RESEARCH

The stone artifacts of the National Archaeological Museum of Adria (Rovigo, Italy): a noteworthy example of heterogeneity

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Abstract

This paper reports on the results of the analyses of 56 stone samples from Roman and pre-Roman artifacts from the ancient town of *Atria*, currently preserved at the National Archaeological Museum of Adria. The city is located in the eastern Veneto lowlands, close to the Po River delta, and far from the main rock outcrops of the region. The objective of this research is to determine the provenance of the stones used in ancient *Atria* and their trade networks. The analytical techniques adopted include polarized-light optical microscopy (PLM), X-ray fluorescence (XRF), and quantitative phase analysis by X-ray powder diffraction (QPA-XRPD). The results reveal a widespread use of imported stones from the central-western territories of Veneto, primarily comprising trachyte from the Euganean Hills and the soft limestone Vicenza Stone from the Berici Hills/eastern Lessini Mounts. Rosso Ammonitico, Maiolica (Biancone) and Scaglia Rossa limestones are also documented. From neighbouring regions, the imported stone types include Aurisina limestone from the Trieste Karst and Istrian Stone. Sandstone was uniquely recognized in G. Popillius's milestone. Moreover, advanced geochemical and mineralogical analyses performed on the Euganean trachytes allow tracking accurately the quarry sites, revealing an extensive exploitation of the main historical quarries of M. Oliveto, Monselice and M. Merlo, although some provenances from outcrops less systematically exploited were also detected. Notably, the use of rhyolite for manufacturing a pre-Roman gravestone provides new insights regarding the exploitation of Euganean stone resources before the Roman era.

Keywords Adria · Ancient quarries and stone trade · PLM · XRF · Discriminant analysis · QPA-XRPD

Introduction

State of art

Provenance of stone materials in archaeology is a fascinating research topic for the reconstruction of the economics and engineering skills of ancient societies, as it offers many insights regarding the distribution of quarries and their relationship with ancient cities, the exploitation patterns of natural resources, the trade routes of stone materials and the ways of selection of rock types according to their final utilization (Gutiérrez Garcia-Moreno 2009; Russell 2013; Bonetto et al. 2014; Previato 2016; Freire-Lista 2021; Finkel et al. 2022; Loyola et al. 2023).

The joint research promoted in the last years by the Department of Cultural Heritage and the Department of Geosciences of the University of Padua has substantially contributed to decipher the dynamics of stone quarrying and trade in Veneto and Friuli Venezia-Giulia regions back to the Roman and pre-Roman ages (Previato et al. 2014; Previato and Zara 2014; Previato 2015a; Previato 2015b; Previato and Zara 2018; Zara 2018; Previato 2018; Paltineri et al. 2020; Boschetti et al. 2021). Those territories, in fact, are characterized by the abundance and variety of good-quality rock outcrops, which were intensively exploited for stone supply in antiquity, by taking advantage of the articulated waterway network of the Po plain and Adriatic coastline that favoured stone transport and trade (Buonopane 1987;

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Calzolari 2003; Previato and Zara 2014; Previato 2015b; Previato and Zara 2021).

Stone resources historically exploited in north-eastern Italy are mainly constituted by sedimentary rock types, with a prevailing attestation of limestones from quarry sites in the Berici Hills, Veneto Prealps, Trieste Karst and Istrian peninsula (Cornale and Rosanò 1994; Lazzarini 2006; Previato 2015a, 2018; Rioda 2015), which were used both as construction materials and for the production of small artifacts (Fig. 1).

Alongside sedimentary rocks, stronger and more compact volcanic rocks, primarily represented by trachyte, were extracted in the Euganean Hills since the prehistory. That is the main magmatic district of the Veneto region, characterized by differentiated eruptive events occurred between Eocene and Oligocene (Astolfi and Colombara 1990). These
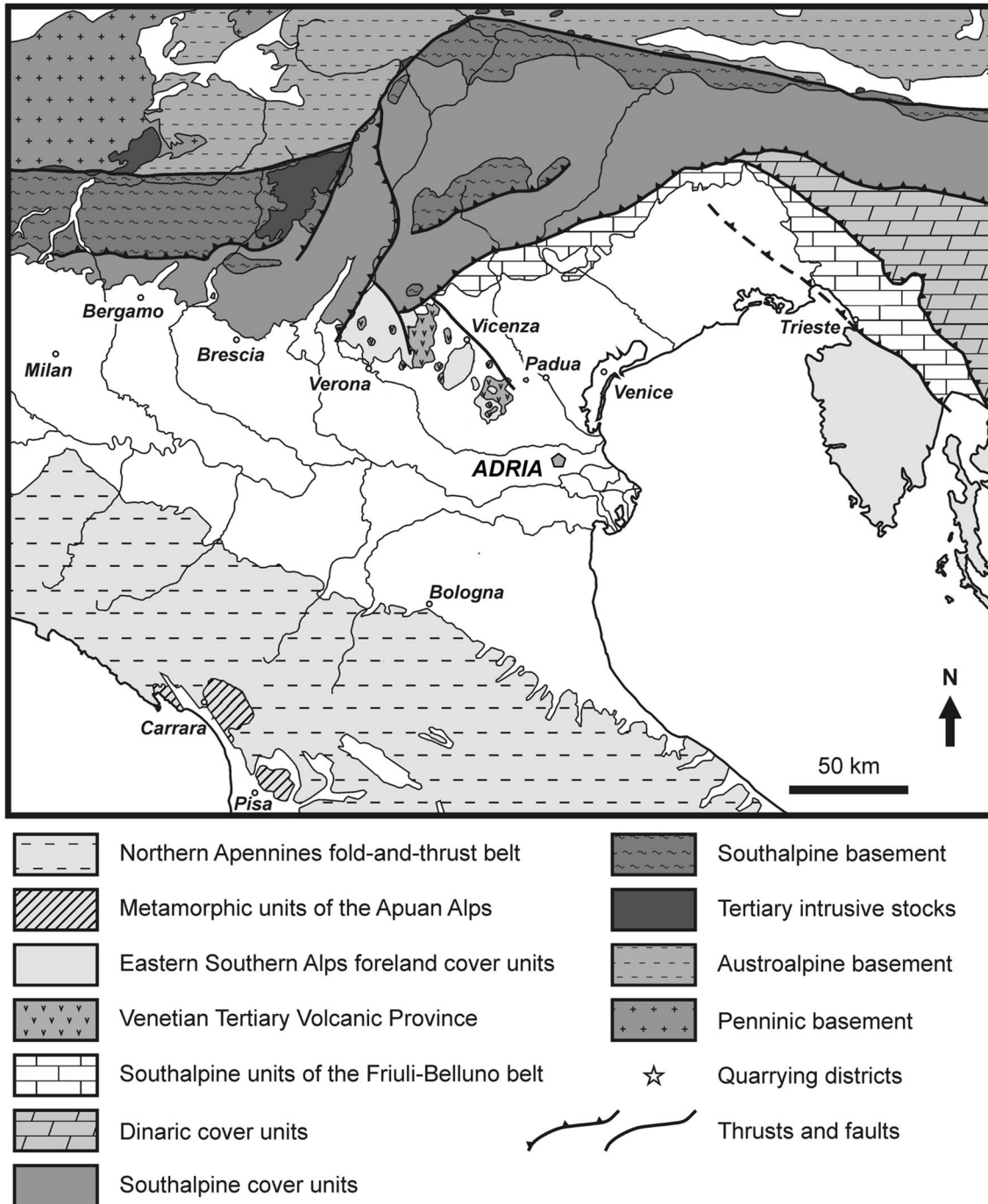

Fig. 1 Simplified geological map of north-eastern Italy with the localization of the town of Adria (modified from Salvini et al. 2023)

volcanic rocks were also quarried to obtain both artefacts (i.e. gravestones, millstones) and building materials for infrastructures (i.e. road paving) and masonries (Zara 2018).

Stone provenance from sources in north-eastern Italy is traditionally determined by scholars encompassing multiple analytical approaches and characterization techniques. For carbonate rock types, their provenance is usually defined through the taxonomic recognition of index fossils by optical microscopy analyses, useful for the classification of discriminant microfacies (Previato 2015a; Flügel and Flügel 1997; Roffia et al. 2009; De Vecchi 2008; Falezza et al. 2015; Previato and Mazzoli 2018; Bonetto et al. 2021; Boschetti et al. 2021; Lazzarini 2022; Brajkovič et al. 2023). In that way, the geological formation can be traced with good accuracy, although the method generally does not allow the identification of specific quarries. Other analytical techniques, such as geochemistry or isotopic analysis, when combined with optical microscopy, in some circumstances can offer more in-depth information for the determination of extraction sites, even though not conclusive (Maritan et al. 2003; Brajkovič et al. 2022).

On the other hand, the Euganean volcanic rocks can be distinguished according to their changing petrographic features, which are diagnostic for the identification of specific outcrops and eruptive geological episodes (Cattani et al. 1997; Previato et al. 2014; Bianchin Citton and De Vecchi 2015). Geochemical analyses offer further crucial elements in this sense, as Euganean volcanic rocks return a significant geochemical variability. Therefore, by combining these techniques, the quarry identification for Euganean volcanic rocks can be tracked with a high confidence level (Renzulli et al. 1999, 2002; Capedri and Venturelli 2003; Capedri et al. 2003; Antonelli et al. 2004; Antonelli and Lazzarini 2012; Maritan et al. 2013; Germinario et al. 2018a; 2018b). Eventually, Germinario et al. (2018a) and Germinario et al. (2018b) demonstrated that the greatest accuracy can be obtained by investigating the phenocryst geochemical fingerprint by LA-ICP MS, which provides more straightforward results for provenancing at very high resolution. However, this is an expensive technique that may require longer timings for analyses and data processing.

Objective of the research

In this paper, stone samples from Roman and pre-Roman stone artefacts, coming from the ancient city of *Atria* (45°3′31.3″ N; 12°3′21.7″ E) and the nearby territories, and currently preserved at the National Archaeological Museum of Adria, were analysed. The objective of this research is the determination of the geological provenance of the rock types used in the city and the trade routes exploited by Adria in antiquity for the supply of stone materials.

The site of Adria: location, geomorphological context and history

Nowadays, the town of Adria (Rovigo, Veneto Region, north-eastern Italy) is located in the Po Valley between the Adige River to the north and the Po River to the south, along the so-called Canal Bianco (Fig. 2) at a distance of approximately 25 km from the Adriatic Sea.

The urban centre of ancient *Atria* dates back to the Iron Age (6th c. BCE), but the area was already inhabited during the Bronze Age (Balista 2013). The settlement was located on a shallow river hump along an ancient branch of the Po river (the Po of Adria) flowing out into the Adriatic Sea. From the 6th c. BCE, that was replaced by the Tartaro/Canal Bianco river network (Piovan et al. 2010, 2012; Balista 2013; Corrò and Mozzi 2017). Around the city, an articulated system of lagoons and canals developed, some of which were certainly navigable. The presence of numerous waterways and the short distance from the sea (at approximately 12 km) made *Atria* an important commercial hub and a connection point between the Adriatic Sea and the Po Valley from the end of the Bronze Age to the Roman Age (Bondesan et al. 1995; Stefani and Vincenzi 2005). In fact, the city had a river port where the goods, coming from all over the Mediterranean, were easily redistributed inland.

In pre-Roman times, the settlement consisted of buildings made of perishable materials (timber, clay and canes) built on piles to overcome the instability of alluvial deposits. The site was characterized by a strong multi-ethnic identity, as it was frequented by *Venetii*, Etruscans and Greeks, who lived and traded their goods there (Bonomi 1993; Bonomi et al. 2002; Peretto et al. 2002).

The commercial role of *Atria* persisted and developed in Roman times, also thanks to the construction of two consular roads, Via Annia and Via Popillia, which crossed the city and connected it with other urban centres in north-eastern Italy (Mimmo 2006). From the 1st c. BCE onwards, the urban centre was surrounded by walls and provided with new public and private buildings, mainly built with non-perishable materials like stones and bricks (Robino 2009). Subsequently, the city continued its life without any interruption until the Middle Ages and beyond (Robino 2009; Corrò and Mozzi 2017).

Due to the lifelong continuity of the site, the remains of the ancient buildings of *Atria* lie several meters below the ground level and have only been partially investigated. Their state of conservation is also very weak, as they have
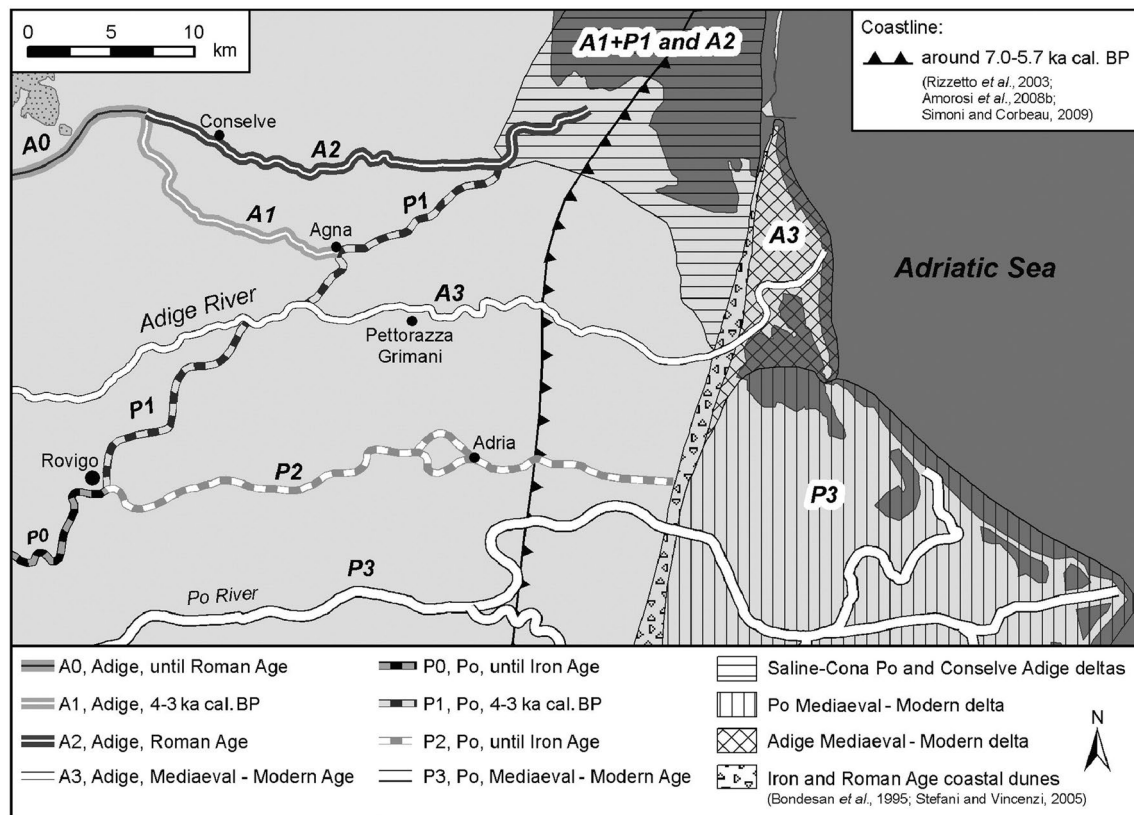
Fig. 2 Location of the town of Adria in relation to the ancient local geomorphology (from Corrò and Mozzi 2017)

been largely spoiled during Medieval and Modern times. Nevertheless, numerous Roman building stones and infrastructures are still preserved in the National Archaeological Museum in Adria, where also pre-Roman stone artefacts found within and in the nearness of the city are stored.

Materials and methods

Sampling

In the framework of this research, 56 stone elements from the National Archaeological Museum of Adria were selected for analyses. Their chronology and function were considered in the sampling, in order to get an extensive and correct picture of the rock types used and imported in the ancient town (Fig. 3). In detail, samples were taken from 18 funerary gravestones, including *stele* and *cippi* (AD_002; AD_013; AD_026; AD_038; AD_044; AD_046; AD_053; AD_057; AD_062; AD_070; AD_074; AD_079; AD_150; AD_188; AD_192; AD_197; AD_198; AD_199), three sarcophagus lids (AD_166; AD_172; AD_181), one votive altar (AD_018), one milestone belonging to the Via Popillia (AD_083), seven paving stones (AD_118B; AD_141B;

AD_143D; AD_145; AD_146B; AD_146F; AD_195) and 26 architectural elements (AD_024; AD_120B; AD_121; AD_122; AD_124; AD_128; AD_130; AD_132; AD_133; AD_138; AD_139; AD_151A; AD_151B; AD_151C; AD_153; AD_155; AD_158A; AD_158B; AD_184; AD_185; AD_187; AD_202; AD_203; AD_204; AD_205; AD_206).

All the artefacts sampled date back to the Roman Age (Bellintani et al. 1995; Bonomi et al. 2006; Bonomi and Zega 2006; Bonomi and Zega 2010), except for two pre-Roman gravestones (AD_197; AD_198), one of which (AD_198) is characterized by a Venetic inscription (Marinetti 2008).

Methodology

All samples were cut using a diamond blade saw. Following the macroscopic observation of fresh cross sections, they were divided in two groups: one consisting of 26 sedimentary rocks, primarily limestone, and the other comprising 30 volcanic rocks, primarily Euganean trachyte. These two groups were characterized using distinct analytical protocols.

