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THEMATIC ISSUE

Petrographic and geochemical investigations on the volcanic rocks used in the Punic-Roman archaeological site of Nora (Sardinia, Italy)

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Abstract

The research focuses on the geochemical and petrographic characterisation of volcanics that were used in the Roman city of Nora archaeological site. These rocks formed during the Late Eocene–Miocene orogenic Sardinian magmatic activity (38–15 Ma), were used as construction materials (ashlars, decorative frame, etc.) and as aggregate in the ancient mortars of some important buildings of Nora (e.g. Roman theatre, first century AD). Several samples coming from the Roman theatre (taken as study cases) and other ancient buildings and artefacts of Nora village were studied and chemically petrographically analysed. To define their provenance, analytical data of major and trace elements by XRF method were compared with those of several volcanics coming from the sector around the Nora archaeological site and from Sulcis area, frequented in ancient times by Romans. To highlight the geochemical discriminant markers or affinities between the sample populations of volcanics, factorial analysis was used, taking some significant variables: SiO_2, Na_2O, K_2O, L.o.I, Al_2O_3, Rb, Ba, Sr. The results of this research allow also defining the aspects of stone quarry extraction and construction technologies used in the Roman period.

Keywords Petrographic · Chemical analysis · XRF · Raw material · Roman technologies

Introduction

The Nora archaeological site is located in the Gulf of Cagliari near the city of Pula (south western Sardinia, Fig. 1). Nora was founded by the Phoenicians around the mid-eighth century BC and it was Carthaginian from the sixth century BC. It became Roman in 238 BC (Bernardini 2004; Mastino 2005). For centuries, Nora has been the main Roman administrative and political centre of Sardinia, a primacy that in the Republican age had to surrender to *Karales* (today Cagliari, Fig. 1) who had supported the emperor Caesar and his faction in the struggles for the conquest of supremacy in Rome. Nora, however, continued to consolidate her importance as a residential centre. It became a "town hall" and had its own magistrates—extending its influence thanks to its strategic position of crossroads of roads connecting the metallic and agricultural hinterland with *Karales*. Its decline began in the fifth century AD, due to the several incursions of the Vandals and the Arabs who forced the inhabitants to flee towards Sardinia. The archaeological remains of Nora (on approximately 30,000 m^2 (Figs. 2, 3) were discovered with the excavations that Gennaro Pesce conducted in 1952 (Pesce 1954; 1972) which brought to light part of the city (Tronchetti 2001). Emerged part reveals the remains of a first Punic settlement pre-existing to the Roman city. A necropolis with well-tombs, remains of several multi-storey houses which have been demolished in Roman times, and a rectangular temple that has been attributed to goddess *Tanit*, located on the culmination of the central relief of the promontory, have been identified. From the top of this temple, the lines of the Roman urban structure can be clearly seen (Figs. 2, 3): imperial straight

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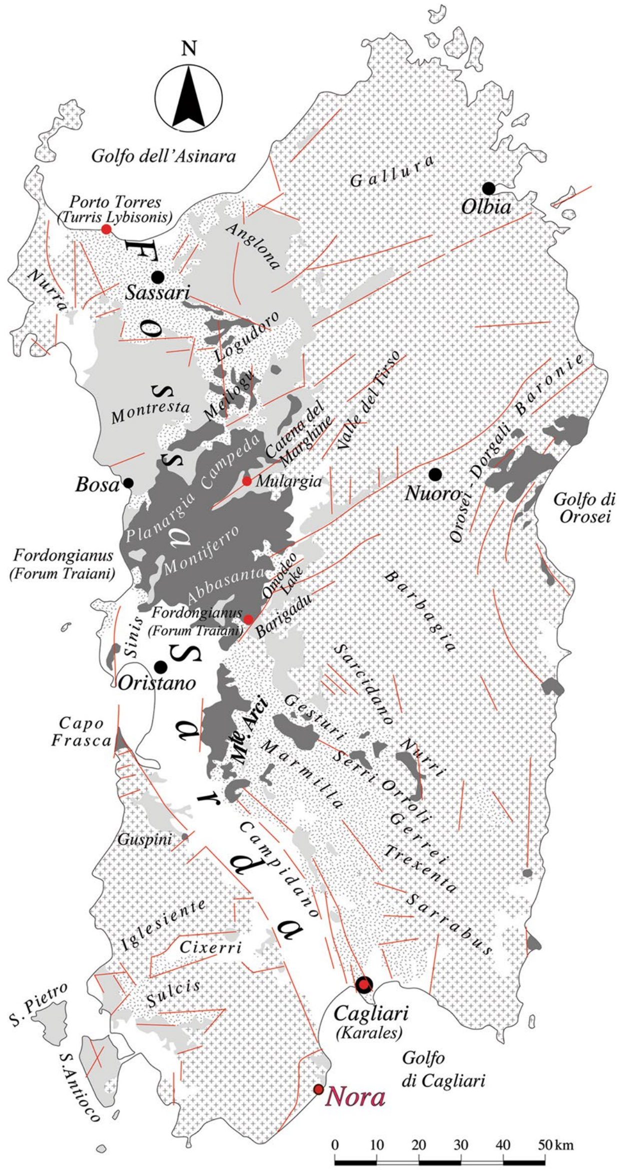

Fig. 1 Geological map of Sardinia with localization of the Roman Nora village and other important Punic-Roman city from the south to the north of island, i.e. *Karales* (today Cagliari), *Forum Traiani* (Fordongianus), *Turris Lybisonis* (Porto Torres); from Columbu and Garau (2017). Legend of patterns and colours refers to lithologies: white, recent alluvial sediments; light gray, Oligo-Miocene volcanics; dark gray, Plio-Pleistocene volcanics; gray stippled, Miocene marine sediments; gray crosses, Paleozoic crystalline basement and Mesozoic formations. Red continuous and dashed lines, faults

and paved streets separate the neighbourhoods including public buildings, shops and houses. Two of these latter have the floors covered with a precious polychrome mosaic with sophisticated and elegant motifs' decoration. There is also a melting workshop (foundry), laundry, tannery and the ruins of a likely covered market (*Macellum horreum*, Fig. 2). The remains of courtyards and chapels that formed the "sanctuary" of the salutary gods are important too, in particular a restored and expanded at different times Punic-Roman temple.

The remains of interesting ancient buildings are well preserved (Fig. 2): "Terme a mare" (i.e. Baths at the Sea), "Piccole Terme" (i.e. small baths), *Eusculapio* Temple, while of other only traces remain: Christian Basilica (now submerged under the sea, Fig. 2), *Tanit* Temple. The most important building, the only one of its kind in Sardinia, is the Roman Theatre (Figs. 2, 3), set in front of the sea. It surely is the best preserved and it was the first monument of the ancient city to be unearthed during the Pesce excavations (Pesce 1954, 1972). It still shows the original construction features, characterised by a semi-circular isodomic front with a W-NW axis (Fig. 4). The theatre building was built during the Augustan or Giulio-Claudio period (first century AD; Bejor 1999) using a variety of geomaterials (sandstones, conglomerates, volcanic rocks, marbles, bricks, mortars, etc.) and different kind of mortars, as often used by the Romans (Columbu et al. 2017; Columbu and Garau 2017). After the abandonment of Roman Nora city (from fourth century AD), over the centuries, the village facilities were plundered and vandalised; more than half of the ashlars of the tiers of *cavea* are missing or have been recently replaced (Fig. 3).

This paper aims to define the provenance of the Eocene–Miocene intermediate-acid volcanics that have been used to construct some ancient buildings of Nora. Due to their easy workability, these volcanic rocks were widely used in Sardinia in different historical times (Antonelli et al. 2014; Columbu 2017; Columbu et al. 2018). The origin of raw materials has always been a topic of great interest and a heated debate both from the petrographic, archaeological and archaeometric points of view, as the data can highlight possible ways of communication and/or existing trade of civilizations. Moreover, the geochemical and petrographic investigations on the features and origin of raw materials are also useful to understand the ancient routes the Romans used for the stone transport, the construction technologies of ancient buildings that have been used in different historical times and also to define the conservative problems (Alvarez et al. 2000; Bianchini et al. 2004; Columbu et al. 2015; De Luca et al. 2015; Franzini et al. 2000; Maravelaki-Kalaitzaki et al. 2003; Moropoulou et al. 2000; Riccardi et al. 1998; Verdiani and Columbu 2010; Vola et al. 2011).

To define the origin of raw volcanic materials: (1) geochemical classification and petrographic characterisation of the main volcanic rocks used in the Roman construct of Nora site (where the theatre was taken as study case); (2) comparison of chemical data between the samples of the theatre and other artefacts of Nora site with the samples coming from probably supply areas: the volcanic district of Sarroch-Pula and the Sulcis basin (Figs. 1, 5), more frequented by Romans

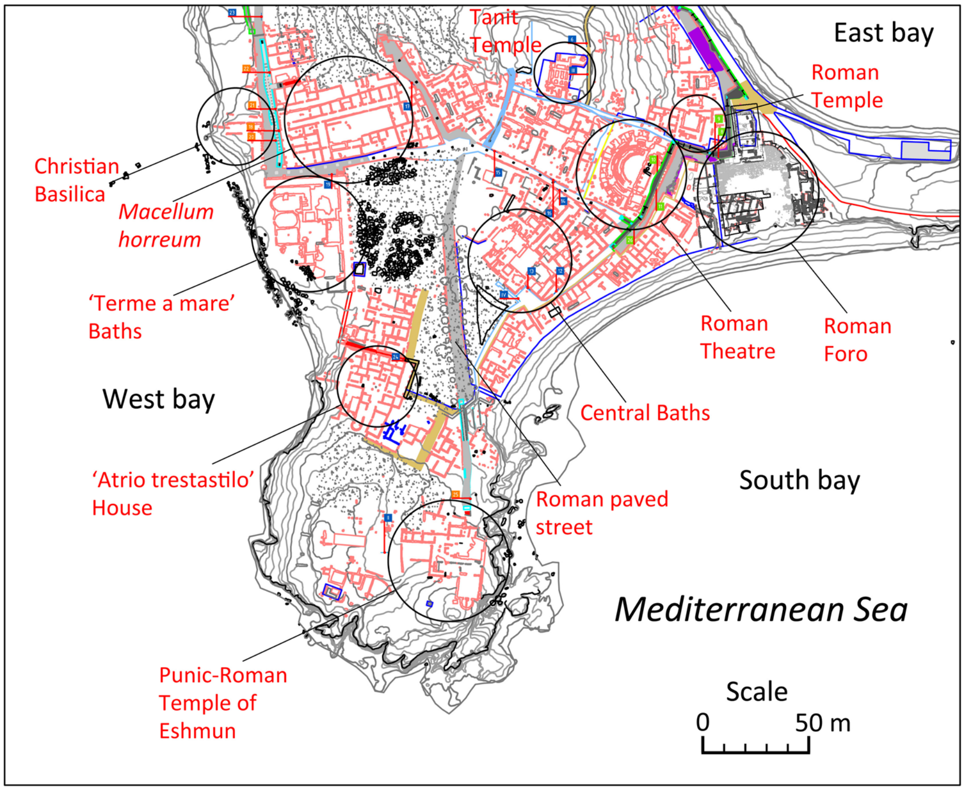

Fig. 2 Sketch map of Roman Nora archaeological site, which highlights the main monument sectors built in Roman age from 238 BC to III sec. AD (from Superintendence of Cultural Heritage of Cagliari, modified)

in ancient times; (3) defining some aspects of stone quarry extraction and construction technologies used in the Roman period.

With the aim of achieving these objectives, 136 samples of rock samples from field outcrops and from Nora monuments were analysed by XRF methods.

Materials and methods

The analysed volcanic rocks were taken from the Roman Theatre (i.e. *cavea* tiers, Fig. 3d, e) and other ancient artefacts of Nora archaeological site (i.e. houses, *Macellum horreum* masonry, inner street, thermal baths; Figs. 2, 3g, h). These volcanics show a clear autoclastic structure (Fig. 6c–f) characterised by a chaotic presence of large lava clasts (up to 30 cm and generally with sharp edges) and smaller clasts (with size < 1 cm and with a rounded edges) immersed in a more glassy matrix characterised by a lower welding degree than the clasts (Fig. 6).

