Analytical techniques for provenance determination of ancient volcanic pozzolans

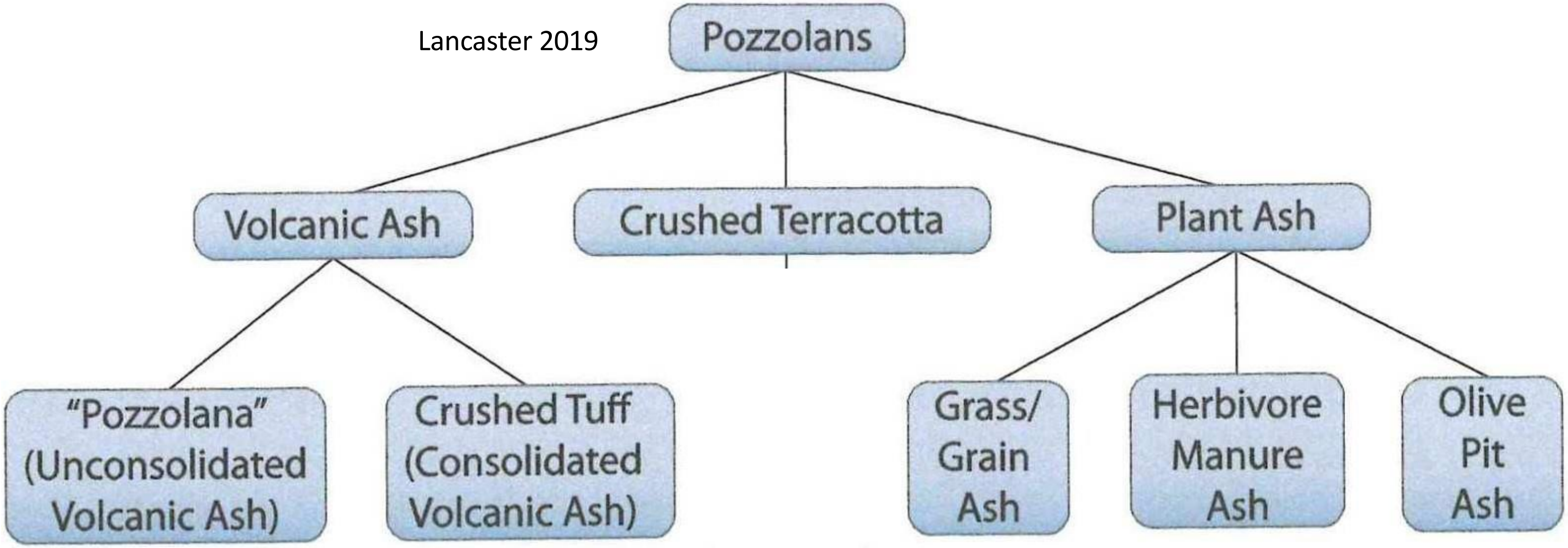
Simone Dilaria

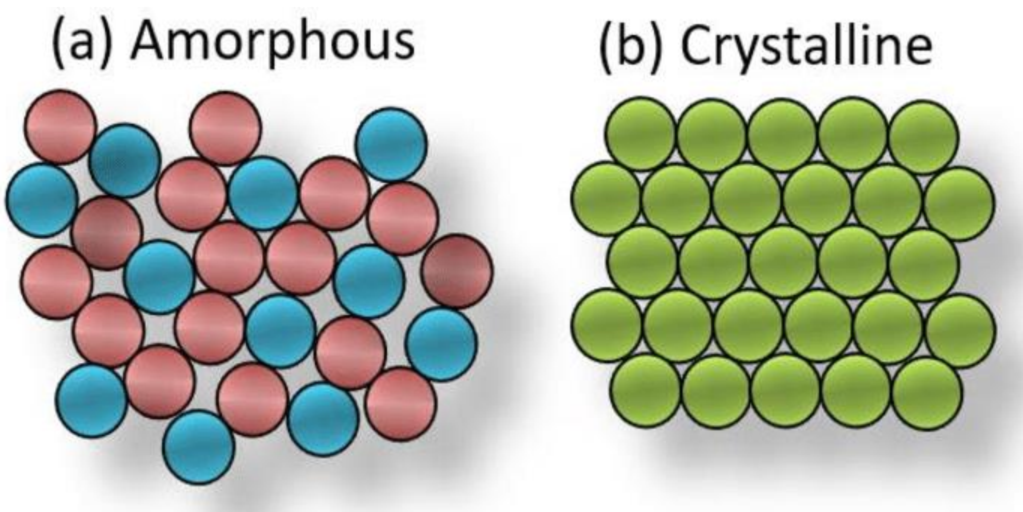
Università degli Studi di Padova
dBC Dipartimento dei Beni Culturali Archeologia, Storia dell'Arte, del Cinema e della Musica
Dipartimento di Geoscienze
CIRCe Centro Interdipartimentale di Ricerca per lo Studio dei Materiali Cementizi e dei Leganti Idraulici
CIBA Centro per i Beni Culturali
Diagnostica . Rilievo . Tecnologie

Volcanic pozzolans and geological origin

Pozzolanic aggregates

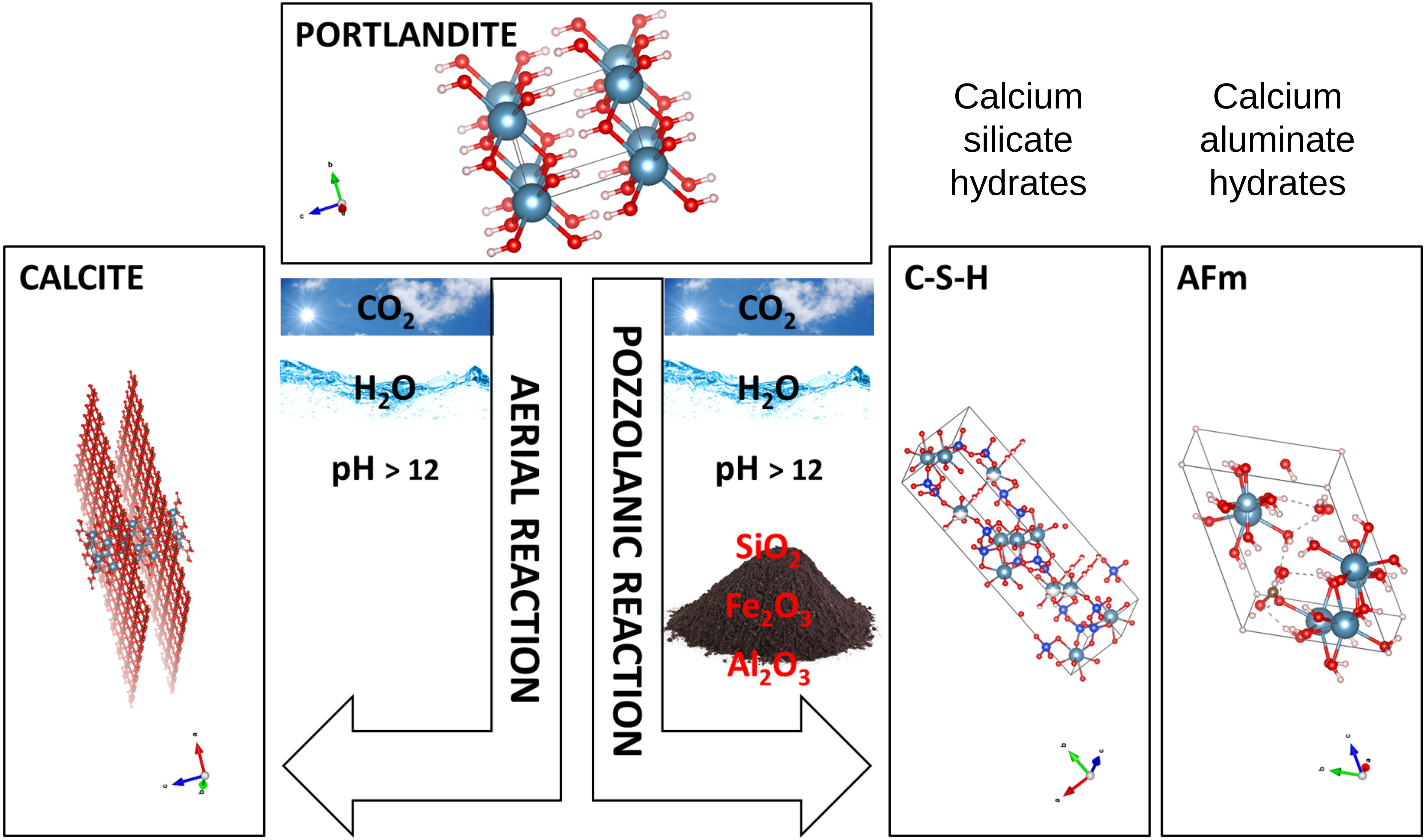
Lancaster 2019





Pozzolanic aggregates are materials with an amorphous structure, rich in silica and alumina, and potentially reactive with a lime binder through the medium of a liquid (water) under slightly alkaline conditions (basic pH)

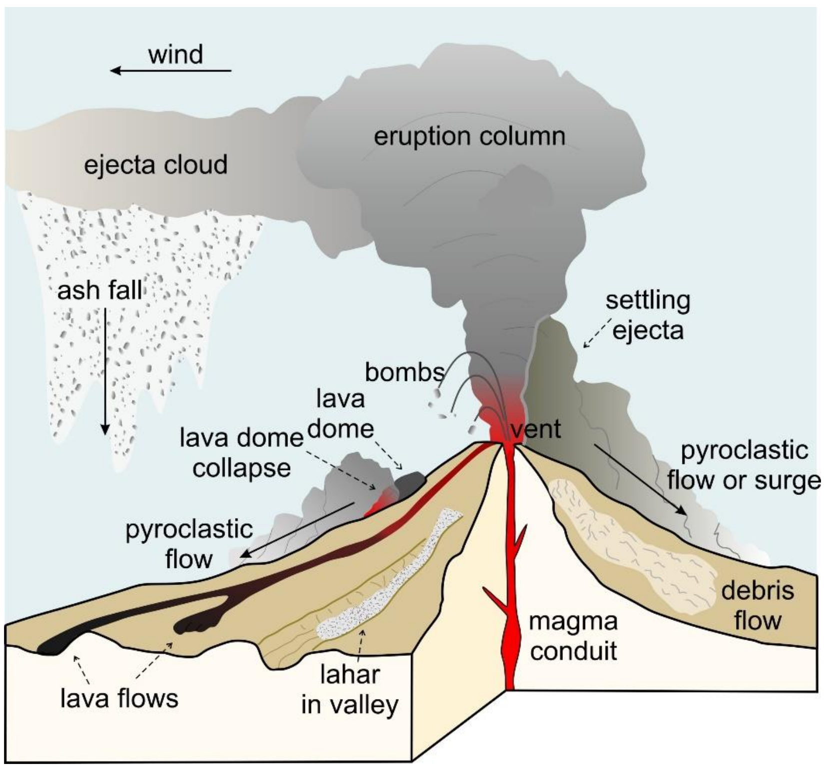
Pozzolanic reaction



Volcanic pozzolans

Volcanic pozzolans consist of <u>volcanic rocks having a quasi-eminently pyroclastic origin </u>(produced by explosive volcanic activities) and having high concentrations of silica and active aluminia in amorphous or poorly crystalline rocks

Therefore they are potentially reactive with lime in mortars: they ecompass many pyroclastic products with abundant volcanic glass, such as <u>pumice, volcanic ash, tephra, perlites and obsidians, poorly lithified tuffs and ignimbrites, and breccias</u>



Volcanic pozzolans

Pumice

Highly vesicular rough-textured volcanic glass

Scoria

Vesicular, dark-colored volcanic rock usually feebly-to-moderately silica undersaturated.

Tuffs

Volcanic ashes, scoria, pumices and other volcanic products lithified after sedimentation into a rock

Unlithified pumice outcrop (Phlegraean Fields, Naples)

Lithified tuff outcrop (Phlegraean Fields, Naples)

Volcanic pozzolans

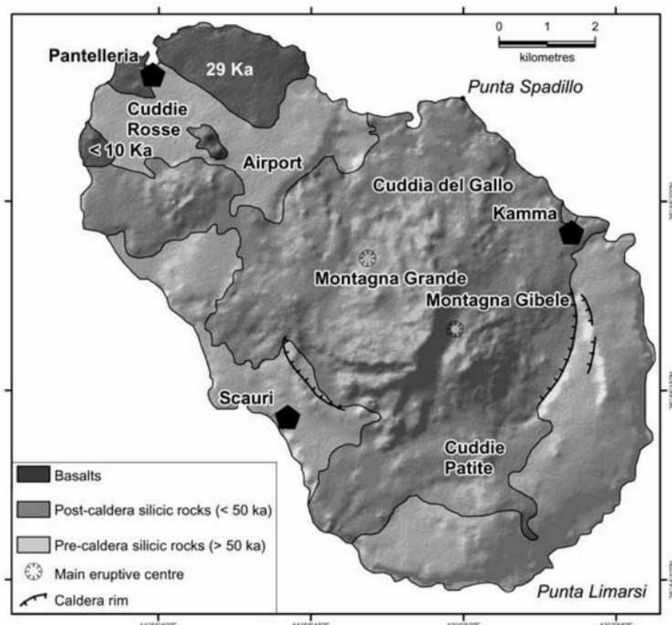
Obsidian and perlites

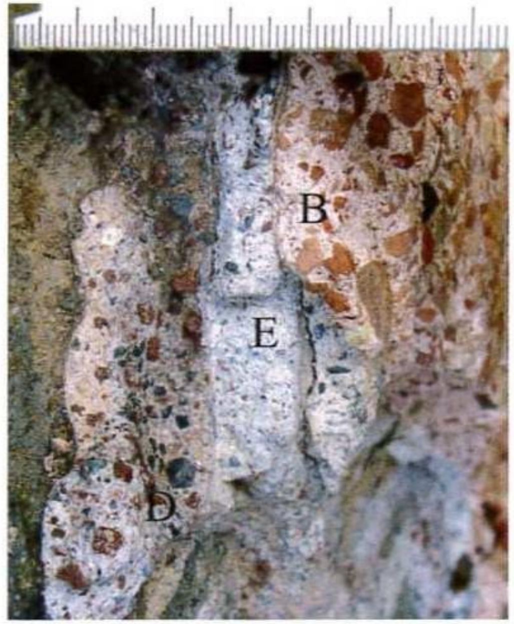
Obsidian is a natural glass formed by the rapid cooling of extremely silica-rich magmas (about 65 to 80%), having a very low in water content.
Perlite is an amorphous volcanic glass, very rich in SiO_2, having a high-water content, typically formed by the hydration of obsidian.

Perlite outcrop embedding obsidians (Monte Arci, Sardinia)

Eploitation of volcanic pozzolans in antiquity

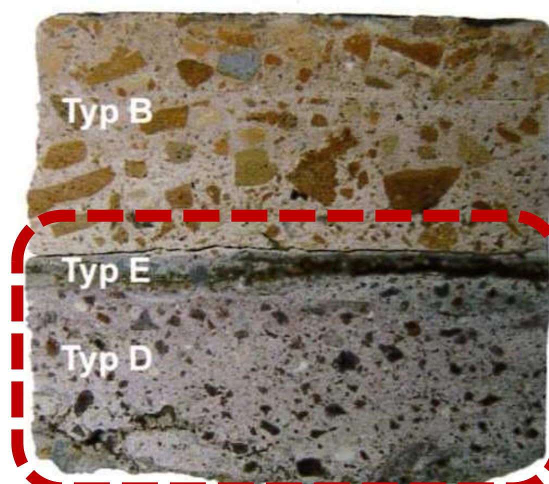
Uses of volcanic pozzolans in antiquity





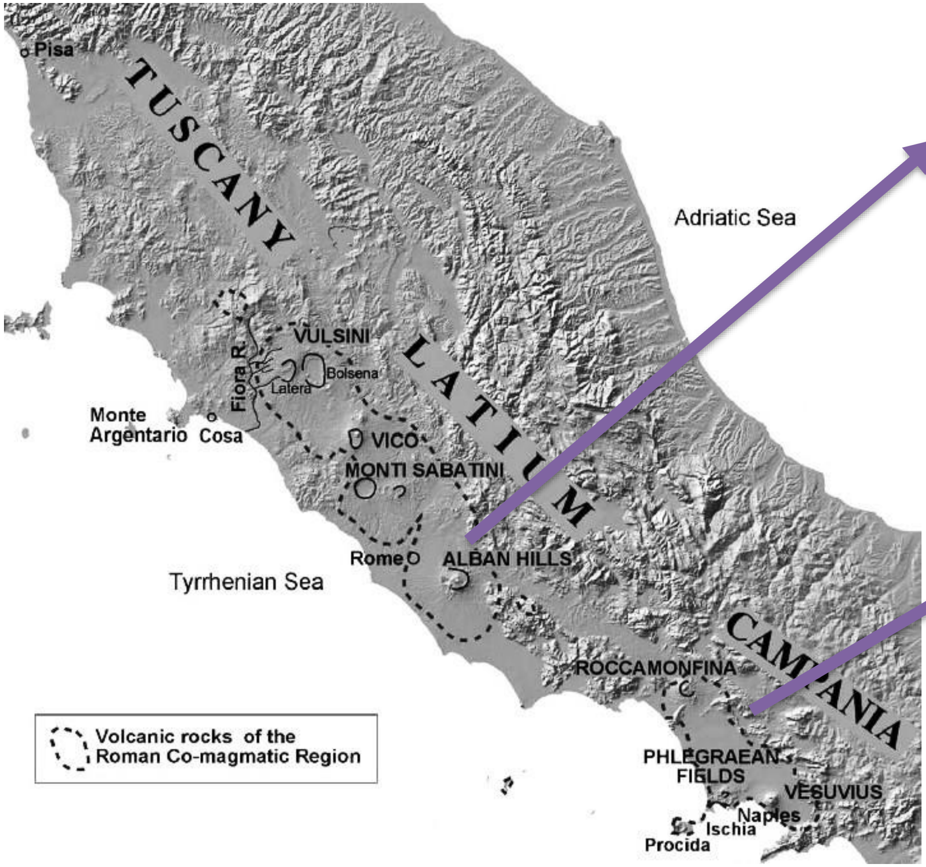
In the coating mortars of Punic Pantelleria cisterns (4th-3rd cent. B.C.) use of local volcanic pozzolans (Cuddia Rossa) for the production of waterproof and hydraulic mortars.

→ Volcanic pozzolans were not "discovered" by the Romans



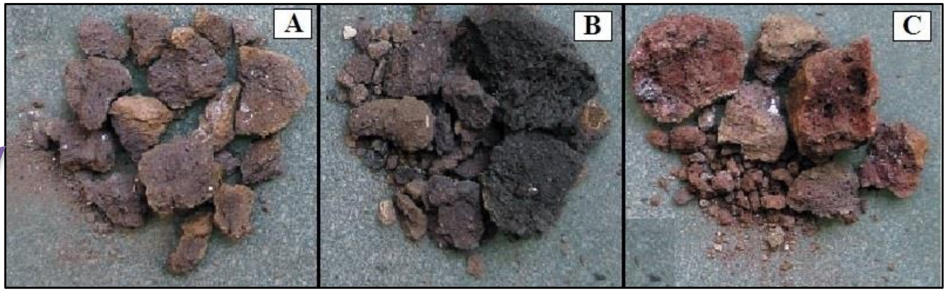
Shön *et alii 2011;* Shön 2012

Vitruvian volcanic pozzolans



Harenae fossiciae (Colli Albani)

(Volcanic scoriaceous cinerites)



POZZOLANELLA

POZZOLANA NERA

POZZOLANA ROSSA

Pulvis Puteolana

(Phlegraean Fields and Vesuvius)

Pumices and tuff from the Bay of Naples

Harenae fossiciae

In caementiciis autem structuris primum est de harena quaerendum**, ut ea sit idonea ad materiem miscendam neque habeat terram commixtam. genera **autem harenae fossiciae sunt haec, nigra, cana, rubra, carbunculus.

In buildings of rubble work it is of the first importance that the sand be fit for mixing with the lime, and unalloyed with earth. The different sorts are these; black, white, deep red, and bright red.