A detailed petrofabric analysis allowed determining the sedimentary rock types and, in most cases, attributing

Fig. 3 A selection of the archaeological artifacts sampled from the National Archaeological Museum of Adria. AD_002 = Roman gravestone; AD_026 = Roman gravestone; AD_044 = Roman gravestone; AD_053 = Roman gravestone; AD_074 = Roman gravestone; AD_079 = Roman gravestone; AD_188 = Roman gravestone; AD_199 = Roman cippus; AD_197 = Pre-Roman gravestone; AD_172 = Sarcophagus lid; AD_018 = Votive altar; AD_083 = Milestone; AD_146B = Road paving; AD_121 = Ashlar block; AD_187 = Lintel (?); AD_024 = Pillar plinth; AD_184 = Semicolumn; AD_202 = Lintel (?); AD_203 = Cornice (?)

them to specific geological formations based on the texture and fossil assemblages. In contrast, the volcanic rocks underwent a comprehensive multi-analytical characterization, allowing for the precise identification of their quarry sites. We initially adopted a geochemical approach, comparing the bulk-rock composition of the archaeological samples with geological samples collected from well-known quarry sites. Our baseline consisted of a collection of Euganean trachyte and rhyolite samples from the main historical Euganean quarries (Calvino 1967), analysed using XRF (X-ray fluorescence) and reported in Germinario et al. (2018a) and Brombin (2014). This dataset was augmented with additional rhyolite samples collected for this study from *Forche del Diavolo* and *Denti dea Vecia* outcrops. To further validate our results, we used a series of archaeological samples attributed to specific Euganean quarry sites based on PLM (polarized light optical microscopy), bulk-rock XRF analysis and trace-element

composition of phenocrysts by LA-ICP MS (laser ablation inductively coupled plasma mass spectrometry), as detailed in Germinario et al. (2018b).

To ensure precision in the geochemical analyses and avoid potential variations that may arise from different techniques (e.g. the preparation method of powder pellets), which could impact the reliability of the results (as previously noted by Maritan et al. 2013 and Germinario et al. 2018a), we prepared the archaeological stone samples for XRF using the same procedure described in Germinario et al. (2018a).

We compared the distribution of the archaeological samples to the geological baseline by creating binary scatterplots with major and trace elements serving as quarry tracers for Euganean trachyte (Na_2O, Al_2O_3, K_2O, TiO_2, V, Rb, Sr, Zr, Nb, Ce, Nd, based on Germinario et al. 2018a; Germinario et al. 2018b) and rhyolite (SiO_2, Ba, Sr based on Milani et al. 1999; Bartoli et al. 2015, and Rb, based on Brombin 2014).

Unfortunately, the use of binary diagrams alone proved insufficient to unequivocally determine the original quarry for some archaeological samples due to partial geochemical overlap of certain Euganean quarry samples.

To enhance the accuracy of our analysis and fully utilize the bulk-rock geochemical data, we applied discriminant analysis (DA). This multivariate statistical method is commonly used to validate the classification of known data into categories or assign unknown observations to these categories. When DA is used for predictive purposes (predictive discriminant analysis, Boedeker and Kearns 2019), it estimates the probability for an unknown observation to belong to a specific group based on a set of descriptive variables (posterior probability). This powerful technique has previously been employed in archaeology (Kovarovic et al. 2011) to relate new observations with already classified data, and it has successfully assessed the provenance of artefacts with unknown origin (Tykot 1997; Montana et al. 2011; Charlton et al. 2012; Brandl et al. 2018; Columbu et al. 2019; Schürch et al. 2022; Dilaria et al. 2023a, b; Prochaska 2023).

In this work, we employed DA to identify the best probabilistic matches between the archaeological volcanic rock samples and the quarry samples, using the known geological provenance as the classification factor and a selected set of discriminant chemical elements as independent variables. At the same time, the method assessed the accuracy of the known observations by measuring the statistical proximity of each geological sample to a quarry site, based on the distance from the group centroid (where 100% indicates completely correct classifications). Through DA, carried out using the integrated tools of Statgraphics Centurion Pro 19, the provenance definition of each archaeological volcanic rock sample was further refined through the detection, in probabilistic terms, of one or, in just few cases, two reliable quarry sites.

Provenance determination of volcanic samples was eventually confirmed by comparing the results inferred from discriminant analysis and scatterplots with PLM. PLM can be embraced to effectively narrow down the number of potential quarry areas by the detection of discriminant petrofabrics, based on the comparison between the archaeological samples and a collection of thin sections from historical Euganean quarries stored at the Department of Geosciences of the University of Padova. Finally, via QPA-XRPD, the mineralogical profiles of a selection of representative archaeological samples correlated to specific quarries after geochemical, multivariate statistical and PLM analyses were described. As already disclosed by previous μ-XRF analyses (Germinario et al. 2016, 2018a), a differentiation among different quarries can be detected even from mineralogy, thus highlighting the potential of a quantitative mineralogical characterization, which is little explored so far for the Euganean volcanic rocks and might consolidate provenance determination.

Analytical equipment

The samples were analysed by PLM in transmitted light (TL) on 30-μm thin sections under a Leica DM750 P microscope operating with an integrated digital camera FLEXACAM C1, in order to describe the textural and mineralogical features of the rocks.

The XRF analyses were performed on volcanic rock samples with a WDS Panalytical Zetium sequential spectrometer, operating under vacuum conditions, equipped with a 2.4-kW Rh tube. The samples were calcined to determine their loss on ignition (L.O.I.) by placing them in a muffle furnace at 860 °C for about 20 min, and then at 980 °C for about 2 h. The samples for the actual XRF analyses were then prepared in beads using lithium tetraborate ($Li_2B_4O_7$) flux with a dilution of 1:10, and melting was carried out using a Claisse Eagon 2 bead mill (maximum temperature achieved of about 1150 °C). The calculated major elements are Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, and P (expressed as percentages of the relative oxides). The L.O.I. was calculated separately. The calculated trace elements (expressed in ppm) are Sc, V, Cr, Co, Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Nb, Ba, La, Ce, Nd, Pb, Th, and U. Instrumental precision (defined by repeated analyses on the same sample) is within 0.6% relative for major elements and within 3.0% relative for trace elements. Detection limits for Al, Mg, and Na are within 0.01%, within 0.2% for Si, and within 0.005% for Ti, Fe, Mn, Ca, K and P; for trace elements, they are (in ppm): $Sc = 3$, $V = 5$, $Cr = 6$, $Co = 3$, $Ni = 3$, $Cu = 3$, $Zn = 3$, $Ga = 3$, $Rb = 3$, $Sr = 3$, $Y = 3$, $Zr = 3$, $Nb = 3$, $Ba = 10$, $La = 10$, $Ce = 10$, $Nd = 10$, $Pb = 5$, $Th = 3$, $U = 3$.

The QPA-XRPD analyses, performed on a selection of representative volcanic rocks, were done using a Bragg–Brentano θ-θ diffractometer (PANalytical X'Pert PRO, Cu Kα radiation, 40 kV and 40 mA) equipped with a real-time multiple strip (RTMS) detector (Malvern PANalytical, Malvern, UKPIXcel by Panalytical). Data acquisition was performed operating a continuous scan in the range 3–85 (°2θ), with a virtual step scan of 0.02 (°2θ). The diffraction patterns were interpreted with X'Pert HighScore Plus 3.0 software by PANalytical (Malvern PANalytical, Malvern, UK), qualitatively reconstructing mineral profiles of the compounds by comparison with PDF databases from the International Centre for Diffraction Data (ICDD). The quantification of both crystalline and amorphous content was obtained through the addition of 20 wt% of zincite to the powders as internal standard. Then, the quantitative phase analysis (QPA) was performed using the Rietveld

method (Rietveld 1967). Refinements were carried out with TOPAS software (version 4.1) by Bruker AXS. The observed Bragg peaks in the powder patterns were modelled through a pseudo-Voigt function, fitting the background with a 12-coefficient Chebyshev polynomial. For each mineral phase, lattice parameters, Lorentzian crystal sizes and scale factors were refined. Any residual preferred orientation effect was modelled during the refinement with the March Dollase algorithm (Dollase 1986). The starting structural models for the refinements were taken from the International Crystal Structure Database (ICSD). For the quantification of low-angle smectite-like peaks, detected in some samples, BGMN-Profex software with dedicated fitting functions for Rietveld refinements of clay phases was adopted (Taut et al. 1998).

Results and discussion

Sedimentary rocks

The sedimentary rocks analysed are primarily carbonate rocks. The main group includes the soft limestones known as Vicenza Stone (11 samples). Other limestones are present in smaller amounts, such as Rosso Ammonitico Veronese (three samples), Maiolica (two samples), Scaglia Rossa (two samples), Aurisina Stone (three samples), crystalline limestone of uncertain provenance (three samples), and, possibly, Istrian stone (one sample). Only one sample is a sandstone (AD_83). These rocks are among those historically exploited and used as building materials in the Veneto region since the ancient times (Buonopane 1987; Lazzarini 2006; Previato 2015a, 2015b; Zara 2018). The full petrographic description of these rock types is provided below.

Vicenza Stone

Most of the sedimentary rocks are Vicenza Stone (Pietra di Vicenza). This stone, also known as "Pietra Tenera" (Soft Stone), is a soft and easily workable limestone quarried in the Berici Hills and eastern Lessini Mounts, respectively south and west of the town of Vicenza in Veneto. All samples refer to the Oligocene *Castelgomberto Limestone Formation* (Cattaneo et al. 1976; Cornale and Rosanò 1994), and they can be classified into four different *petrofacies*, based on specific petrographic features.

Petrofacies 1 comprises five samples (AD_74, 133, 139, 151C, 205). According to Dunham's classification (Dunham 1962), the samples can be described as grainstone with sparite cement. Abundant encrusting and articulated red algae are present, along with benthic foraminifera of the Miliolida order (with size up to 30–40 µm), including *Quinqueloculina* sp., *Archaias* sp. and *Textularia* sp. There is also

the minor presence of hyaline foraminifera (with diameter up to 70–110 µm), represented by *Nummulites* sp. and individuals of the Rotaliida order (*Amphistegina* sp., *Asterigerina* sp. and *Neorotalia* sp.). Less commonly, there are occurrences of bryozoans, serpulids, echinoderms, small bivalves, gastropods and corals (Fig. 4a). Localized concentrations of goethite-limonite were observed. The abundance of benthic foraminifera is characteristic of the Costozza Stone variety of Pietra di Vicenza (Cornale and Rosanò 1994; Salvini et al. 2023).

Petrofacies 2 includes two samples (AD_124 and AD_128). These can be defined as moderately sorted rudstone/boundstone, with abundant micrite and predominantly intergranular, occasionally intragranular, sparitic cement. The key feature of this *petrofacies* is the presence of large hyaline foraminifera, including *Nummulites* sp. (with size up to 240–250 µm), *Operculina* sp. and Rotaliida (*Asterigerina* sp., up to 100 µm; *Amphistegina* sp., up to 150 µm and to a lesser extent, *Neorotalia* sp.). Occasional benthic foraminifera of the Miliolida order (*Austrotrillina* sp.), serpulids (*Ditrupa* sp.), encrusting red algae (*Lithothamnion* sp., up to 300 µm), echinoderms (often rimmed with a syntaxial calcite cement), bryozoans, corals and planktonic foraminifera are also present (Fig. 4b). The porosity is moderate.

Petrofacies 3 encompasses three samples (AD_26, 204 and 206). These are well-sorted grainstones with small to medium-sized clasts (averaging 30–40 µm) and abundant micritic clasts, articulated red algae and echinoderms (including crinoids). Benthic foraminifera are also abundant, including small individuals of *Amphistegina* sp. (up to 700 µm ca), *Neorotalia* sp., serpulids (*Ditrupa* sp.), agglutinated foraminifera (*Textularia* sp.), small mollusc shells (primarily bivalves), planktonic foraminifera and sponge spicules (Fig. 4c). Minute quartz grains and goethite were observed in the spaces among bioclasts.

Petrofacies 4 consists of only one sample (AD_62). This is a wackestone/floatstone with intracrystalline sparitic cement, characterized by abundant intraclasts, often oxidized articulated and encrusting red algae, and subordinate benthic and encrusting foraminifera (including Miliolida and *Gypsina* sp.). There are occasional hyaline-shelled foraminifera (*Amphistegina* sp.), gastropod shells and bryozoans (Fig. 4d).

Rosso Ammonitico Veronese

Three samples (AD_121, AD_158B and AD_155) are limestones characteristic of the Rosso Ammonitico Veronese (RAV) Formation, with an age ranging from the late Bajocian to the Tithonian. This formation comprises pelagic limestones, often nodular and locally cherty, distinguished by the skeletal remains of planktonic and benthic organisms within a micritic
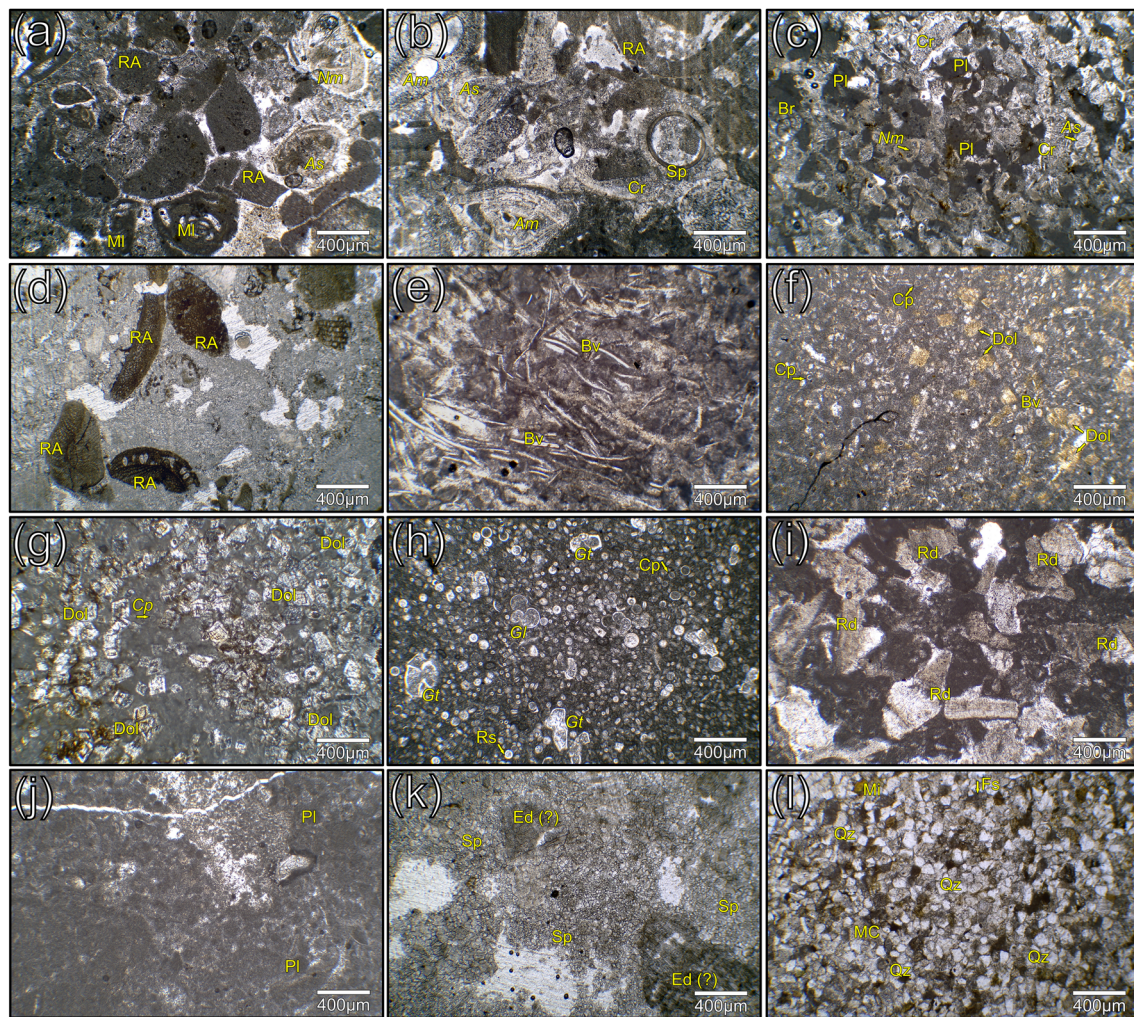
Fig. 4 PLM micrographs (plane polarized light) of representative samples of sedimentary rocks. **a** AD_151C (Vicenza Stone, *petrofacies* 1 — Costozza Stone variety; **b** AD_124 (Vicenza Stone, *petrofacies* 2); **c** AD_204 (Vicenza Stone, *petrofacies* 3); **d** AD_64 (Vicenza Stone, *petrofacies* 4); (e) AD_121 (Rosso Ammonitico Veronese); **f** AD_202 (Maiolica, with dolomitization phenomena); **g** AD_185 (Maiolica, with pronounced dolomitization phenomena); **h** AD_53 (Scaglia Rossa); **i** AD_151 (Aurisina Stone); **j** AD_184 (possibly Istrian Stone); **k** AD_203 (Crystalline limestone); **l** AD_83 (Litarenite). RA, Red Algae; *Nm*, *Nummulites* sp.; Ml, Miliolida; *As*, *Asterigerina* sp.; *Am*, *Amphistegina* sp.; Br, Briozoans; Pl, Peloids; Cr, Crinoids; Bv, Bivalves; Cp, Calpionellids; Dol, dolomite; *Gt*, *Globotruncana* sp.; Rs, Radiolarians; *Gl*, *Globigerina* sp.; Rd, Rudists; Sp, Sparite; Ed, Echinoderms; MC, Micritic Carbonates; Mi, Micas; Qz, Quartz; Fs, Feldspars

matrix. Ammonite moulds are frequently found and, at times, microbial mats have stromatolithic layers (Martire 1990, 1996; Lukeneder 2011). These rock types, displaying a distinctive reddish, yellowish or whitish colour and thinly bedded, nodular structure, have been quarried since Roman times primarily from the western Lessini Mounts in the Venetian Prealps, north of Verona. Presently, they are extracted in the Valpolicella Valley (Verona) and on the Asiago plateau (Clari et al. 1984; Martire 1996; Martire et al. 2006). The samples are either wackestones (AD_155 and AD_158B) or thin-shelled bivalve-rich packstones (AD_121), with a micritic matrix. Abundant thin-shelled bivalves (up to 70–100 μm) are accompanied by occasional ostracod, small calpionellid loricas (around 10–20 μm), planktonic foraminifera (globigerinids), dinoflagellates and sporadic radiolarians and sponge spicules (Fig. 4e). In the case of sample AD_158B, sponges and spicules are prevalent, alongside crinoid ossicles, and remnants of dasycladacean algae (*Clypeina* sp.). Stylolites are filled with iron hydroxides, while fractures are sealed with sparitic calcite.