Sampling activity from Nora monuments, subject to the approval of the Archaeological Superintendence of Cagliari, was performed taking into account the most representative and/or predominant lithotypes in the entire architectural structure; the planning was done examining what analysis would be carried out on the samples, and knowing, therefore, the amount of material needed to achieve them. It was carried out according to the NORMAL Recommendations (3/80 1980). The sampling points of the materials have been chosen taking into account the need not to disfigure the monuments.

68 samples from Nora monuments (#43 from the theatre signed with TN in the tables ESM 1a, 1b (see Fig. 4) and #25 from Nora site other ancient artefacts, Fig. 2, signed with VN in the table ESM 2) were taken. However, due to small size of specimen, six samples taken from the theatre were studied but not chemically analysed. The rock samples of theatre come from the volcanic ashlars used for the tiers of *cavea* sector (Fig. 4) that have a size about $80 \times 60 \times H = 50$ cm. The other samples belong to the other Roman artefacts located inside the archaeological Nora area (i.e. Roman paved street, ashlars of building walls, frames, thresholds of house doors; Figs. 2, 3).

To find the origin of monument samples, 68 samples of rock samples from the following field outcrops: Nora area (within the archaeological site, signed with PN in the table ESM 3), *Perdu Pranu* (near to archaeological site, signed with PN), *Su Casteddu* (volcanic apparatus, signed with CVR), St. Antioco area were taken (Figs. 1, 5).

Mineralogical and petrographic analysis of volcanic rocks was performed on thin sections under the polarising microscope (Zeiss photomicroscope Pol II).

Chemical composition of volcanic rock samples from field outcrops and Nora site was determined with a

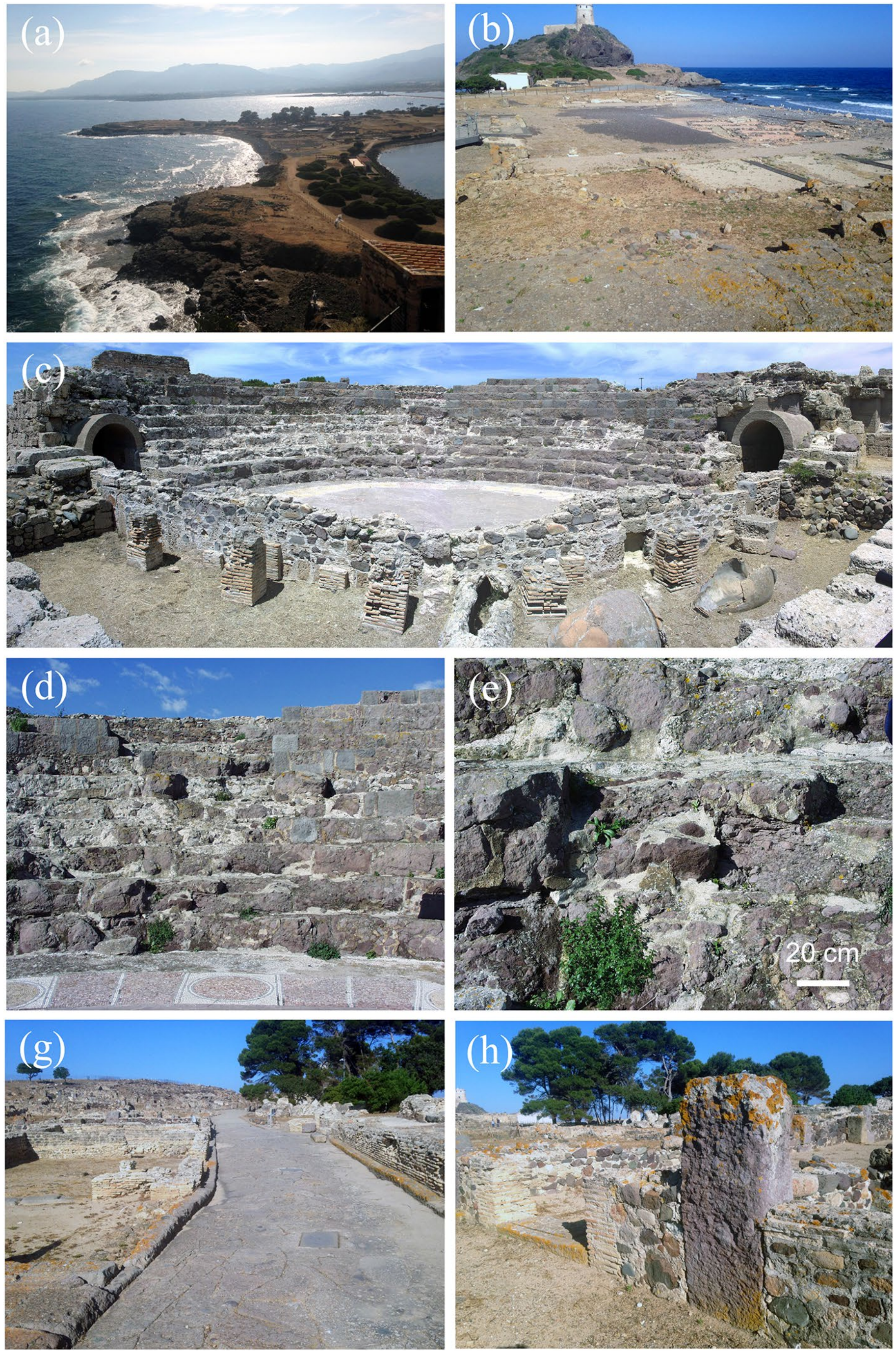

Fig. 3 Views of Roman Nora site: **a** south-east overview of Nora archaeological area; **b** northwest overview of *Foro*, the Roman public square with part of original volcanic stone paving; **c** completed overview of the theatre (down on the left the *hyposcenium*, space under the stage, the *palcoscenium*) with the two *tribunalia* sectors on the left and right (see also Fig. 4); **d** south view of *cavea* tiers of theatre (and *orchestra* floor with mosaic, down) realised with volcanic ashlars (now partially changed by other sandstone ashlars); **e** view detail of central sector of *cavea* tiers; **g** original Roman volcanic stone paving between the *Macellum horreum* and "Terme a mare" Bath sectors (see Fig. 2); **h** wall masonry within the *Macellum horreum* sector (see Fig. 2) with big squared volcanic ashlars positioned at the crossing point of walls

spectrometer in X-ray fluorescence (XRF) Philips PW1400 with a Rh tube to analyse the major elements and some trace elements (Rb, Sr, Pb, Zn, Y, Nb, Zr), and with a W tube to analyse of Ni, Cr, Ba, V, La, and Ce. Data reduction of major elements was performed by the Franzini et al. method (1975). Data reduction of trace elements was performed by Criss method modified (Criss 1977). Measurement accuracy is ± 1% for SiO_2, TiO_2, Al_2O_3, Fe_2O_3, CaO, K_2O and MnO and ± 4% for MgO, Na_2O and P_2O_5. Detection limits are about 3 ppm to 3σ for most of the elements. For trace elements, after repeated determinations, the values of detection limits were determined according to 3σ, 2σ and 1σ; they are reported in Table 1 (Garau 2005). The accuracy of trace elements is ± 2–3% to 1000 ppm, ± 5–10% at 100 ppm and ± 10–20% to 10 ppm.

Weight loss for calcination (L.o.I., loss on ignition) was determined by calculating the loss in wt% at 1100 °C, while the FeO was determined by volumetric titration with $KMnO_4$ 10 N in acid solution.

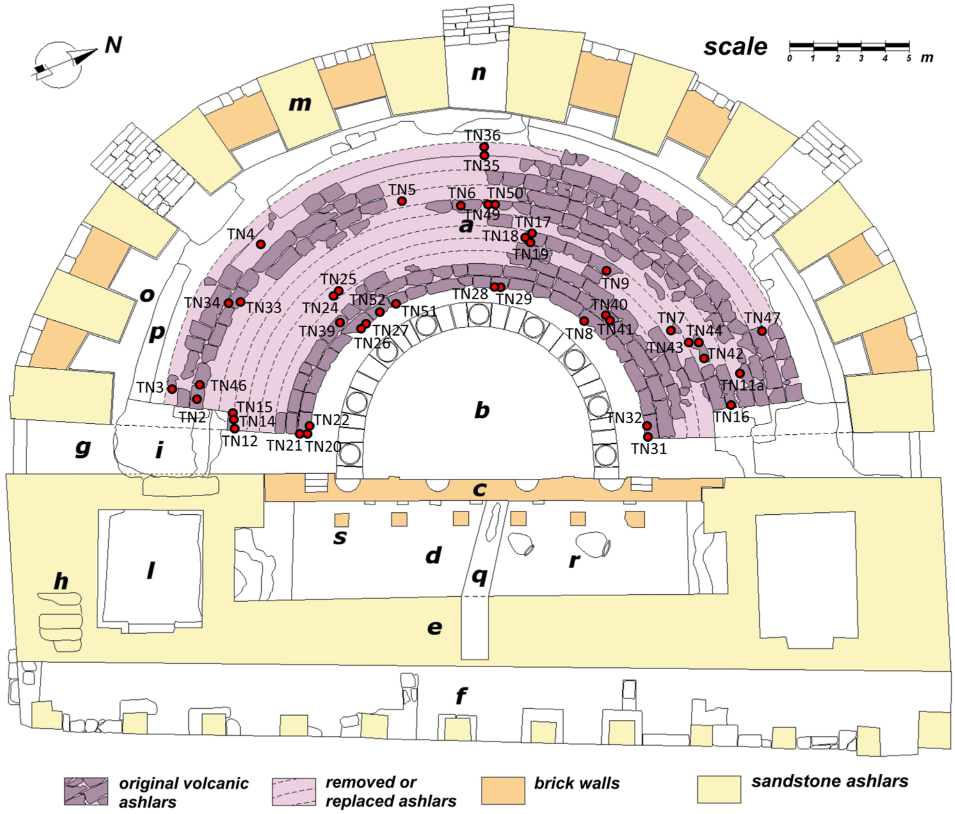

Fig. 4 Plan of the Nora Roman theatre with the sampling points (in red) of volcanic rocks. Legend of sectors: **a** *cavea* (auditorium); **b** *orchestra*; **c** wall of stage; **d** *hyposcenium* (space under the *palcoscenium*); **e** front scene; **f** portico behind the scene; **g** west archway entrance; **h** access ladder at the west *tribunalia*; **i** west *tribunalia*; **l** *parasceni*; **m** external niches; **n** enclosure; **o** *via* (corridor atop the *cavea*); **p** scalaria; **q** *euripus* (underground channel for water drainage); **r** *dolia*; **s** small pillars under the *palcoscenium* (from Columbu and Garau 2017; Garau 2005, modified)

Following petrochemical parameters have been calculated: Differentiation Index (given by the sum of normative sialic minerals except the anortite; D.I. = normative Q + Ab + Or + Ne + Kp + Lc) according to Thornton and Tuttle (1960); Solidification Index according to Kuno (1968) as

$$\text{S.I.} = \frac{\text{MgO}}{\text{MgO} + \text{FeO}_{\text{tot}} + \text{Na}_2\text{O} + \text{K}_2\text{O}} \quad \text{(by weight \%)};$$

Agpaitic Index according to Shand (1951) as

$$\text{A.I.} = \frac{\text{Na}_2\text{O} + \text{K}_2\text{O}}{\text{Al}_2\text{O}_3} \quad \text{(in molecular terms)};$$

SAL, given by the sum of all normative sialic minerals; FEM, given by the sum of normative mafic minerals; C.I.P.W. norm according to Cross et al. (1903).

Geological setting

The volcanic rocks, which have been used as construction materials in the archaeological Nora site, belong to the significant Sardinian Late Eocene–Miocene orogenic magmatic phase (Fig. 1; Beccaluva et al. 1985, 1989, 2005a, b, 2011; Lustrino et al. 2011), that includes tholeiitic, calcalkaline, shoshonitic and ultrapotassic products. This phase occurred between 38 and 15 Ma, mainly along the Sardinian Oligo-Miocene rift, a large tectonic pit, which structure crossing Sardinia (Cherchi and Montadert 1982a, b; Coulon 1977; Dostal et al. 1982).

The volcanic activity shows a peak during the 22–18 Ma time range (Beccaluva et al. 1985; Carminati and Doglioni 2012; Gattaceca et al. 2007; Speranza et al. 2002 and references therein). Since that time, in various areas of Sardinia, prevalently along the western graben trending N–S, known as the "Fossa tettonica sarda" (Vardabasso and Atzeni 1962; Fig. 1), a highly explosive fissural activity, with simultaneous and alternating emissions of basaltic and andesitic lavas, produced abundant pyroclastics and dacitic–rhyolitic products.

