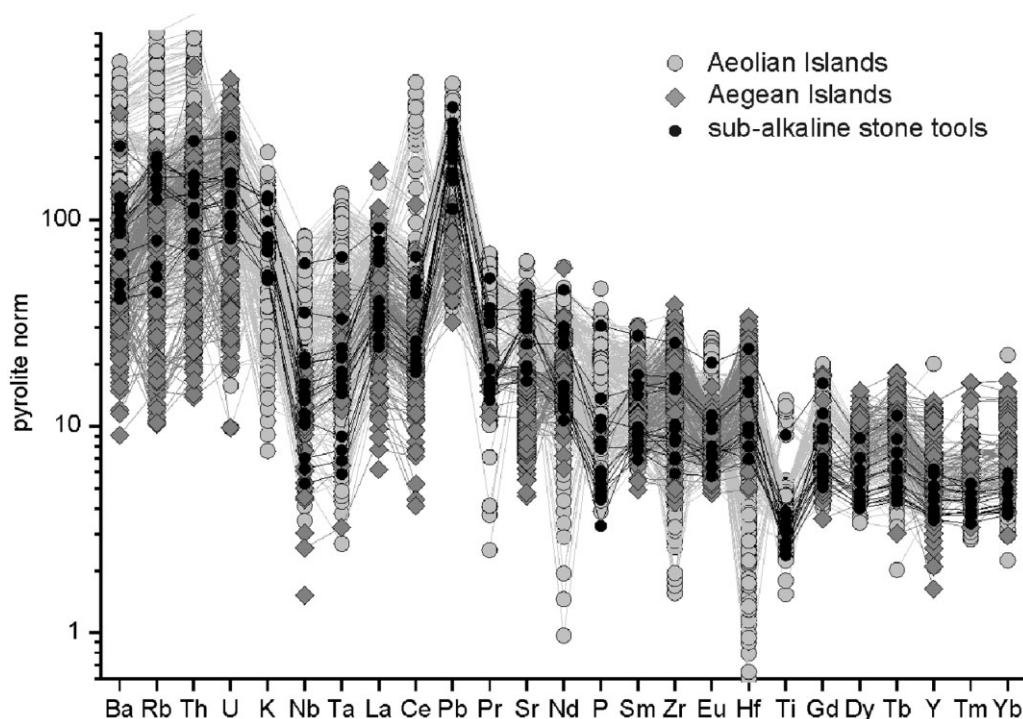


Figure 13 A comparison of the pyrolite-normalized trace element composition of the subduction-related rock stone tools with rocks from the Aeolian and Aegean Islands. For key for pyrolite values, see Figure 6.⁷

phenocrysts are clinopyroxenes and plagioclase as well as orthopyroxenes intergrown with the clinopyroxenes, a few sanidines and rare quartz (Fig. S9). Pounder 23 displays a matrix mainly composed of glass, with few microcrysts of opaque grains, sanidine and clino- and orthopyroxene. The phenocrysts are serially distributed plagioclase, clino- and orthopyroxene and a few sanidines (Fig. S10).

DISCUSSION

The determination of the provenance of the grinding stones and pounders from Selinunte benefits from the complex geodynamic setting of the central and western Mediterranean, which causes the specific geochemical characteristics of the volcanic products. In approximate terms, the geodynamic processes resulted in different mantle source conditions and produced a wide range of geochemically distinct magmas in the Tyrrhenian Sea, which can be typical for certain locations. These characteristics made a provenance determination for the grinding stones and pounders possible, and unequivocal at least with regard to the alkaline and tholeiitic artefacts. The determination of the origin of the sub-alkaline tools proves rather difficult. In general, two regions have to be considered in the Mediterranean for the provenance of the subduction-related rock items: the central/western Mediterranean as well as the Aegean region—especially as we are

⁷For Aegean and Aeolian rocks, see the supplementary data.

