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Volcanic Grinding Tools in Ustica Island (Tyrrhenian Sea, Italy): Local Production vs. Import of Morgantina-Type Millstones in the Hellenistic-Roman Period

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Abstract: This archaeometric study was focused on 28 grey to dark-grey lava artifacts found in Ustica Island (Southern Tyrrhenian Sea, Italy) and referable to different grinding tools: saddle querns, rotary Morgantina-type millstones, rotary hand-mills and one small mortar. Mineralogy, petrography and bulk rock geochemical analyses emphasized that most of the grinding artifacts belonged to the Na-Alkaline series of Ustica, mainly basalts, hawaiites and mugearites. Nevertheless, some millstone samples did not match major and trace elements of Ustica lavas, in particular, one high-TiO_2 Na-Alkaline basalt from Pantelleria Island, some tholeiitic/transitional basalts from the Iblei Mountains and one Calcalkaline basaltic andesite, most likely from the Aeolian Archipelago. The Hellenistic–Roman re-colonisation of Ustica Island, after ca. one millennium of nearly complete abandonment, was testified by the import of the non-local Morgantina-type rotary millstones, very widespread in the Mediterranean area from 4th–3rd century BC. This import of millstones represented, for the Ustica inhabitants, a real breakthrough for developing a local production of grinding artifacts on the basis of the new rotary technique which was much more efficient than that of the archaic saddle querns, largely used in the Middle Bronze Age. The results are also discussed in the framework of the overall volcanic millstone trade in the Mediterranean area and the different milling technology in antiquity.

Keywords: grinding tools; lavas; magmatic series; Hellenistic–Roman period; Morgantina-type rotary millstones; trade; Mediterranean; Sicily; Ustica

1. Introduction

Most of the millstones for grinding cereals in antiquity and discovered throughout the Mediterranean area were made of volcanic rocks, with a widespread trade mostly in the Hellenistic Greek and Roman period [1–10]. However, long-distance volcanic millstone trade is also testified in the Phoenician–Punic period both in shipwrecked cargoes and terrestrial archaeological sites [11,12]. Grinding stones occurred in settlements and quarries in a variety of shapes used as base-stones (oval/suboval, rectangular, triangular and other irregular shapes) since the Late Palaeolithic Period [13].

Lavas are particularly suitable for millstones because of their abrasive property and rough vesicular surface [14,15], providing good grinding capacity [16,17]. As a matter of fact, the wear resistance of lavas made some volcanic lithotypes also suitable as flagstones in antiquity [18–20]. Among the different milling techniques (Figure 1) the most archaic millstones are represented by both flat and saddle querns [21], with examples in Cyprus and Israel from the Middle–Late Bronze Age and Iron Age [22] and also from the Upper Palaeolithic Period [13,23]. In the early 7th century BC, saddle querns underwent some refinements in their shape and in the method of working the upper stone [24]. At the beginning of the 5th century BC, a major innovation in grain milling took place somewhere in Greece, with the development of hopper mills operating on reciprocal motion (as had the saddle querns); the upper stone was widened and now had a central cavity cut large enough to receive a fair quantity of grain [16,24]. The hopper-rubber, as it is often called, had a narrow slit running the length of the stone, allowing the grain to fall through to the lower grinding slab, where it was crushed when the upper stone was worked in a back-and-forth motion [24]. Millstones of this type, as found at Priene, Delos and Thera (Greece), were eventually replaced by more advanced types of hopper mills with a rectangular shape, of which the best examples come from Olynthus (northern Greece); due to this circumstance, they are referred to as Olynthian-type millstones [16,24,25]. These millstones were worked by means of a wooden handle used as a lever, which was placed across the top of the upper stone and held in place by two shallow slots cut into the rim at the two shore ends [26]. With the Olynthian hopper-rubber millstones, the milling technology switched in flour production from domestic use to a more mechanized one. These millstones continued to be used, at least in the eastern Mediterranean, until Romanization (between 1st century BC and 1st century AD [27]).

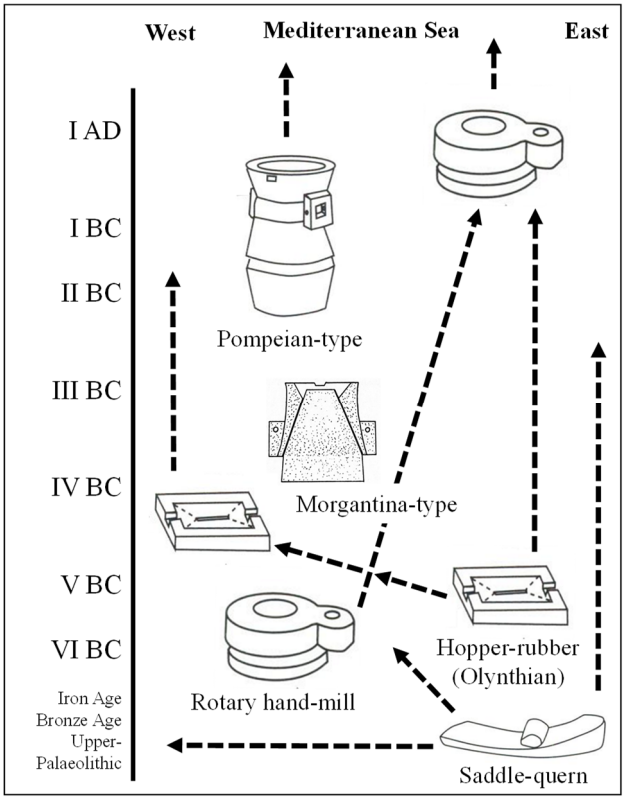


Figure 1. Sketch diagram showing the chronology of appearance of the different milling techniques in antiquity and their inferred diffusion throughout the Mediterranean Sea (roughly from East to West and vice versa). See also text (introduction section) for a more detailed framework of their first appearance and trade.

As a further technological advancement, the invention of rotary millstones replaced the inefficient back and forth motion with a continuous rotating movement. With regard to the origin of the rotary millstones, one group, dating back to the late Iron Age, consisted of small devices that could be powered by a single person (rotary hand-mill [28]). Although the origin of the rotary motion for milling is still debated, it is very likely that the rotary hand mill is an Iberian cultural innovation, invented in the north-east of the Iberian Peninsula and south of France during the end of the 6th or beginning of the 5th century BC [21,29]. Another kind of rotary millstone, termed the Morgantina-type, had to be operated by one or two people because of their larger size [16]. They were characterized by a lower stable portion (meta) and an upper rotating stone (catillus). These are known in Sicily both in the Phoenician settlement of Motya (5th–4th centuries BC), and in the Greek site of Morgantina (4th–3rd centuries BC [24]). An additional evolution of the rotary milling technique was undoubtedly represented by the hourglass Pompeian-type millstones. These latter are larger and animal-driven with respect to the man-powered Morgantina-type [26]. While both are formed with a lower stable portion (meta), they differ in the upper rotating catillus, which is perfectly reversible in the Pompeian millstones, consisting of two equal cones joined at their apices with a typical hourglass profile. In contrast, the Morgantina-type catillus (not reversible) shows two sockets "projecting like large ears" [26] at either side of the stone into which wooden beams were fitted. It is worth noting that the Morgantina-type mill should be regarded as a prototype [26] rather than as a slightly older and reduced version of the Pompeian mills, dating to the 2nd and, primarily, 1st century BC [24,30–32].

The present study deals with a comprehensive petrographic and geochemical study of 27 grinding stones (large saddle querns, rotary Morgantina-type millstones and rotary hand-mills) and one small mortar, all sampled in Ustica Island (Table 1).

Table 1. Summary of the investigated grinding stones, showing the different milling techniques (millstone type) and their locality of sampling in Ustica Island.