The volcanic rocks used in the theatre and other buildings of the Nora archaeological site belong to the volcanic Sarroch-Pula district (Figs. 1, 5), which can be attributed to this later volcanic activity. According to the radiometric analysis of various authors, the volcanic rocks of the Sarroch-Pula district have the following ages: 24–21.6 Ma (Savelli et al. 1979), 24.7–22.2 Ma (Beccaluva et al. 1985) according in part to the data for Arcuentu volcanic district determined by Coulon (1977; 22.3–17.5 Ma) and Assorgia et al. (1984; 30.5–16 Ma).

The Sarroch-Pula district (Sheet 234 of the "Carta d'Italia") is located at the southwestern Sardinia and it has

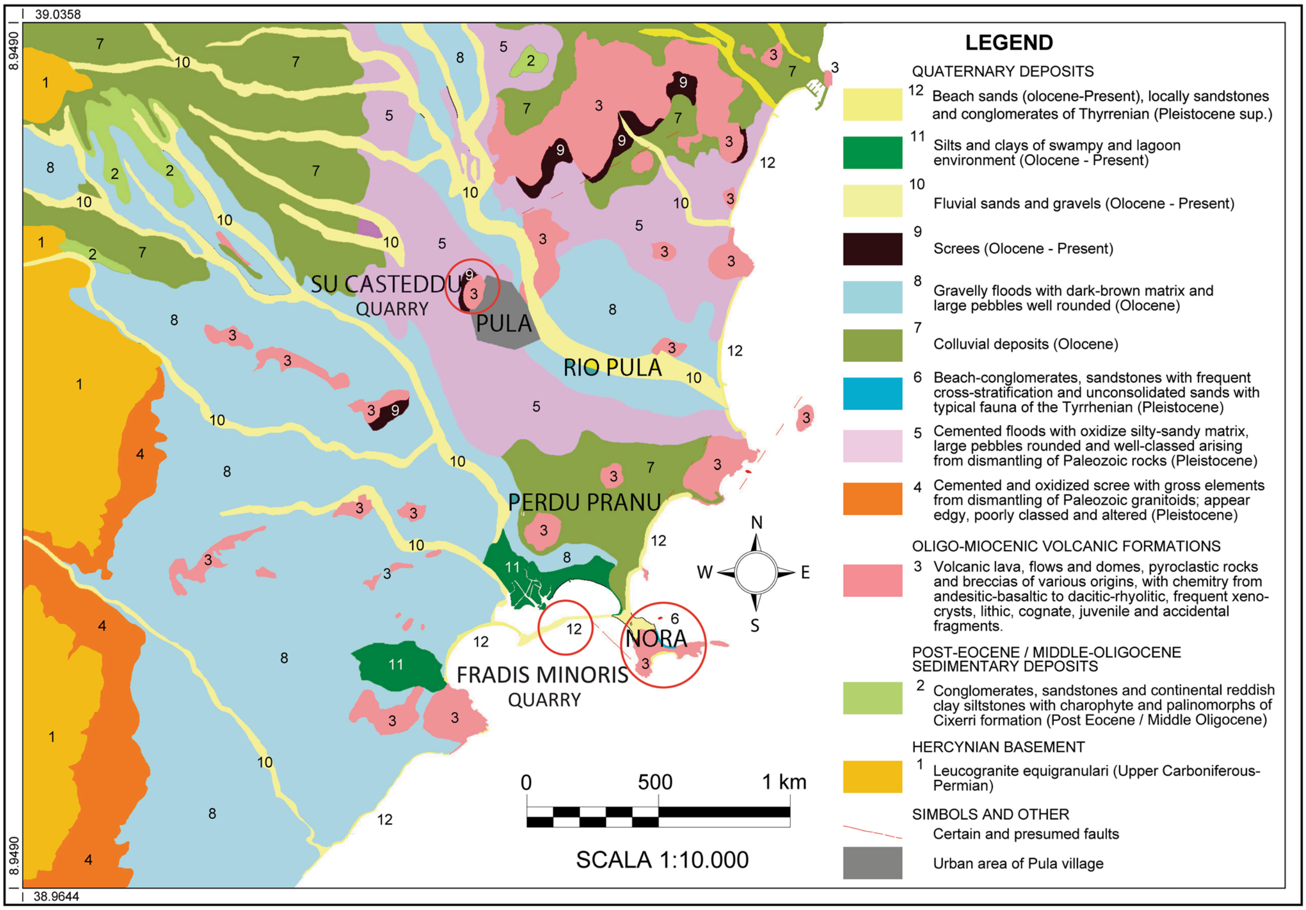

Fig. 5 Geological sketch map of Nora-Pula sector, showing the different volcanic outcrops and the localization of the ancient quarries of "*Su Casteddu*" (northwest of Pula village) and "Fradis Minoris" (northwest of Nora) from which the Romans extracted the volcanic and sandstone ashlars to realise the *cavea* tiers and structure walls of the theatre, respectively. NW and SW map vertices have the following geographical GPS coordinates (according to World Geodetic System, 1984): N 39.035800, E 8.949000; N 38.964400, E 8.949000

a main NW–SE orientation, occupying altogether an area of about 90 km^2. It is separated from the rest of the island by the Campidano graben and displays abundant Miocene calcalkaline volcanism (Sulcis and Sarroch areas, Fig. 1). In the Miocenic age, a series of fractures affected the area comprising both the edges of the Campidano graben and the nearby Paleozoic reliefs. By these fractures, considerable volcanic manifestations occurred, including those with mainly andesitic character of the Sarroch-Pula district. Miocene volcanism in the Sulcis area is represented by an accumulation of up to 500 m of volcanic products, mainly extensive pyroclastic flows well exposed on San Pietro and St. Antioco islands, and on the mainland near Carbonia (Assorgia et al. 1990; Garbarino et al. 1990).

Sarroch volcanic area is characterised by the presence of a main tectonic line N25E that allows distinguishing into eastern and western sectors (Conte 1989).

In the Sarroch western sector, the volcanic breccias and conglomerates are the dominant element while in the eastern sector the massive rocks are prevalent. Western pyroclastic outcroppings in the Sarroch area, as well as those from Nora-Pula, are often rich in volcanic clasts (as cognate fragments or "inclusions", from centimetric to decimetric) that are dispersed in an substantially cineritic matrix. These clasts vary in shape, nature and size: from sharp edges, predominant (usually in larger clasts), to more rare rounded edges (in smaller clasts) and they are usually of sub-volcanic type. These rocks with clasts can be framed between volcanic breccias passing through conglomerate types as they move away from their emission volcanic centres. Such breccias and conglomerates are sometimes associated with particular massive lava, which also have a breccia appearance and they have no substantial differences between the clasts and the matrix. These are autobreccias, which are quite similar to those present in the lower part of the Mount Arcuentu series (Assorgia et al. 1986).

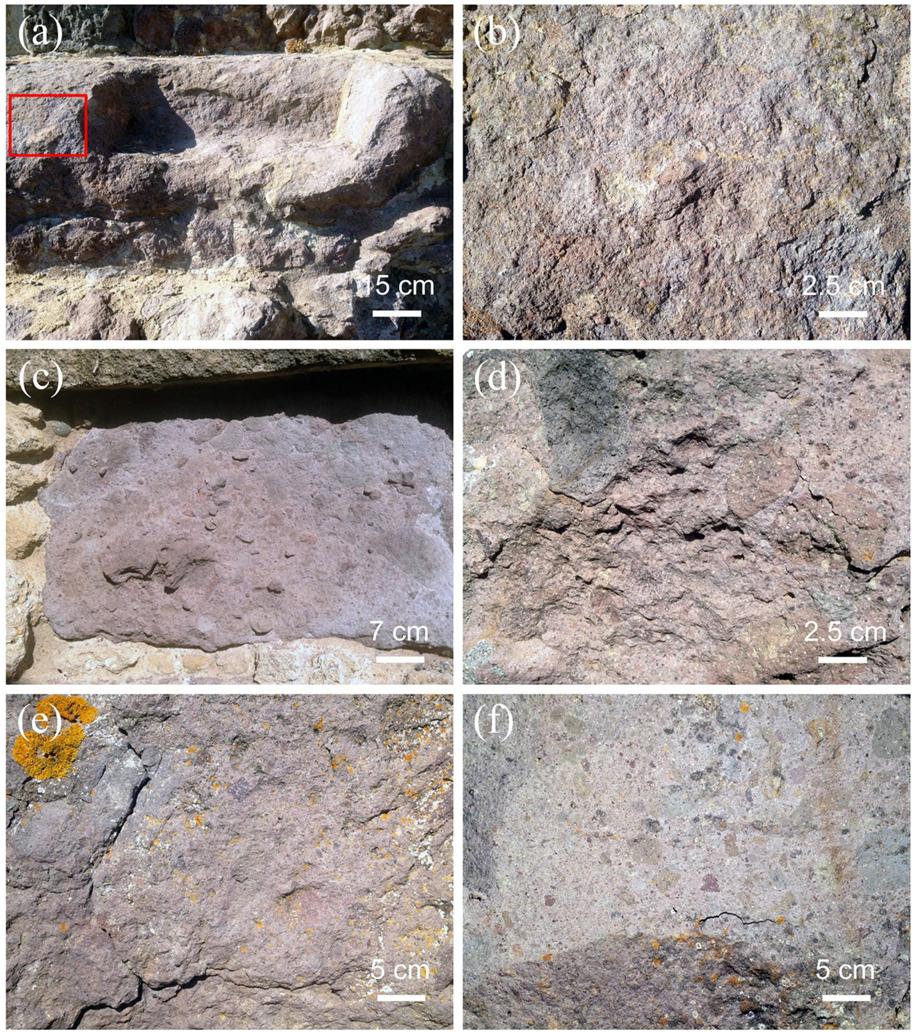

Fig. 6 Macro-photographs of volcanic stone used in the Roman theatre: **a** worked ashlars of staircase steps positioned in the east *cavea* sector, near *tribunalia* sector (see Fig. 4); **b** photo detail of previous photo (look at red rectangle highlighted in the photo **b**); **c** volcanic ashlars used for the wall under the *tribunalia* vault (Fig. 4) belonging to *Su Casteddu* outcrop, where it is a typical breccia structure of rock; **d, e** volcanic ashlars used for the wall *Macellum horreum*, in front of the stone paving; **f** volcanic ashlar from the wall near "Terme a mare" Baths (with more welded lithoclasts and cognate fragments immersed within a less welded matrix) coming probably from *Perdu Pranu* outcrops

Table 1 Detection limit values (at 3σ, 2σ and 1σ, respectively; Garau 2005) established after repeated determinations for trace elements of samples from Roman theatre, Nora artefacts and Oligo-Miocenic volcanic rocks outcropping in the Nora and *Perdu Pranu* areas, *Su Casteddu* apparatus, Sant'Antioco

Element	3 σ	2 σ	1 σ
Nb	3.2	2.1	1.1
Zr	3.0	2.0	1.0
Y	3.0	2.0	1.0
Sr	4.5	3.0	1.5
Rb	4.3	2.8	1.4
Pb	12.2	8.2	4.1
Zn	5.1	3.4	1.7
Ni	2.1	1.4	0.7
Cr	3.3	2.2	1.1
Ce	16.6	11.1	5.5
V	2.9	1.9	1.0
Ba	10.2	6.8	3.4
La	8.9	6.0	3.0

Results

Petrographic features

Volcanics from probable origin areas

The volcanic rock outcroppings in the Sarroch-Pula volcanic district show different petrographic and volcanological features (Table 2). In the area of Pula-Nora, the rocks show a porphyritic index from 5 to 8% in more evolved products (dacitic rocks of north Pula) to 14–28% in more basic (andesitic) lava (Nora area). The groundmass varies from hypocrystalline, to hypohyaline, to glassy. According to Conte (1989), among these rocks there are both lithotypes that have the phenocrystals the amphibole and other lithotypes in which it is absent. In paragenesis of the first lithotype (most represented in the outcrops around the Nora area), the amphibole phenocrystals, generally partially opaque and sometimes pecilitic, coexist with plagioclases, opaques and orthopyroxene (sometimes altered), while the

Table 2 Summary scheme of petrographic features defined by polarised microscope analysis on thin sections and geochemical characteristics by XRF analysis (with rock classification) of samples from Roman theatre, other Nora artefacts and Oligo-Miocenic volcanic rocks outcropping in the Nora and *Perdu Pranu* areas and *Su Casteddu* apparatus