dealing with finds from a Greek context. The compilation of all recently available major and trace element data of rocks from both subduction-related regions, which are geochemically compatible with the grinding stones and pounders, shows that there is no possibility of discriminating clearly between the Aegean and the Aeolian Islands. Although importation from the Aeolian Islands seems more probable simply because of the geographical situation of Selinunte, it cannot be entirely excluded that the subduction-related artefacts, or at least some of them, were instead imported from the Aegean region, especially as a vivid contact between the Greek colony of Selinunte and Greece itself can be assumed. Comparing our study to the results of Daniele (1997, 1999), the affiliation of grinding stones to certain Aeolian Islands as achieved there is difficult to reproduce; especially as in those publications no geochemical data are given from most of the potential extraction sites. Santi *et al.* (2013) also affiliate their artefacts with certain Aeolian Islands (Lipari, Vulcano). However, when a bigger set of geochemical data from the region is used as reference data, as in our present study, it is evident that the islands strongly overlap in their major and trace element compositions. Thus, as no unequivocal affiliation within the Aeolian Islands is possible in our cases, we prefer not to go further than to state that the finds are—probably—of Aeolian Island origin, without being able to finally exclude an Aegean provenance. Williams-Thorpe (1988), who matches two Roman millstones to Lipari Island and three millstones to the Aegean Island of Nisyros, also gives no unequivocal clue as to how she succeeded in discriminating these locations, especially as in our study the Nisyros major and trace elements overlap with all other Aegean Island rocks and in parts with Aeolian Islands volcanics. However, lead isotope analyses could serve as a solution for the Aeolian–Aegean provenance problem. The island arc volcanics differ in their lead isotopic compositions: Aegean Arc volcanic rocks have lower ratios of $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ than most of the volcanic rocks from the Aeolian Islands.⁸ Thus, although comparably elaborate and expensive, in the light of the present study we regard lead isotope analyses as the method of choice to affiliate a subduction-related rock tool with the Aeolian or Aegean Islands.

We have shown that petrographic studies are an essential tool in constraining the exact number of different ‘lithotypes’ used for grinding stone production, which is not always possible by geochemistry alone. Unfortunately, in our case the lack of our own field samples precludes a comparison of the petrographic features of both artefacts and geological samples.

In general, cluster analyses are an appropriate method by means of which to affiliate rock artefacts of unknown provenance with rock samples of known provenance. One may ask why this method was not applied here. First, although all the samples are of volcanic whole rock, the rocks in the GEOROC database are analysed to answer completely different questions, rather than for provenance determinations. Aspects such as, for example, traces of rock extraction, raw material availability and quality for tool production, criteria to be kept in mind when rocks are sampled in the field to serve as a basis for provenance analyses, did not play any role in the publications from which the values were collected. The second, even more important, reason is that these data are not ‘our own’ in-house data. The whole-rock compositions taken from the GEOROC database are analysed under different measurement conditions or using different methods. It is impossible to calibrate these results to the methods and measurement conditions that we have used on the artefacts, which would be the precondition for a reliable comparability. We regard this error as small enough to compare the ‘foreign’ values to our own artefact values in two-dimensional plots, but as too large to apply ‘sensitive’ multivariate analytical methods such as cluster analyses.

⁸For references, see the supplementary data.

Regarding the alkaline and tholeiitic tools, similar provenance results have been achieved by studies of coeval grinding stones from the indigenous settlement of *Monte Castellazzo di Poggioreale* in the hinterland of Selinunte (Ferla *et al.* 1984; Spatafora 1993), which also showed that the volcanic rocks of eastern Sicily only played an inferior role as resources up to the sixth century BC. Whether the imports from Mount Etna/Mongibello and the Hyblean Mountains reached Selinunte by exchange connections over land or sea remains an open question. Fortunately, the archaeometric ‘failure’ of not being able to discriminate between the Aeolian and Aegean Islands on the basis of the present data has only a small effect on the archaeological interpretation. Independent of the ‘final’ provenance determination for the Aeolian (Aegean?) Islands stone tools, for the sixth-century Greek colony of Selinunte, the analyses attest to the procurement of volcanic rocks exclusively from sources that were then entirely under Greek control. The provenance results for the stone tools presented here highlight the use of rock resources in the case of just one settlement. The determination of the origin of additional well-stratified finds of grinding stones, Olynthian mills and rotary querns from other Greek, and also Punic, colonies or indigenous settlements on Sicily—as done for the two local sites by Ferla *et al.* (1984) and Daniele (1997, 1999)—would be an important contribution for understanding the whole procurement system of volcanic rocks during the sixth century BC and at later times, and especially its development towards the Roman period.