Civic and Archaeological Museum (Courtyard)	Piano Dei Cardoni Area (Private Properties)	Prehistoric Villaggio Dei Faraglioni (Warehouse)
UST1: Meta (rotary Morgantina-type)	UST12,Catilli (rotary Morgantina-type)	UST21: Meta (rotary Morgantina-type)
UST2: Catillus (rotary Morgantina-type)	UST14: rotary hand-mill	UST22, UST23, UST24, UST28: Catilli (rotary Morgantina-type)
UST4, UST5: Saddle querns		UST25, UST26, UST27: Rotary hand-mills
Between the Falconiera Tuff Cone and the Tramontana area (Private Properties)		**Punta Spalmatore (Private Property)**
UST6, UST17, UST18: Catilli (rotary Morgantina-type) UST8, UST10, UST11: Metae (rotary Morgantina-type) UST9, UST15, UST16, UST19, UST20: rotary hand-mills UST7: small mortar		UST29: Catillus (rotary Morgantina-type)

Studying volcanic millstones used in antiquity is generally aimed at the provenance of the raw material (lavas), because these artefacts are often found in terrestrial archaeological sites or shipwrecked cargoes hundreds of kilometres away from potential volcanic exploited areas. It is therefore possible to link a volcanic rock to a specific volcano provenance using the major-trace elements' geochemistry. In contrast, it is very difficult, or often impossible, to detect the source rocks for stone tools of sedimentary origin (e.g., sandstones), especially if not belonging to the local stratigraphic sequence. Distinguishing the millstone provenance from particular volcanic areas or volcanoes can lead to outlining commercial routes in the Mediterranean (often sea-trade) and cultural exchanges. Focusing the study on lava millstones found within a volcanic island (i.e., Ustica), our investigation could be poorly stimulating, as suitable lavas to manufacture grinding stones are already present in the volcanic island itself. Nevertheless, people living in a volcanic island could have abundant raw material

(i.e., vesicular lavas) but could not produce more efficient grinding stones if the evolution in milling technique developed elsewhere was precluded by the absence of trade and cultural contacts with people outside that island. A working hypothesis that archaic saddle querns of Middle Bronze Age settlements (e.g., Villaggio dei Faraglioni) are autochthonous both in technology and raw material could be plausible for the relatively poor exchanges in that period. By contrast, the flourishing trade in the Hellenistic–Roman period should have allowed the people of Ustica to become aware of a new milling technique such as the Morgantina-type rotary millstones.

2. Ustica Island

2.1. Prehistoric and Historic Background

Ustica Island has been inhabited from the Neolithic period, around the 6th millennium BC, as demonstrated by the discovery of ceramic and lithic finds on a hill overlooking the sea near Punta Spalmatore on the south-western side of the island (Figure 2, [33]). This was probably the first human settlement founded by colonizers from the Palermo coast [33]. In the same area of Spalmatore, the human occupation seems to have continued without interruption until the Bronze Age [33,34]. Nevertheless, evidence of prehistoric settlements can be found across almost the whole island in the form of abundant ceramic finds, obsidian splinters and tools imported from Lipari and Pantelleria, and the remains of huts, the latter in sites where excavations were made [34–38]. Other important settlements comprise the Copper Age (or Eneolithic) horizon (4th–3rd millennium BC) found at Piano dei Cardoni, on the south-eastern side of the island; the Early Bronze Age (3rd–2nd millennium BC) at the central hill called Colunnella (238 m a.s.l.); and the Middle Bronze Age (14–13th century BC) at Villaggio dei Faraglioni, which represents the largest and richest prehistoric settlement brought to light so far [34,35,39]. After the sudden and still unexplained abandonment of the Middle Bronze Age Villaggio dei Faraglioni around 1200 BC, the island remained uninhabited for many centuries [40,41]. Between the 4th and 3rd century BC, during the Hellenistic–Roman period, there is evidence of the re-colonization of the island. A large settlement with nearby necropolis flourished on the Rocca della Falconiera, the top of an extinct tuff cone volcano, 157 m a.s.l. in the north-eastern corner of the island. The choice of that isolated position, exposed to winds and bad weather, must have been prompted by defensive needs and by the possibility of controlling the main natural harbour of the island, Cala S. Maria [34,35]. Among the most significant finds recovered from the Rocca della Falconiera are abundant ceramic table vases and transport vases, most of which datable between the 3rd and 1st century BC, along with bronze necklaces and coins. In the flat areas along the western side of the Rocca della Falconiera, some smaller settlements of the same period have been found, probably of agricultural vocation [34,35].

The Morgantina-type millstones (metae and catilli), many of which are nowadays kept in museums and warehouses or exhibited in villas and private lands as ornamental objects, belong to the Hellenistic–Roman period. A few centuries later, in the Late-Roman and Byzantine Age, it seems that a more widespread occupation of the island occurred, as emphasized by the ruins of some villages and by the abundance of ceramic finds dating from the 5th to 6th century AD, scattered in the Petriera, Tramontana and Spalmatore areas.

2.2. Geology, Petrography and Geochemistry

Ustica Island is the emerging top of a volcanic seamount that rises more than 2000 m from the bottom of the Tyrrhenian Sea and lies on a thinned continental crust (15–20 km, [42]), ca. 60 km north of the Sicily coast and ca. 160 km west of the Aeolian Arc Archipelago (Figure 2). The island covers an area of 8.6 km^2 and reaches a maximum elevation of 248 m a.s.l. It mainly consists of volcanic rocks and subordinately of marine and continental sedimentary deposits. Volcanic rocks are the product of both subaqueous and subaerial effusive and explosive eruptions [43–47]. Marine sedimentary rocks were deposited during Middle-Upper Pleistocene sea level high-stands related to glacio-eustatic movements,

which also generated five orders of marine terraces [48], later displaced at variable elevations a.s.l. by tectonic activity [46]. The continental sediments are landslide and slope deposits related to the more recent geomorphological evolution of the island [45].

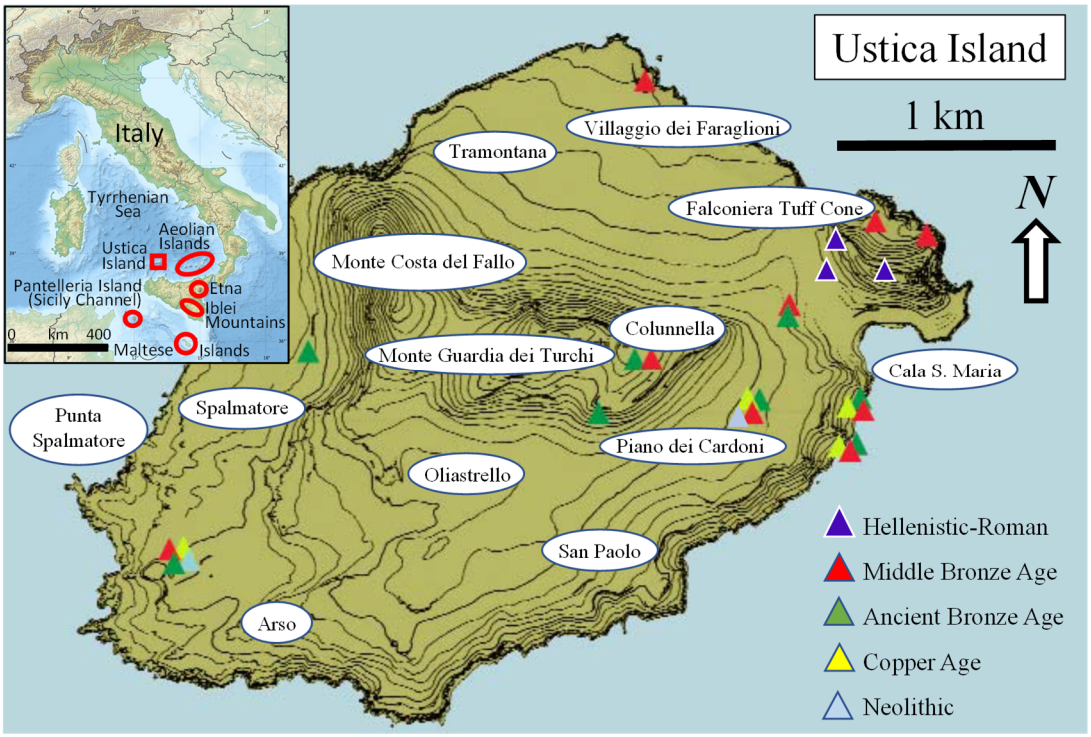


Figure 2. Ustica Island with the location of the most important archaeological sites (from [35], modified).

The Ustica volcanics have an Na-Alkaline affinity, ranging in composition from basalt to trachyte with a compositional gap in the field of benmoreites (55–60 wt% SiO_2 [45,49]. Incompatible trace elements and rare earth elements (REE) patterns, respectively normalized to primordial mantle and chondrites, generally define, for the Ustica volcanic rocks, an anorogenic (intraplate) ocean island basalts (OIB) alkaline series [49]. In particular, the Ustica basalts have incompatible elements and Sr-isotope ratios that are intermediate between the intraplate basalts of the African plate (Sicily Magmatic Province sensu [49]) and the calcalkaline mafic rocks from Alicudi, the westernmost island of the subduction-related Aeolian Volcanic Arc. This has led to the conclusion that the source of Ustica magmas is an intraplate-type mantle contaminated by subduction fluids or melts [44]. The textures of the Ustica mafic rocks [44] are variably porphyritic, with phenocrysts of olivine, weakly zoned plagioclase and clinopyroxene (from diopside to salite) in decreasing order of abundance. Fe-Ti oxides are generally found as microphenocrysts in the most differentiated terms.