Origin of samples	Petrographic features by microscopic analysis					Geochemical characteristics by XRF analysis					
	Structure	Porphyritic Index (%)	Phenocrystsa	Ground mass	Texture	Rock classification		Affinity series			D.I. range
						De La Roche et al. (1980)	Le Bas et al. (1986)	Peccerillo and Taylor (1976)	Middlemost (1975)	Irvine and Baragar (1971)	Thornton and Tuttle (1960)
Theatre tiers of *cavea*	Porphyric, (glomero-porphyric)	5–8	Pl, Hbl, Opq (i.e. Mt, Ti-Mt), ± Cpx, ± Opx	From hypo-hyaline to hypocrystalline	From vitroclastic to eutaxitic to massive vitrophyric	(An), Dc, RyDc, (LtAn), (Lt)	An, Dc, TrAn, (TrDc)	An, Dc Calcalkaline, (high-K calcalkaline)	Na	Subalkaline, (transitional)	53–68
Su Casteddu volcanic apparatus	Porphyric, (glomero-porphyric)	5–8	Pl, Hbl, Opq (i.e. Mt, Ti-Mt), ± Cpx, ± Opx	From hypo-hyaline to hypocrystalline	From vitroclastic to eutaxitic to massive vitrophyric	Dc, RyDc	Dc	Dc Calcalkaline	Na	Subalkaline	66–70
Perdu Pranu volcanic outcrops	Porphyric, (glomero-porphyric)	12–22	Pl, Hbl, Opq (i.e. Mt, Ti-Mt), ± Cpx, ± Opx, (± Bt)	Hypocrystalline, microgranular	From vitroclastic to eutaxitic to massive	An, Dc	An	An Calcalkaline, (high-K calcalkaline)	Na, (K)	Subalkaline	50–56
Nora volcanic outcrops	Porphyric	16–28	Pl, Hbl, Opq (i.e. Mt, Ti-Mt, Il), ± Opx, (± Cpx)	From hypocrystalline to holocrystalline	Tendentially isotrope	An, Dc	An	An Calcalkaline, (high-K calcalkaline)	K, (Na)	subalkaline	45–57

Minerals abbreviations: *Opq* opaque minerals, *Pl* Plagioclase, *Opx* Orthopyroxene, *Cpx* Clinopyroxene, *Bt* Biotite, *Hbl* Horneblende, *Mt* magnetite, *Ti-Mt* titano-magnetite. Rock classification abbreviations: *RyDa* rhyodacite, *Dc* dacite, *TrAn* trachi-andesite, *TrDc* trachi-dacite, *Lt* latite, *LtAn* lati-andesite, *An* andesite, *AnBa* andesitic-basalt, *BaAn* basaltic andesite, ( ) subordinate sample number

[a]Minerals according to their increasing abundance

clinopyroxene is generally subordinated or almost absent. Some samples show the presence of rare olivine microphenocrystals, which are completely transformed in iddingsite, sometimes included in opaque amphiboles together with pyroxenes. Clinopyroxene phenocrystals often form monomineral aggregates, sometimes together with orthopyroxene, plagioclase and opaque, thus conferring on these rocks a glomerular-porphyric structure. Orthopyroxene crystals are generally isolated and idiomorphic, but quantitatively subordinate to those rich in calcium. Plagioclase phenocrystals have an evident zonation and they are often characterised by the presence of corroded and partially reabsorbed nucleus surrounded by oscillatory zoning edges. Opaque minerals are mostly at the edge of the orthopyroxene or included in the clinopyroxenes. The groundmass is generally hypocrystalline and it consists of plagioclase, clinopyroxene, orthopyroxene and opaques.

The paragenesis of second lithotypes (without amphibole) consists of plagioclase, clinopyroxene, orthopyroxene, and opaque, both as phenocrystals and in the groundmass. Plagioclase phenocrystals usually have normal zoning with a composition in the edges generally similar to that of the microlites of the groundmass. However, plagioclases with inverse zoning and crystals with glassy inclusions are also present. Orthopyroxenes are hypidiomorphic and isolated, while clinopyroxenes often form aggregates giving to the rock a glomerular-porphyric structure. Opaques are rare and mostly confined to the edges of orthopyroxenes and clinopyroxenes or nucleus of these latter. All of the abovementioned phases also constitute the groundmass.

Volcanics of Roman Nora artefacts

The samples taken from the theatre generally show a porphyritic structure (Fig. 7) and a hypocrystalline groundmass. The porphyritic index generally varies between 5 and 8% for early opaque phenocrystals, dominant plagioclase, pyroxene and brown hornblende. Due to their shape, the opaque minerals are presumably made up of magnetite or titanium–magnetite. Plagioclases often are heuedral or subheuedral, zoned, sometimes corroded and/or with reabsorption processes for disequilibrium with the liquid, with cribrous appearance due to dust inclusions. They have a size between 0.5 and 1.5 mm and they are geminated according to albite (and more rarely albite-Carlsbad). Meta-somatization processes (for circulation of late fluids) with pseudomorphic calcite on plagioclase and secondary alteration are frequent.

Another generation of plagioclase (less frequent) is represented by smaller microphenocrystals (of about one order of magnitude compared to the previous ones), with nonzoned heuedral crystals, geminated according to albite and albite-Carlsbad, in equilibrium with the liquid, with more evolved chemical composition, and devoid of alteration processes. Pyroxenes are smaller than plagioclases (about 0.5 mm although some individuals reach the millimetre). The classification of pyroxenes is doubtful due to advanced alteration in bastite: sometimes the habit assumes that it is orthopyroxene. Amphiboles (i.e. brown hornblende) are about 1–1.5 mm in size and they are less altered than pyroxenes and plagioclases; they often crowned by edges of opaque minerals, due to the disequilibrium with the liquid. More rarely, the opacity phenomenon affects the entire crystal. Mesostasis consists predominantly of plagioclase microlites, secondarily of pyroxene and/or amphibole, and more or less abundant glass. The crystals are oriented in the direction of the major axis, resulting in a strongly fluidal hyalopilitic structure. In these rocks, there are also cognate fragments, having a different degree of crystallinity but similar paragenesis. As already described before, such fragments (clasts) give at macroscopic level to an autoclastic brecciate structure, characteristic of these rocks.

Due to their different origin from several outcrops with different compositions, the volcanic samples taken from other Nora artefacts generally show a porphyritic structure with a variable index (from 5% in the rhyodacitic and dacitic rocks, to about 28% in andesitic rocks) for phenocrystals of opaque, abundant plagioclase (from 0.4 to 2 mm in size), highly-altered clinopyroxenes (that make every determination difficult), and brown hornblende (often completely opacified) varying in size between 0.5 and 1 mm (though often exceeding 3 mm). The groundmass consists of plagioclase, clinopyroxene, amphibole and subordinately glass.

Geochemical features and rock classification

Tables ESM 1, 2, and 3 show the chemical analysis of the major elements (wt.%) and trace elements (ppm) of volcanics belonging to Roman theatre, Nora artefacts and from probable origin areas: *Su Casteddu* volcanic structure, *Perdu Pranu* area, Nora outcrops.

Figure 8a, b shows the trend of the major and trace elements against D.I.: as expected from normal magmatic evolutionary series, a positive correlation is observed between D.I. and SiO_2, Na_2O, and K_2O, while there is a negative correlation between D.I. and FeO_{Tot}, TiO_2, MgO, and CaO. Sr shows a weak negative correlation with increasing the evolution degree of the series for the samples of Nora theatre, *Su Casteddu* and St. Antioco outcrops, probably in conjunction with the crystallisation of plagioclase. For some elements (i.e. Rb, Sr, Ba and Nb), it is evident the trends of the samples coming from theatre and *Su Casteddu*, other artefacts and those of *Perdu Pranu* and Nora outcrops, while the samples from St. Antioco show an evolutionary trend almost always different and separate from other samples.

According to the Middlemost diagram (1975, Fig. 9), the Eocene–Miocene volcanics of all the Roman monuments

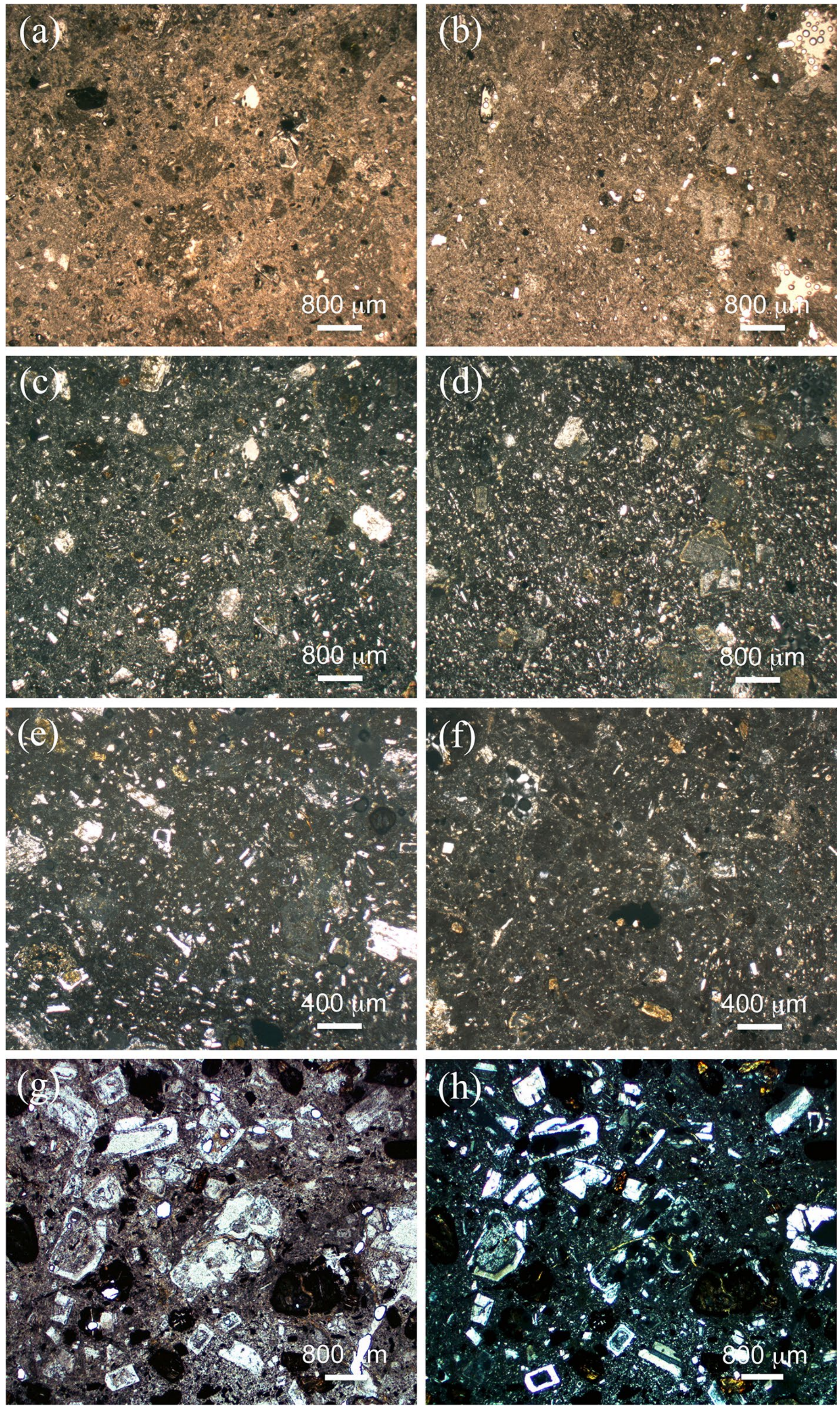

Fig. 7 Microphotographs of volcanic rocks coming from theatre (sigle TN), from *Su Casteddu* ancient quarry (CVR) and *Perdu Pranu* outcrop (PN). **a, b** Plain polars: TN49 and CVR3 samples with altered phenocrystals (i.e. mainly plagioclase, hornblende, pyroxene) and cognate fragment immersed in from hypohyaline to hypocrystalline groundmass; **c–f** crossed Nicol: TN49, CVR3, TN41, CVR5 samples with plagioclase, hornblende with opacified border, pyroxene phenocrystals with porphyritic index of 7%; **g, h** plain and crossed Nicol: PN63 sample, with phenocrystals of plagioclase and hornblende, and higher porphyritic index (22%)

(including the theatre and other ancient artefacts) and field samples from Nora area and St. Antioco are generally of sodium series, more rarely of potassium series while the similar volcanics of the nearby island of St. Antioco belong to both potassium and sodium series and are rarely too high in potassium series (Fig. 9; Table 3). According to the AFM diagram of Irvine and Baragar (1971; Fig. 10), the same samples show the typical trends of the calcalkaline series.