Vitr. *De arch*. 2.5.1

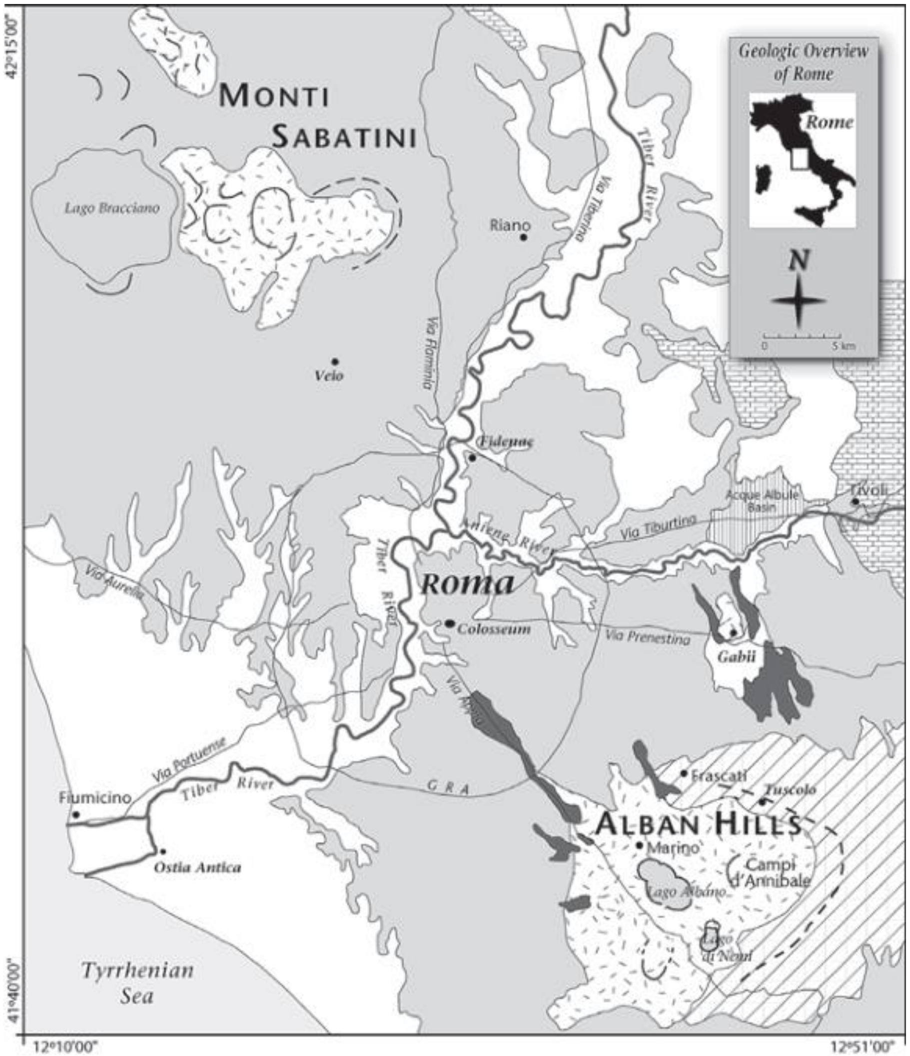
*recentes autem **fossiciae cum in structuris tantas habeant virtutes**, eae in tectorio ideo non sunt utiles quod pinguitudine **eius calx palea commixta propter vehementiam non potest sine rimis inarescere**.*

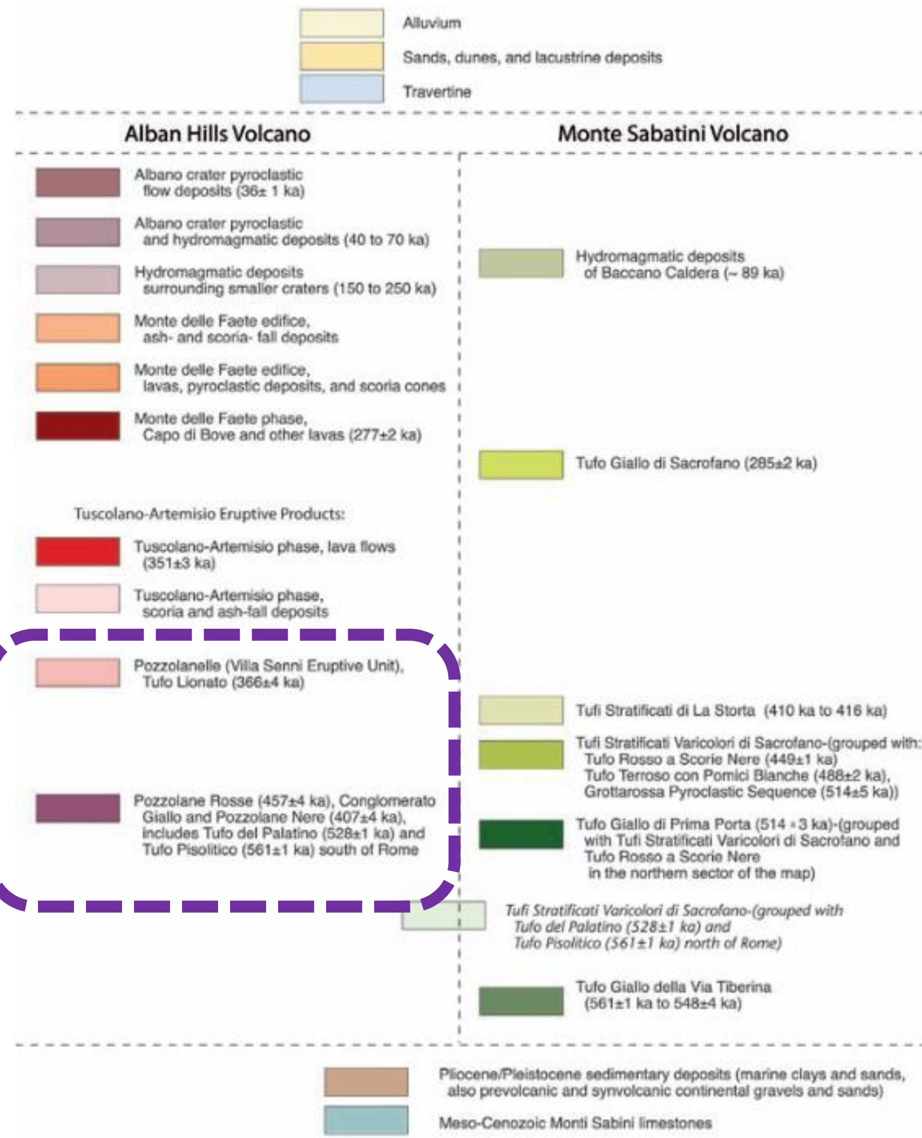
Though pit sand (*harenae fossiciae*) is excellent for mortar, it is unfit for plastering; for being of such a rich quality, when added to the lime and straw, its great strength does not suffer it to dry without cracks.

Vitr. *De arch*. 2.5.3

Harenae fossiciae

Latial Volcaninc Districts (Pleistocene)





Harenae fossiciae

Pozzolanelle
366k.a. BP

Black
Pozzolan
407k.a. BP

= Vitruvian *nigra ?*

Red
Pozzolan
475k.a. BP

= Vitruvian *rubra + nigra (?)*

According to Jackson 2007

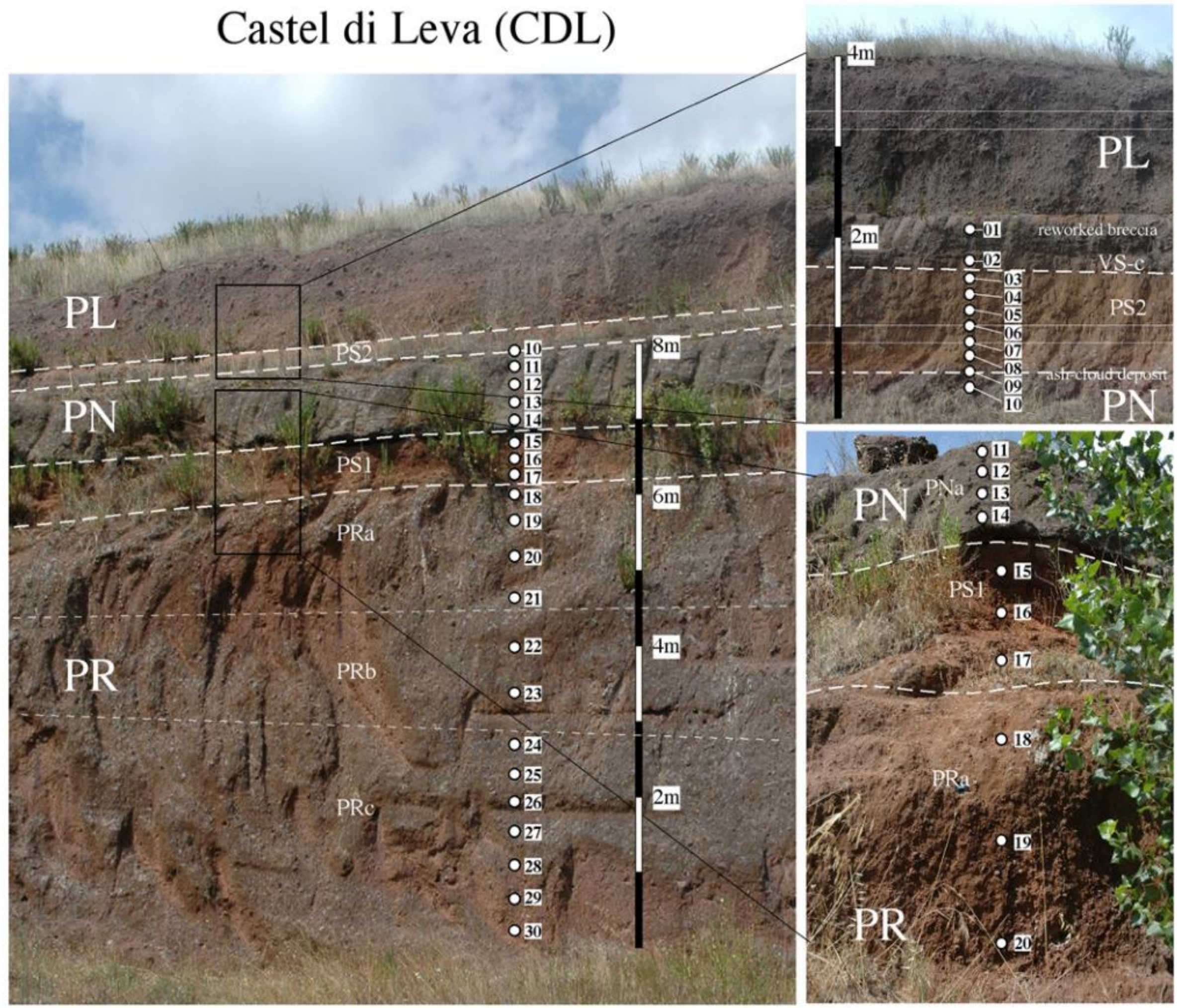


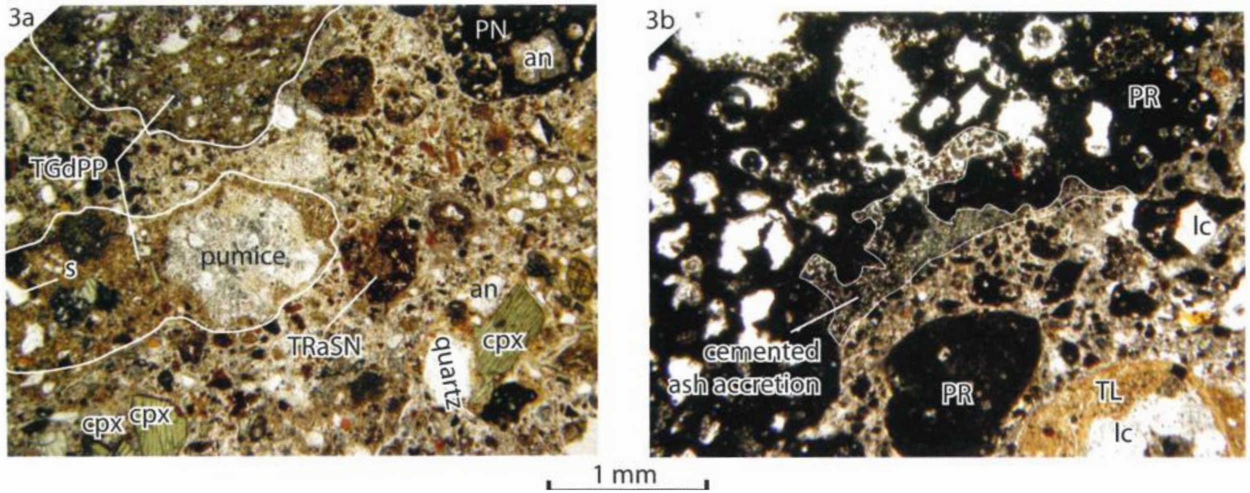
Fig. 3. Stratigraphy and sample locations of Castel di Leva (CDL) section. PR: Pozzolane Rosse; PN: Pozzolane Nere; PL: Pozzolanelle.

Harenae fossiciae

The Origins of Concrete Construction in Roman Architecture

Technology and Society in Republican Italy

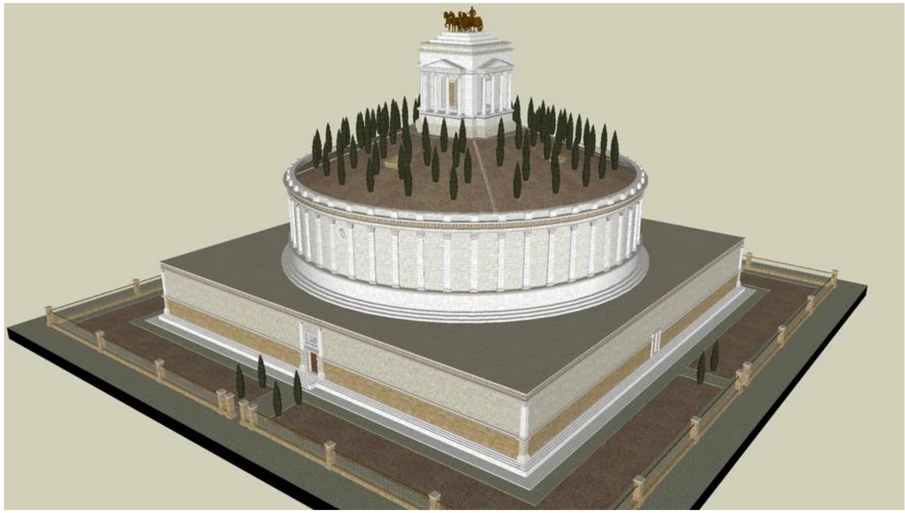
Marcello Mogetta



Da Jackson et al. 2007

Harenae fossiciae

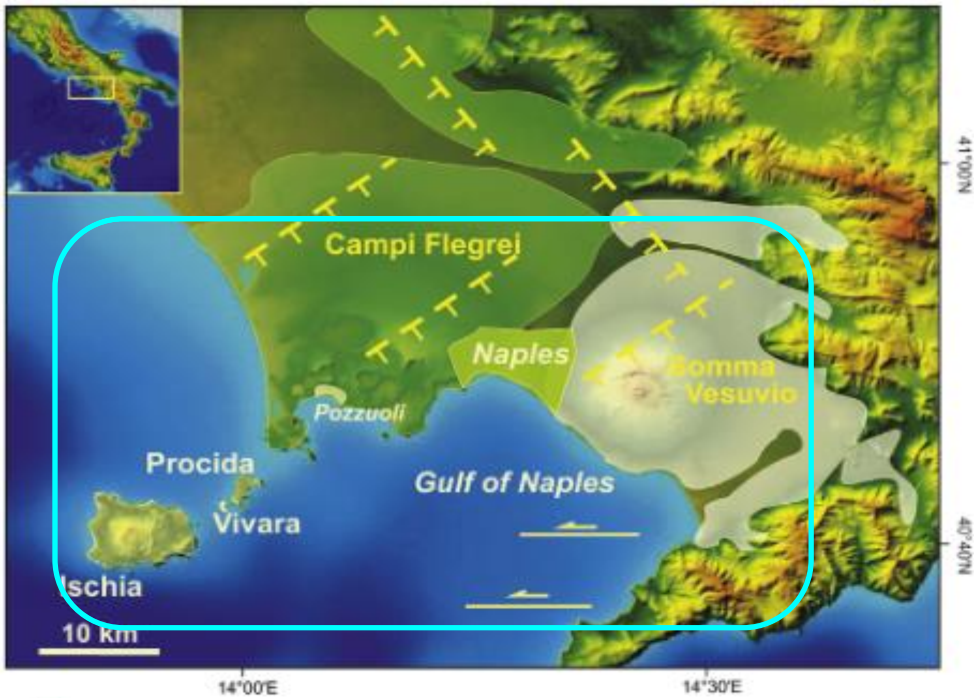
Hadrian Mausoleum (2nd c. CE),
nowadays Castel Sant'Angelo in Rome



Pulvis puteolana

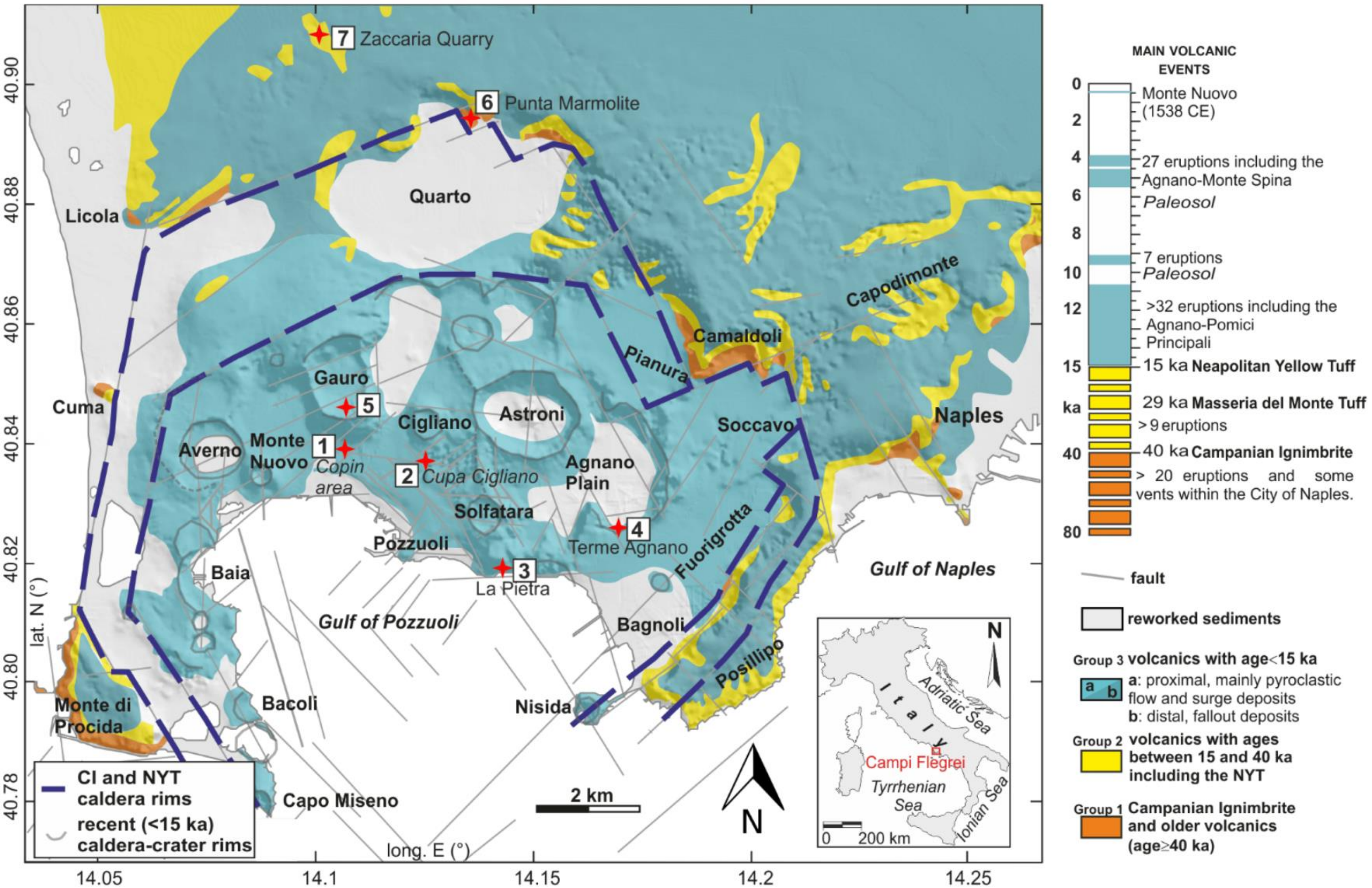
Est etiam genus pulveris quod efficit naturaliter res admirandas. Nascitur in regionibus Baiais in agris municipiorum quae sunt circa Vesuvium montem.
Vitr. 2.6.1

There is also a kind of powder that naturally makes things amazing. It grows in the regions of Baiani and in the fields of the municipalities around Mount Vesuvius.