Recent stratigraphic, structural and geochronological studies have demonstrated that the exposed rocks were erupted between 750 and 130 kyr [47]. The emersion of the island is strictly related to the birth of the subaerial basaltic strato-volcano of Monte Guardia dei Turchi (Figure 2) at about 520 kyr [47], whose initial eruptions occurred while still underwater, forming pillow-lava flows. The subaerial volcanic activity continued with the formation of the Monte Costa del Fallo basaltic tuff-cone and a series of moderately explosive and effusive eruptions, the most recent of which occurred at 475 kyr, along the western flank of Monte Costa del Fallo [47]. After a 50-kyr-long period of quiescence, during which there was the possibility for magma to differentiate in a shallow magma chamber, volcanism restarted at 425 kyr with the explosive (likely sub-Plinian) eruption of the Grotte del Lapillo Tephra [47]. This was a unique episode in the history of the island for which there is evidence that trachytic magma was produced. The explosive eruption took place in the present Tramontana plain (Figure 2) and was associated with the formation of a small caldera-type depression in the northern sector of the island.

After this activity, volcanism continued with small magmatic and phreatomagmatic basaltic eruptions fed by vents in the western sector of the island and the production of basaltic and mugearitic lava flows (Gorgo Salato and Tramontana Lavas [45,47]) that filled the Tramontana depression. The island's volcanic activity ended at around 130 kyr with an explosive phreatomagmatic eruption and the formation of the asymmetric Falconiera tuff cone, which is the most easily recognizable Ustica volcanic edifice [50].

3. Materials and Methods

In order to determine the provenance of the volcanic raw materials, 27 very small (<<1 cm^3) rock fragments of different mills and one mortar were collected using a chisel. All the investigated grinding tools did not derive from a unique archaeological excavation stricto sensu. In contrast, they were originally found in private properties close to superficial archaeological contexts or in the most important archaeological sites of Ustica Island (Figure 2). Nowadays, they are stored in (i) the warehouse of the Prehistoric Villaggio dei Faraglioni, (ii) the courtyard of the Civic and Archaeological Museum or (iii) simply left in the private properties themselves (Table 1). In this way, all the investigated millstones were dated on the basis of the millstone typology (i.e., the milling technique; Figure 1). The representative sampling included saddle querns (Figure 3a), rotary Morgantina-type (Figure 3b,c) and rotary hand-mills (Figure 3d).



Figure 3. Representative millstone types found in Ustica Island: (**a**)—large saddle quern; (**b**)—meta of a rotary Morgantina-type millstone; (**c**)—catillus of a rotary Morgantina-type millstone with a damaged (lacking) lower part; (**d**)—rotary hand-mill. See text (materials and methods section) for the archaeological contexts.

Some artefacts (n.12) were stored in the courtyard of the Civic and Archaeological Museum "Padre Seminara" of Ustica and in the warehouse of the Middle Bronze Age Villaggio dei Faraglioni. The other samples (n.16) came from the private properties of the island. In particular, we analysed two saddle-querns, five metae, eleven catilli, nine rotary hand-mills and one small mortar (Table 1). All the

mills were made of grey to dark-grey lavas, showing moderate degrees of vesicularity (vesicles from 5 to 20 vol.% and up to 4 mm across) and a variable porphyricity (see Section 4.1). The large saddle querns of Ustica consisted of an elliptical base (*ca.* 80 × 50 cm) with a thickness of about 40–50 cm (Figure 3a), very different with respect to the typical saddle querns with a thin and flat lower portion (*ca.* 30 × 40 cm). Some of these artefacts, still well preserved, were located in the Prehistoric Villaggio dei Faraglioni. The Morgantina-type rotary millstones were represented by more or less well preserved metae and damaged, fractured catilli. In the Civic and Archaeological Museum, a well preserved catillus (*ca.* 50 cm in diameter) was found, coupled with a meta (probably not the original one of the complete mill device), for a total height of the millstone of ca. 60 cm. Obviously, the metae were best preserved and recognizable with respect to the more fragile hourglass shape catilli with their "sockets" necessary for facilitating the manual rotation of the upper part of the mill. The observed size of the different parts (catilli and metae) of the Morgantina-type millstones were in agreement with those reported in literature [26]. The rotary hand-mills were all located in private properties, with a diameter varying between 34 and 43 cm. Additionally, the small mortar (diameter ca. 35 cm) was collected in a private house.

Thin section analyses for the modal mineralogy and petrography were performed using a polarizing light optical microscope (Nikon Optiphot2-Pol). In order to define whole-rock chemistry, the samples were crushed and powdered in an agate mortar to avoid contamination. The concentration of major oxides (wt%) and a complete set of trace elements (ppm) were measured at the Activation Laboratories Ltd. (Ancaster, Ontario, Canada). The powdered samples were digested by lithium metaborate/tetraborate fusion. The major and trace element concentrations were then determined using ICP-OES (Inductively Coupled Plasma-Optical Emission Spectrometry) and ICP-MS (Inductively Coupled Plasma-Mass Spectrometry) techniques, respectively. Duplicate analyses were performed for some samples. For most of these elements, the 2σ values of the errors, calculated using a series of certified natural rock standards were similar to the differences between the duplicates.

4. Results

4.1. Chemical Classification and Petrography

According to the IUGS recommendations [51], in order to achieve a correct chemical classification of the investigated lava millstones, we plotted, on an anhydrous basis, the compositional data (Tables 2–4) in the total alkali ($Na_2O + K_2O$) vs. silica (SiO_2) diagram (TAS, [52]; Figure 4). All these data were coupled with thin section modal mineralogy and petrography (texture), therefore using the fundamental igneous petrology approaches to investigate the volcanic rocks.

In the TAS classification diagram, we can observe three groups: 23 samples are within the basalt and trachybasalt fields, 4 samples fall in the basaltic trachyandesite field and finally only one is a basaltic andesite (Figure 4a). According to their major elements, we can emphasize that most of the samples (full circles in Figure 4b) display Na_2O minus 2 ≥ K_2O. This and other chemical parameters (K_2O/Na_2O ratio 0.2–0.4, Na_2O 2.9–5 wt%) strongly support an Na-Alkaline series, from basalts to hawaiites and mugearites (Tables 2 and 3). Among the Na-Alkaline samples, UST28 (black full circle in Figure 4b), which is comparable for its alkali content (Na_2O 2.9 wt%, K_2O 0.8 wt%) with all the other Na-Alkaline samples (grey full circle in Figure 4b), is however characterized by a very high TiO_2 content (2.7 wt%), and therefore it can be distinguished from all the other basalts (TiO_2 1.4–2 wt%; Table 2). UST28 consists of a seriate porphyritic texture (Porphyritic Index, P.I., 10%–15%) in an oxidized microcrystalline intergranular groundmass. The phenocrysts and glomeroporphyritic aggregates consist of plagioclase, olivine and clinopyroxene, whereas the opaque minerals are the main accessory phase in the groundmass (Figure 5a). The main group of Na-Alkaline basalts (Table 2) are characterized by Na_2O 2.9–3.7 wt%, K_2O 0.7–1.4 wt%, MgO 3.6–6.1 wt% and a porphyritic texture (I.P. 10%–20%). The paragenesis is constituted by phenocrysts of plagioclase, olivine and clinopyroxene (reaching 5.6, 2.2 and 2.5 mm respectively), with opaque minerals as accessory phases, dispersed in

a microcrystalline groundmass with an intergranular-pilotassitic texture (Figure 5b,c). The hawaiite group of lavas (Table 3) shows a seriate porphyritic texture (P.I. 10%–15%) in a micro to criptocrystalline groundmass containing plagioclase, olivine, clinopyroxene and opaque minerals (Figure 5d). Some glomeroporphyritic aggregates are also detected. Finally, the four mugearites samples (Table 3) are characterized by lower porphyricity (P.I. 5%–10%) with phenocrysts of plagioclase, olivine and accessory opaque minerals in a cryptocrystalline to glassy groundmass (Figure 5e).

Table 2. Major (wt%) and trace elements (ppm) contents of the investigated millstones—basalts of the Na-Alkaline series.