Within the TAS diagram of Le Maitre et al. (2002) (Fig. 11), the samples of the theatre, other artefacts and Nora

(a)

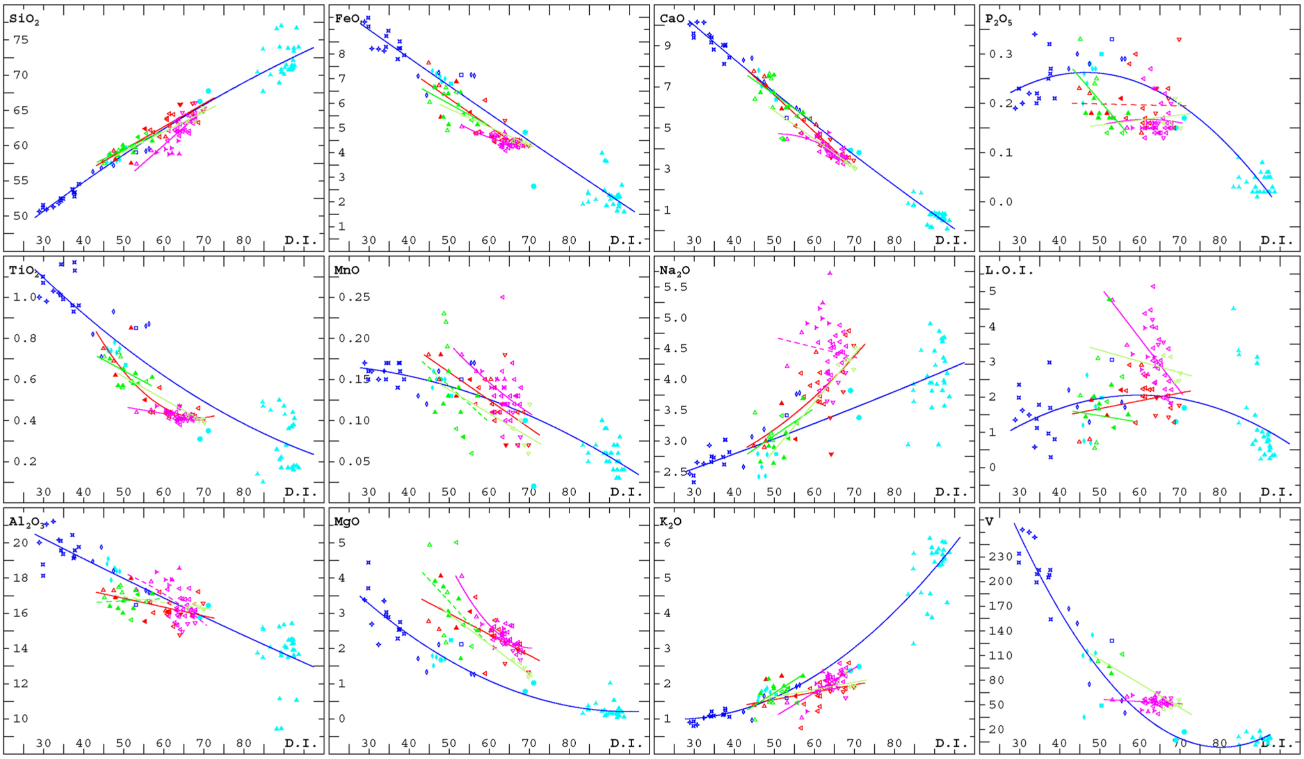

Fig. 8 **a** Variation diagrams: major elements (wt%) vs. differentiation index (D.I.) of Thornton and Tuttle (1960) (where D.I. = normative Q + Ab + Or + Ne + Kp + Lc) for the volcanic samples from the theatre, other artefacts of Nora and field volcanic outcrops. Curves represented are the regression for each set of samples: in violet for the samples of the theatre; in red for the samples of Nora artefacts; in dark green for the samples of *Perdu Pranu* and Nora field; in light green for the samples of *Su Casteddu*; in blue for samples from Sant'Antioco. Dotted curves indicate less significant correlations. Symbols as legend of Fig. 9. **b** Variation diagrams: trace elements (ppm) vs. differentiation index (D.I.) of Thornton and Tuttle (1960) (where D.I. = normative Q + Ab + Or + Ne + Kp + Lc) for the volcanic samples from the theatre, other artefacts of Nora and field volcanic outcrops. Colour regression curve notes as Fig. 14a. Symbols as legend of Fig. 9

outcrops fall into the field of subalkaline series, although numerous exception samples fall into the field of transitional series. The theatre samples are classified as andesite, dacite, trachy-andesite and trachy-dacite. The samples of other artefacts are classified as andesite and dacite (with some rare cases falling in the fields of basaltic andesite and trachy-dacite). The volcanics of the countryside surrounding Nora areas (*Perdu Pranu* and Nora areas, Fig. 5) fall into the andesite and dacite.

Volcanics from the St. Antioco island fall into subalkaline and transitional fields, ranging from basalt, to basaltic andesite, (to dacite), to rhyolite and were analysed. In Fig. 12, the same data were projected on the diagram of De La Roche et al. (1980), where the segment that cuts the origin of the axes (with a slope of 45°) represents the under-saturation critical plan. The representative points of the analysis samples fall between that plane and the axis of the abscissas; so the samples are over-saturated and belong to subalkaline series in accordance with TAS diagram (Fig. 11). In diagram of De La Roche et al. (1980; Fig. 12), the analytical values are reported according to the two parameters R_1 and R_2, which take into account all the major elements (expressed in cations multiplied by 1000) with the only exception of P and Mn. For these reasons, this diagram has been finally selected as the most suitable for the classification of all volcanics. The samples of the Roman theatre mainly fall in dacite field and, subordinately, in lati-andesite, rhyodacite, andesite and latite fields, in order of abundance (Fig. 12; Table 3). The samples of other Nora artefacts are classified as dacite, andesite, rhyodacite and basaltic andesite. The rocks of *Su Casteddu* volcanic apparatus consist of rhyodacites and dacites. *Perdu Pranu* volcanics are mainly dacites, in some cases with transitional products to the andesite. The samples from Nora outcrops mainly show an andesitic composition, with some dacitic samples. Samples from the island of St. Antioco are classified as alkali-rhyolite, basaltic andesite, rhyolite, basalt, rhyodacite and dacite (Fig. 12; Table 3).

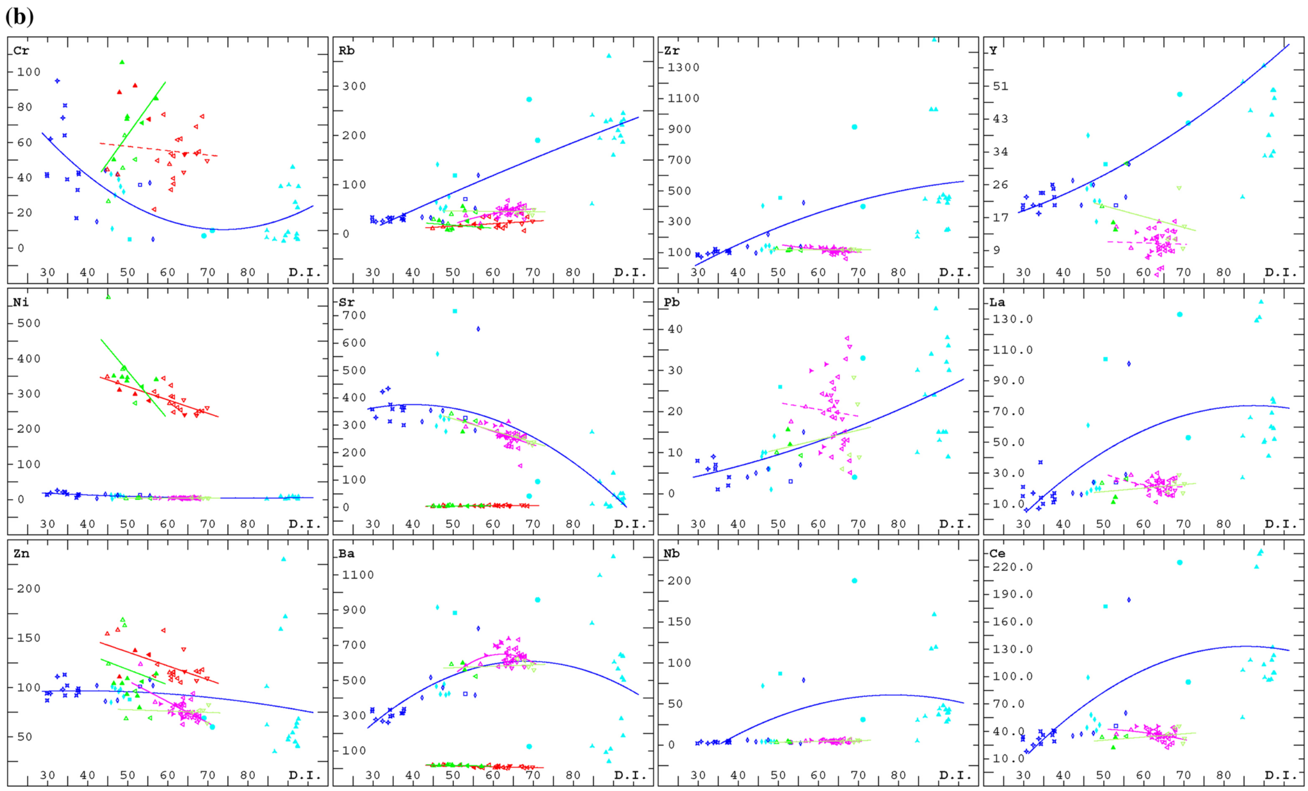

Fig. 8 (continued)

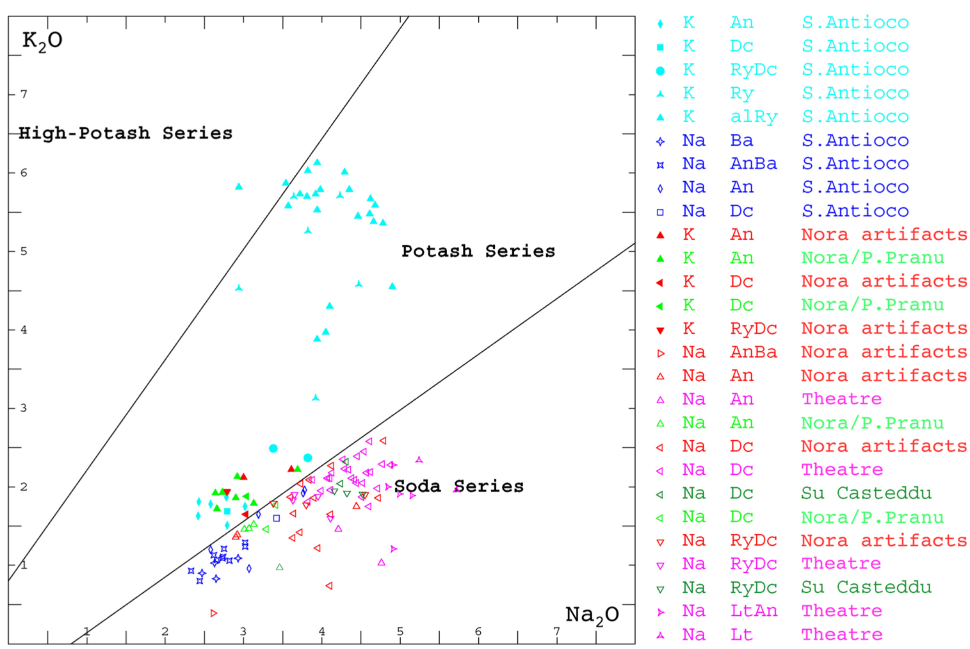

Fig. 9 Na_2O vs. K_2O wt% classification diagram of Middlemost (1975) between the high-potassium, potassium and sodium volcanic series, where the volcanic samples from the theatre, other artefacts of Nora and field volcanic outcrops were plotted