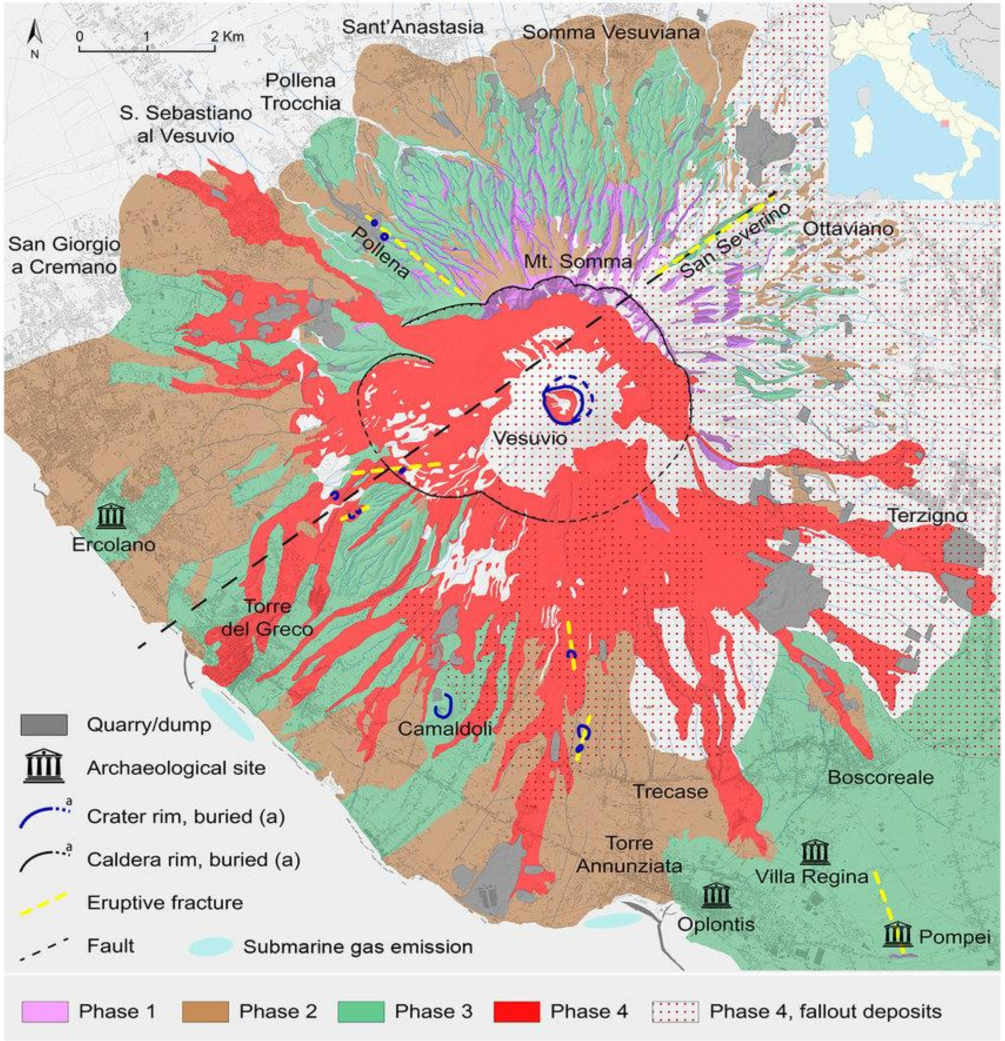
Pulvis puteolana

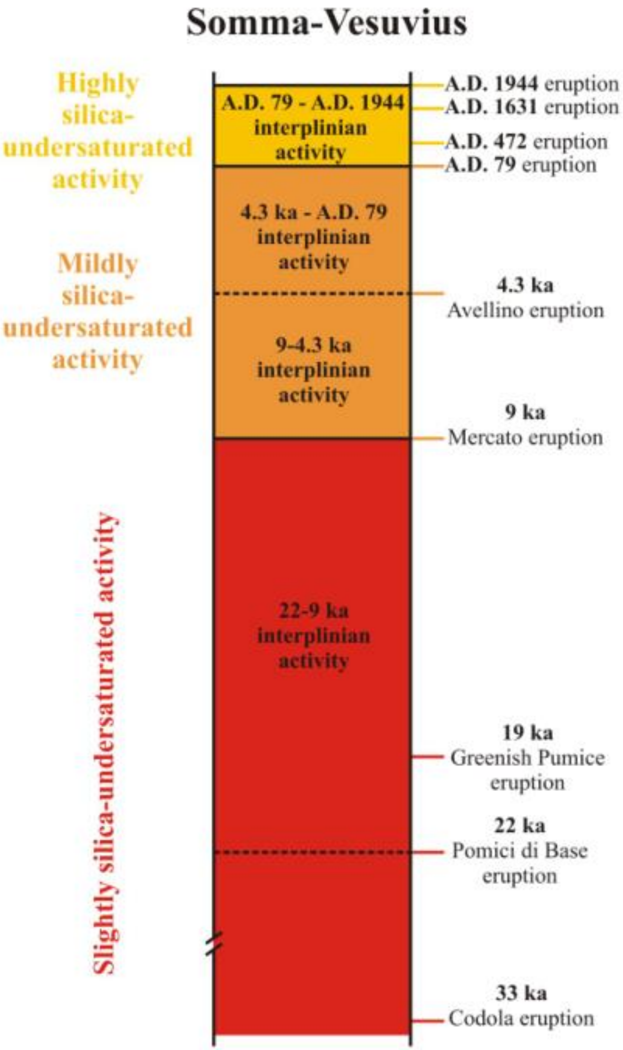
Phlegraean fields eruptions (Late Pleistocene 40 k.a. BP – present)



Pulvis puteolana

Somma-Vesuvius eruptions (Late Pleistocene 40 k.a. BP – present)





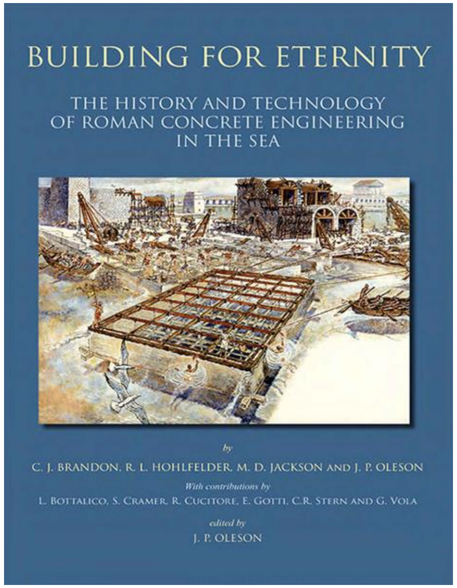
Pulvis puteolana

Vitruvio, *De arch.*, V, 12, 2-3.

Eae autem structurae, quae in aqua sunt futurae, videntur sic esse faciendae, uti portetur pulvis a regionibus quae sunt a Cumis continuatae ad promontorium Minervae […]. Deinde tunc in eo loco, qui definitus erit, arcae stipitibus robusteis et catenis inclusae in aquam demittendae destinandaeque firmiter: deinde inter eas ex transtillis inferior pars sub aqua exequenda et purganda, et caementis ex mortario materia mixta (quemadmodum supra scriptum est) ibi congerendum, donicum compleatur structurae spatium, quod fuerit inter arcas.

The structures to be made in the water, it seems to me, should be done in this manner. Let the dust be transported from those reasons which extend from Cumae to the promontory of Minerva [...]. In the place that will be established, let the closed arches be dropped into the water and connected validly with strong poles and chains: moreover inside those by means of rafts purge and level the lower part under the water, and then throw in cement matter mixed with lime (as was said above), until that space of structure that there is between the arches is filled.

Pulvis puteolana



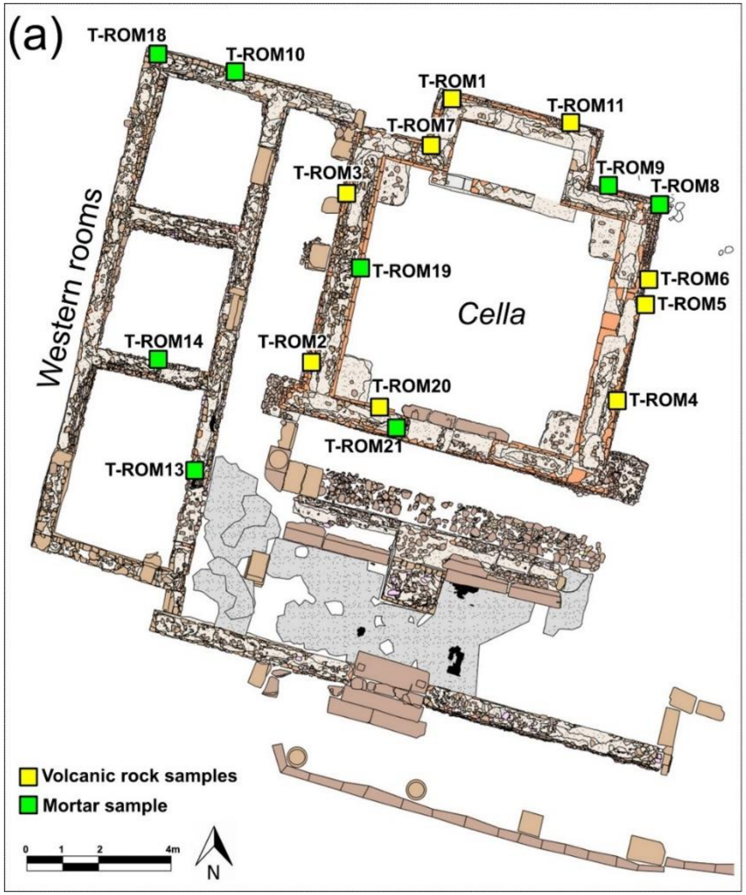
Hohfelder et al., 2014 ***ROMACONS Project***

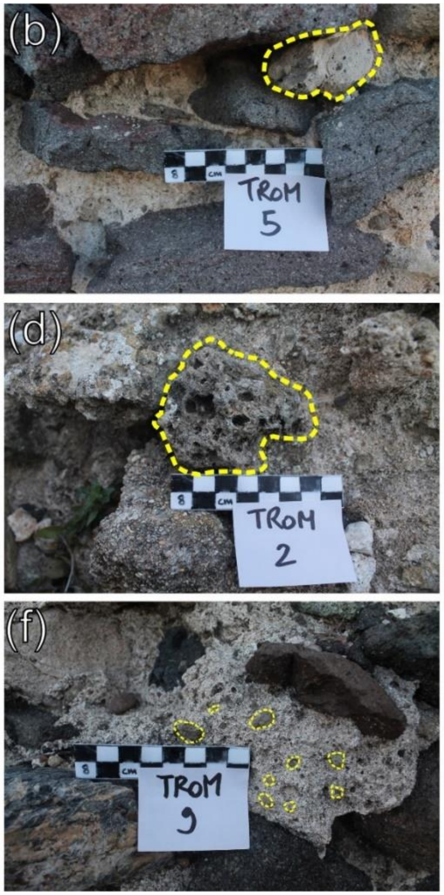
Pulvis puteolana

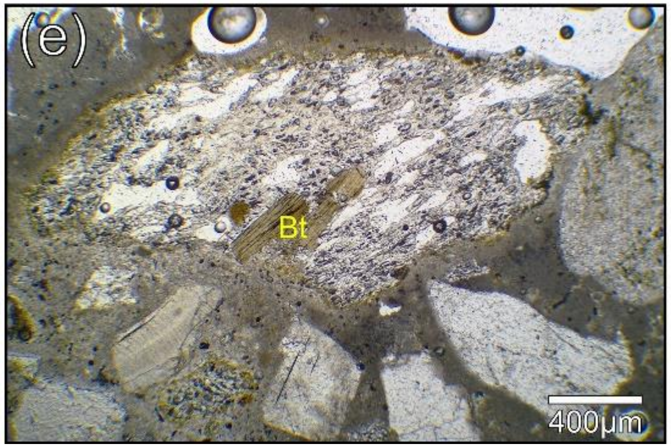
Thermae of Baia, Gulf of Naples

Analisi: Rispoli et al. 2019

Pulvis puteolana





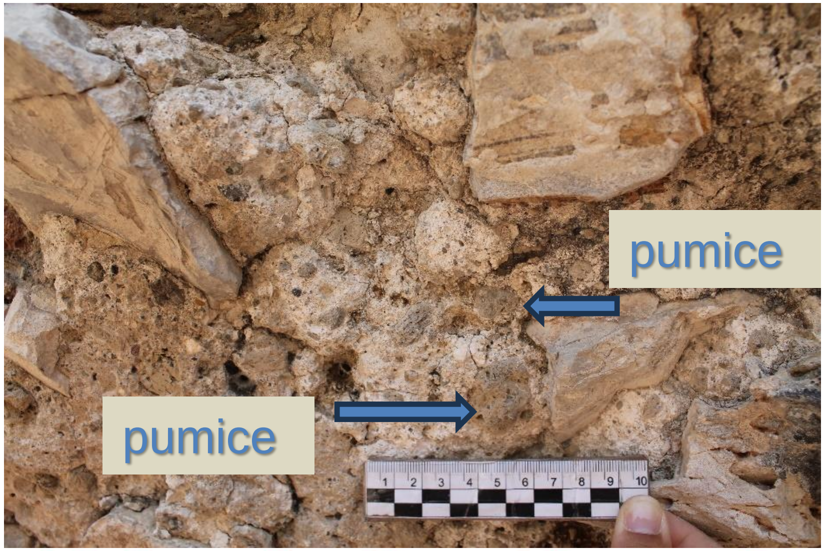


Roman temple of Nora (3rd c. CE)

*…Commixtum cum calce et caemento non modo ceteris aedificiis praestat firmitatem, sed etiam moles, quae struuntur in mari, sub aqua solidescunt (*Vitr. 2.6.1)

The mixture with lime and cement <u>not only guarantees stability</u> to the rest of the buildings, but also solidifies the masses that are built in the sea under water.

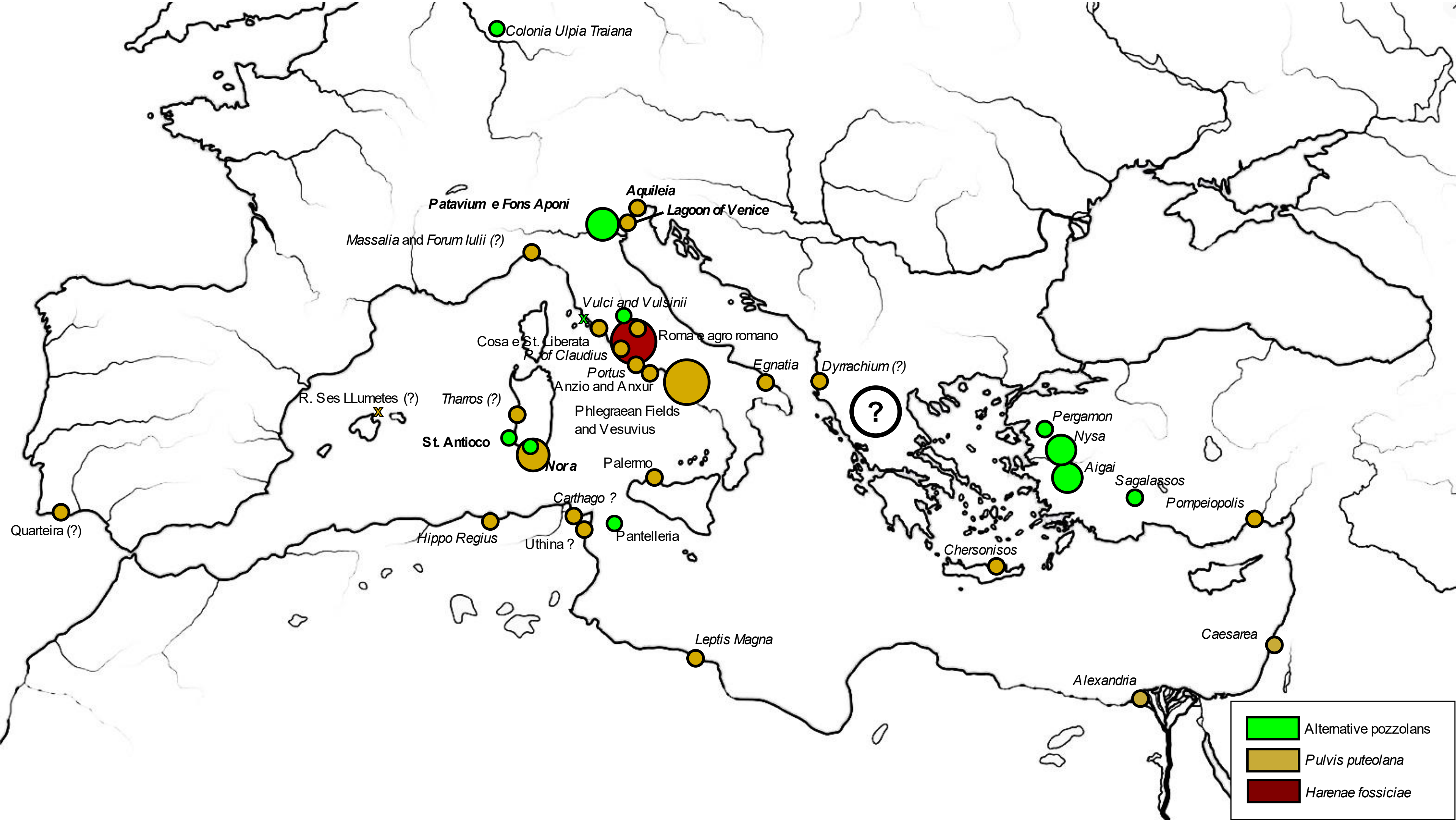
Pulvis puteolana



Roman amphitheater of Dyrrachium (Durrës, Albania)

Trajan Age (2nd c. CE)

Volcanic pozzolans diffusion (Imperial era)



Volcanic pozzolans diffusion (Imperial era)

Wall-painting from Stabiae (I c. CE) reporting the port of *Puteoli*

The massive diffusion and commercialization of Pulvis Puteolana from the Bay of Naples in the Mediterranean **from the Augustan Age onwards.** Presence of some of the most importer harbors of the Roman era by side of the area of procurement of the raw material → **commercialization as ship ballast of the material to sites located primarily along coastal areas.**

Alternative volcanic pozzolans

Region	Site	Function	Cronology	Rock type	References
Etruria	Vulci e Vulsinii	structural	Republican Age	Pyroclastic rocks (Vulsinii, Latera)	Marra, D'Ambrosio 2013;D'Ambrosio et al. 2015;
Pantelleria	-	Cistern revetments	4th-3rd c. BC	Volc. Scorias (Cuddia Rossa/Bruciata)	Schön et al. 2012; Schön 2014, 203-212
Pantelleria	Scauri	Plasters	4th c. AD	Volcanic scoria (Cuddia rossa)	Montana et al. 2013
Sardinia	Nora	Structural	1st c. BC	Perlites and obsidians (Mt. Arci)	Columbu et al. 2019
Germany	Koln	Structural	2nd c. AD	Tuff (Rhineland Trass)	Lamprecht 1984, 46-49; Wang, Althaus 1994
Asia Minor	Sagalassos	Structural	Imperial age	Differentiated volcanics (Lake Golcuk)	Callebaut et al. 2000; Degryse et al. 2002
Asia Minor	Nysa and Aigai	Structural	Imperial Age	Differentiated volcanics (Dikili-Çandarlı)	Uğurlu Sağın, Engin Duran, Böke 2021

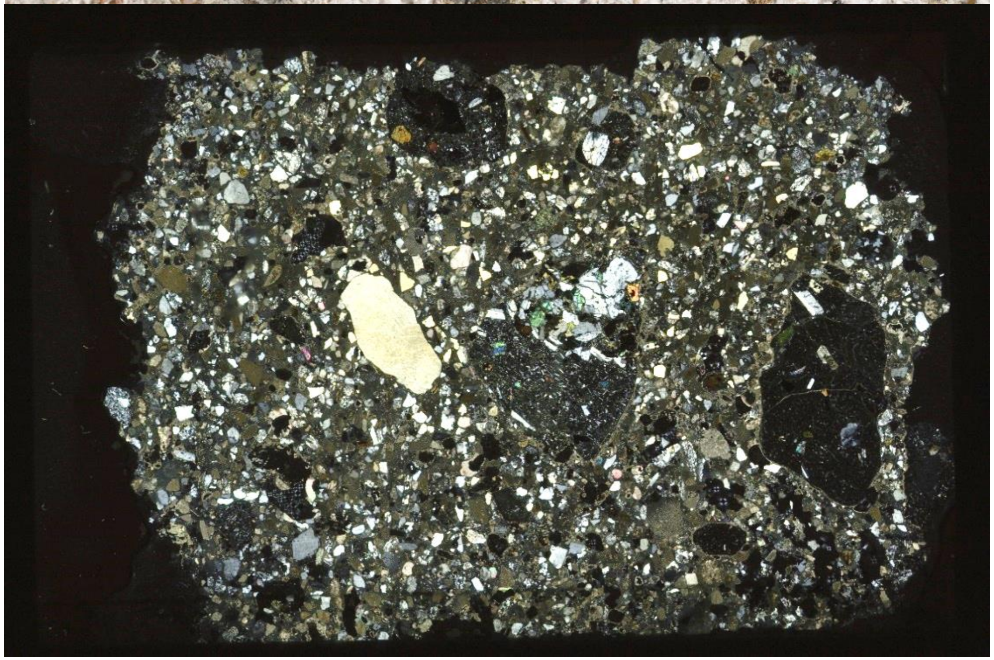
Patavium and *Fons Aponi*

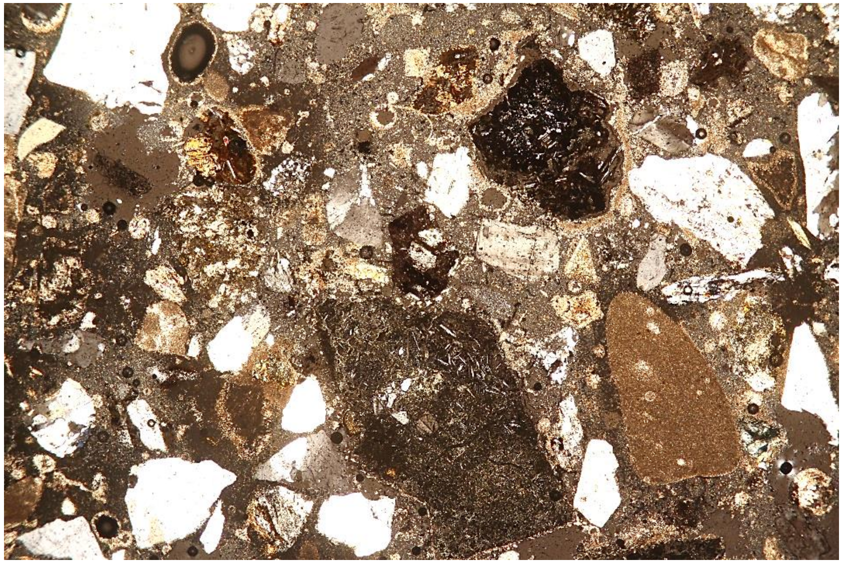
Teatro romano (Prato della Valle - PD)