	Basalts										
Sample	**UST4**	**UST5**	**UST10**	**UST11**	**UST17**	**UST20**	**UST22**	**UST23**	**UST24**	**UST26**	**UST28**
											High-TiO_2
SiO_2	48.52	49.13	49.51	49.28	49.10	48.29	49.44	50.03	48.28	49.73	48.08
TiO_2	1.41	1.48	1.54	1.37	1.56	2.04	1.47	1.53	1.88	1.50	2.71
Al_2O_3	18.84	18.77	18.16	17.82	16.60	16.78	18.37	18.84	17.58	19.42	15.76
Fe_2O_3(t)	9.90	9.28	9.39	9.92	12.63	12.15	9.09	9.31	11.27	8.60	12.34
MnO	0.14	0.12	0.14	0.15	0.19	0.16	0.14	0.14	0.15	0.14	0.16
MgO	4.40	3.58	4.89	5.02	5.47	5.91	4.43	4.40	6.08	3.73	6.07
CaO	10.61	11.07	9.90	10.47	8.79	9.78	10.49	9.90	8.98	9.77	11.14
Na_2O	2.92	3.12	3.56	3.21	3.65	3.39	3.33	3.40	3.65	3.68	2.89
K_2O	1.22	1.34	1.20	1.29	0.66	0.81	1.18	1.22	1.09	1.44	0.78
P_2O_5	0.54	0.58	0.60	0.56	0.29	0.72	0.75	0.62	0.72	0.71	0.53
LOI	1.89	1.98	0.71	1.10	1.12	0.65	1.22	0.94	0.67	0.35	−0.15
Total	100.4	100.4	99.61	100.2	100.1	100.7	99.91	100.3	100.3	99.06	100.3
K_2O/Na_2O	0.42	0.43	0.34	0.40	0.18	0.24	0.35	0.36	0.30	0.39	0.27
V	205	211	210	209	301	234	209	213	200	224	296
Cr	240	230	100	260	310	200	110	100	170	40	150
Co	34	27	29	37	53	41	26	27	37	23	43
Ni	140	90	80	120	190	130	70	60	140	30	80
Rb	29	34	29	32	13	14	27	28	21	29	12
Sr	946	967	830	887	397	831	801	831	903	912	473
Y	24	27	24	23	36	23	23	24	23	24	19
Zr	125	130	129	127	98	133	127	133	160	149	145
Nb	37	39	34	37	21	39	32	35	49	42	30
Ba	605	1221	462	775	342	493	514	565	590	602	252
La	48.6	57.1	41.6	50.8	65.7	43.5	40.4	43.2	54.4	53	22
Ce	86.3	87.2	76.3	83.6	74.4	79.9	71.9	77.5	98.4	93.7	45.5
Pr	9.34	10.2	8.43	9.5	9.87	8.81	7.94	8.55	10.4	9.94	5.69
Nd	35.3	37.6	31.7	34.5	36.1	33.3	30.2	31.9	38.6	35.8	24
Sm	6.8	7.3	6.7	6.7	7.3	7	5.9	6.5	7.2	7.2	5.8
Eu	2	2.28	2.06	2.11	2.17	2.25	1.91	2.14	2.32	2.03	2.12
Gd	5.7	6.3	5.7	6	8.1	6.6	5.4	5.9	6.5	6	5.6
Tb	0.8	1	0.9	0.9	1.2	0.9	0.8	0.9	1	0.9	0.8
Dy	4.7	5.4	4.9	4.8	6.8	5.1	4.6	4.8	5.1	5.1	4.4
Ho	0.9	1	0.9	0.9	1.3	0.9	0.9	0.9	0.9	0.9	0.8
Er	2.5	2.7	2.5	2.5	3.4	2.5	2.5	2.7	2.6	2.5	2.2
Tm	0.37	0.38	0.35	0.37	0.45	0.34	0.32	0.35	0.35	0.35	0.29
Yb	2.3	2.4	2.2	2.5	2.8	2	2.2	2.2	2.3	2.2	1.8
Lu	0.34	0.34	0.37	0.38	0.43	0.29	0.31	0.36	0.33	0.32	0.26
Hf	2.3	2.7	2.8	2.7	2.1	2.9	2.6	2.7	3.1	2.9	3.2
Ta	1.8	1.8	1.7	1.8	1.1	1.9	1.5	1.6	2.4	2	1.9
Th	6.1	6.3	5.6	6.3	3.2	4.9	5.5	5.8	6.8	7.7	2.2
U	1.6	1.7	1.5	1.5	0.5	1.4	1.5	1.5	1.9	1	0.6
Zr/Nb	3.4	3.3	3.8	3.4	4.7	3.4	4.0	3.8	3.3	3.5	4.8
La/Yb	21.1	23.8	18.9	20.3	23.5	21.8	18.4	19.6	23.7	24.1	12.2
Sm/Yb	3.0	3.0	3.0	2.7	2.6	3.5	2.7	3.0	3.1	3.3	3.2
La/Sm	7.1	7.8	6.2	7.6	9.0	6.2	6.8	6.6	7.6	7.4	3.8

Table 3. Major (wt%) and trace elements (ppm) contents of the investigated millstones—hawaiites and mugearites of the Na-Alkaline series.

	Hawaiites						Mugearites			
Sample	**UST7**	**UST8**	**UST15**	**UST16**	**UST21**	**UST29**	**UST1**	**UST18**	**UST19**	**UST27**
SiO_2	49.31	49.11	49.71	49.23	50.22	49.03	53.26	53.05	52.87	54.10
TiO_2	1.57	1.58	1.49	1.53	1.59	1.75	1.23	1.33	1.34	1.20
Al_2O_3	19.34	20.54	18.27	18.95	20.12	17.05	17.32	17.51	17.53	17.87
Fe_2O_3(t)	9.15	9.25	9.27	8.86	9.16	10.56	9.02	9.54	9.83	8.69
MnO	0.15	0.10	0.14	0.11	0.11	0.15	0.16	0.16	0.16	0.16
MgO	4.19	1.74	4.23	3.45	2.49	5.96	3.83	4.32	4.46	3.63
CaO	10.21	9.60	9.89	10.30	9.66	8.91	6.82	7.25	7.13	6.84
Na_2O	3.63	3.75	3.80	3.58	3.89	3.79	4.77	4.71	4.65	4.98
K_2O	1.24	1.39	1.26	1.29	1.51	1.03	1.61	1.53	1.53	1.59
P_2O_5	0.61	0.64	0.56	0.83	0.64	0.67	0.77	0.67	0.64	0.61
LOI	0.76	1.70	0.98	1.60	1.24	0.58	0.84	0.38	0.38	0.52
Total	100.2	99.4	99.61	99.73	100.6	99.48	99.63	100.5	100.5	100.2
K_2O/Na_2O	0.34	0.37	0.33	0.36	0.39	0.27	0.34	0.32	0.33	0.32
V	446	231	204	226	219	190	128	137	140	288
Cr	80	60	90	90	50	200	120	130	130	120
Co	26	21	27	24	22	36	24	26	26	25
Ni	70	30	60	60	50	130	90	100	100	100
Rb	28	29	31	32	36	19	30	28	28	29
Sr	880	919	802	1003	914	928	702	711	671	728
Y	26	27	23	26	28	23	36	23	25	24
Zr	134	142	131	132	160	152	200	197	201	196
Nb	35	37	34	35	45	45	56	57	59	56
Ba	540	654	469	508	727	614	964	884	941	1002
La	52.4	55	41.9	45.6	60.8	52	85.8	62.8	66.8	70.8
Ce	82.1	86.4	75.7	79.7	96.7	92.5	128	107	109	110
Pr	9.38	10.4	8.19	9.15	11.1	9.93	13.6	10.7	11.3	11
Nd	34.2	38.2	31.2	35.1	38.5	37.1	48.2	37.6	38.2	37.6
Sm	7	7.4	6.2	7.2	7.5	6.9	8.7	6.7	7	7
Eu	2.11	2.33	2.03	2.12	2.23	2.25	2.67	2.16	2.24	2.29
Gd	6.3	6.2	5.8	6.1	6.4	6	7.7	5.6	5.9	5.8
Tb	0.9	1	0.9	0.9	0.9	0.9	1.1	0.8	0.9	0.8
Dy	5.3	5.5	4.9	5.3	5.3	4.6	6.3	4.7	5	4.5
Ho	1	1	0.9	1	1	0.9	1.2	0.9	1	0.9
Er	2.7	2.9	2.7	2.7	2.8	2.4	3.6	2.4	2.7	2.5
Tm	0.4	0.4	0.37	0.37	0.38	0.32	0.48	0.34	0.38	0.34
Yb	2.5	2.5	2.3	2.4	2.6	2	3	2.2	2.6	2.4
Lu	0.36	0.39	0.38	0.36	0.38	0.3	0.47	0.35	0.39	0.36
Hf	2.7	3	2.8	2.7	3.1	3	3.8	3.6	3.9	3.8
Ta	1.7	1.8	1.7	1.7	2	2.1	2.8	2.7	2.8	2.7
Th	5.8	6.3	5.9	5.8	7.7	6.4	10.3	9.6	10	9.9
U	1.7	1.9	1.5	1.7	2	1.7	2.7	1.9	2.5	1.4
Zr/Nb	3.8	3.8	3.9	3.8	3.6	3.4	3.6	3.5	3.4	3.5
La/Yb	21.0	22.0	18.2	19.0	23.4	26.0	28.6	28.5	25.7	29.5
Sm/Yb	2.8	3.0	2.7	3.0	2.9	3.5	2.9	3.0	2.7	2.9
La/Sm	7.5	7.4	6.8	6.3	8.1	7.5	9.9	9.4	9.5	10.1

Table 4. Major (wt%) and trace elements (ppm) contents of the investigated millstones—basalts of the tholeiitic/transitional series and basaltic andesite of the Calcalkaline series.