Table 3 Distribution of all analysed volcanic samples within sodium (Na), potassium (K), and high-potassium (HK) series, according to Middlemost (1975)

Origin	De La Roche et al. (1980) classification	Middlemost (1975) classification		
		Na	K	HK
Theatre tiers of *cavea*	An	2	–	–
	Dc	24	–	–
	RyDc	4	–	–
	LaAn	5	–	–
	Lt	2	–	–
	Sub-total	37	–	–
Nora artefacts	An	3	2	–
	AnBa	2	–	–
	Dc	13	1	–
	RyDc	2	1	–
	Sub-total	20	4	–
Su Casteddu volcanic apparatus	An	1	–	
	Dc	2	3	–
	RyDc	3	–	–
	Sub-total	6	3	–
Other volcanic outcrops (*Perdu Pranu*, Nora area)	An	3	2	–
	Dc	2	3	–
	Sub-total	5	5	–
Sant'Antioco area	Ba	4	–	–
	BaAn	10	–	–
	An	5	6	–
	Dc	1	1	–
	RyDc	–	2	–
	Ry	–	6	–
	AlRy	–	20	2
	Sub-total	20	35	2
Total samples		88	47	2

Rock classification according to De La Roche et al. (1980). Abbreviations as Table 2

Discussion

Regarding the geochemical aspects of volcanic series, the results of chemical analysis highlight that all analysed samples from Nora ancient buildings and field outcrops are subalkaline-like volcanics according to the De La Roche et al. (1980) R_1–R_2 diagram (Fig. 12). The samples show an affinity calcalkaline s.s. in agreement with Irvine and Baragar Alk-FeO_T–MgO (AFM) diagram (Fig. 10). In addition, most volcanics, particularly those from the theatre and *Su Casteddu* outcrop, have sodium affinity according to Middlemost diagram (Fig. 9). The other volcanics are both sodium and potassium series, and are rarely high in potassium series (the latter being among the alkali-rhyolitic samples coming from St. Antioco).

The provenance study of stone materials, which have been used in the construction of Nora monuments, has been tackled both petrographically and chemically, comparing the volcanics from the theatre and other artefacts of Nora archaeological site with the field samples from the nearest areas (*Su Casteddu, Perdu Pranu* and Nora volcanic outcrops, Fig. 5) and with those from St. Antioco area (more distant but frequented by Romans). However, this comparison shows almost always that the volcanics of St. Antioco area have different trends in all the diagrams previously considered. Observing Fig. 8a, b, these samples have an evolutionary trend separated from the others, while the samples of the theatre and the *Su Casteddu* area form overlapping sample populations. This is evident in all analysed diagrams (Figs. 8, 9, 10, 11, 12). By contrast, the samples of Nora artefacts, together with the samples of *Perdu Pranu* and Nora volcanics (outcrop in the countryside around the Roman city) projected in all diagrams outline evolutionary trends that overlap well.

These reasons led to the exclusion of St. Antioco area as source of material supply for the construction of both the theatre *cavea* and other Roman artefacts of Nora city.

Thus, chemical data show similarities between the samples of the theatre and the area of *Su Casteddu* (located in the northern suburbs of Pula; Figs. 5, 14), and among the volcanics of the other artefacts and those of Nora and *Perdu Pranu* outcrops. To better highlight such geochemical affinities, factorial analysis has been used. The variables that were most significant are diagrammed in the Fig. 13. In most of the binary diagrams, there are two distinct populations formed, respectively, by the samples of the theatre and *Su Casteddu* together, and by those of Nora artefacts and the countryside surrounding the city together. The first (upper-left) diagram is the one that better separates the two sample populations.

Based on both the diagrams (especially Ba vs. Ni, SiO_2 vs. V, Sr vs. CaO, Rb vs. Zn, K_2O vs. Cr; Fig. 13) and the above-mentioned similarities, the volcanics of the Nora theatre tiers come from the *Su Casteddu* outcrop and in no case from the *Perdu Pranu* outcrops. Only some samples from the theatre, most likely referable to lithoclasts or cognate fragments, have lower values of Na_2O (ranging in 3.63–3.65%, rhyodacites TN 36, 33, Table ESM 1b) with respect to the mean (normally > 4%), and another sample has a greater value of MgO (4.05%, andesite TN 50, Table ESM 1a).

These assumptions made on the basis of chemical data are supported by the results of the other investigations. The macroscopic analysis of the petro-vulcanological characteristics (i.e. structures, welding degree, etc.) showed that the volcanic lithotypes of theatre and those of *Su Casteddu* are very similar. They are both purplish-red and with a characteristic autoclastic structure, with their cognate fragments, which usually have a darker colour of embedded rock and

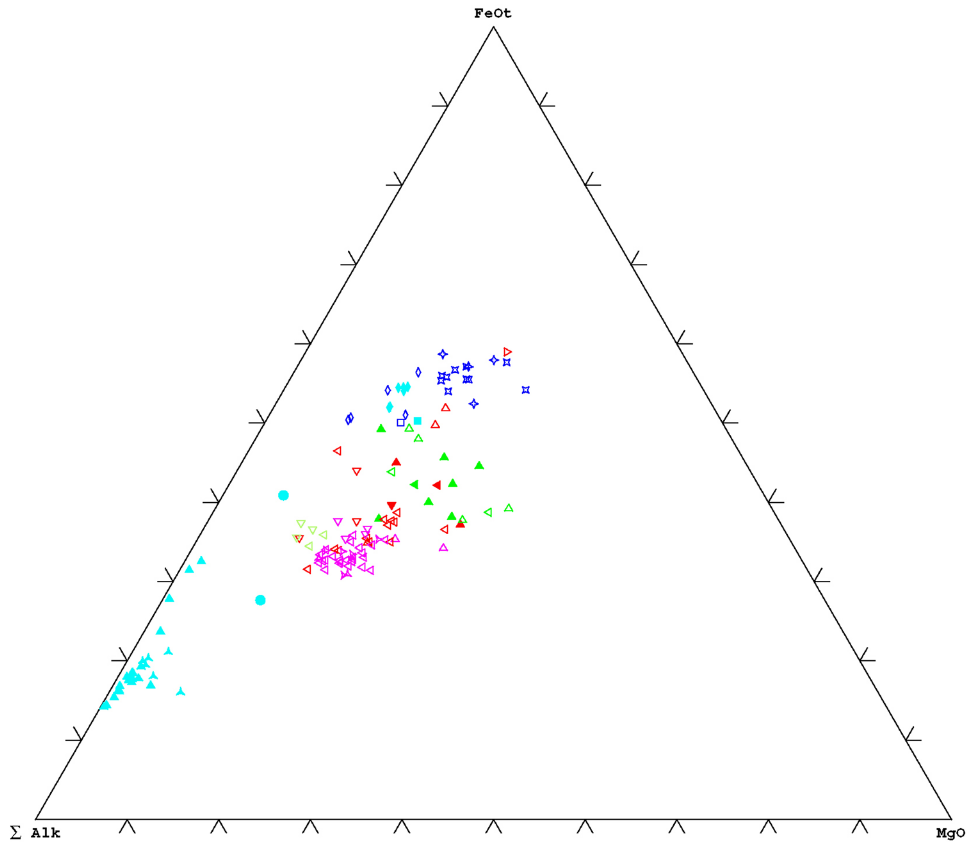

Fig. 10 AFM diagram of Irvine and Baragar (1971) where the volcanic samples from the theatre, other artefacts of Nora and field volcanic outcrops were plotted. Symbols as legend of Fig. 9

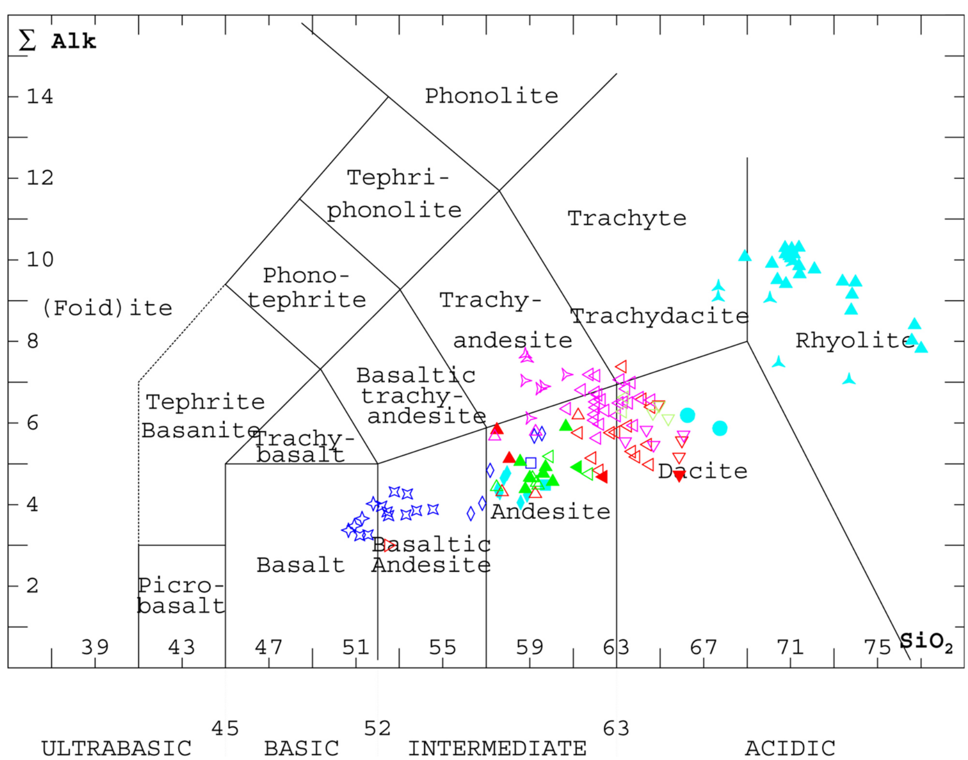

Fig. 11 Total alkali-silica (TAS) diagram [($Na_2O + K_2O$) vs. SiO_2 wt%] of Le Maitre et al. (2002; after Le Bas et al. 1986), where the volcanic samples from the theatre, other artefacts of Nora and field volcanic outcrops were plotted. Symbols as legend of Fig. 9. Data were not reported at 100% excluding H_2O^+ (according to the IUGS recommendations; Streckeisen 1976, 1978). Without the analytical values of Zr, Pb, Nb Y, La and Ce, the two series of the samples from Nora and *Perdu Pranu* areas are not included in the respective variation diagrams

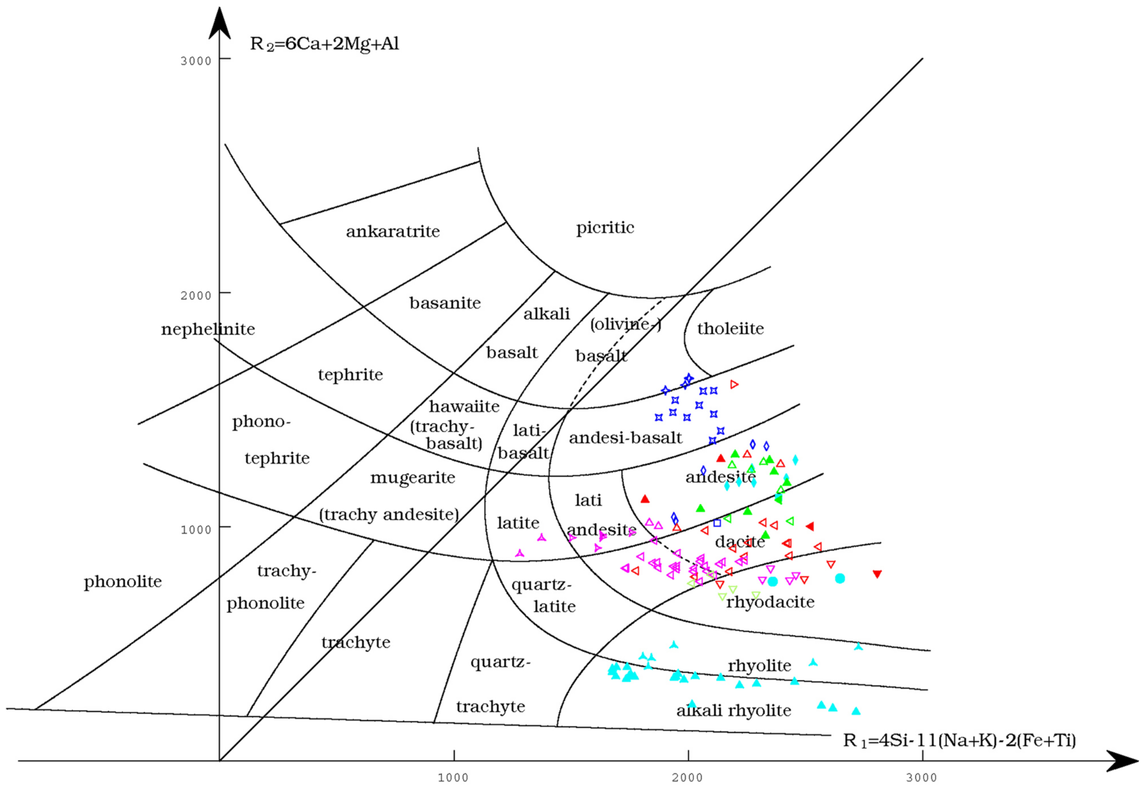

Fig. 12 R_1 vs. R_2 classification diagram of De La Roche et al. (1980) where the volcanic samples from the theatre, other artefacts of Nora and field volcanic outcrops were plotted. Symbols as legend of Fig. 9

a rounded shape; the dimensions can be very variable from one millimetre to several centimetres. Even microscopically, the rocks of *Su Casteddu* have many similarities with the theatre volcanics (Fig. 7). Both show from hyalopilitic to hypocrystalline structure, porphyric (with a porphyry index variable between 3 and 10) for opaque phenocrystals of magnetite or Ti-magnetite. Plagioclase is dominant, very altered and with the substitution characteristics with calcite that has also been observed in the volcanics of the theatre. The pyroxenes are very altered and there are relicts of brown hornblende with opacity edges. Mesostasis is characterised by dominant plagioclase, pyroxene and/or brown hornblende and more or less abundant glass.