Maiolica (Biancone)

Two samples (AD_185 and AD_202) relate to the Maiolica Formation (formerly known as the Biancone Formation in the early literature about the Southern Alps). This formation is characterized by white pelagic mudstones and wackestones deposited from the late Jurassic to the early to middle Cretaceous (early Tithonian to early Aptian). It is exposed in multiple regions of the Italian peninsula (Petti and Falorni 1990a). The Maiolica Formation is widely distributed in the Veneto Region (Channell and Grandesso 1987; Astolfi and Colombara 1990; Lukeneder 2015; Zuccari et al. 2021) and is quarried as dimension stone in the area of Lessini Mounts (Faraoni et al. 1996), the Asiago Plateau (Martire et al. 2006) and, to a lesser extent, the Euganean Hills (Astolfi and Colombara 1990). The samples analysed can be categorized as wackestones/mudstones with a micritic matrix. They are characterized by abundant calpionellids, radiolarians, dinoflagellates (10–20 μm) and planktonic foraminifera (*Globigerina* sp.). Sponge spicules, bivalves and echinoderms are infrequent (Fig. 4f). Dolomitization phenomena are evident in both samples, particularly in AD_185 (Fig. 4g). Some zones are enriched in iron hydroxides.

Scaglia Rossa

Two samples, AD_53 and AD_122, are associated with the late Cretaceous to early Eocene Scaglia Rossa Formation (Turonian–Maastrichtian). This formation is observable in various regions of the Italian peninsula (Petti and Falorni 1990b). The samples are wackestones with a micritic cement and abundant planktonic foraminifera (*Globigerina* sp., *Globotruncana* sp.), along with calcispheres and radiolarians. Conversely, calpionellids, bivalves, echinoderms and sponges are infrequent (Fig. 4h). Iron hydroxides and clay minerals are typically localized along stylolites. The outcrops of Scaglia Rossa in the Veneto region are primarily located in the north/northwestern area of the region (Dal Piaz, et al. 1990). The outcrops closer to Adria encompass the sedimentary sequences of the Euganean Hills (Astolfi and Colombara 1990) and Western Prealps in the Lessini Mounts (Massari and Medizza 1973), where this stone is also known as Pietra di Prun.

Aurisina Stone

AD_18, 24 and 151A samples refer to Aurisina Stone, a limestone belonging to the late Cretaceous Sežana Formation (late Turonian–early Santonian) and Lipica Formation (Santonian–Campanian) (Cucchi and Piano 2013; Cucchi et al. 2015; Jurkovšek et al. 2016). This limestone is commercially known by several names, such as Aurisina fiorita, Aurisina granitello and Roman stone. It has been historically exploited in specific quarries (e.g. the top portion of the so-called "Roman Quarry"; Maritan et al. 2003), located in the Classic Karst region of Friuli Venezia-Giulia (Carulli and Onofri 1969; Cucchi and Gerdol 1985; Salvini et al. 2023). Aurisina Stone is composed of various types of biomicritic and fossiliferous limestones, typically distinguished based on their textural features, grain size and roundness. The samples under study are primarily grainstones, with the exception of AD_151A, which is classified as a wackestone. This type of stone features micritic matrix and bioclasts filled with sparite. Fragmented rudists (ranging from 50 to 100 up to 250 μm) are abundant, while benthic foraminifera (Miliolida and Textulariidae), fragmented red algae and green algae (*Thaumatoporella parvovesiculifera*) are present in lower concentrations. Occasional echinoderms, sponges and bryozoans are also visible (Fig. 4i). In the case of sample AD_24, observations reveal the presence of dolomitization processes. Porosity across the samples is notably low.

Istrian Stone (?)

One sample (AD_184) is a mudstone with abundant micritic mud and occasional fossils, including large bivalve shells (5 mm) in dissolution and filled with coarse sparitic calcite, alongside scattered remains/ghosts of echinoderms, sponges, bivalves, calcispheres and planktonic foraminifera (Fig. 4j). The porosity is very low. The petrography of the sample is consistent with that of Istrian Stone, pertaining to the Istria Mesozoic carbonate platform (Lazzarini 2006), although attribution remains uncertain. In Roman times, the quarries were primarily located along the coastline on the western side of the Istrian peninsula (Šprem 2020, 2021).

Crystalline limestones

Three samples are crystalline limestones (AD_203, 151B and 138), each exhibiting different textures. AD_203 features sparite grains ranging from 1–2 to 10–15 μm. Recognizable recrystallized remnants of corals, echinoderms and sponges can be observed (Fig. 4k). AD_151B is a porous crystalline limestone with a consistent homogeneous fine-grained sparite matrix and occasional recrystallized relicts of bivalves, echinoderms and algae. AD_138 displays sparite grains with a size up to 50 μm and abundant recrystallized relics of colonial corals. The provenance of these stones cannot be determined based on PLM observations.

Sandstone

Sample AD_83 is a polygenic litharenite, characterized by the presence of numerous sub-angular clasts of quartz (and occasionally quartzites), which prevail over sub-rounded micritic carbonate and sub-angular cherts/chalcedony grains.

Micas, feldspars and opaque minerals are present in traces. The cement is primarily carbonate, with localized precipitation of iron hydroxides (Fig. 4j). Determining the provenance of this stone using PLM is challenging. The sample is compatible with the consolidated early Miocene turbidites of the Molassa formation, cropping out in the Veneto Prealps around Conegliano and Treviso (i.e. the historical quarry of Caglieron and Combai). Its petrofabric is also compatible with other turbidite formations, as the clay-interstratified *flysch* outcrops of the Trieste coastline in Friuli Venezia Giulia (north-eastern Italy), with historical exploitation in Muggia (Calligaris 1999; Cucchi and Piano 2013) or with the main Northern-Apennine sandstones of the Marnoso-Arenacea formation in Emilia Romagna, south of Adria (Mutti and Ricci Lucchi 1972; Gandolfi and Paganelli 1983; Conti et al. 2019).

Volcanic rocks

Thirty samples are volcanic rocks. All of them were analysed by XRF in order to describe their bulk-rock geochemical fingerprint (Suppl. Tab. 1). According to the TAS (Total Alkali vs. Silica) classification (Le Bas et al. 1986), most samples fall in the field of trachyte (Fig. 5), while only AD_197 falls in the field of rhyolite, due to the high content of SiO_2 (72.15%). AD_198 and AD_057 plot close to the boundary between those two fields. The geochemistry is compatible with that of differentiated volcanic rocks (trachytes and rhyolites) of the Euganean magmatic units (Astolfi and Colombara 1990).
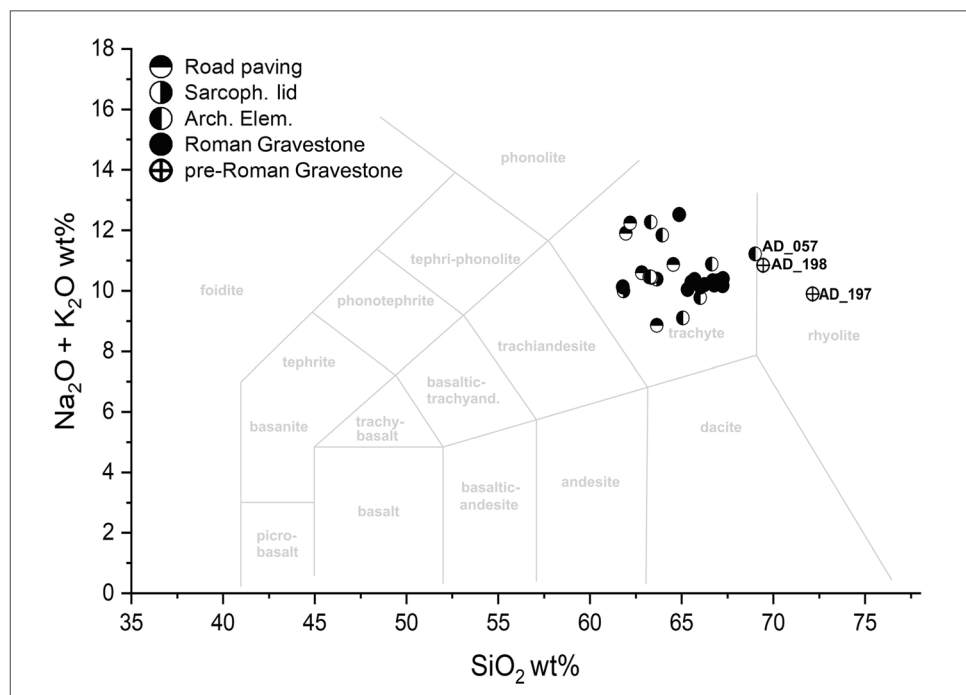
For provenance determination, the archaeological samples were firstly compared with geological samples from known Euganean quarries on the basis of a selection of major and trace chemical elements, considered as discriminating for trachyte (Fig. 6) and rhyolite (Fig. 7).

In detail, the V/Nb scatterplot is one of the most informative diagrams (Fig. 6a), as it allows clustering some of the main Euganean trachyte quarries. In particular, the trachyte from Monselice (45° 14′ 30.5″ N; 11° 45′ 28.8″ E) is clearly distinguished from the others due to the high Nb concentration (> 120 ppm). Around the reference cluster of Monselice, five samples plot (AD_143D, 146B, 146F, 150 and 153), mainly referring to urban infrastructures (paving stones and road elements). Their correlation with Monselice quarries can be verified also in the other diagrams, and in particular in Rb/Zr (Fig. 6e), TiO_2/Zr (Fig. 6b) as well as Rb/SiO_2 and Rb/Sr in Fig. 7a and c respectively, due to the high concentrations of Rb.

In the V/Nb scatterplot (Fig. 6a), two other samples (AD_118B and AD_120B) clearly overlap the field of the V-enriched trachyte of M. Rosso (45° 22′ 21.5″ N; 11° 45′ 09.7″ E). This clear overlap can be noticed also in the discriminant diagrams TiO_2/Zr (Fig. 6b) and TiO_2/K_2O (Fig. 6c), due to the characteristic high-Ti and low-Zr and low-K rates of M. Rosso quarry samples.

Finally, in the V/Nb scatterplot (Fig. 6a), some samples (in particular, AD_145, 172, 181, 166, 188), primarily collected from sarcophagus lids, distribute inside or close to the field of M. Merlo (45° 22′ 42.6″ N; 11° 42′ 06.0″ E) trachyte. The relationship of these samples with

Fig. 5 Total alkali vs silica geochemical distribution diagram (TAS) of the volcanic rock samples analysed by XRF (after Le Bas et al. 1986). The samples falling within the rhyolite field or close to the boundary with the trachyte field are labelled
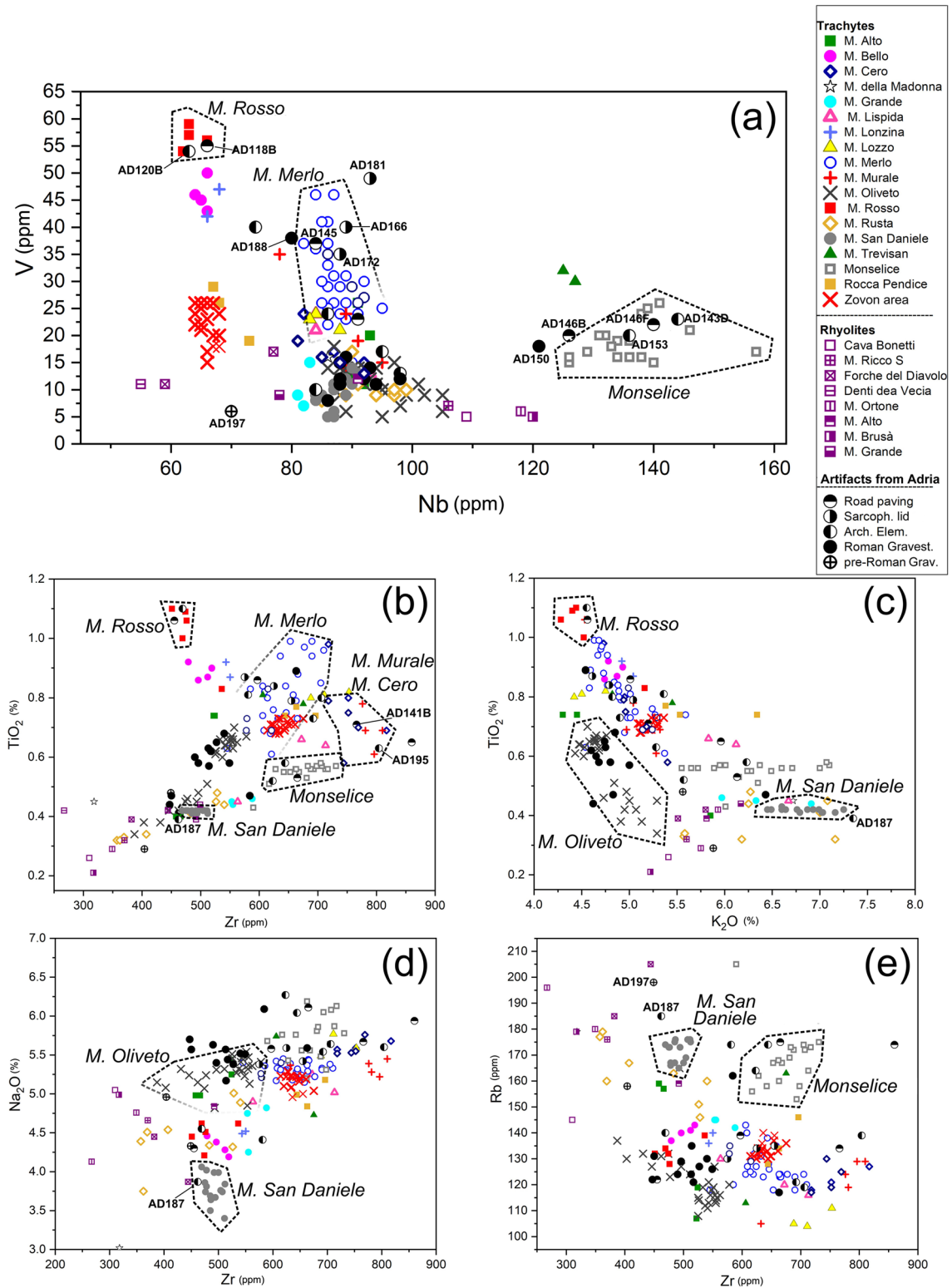
Fig. 6 V/Nb, TiO$_2$/Zr, TiO$_2$/K$_2$O, Na$_2$O/Zr and Rb/Zr scatterplots used for provenance discrimination of the archaeological volcanic rock samples (geological marker samples plotted from Germinario et al. 2018a; Germinario et al. 2018b; Brombin 2014; *Denti dea Vecia* and *Forche del Diavolo samples* were analysed in this work). The reference clusters with homogeneous samples from the same quarry sites are bordered marked by dotted lines. Certain archaeological samples are labelled and described in detail in the main text
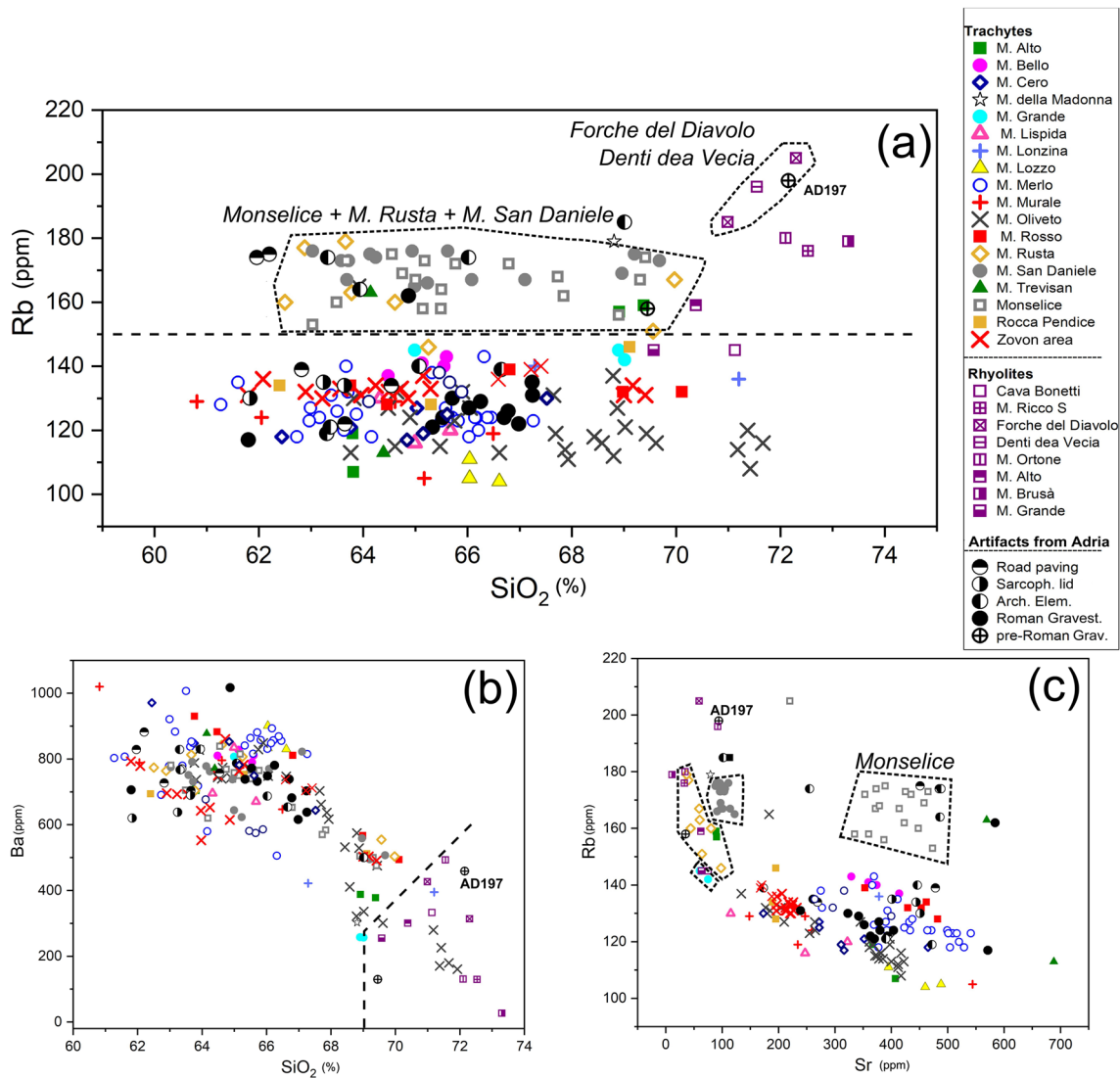
Fig. 7 Rb/SiO₂, Ba/SiO₂, Rb/Sr scatterplots used for provenance discrimination of the archaeological volcanic rock samples. Geological marker samples are taken from Germinario et al. (2018a), Germinario et al. (2018b); Brombin (2014). *Denti dea Vecia* and *Forche del Diavolo* samples were analysed in this work (see Suppl. Tab. 1). The reference clusters with homogeneous samples from the same quarry sites are bordered by dotted lines. Certain archaeological samples are labelled and described in detail in the main text