	Basalts						Basaltic Andesite
Sample	**UST2**	**UST6**	**UST12**	**UST13**	**UST14**	**UST25**	**UST9**
Series	**Tholeiitic/Transitional**						**Calkalkaline**
SiO_2	47.18	49.93	50.01	49.36	49.08	50.03	54.27
TiO_2	1.37	1.37	1.63	1.43	1.38	1.57	0.71
Al_2O_3	15.93	16.05	15.54	15.24	15.72	16.19	16.28
Fe_2O_3(t)	11.01	12.07	12.46	12.41	12.32	12.21	9.47
MnO	0.13	0.16	0.16	0.16	0.16	0.16	0.16
MgO	7.57	7.53	7.02	8.72	8.96	7.23	4.97
CaO	10.48	8.95	9.24	9.01	8.98	9.16	9.37
Na_2O	3.30	3.37	3.42	3.22	3.29	3.39	2.16
K_2O	0.47	0.49	0.58	0.47	0.44	0.52	2.14
P_2O_5	0.25	0.31	0.35	0.29	0.30	0.29	0.28
LOI	1.86	0.19	0.07	0.11	−0.18	−0.17	0.42
Total	99.55	100.4	100.5	100.4	100.4	100.6	100.2
K_2O/Na_2O	0.14	0.15	0.17	0.15	0.13	0.15	0.99
V	190	172	205	183	174	196	290
Cr	340	300	290	330	340	280	40
Co	49	49	44	52	51	45	28
Ni	270	260	200	280	290	190	30
Rb	6	9	11	8	7	9	61
Sr	511	377	382	374	383	373	876
Y	17	18	20	19	18	21	21
Zr	84	89	100	88	84	98	92
Nb	18	18	21	18	17	20	6
Ba	214	309	271	279	271	230	532
La	17.9	18.5	21.8	19	17.3	19.4	27.3
Ce	32.9	32.9	38.5	33.7	31.6	35.7	51.6
Pr	3.74	3.75	4.41	3.83	3.61	4.02	6.05
Nd	14.6	15.2	18	15.4	14.4	15.9	23.5
Sm	3.8	3.9	4.3	3.5	3.4	3.9	5.3
Eu	1.31	1.29	1.46	1.32	1.26	1.36	1.37
Gd	3.7	3.9	4.5	4	3.7	4.4	4.6
Tb	0.6	0.6	0.7	0.6	0.6	0.7	0.7
Dy	3.8	3.8	4.4	4	3.7	4.1	3.8
Ho	0.7	0.7	0.9	0.8	0.7	0.8	0.8
Er	2.1	2.1	2.2	2.1	2	2.2	2.3
Tm	0.31	0.31	0.31	0.28	0.28	0.3	0.32
Yb	1.9	1.9	2.2	1.7	1.8	1.8	2.1
Lu	0.27	0.28	0.33	0.26	0.27	0.28	0.33
Hf	1.9	1.9	2.3	1.9	1.8	2.2	2.3
Ta	0.9	0.9	1	0.9	0.8	0.9	0.4
Th	2.7	2.7	2.9	2.5	2.4	2.7	6.1
U	0.9	0.7	0.8	0.6	0.6	0.7	1.9
Zr/Nb	4.7	4.9	4.8	4.9	4.9	4.9	15.3
La/Yb	9.4	9.7	9.9	11.2	9.6	10.8	13.0
Sm/Yb	2.0	2.1	2.0	2.1	1.9	2.2	2.5
La/Sm	4.7	4.7	5.1	5.4	5.1	5.0	5.2

The second group of samples (full triangle in Figure 4b), even if they fall in the basalt field, belong to a tholeiitic/transitional series, being characterized by very low K_2O (0.4–0.6 wt%) and K_2O/Na_2O ratio (0.13–0.17) and higher MgO (7–9 wt%; Table 4). Petrographically, they show a porphyritic index of 10%–15%. The phenocrysts of plagioclase, olivine, clinopyroxene ± orthopyroxene have sizes of up to 3.0, 3.4, 1.5 and 1 mm, respectively (Figure 5f,g). The groundmass is microcrystalline, with a

widespread oxidation and some opaque minerals consisting of both mostly equidimensional magnetite and acicular prismatic ilmenite.

The UST9 basaltic andesite (full diamond in Figure 4b) is characterized by a K_2O 2.1 wt% and a K_2O/Na_2O ratio of 1.0 (Table 4) and thus with a clear sub-alkaline affinity. Thin section analyses show a phorphyritic texture (P.I. 10%–15%) with a micro to crypto-crystalline groundmass. The phenocrysts are plagioclase, clinopyroxene, ± orthopyroxene and olivine, with opaque minerals as the main accessory phase (Figure 5h).

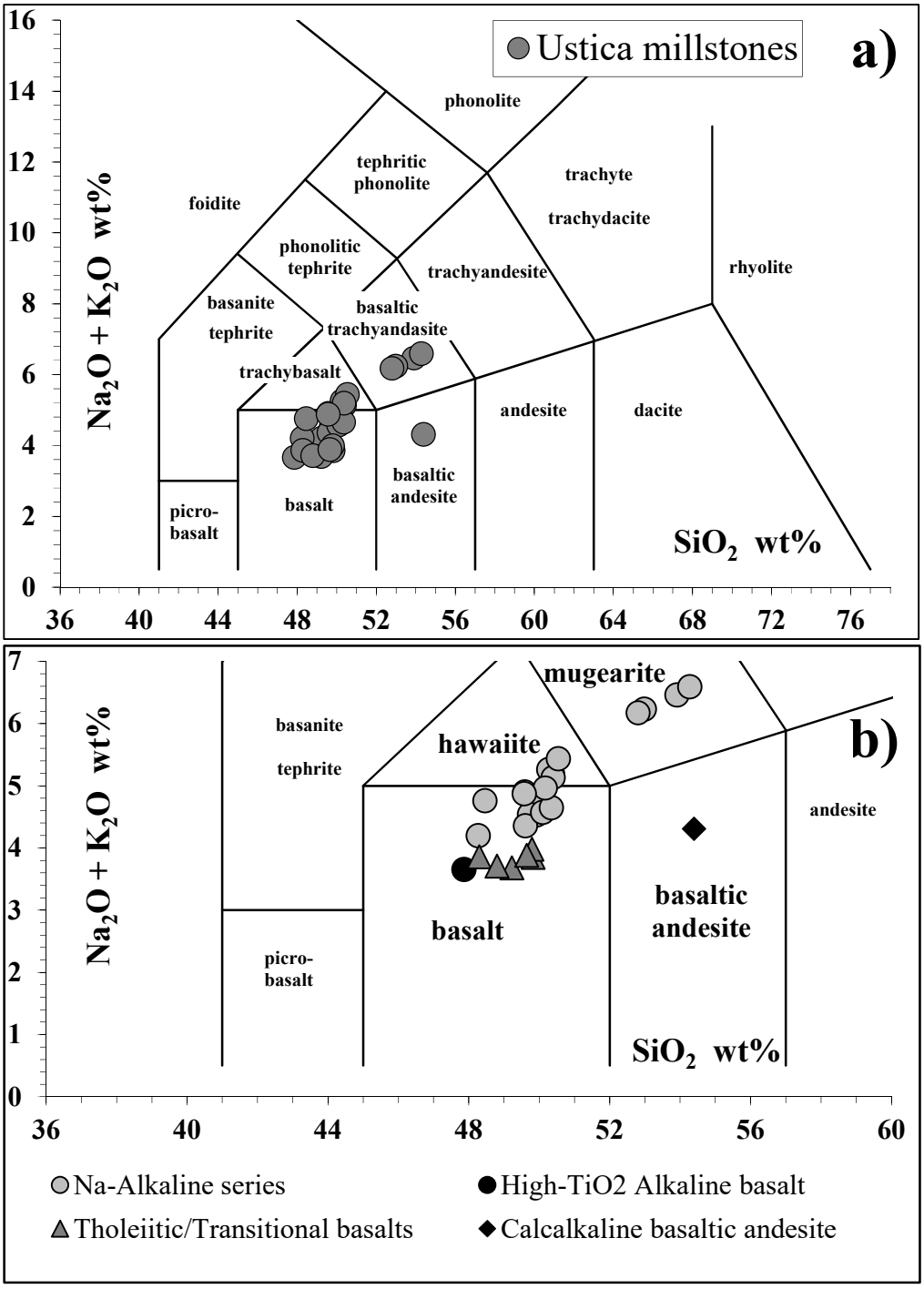


Figure 4. Total Alkali-Silica classification diagram [52]. The investigated millstones are reported as a whole (**a**) and following their magmatic series (**b**).