Other important information can be derived from the extraction modes of raw material and the morphology of the volcanic outcrop (Fig. 14): (1) the volume of extracted volcanic material is certainly compatible with the size of *Su Casteddu* apparatus; (2) the steep slopes of *Su Casteddu* facilitated the extraction and transport of the ashlars to the flat land.

The volcanics, which were used to construct the other Roman buildings in Nora archaeological site (i.e. houses, *Macellum horreum* masonry, inner street, thermal baths; Figs. 2, 3), come mainly from the countryside of Nora and *Perdu Pranu* areas and probably not from *Su Casteddu*, because they show different geochemical characteristics, as highlighted by the various figures (Figs. 8, 9, 10, 11, 12) in the previous paragraphs where they form a separate population practically in every diagram. Observing chemical data (Table ESM 3), the analysed samples from *Perdu Pranu* area (PN 61–64), that between the all outcrop samples show more similar macroscopic features (i.e. sample PN 63) with the volcanics of *Su Casteddu*, and have following values: $SiO_2 < 62\%$, $TiO_2 > 0.5\%$, $FeO_{tot} > 4.92\%$, $MgO > 1.71\%$, $CaO > 4.43\%$, $Na_2O < 3.75\%$, $V > 88$ ppm, while *Su Casteddu* samples (i.e. CVR 3–7) have: $SiO_2 > 63\%$, $TiO_2 < 0.5\%$, $FeO_{tot} < 4.83\%$, $MgO < 1.68\%$, $CaO < 3.67\%$, $Na_2O > 4.1\%$, $V < 56$ ppm.

Also microscopically they appear different (Fig. 7): the samples from *Perdu Pranu* and Nora generally have porphyritic structure with a higher index (> 15%) for phenocrystals of opaque, abundant plagioclase, highly-altered clinopyroxenes, opacified brown hornblende.

However, despite the geochemical differences, the samples taken from the Roman street (e.g. VN 1, 12, 16, 18, 19, 47) and other found within "Terme a mare" building (VN 21, 22, 23, probably coming from the paving of Roman street) show clear macroscopic and microscopic similarities to those of the theatre and *Su Casteddu* volcanics. Nevertheless, a more careful observation of the samples of such

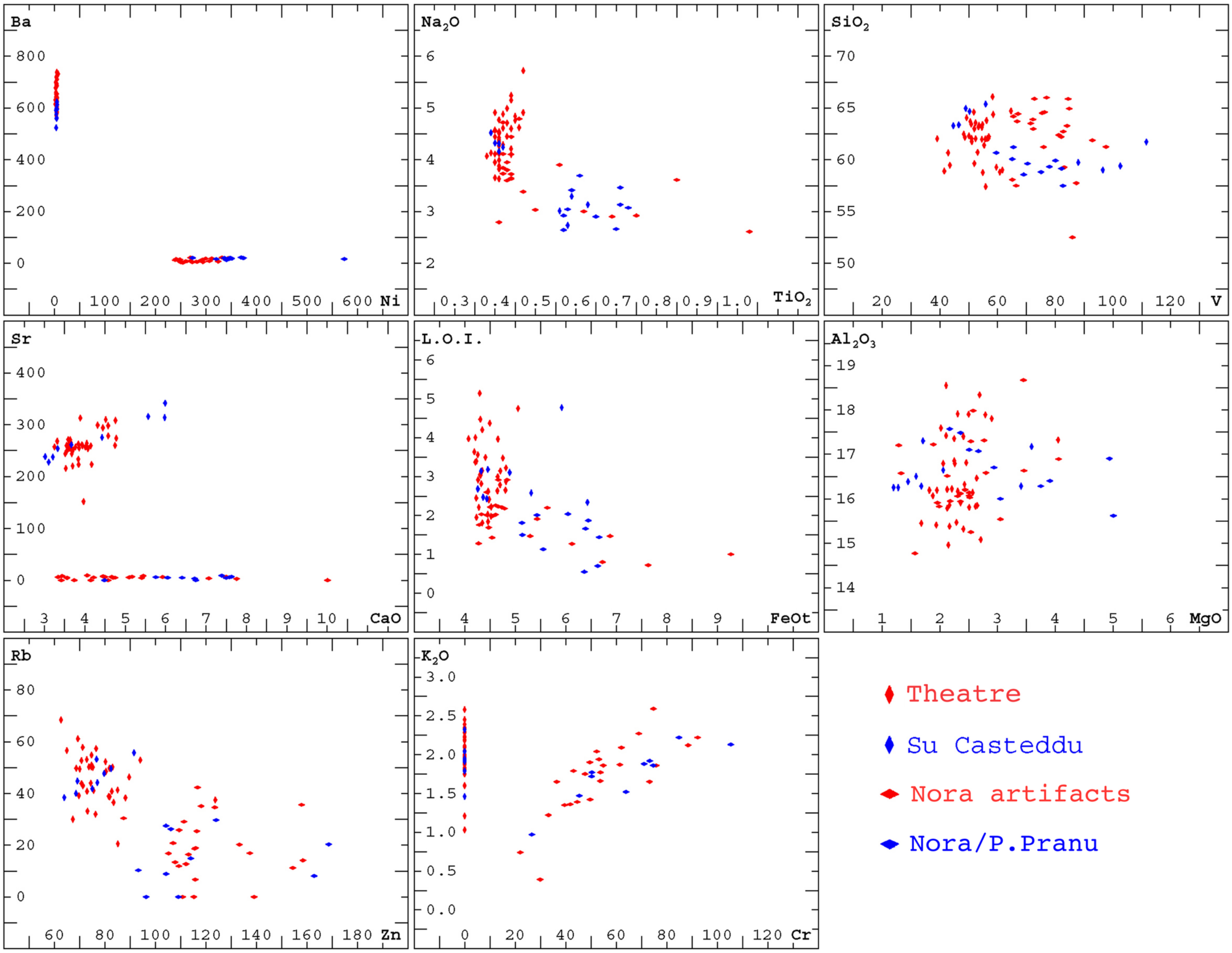

Fig. 13 Variation diagrams of major (wt%) and trace (ppm) elements derived from the factorial analysis on the samples of theatre, other Nora artefacts, Nora and *Perdu Pranu* outcrops and ancient *Su Casteddu* quarry (Garau 2005)

artefacts shows some petro-vulcanological differences: they generally have a greater welding degree and a slightly higher of porphyritic index; the phenocrystals are less altered.

The wide use of the volcanics from *Su Casteddu* outcrop for the construction of the Nora theatre probably depends on the good workability of these rocks (due to their lower welding degree with respect to the other outcropping volcanics) and on the possibility of extracting large and regular ashlars to be used for the tiers of *cavea*, which in some cases even have dimensions of 80 × 60 × 50 cm (Fig. 14b–d). Instead, the andesitic rocks of Nora outcrops (inside the archaeological site and, therefore, potentially exploitable) were not taken into account to realise the volcanic ashlars for the theatre, because they show different petrographic and physical features that also involve a lower workability of the materials.

The andesitic rocks, along with other sedimentary and intrusive rocks, were used to make ashlars of various shapes (from irregular to squared) with decimetric and submetric size. Internally, in these walls there are occasionally large metric volcanic blocks too (positioned in the wall crossings, Fig. 3h) with very similar characteristics to those of *Perdu Pranu* and *Su Casteddu* areas.

These clear evidences indicate that the Romans chose the construction materials on the base of petro-physical features of stones. Due to a good workability and easy quarry extractability and, at the same time, to their optimal physical–mechanical characteristics, the volcanic rocks from *Su Casteddu* were used to realise big and curved ashlars for the *cavea* tiers of theatre without problems of fracturing during the processing. Vice versa, to realise the Roman architectural buildings of Nora (e.g. irregular and variable in size ashlars for masonry wall), where it is not necessarily particular features of rocks, the Romans used more comfortably all different volcanic outcroppings inside the archaeological site or outside from other outcrops.

Fig. 14 Macro-photographs of *Su Casteddu* volcanic apparatus where located the Roman ancient quarry: **a** north view of volcanic neck; **b, c** ancient excavation traces in two different extraction points of the Roman quarry, with the average dimensions of the extracted ashlars/blocks; **d** working trace in the volcanic rock at the base of the ashlars to be extracted

Conclusions

The results of the research have allowed defining the geochemical characteristics and the origin of the volcanics that have been used in the construction of the Roman Nora city. These rocks belong to subalkaline series of the Sardinian Late Eocene–Miocene volcanic cycle, with a mainly sodic affinity and more rarely potassic. The samples from the Roman theatre were mainly classified (in order of abundance) as dacites and, subordinately, as lati-andesites, rhyodacites, andesites and latites, while the samples taken from the other masonries of Nora site are classified as dacites, andesites, rhyodacites and basaltic andesites.

The andesitic and dacitic volcanics were mainly used as construction material for artefacts of Nora (i.e. Roman stone paving of roads inside the village) but also as aggregate in the mortars (i.e. wall bedding mortars, concretes of vaults and *cavea* foundation, plasters) together obsidian rocks, quartz–feldspar sandy, Paleozoic rocks.

To define their provenance, the volcanics from Nora archaeological site have been compared with those from the surrounding areas and from Sulcis basin, more frequented by the Romans, and in which the Nora territory is included.

Chemical and petrographic data highlight that the dacitic rocks (represented by volcanic autobreccias), which have been used on the Nora theatre tiers, come from the *Su Casteddu* volcanic apparatus, located 2 km at north-east of Nora site. This assumption is also confirmed by the comparable material volumes of extracted stone from the *Su Casteddu* quarry and those used for the tiers of *cavea*, and by possibility that the Romans (as they often used to do) used the near Rio Pula river and then the sea to transport the material from the quarry to Nora site.

In different way, the volcanics, which have been used for the Nora artefacts, mainly come from the more nearly countryside areas. Due to their higher physical–mechanical resistance, for the stone paving of the main inner street, the Roman *Foro* and parts of the other buildings (i.e. base of public fountain), more welded andesitic–dacitic volcanic rocks (as autobreccias) were used, mainly coming from *Perdu Pranu* area.

To construct the masonry of the houses and commercial area to the west seaport (i.e. *Macellum horreum*), andesitic rock outcroppings inside the Nora site were used, especially as irregular ashlars of the walls.

For frames and door thresholds of Nora buildings, the Romans used different volcanic materials, mainly represented by welded volcanic breccias and conglomerates coming from Nora area and surrounding outcrops, together occasionally grey fine sandstones (i.e. thresholds of *Macellum horreum*).