CONCLUSIONS

In the event that no own geochemical field data are available for correlation with the tested artefacts, we recommend the use of continuously updated online databases on volcanic rocks—such as GEOROC, for example. These databases are helpful tools, but obviously so far they are unknown to researchers in the field of archaeometry. Furthermore, we want to emphasize the importance of thin-section analyses, which essentially contribute to defining how many different raw material sources were actually used. By comparison of the geochemical composition of the grinding stones and pounders with volcanic rocks from the Mediterranean, we succeeded in determining the provenance of at least some of the artefacts definitively. Only seven grinding stones and one pounder were extracted from Sicilian volcanic rocks; five from Mount Etna/Mongibello (including the pounder) and three from the Hyblean Mountains. The petrographic features show that the Hyblean Mountains grinding stones all have the same source. In the case of the Mount Etna/Mongibello tools, we are apparently confronted with two extraction sites.

Astonishingly, the majority of the grinding stones found in Selinunte were imported from outside Sicily, probably from the Aeolian Islands. According to their geochemical composition combined with their petrographic characteristics, we can define seven distinct extraction sites. Unfortunately, the geochemical similarities of the Aeolian Islands do not allow an affiliation with a particular island. However, although an Aeolian Island provenance seems most probable, based on our data an origin from the Aegean region cannot be completely excluded. Nevertheless, in general, we can state that concerning Selinunte, no stone tool was made from raw material located in the Punic–Phoenician sphere of influence. The provenance results, summarized in Table 3, show a preferential importation of grinding stones from rock quarries controlled by Greek colonies or—perhaps—from the Greek mainland in the sixth century BC. These results are supported by preliminary studies on transport amphora in the same excavation area of Selinunte, which demonstrate the strong affinity in this period to the Greek mainland, as well as connections to settlements of *Magna Graecia* (Dehl-von Kaenel 2003). However, the provenance of the

Table 3 The dating and provenance of the finds: a question mark indicates that an Aegean Island provenance cannot be entirely excluded

Dating	Provenance	Find/sample number	Grinding tool
Sixth century BC	Aeolian Islands?	12	Grinding stone (upper part)
	Aeolian Islands?	18	Grinding stone (upper part)
	Aeolian Islands?	19	Grinding stone (lower part)
	Aeolian Islands?	21	Grinding stone (upper part)
	Aeolian Islands?	23	Pounder
	Mt Ibleii	20	Grinding stone (upper part)
Sixth to fifth/fourth century BC	Mt Ibleii	26	Grinding stone (upper part)
	Aeolian Islands?	16	Grinding stone (upper part)
	Aeolian Islands?	24a	Grinding stone (upper part)
	Mt Etna	27	Grinding stone (upper part)
Fourth/third century BC	Aeolian Islands?	4	Grinding stone (upper part)
	Aeolian Islands?	8	Grinding stone (upper part)
	Aeolian Islands?	10	Grinding stone (?)
	Aeolian Islands?	24b	Grinding stone (upper part)
	Mt Etna	2	Pounder
	Mt Etna	14	Grinding stone (upper part)
	Mt Ibleii	17	Grinding stone (upper part)
Medieval times	Mt Etna	29	Grinding stone (?)
Not datable	Aeolian Islands?	7	Grinding stone (upper part)
	Aeolian Islands?	11	Grinding stone (upper part)
	Aeolian Islands?	25	Grinding stone (lower part)
	Mt Etna	9	Grinding stone (?)
	Aeolian Islands?	6	Grinding stone (?)

grinding stones confirms the assumption that the Greek colony of Selinunte was a settlement with expanded trading activities in the central Mediterranean region.

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REFERENCES

- Alonso, N., 1995, Les premières meules rotatives manuelles dans le nord-est de la Péninsule Ibérique, in *La transmission des connaissances techniques. Actes des tables rondes d'Aix-en-Provence, avril 1993 à mai 1994* (eds. M.-C. Amouretti and G. Comet), 15–23, Cahiers d'histoire des techniques, 3, Aix-en-Provence.
- Alonso, N., 1996, Els molins rotatius: origen i expansió en la Mediterrània Occidental, *Revista d'Arqueologia de Ponent*, 6, 183–98.
- Alonso, N., 1997, Origen y expansión del molino rotativo bajo en el Mediterraneo occidental, in *Techniques et économies antiques et médiévales: le temps de l'innovation. Colloque international (C.N.R.S.) d'Aix-en-Provence, 22.–23. mai 1996* (eds. D. Meeks and D. Garcia), 15–19, Paris.