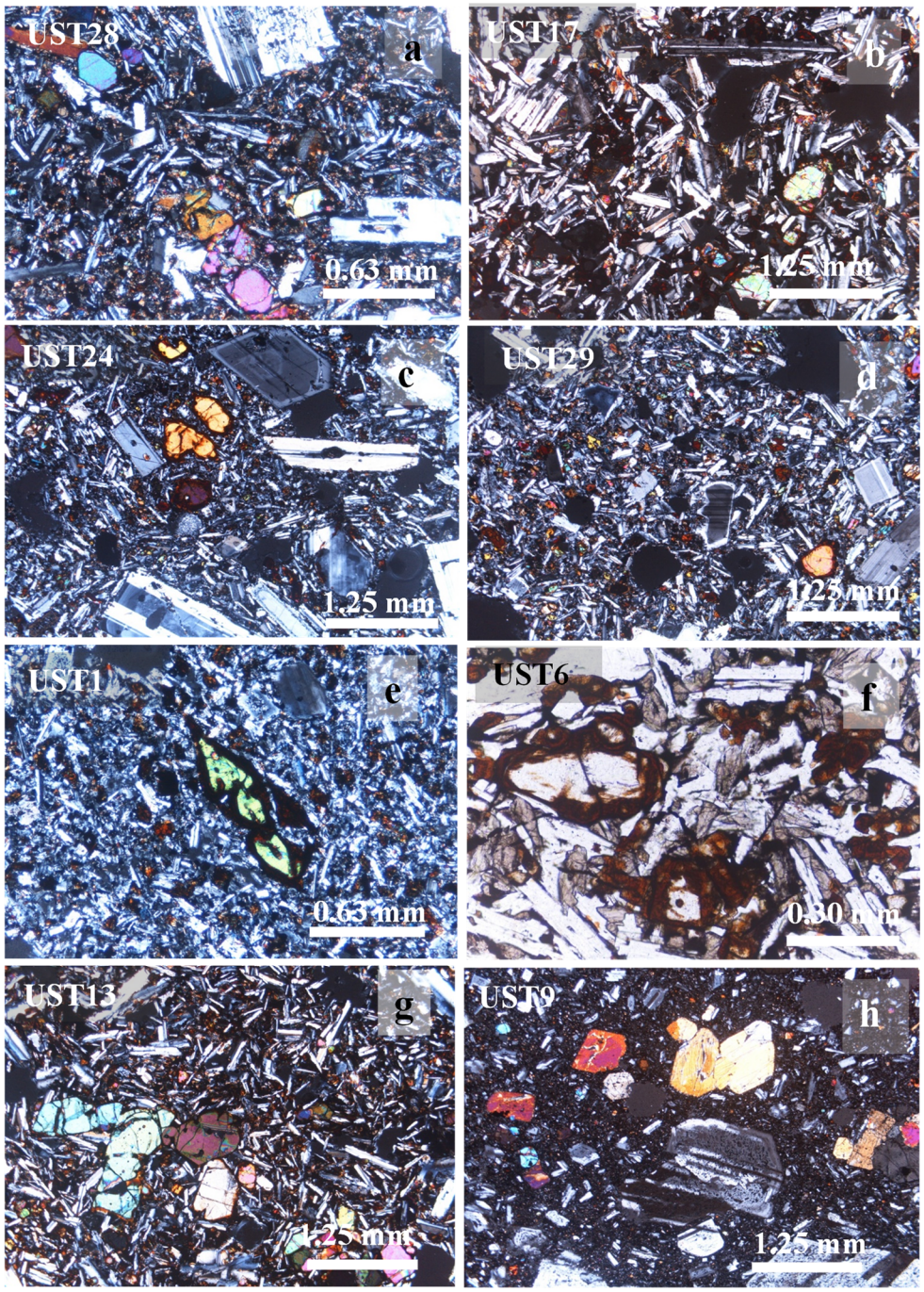


Figure 5. Thin section micrographs of the investigated volcanic millstones at the polarized light optical microscope (Plane Polarized Light, PPL or crossed nicols Polarized Light, XPL). (**a**)—High-TiO_2 alkaline basalt (XPL); (**b**,**c**)—basalts (XPL); (**d**)—hawaiite (XPL); (**e**)—mugearite (XPL) of the Na-Alkaline series; (**f**,**g**)—tholeiitic/transitional basalts (PPL and XPL respectively); (**h**)—Calcalkaline basaltic andesite (XPL).

4.2. Constraining Magma Series and Provenance Area

Trace element patterns in the investigated volcanic rock millstones clearly allowed us to confirm and better constrain the distinct magmatic series among the artefacts, previously inferred from their major oxide elements. In the normalized incompatible trace elements spider diagram (Figure 6a), all the samples of both the Na-Alkaline series (enriched in HFSE and LILE) and the tholeiitic/transitional series

(relatively depleted) show similar sub-parallel patterns, typical of anorogenic (ocean island basalts, OIB) volcanic rocks. The High-TiO_2 alkali basalt UST28 can be slightly distinguished from the main group of the Na-Alkaline series by its lower enrichment of LILE (Rb, Ba), Th, LREE (La, Ce, Nd,), HREE (Yb, Lu) and Y. The positive anomaly of Ti is straightforward (Figure 6a). The sub-Alkaline basaltic andesite UST9 clearly emphasizes a subduction related pattern, being characterized by Ta-Nb-Ti negative anomalies (Figure 6a), thus indicating a calcalkaline series. The Zr/Nb ratios are between 3.3 and 4.8 for the Na-Alkaline series and 4.7–4.9 for the tholeiitic/transitional basalts (Tables 2–4). These trace element ratios are strictly related to OIB volcanic rocks, well below the medium-high Zr/Nb ratios of typical MORB-tholeiitic basalts (Mid Ocean Ridge Basalts; cf., Figure 5a of [53]). In the rare earth elements (REE) normalized spider diagram (Figure 6b), the Na-Alkaline and tholeiitic/transitional series can be further constrained.