M. Merlo quarries can be also detected in the TiO₂/Zr diagram (Fig. 6b), where M. Merlo samples are slightly detached from the main core of the other quarries due to the relevant concentrations of Zr and TiO₂, which appear positively correlated.

Most of the gravestone samples might match the clusters of M. Oliveto (45° 19′ 03.7″ N; 11° 46′ 51.6″ E). Unfortunately, these quarry samples do not exhibit a peculiar geochemical fingerprint. Therefore, their clustering in the scatterplots is minimized, except for TiO₂/K₂O (Fig. 6c), due to the low-K rates negatively correlated with Ti.

On the other hand, this latter scatterplot is discriminant for the trachyte samples from M. San Daniele (45° 20′ 33.1″ N; 11° 45′ 41.6″ E), characterized by a low Na

content. Within this field, only one sample (AD_187) falls univocally. A strong correlation of AD_187 with that quarry can be observed also in the TiO₂/Zr (Fig. 6b), TiO₂/K₂O (Fig. 6c), Na₂O/Zr (Fig. 6d) and Rb/Zr (Fig. 6e) scatterplots.

Two samples (AD_141B and 195) in the TiO₂/Zr diagram (Fig. 6b) plot inside the cluster of the trachytes from M. Murale (45° 14′ 32.8″ N; 11° 39′ 44.4″ E) or M. Cero (45° 15′ 13.2″ N; 11° 39′ 58.9″ E), characterized by the high-Zr content.

Finally, it must be outlined that at least one sample (AD_197, pre-Roman gravestone) exhibits weak correlations with all the marker samples from trachyte quarries, while it returns a stronger compatibility with Euganean rhyolites, as noticeable in the discriminant scatterplots for

both trachyte (Fig. 6) and rhyolite (Fig. 7). In detail, the associations with rhyolitic outcrops of *Forche del Diavolo* (45° 19′ 40.0″ N; 11° 40′ 41.1″ E) and *Denti dea Vecia* (45° 19′ 33.8″ N; 11° 40′ 57.3″ E) are recurrent, as noticeable in the Rb/SiO$_2$ diagram (Fig. 7a), as well as in Rb/Sr (Fig. 7c) and Ba/SiO$_2$ (Fig. 7b). In fact, AD_197 is SiO$_2$- and Rb-enriched (Brombin 2014) and Ba- and Sr-depleted, in agreement with the peculiar features of Euganean rhyolites (Milani et al. 1999; Bartoli et al. 2015), with the sole exception of M. Oliveto trachyte, which can have low Ba rates too.

For the remaining samples, univocal associations are hardy detectable in the scatterplots. Nevertheless, it can be assumed that no samples present evident affinities with Zovon area, Rocca di Pendice, M. Trevisan, M. Lispida and M. della Madonna quarries.

Therefore, the discriminant analysis was crucial for certifying the provenance of the archaeological volcanic stone samples. The chemical elements used in the explorative scatterplots for trachyte (Na$_2$O, K$_2$O, TiO$_2$, V, Rb, Sr, Zr, Nb, plus Al$_2$O$_3$, Nd, Ce, adopted by Germinario et al. 2018a, b as subordinate discriminant elements) and for rhyolite discrimination (SiO$_2$, Ba, Rb and Sr) were selected as independent variables. The known quarry attributions of geological samples were indicated as classification factors.

The DA processing returned 97.55% correct classifications of the quarry samples, highlighting that the selected variables are suitable for adequately distinguishing the geochemical signature of each quarry site. The results reported in Table 1 confirm the observations already suggested on the basis of the scatterplots and pinpoint the best matches to quarry sites for the remaining unassociated archaeological samples.

Moreover, the DA results were confirmed, in most cases, by the PLM analyses (Table 2), according to the peculiar textural and mineralogical features of reference quarry samples, as reported in Germinario et al. (2018a). DA and PLM cross-matched results confirm the provenance of the main

Table 1 Results of the discriminant analysis of the archaeological volcanic stone samples (see Suppl. Tab. 2 for analytical details)

Sample	Provenance	1st Prob. (%)	Provenance	2nd Prob. (%)
AD_002	M. Oliveto	100.0	*Null*	
AD_013	M. Oliveto	100.0	*Null*	
AD_038	M. Oliveto	100.0	*Null*	
AD_044	M. Oliveto	100.0	*Null*	
AD_046	M. Oliveto	99.0	M. Alto	1.0
AD_057	M. Oliveto	100.0	*Null*	
AD_070	M. Oliveto	100.0	*Null*	
AD_079	M. Oliveto	99.7	M. Alto	0.3
AD_118B	M. Rosso	100.0	*Null*	
AD_120B	M. Rosso	100.0	*Null*	
AD_130	M. Merlo	97.4	M. Alto	1.8
AD_132	M. Bello	84.6	M. Lonzina	15.4
AD_141B	M. Murale	97.4	M. Cero	2.7
AD_143D	Monselice	100.0	*Null*	
AD_145	M. Merlo	100.0	*Null*	
AD_146B	Monselice	100.0	*Null*	
AD_146F	Monselice	100.0	*Null*	
AD_150	Monselice	100.0	*Null*	
AD_153	Monselice	100.0	*Null*	
AD_158A	M. Lozzo	98.9	M. Oliveto	0.7
AD_166	M. Merlo	100.0	*Null*	
AD_172	M. Merlo	100.0	*Null*	
AD_181	M. Merlo	100.0	*Null*	
AD_187	M. San Daniele	100.0	*Null*	
AD_188	M. Merlo	100.0	*Null*	
AD_192	M. Oliveto	100.0	*Null*	
AD_195	M. Cero	93.6	M. Murale	6.4
AD_197	Forche del Diavolo	100.0	*Null*	
AD_198	M. Grande	100.0	*Null*	
AD_199	M. Oliveto	99.8	*Null*	0.2

Table 2 Results of PLM analyses and provenance attribution cross-matched with DA results

| Samples | Bulk-rock XRF | | PLM Observations | | | | | Provenance attribution from petrography |
| | Provenance by DA | | Rock-forming minerals | | Accessory minerals | Textural features | | |
	1st probability	2nd probability	Major	Minor		General texture	Groundmass texture	
AD_002, 013, 038, 044, 046, 057, 070, 079, 192, 199	M. Oliveto (>98%)	M. Alto (<1%)	Ano, Pl	Bt, Qz	Opq, Ap, Ep, Zrn	Porphyritic (glomeroporphyritic) hiatal	Microcrystalline with felty texture	M. OLIVETO (M. Alto)
AD_143D, 146B, 146F, 150, 153	Monselice	n.d	Ano	Bt, Aug, Krs	Opq, Ap, Zrn	Porphyritic (glomeroporphyritic) hiatal	Microcrystalline with trachytic texture	MONSELICE
AD_130, 145, 166, 172, 181, 188	M. Merlo	M. Alto (<1.8% for sample AD130)	Ano, Pl	Bt, Krs, Aug, Qz	Opq, Ap, Zrn	Porphyritic (glomerocumuloporphyritic) seriate	Microcrystalline with felty texture	M. MERLO/M. LOZZO
AD_118B, 120B	M. Rosso	n.d	Pl	Ano, Bt	Opq, Ap	Porphyritic (glomerocumuloporphyritic) weakly seriate	Microcrystalline with felty texture	M. ROSSO
AD 187	M. San Daniele	n.d	Ano, Qz	Bt, Sa, Pl	Opq, Ap, Zrn	Porphyritic (glomeroporphyritic) hiatal	Microcrystalline with felty texture	M. SAN DANIELE (M. Grande/M. Rusta)/FORCHE d. D
AD_158A	M. Lozzo	n.d						
AD_132	M. Bello	M. Lonzina	Pl	Ano, Bt, Sa	Opq, Ap, Zrn	Porphyritic (glomerocumuloporphyritic) hiatal	Micro- to cryptocrystalline with felty to trachytic texture	M. LONZINA
AD_195, 141B	M. Cero/M. Murale	M. Cero/M. Murale	Ano	Bt, Sa, Pl	Opq, Ap, Zrn	Porphyritic (glomeroporphyritic) hiatal	Microcrystalline with felty texture	M. OLIVETO (M. Cero/M. Murale)
AD_197	Forche del Diavolo	n.d	Sa, Qz	Bt, Pl, Ano	Opq, Ap, Zrn	Porphyritic (glomerocumuloporphyritic) hiatal	Microcrystalline with felty texture	M. SAN DANIELE (M. Grande/M. Rusta)/FORCHE d. D
AD_198	M. Grande	n.d	Sa	Qz, Bt, Ano	Opq, Ap, Zrn	Porphyritic (glomerocumuloporphyritic) hiatal	Microcrystalline with felty texture	M. SAN DANIELE/M. GRANDE/M. RUSTA/FORCHE d. D

Mineral phases are labelled according to Whitney and Evans 2010: *Ano* anorthoclase, *Ap* apatite, *Bt* biotite, *Aug* augite, *Ep* epidote, *Krs* kaersutite, *Opq* opaque minerals, *Pl* plagioclase, *Qz* quartz, *Sa* sanidine, *Zrn* zircon
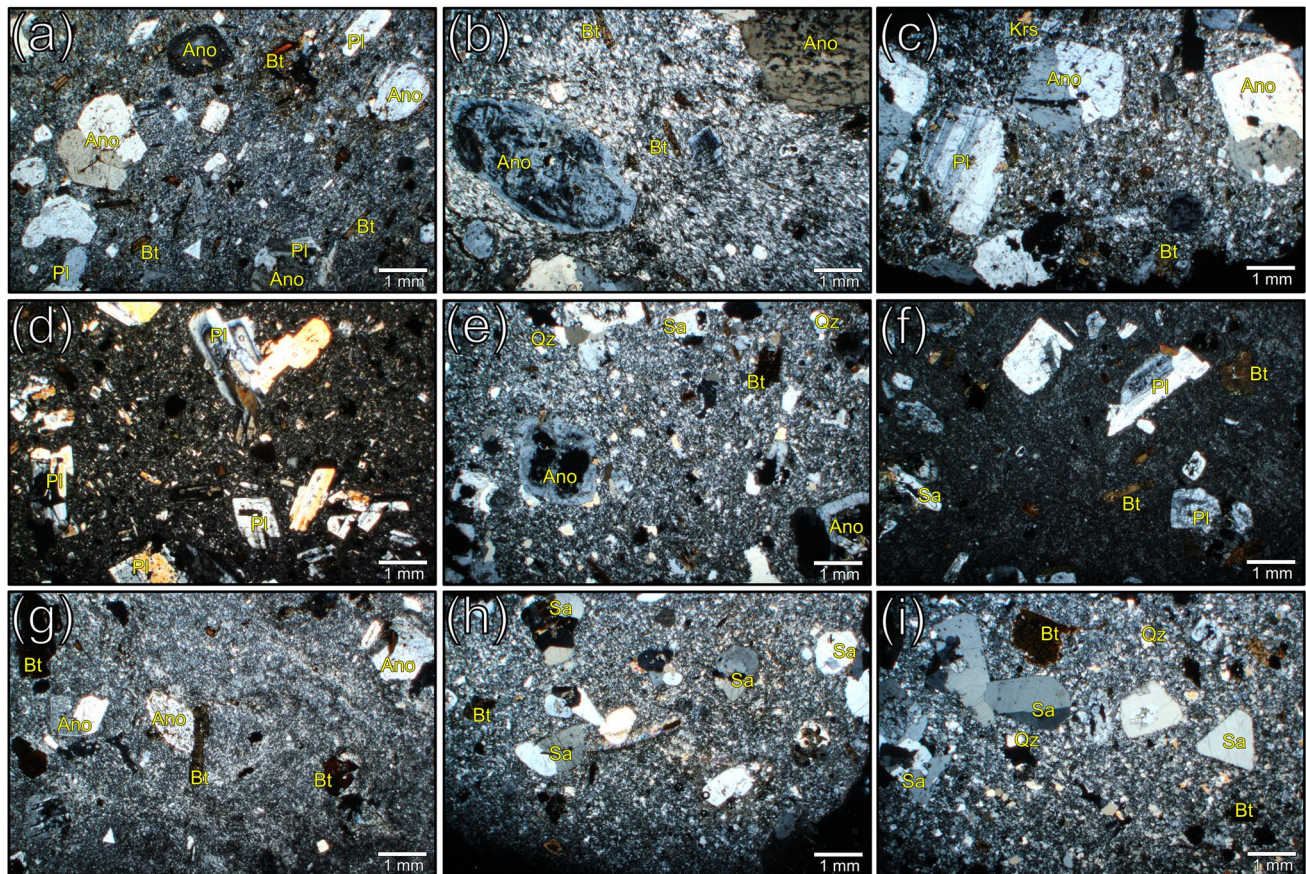
Fig. 8 PLM micrographs (crossed polars) of representative samples of Euganean volcanic rocks. **a** AD_79 (Trachyte, petrofabric compatible with M. Oliveto quarry, with feeble compatibility also with M. Alto); **b** AD_153 (Trachyte, Monselice quarry); **c** AD_172 (Trachyte, petrofabric compatible with M. Merlo and M. Lozzo quarries); **d** AD_120B (Trachyte, petrofabric compatible with M. Rosso quarry); **e** AD_187 (Trachyte, petrofabric compatible with M. San Daniele quarry, with affinities also with M. Grande and M. Rusta quarries); **f** AD_132 (Trachyte, petrofabric compatible with M. Lonzina quarry);

g AD_195 (Trachyte, petrofabric compatible with M. Cero and M. Murale quarries, with affinities with M. Oliveto quarry); **h** AD_198 (Trachyte, petrofabric compatible with M. Grande, M. Rusta and M. San Daniele quarries); **i** AD_197 (Rhyolite, petrofabric compatible with *Forche del Diavolo* outcrop, with affinities to Si-enriched terms of M. San Daniele trachyte). An, Anorthoclase; Bt, Biotite; Pl, Plagioclase; Krs, Kaersutite; Sa, Sanidine; Qz, Quartz (mineral phases are labeled according to Whitney and Evans 2010)

group of samples from M. Oliveto (Fig. 8a), followed by Monselice (Fig. 8b), M. Merlo (Fig. 8c), M. Rosso (Fig. 8d) and M. San Daniele (Fig. 8e).