The supply of the raw materials from different areas around the Nora site highlights that the Romans chose the stones for the construction of ancient Nora village according to their petro-physical characteristics which clearly affect the workability and quarry extractability. Thus, considering only the sources around Nora site (or at a reasonable distance from it) and only within them, the distance between the quarry and the building site is not the main factor leading material selection.

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References

Alvarez JI, Navarro I, Martin A, Garcia Casado PJ (2000) A study of the ancient mortars in the north tower of Pamplona's San Cernin Church. Cem Concr Res 30:1413–1419

Antonelli F, Columbu S, De Vos Raaijmakers M, Andreoli M (2014) An archaeometric contribution to the study of ancient millstones from the Mulargia area (Sardinia, Italy) through new analytical data on volcanic raw material and archaeological items from Hellenistic and Roman North Africa. J Archaeol Sci 50:243–261

Assorgia A, Brotzu P, Morbidelli L, Nicoletti M, Traversa G (1984) Successione e cronologia (K-Ar) degli eventi vulcanici del complesso calco-alcalino Oligo-Miocenico dell'Arcuentu (Sardegna centro-occidentale). Period Mineral 53:89–102

Assorgia A, Barca S, Onnis G, Secchi FAG, Spano C (1986) Episodi sedimentari e vulcanici oligo-miocenici nel settore occidentale dell'Arcuentu e loro contesto geodinamico (Sardegna SW). Mem Soc Geol It 35(10):229–240

Assorgia A, Fadda A, Gimeno Torrente G, Morra V, Ottelli L, Secchi FA (1990) Le successioni ignimbritiche terziarie del Sulcis (Sardegna sud-occidentale). Mem Soc Geol Ital 45:951–963

Beccaluva L, Civetta L, Macciotta G, Ricci CA (1985) Geochronology in Sardinia: results and problems. Rend Soc Ital Mineral Petrol 40:57–72

Beccaluva L, Brotzu P, Macciotta G, Morbidelli L, Serri G, Traversa G (1989) Cainozoic tectono-magmatic evolution and inferred mantle sources in the Sardo-Tyrrenian area. In: Boriani A, Bonafede M, Piccardo GB, Vai GB (eds) The lithosphere in Italy. Advances in Earth Science Research, vol 80. Atti Conv. Acc. Naz. Lincei, Rome, pp 229–248

Beccaluva L, Bianchini G, Coltorti M, Siena F, Verde M (2005a) Cenozoic Tectono-magmatic evolution of the Central western Mediterranean: migration of an Arc-interarc Basin System and Variations in the Mode of Subduction. In: Finetti I (ed) Elsevier Special Volume, "Crop Project—Deep Seismic Exploration of the Central Mediterranean and Italy", pp 623–640

Beccaluva L, Bianchini G, Bonadiman C, Coltorti M, Macciotta G, Siena F, Vaccaro C (2005b) Within-plate Cenozoic Volcanism and Lithospheric Mantle Evolution in the Western-central Mediterranean Area. In: Finetti I (ed) Elsevier Special Volume, "Crop Project—Deep Seismic Exploration of the Central Mediterranean and Italy", pp 641–664

Beccaluva L, Bianchini G, Natali C, Siena F (2011) Geodynamic control on orogenic and anorogenic magmatic phases in Sardinia and Southern Spain: inferences for the Cenozoic evolution of the western Mediterranean. Lithos 180–181:128–137

Bejor G (1999) L'area del teatro. In: Tronchetti C (ed) AA. VV. Ricerche su Nora-I (anni 1990–1998). Sainas Ed, Cagliari

Bernardini P (2004) Cartagine e la Sardegna. Dalla conquista all'integrazione (540–238 a.C.). RS-tFen 32:35–56

Bianchini G, Marrocchino E, Vaccaro C (2004) Chemical and mineralogical characterisation of historic mortars in Ferrara (NE, Italy). Cem Concr Res 34(8):1471–1475

Carminati E, Doglioni C (2012) Alps vs. Apennines: the paradigm of a tectonically asymmetric Earth. Earth Sci Rev 112:67–96

Cherchi A, Montadert L (1982a) Il sistema di rifting oligo-miocenico del Mediterraneo occidentale e sue conseguenze paleogeografiche sul terziario sardo. Mem Soc Geol Ital 24:387–400

Cherchi A, Montadert L (1982b) Oligo-Miocene rift of Sardinia and the early history of the western Medittanean basin. Nature 298:736–739

Columbu S (2017) Provenance and alteration of pyroclastic rocks from the Romanesque Churches of Logudoro (north Sardinia, Italy) using a petrographic and geochemical statistical approach. Appl Phys A Mater Sci Process 123(3):165. https://doi.org/10.1007/s00339-017-0790-z

Columbu S. Garau AM (2017) Mineralogical, petrographic and chemical analysis of geomaterials used in the mortars of Roman Nora theatre (south Sardinia, Italy). Ital J Geosci 136:238–262

Columbu S, Sitzia F, Verdiani G (2015) Contribution of petrophysical analysis and 3D digital survey in the archaeometric investigations of the Emperor Hadrian's Baths (Tivoli, Italy). Rend Fis Acc Lincei 26:455–474

Columbu S, Sitzia F, Ennas G (2017) The ancient pozzolanic mortars and concretes of Heliocaminus baths in Hadrian's Villa (Tivoli, Italy). Archaeol Anthropol Sci 9:523–553

Columbu S, Garau AM, Lugliè C (2018) Geochemical characterisation of pozzolanic obsidian glasses used in the ancient mortars of Nora Roman theatre (Sardinia, Italy): provenance of raw materials and historical–archaeological implications. Archaeol Anthropol Sci. https://doi.org/10.1007/s12520-018-0658-y

Conte A (1989) Studio petrografico, mineralogico e geochimico delle rocce magmatiche calcoalcaline dei distretti di Sarroch (Sardegna meridionale) e di S.Antioco (Sardegna Sud-Occidentale), Ph.D. Thesis. Roma University, Italy

Coulon C (1977) Le volcanism calco-alcalin cenozoique de Sardaigne, Italie. Unpublished master's thesis. Univesité St. Jerome, Marseille

Criss JW (1977) NRLXRF: a fortran program for X-ray fluorescence analysis. Cosmic, Athens

Cross W, Iddings JP, Pirsson LV, Washington HS (1903) Quantitative classification of igneous rocks. University of Chicago Press, Chicago

De Luca R, Miriello D, Pecci A, Domìnguez-Bella S, Bernal-Casasola D, Cottica D, Bloise A, Crisci GM (2015) Archaeometric study of mortars from the Garum Shop at Pompeii, Campania, Italy. Geoarchaeology 30:330–351

De La Roche H, Leterrier J, Grandclaude P, Marchal M (1980) A classification of volcanic and plutonic rocks using R_1–R_2 diagram and major-element analyses—its relationships with current nomenclature. Chem Geol 29:183–210

Dostal J, Coulon C, Dupuy C (1982) Cainozoic andesitic rock of Sardinia (Italy). In: Thorpe RS (ed) Andesites: orogenic andesites and related rocks. Wiley, Chichester, pp 353–370

Franzini M, Leoni L, Saitta M (1975) Revisione di una metologia analitica per fluorescenza-X, basata sulla correzione completa degli effetti di matrice. Soc Ital Mineral Petrol Rendiconti XXXI(2):365–378

Franzini M, Leoni L, Lezzerini M, Sartori F (2000) The mortar of the "Leaning Tower" of Pisa: the product of a medieval technique for preparing high-strenght mortars. Eur J Mineral 12:1151–1163

Garau AM (2005) Le pietre e le malte del teatro di Nora (Sardegna SW). Unpublished doctoral dissertation. University of Cagliari, Cagliari

Garbarino C, Lirer L, Maccioni L, Salvadori I (1990) Carta vulcanologica della'Isola di San Pietro (Sardegna). Scala 1/25000. SELCA Eds, Firenze

Gattaceca J, Deino A, Rizzo R, Jones DS, Henry B, Beaudoin B, Vadeboin F (2007) Miocene rotation of Sardinia: new paleomagnetic

and geochronological constraints and geodynamic implications. Earth Planet Sci Lett 258:359–377
Irvine TN, Baragar WRA (1971) A guide to the chemical classification of the common volcanic rocks. Can J Earth Sci 8:523–548
Kuno H (1968) Differentiation of basalt magma. In: Hess H, Poldervaart A (eds) The Poldervaart treatise on rocks of basaltic composition, vol II. Wiley, New York, pp 623–688
Le Bas MJ, Le Maitre RW, Strekeisen AL, Zanettin B (1986) A chemical classification of volcanic rocks based on the total alkali-silica diagram. J Petrol 27:745–750
Le Maitre RW, Streckeisen A, Zanettin B, Le Bas MJ, Bonin B, Bateman P, Bellieni G, Dudek A, Efremova S, Keller J, Lamere J, Sabine PA, Schmid R, Sorensen H, Woolley AR (2002) Igneous rocks: a classification and glossary of terms. Recommendations of the International Union of Geological Sciences, Subcommission of the Systematics of Igneous Rocks. Cambridge University Press, Cambridge
Lustrino M, Duggen S, Rosenberg CL (2011) The Central-Western Mediterranean: anomalous igneous activity in an anomalous collisional tectonic setting. Earth Sci Rev 104:1–40
Maravelaki-Kalaitzaki P, Bakolas A, Moropoulou A (2003) Phisico-chemical study of Cretan ancient mortars. Cem Concr Res 33:651–661
Mastino A (2005) Storia della Sardegna antica. Ed. Il Maestrale, Sassari
Middlemost EAK (1975) The basalt clan. Earth Sci Rev 11:337–364
Moropoulou A, Bakolas A, Bisbikou K (2000) Investigation of the technology of historic mortars. J Cult Heritage 1:45–58
Peccerillo A, Taylor SR (1976) Geochemistry of eocene calc-alkaline volcanic rocks from the Kastamonu area, Northern Turkey. Contrib Mineral Petrol 58(1):63–81
Pesce G (1954) Scavi nell'area della città, 1952–1954. In: Fasti Archeologici 9. Editrice Belriguardo Libreria, Ferrara, pp 356–358
Pesce G (1972) Nora. Guida agli scavi, II. Fossataro Ed, Cagliari
Recommendations Nor.3/80 MaL (1980) Stone materials: sampling. CNR-ICR, Roma
Riccardi MP, Duminuco P, Tomasi C, Ferloni P (1998) Thermal, microscopic and X-ray diffraction studies on ancient mortars. Thermochim Acta 321:207–214
Savelli C (1975) Datazioni preliminari col metodo K-Ar di vulcaniti della Sardegna sud-occidentale. Rend Soc Ital Mineral Petrol 31:191–198
Savelli C, Beccaluva L, Deriu M, Macciotta G, Maccioni L (1979) K/Ar geochronology of the tertiary "Calc-Alcalik" volcanism of Sardinia (Italy). J Volc Geotherm Res 5:257–269
Shand SJ (1951) Eruptive rocks; their genesis, composition, classification, and their relation to ore-deposits, with a chapter on meteorites, 4th edn. Wiley, New York
Speranza F, Villa IM, Sagnotti L, Florindo F, Cosentino D, Cipollari P, Mattei M (2002) Age of the Corsica-Sardinia rotation and Liguro-Provençal Basin spreading: New paleomagnetic and Ar/Ar evidence. Tectonophysics 347(4):231–251
Streckeisen A (1976) Classification of the common igneous rocks by means of their chemical composition. Neues Jahrb Mineral Monatsh, pp 1–15
Streckeisen A (1978) Classification and nomenclature of volcanic rocks. I.U.G.S. (Int. Union Geol. Sci.), Subcomm. on the Systematics of Igneous Rocks. Inter. Rep. Contrib., p 70
Thornton CP, Tuttle OF (1960) Chemistry of igneous rocks--[Part] 1, Differentiation index. Am J Sci 258:664–684
Tronchetti C (2001) Nora. Collana Sardegna Archeologica. Carlo Delfino Editore and C, Sassari
Vardabasso S, Atzeni A (1962) Il bacino Ooligocenico di Oschiri-Berchidda nella Sardegna nord-occidentale. Mem Soc Geol Ital 3:717
Verdiani G, Columbu S (2010) E.Stone, an archive for the Sardinia monumental witnesses. Lect Notes Comput Sci 6436:356–372
Vola G, Gotti E, Brandon C, Oleson JP, Hohlfelder RL (2011) Chemical, mineralogical and petrographic characterization of roman ancient hydraulic concretes cores from Santa Liberata, Italy, and Caesarea Palestinae. Israel Period Mineral 80:317–338