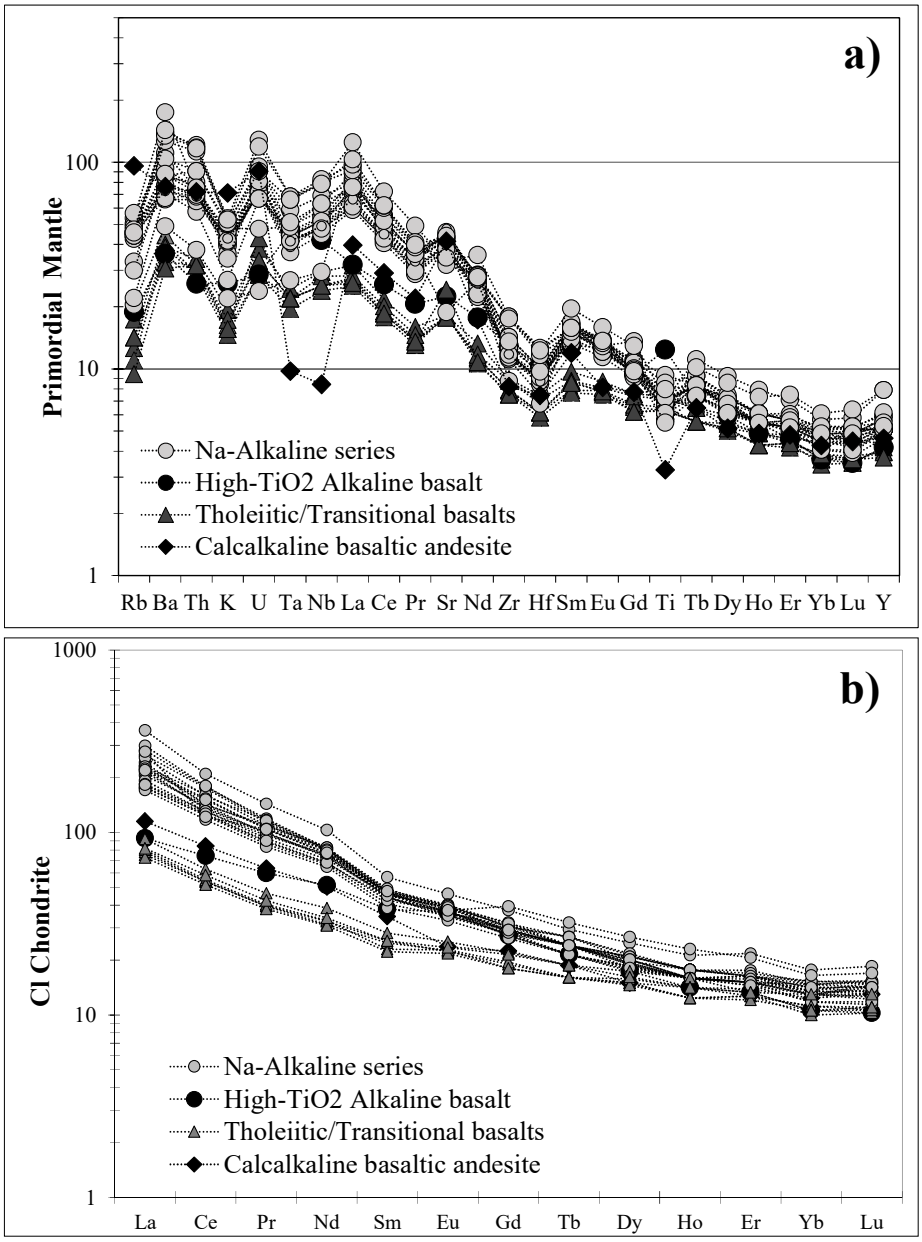


Figure 6. Incompatible trace elements (**a**) and rare earth elements (**b**) diagrams of the investigated millstones normalized to the primordial mantle (**a**) and CI Chondrites (**b**). Normalized values are from [54].

The REE patterns are similar to the highest enrichment for basalts, hawaiites and mugearites of the Na-Alkaline series. The REE slopes strongly increase in the Na-Alkaline series (La/Sm 6.2–10.1, La/Yb 18.2–29.5 and Sm/Yb 2.6–3.5; Tables 2 and 3) with respect to the tholeiitic/transitional series (La/Sm 4.7–5.4, La/Yb 9.4–11.2 and Sm/Yb 1.9–2.2; Table 4). The high-TiO_2 Na-Alkaline basalt (UST28) is characterized by lower LREE slopes (La/Sm 3.8) and intermediate La/Yb and Sm/Yb ratios (12.2 and 3.2 respectively; Table 2). The calcalkaline UST9 millstone shows an intermediate REE pattern between the two above described series, with a slight negative Eu anomaly (Figure 6b).

Except for the calcalkaline UST9 basaltic andesite, we selected major oxides and trace elements binary diagrams for testing the compositional compatibility of the volcanic millstones of Ustica with magmatic rocks of the Sicily Province consisting of Na-Alkaline and tholeiitic products [49]. This choice arose from the fact that most of the OIB volcanoes of the Central Mediterranean exploited in antiquity for the manufacture of lava millstones (in the period covering the 7th century BC to the Roman Empire [1,7,8,11,12,15]) were mainly located in Sicily (Etna and Iblei Mountains) and the Sicily Channel (Pantelleria and Linosa). In this way, we selected some major and trace elements to distinguish the provenance of the millstones among the Na-Alkaline and tholeiitic/transitional type volcanic rocks of Etna, the Iblei Mountains, Linosa, Pantelleria and Ustica itself. Among the literature database used for the comparisons [49], we excluded strongly silica-undersaturated lavas of the highly Na-Alkaline series (e.g., nephelinites and basanites of the Iblei Mountains) and rocks with $SiO_2 > 57$ wt%, as they were geochemically inconsistent with the investigated millstones.

In the binary diagram Zr vs. Nb (Figure 7a), the Ustica millstones of the Na-Alkaline series (UST28 included) overlap the compositional field of the Etna, Pantelleria and Ustica lavas, whereas the Linosa volcanic rocks can be ruled out. Although the Ustica millstones belonging to the tholeiitic/transitional series are very close to the lowest Zr-Nb rocks of the Iblei Mountains, a provenance from a few Etna lavas cannot be excluded (Figure 7a). The La/Yb vs. Sm/Yb diagram (Figure 7b) however clearly constrains that the Ustica millstones of the tholeiitic/transitional series are only compatible with the Iblei Mountains lavas. As a matter of fact, a tholeiitic/transitional series of the Iblei Mountains can be envisaged because of the overlapping of the incompatible trace elements and REE normalized patterns of the Na-Alkaline and tholeiitic series [49]. Concerning the artefacts of the Na-Alkaline series, they really come from Ustica Island itself, with the exception of the UST28 high-TiO_2 basalt, which mainly overlaps the Pantelleria lavas and a few Iblei Mountains samples (Figure 7b). This latter provenance area can however be ruled out for UST28 on the basis of the Nb vs. TiO_2 diagram (Figure 8). Thehigh-TiO_2 Na-Alkaline basalt millstone therefore belongs to the high TiO_2-low P_2O_5 basalts of Pantelleria (those with an age > 50 ka [55]). The high TiO_2-P_2O_5 basalt group of Pantelleria Island can be chemically distinguished from the low TiO_2-P_2O_5 basalt group (those with an age < 50 ka), the former being characterized by twice the incompatible trace element contents, including Sr, Y, Zr, Nb, Ba and LREE [55–57].

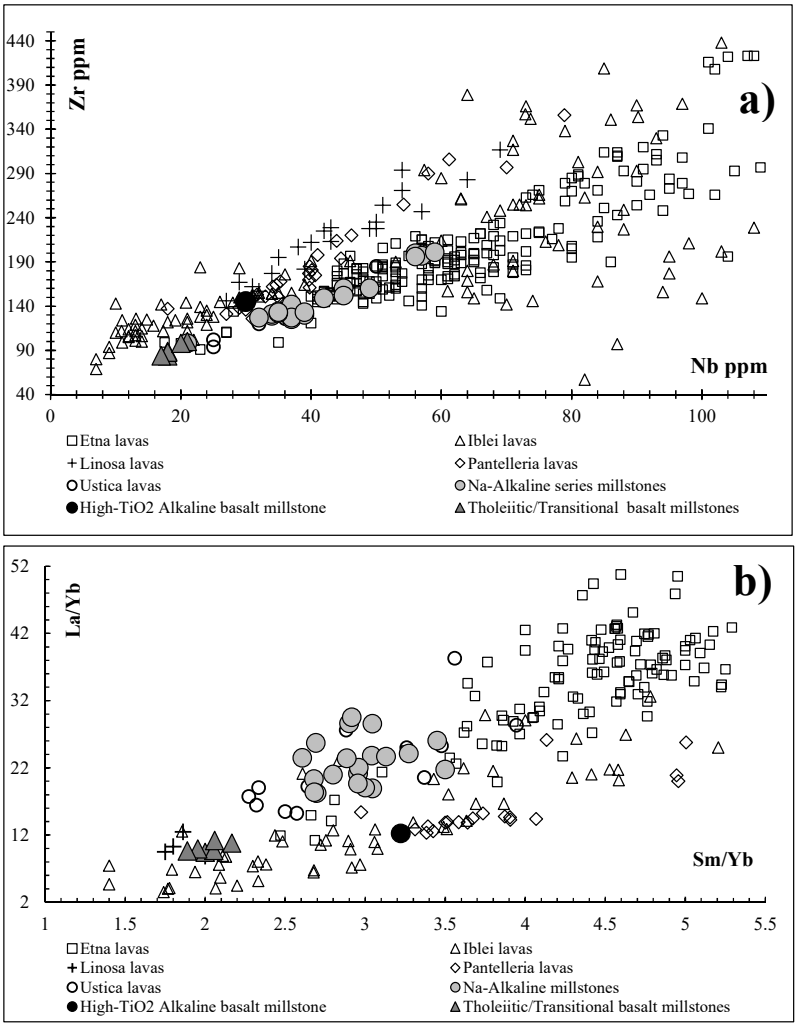


Figure 7. Nb vs. Zr (**a**) and Sm/Yb vs. La/Yb (**b**) diagrams comparing the investigated millstones with selected ocean island basalts (OIB) lavas from the Mediterranean—Etna, Iblei, Linosa, Pantelleria and Ustica (literature data from [49]).