Unfortunately, for the remaining samples, the DA does not report univocal attributions. Regarding AD_132, a prevalent compatibility with M. Bello (84.57%) is reported by the DA, with M. Lonzina ranking as second highest probability (15.42%). However, based on the PLM observation, AD_132 is compatible with M. Lonzina (45° 22′ 03.3″ N; 11° 43′ 32.2″ E), due to the characteristic micro- to crypto-crystalline texture and felty-trachytic groundmass. For the samples AD_141B and 195, the DA attribution between M. Cero and M. Murale is not straightforward and the PLM analyses cannot distinguish the two sources, since both show similar mineralogical and textural features.

AD_158A is ascribed by DA to M. Lozzo (45° 17′ 40.2″ N; 11° 37′ 15.8″ E), with an almost null probability with M. Oliveto, but unfortunately, it was not possible to certify this provenance due to the shortage of left-over material for other analyses.

According to the DA, the two Pre-Roman gravestones, when compared with all the Roman gravestones, report diverging provenance attributions. In agreement with the scatterplot clusters, AD_197 appears compatible with Euganean rhyolites. In fact, by DA, it matches the rhyolite outcrop of *Forche del Diavolo* (Fig. 9a) with a 100% confidence level for the 1st probability. The geochemical affinity is confirmed also by PLM, as AD_197 is completely compatible with FD_01, a geological sample coming from that rhyolitic dyke (Fig. 9b). In fact, both samples show a glomero- or cumulo-porphyritic hiatal texture with felty
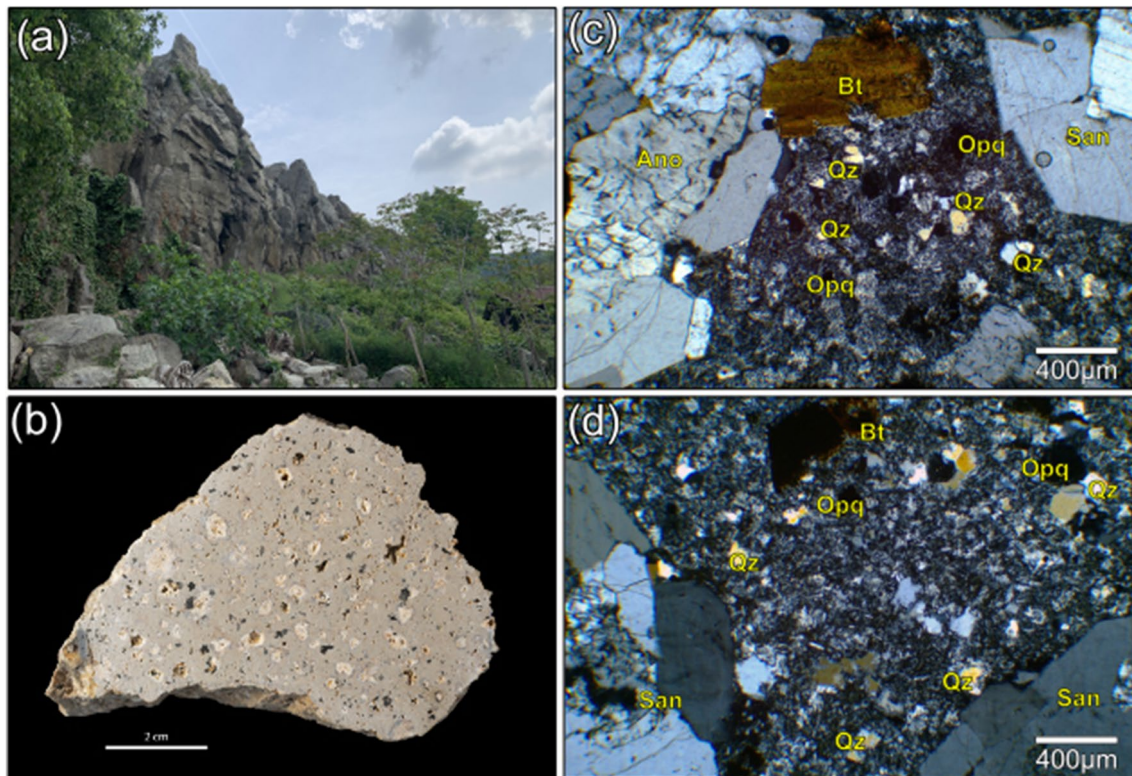
Fig. 9 a The columnar rhyolite dyke intruded within basalts at the *Forche del Diavolo* outcrop (western Euganean Hills). At the base, many naturally shaped blocks detached from the main outcrop are present; **b** cross section of the sample FD_01, with clearly recognizable phenocrysts in a compact groundmass; **c**, **d** PLM micrographs (crossed polars) of sample FD_01 and AD_197 respectively; both these samples have a glomero- or cumulo-porphyritic hiatal texture with recognizable phenocrysts of sanidine (Sa) and anorthoclase (Ano), in a felty microcrystalline groundmass with abundant minerals of quartz (Qz). The accessory minerals are biotite (Bt) and opaque minerals (Opq)

microcrystalline groundmass and with sanidine as the main rock-forming mineral, slightly prevalent over quartz (Fig. 9c and d). However, it must be outlined that this petrofabric is similar to that of M. Grande and M. Rusta trachytes, and even more of M. San Daniele trachyte, showing the greatest affinity to Euganean rhyolites, also from a geochemical point of view.

On the other hand, the provenance of the second Pre-Roman gravestone sample (AD_198) is not straightforward from the scatterplot analysis. By PLM, it displays a petrofabric similar to AD_197, but, according to the DA, it matches with M. Grande (45° 21′ 33.4″ N; 11° 40′ 29.3″E), suggesting this quarry as the favourite candidate for its source.

Finally, following the attribution to the quarry sites, a selection of representative archaeological samples of the volcanic rocks were analysed by XRPD (Fig. 10) to determine whether they could also be distinguished according to mineralogical criteria. It resulted that the samples present extremely variable concentrations of mineral phases, which are substantially in agreement with the petrographic features detected by PLM, although with slight variations. In detail, cristobalite and tridymite minerals were uniquely parametrized via XRPD. These phases are high-temperature polymorphs of quartz, coherent within the Euganean magmatism (Cucato et al. 2012), and were not detected by PLM probably because of their scattered distribution and very fine grain size, blending into the other microcrystalline components of the groundmass. In some cases, this applies also to augitic clinopyroxenes, quartz and the quantitative ratios of feldspars. On the other hand, it was not possible to detect and quantify the concentration of some accessory minerals, probably because their amount is below the detection limit of XRPD technique.

According to the QPA-XRPD results (Table 3), the main discriminating component of the selected volcanic rock samples is the concentration of the SiO_2 minerals (Fig. 11), which is extremely variable. In fact, the sum of the SiO_2 minerals ranges from 23.4 wt% in AD_197 (*Forche del Diavolo*) to 1.93 wt% in AD_150 (Monselice). In the samples AD_132 (M. Lonzina or M. Bello) and AD_118 (M. Rosso), cristobalite concentration is significant, while quartz prevails in the remaining samples. This phase is > 20 wt% only in AD_197 and in the geological sample FD_01, and it progressively downgrades below 20 wt% in AD_187 (M.
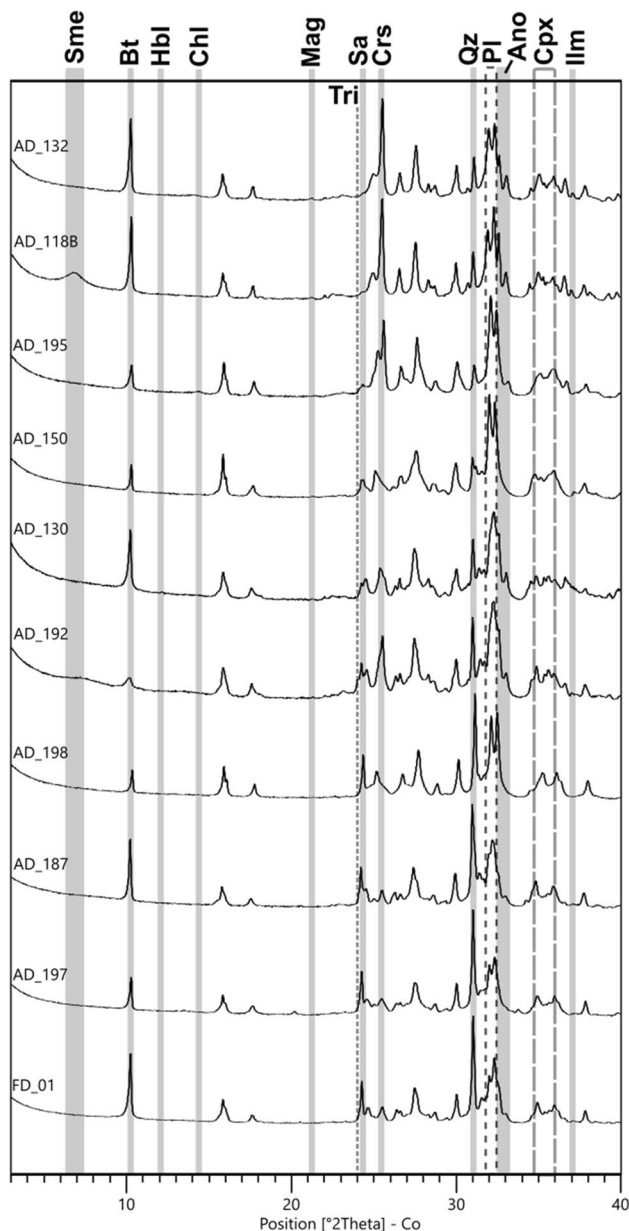
Fig. 10 XRPD profiles of selected archaeological volcanic rock samples plus the geological sample FD_01 from the rhyolitic outcrop of *Forche del Diavolo*. For each phase, the principal peaks are highlighted. Mineral phases are labelled according to Whitney and Evans 2010: Ano, Anorthoclase; Bt, Biotite; Chl, Chlinochlore; Cpx, Clinopyroxene; Crs, Cristobalite; Hbl, Hornblende (Kaersutite); Ilm, Ilmenite; Mag, Magnetite (opaque mineral); Pl, Plagioclase; Qz, Quartz; Sa, Sanidine; Sme, Smectite; Tri, Tridymite

San Daniele) and AD_198 (M. Grande), in agreement with the PLM analyses. Tridymite, when detected, represents a totally subordinate component.

The concentration of sanidine is very variable too. The highest rate of this phase was detected in AD_187, followed by the geological sample FD_01 and AD_197. However, this phase is abundant also in AD_150 (Monselice), and

characterized by the lowest amount of quartz in the dataset. Plagioclases, on the other hand, are negatively correlated with the SiO_2 minerals and sanidine, as they decrease progressively from 51.6 wt% in AD_195 (M. Cero or M. Murale), to 49.7 wt% in AD_192 (M. Oliveto), 46.1 wt% in 150 (Monselice) and finally 45.7 wt% in 130 (M. Merlo). In all the remaining samples, the plagioclase component is below 35 wt%. Anorthoclase reports a lower variability, ranging from 10 to 20 wt% in most samples. However, only in AD_197 and FD_01 its concentration is lower than 10 wt%, remarking the strong correlation between these two samples also from a mineralogical point of view.

Most of the remaining crystalline phases have minor concentrations, usually lower than 1 wt%. Nevertheless, it must be outlined that clay minerals (smectite) are attested only in AD_192, AD_187 and, in particular, AD_118B from M. Rosso samples, where smectite reaches the 6.3 wt%, evidencing that argillification phenomena are strongly developed in this stone.

Archaeological inferences and implications

The artefacts and their rock types

The archaeometric analysis allowed defining the rock types constituting the sampled artefacts and their geographic provenance at various degrees of resolution. For the sedimentary stones, we assessed a compatibility at the stage of geological formation, while the provenances of the volcanic stones were detected more precisely, by identifying one or at least two probable quarry sites for almost all samples (Table 4).

In general, the results show that a wide range of rock types were imported in *Atria* from extraction basins located at significant distances from the town. Among the analysed samples, the volcanic rocks from the Euganean Hills occur most frequently (30 samples out of 56). Most of them are trachytes coming from M. Oliveto, M. Merlo and Monselice, representing some of the quarry sites most intensively exploited in ancient times. However, the analyses demonstrated the provenance of some artefacts from other historical quarry sites, such as M. Rosso, M. San Daniele, M. Cero/M. Murale and M. Grande.

Vicenza Stone, from the Berici Hills or eastern Lessinia, represents the second most attested rock type (11 samples), followed by other sedimentary rocks, that is, Rosso Ammonitico Veronese (three samples), Scaglia Rossa (two samples) and Biancone/Maiolica (two samples). In these last cases, the exact location of the quarry areas cannot be determined, but their provenance can be confidently traced within the central-western areas of the Veneto region.

Imported rock types from the northern Adriatic Arc are also documented. These are Aurisina Stone, quarried in the

Table 3 Results of the QPA-XRPD analysis of selected quarry-correlated archaeological samples of volcanic rocks, plus the geological marker of *Forche del Diavolo*(FD_01)

| Sample | AD_132 | AD_118B | AD_195 | AD_150 | AD_130 | AD_192 | AD_198 | AD_187 | AD_197 | FD_01 |
Provenance	M. Lonzina (M. Bello ?)	M. Rosso	M. Cero/M. Murale	Monselice	M. Merlo	M. Oliveto	M. Grande	M. San Daniele	Forche del Diavolo	Forche del Diavolo (marker)
Quartz	0.5	1.0	1.6	1.9	3.7	6.0	17.1	17.3	23.0	24.9
Cristobalite	11.5	10.3	7.0	b.d	3.7	1.4	0.3	b.d	b.d	b.d
Tridymite	b.d	b.d	0.6	b.d	b.d	2.3	b.d	b.d	0.5	0.2
Sanidine	13.9	11.5	6.0	26.3	20.2	22.5	20.7	34.6	25.1	31.5
Anorthoclase	27.8	22.2	20.2	18.2	10.2	10.2	20.2	11.1	9.9	8.7
Plagioclase	27.0	33.4	51.6	46.1	45.7	49.7	26.1	26.0	33.8	28.6
Clinopyroxenes	4.3	4.5	3.2	1.6	2.3	2.5	2.3	1.7	1.8	2.6
Biotite	2.2	2.1	0.9	0.4	2.1	0.1	0.4	0.8	0.7	1.2
Hornblende	0.5	0.6	0.5	0.4	1.6	0.6	0.1	0.3	0.3	1.2
Clinochlore	b.d	b.d	1.6	b.d	b.d	b.d	b.d	b.d	b.d	b.d
Ilmenite	0.5	1.4	0.3	0.8	0.7	0.3	0.5	0.4	0.2	0.6
Magnetite	0.1	0.3	0.7	0.5	0.5	0.3	0.1	0.2	b.d	b.d
Smectite	b.d	6.2	b.d	b.d	b.d	1.4	b.d	2.3	b.d	b.d
Amorphous	11.6	6.6	5.9	3.9	9.4	2.8	12.0	5.3	4.7	0.4

b.d. below detection limit

Fig. 11 Cumulative histogram bars of descriptive mineral phases of the archaeological samples of Euganean volcanic rocks and the geological sample FD_01 from the rhyolitic outcrop of *Forche del Diavolo* analyzed by QPA-XRPD
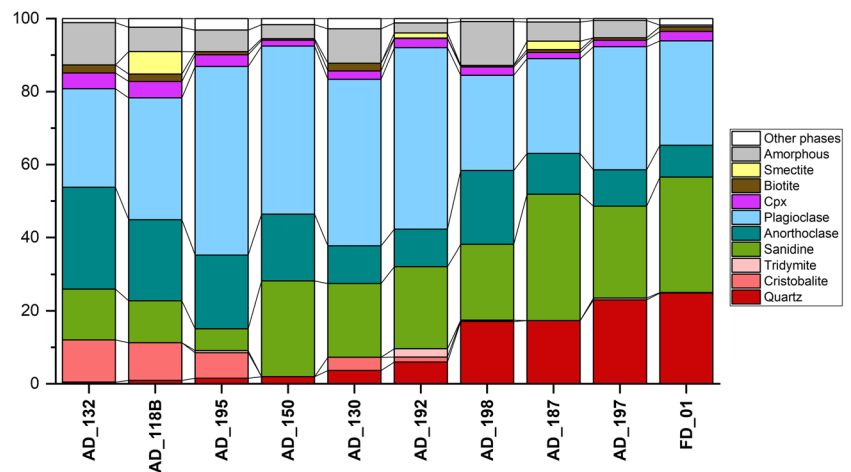
Trieste Karst (three samples), and, possibly, Istrian stone (one sample). This framework is further enriched by the presence of three artefacts made of a crystalline limestone of unknown origin and a sandstone sample, whose exact provenance cannot be determined.