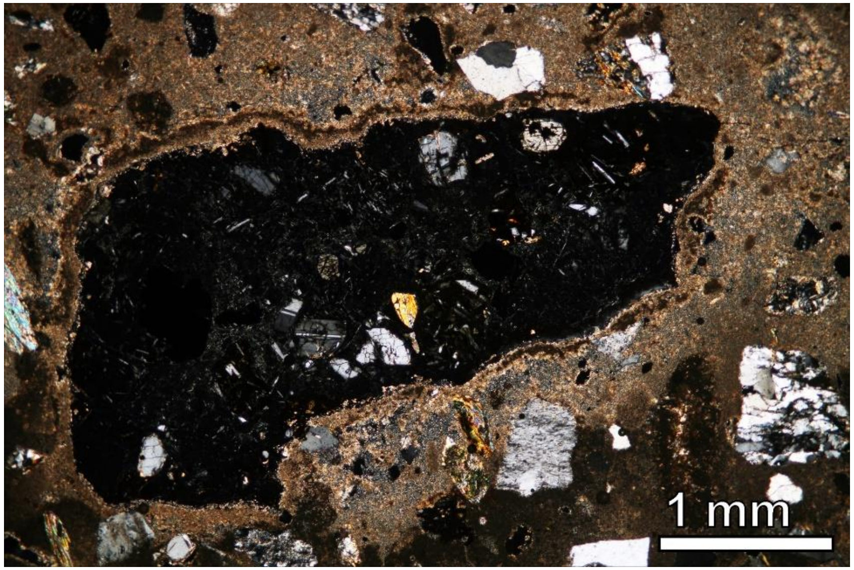
Piccolo teatro (Montegrotto)

Anfiteatro (Giardini Eremitani - PD)

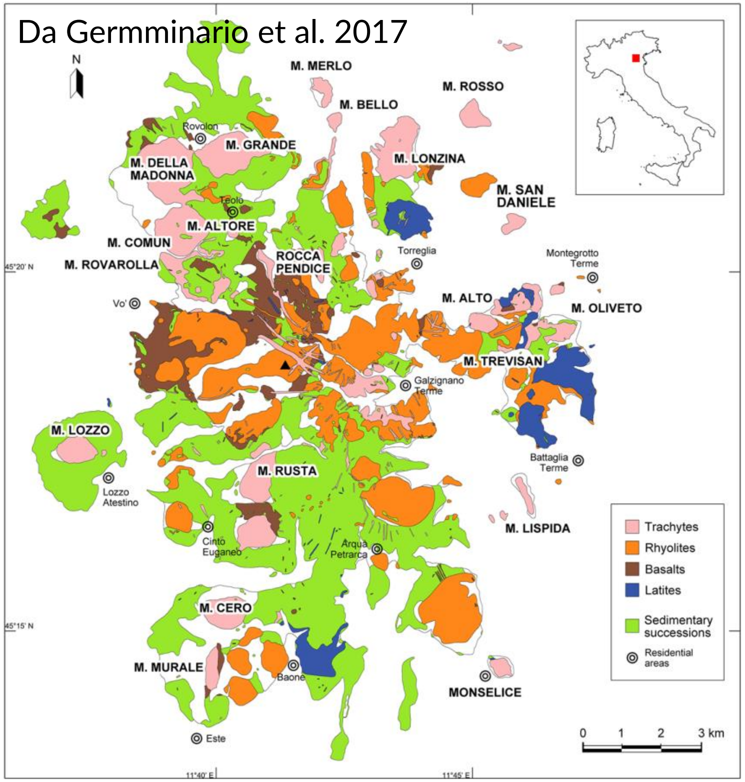
Patavium and *Fons Aponi*



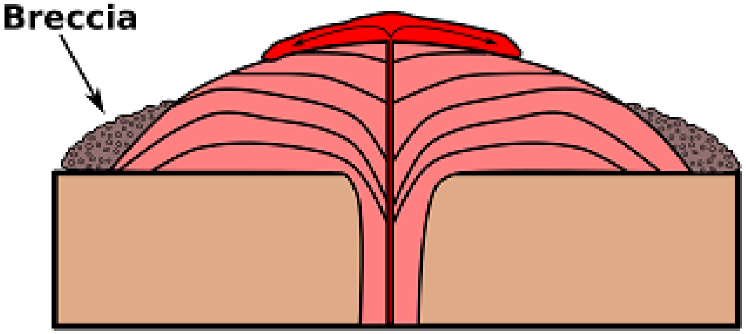




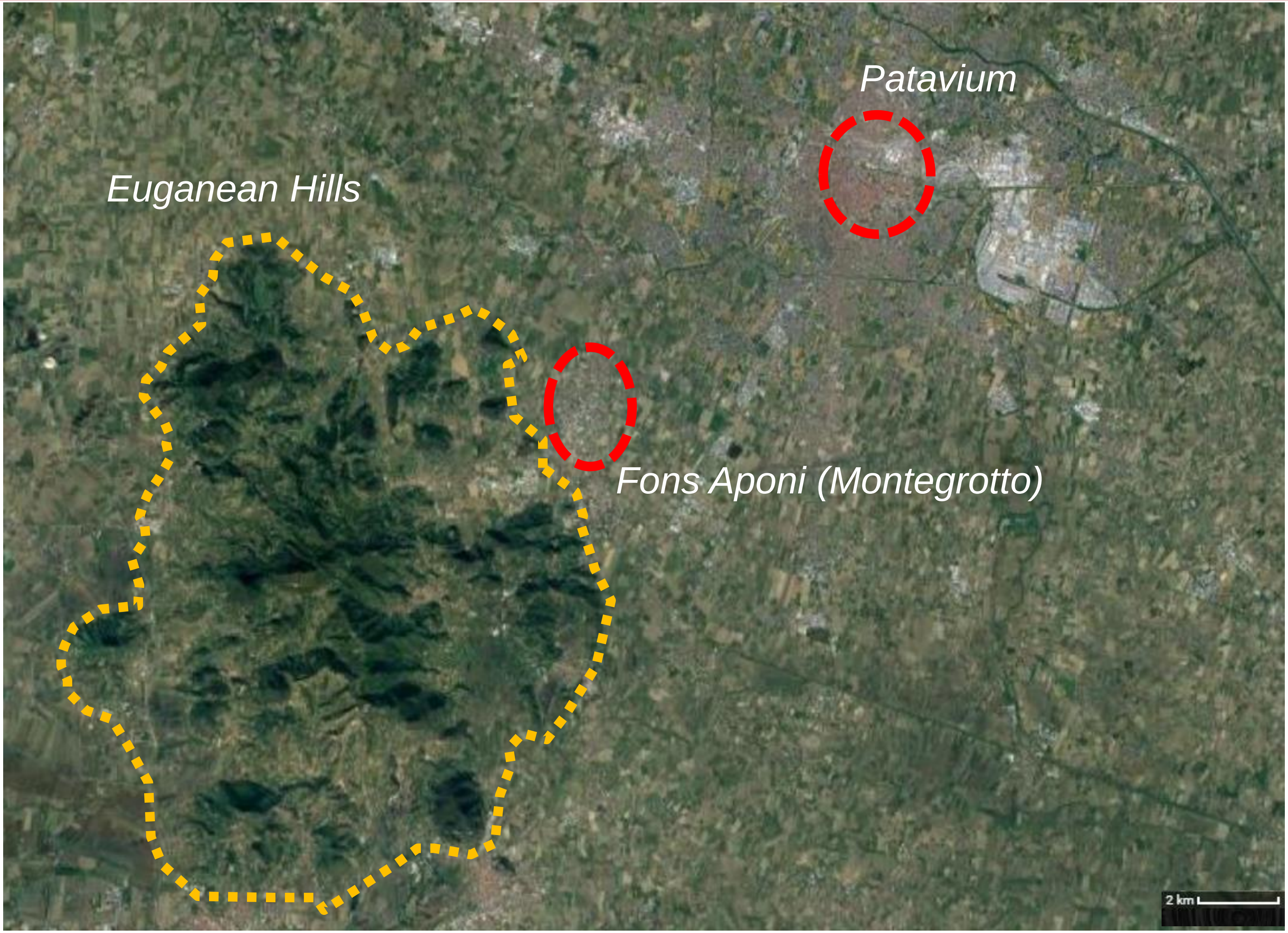
Euganean Hills



- Trachyte / Latite breccias

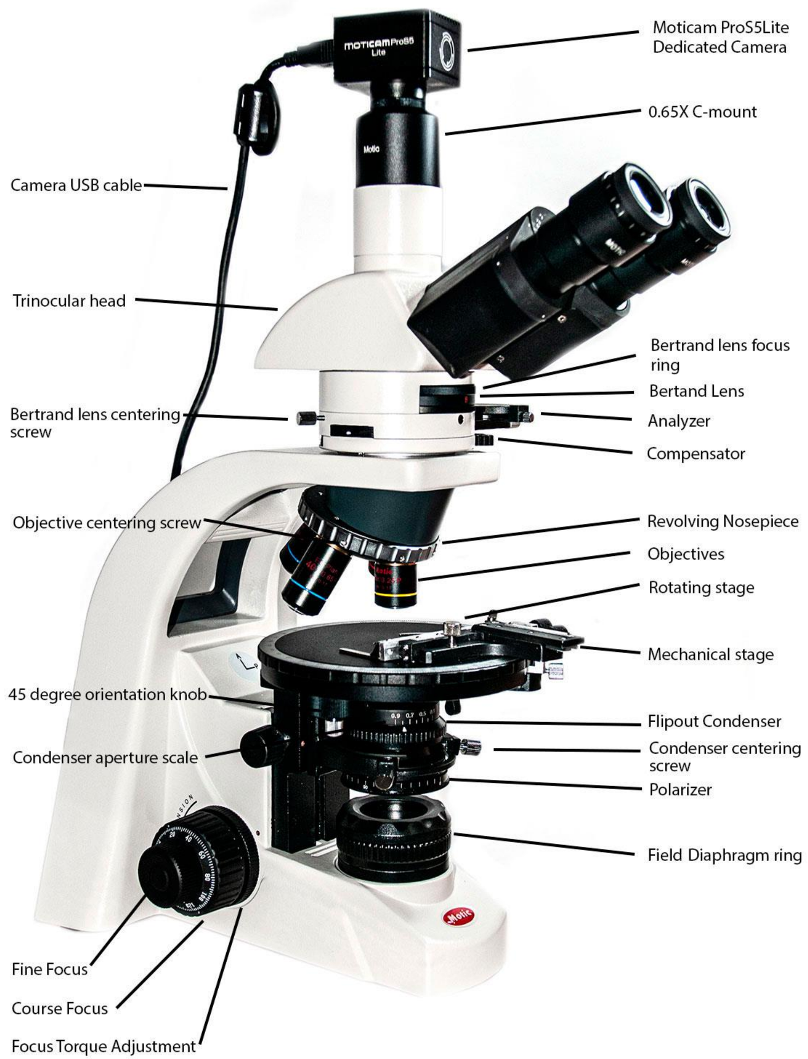


Patavium and *Fons Aponi*

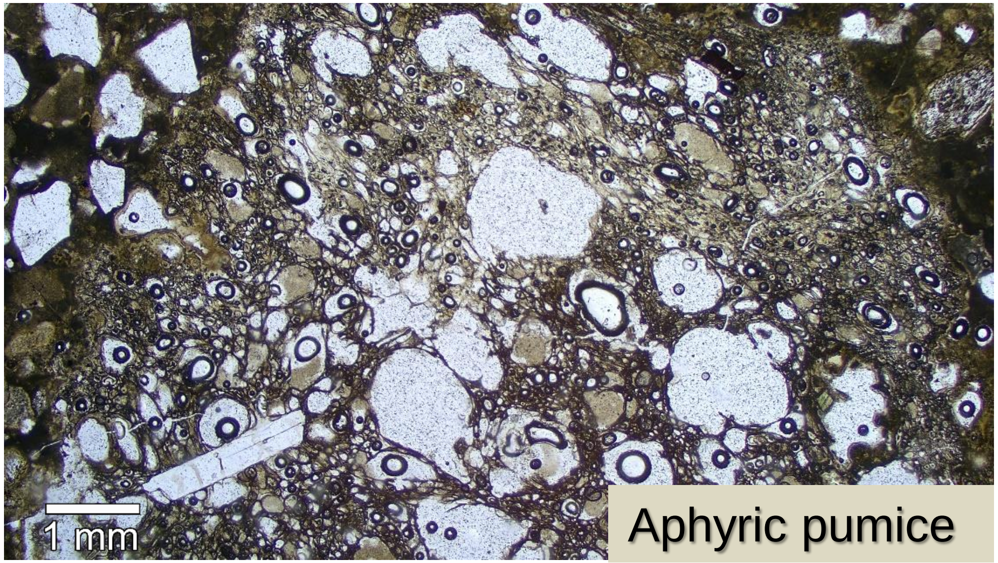


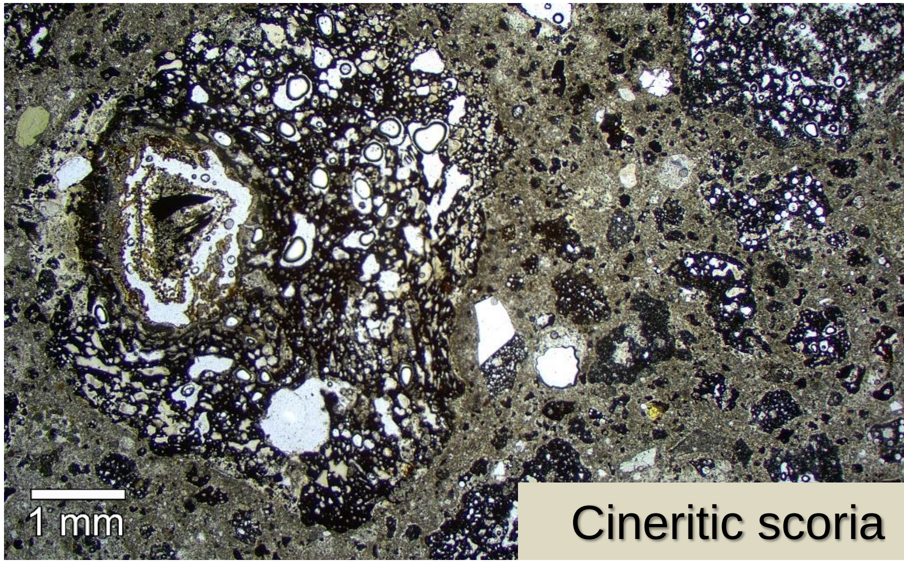
Analytical techniques for provenance determination

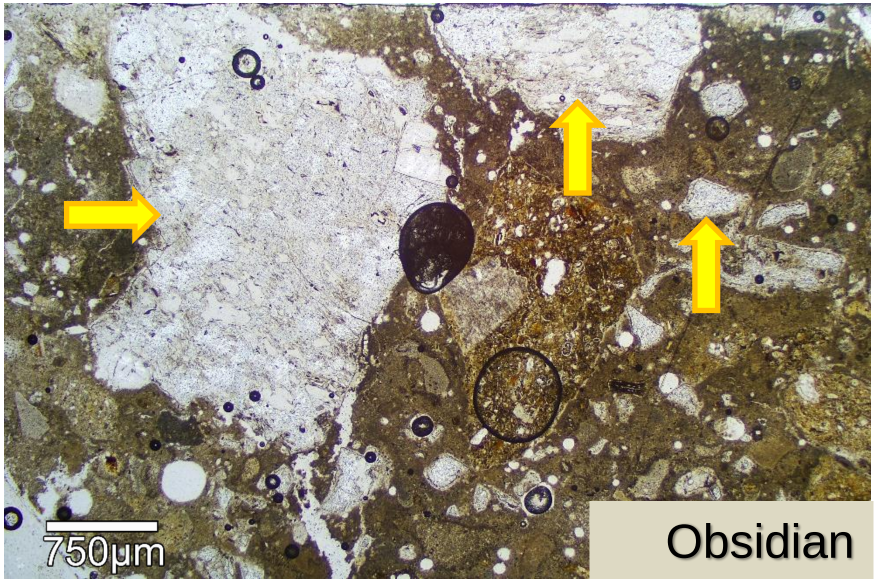
Optical microscopy

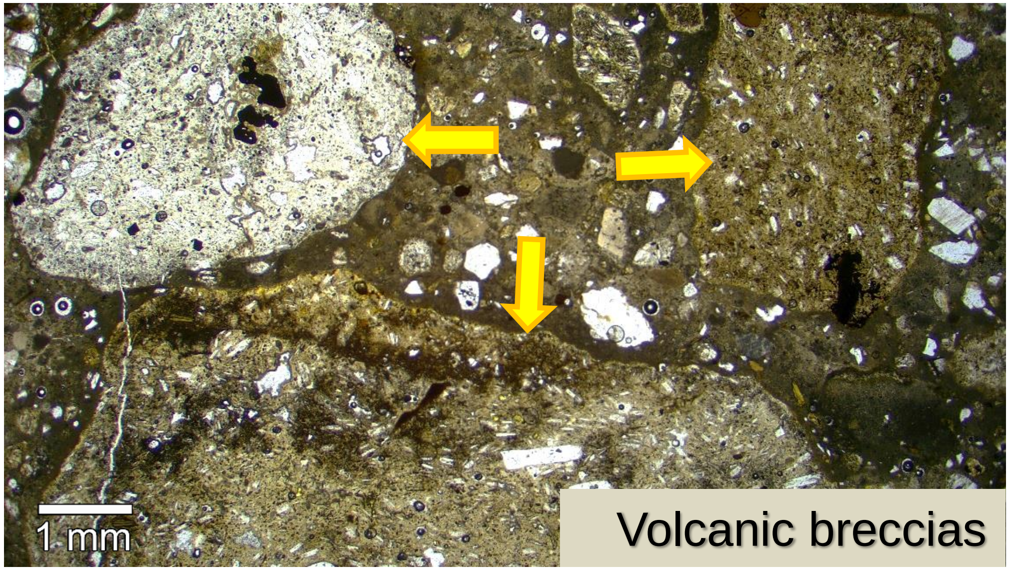


Optical microscopy









Geochemistry of volcanic rocks

- **Geochemistry** is the science that uses the tools and principles of chemistry to explain the mechanisms behind major geological systems such as the Earth's crust and its oceans.

- In geology, **igneous differentiation, or magmatic differentiation**, is an umbrella term for the various processes by which magmas undergo bulk chemical change during the partial melting process, cooling, emplacement, or eruption. The sequence of magmas produced by igneous differentiation is known as a **magma series**.

- In magmatic differentiation differences in chemical composition are affected by several factors (i.e. Distinct melting events from distinct sources; Crystal fractionation; Mixing of 2 or more magmas; Assimilation/contamination of magmas by crustal rocks

- This results in variation in the concentration of chemical **mayor elements** (in particular Si), and in the **trace element** concentrations. Trace elements are elements that occur in low concentrations in rocks, usually less than 0.1 % (usually reported in units of parts per million, ppm).

Geochemistry of volcanic rocks

When considering the rocks in the mantle, trace elements can be divided into ***incompatible elements***, those that do not easily fit into the crystal structure of minerals in the mantle, and ***compatible elements***, those that do fit easily into the crystal structure of minerals in the mantle.

- Incompatible elements - these are elements like K, Rb, Cs, Ta, Nb, U, Th, Y, Hf, Zr, and the ***Rare Earth Elements*** (REE)- La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, & Lu. Most have a large ionic radius. Mantle minerals like olivine, pyroxene, spinel, & garnet do not have crystallographic sites for large ions.