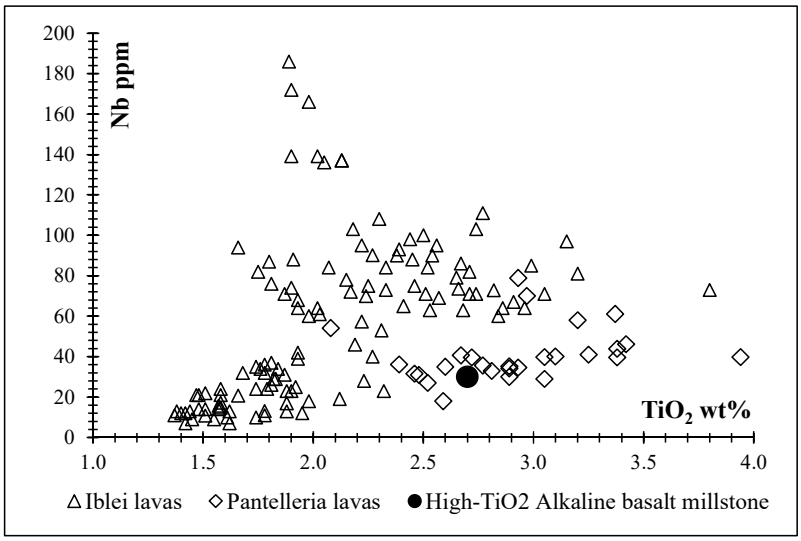


Figure 8. TiO_2 vs. Nb diagram comparing the high-TiO_2 alkaline basalt millstone with the Iblei and Pantelleria lavas (literature data from [49]).

5. Discussion

The volcanic raw material used to manufacture the grinding stones found at Ustica does not entirely come from the lavas of the volcanic island itself. The exploitation of local lavas of the Na-Alkaline series (basalts, hawaiites and mugearites) comprises all types of the investigated grinding stones (saddle querns, rotary hand-mills, metae and catillus of the Morgantina-type millstones) and the only mortar analysed. In other words, the local lavas were always exploited from the Middle Bronze Age (saddle querns) to the Hellenistic–Roman period (Morgantina-type rotary millstones) and modern time. Nevertheless, rotary hand-mills do not have a unique time interval of use, as they were widespread from the Archaic period to modern centuries. In this way, they give poor information on millstone trade networks in antiquity. The basaltic andesite rotary hand-mill (UST9, Table 5) could be linked to modern exchanges with the Aeolian Archipelago, which is the closest area characterized by the subduction-related calcalkaline series.

Table 5. Provenance, millstone type and composition of the investigated samples.

Provenance	Sample	Millstone Type	Composition
Ustica Island	UST4, UST5	Saddle querns	Basalts (Na-Alkaline series)
	UST10, UST11	Morgantina-type (Metae)	
	UST17, UST22, UST23, UST24	Morgantina-type (Catilli)	
	UST20, UST26	Rotary hand-mills	
	UST8, UST21	Morgantina-type (Metae)	Hawaiites (Na-Alkaline series)
	UST29	Morgantina-type (Catillus)	
	UST15, UST16	Rotary hand-mills	
	UST7	Mortar	
	UST1	Morgantina-type (Meta)	Mugearites (Na-Alkaline series)
	UST18	Morgantina-type (Catillus)	
	UST19, UST27	Rotary hand-mills	
Iblei Mountains	UST2, UST6, UST12, UST13 UST14, UST25	Morgantina-type (Catilli)	Basalts (tholeiitic/transitional series)
		Rotary hand-mills	
Pantelleria Island	UST28	Morgantina-type (Catillus)	High-TiO_2 basalt (Na-Alkaline series)
Aeolian Archipelago?	UST9	Rotary hand-mill	Basaltic andesite (Calcalkaline series)

Although only two saddle querns from the Middle Bronze Age were analysed (UST4, UST5; Table 5), their local provenance from the Na-Alkaline basalts of Ustica well agree with the hypothesis of limited cultural contacts outside the island and trade in that period. The abundant raw material (i.e., vesicular lavas) of Ustica could ensure the manufacture of the saddle querns, but the production of more efficient grinding stones could be largely precluded if the absence of exchanges with people outside the island would not have introduced new milling techniques. The breakthrough occurred with the Morgantina-type rotary millstones coming from Pantelleria (catillus UST28 high-TiO_2, Na-Alkaline basalt; Table 5) and the Iblei Mountains (catilli UST2, UST6, UST12, UST13 tholeiitic/transitional basalts; Table 5), really constraining that some grinding stones were imported to Ustica during the Hellenistic–Roman period. It was of paramount importance to the inhabitants of the island to learn how the local lavas could be hewn to produce more efficient grinding stones (with respect saddle querns), as testified by several metae (UST1, UST10, UST11, UST8, UST21; Table 5) and catilli (UST17, UST18, UST22, UST23, UST24, UST29; Table 5) of Morgantina-type millstones made of local Na-Alkaline lavas.

The compatibility of the Pantelleria high-TiO_2 Na-Alkaline basalts with the UST28 millstones studied in the present work is not surprising. This is because the provenance from Pantelleria Island was already documented for some volcanic millstones discovered at the Phoenician sites and

Carthaginian settlements of Sicily (e.g., Motya and Entella [15,58]) and Tunisia (e.g., Utica, Carthage, El Maklouba, Thuburbo Maius and Kelibia [15]). Moreover, most of the basaltic hopper-rubber millstones from the shipwreck of El Sec (off the coast of Mallorca, ca. 4th century BC), also come from Pantelleria [11], approximately 800 km away. Recently, saddle querns from Pantelleria were detected (i) in the shipwreck cargo off Gozo (Maltese Islands), dated at 7th–6th century BC and (ii) in the westernmost Phoenician colony of Gadir (i.e., Cádiz, Cerro del Castillo archaeological site), which is >1500 km to the west [12]. The position of Pantelleria Island, in the middle of the Sicily Channel, was really strategic since the Phoenician–Punic period up to the Roman Empire; basaltic mills could be loaded from Pantelleria and transported on ships to various destinations. In this way, it is very likely that during the flourishing Mediterranean trade [59] of the Hellenistic–Roman period, a ship cargo(es) arrived at Ustica with Morgantina-type rotary millstones from Pantelleria and the Iblei Mountains, leading to the breakthrough in starting the production of this type of rotary millstones with local basalts, hawaiites and mugearites. A provenance from the Iblei Mountains was already proved for millstones widespread from the Classical Greek period to the Roman Empire [11,15]. The Greek settlement of Mégara Hyblaea could have played a fundamental role as a collecting centre of Hyblean millstones [15] for their trade in the Mediterranean area. More than a hundred lava millstones with different milling techniques (e.g., saddle querns, hopper-rubber, Morgantina-type and Pompeian-type) were discovered and catalogued at Mégara Hyblaea ([60], and reference therein). A petrographic–geochemical study of these millstones is in progress. The great variety of millstones found at Mégara Hyblaea can be explained by the wide time interval of this settlement—from its first foundation (728 BC, according to Thucydides) through to its destruction by Hieron I of Syracuse (483 BC), then from its second foundation in the Hellenistic period (340 BC) and finally to its destruction by Marcus Claudius Marcellus in 213 BC during the second Punic War. In addition to four Morgantina-type catilli, the two rotary hand-mills (UST14 and UST25) that also have a provenance from the tholeiitic/transitional basalts of the Iblei Mountains are probably the result of the trade network linked to Mégara Hyblaea.

6. Concluding Remarks

The investigated saddle querns are only made of Na-Alkaline Ustica lavas and we can therefore infer that during the Middle Bronze Age, the production of the grinding stones was entirely due to the exploitation of local volcanic rocks because of the limited trade.

When, in the Mediterranean area, the milling technique turned to the more efficient Morgantina-type rotary millstones (from 4th–3rd century BC), some of them arrived in Ustica during the flourishing Mediterranean Sea trade of the Hellenistic–Roman period, as testified by some catilli having a provenance from other volcanoes—(i) four tholeiitic/transitional basalts from the Iblei Mountains and (ii) one High-TiO_2 Na-Alkaline basalt from Pantelleria Island. As a matter of fact, the lava millstone production and sea trade from the Iblei Mountains and Pantelleria Island were favoured, respectively, by Mégara Hyblaea on the eastern coast of Sicily and by the strategic commercial position in the middle of the Sicily Channel.

Bearing in mind this imported new rotary grinding stone technology, during the Hellenistic–Roman period, people of Ustica Island (e.g., settlements near the Falconiera tuff cone) started to manufacture Morgantina-type millstones using the local Na-Alkaline basalts, hawaiites and mugearites. The flourishing millstone Mediterranean trade in the Hellenistic–Roman period should have therefore represented a breakthrough for Ustica Island, allowing the development of a production of more efficient Morgantina-type millstones (with respect to the archaic saddle querns). The absence at Ustica of the hopper-rubber Olynthian-type millstones, widespread from the 5th century BC around the Mediterranean area, could also confirm that the island was not frequented for at least one millennium, from the abandonment of the Middle Bronze Age Villaggio dei Faraglioni (ca. 1200 BC) up to the Hellenistic–Roman re-colonization in the 4th–3rd century BC.

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