Considering the relationship between these rock types and their ways of use (Fig. 12), it can be observed that Euganean trachyte was primarily used for the production of gravestones, in the form of *cippi* in pre-Roman times, and *stelae* in Roman times. The latter are mostly made of trachyte from M. Oliveto, although the trachytes from Monselice and M. Merlo are also attested in few samples. This result matches the archaeometric analyses carried out by Capedri et al. (1997) and Capedri and Venturelli (2003) that identified M. Oliveto as the quarry site for the Roman gravestones of Reggio Emilia (Emilia Romagna region). Trachyte also constitutes the three Roman sarcophagus lids analysed, all coming from M. Merlo quarries. This split provenance distribution between gravestones and sarcophagus lids may be explained with the diversification of the professional domains of stoneworker companies in the quarries of the Euganean Hills. Otherwise, it could rely on an intentional choice based on the physical features of the volcanic stones of those two outcrops (see also Germinario et al. 2017).

Trachyte was also used for the making of all the road paving stones analysed, coherently with other attestations of Roman roads in northern Italy (Germinario et al. 2018b; Zara 2018; Previato and Zara 2021). Regarding the provenance, a certain variability of source quarry areas for road paving stones was highlighted, demonstrating that the production of this building material was not organized according to professional domains, as the sources attested from previous studies (Previato et al. 2014; Zara 2018) comprise most of the Euganean historical quarry sites.

Much more limited is the use of trachyte for architectural elements, comprising 1 smooth column shaft and 1 fragment of a fascia lintel. This probably depends on the difficult workability of trachyte as well as its dark colour, which was not much appreciated in architecture in comparison with light-coloured stones, for example limestones, especially those most easily workable.

This is the case of the soft Vicenza Stone, whose utilization in *Atria* is recurrent. This rock type was used for making gravestones (three elements), column shafts (two plain and one fluted) and ashlar blocks. It should be highlighted that the three Vicenza Stone gravestones are "disk stelae" type, possibly suggesting that in the Berici Hills/eastern Lessinia, a manufacture centre of this kind of funerary artefact was located. The import of these artefacts was maybe motivated by a specific request from the patrons, linked to their aesthetic taste.

The remaining rock types were mainly used for the production of more or less elaborate structural and architectural elements (i.e. flooring slabs, columns and pillar plinths). The sole artefact having no structural function made with stone materials other than trachyte and Vicenza Stone is a votive altar made of Aurisina stone, a gravestone made of Scaglia Rossa and G. Popillius's sandstone milestone.

Unfortunately, the discussion about possible differences in the utilization of the stone materials along time is not doable as most of them are generally dated to the Roman Era between the 1st c. BCE and the 1st–2nd c. CE, and also because very few pre-Roman artefacts were analysed.

Nevertheless, trying to outline a sort of timeline in the selection of quarry districts on which ancient *Atria* relied, it seems that in pre-Roman and Republican times, the city imported stone materials almost exclusively from the Euganean basin. Later on, from the end of the 1st c. BCE onward, a larger array of rock types are attested, demonstrating the extent and articulation of the commercial networks in which the town was included. From the Augustan age onwards, in fact, stone materials imported from different quarry basins located mainly in central-western Veneto (i.e. Vicenza Stone and Rosso Ammonitico Veronese), but also

Table 4 The analysed samples and their provenance determined after the scientific investigations

Sample	Artefact type and find-site coord. (when known)	Age	Rock type	Commercial name	Extraction basin/ quarry site	Archaeological references
AD_002	Gravestone 45°04′28.0″N 12°03′30.2″E	1st c. BCE — 1st c. CE	Volcanic rock	Euganean trachyte	Euganean Hills, M. Oliveto	Bonomi et al. 2006; Bonomi and Zega 2006 (I.G. 12728)
AD_013	Gravestone 45°02′55.5″N 12°03′03.9″E	End of the 1st c. BCE	Volcanic rock	Euganean trachyte	Euganean Hills, M. Oliveto	Bonomi et al. 2006 (I.G. 180164)
AD_018	Votive altar 45°02′55.5″N 12°03′03.9″E	First half of the 1st c. CE	Compact limestone	Aurisina Stone	Triestin Karst	Bonomi et al. 2006 (I.G. 12740)
AD_024	Architectural element (pillar plinth)	First half of the 1st c. CE	Compact limestone	Aurisina Stone	Triestin Karst	Bonomi et al. 2006 (I.G. 15061)
AD_026	Gravestone 45°02′46.2″N 12°05′59.1″E	1st c. BCE — 1st c. CE	Soft limestone	Vicenza Stone (facies 3)	Berici Hills/Eastern Lessinia	Bonomi et al. 2006; Bonomi and Zega 2006 (I.G. 12761)
AD_038	Gravestone 45°02′48.5″N 12°03′38.6″E	1st c. BCE	Volcanic rock	Euganean trachyte	Euganean Hills, M. Oliveto	Bonomi et al. 2006; Bonomi and Zega 2006 (I.G. 12757)
AD_044	Gravestone 45°02′59.9″N 12°04′12.1″E	1st c. BCE	Volcanic rock	Euganean trachyte	Euganean Hills, M. Oliveto	Bonomi et al. 2006 (I.G. 180166)
AD_046	Gravestone 45°02′45.2″N 12°03′19.9″E	1st c. BCE	Volcanic rock	Euganean trachyte	Euganean Hills, M. Oliveto	Bonomi et al. 2006; Bonomi and Zega 2006 (I.G. 1256)
AD_053	Gravestone 45°05′59.7″N 12°03′30.3″E	beginning of the 1st c. CE	Compact limestone	Scaglia Rossa	Euganean Hills/Mt. Lessini	Bonomi et al. 2006; Bonomi and Zega 2006 (I.G. 12713)
AD_057	Gravestone	1st c. BCE — 1st c. CE	Volcanic rock	Euganean trachyte	Euganean Hills, M. Oliveto	Bonomi et al. 2006 (I.G. 12771)
AD_062	Gravestone 45°02′59.9″N 12°04′12.1″E	1st c. BCE — 1st c. CE	Soft limestone	Vicenza Stone (facies 4)	Berici Hills/Eastern Lessinia	Bonomi et al. 2006 (I.G. 12721)
AD_070	Gravestone	1st c. BCE — 1st c. CE	Volcanic rock	Euganean trachyte	Euganean Hills, M. Oliveto	Bonomi et al. 2006 (I.G. 12776)
AD_074	Gravestone 45°02′55.5″N 12°03′03.9″E	1st c. BCE — 1st c. CE	Soft limestone	Vicenza Stone (facies 1 — Costozza)	Berici Hills/Eastern Lessinia	Bonomi et al. 2006 (I.G. 12742)
AD_079	Gravestone 45°02′55.5″N 12°03′03.9″E	1st c. BCE — 1st c. CE	Volcanic rock	Euganean trachyte	Euganean Hills, M. Oliveto	Bonomi et al. 2006 (I.G. 12736)
AD_083	Milestone 45°03′03.0″N 12°03′33.0″E	end of the 2nd c. BCE	Sandstone	n.d	n.d	Bonomi and Zega 2006
AD_118B	Road paving 45°03′01.9″N 12°03′23.0″E	Roman Age	Volcanic rock	Euganean trachyte	Euganean Hills, M. Rosso	
AD_120B	Architectural element (ashlar block) 45°03′01.9″N 12°03′23.0″E	Roman Age	Volcanic rock	Euganean trachyte	Euganean Hills, M. Rosso	
AD_121	Architectural element (ashlar block) 45°03′01.9″N 12°03′23.0″E	Roman Age	Compact limestone	Rosso Ammonitico	Mt. Lessini/Asiago plateau	

Table 4 (continued)

Sample	Artefact type and find-site coord. (when known)	Age	Rock type	Commercial name	Extraction basin/ quarry site	Archaeological references
AD_122	Architectural element (ashlar block) 45°02′56.1″N 12°03′28.6″E	Roman Age	Compact limestone	Scaglia Rossa	Euganean Hills/Mt. Lessini	
AD_124	Architectural element (column) 45°02′56.1″N 12°03′28.6″E	Roman Age	Soft limestone	Vicenza Stone (facies 2)	Berici Hills/Eastern Lessinia	
AD_128	Architectural element (column) 45°02′56.1″N 12°03′28.6″E	Roman Age	Soft limestone	Vicenza Stone (facies 2)	Berici Hills/Eastern Lessinia	
AD_130	Architectural element (column) 45°02′56.1″N 12°03′28.6″E	Roman Age	Volcanic rock	Euganean trachyte	Euganean Hills, M. Merlo	
AD_132	Architectural element (sub-circular section block) 45°02′56.1″N 12°03′28.6″E	Roman Age	Volcanic rock	Euganean trachyte	Euganean Hills, M. Lonzina (M. Bello)	
AD_133	Architectural element (ashlar block) 45°02′56.1″N 12°03′28.6″E	Roman Age	Soft limestone	Vicenza Stone (facies 1 — Costozza)	Berici Hills/Eastern Lessinia	
AD_138	Architectural element (column?) 45°02′56.1″N 12°03′28.6″E	Roman Age	Compact limestone	Crystalline limestone	n.d	
AD_139	Architectural element (ashlar block?) 45°02′56.1″N 12°03′28.6″E	Roman Age	Compact limestone	Vicenza Stone (facies 1 — Costozza)	Berici Hills/Eastern Lessinia	
AD_141B	Road paving 45°02′51.9″N 12°03′12.9″E	Roman Age	Volcanic rock	Euganean trachyte	Euganean Hills, M. Murale (M. Cero)	
AD_143D	Road paving 45°02′51.9″N 12°03′12.9″E	Roman Age	Volcanic rock	Euganean trachyte	Euganean Hills, Monselice	
AD_145	Road paving 45°02′51.9″N 12°03′12.9″E	Roman Age	Volcanic rock	Euganean trachyte	Euganean Hills, M. Merlo	
AD_146B	Road paving 45°02′51.9″N 12°03′12.9″E	2nd — 1st c. BCE	Volcanic rock	Euganean trachyte	Euganean Hills, Monselice	
AD_146F	Road paving 45°02′51.9″N 12°03′12.9″E	2nd — 1st c. BCE	Volcanic rock	Euganean trachyte	Euganean Hills, Monselice	
AD_150	Gravestone 45°02′58.2″N 12°03′11.8″E	1st c. BCE — 1st c. CE	Volcanic rock	Euganean trachyte	Euganean Hills, Monselice	

Table 4 (continued)

Sample	Artefact type and find-site coord. (when known)	Age	Rock type	Commercial name	Extraction basin/ quarry site	Archaeological references
AD_151A	Architectural element (n.d.) 45°02′58.2″N 12°03′11.8″E	1st c. BCE — 1st c. CE	Compact limestone	Aurisina Stone	Triestin Karst	
AD_151B	Architectural element (n.d.) 45°02′58.2″N 12°03′11.8″E	1st c. BCE — 1st c. CE	Compact limestone	Crystalline limestone	n.d	
AD_151C	Architectural element (n.d.) 45°02′58.2″N 12°03′11.8″E	1st c. BCE — 1st c. CE	Soft limestone	Vicenza Stone (facies 1)	Berici Hills/Eastern Lessinia	
AD_153	Architectural element (n.d.) 45°02′58.2″N 12°03′11.8″E	1st c. BCE — 1st c. CE	Volcanic rock	Euganean trachyte	Euganean Hills, Monselice	
AD_155	Architectural element (stone slab) 45°02′58.2″N 12°03′11.8″E	1st c. BCE — 1st c. CE	Compact limestone	Rosso Ammonitico	Mt. Lessini/Asiago plateau	
AD_158A	Architectural element (n.d.) 45°02′58.2″N 12°03′11.8″E	1st c. BCE — 1st c. CE	Volcanic rock	Euganean trachyte	Euganean Hills, M. Lozzo	
AD_158B	Architectural element (n.d.) 45°02′58.2″N 12°03′11.8″E	1st c. BCE — 1st c. CE	Compact limestone	Rosso Ammonitico	Mt. Lessini/Asiago plateau	
AD_166	Sarcophagus lid 45°02′58.2″N 12°03′11.8″E	1st c. BCE — 1st c. CE	Volcanic rock	Euganean trachyte	Euganean Hills, M. Merlo	Bellintani et al. 1995
AD_172	Sarcophagus lid 45°02′58.2″N 12°03′11.8″E	1st c. BCE — 1st c. CE	Volcanic rock	Euganean trachyte	Euganean Hills, M. Merlo	Bellintani et al. 1995
AD_181	Sarcophagus lid 45°02′58.2″N 12°03′11.8″E	1st c. BCE — 1st c. CE	Volcanic rock	Euganean trachyte	Euganean Hills, M. Merlo	Bellintani et al. 1995
AD_184	Architectural element (semi-column) 45°02′58.2″N 12°03′11.8″E	1st c. BCE — 1st c. CE	Compact limestone	Istria Stone (?)	Istrian peninsula?	
AD_185	Architectural element (cornice) 45°02′58.2″N 12°03′11.8″E	1st c. BCE — 1st c. CE	Compact limestone	Biancone/Maiolica	Euganean Hills/Mt. Lessini/Asiago plateau	
AD_187	Architectural element (lintel?) 45°02′58.2″N 12°03′11.8″E	1st c. BCE — 1st c. CE	Volcanic rock	Euganean trachyte	Euganean Hills, M. San Daniele	
AD_188	Gravestone 45°02′58.2″N 12°03′11.8″E	1st c. BCE — 1st c. CE	Volcanic rock	Euganean trachyte	Euganean Hills, M. Merlo	I.G. 12764
AD_192	Gravestone 45°02′58.2″N 12°03′11.8″E	1st c. BCE — 1st c. CE	Volcanic rock	Euganean trachyte	Euganean Hills, M. Oliveto	

Table 4 (continued)

Sample	Artefact type and find-site coord. (when known)	Age	Rock type	Commercial name	Extraction basin/quarry site	Archaeological references
AD_195	Architect. element (road paving?) 45°02′51.9″N 12°03′12.9″E	Roman Age	Volcanic rock	Euganean trachyte	Euganean Hills, M. Cero (M. Murale)	
AD_197	Gravestone 45°03′01.6″N 12°03′22.4″E	Pre-Roman Age	Volcanic rock	Euganean rhyolite	Euganean Hills, Forche del Diavolo outcrop	
AD_198	Gravestone 45°17′25.9″N 12°07′30.8″E	350 BCE	Volcanic rock	Euganean trachyte	Euganean Hills, M. Grande (?)	Marinetti 2008 (I.G. 2498)
AD_199	Gravestone 45°02′50.8″N 12°03′08.1″E	1st c. CE	Volcanic rock	Euganean trachyte	Euganean Hills, M. Oliveto	
AD_202	Architectural element (lintel?) 45°02′50.8″N 12°03′08.1″E	Roman Age	Compact limestone	Biancone/Maiolica	Euganean Hills/Mt. Lessini/Asiago plateau	
AD_203	Architectural element (cornice?)	Roman Age	Compact limestone	Crystalline limestone	n.d	
AD_204	Architectural element (column)	Roman Age	Soft limestone	Vicenza Stone (facies 3)	Berici Hills/Eastern Lessinia	
AD_205	n.d	Roman Age	Soft limestone	Vicenza Stone (facies 1 — Costozza)	Berici Hills/Eastern Lessinia	
AD_206	Architectural element (threshold?)	Roman Age	Soft limestone	Vicenza Stone (facies 3)	Berici Hills/Eastern Lessinia	
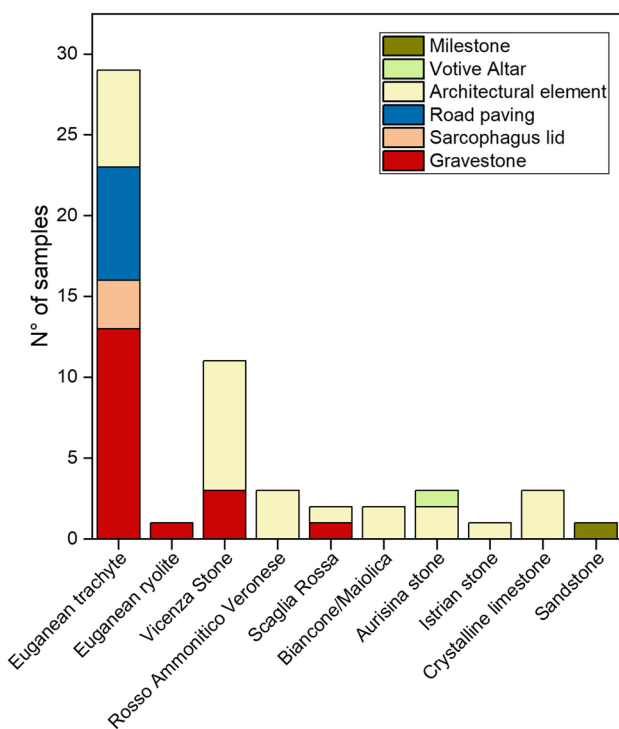
Fig. 12 The rock types documented in ancient *Atria* and their functional attribution

in the eastern sector of the region (Aurisina stone, maybe Istrian stone), were used in *Atria*.