- Compatible elements - these are elements like Ni, Cr, Co, V, and Sc, which have smaller ionic radii and fit more easily into crystallographic sites that normally accommodate Mg, and Fe.

When a mantle rock begins to melt, the incompatible elements will be ejected preferentially from the solid and enter the liquid. This is because if these elements are present in minerals in the rock, they will not be in energetically favorable sites in the crystals. As melting proceeds the concentration of these incompatible elements will decrease because (1) there will be less of them to enter the melt, and (2) their concentrations will become more and more diluted as other elements enter the melt.

Geochemistry of volcanic rocks

Periodic Table of Elements and Oxides for Petrologists

Atomic # Symbol Element Atomic Wt.	• Valence state • Ionic radii (nm) for oxygen coordination numbers (e.g. VI) • Pauling % ionic character of bond with oxygen	Average composition of oxide (weight percent) or element (ppm) in various rock types . See caption for sources.	Average composition of oxide (weight percent) or element (ppm) in various reservoirs . See caption for sources	Valence Oxide Formula Formula Wt.

Links to other Periodic Tables
- Royal Society of Chemistry Periodic Table
- IUPAC Periodic Table of the Elements and Isotopes
- The Earth Scientist's Periodic Table of the Elements and Their Ions
- Michael Dayah Dynamic Periodic Table

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H 1.008																	2 He 4.003
3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.18
11 Na 22.990	12 Mg 24.305											13 Al 26.982	14 Si 28.085	15 P 30.974	16 S 32.06	17 Cl 35.45	18 Ar 39.948
19 K 39.098	20 Ca 40.078	21 Sc 44.956	22 Ti 47.987	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.693	29 Cu 63.546	30 Zn 65.38	31 Ga 69.723	32 Ge 72.630	33 As 74.922	34 Se 78.971	35 Br 79.904	36 Kr 83.798
37 Rb 85.468	38 Sr 87.62	39 Y 88.906	40 Zr 91.224	41 Nb 92.906	42 Mo 95.95	43 Tc 98	44 Ru 101.070	45 Rh 102.906	46 Pd 106.42	47 Ag 107.868	48 Cd 112.414	49 In 114.818	50 Sn 118.710	51 Sb 121.760	52 Te 127.60	53 I 126.904	54 Xe 131.293
55 Cs 132.905	56 Ba 137.327	57-71	72 Hf 178.49	73 Ta 180.948	74 W 183.84	75 Re 186.207	76 Os 190.23	77 Ir 192.217	78 Pt 195.084	79 Au 196.967	80 Hg 200.592	81 Tl 204.38	82 Pb 207.2	83 Bi 208.980	84 Po 209	85 At 210	86 Rn 222
87 Fr 223	88 Ra 226	89-103	104 Rf 267	105 Db 268	106 Sg 269	107 Bh 270	108 Hs 269	109 Mt 278	110 Ds 281	111 Rg 280	112 Cn 285	113 Nh 286	114 Fl 289	115 Mc 289	116 Lv 293	117 Ts 294	118 Og 294

57 La 138.905	58 Ce 140. 116	59 Pr 140.908	60 Nd 144.242	61 Pm 145	62 Sm 150.36	63 Eu 151.964	64 Gd 157.25	65 Tb 158.925	66 Dy 162.500	67 Ho 164.930	68 Er 167.259	69 Tm 168.934	70 Yb 173.045	71 Lu 174.967
89 Ac 227	90 Th 232.038	91 Pa 231.036	92 U 238.029	93 Np 237	94 Pu 244	95 Am 243	96 Cm 247	97 Bk 247	98 Cf 251	99 Es 252	100 Fm 257	101 Md 258	102 No 259	103 Lr 262

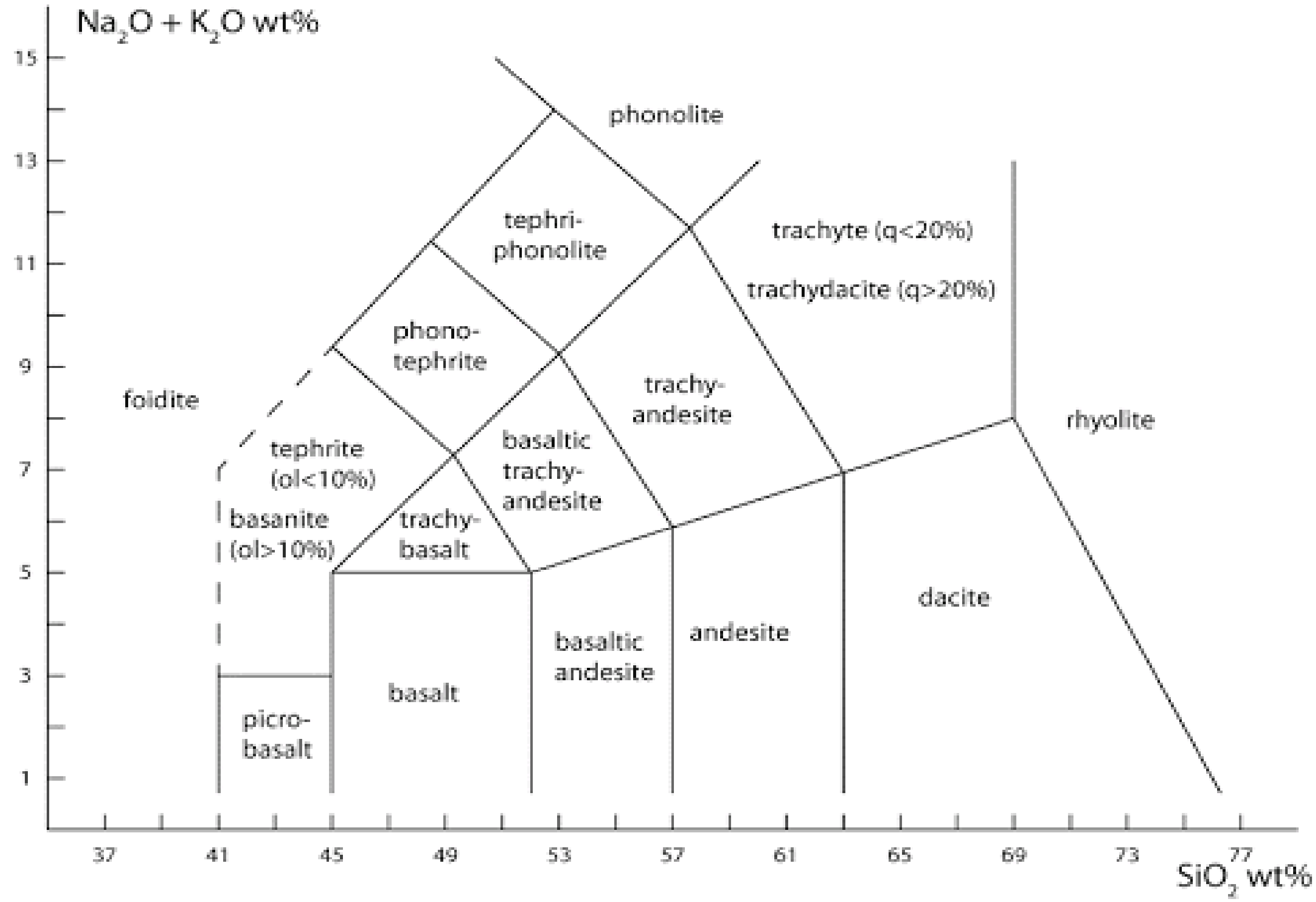
MORB Values
- 0.1-100 wt%
- 10-1000 ppm
- 0.1-10 ppm
- < 0.1 ppm
- n.a.

Abundance of the elements in various average volcanic rocks is shown as weight percent (wt.%=g per 100 g of rock) of the oxide for SiO2, TiO2, Al2O3, FeO, MnO, MgO, CaO, Na2O, K2O, P2O5 or as parts per million (ppm=micrograms per g) for all other elements.

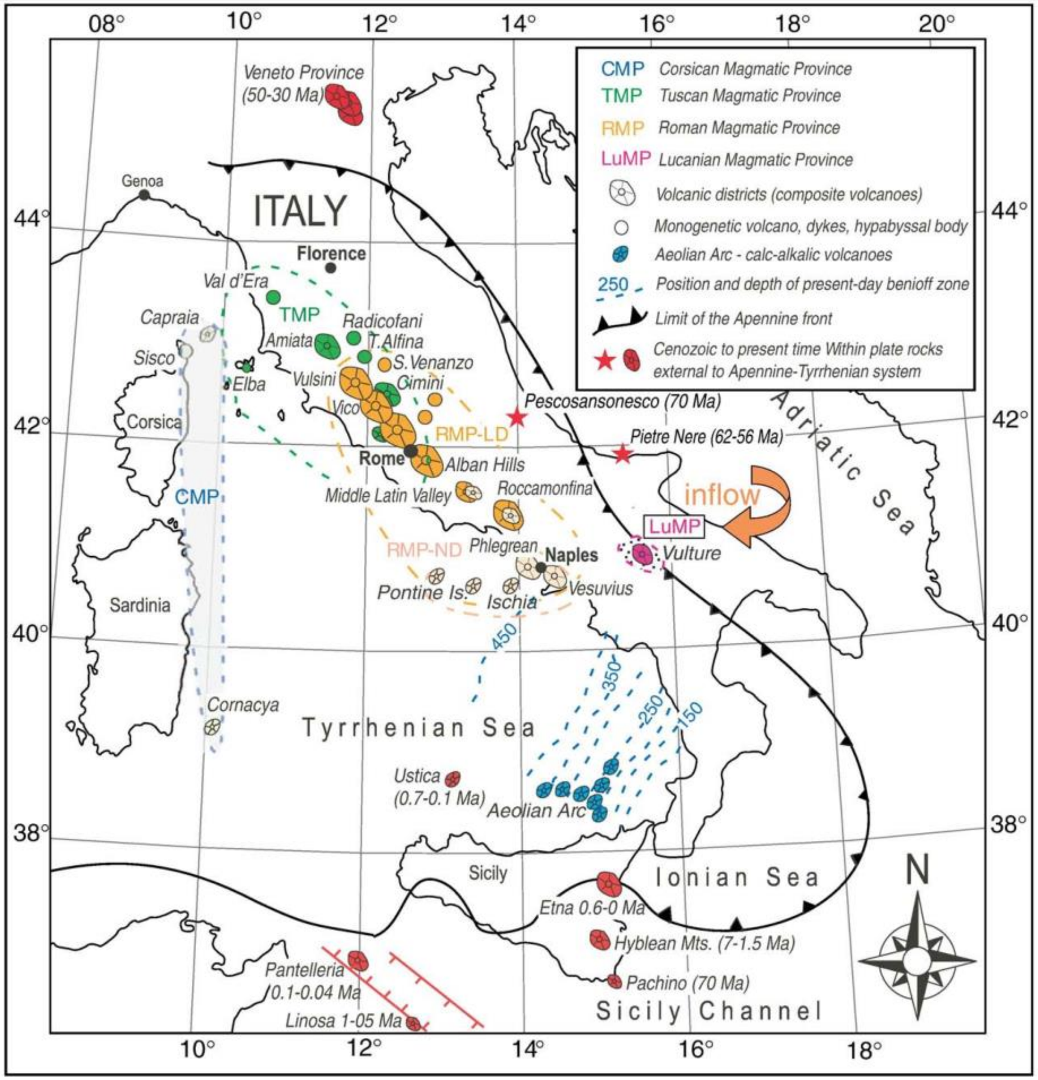
Geochemistry of volcanic rocks

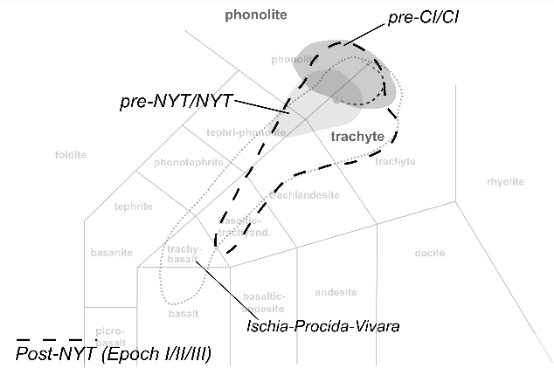
TAS - Total Alkalis vs. Silica Variation Diagram. The TAS Diagram for volcanic rocks is used to classify igneous rocks using whole rock chemical data as adopted by the International Union of Geological Sciences (IUGS).

The variation diagram scatter plot of weight percent Na2O + K2O vs. weight percent SiO2 is divided into regions based on the whole rock chemistry of rocks with petrographicallydefined names (see the QAPF diagram). The TAS diagram enables classification of glassy (i.e. volcanic pozzolans) and other volcanic rocks without, or in support to, petrographic data.

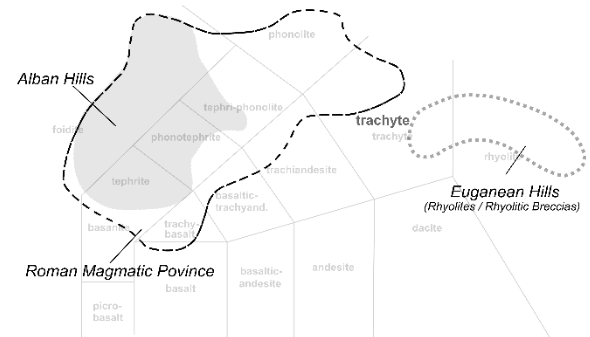


Geochemistry of volcanic rocks

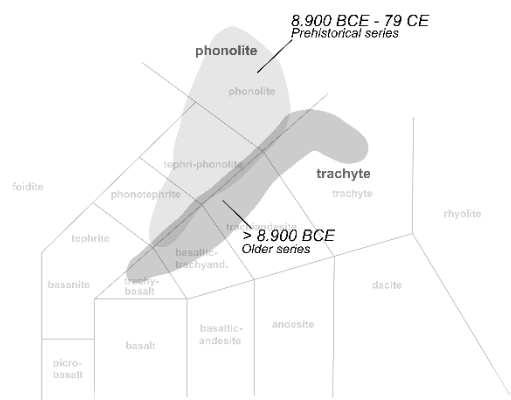




Phlegraean Fields (main eruptive events)



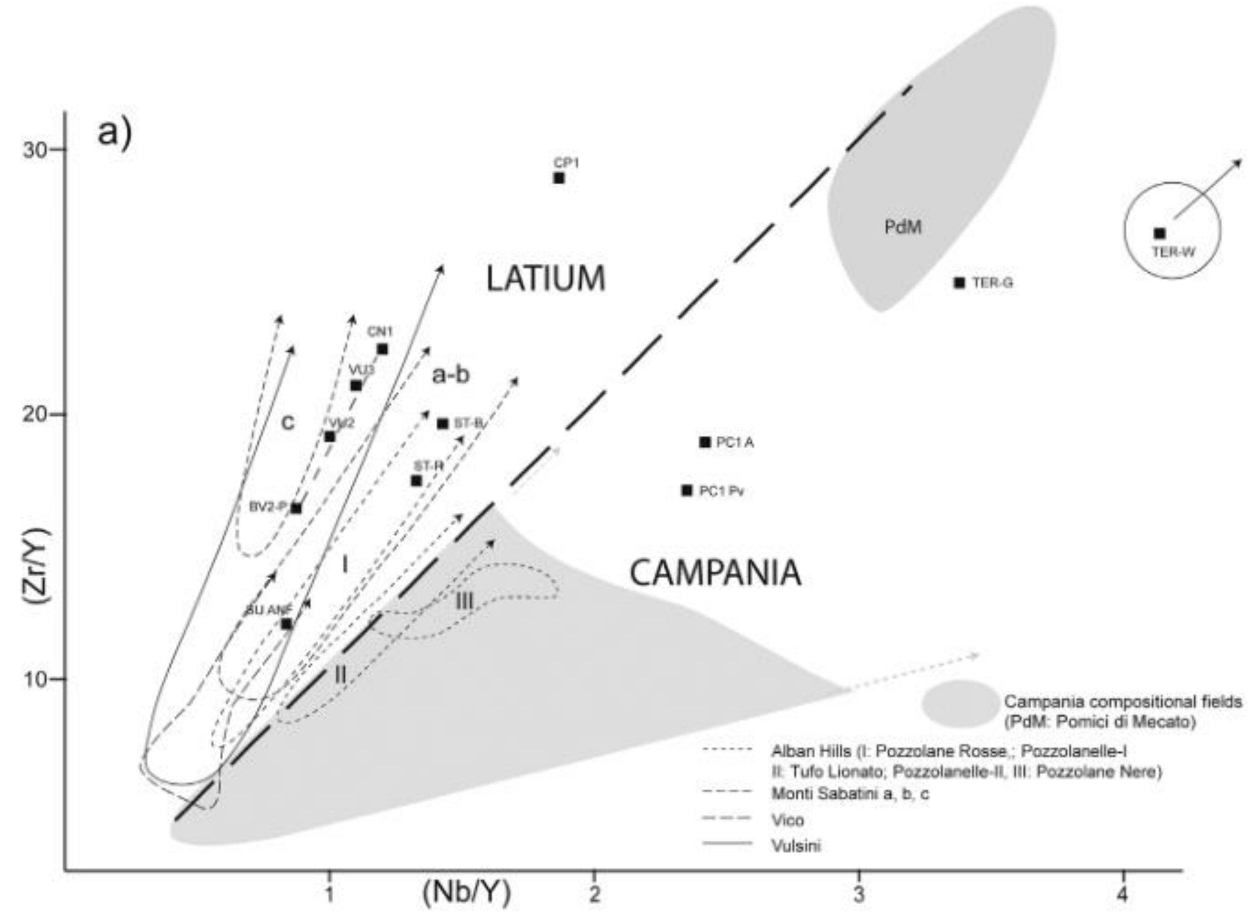
Latial and Euganean District



Somma Vesuvius (main eruptive events)

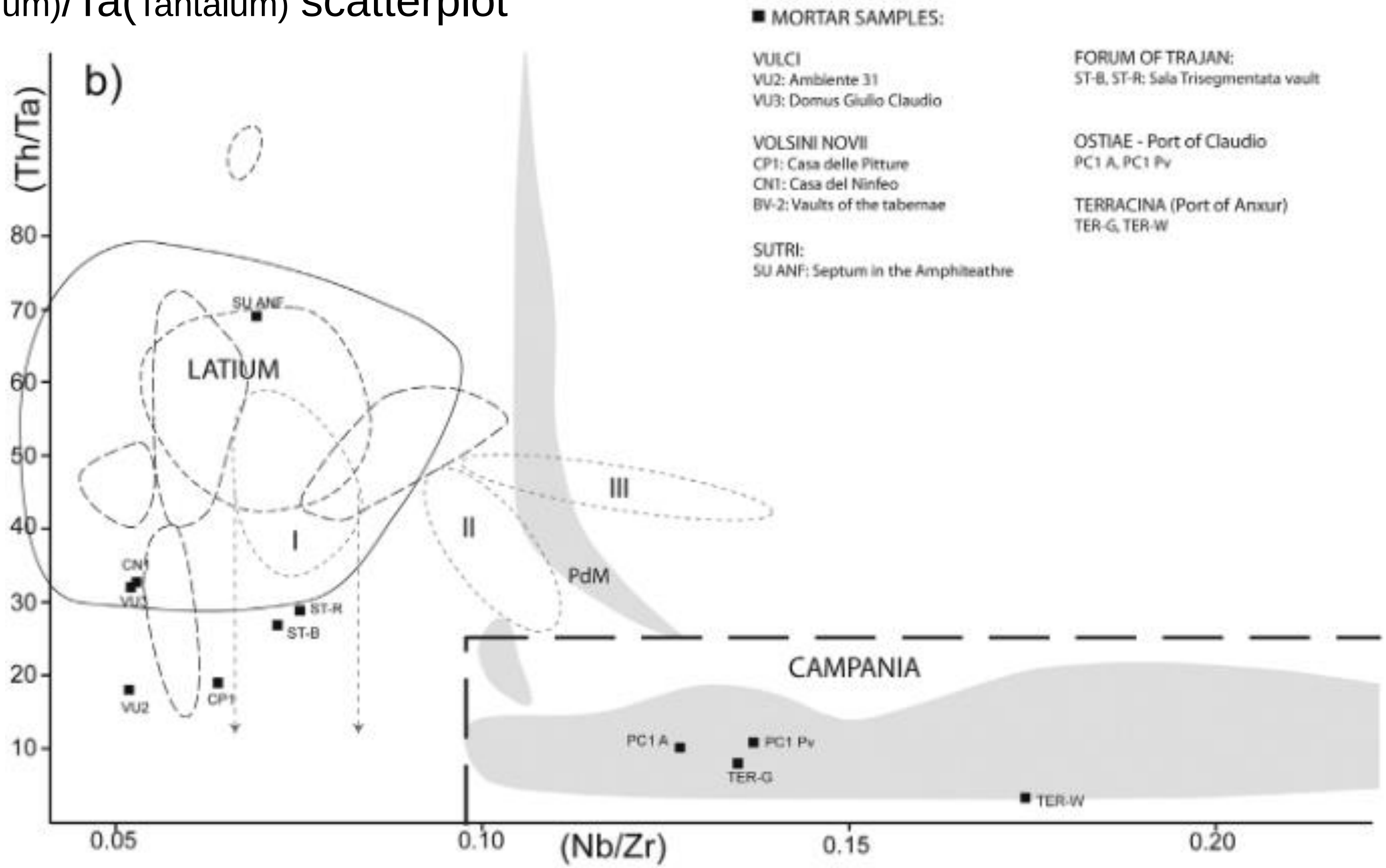
Geochemistry of volcanic rocks

The analysis of discriminant trace elements (or sometimes of ratio among discriminant trace elements) can help in the discrimination of volcanic domains. i.e. in this case, to distinguish Latian from Campania magmatic districs, based on the concentrations of Nb(Niobium)/Y(Yttrium) vs Zr(Zirconium)/Y(Yttrium)