- Antonelli, F., and Lazzarini, L., 2010, Mediterranean trade of the most widespread Roman volcanic millstones from Italy and petrochemical markers of their raw materials, *Journal of Archaeological Science*, **37**, 2081–92.
- Antonelli, F., and Lazzarini, L., 2012, The first archaeometric characterization of Roman millstones found in the Aquileia archaeological site (Udine, Italy), *Archaeometry*, **54**, 1–17.
- Bentz, M., Adorno, L., Albers, J., Müller, J. M., and Zuchtriegel, G., 2013, Das Handwerkerviertel von Selinunt. Die Töpferwerkstatt in der Insula S 16/17-E. Vorbericht zu den Kampagnen 2010–2012, *Mitteilungen des Deutschen Archäologischen Instituts, Römische Abteilung*, **119**, 69–98.
- Carminati, E., Lustrino, M., and Doglioni, C., 2012, Geodynamic evolution of the central and western Mediterranean: tectonics vs. igneous petrology constraints, *Tectonophysics*, **579**, 173–92.
- Chataigner, C., Işık, M., Gratuze, B., and Çil, V., 2013, Obsidian sources in the regions of Erzurum and Kars (north-east Turkey): new data, *Archaeometry*, doi:10.1111/arc.12002.
- Daniele, D., 1997, Studio chimico-petrografico e individuazione delle aree di provenienza del materiale la vico delle macine di Entella, in *Atti della II Giornate internazionali di studi sull'Area Elima. Gibellina*, 465–527, Pisa, Gibellina.
- Daniele, D., 1999, Le macine laviche di Entella in Sicilia: studio chimico-petrografico finilizzato alla determinazione della provenienza, in *Le Scienze della terra e l'archeometria—5a Giornata, Bari – Febbraio 1998* (eds. C. D'Amico and C. Tampellini), 89–95, Bologna.
- Darabi, H., and Glascock, M. D., 2013, The source of obsidian artefacts found at East Chia Sabz, western Iran, *Journal of Archaeological Science*, **40**(10), 3804–9.
- De Angelis, F., 2003, *Megara Hyblaia and Selinous: the development of two Greek city-states in archaic Sicily*, Oxford University School of Archaeology Monographs, **55**, Oxford.
- Dehl-von Kaenel, C., 2003, Transportamphoren aus der Ladenzeile, in *Die Agora von Selinunt. Neue Grabungsergebnisse zur Frühzeit der griechischen Kolonialstadt* (ed. D. Mertens), 438–45, *Mitteilungen des Deutschen Archäologischen Instituts, Römische Abteilung*, **110**.
- Ferla, P., Alaimo, R., Falsone, G., and Spatafora, F., 1984, Studio petrografico delle macine di età arcaica e classica sa Monte Castellazzo di Poggioreale (Sicilia occidentale), *Sicilia Archaeologica*, **56**, 25–52.
- Frankel, R., 2003, The Olynthus mill, its origin, and diffusion: typology and distribution, *American Journal of Archaeology*, **107**(1), 1–21.
- Gluhak, T., and Hofmeister, W., 2009, Roman lava quarries in the Eifel region (Germany): geochemical data for millstone provenance studies, *Journal of Archaeological Science*, **36**, 1774–82.
- Gluhak, T., and Hofmeister, W., 2011, Geochemical provenance analyses of Roman lava millstones north of the Alps: a study of their distribution and implications for the beginning of Roman lava quarrying in the Eifel region (Germany), *Journal of Archaeological Science*, **38**, 1603–20.
- Gluhak, T. M., and Rosenberg, D., 2013, Geochemical discrimination of basaltic sources as a tool for provenance analyses of bifacial tools in the Southern Levant: first results from the Jezreel Valley, Israel, *Journal of Archaeological Science*, **40**, 1611–22.
- Kuzmin, Y. V., Glascock, M. D., and Izuho, M., 2013, The geochemistry of the major sources of archaeological obsidian on Hokkaido Island (Japan): Shirataki and Oketo, *Archaeometry*, **55**, 355–69.
- Le Bas, M. J., Le Maitre, R. W., Streckeisen, A., and Zanettin, B., 1986, A chemical classification of volcanic rocks based on the total alkali-silica diagram, *Journal of Petrology*, **27**(3), 745–50.
- Lustrino, M., and Wilson, M., 2007, The circum-Mediterranean anorogenic Cenozoic igneous province, *Earth-Science Reviews*, **81**, 1–65.
- Lustrino, M., Duggen, S., and Rosenberg, C. L., 2011, The central–western Mediterranean: anomalous igneous activity in an anomalous collisional tectonic setting, *Earth-Science Reviews*, **104**, 1–40.
- McDonough, W. F., and Sun, S.-S., 1995, The composition of the Earth, *Chemical Geology*, **120**, 223–53.
- Mertens, D., 2003, *Selinus I. Die Stadt und ihre Mauern*, *Sonderschrift DAI Rom* **13**, Mainz.
- Morel, J. P., 2001, Aux origines du moulin rotatif? Une meule circulaire de la fin du VI^e siècle avant notre ère à Carthage, in *Techniques et sociétés en Méditerranée* (eds. J.-P. Brun and P. Jockey), 241–50, Collection L'Atelier méditerranéen, Paris.
- Nehring, F., Jacob, D. E., Barth, M., and Foley, S. F., 2008, Laser-ablation ICP–MS analysis of siliceous rock glasses fused on an iridium strip heater using MgO dilution, *Microchimica Acta*, **160**, 153–63.
- Santi, P., Renzulli, A., and Gullo, R., 2013, Archaeometric study of the hopper-rubber and rotary Morgantina-type volcanic millstones of the Greek and Roman periods found in the Aeolian archipelago (southern Italy), *European Journal of Mineralogy*, **25**, 39–52.
- Spatafora, F., 1993, Un gruppo di macine da Monte Castellazzo di Poggioreale, in *Studi sulla Sicilia Occidentale in onore di Vincenzo Tusa* (eds. J. de La Genière et al.), 165–71, Aldo Ausilio Editore, Padova.