In addition, it can be observed that the provenance of both the two pre-Roman gravestones substantially differs from that of the other archaeological materials from the Roman times (Dilaria et al. in press). In particular, the utilization of Euganean rhyolites is intriguing, since there are no pieces of evidence about the exploitation of this rock type in antiquity verified with an archaeometric approach. On an archaeological basis, a funerary stone in "rhyolite" was reported for the pre-Roman necropolis in *Patavium* excavated in the modern Via S. Eufemia (Paltineri et al. 2020), but on this element, further research is required to scientifically establish the actual rock type. From what we observed, the geochemical and petrographic features of the rhyolite sample AD_197 strongly match those of the geological sample from *Forche del Diavolo* (FD_01). *Forche del Diavolo* is a rhyolite dyke intruded within basalts in the central-western Euganean Hills and, although there is no evidence of quarrying there, the size of the outcrop can be considered suitable for extraction. This might represent the first proved evidence of utilization of Euganean rhyolite in antiquity, highlighting the need for a more detailed geochemical and petrographic mapping of the Euganean

volcanic rocks, apart from the trachytes. Eventually, the parametrization of the distinguishing features among all the different Euganean rock types might be needed. The case of M. San Daniele quarries is illustrative, since the rock extracted therein is a trachyte but, considering its composition, is also the closest to *Forche del Diavolo* rhyolites, here analysed.

Inferences on trading networks and commercial strategies

The data about the provenance of stone materials in Adria can generate other inferences on the trade network in which the city was included and the transport routes connecting the quarry districts with the Po delta in antiquity. This region is well known thanks to ancient essays (Servius, *In Vergilii Georgica comm.*, 1.262; Strabo, *Geographia*, 5.1.5 and 5.1.8; Pliny the Elder, *Naturalis Historia*, 3.126–130) and palaeoenvironmental studies (Balista 2013; Corrò and Mozzi 2017; Mozzi et al. 2020) for its exceptional network of waterways, which connected the cities and the inland territories with the lagoon of Venice and the Adriatic Sea (Bonetto 2009). These waterways, constituting an easy and economical way for transporting heavy goods, were probably used for the movement of stone loads over medium and long distances, as commonly documented in the ancient world and in later ages up to the modern era (Russell 2013).

Considering the layout of these waterways, a detailed reconstruction of the trade routes by which the stones reached Adria can be proposed (Fig. 13).

The first point concerns the prevalence in the town of stones from the Euganean district (around 60% of the whole sample collection). This can be explained by the excellent quality of the volcanic rock cropping out there and the geographic position of the quarry area, the closest to Adria.

However, the Euganean district was not directly connected by waterways to the ancient town. In fact, according to the most recent palaeoenvironmental reconstructions, until the sixth century BCE, Adria was lapped by the northern branch of the Po river, which was later replaced by the Tartaro-Canal Bianco river system (Pliny the Elder, *Naturalis Historia*, 3.121), connecting the territory around Verona to the sea, but without passing nearby the Euganean Hills. However, at least two possible water routes allowing the Euganean stones to reach Adria can be traced based on geomorphological studies. In fact, the southern part of the Euganean Hills was lapped by a palaeo-branch of the river Adige, flowing eastwards to the sea and reaching the southern sector of today's Venice Lagoon. This river could have been used in antiquity to transport the stones extracted in the western and southern Euganean quarries. A second waterway for the transport of Euganean stones down to the coast can be identified with

the Vigenzone canal, nowadays extending with a straight course from the southeastern side of the Hills to the southern Lagoon of Venice. This canal can be identified in the *Togisonus* mentioned by Pliny the Elder (*Naturalis Historia*, 3.121) as flowing towards the lagoon from the territory of ancient *Patavium* (*ex Patavinorum agris*). This could be the route exploited for the transport of the stone materials quarried in the eastern and northern part of the Euganean Hills.

From the coastline, the transport ships could have continued southwards along the system of inland lagoons and artificial ditches, such as the fossa Clodia mentioned by Pliny (*Naturalis Historia*, 3.121), connecting together the river delta placed between Ravenna and Aquileia (Rosada 1984) and finally entering to *Atria* through the Tartaro/Canal Bianco river.

However, the transport of Euganean stones to *Atria* through waterways does not represent the only possibility. In fact, at least from the mid-2nd c. BCE, Adria was crossed by the Via Annia road, promoted by the consul T. Annius Luscus (Uggeri 2012), connecting Rome to Aquileia and passing close to the Euganean area. Small blocks, possibly already processed or even finished, could have been transported through this land route.

Also Vicenza Stone, attested in significant concentrations in the town (around 20% of the samples analyzed here), was probably transported through waterways following the Bacchiglione river, as testified by the discovery of a wreck with a stone cargo of semi-finished architectural elements (Previato and Zara 2014). In antiquity, this river flowed down from the Prealps, passing by the north-eastern area of the Berici Hills, near Costozza, and proceeding eastwards to the Lagoon of Venice. From this point, the ships, following the peri-lagoonal canalization systems, could have entered the Tartaro/Canal Bianco finally reaching *Atria*.

The final part of this coastal path (Lagoon of Venice — Tartaro/Canal Bianco — *Atria*) was probably used also for the transport of the stone types imported from the northern Adriatic Arc (i.e. Aurisina Stone, Istrian Stone) to *Atria*. Considering the great distance between the Trieste and Istrian quarry areas to Adria, it is likely that the maritime route was preferred over land transports, being more economically convenient.

Tracking at the same resolution the path of the other stone types documented in *Atria* is more difficult as their origin is not uniquely defined from a geographic point of view. Most of them (Rosso Ammonitico Veronese, Biancone/Maiolica, Scaglia Rossa) possibly come from different outcrops in the Prealps, from western Lessinia to Asiago plateau to the east and the Euganean Hills. Even in this case, they were probably transported through the alpine rivers of the region (Adige, Brenta, Piave) to the coast and then followed the

Fig. 13 The extraction basins and the trade network of the stone materials documented in ancient *Atria*

aforementioned peri-lagoonal and Tartaro/Canal Bianco route.

In conclusion, the results show the presence in *Atria* of a wide range of different rock types from extraction basins mainly located in north-eastern Italy. Two aspects are extremely evident. The first is the prevalence of rock types from the central-western area of Veneto. This testifies the great extent of the commercial relationships of *Atria* with the inland territories, rather than with the Adriatic area, as far as the stone trade was concerned; in fact, stone transport probably relied on a branched river and peri-lagoonal waterway network, thanks also to the key role played by the Tartaro River/Canal Bianco. Moreover, it can be outlined that the amount of imported stone material progressively decreases as the distance between the quarry basins and the city increases. This clearly relates to the economic convenience and timings of material transport (Russell 2013).

Conclusions

The results obtained in this research offer important insights for reconstructing the trade dynamics and use of stone materials in the ancient town of *Atria*. They can be summarized in three main points:

- Methodology. As primary objective, this study aimed at establishing a protocol to define the provenance of ancient stone materials from northern Italy, adopting cost-effective analytical methods to efficiently process large datasets. Considering the different resolution rate achievable in the provenance determination of volcanic rocks in respect to sedimentary ones, the stone samples were analysed adopting two analytical approaches. Sedimentary stones were uniquely analysed via PLM. The recognition of index fossils allowed determining, in most cases, the correlation with specific geological formations. The main problem of this fast and low-cost approach is the high uncertainty about the area of origin, as the same sedimentary formations may outcrop in scattered locations within the regional territory, or even in extra-regional territories (i.e. Scaglia Rossa limestone, Rosso Ammonitico Veronese limestone and, in particular, sandstone). On the other hand, as far as the volcanic rocks are concerned, the analysis was more sophisticated, and an updated protocol combining the results of XRF, PLM and QPA-XRPD analyses with published petrographic and geochemical datasets of Euganean trachytes from different sources was developed. This protocol allows assigning most of the samples to specific quarry sites in the Euganean district. This workflow demonstrates to be efficient for provenance determination of Euganean volcanic rocks, allowing processing and identifying at high resolution, in most cases, the quarry sites, when the more precise LA-ICP-MS investigations cannot be performed (e.g. due to budget constraints or instrument unavailability).

- The stones and their use. The results of the archaeometric investigations demonstrated that the stone materials were accurately selected according to the function of the artefacts. This was evident both in the diversification of the trachytes used for manufacturing the gravestones as opposed to sarcophagus lids, and in the prevalent utilization of the soft Vicenza Stone for making disk stelae, thus revealing the profound knowledge of ancient stone workers about the workability and mechanical properties of these materials and, possibly, the diversification of the professional domains of the mason companies. Intriguing is the provenance of the pre-Roman rhyolite gravestone from *Forche del Diavolo* outcrop, which might represent the first evidence of utilization of Euganean rhyolite in antiquity, rising new perspectives about the management of stone resources between pre-Roman (collection of erratic boulders?) and Roman times (systematic exploitation of quarries), which cannot be adequately discussed here.

- Trading network. Once the provenances of the analysed stones were defined and the quarry sites reported in a map, inferences regarding the transport routes of the material have been proposed. Most of the stones used in the town came from the inland territories of the Veneto region, with a prevalent exploitation of the Euganean Hills over the Prealps and Berici Hills. Considering the short distance of *Atria* from the Adriatic Sea, this evidence is even more remarkable and shows how the regional river network was capillary, allowing the stones to reach *Atria* probably exploiting endo-lagoon routes beyond the delta areas and, for the last stretch, the route of the Tartaro/Canal Bianco river that, in antiquity, was passing through the ancient town.

Additional information

and XRPD analyses were developed at the Department of Geosciences of the University of Padova.

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Declarations

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References

Antonelli F, Lazzarini L (2012) The first archaeometric characterization of Roman millstones found in the aquileia archaeological site (Udine, Italy). Archaeometry 54:1–17. https://doi.org/10.1111/j.1475-4754.2011.00615.x

Antonelli F, Bernardini F, Capedri S et al (2004) Archaeometric study of protohistoric grinding tools of volcanic rocks found in the Karst (Italy-Slovenia) and Istria (Croatia). Archaeometry 46:537–552. https://doi.org/10.1111/j.1475-4754.2004.00172.x

Astolfi G, Colombara F (1990) La geologia dei Colli Euganei, Programma. Padova

Balista C (2013) Dal Po di Adria al fiume Tartaro. Trasformazioni paleoidrografiche tra l'età del Bronzo e l'età del Ferro attraverso le evidenze petrografiche dei sedimenti del sito dell'Amolara di Adria (RO). Padusa 49:159–192

Bartoli O, Meli S, Bergomi MA et al (2015) Geochemistry and zircon U-Pb geochronology of magmatic enclaves in trachytes from the Euganean Hills (NE Italy): further constraints on Oligocene magmatism in the eastern Southern Alps. Eur J Min 27:161–174. https://doi.org/10.1127/ejm/2015/0027-2425

Bellintani P, Bonomi S, Tamassia K, Trentin T (1995) Adria. Aggiornamento sui rinvenimenti archeologici nell'area dell'azienda ospedaliera. Padusa 31:51

Bianchin Citton E, De Vecchi G (2015) L'impiego della trachite euganea nella fabbricazione di macine in età preromana, Dinamiche insediative nel territorio dei Colli Euganei dal Paleolitico al Medioevo. In: Bianchin Citton E et al (ed) Dinamiche insediative nel territorio dei Colli Euganei dal Paleolitico al Medioevo, Atti del convegno di studi. Padova, pp 139–150

Boedeker P, Kearns NT (2019) Linear discriminant analysis for prediction of group membership: a user-friendly primer. Adv Methods Pract Psychol Sci 2:250–263. https://doi.org/10.1177/2515245919849378

Bondesan M, Favero V, Viñals MJ (1995) New evidence on the evolution of the Po-delta coastal plain during the Holocene. Quat Int 29–30:105–110

Bonetto J, Camporeale S, Pizzo A (2014) Arqueología de la Construcción IV. Las canteras en el mundo antiguo: sistemas de explotación y procesos productivos, Proceedings of the 4th International Workshop on the Archaeology of Roman Construction (Padova, 22–24/11/2012), Anejos de AEspA LXIX. Madrid-Mérida

Bonetto J, Pettenò E, Previato C et al (2021) Il teatro romano di Padova. Orizzonti 37–63. https://doi.org/10.19272/202107501003

Bonetto J (2009) Veneto. Archeologia delle regioni d'Italia, Roma

Bonomi S, Zega L (2006) Il museo archeologico nazionale di Adria: cinque anni di lavoro per il completo rinnovamento. Milano

Bonomi S, Zega L (2010) L'età romana e l'alto medioevo: Adria e il Basso Polesine tra i secoli II a.C. e IX d.C. Adria

Bonomi S, Camerin N, Tamassia K (2002) Adria. Via San Francesco, scavo 1994: materiali dagli strati arcaici. Padusa 38:201–213

Bonomi S, Sigolo R, Zega L (2006) Le pietre parlano: il lapidario romano di Adria. Apogeo Editore, Adria

Bonomi S (1993) Gli scavi di Francesco Antonio Bocchi nell'abitato arcaico di Adria. In: Lodo A (ed) Francesco Antonio Bocchi e il suo tempo: 1821–1888. Atti del 16° Congresso di studi storici, Adria, 21–22 aprile 1990. Associazione Culturale Minelliana. Rovigo, pp 75–85

Boschetti C, Dilaria S, Mazzoli C, Salvadori M (2021) Making Roman mosaics in Aquileia (I BC – IV AD): technology, materials, style and workshop practices. Two case studies from Domus delle Bestie ferite. In: Thomas R (ed) Proceedings of the 19th International Congress of Classical Archaeology – AIAC (Cologne/Bonn, 22–26/05/2018). Cologne, pp 91–112

Brajkovič R, Gale L, Djurić B (2022) Multi-method study of the Roman quarry at Podpeč sedimentary succession and stone products. Geologija 65:101–121. https://doi.org/10.5474/geologija.2022.007

Brajkovič R, Djurić B, Gerčar D et al (2023) Mid-Cretaceous calcarenite in stone products from the Roman colony of Emona, Regio X (modern Ljubljana, Slovenia). Archaeometry 65:17–35. https://doi.org/10.1111/arcm.12814

Brandl M, Martinez MM, Hauzenberger C et al (2018) A multi-technique analytical approach to sourcing Scandinavian flint: provenance of ballast flint from the shipwreck "Leirvigen 1", Norway. PLoS ONE 13. https://doi.org/10.1371/journal.pone.0200647

Brombin V (2014) Geochimica delle rocce magmatiche dei Colli Euganei (PD) e dei Monti Berici (VI). Dissertation, Università degli Studi di Padova

Buonopane A (1987) Estrazione, lavorazione e commercio dei materiali lapidei. In: Buchi E (ed) Il Veneto nell'età romana. Storiografia, organizzazione del territorio, economia e religione, Verona, pp 185–224

Calligaris R (1999) La geologia. In: Bressi N (ed) Flysch. Trieste tra marna e arenaria. Opicina, Trieste, pp 9–82

Calvino F (1967) Le cave dei Colli Euganei. Caratteristiche geominerarie. Importanza economica. Prospettive di Sviluppo. Consorzio per la valorizzazione dei Colli Euganei. Padova

Calzolari M (2003) La diffusione dei marmi veronesi in età romana nell'Italia settentrionale: aspetti topografici. In: Buonopane A, Brugnoli A (ed), La Valpolicella in età romana, Atti del II Convegno (Verona, 11 maggio 2002), Annuario Storico della Valpolicella 19:169–184

Capedri S, Venturelli G (2003) Trachytes employed for funerary artefacts in the Roman Colonies Regium Lepidi (Reggio Emilia) and Mutina (Modena) (Italy): provenance inferred by petrographic and chemical parameters and by magnetic susceptibility. J Cult Herit 4:319–328. https://doi.org/10.1016/j.culher.2003.01.002

Capedri S, Grandi R, Venturelli G (2003) Trachytes used for paving Roman roads in the Po Plain: characterization by petrographic and chemical parameters and provenance of flagstones. J Archaeol Sci 30:491–509. https://doi.org/10.1006/jasc.2002.0857

Capedri S, Grandi R, Venturelli G (1997) Manufatti di età romana in trachite conservati nei Musei Civici di Reggio Emilia. Pagine di archeologia. Studi e materiali 2:1-29

Carulli GB, Onofri R (1969) I marmi del Carso. Del Bianco, Udine

Cattaneo A, De Vecchi GP, Menegazzo Vitturi L (1976) Le pietre tenere dei Colli Berici. Società Cooperativa Tipografica, Padova

Cattani M, Lazzarini L, Falcone R (1997) Macine protostoriche dall'Emilia e dal Veneto: note archeologiche, caratterizzazione chimico-petrografica e determinazione della provenienza. Padusa 31:105–137

Channell JET, Grandesso P (1987) A revised correlation of Mesozoic polarity chrons and calpionellid zones. Earth Planet Sci Lett 85:222–240. https://doi.org/10.1016/0012-821X(87)90033-1

Charlton MF, Blakelock E, Martinón-Torres M, Young T (2012) Investigating the production provenance of iron artifacts with multivariate methods. J Archaeol Sci 39:2280–2293. https://doi.org/10.1016/j.jas.2012.02.037

Clari PA, Marini P, Pastorini M, Pavia G (1984) Il Rosso Ammonitico Inferiore (Baiociano-Calloviano) nei Monti Lessini Settentrionali. Riv It Pal Strat 90:15–86