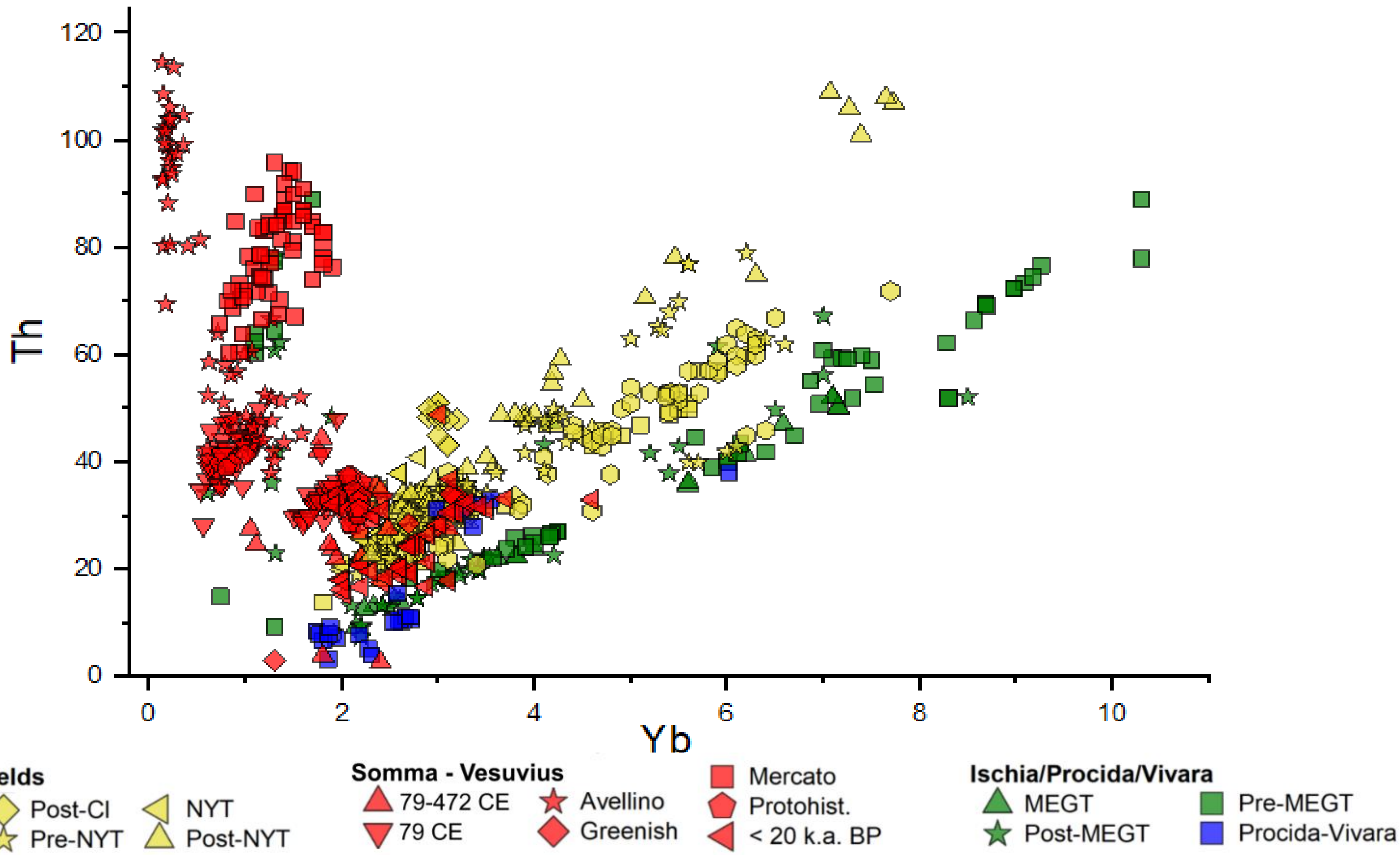
Analytical techniques

Discriminant diagrams can report multiple traces (or ratios among traces) useful for discrimination, in this case a further discriminant diagram for distinguiscing Campanian Volcanoes from Latial ones is the Nb (*Niobium*)/Zr(*Zirconium*) vs Th (Thorium)/Ta(Tantalum) scatterplot



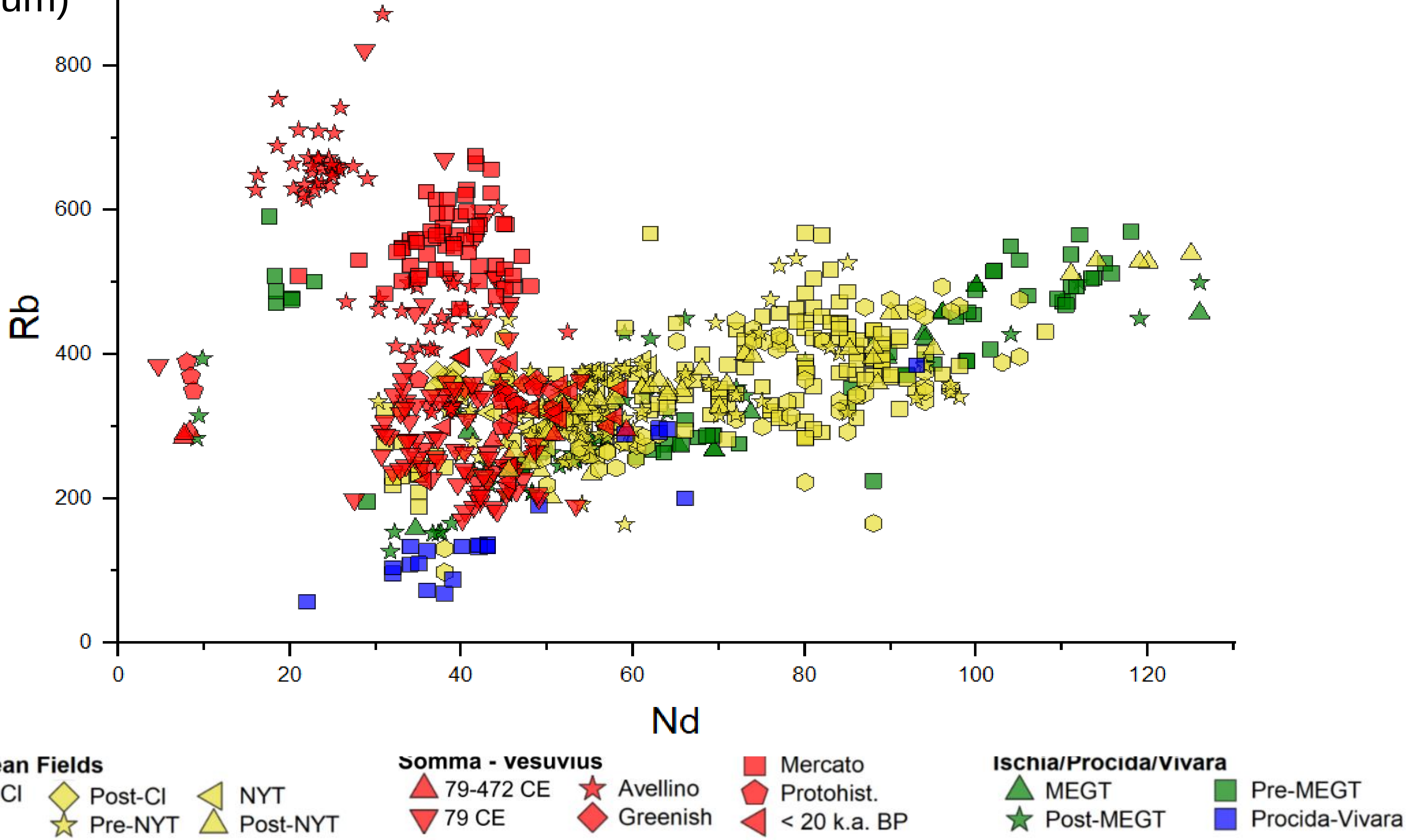
Geochemistry of volcanic rocks

Based on around 950 geochemical fingerprint of pyroclastic rocks from magmatic units of the Gulf of Naples → in-detail intra-regional provenance Yb(Ytterbium) vs Th (Thorium) scatterplot



Geochemistry of volcanic rocks

Based on around 950 geochemical fingerprint of pyroclastic rocks from magmatic units of the Gulf of Naples → in-detail intra-regional provenance definition (Neodimium Vs Rubidium)



Geochemistry of volcanic rocks

Eruptive event	unit	sample	type	Zr	Nb	Th	Rb	Sr	Y	Ba	La	Ce	Nd	U	Zn	Pr	Sm	Eu	Gd	Dy	Er	Yb	Lu	Ta	V	reference
Post-NYT	fondo riccio	CF-FR-C2	bomb	229.2	33.2	22.8	309.6	919.8	33.4	1712.1	63.7	123.8	56.8	6.1	73	13.74	10.5	2.5	7.78	5.97	2.95	2.6	0.42	1.8	209	Cannatelli et al 2007
Post-NYT	fondo riccio	CF-FR-C1	scoria	233.2	35	22.1	274.8	903	32.5	1719.2	64.1	123.6	53.9	6.8	62	13.4	10.1	2.37	7.66	5.89	2.89	2.5	0.41	1.8	193	Cannatelli et al 2007
Post-NYT	Minopoli	CF-MI1-C1	scoria	182	26.7	18.1	238.5	946	28.7	1715.2	56	109.7	49.2	5.2	44	12.37	9.7	2.24	6.99	5.47	2.68	2.4	0.36	1.4	208	Cannatelli et al 2007
Post-NYT	Minopoli	CF-MI1-C2	scoria	267.9	42.1	29.7	305.1	724.7	32.1	1048.9	74.3	139.6	57	9	9	14.82	9.9	2.27	7.14	5.65	2.95	2.7	0.41	2.3	110	Cannatelli et al 2007
Post-NYT	Fondi di Baia		tephra	794.0	108.0	75.0	408.0	25.0	61.0	3.0	148.0	247.0	95.0	21.0		27.0	16.4	1.7	13.4	10.6	6.2	6.3	0.9	5.7		Smith et al 2011
Post-NYT	P.S. Nicola		tephra	504.0	66.0	46.0	328.0	331.0	41.0	221.0	103.0	171.0	70.0	12.1		20.0	12.7	2.0	10.4	7.5	4.3	4.6	0.7	3.6		Smith et al 2011
Post-NYT	Pisani 1		tephra	280.0	37.0	25.0	257.0	935.0	34.0	1625.0	68.0	122.0	55.0	7.8		15.0	10.9	2.2	9.0	6.8	3.4	3.2	0.5	2.1		Smith et al 2011
Post-NYT	Pisani 2		tephra	256.0	36.0	21.0	249.0	1007.0	30.0	1517.0	60.0	106.0	47.0	6.3		13.0	9.4	1.9	7.6	5.6	2.8	2.8	0.4	1.9		Smith et al 2011
Post-NYT	Pomici Principali		tephra	312.0	45.0	30.0	308.0	919.0	31.0	1779.0	72.0	124.0	52.0	9.1		15.0	9.9	2.1	8.1	6.0	2.8	2.9	0.4	2.3		Smith et al 2011
Post-NYT	S. Martino	CFA81a		465.0	54.0		309.0	437.0	22.0	326.0	76.0	165.0														Civetta et al 1991

Geochemical techniques

Main techniques used to determine the geochemical profile of volcanic rocks

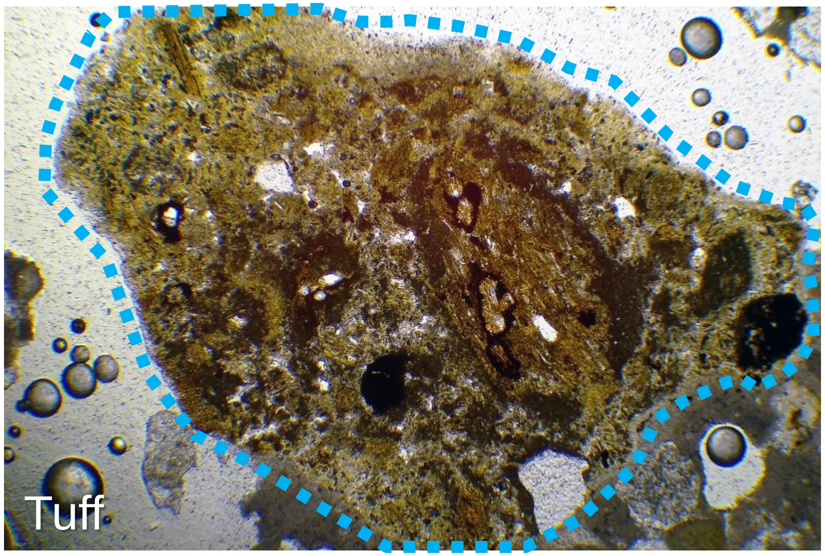
- **SEM-EDS** (Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy): semi-quantitative major chemical element profiling (expeditious but not resolving for provenance determination)
- **XRF** (X-ray fluorescence): exact quantification in terms of percentages of major and trace chemical elements, useful for provenance determination but need enough sample quantity (at least 2 grams)
- **LA-ICP-MS** (laser ablation-inductively coupled plasma-mass spectrometry): extremely useful for very high precision quantification of major and trace chemical elements in volcanic rocks. <u>It can be done punctually to map even extremely minute areals of material, even on individual minerals.</u>

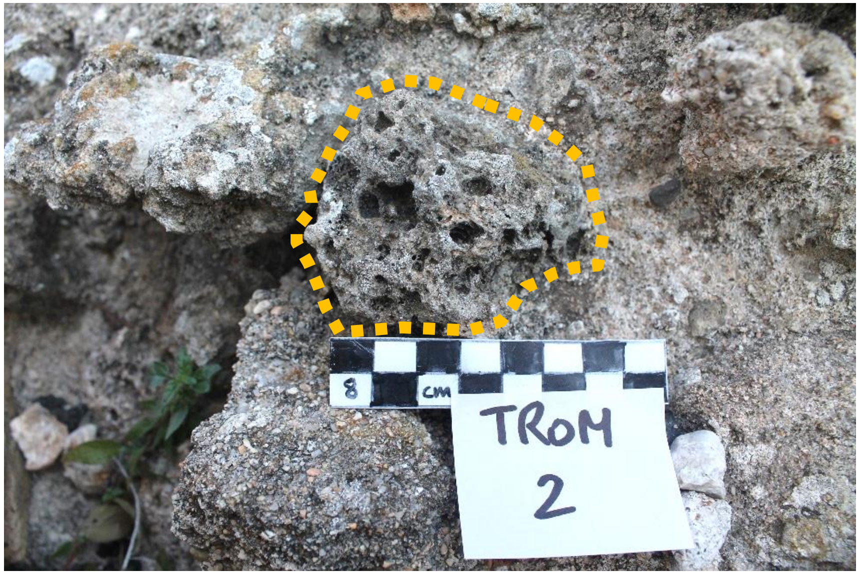
Case Studies

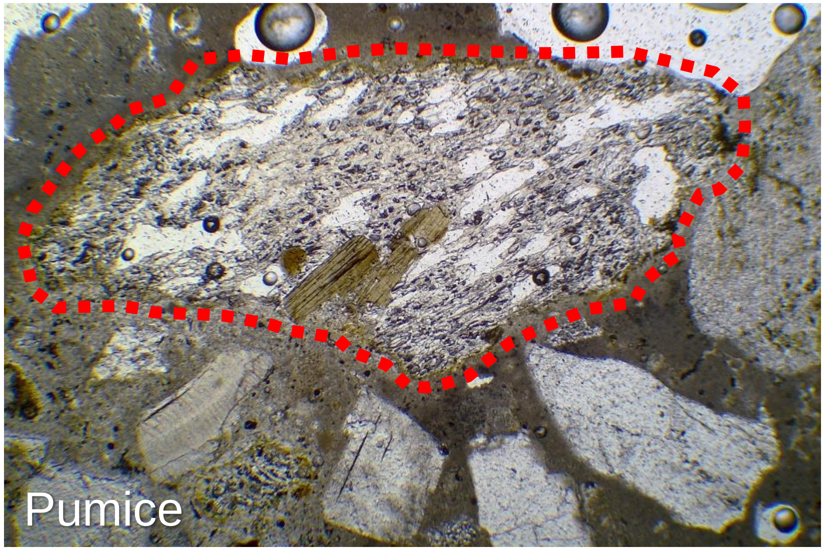
The Punic-Roman town of Nora (Sardinia)

- Established by Phoenicians in the 8th c. BC become a Punic settlement during the 5th c. BC;
- After the Roman conquest of Sardinia, in the 3rd c. AD Nora (and Sardinia) was involved in a flourishing period of renovation, with the construction of new temples, baths and an aqueduct;
- The University of Padova (DBC) has ongoing excavation activities since 1990 (urban infrastructures, necropolis, private and public buildings)

Roman Temple (3rd c. AD)





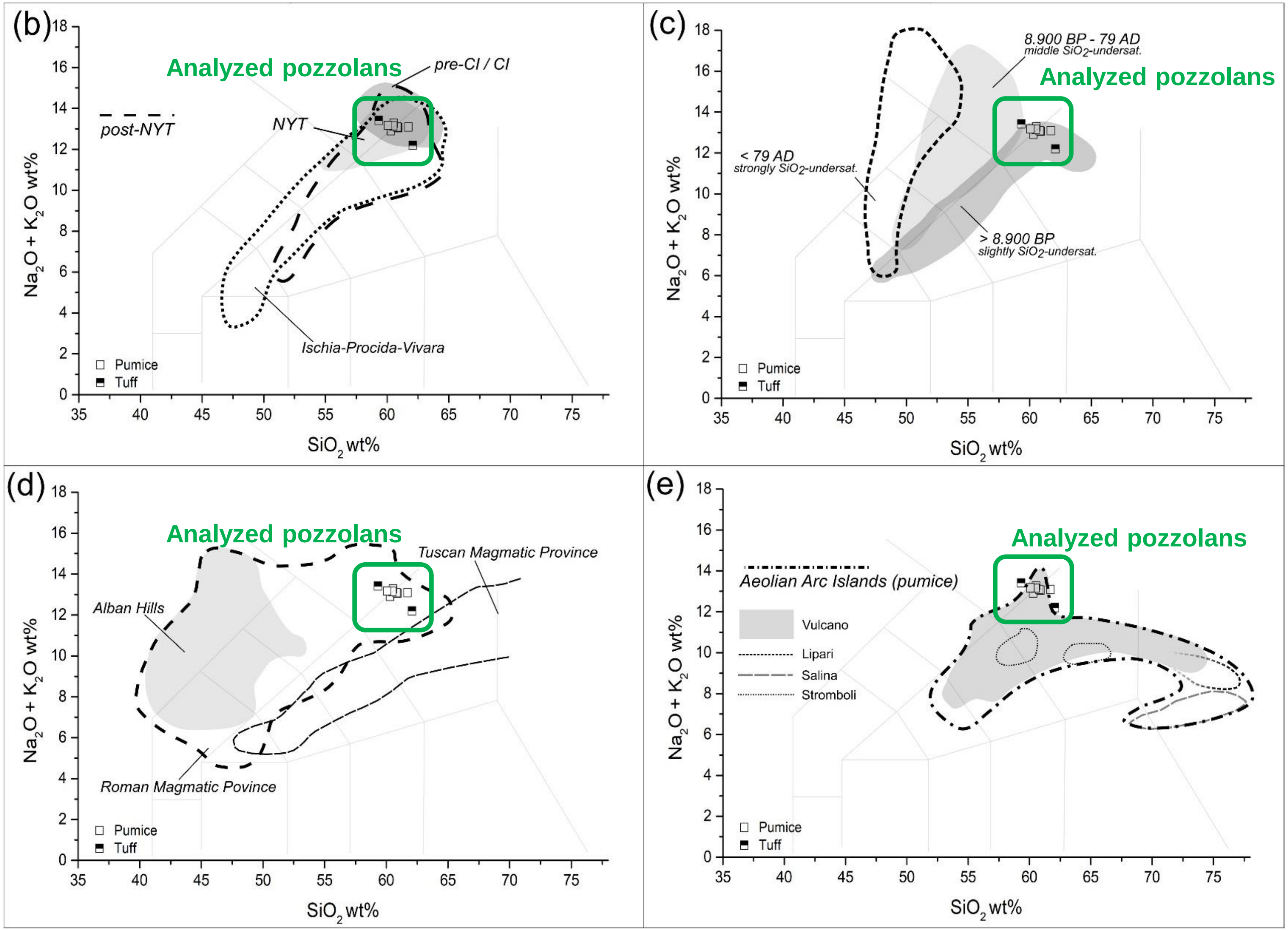


Roman Temple (3rd c. AD)