- Sun, S.-S., and McDonough, W. F., 1989, Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes, in *Magmatism in the ocean basins* (eds. A. D. Saunders and M. J. Norry), 313–45, Special Publication, Geological Society of London, London.
- Wefers, S., 2011, Still using your saddle quern? A compilation of the oldest known rotary querns in Western Europe, in *Bread for the people: the archaeology of mills and milling. Proceedings of a colloquium held in the British School at Rome, 4th–7th November 2009* (eds. D. Peacock and D. Williams), 67–76, British Archaeological Reports, International Series, **2274**, Archaeopress, Oxford.
- Wefers, S., 2012a, *Latènezeitliche Mühlen aus dem Gebiet zwischen den Steinbruchrevieren Mayen und Lovosice*, Monographien des RGZM, **95**, Mainz.
- Wefers, S., 2012b, Reibst Du noch oder drehst Du schon? Die ältesten bekannten Drehmühlen des westlichen Europa, in *Technologieentwicklung und -transfer in der Hallstatt- und Latènezeit. Beiträge zur Internationalen Tagung der AG Eisenzeit und des Naturhistorischen Museums, Prähistorische Abteilung—Hallstatt 2009* (eds. A. Kern, J. K. Koch, I. Balzer, J. Fries-Knoblach, K. Kowarik, C. Later, P. C. Ramsel, P. Trebsche and J. Wiethold), 13–24, Beiträge zur Ur- und Frühgeschichte Mitteleuropas, **65**, Langenweißbach.
- White, D., 1963, A survey of millstones from Morgantina, *American Journal of Archaeology*, **67**(2), 199–206.
- Williams-Thorpe, O., 1988, Provenancing and archaeology of Roman millstones from the Mediterranean area, *Journal of Archaeological Science*, **15**, 253–305.
- Williams-Thorpe, O., and Thorpe, R. S., 1990, Millstone provenancing used in tracing the route of a fourth-century BC Greek merchant ship, *Archaeometry*, **32**, 115–37.

Web references

Georem database: <http://georem.mpch-mainz.gwdg.de/>
 GEOROC database: <http://georoc.mpch-mainz.gwdg.de/georoc/>

Supplementary material

Additional Supplementary material may be found in the online version of this paper on the publisher's website:

Supplementary references.

- Figure S1. Sample 26, theoleiite group.
- Figure S2. Sample 29, alkaline group.
- Figure S3. Sample 9, alkaline group.
- Figure S4. Sample 4, latite group.
- Figure S5. Sample 19, andesite group.
- Figure S6. Sample 11, high alkali basaltic andesite group.
- Figure S7. Sample 10, high alkali basaltic andesite group.
- Figure S8. Sample 6, shoshonitic latite.
- Figure S9. Sample 16, basaltic andesite.
- Figure S10. Sample 23, shoshonite.