Columbu S, Garau AM, Lugliè C (2019) Geochemical caracterisation 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 11:2121–2150. https://doi.org/10.1007/s12520-018-0658-y

Conti P, Cornamusini G, Carmignani L (2019) Note Illustrative della Carta Geologica delle regioni Emilia-Romagna, Marche, Toscana e Umbria. Bologna: Archivio Cartografico della Regione Emilia Romagna

Cornale P, Rosanò P (1994) Le pietre tenere del vicentino. Uso e restauro. La Grafica & Stampa Ed., Vicenza

Corrò E, Mozzi P (2017) Water matters. Geoarchaeology of the city of Adria and palaeohydrographic variations (Po Delta, Northern Italy), in J Archaeol Sci Reports 15:482–491

Cucato M, De Vecchi GP, Mozzi P, Abbà T, Paiero G, Sedea R (2012) Note illustrative della Carta Geologica d'Italia alla scala 1:50.000 Foglio 147 Padova Sud. LTS Land Tecnology & Services

Cucchi F, Gerdol S (1985) I marmi del Carso triestino. Trieste

Cucchi F, Piano C (2013) Brevi note illustrative della carta geologica del carso classico italiano. Trieste

Cucchi F, Biolchi S, Zini L et al (2015) Geologia e geomorfologia del Carso Classico. In: Le acque del Carso Classico. Progetto Hydrokarst/Vodonosnik Klasičnega Krasa. Projekt Hydrokarst, EUT Edizioni, pp 23–52

Dal Piaz et al (1990) Carta Geologica del Veneto 1:250.000, una storia di cinquecento milioni di anni, Regione del Veneto. Padova

De Vecchi G (2008) Analisi delle pietre e dei materiali edilizi. In: Cavalieri Manasse G (ed) L'Area del Capitolium di Verona. Ricerche Storiche e Archeologiche. Padova

Dilaria S, Germinario L et al (2023a) Archaeometric investigations on ancient funerary stone elements from the National Archaeological Museum of Adria (Rovigo, Italy). In: Proceedings of the IMEKO International Conference on Metrology for Archaeology and Cultural Heritage Rome, Italy, October 19–21, pp 736–741

Dilaria S, Previato C, Bonetto J et al (2023b) Volcanic Pozzolan from the Phlegraean Fields in the structural mortars of the Roman Temple of Nora (Sardinia). Heritage 6:567–586. https://doi.org/10.3390/heritage6010030

Dollase W (1986) Correction of intensities for preferred orientation in powder diffractometry: application of the March Model. J Appl Crystallogr 19:267–272

Dunham RJ (1962) Classification of carbonate rocks according to depositional texture. In: Classification of Carbonate Rocks (Ed. W.E. Ham), Am Assoc Pet Geol Mem 1:108–121

Falezza G, Zorzin R, Lazzarini L, Bonetto J, Falezza et al (2015) Lapidei Santuario Marano. In: Archeologia e storia sul Monte Castelon di Marano di Valpolicella. Mantova, pp 233–244

Faraoni P, Marini A, Pallini G, Pezzoni N (1996) The Maiolica Fm. of the Lessini Mts and Central Apennines (Northeastern and Central Italy): a correlation based on new biolithostratigraphical data from the uppermost Hauterivian. Paleopelagos 249–259

Finkel M, Erel Y, Ben Dor Y et al (2022) High resolution elemental characterization of prehistoric flint sources in southern Israel: implications for archaeological provenance studies. J Archaeol Sci Reports 43:103438. https://doi.org/10.1016/j.jasrep.2022.103438

Flügel E, Flügel C (1997) Applied microfacies analysis: provenance studies of Roman mosaic stones. Facies 1–48

Freire-Lista DM (2021) The forerunners on heritage stones investigation: historical synthesis and evolution. Heritage 4:1228–1268. https://doi.org/10.3390/heritage4030068

Gandolfi G, Paganelli L (1983) Petrology and dispersal pattern in the marnoso-arenacea formation (Miocene, Northern Appenines). J Sediment Res 53:493–507

Germinario L, Cossio R, Maritan L et al (2016) Textural and mineralogical analysis of volcanic rocks by μ-XRF mapping. Microsc Microanal 22:690–697. https://doi.org/10.1017/S1431927616000714

Germinario L, Siegesmund S, Maritan L, Mazzoli C (2017) Petrophysical and mechanical properties of Euganean trachyte and implications for dimension stone decay and durability performance. Environ Earth Sci 76:739. https://doi.org/10.1007/s12665-017-7034-6

Germinario L, Hanchar JM, Sassi R et al (2018a) New petrographic and geochemical tracers for recognizing the provenance quarry of trachyte of the Euganean Hills, northeastern Italy. Geoarchaeology 33:430–452. https://doi.org/10.1002/gea.21666

Germinario L, Zara A, Maritan L et al (2018b) Tracking trachyte on the Roman routes: provenance study of Roman infrastructure and insights into ancient trades in northern Italy. Geoarchaeology 33:417–429. https://doi.org/10.1002/gea.21667

Gutiérrez Garcia-Moreno A (2009) Roman quarries in the Northeast of Hispania (Modern Catalonia). Tarragona

Jurkovšek B, Biolchi S, Furlani S et al (2016) Geology of the Classical Karst Region (SW Slovenia–NE Italy). J Maps 12:352–362. https://doi.org/10.1080/17445647.2016.1215941

Kovarovic K, Aiello L, Cardini A, Lockwood CA (2011) Discriminant function analyses in archaeology: are classification rates too good to be true? J Archaeol Sci 38:3006–3018

Lazzarini L (2006) Pietra d'Istria: genesi, proprietà e cavatura della pietra di Venezia. In: Fiorentin N (ed) La pietra d'Istria e Venezia. Atti del Seminario di Studio. Verona, pp 24–45

Lazzarini L (2022) The minero-petrographic analysis of two flagstones ("basoli") recovered from Treporti (Venice Lagoon) and Altinum. In: Bassani M, D'Acunto G, Madricardo F (ed) Crossing the water. The Venice Lagoon from antiquity throughout the centuries. Roma, pp 155–161

Le Bas MJR et al (1986) IUGS Subcommission on the systematics of igneous rocks, a chemical classification of volcanic rocks based on the total alkali-silica diagram. J Petrology 27(3):745–750

Loyola R, López-Mendoza P, Carrasco C et al (2023) Provenance and long-term circulation of archaeological obsidian in the Puna de Copiapó (25-27°S), South-Central Andes. J Archaeol Sci Reports 51:104134. https://doi.org/10.1016/j.jasrep.2023.104134

Lukeneder A (2011) The Biancone and Rosso Ammonitico facies of the northern Trento Plateau (Dolomites, Southern Alps, Italy). Annalen des Naturhistorischen Museums in Wien Serie A, 113:9-33

Lukeneder A (2015) Biancone transformed into dolosparite: evidence for secondary recrystallisation (Dolomite Mountains, S. Tyrol, N. Italy). Annalen des Naturhistorischen Museums in Wien Serie A 117:35–62

Marinetti A (2008) Iscrizioni venetiche dalla Saccisica. In: Zatta P (ed) Archeologia in Saccisica. Padova, pp 23–30

Maritan L, Mazzoli C, Melis E (2003) A multidisciplinary approach to the characterization of Roman gravestones from Aquileia (Udine, Italy). Archaeometry 45:363–374

Maritan L, Mazzoli C, Sassi R et al (2013) Trachyte from the Roman aqueducts of Padua and Este (north-east Italy): a provenance study based on petrography, chemistry and magnetic susceptibility. Eur J Min 25:415–427. https://doi.org/10.1127/0935-1221/2013/0025-2282

Martire L (1996) Stratigraphy, facies and synsedimentary tectonics in the Jurassic Rosso Ammonitico Veronese (Altopiano di Asiago, NE Italy). Facies 35:209–236

Martire L, Clari P, Lozar F, Pavia G (2006) The Rosso Ammonitico Veronese (Middle-Upper Jurassic of the Trento Plateu): a proposal of lithostratigraphic ordering and formation. Riv Ital Paleontol Stratigr 112:227–250

Martire L (1990) Rosso Ammonitico Veronese. In: Carta geologica d'Italia – 1:50.000 Catalogo delle formazioni – Unità tradizionali. APAT Dipartimento difesa del suolo. Quaderni serie III, Vol. 7 – Fascicolo VII :98–105

Massari F, Medizza F (1973) Stratigrafia e paleogeografia del Campaniano e Maastrichtiano nelle Alpi Meridionali (con particolare riguardo agli hard grounds della Scaglia rossa veneta). Memorie degli Istituti di Geologia e Mineralogia dell'Università di Padova 28:1-64

Milani L, Beccaluva L, Coltorti M (1999) Petrogenesis and evolution of the Euganean Magmatic Complex, Veneto Region, North-East Italy. Eur J Min 11 (2):379–399

Mimmo M (2006) Analisi della viabilità per la ricostruzione della topografia di Adria. Revisione dei dati d'archivio. Padusa 42:199-21

Montana G, Cau Ontiveros MÁ, Polito AM, Azzaro E (2011) Characterisation of clayey raw materials for ceramic manufacture in ancient Sicily. Appl Clay Sci 53:476–488. https://doi.org/10.1016/j.clay.2010.09.005

Mozzi P, Piovan S, Corrò S (2020) Long-term drivers and impacts of abrupt river changes in managed lowlands of the Adige River and northern Po delta (Northern Italy). Quat Int 538:80–93

Mutti E, Ricci Lucchi F (1972) Le torbiditi dell'Appennino settentrionale: introduzione all'analisi di Facies. Memorie Società Geologica Italiana 161–199

Paltineri S, Binotto S, Zara A (2020) L'impiego dei materiali lapidei a Padova nell'età del Ferro tra simbologia, funzione e rapporti con il territorio. Preist Alp 50:53–88

Peretto R, Vallicelli MC, Wiel Marin F (2002) L'entroterra di Adria. Conoscenze archeologiche e paleoambientali. Padusa 38:91–106

Petti FM, Falorni P (1990a) Maiolica. In: Carta geologica d'Italia 1:50.000 - Catalogo delle formazioni 167–180

Petti FM, Falorni P (1990b) Maiolica. In: Carta geologica d'Italia 1:50.000 - Catalogo delle formazioni 211–222

Piovan S, Mozzi P, Stefani C (2010) Bronze Age paleohydrography of the southern Venetian plain. Geoarchaeology 25(1):6–35

Piovan S, Mozzi P, Zecchin M (2012) The interplay between adjacent Adige and Po alluvial systems and deltas in the late Holocene (Northern Italy). Géomorphologie: relief, processus, environment 4: 427–440

Previato C, Mazzoli C (2018) Le analisi petrografiche. In: Basso P (ed) L'anfiteatro di Aquileia. Ricerche d'archivio e nuove indagini di scavo, Scavi di Aquileia V. Quingentole, Mantova, pp 187–192

Previato C, Zara A (2014) Il trasporto della pietra di Vicenza in età romana. Il relitto del fiume Bacchiglione. Marmora 10:59-78

Previato C, Zara A (2018) A Database and GIS project about quarrying, circulation and use of stone during the Roman age in Regio X - Venetia et Histria. The case study of Euganean trachyte. In: Matetić Poljak D, Marasović K (eds) ASMOSIA XI – Interdisciplinary Studies of Ancient Stone, Proceedings of the Eleventh International Conference of ASMOSIA (Split, 18–22 May 2015). Split, pp 597–609

Previato C, Zara A (2021) Mezzi, vie e tempi del trasporto della pietra nell'Alto Adriatico in età romana: il caso di Aquileia. In: Raux S (ed) Les modes de transport dans l'Antiquité et au Moyen-Âge. Mobiliers d'équipement et d'entretien des véhicules terrestres, fluviaux et Maritimes, Actes des Rencontres internationals Instrumentum Arles 14–16 juin 2017. Bouches-du-Rhône, pp 369–384

Previato C, Bonetto J, Mazzoli C, Maritan L (2014) Aquileia e le cave delle regioni alto-adriatiche: il caso della trachite euganea. In: Bonetto J, Camporeale S, Pizzo A (eds) Arqueología de la construcción. Las cantera en el mundo antiguo: sistemas de la explotación y procesos productivos. Merida, pp 149–166

Previato C (2015a) Aquileia. Materiali, forme e sistemi costruttivi dall'età repubblicana alla tarda età imperiale. Padova University Press, Padova

Previato C (2015b) Tra monti, fiumi e mare: l'estrazione e il commercio della pietra nella Regio X – Venetia et Histria. In: Cambi F, De Venuto G, Goffredo R (ed) I pascoli, i campi, il mare. Paesaggi d'altura e di pianura in Italia dall'Età del Bronzo al Medioevo. Storia e Archeologia Globale 2. Bari, pp 31–49

Previato C (2016) Nora. Le cave di pietra della città antica. Scavi di Nora VI. Quasar, Roma

Previato C (2018) Aurisina limestone in the Roman Age: from Karst Quarries to the cities of the Adriatic Basic. In: Matetić Poljak D, Marasović K (eds) ASMOSIA XI: interdisciplinary studies of ancient stone : Proceedings of the Eleventh International Conference of ASMOSIA, Split, 18–22 May 2015. Arts Academy, pp 933–939

Prochaska W (2023) The use of geochemical methods to pinpoint the origin of ancient white marbles. Mineral Petrol 117:401–409. https://doi.org/10.1007/s00710-023-00833-2

Renzulli A, Antonelli F, Santi P et al (1999) Provenance determination of lava flagstones from the Roman "via Consolare Flaminia" pavement (Central Italy) using petrological investigations.

Archaeometry 41:209–226. https://doi.org/10.1111/j.1475-4754.1999.tb00978.x

Renzulli A, Santi P, Serri G, Luni M (2002) The Euganean trachyte flagstones ("basoli") used by the Romans along the mid-Adriatic coast (Marche, central Italy): an archaeometric study. Periodico di Mineralogia 71:189–201

Rietveld HM (1967) Line profiles of neutron powder-diffraction peaks for structure refinement. Acta Crystallogr 22:151–152

Rioda V (2015) Formazioni geologiche e zone di provenienza dei principali materiali lapidei locali utilizzati nel prospetto. In: Butturini F, Pachera F (eds) San Zeno Maggiore a Verona Il campanile e la facciata Restauri, analisi tecniche e nuove interpretazioni. Verona, pp 295–304

Robino MTA (2009) Edilizia privata ad Adria. Alcune considerazioni. In: Annibaletto M, Ghedini F (eds) Intra illa moenia domus ac penates (liv. 2, 40, 7). Il tessuto abitativo nelle città romane della cilsapina. Atti delle giornate di studio, Padova, 10–11 aprile 2008. Anthropol. Q. 14:41–51

Roffia E, Bugini R, Folli L (2009) Stone materials of the Roman villas around Lake Garda (Italy). In: Maniatis Y (ed) ASMOSIA VII (BCH Supplement 51). Athens, pp 559–570

Rosada G (1984) Funzione e funzionalità della Venetia romana: terra, mare, fiumi come risorse per un'egemonia espansionistica. In: Misurare la terra: centuriazione e coloni nel mondo romano. Il caso veneto. Modena, pp 22–37

Russell B (2013) The Economics of Roman Stone Trade. Oxford

Salvini S, Coletti C, Maritan L et al (2023) Petrographic characterization and durability of carbonate stones used in UNESCO World Heritage Sites in northeastern Italy. Environ Earth Sci 82:49. https://doi.org/10.1007/s12665-022-10732-y

Schürch B, Wettengl S, Fröhle S, et al (2022) The origin of chert in the Aurignacian of Vogelherd Cave investigated by infrared spectroscopy. PLoS ONE 17. https://doi.org/10.1371/journal.pone.0272988

Šprem K (2020) Stone as a resource in Istrian antiquity. In: Oszkó DR (ed) About Two Provinces, Proceedings of the 3rd Croatian–Hungarian PhD Conference on Ancient History and Archaeology, HPS 26:103–115

Šprem K (2021) All aboard! Quarries and transport in Roman Istria. In: Proceedings from the 7th Scientific Conference Methodology and Archaeometry, Zagreb 2nd-3th December 2019. Zagreb, pp 67–85

Stefani M, Vincenzi S (2005) The interplay of eustasy, climate and human activity in the late Quaternary depositional evolution and sedimentary architecture of the Po Delta system. Mar Geol 222–223:19–48

Taut T, Kleeberg R, Bergmann J (1998) The new Seifert Rietveld program BGMN and its application to quantitative phase analysis. Mater Struct 5:55–64

Tykot RH (1997) Characterization of the Monte Arci (Sardinia) Obsidian Sources. J Archaeol Sci 24:467–479

Uggeri G (2012) La nuova Via Annia da Roma ad Aquileia (153 a.C.). J Anc Topography 22:133–174

Whitney DL, Evans BW (2010) Abbreviations for names of rock-forming minerals. Am Mineral 95:185–187

Zara A (2018) La trachite euganea. Archeologia e storia di una risorsa lapidea del Veneto antico, Antenor Quaderni 44.1/2. Roma

Zuccari C, Vignaroli G, Viola G (2021) Geological map of the San Donato – Costa Thrust Zone, Belluno Thrust System, eastern Southern Alps (northern Italy). J Maps 17(2):337–347. https://doi.org/10.1080/17445647.2021.1946444