Analytical method: XRF (coarse clasts, more than 2 grams of material from each sample available for analysis)

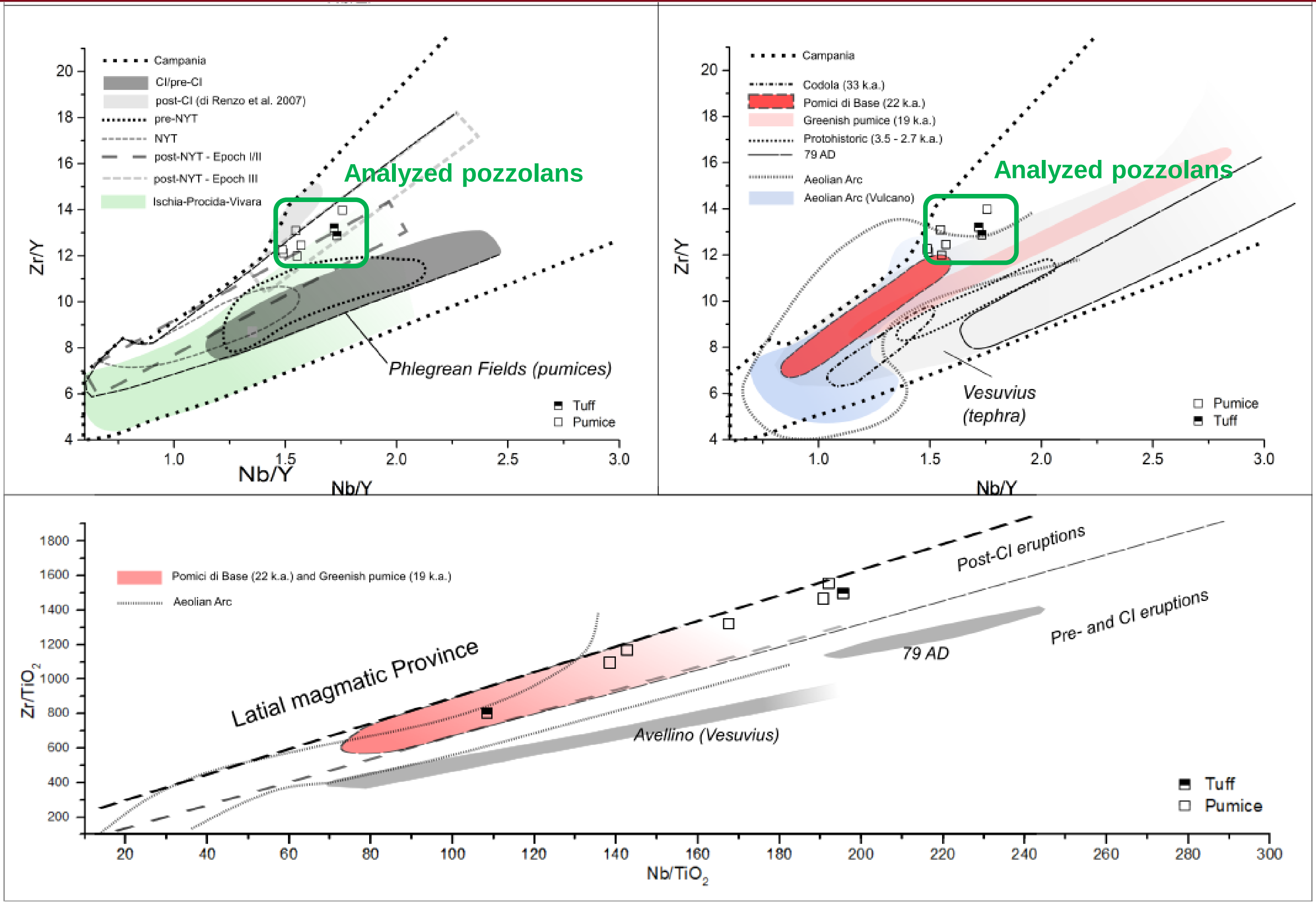
	T.ROM_1	T.ROM_2	T.ROM_3	T.ROM_4	T.ROM_5	T.ROM_6	T.ROM_7	T.ROM_11	T.ROM_20
%Ox	tuff	pumice	pumice	pumice	pumice	pumice	pumice	pumice	tuff
SiO_2	59.31	60.29	60.89	60.82	60.53	61.71	60.5	60.07	62.07
TiO_2	0.48	0.47	0.49	0.53	0.46	0.44	0.47	0.45	0.44
Al_2O_3	18.29	18.55	18.45	18.30	18.38	18.26	18.89	18.41	17.75
Fe_2O_3	3.88	3.67	3.51	3.59	3.44	3.18	3.71	3.47	3.17
MnO	0.15	0.15	0.17	0.17	0.15	0.18	0.13	0.14	0.16
MgO	1.27	0.39	0.14	0.24	0.33	0.09	0.29	0.27	0.92
CaO	1.94	2.61	2.17	2.88	2.41	1.99	2.55	2.67	2.97
Na_2O	4.11	4.91	5.42	5.68	5.26	5.94	4.63	4.94	2.95
K_2O	9.30	8.00	7.63	7.41	8.01	7.15	8.52	8.23	9.25
P_2O_5	0.27	0.08	0.05	0.05	0.07	0.03	0.09	0.07	0.08
Tot	99.00	99.12	98.92	99.67	99.04	98.97	99.78	98.72	99.76
L.O.I.	14.97	4.96	3.55	3.76	3.48	2.34	3.38	3.27	11.71
ppm									
S	169	137	38	126	76	63	56	95	145
Sc	3	<3	3	13	11	<3	3	<3	3
V	62	50	26	32	38	18	49	45	38
Cr	6	<6	4	<6	7	<6	5	<6	12
Co	3	9	<3	6	6	<3	<3	6	<3
Ni	5	<3	<3	<3	<3	<3	<3	<3	<3
Cu	33	9	17	217	143	24	24	31	10
Zn	103	102	100	106	126	109	89	411	81
Ga	12	18	13	14	14	17	10	12	13
Rb	362	390	436	440	411	478	381	392	366
Sr	223	203	127	81	110	45	278	152	196
Y	30	45	63	65	49	73	37	43	50
Zr	386	550	763	779	610	956	517	528	660
Nb	52	67	94	101	77	113	65	64	86
Ba	766	104	122	35	46	21	182	73	231
La	81	102	122	132	108	161	97	93	118
Ce	161	204	252	267	220	323	196	193	238
Nd	60	73	103	105	82	110	72	71	87
Pb	75	71	62	62	55	50	62	53	49
Th	43	49	72	74	56	89	50	52	67
U	8	16	22	20	18	26	14	15	16

Roman Temple (3rd c. AD)



Analytical method: XRF (coarse clasts, more than 2 grams of material from each sample available for analysis)

Roman Temple (3rd c. AD)

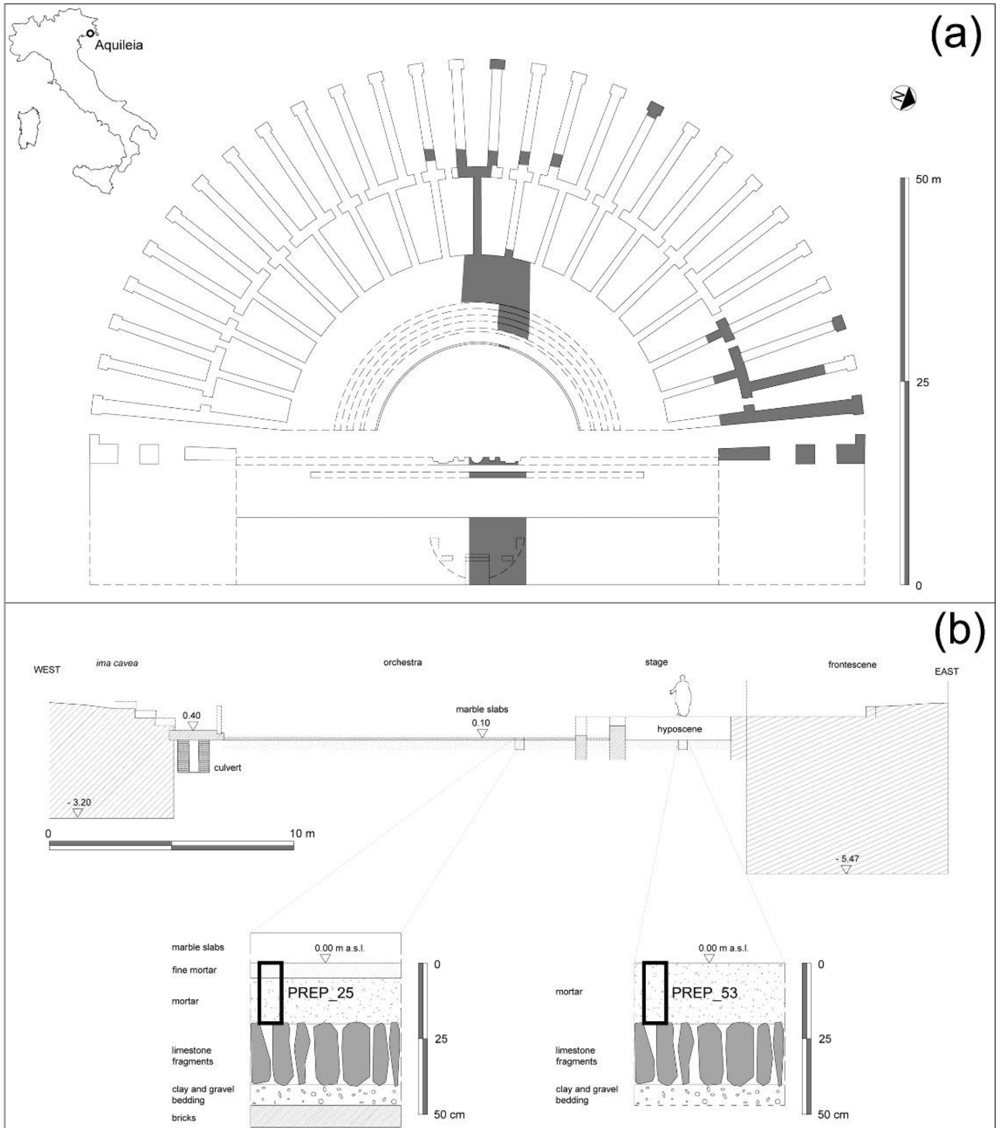


Full compatibility with pyroclastic products of the Gulf of Naples, in particular with the late eruptions of Phlegraean Fields (post-NYT, along the coastline of the Gulf of Naples)

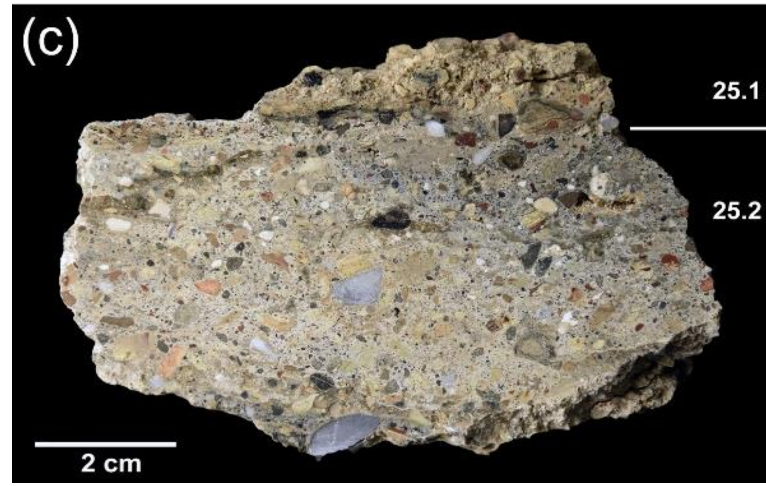
Aquileia (Friuli Venezia Giulia)

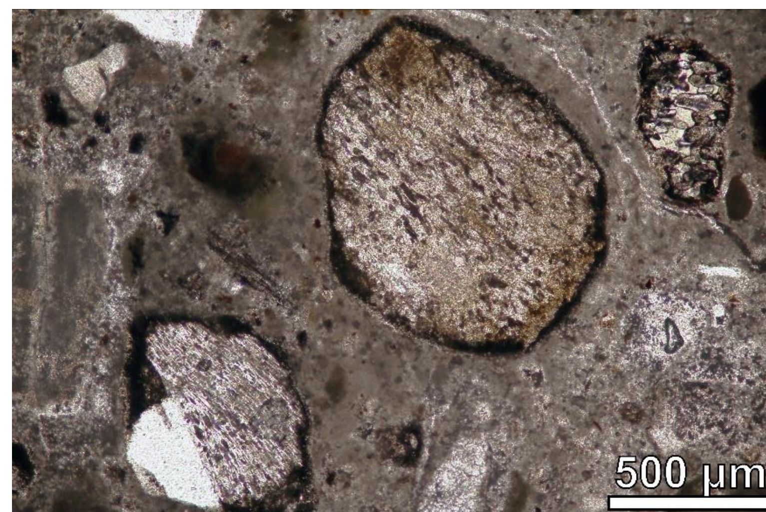
- Established as *colonia latina* in 181 bC
- During the Imperial age was enriched by construction of theatre, amphitheater, circus
- In 4th-c. AD was celebrated as one of the most prestigious centers in Roman world
- In 5th-c AD falled against Attila invasion
- Reconquered by Byzantium in 6th-c. AD
- Progressively abandoned since the 7th-c. AD

Aquileia – Theatre (beginning 1st c AD)

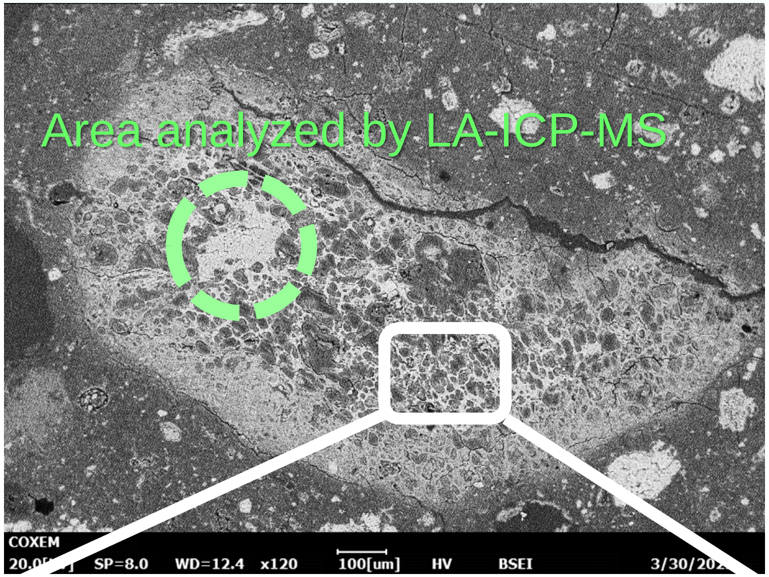


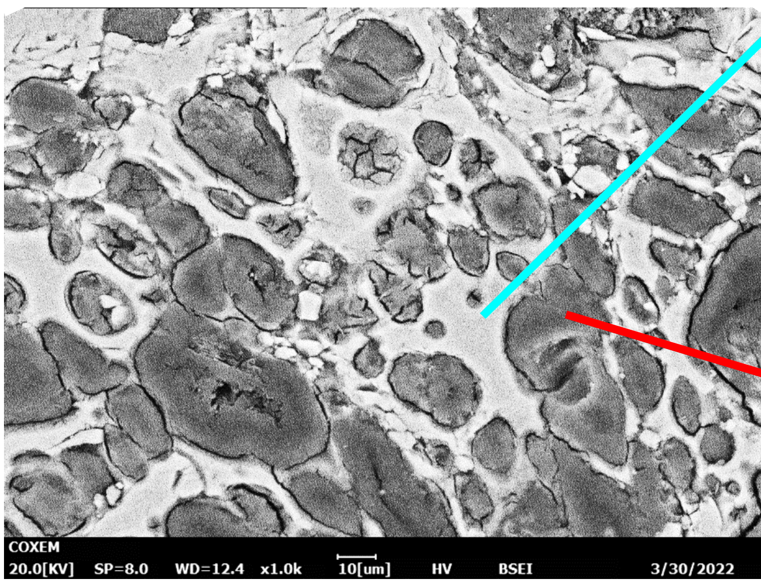
Currently under excavation by the Department of Cultural Heritage of the University of Padova

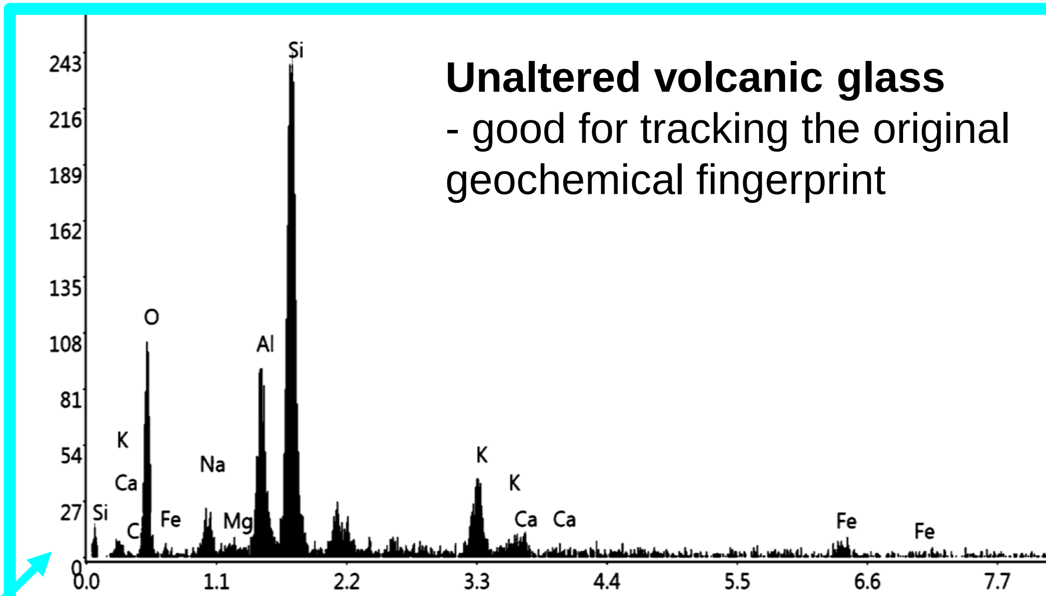




Aquileia – Theatre (beginning 1st c AD)

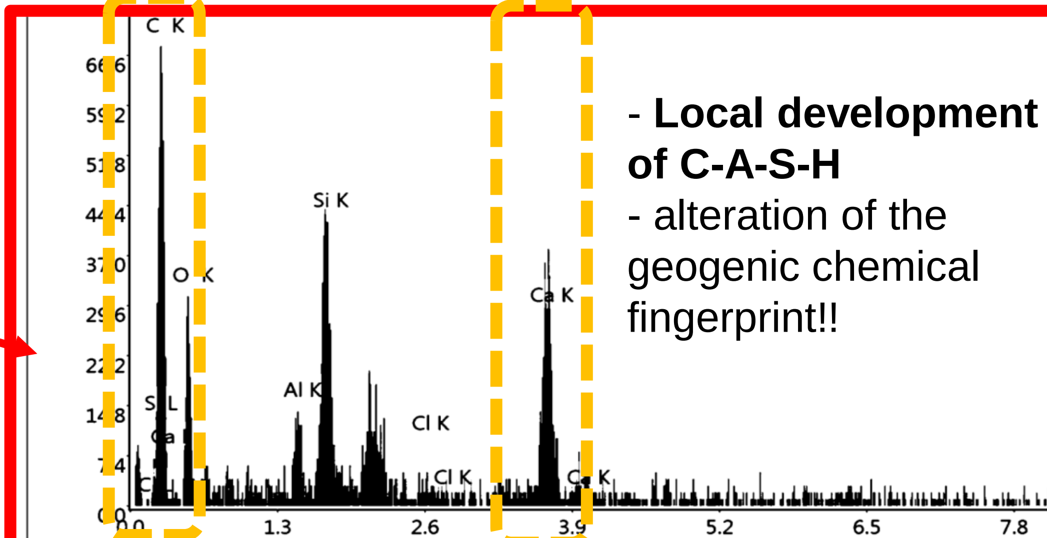






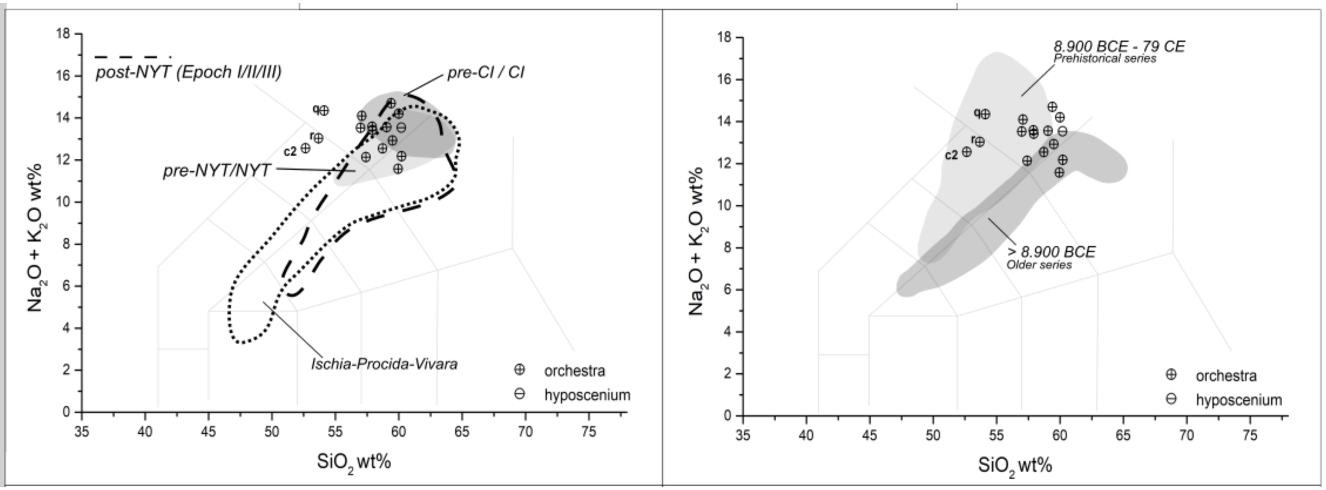
Unaltered volcanic glass

- good for tracking the original geochemical fingerprint

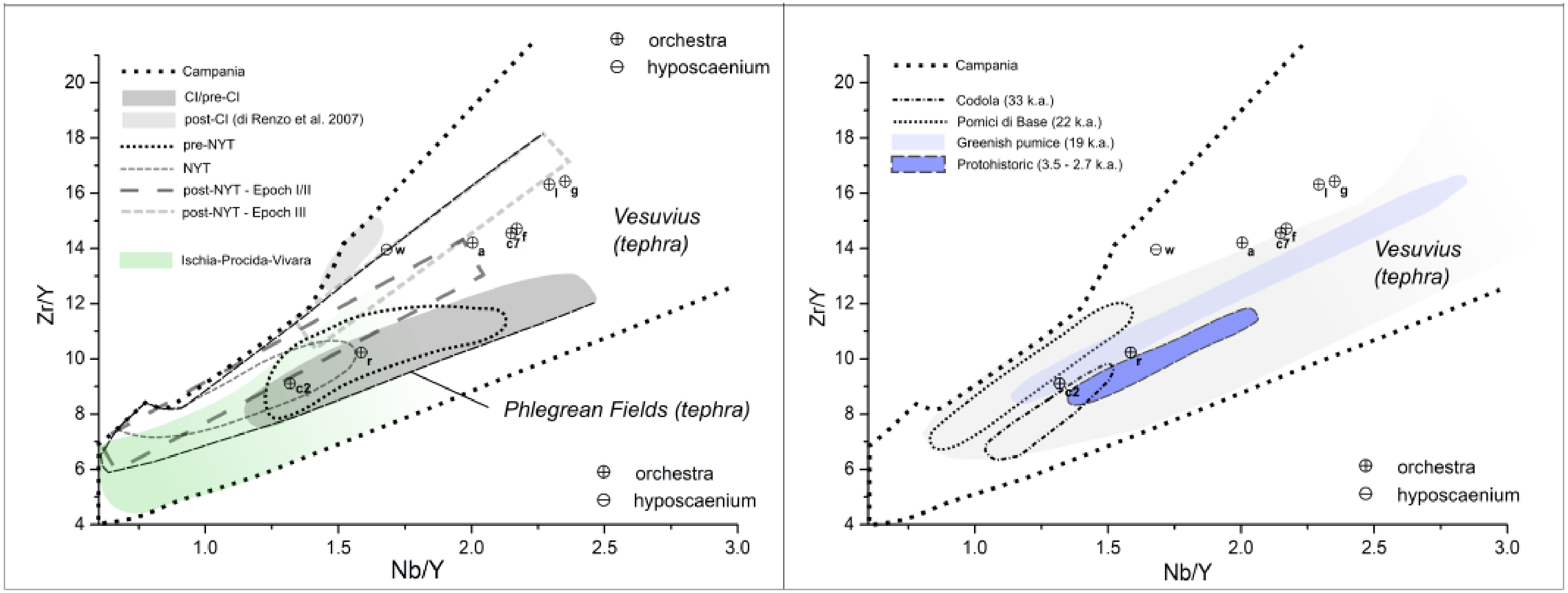


- **Local development of C-A-S-H**
- alteration of the geogenic chemical fingerprint!!

Aquileia – Theatre (beginning 1st c AD)



Analytical method:
SEM-EDS (mayor elements)



Analytical method (trace elements): LA-ICP-MS

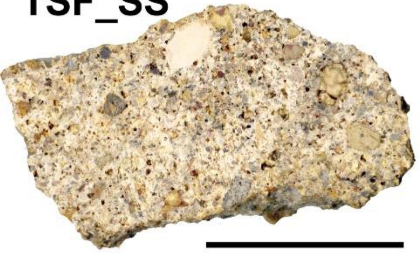
Lagoon of Venice – TSF (1st c AD)

Roman water-tank (weel cistern type) buried in underwater environment in the lagoon of Venice, dated to the Roman Imperial Age (1st – 2nd c. CE)

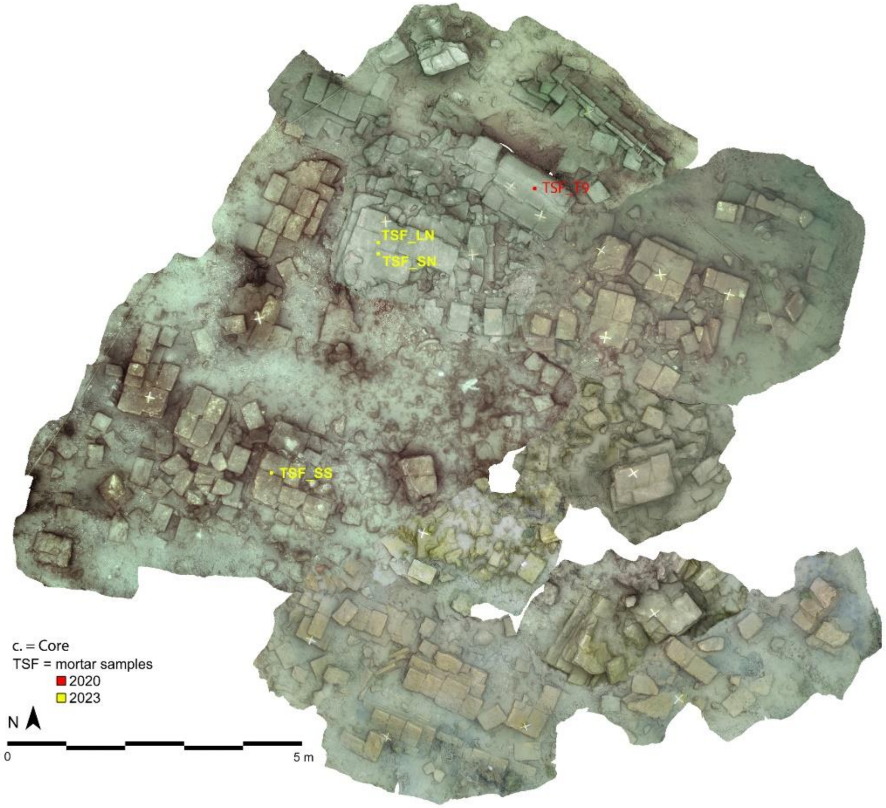
TSF_LN

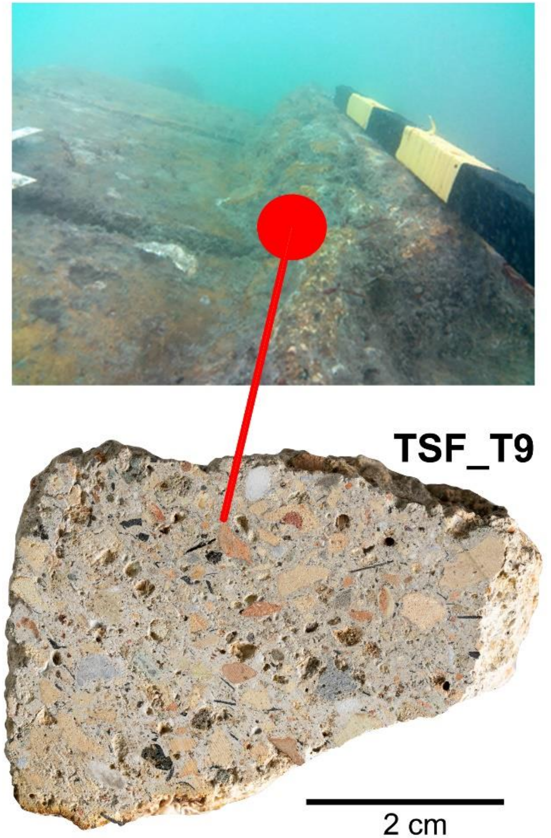
TSF_SN

TSF_SS



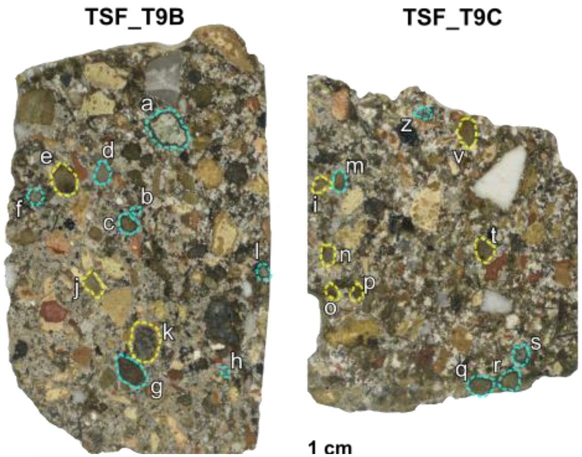
2 cm

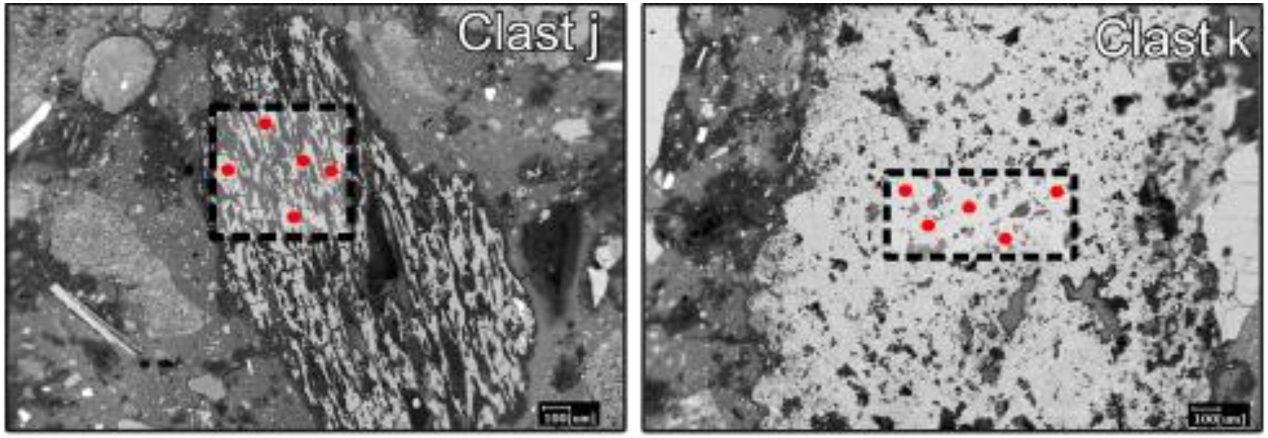


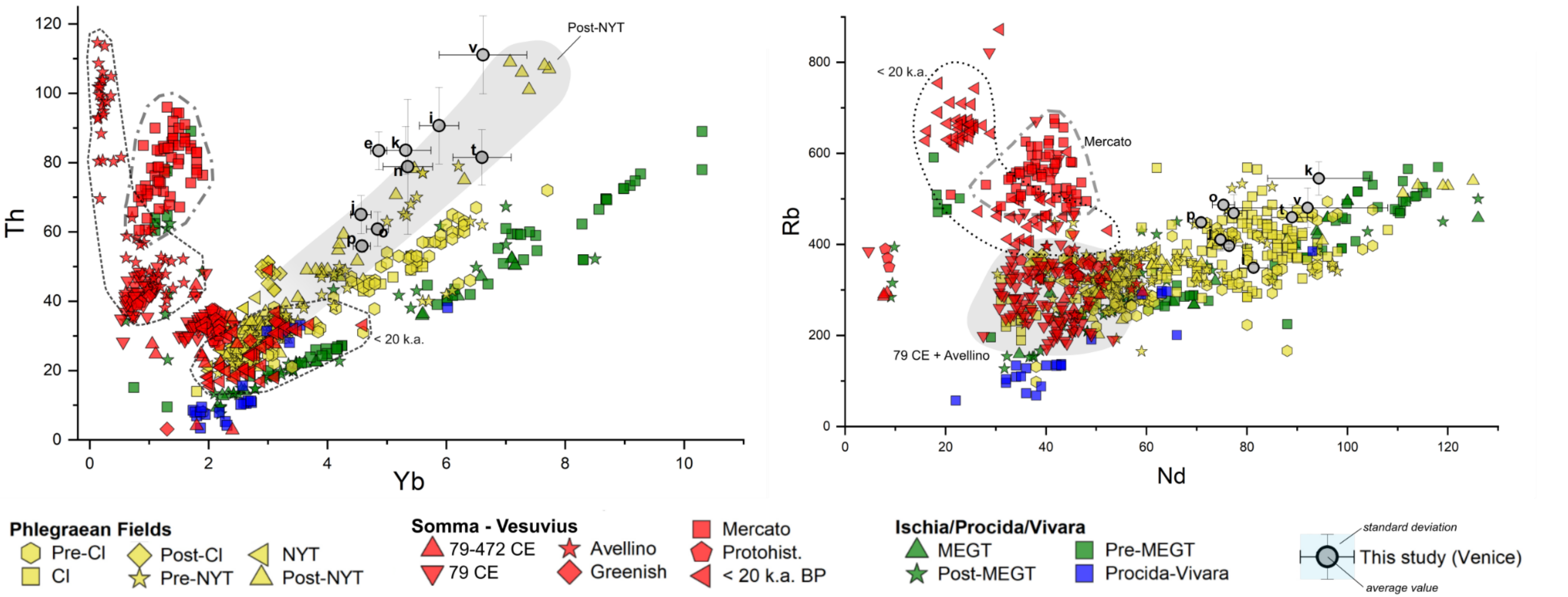


2 cm

Lagoon of Venice – TSF (1st c AD)







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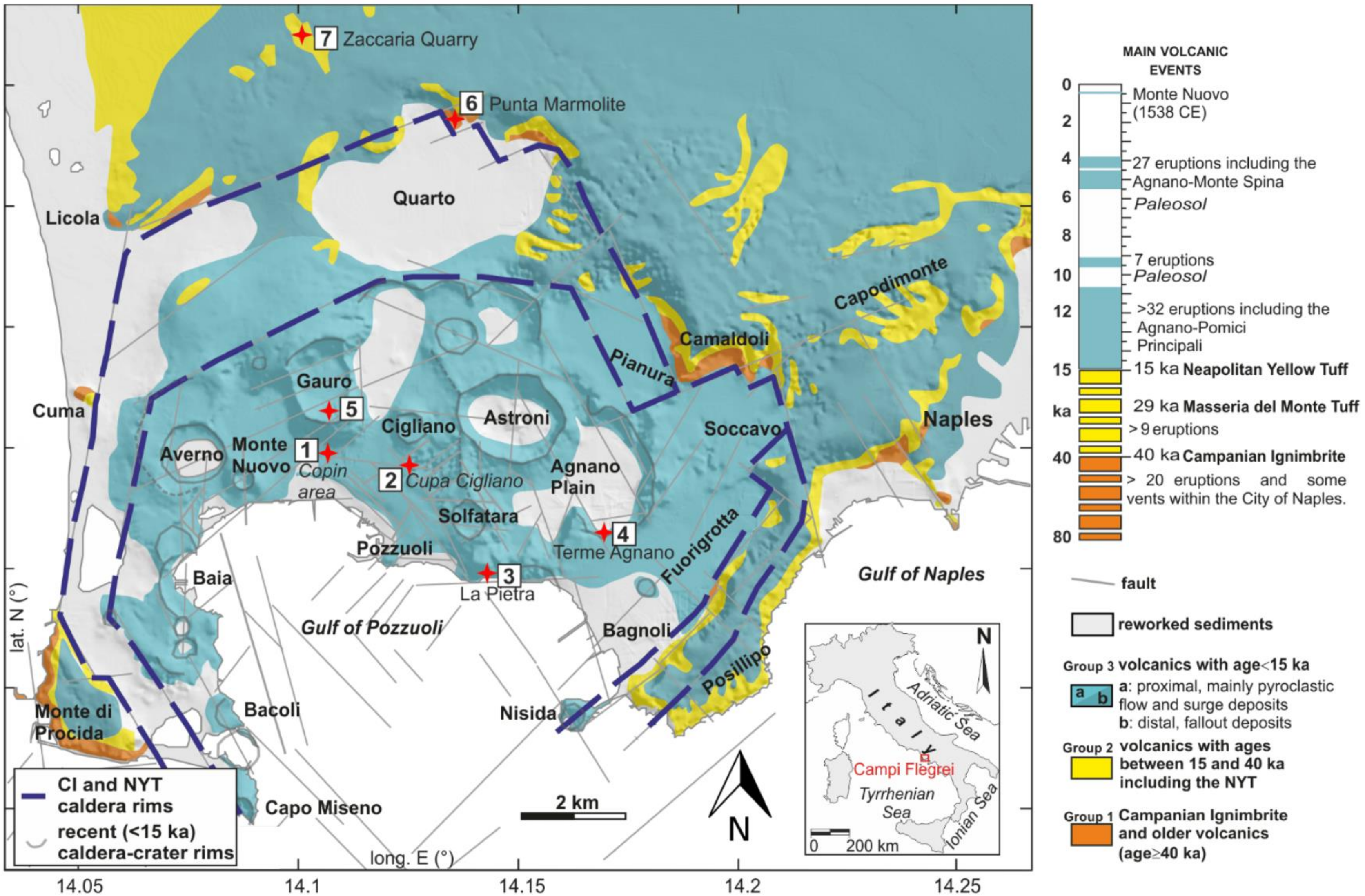
Conclusive remarks



Conclusive remarks

- These **provenance studies** are extremely helpful in tracking the trading of materials, in this case particular building materials, in antiquity.

- Obviously, this is only the first step: the archaeometrical analysis makes it possible to verify the provenance in many cases (or to narrow the field of possible provenances) of pozzolanic material, but from this point it is important to con**textualize the data in relation to a precise historical, historical-economic, historical-cultural framework**: **this is the archeological component, which must explain and motivate certain commercial choices**, with dynamics of shifting workers, technological choices required by clients

→ Transition to the realm of pure archeology.

Bibliographic references

Use of volcanic pozzolans in antiquity

- Lancaster L.C. 2021, Mortars and plasters - How mortars were made. The literary sources, in Mortars, plasters and pigments 2021, 192.
- Lancaster L.C. 2019, Pozzolans in Mortar in the Roman Empire: An Overview and Thoughts on Future Work, in I.F. Ortega, S. Bouffier (dir.), Mortiers et hydraulique en Méditerranée antique, Archéologies Médi-terranéennes 6, Aix-en-Provence, 31-39.
- Dilaria S., Secco M. 2022, Mortar recipes through the ages. A brief review of data from Prehistory to Late Antiquity, Archaeology and Science, 18, 133-126.

Geochemistry of Plio-Quaternary Vulcanism in italy

- Peccerillo A. 2005, Plio-Quaternary Volcanism in Italy: Petrology, Geochemistry, Berlin.

Case studies

- Dilaria S., Previato C., Bonetto J., Secco M., Zara A., De Luca R., Miriello D. 2023, Volcanic pozzolan from the Phlegraean Fields in the structural mortars of the Roman Temple of Nora (Sardinia), Heritage 6, 567–587.

- Dilaria S., Ghiotto A.R., Secco M., Furlan G., Giovanardi T., Zorzi F., Bonetto J. 2023, Early exploitation of Neapolitan pozzolan (*pulvis puteolana*) in the Roman theatre of Aquileia, Northern Italy, Scientific Reports, 13, 4110.

THANK YOU FOR YOUR ATTENTION!

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