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Geochemistry and tectonic setting of the Upper Cretaceous volcanics from Capo San Vito Peninsula (Western Sicily, Italy)

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ABSTRACT

Petrological and geochemical data of the Upper Cretaceous volcanic rocks from Western Sicily are here reported with the aim to provide new information about the African paleomargin magmatic activity before the onset of the Alpine Orogeny. The studied alkaline basalts and basanites/nephelinites crop out as pillow breccias interbedded within the carbonate platform sequence of the Capo San Vito Peninsula. Abundances and ratios of incompatible elements resemble OIB-type volcanics from intraplate environment. They were generated from a low partial melting degree of a mantle source located in the transition zone between garnet- and spinel-lherzolite fields. Comparison with literature data of the coeval Hyblean volcanics show similar geochemical features of a plausible common source for the anorogenic magmas involved in their genesis. The Cretaceous magmatism of the S. Vito Lo Capo Peninsula is the result of magmatic intrusions in response to the extensional tectonic regime of the African plate northern edge.

Keywords: Forgia Valley; pillow breccias; incompatible trace elements; anorogenic volcanism; extensional tectonics; Western Sicily.

INTRODUCTION

Sicily is located at the Eurasia-Africa plate boundary, and suffered of igneous activity in response to the various geodynamic processes from the Late Palaeozoic to the Quaternary. Late Variscan plutonic rocks and dykes intruded the metamorphic rocks of the Peloritani Mountains (*e.g.* Atzori et al., 1989; Rottura et al., 1993; Fiannacca et al., 2005, 2008), whereas Triassic to Early Jurassic volcanics are interbedded within the terrigenous-carbonate sequences belonging to the African paleomargin (*e.g.* Lucido et al., 1978; Patacca et al., 1979; Bellia et al., 1981; Catalano et al., 1984; Grasso and Scribano, 1985; Cirrincione et al., 2014, 2016; Di Bella et al., 2017). Palaeozoic and early Mesozoic rocks emplaced during extensional phases associated to the post-collisional stage of the Variscan Orogeny, and with the rifting and opening of the Neo-Tethys and Alpine Tethys oceans (see Ziegler et al., 1993, 2001; Stampfli and Borel, 2002). Upper Cretaceous alkaline volcanics are found both along the San Vito lo Capo Peninsula and in the Hyblean Plateau, whereas Late Miocene volcanism affected only the Hyblean area. The Plio-Pleistocene products exhibit both orogenic and anorogenic geochemical signatures: within-plate volcanic activity took place over the eastern Sicily (Hyblean Hills and Mt. Etna) and in the Sicily Channel, while along the Aeolian Arc orogenic volcanism developed.

The Upper Cretaceous alkali-basalts occurring in the thick carbonate succession of the Hyblean Plateau

(Eastern Sicily) consist of submarine products with minor dykes and subaerial lavas (Amore et al., 1988; Longaretti and Rocchi, 1990; Rocchi et al., 1998). They are located in the eastern side of the plateau from the town of Augusta to Capo Passero localities, and probably represented an N-S seamounts chain alignment (Carbone et al., 1982). Recent works (*e.g.* Avanzinelli et al., 2012) suggest that Hyblean Upper Cretaceous volcanism occurred in response to the lithospheric stretching produced by extensional deformation. The Upper Cretaceous volcanic bodies outcropping in the San Vito lo Capo area (Western Sicily) are the less studied volcanics of Sicily. Only dated studies by Vianelli (1968) and Bellia et al. (1981) provided some petrographic and geochemical data about these rocks.

To broaden the field of knowledge on the Upper Cretaceous volcanism of the San Vito lo Capo Peninsula magmatism, we provide new petrological and geochemical data of volcanic rocks outcropping along the Forgia Valley.

This paper accounts for the results of a multidisciplinary approach that includes petrographic, mineralogical and geochemical analysis used to constrain origin and tectonic setting of the investigated volcanic rocks. The new data set is also compared with the available literature data of coeval volcanics from the Hyblean Plateau.

GEOLOGICAL SETTING

Western Sicily represents a portion of the African paleomargin affected by the Alpine Orogeny. The Alpine thrust belt outcropping in Sicily is formed by a multilayer pile lying in a duplex geometry and derives from the deformation of three distinct domains: i) the African paleomargin composed of both deep and shallow-water basin sequences; ii) the Alpine Tethys basin, located between the Eurasian and African-Adria plates; iii) the European paleomargin (*e.g.* Lentini et al., 1990 a,b, 1996, 2000, 2006; Lentini and Carbone, 2014).

The volcanic rocks here studied are located in the southwestern area of the Capo San Vito Peninsula. This area is characterized by a succession of Meso-Cenozoic carbonates (some hundreds of meters thick) followed by Miocene terrigenous-carbonate covering levels. A compressive tectonic phase involved these deposits since Late Miocene and drove the development of the thrust system (Finetti et al., 2005; Lentini et al., 2006; Lentini and Carbone, 2014). A great debate has been ongoing about the assignment of the San Vito lo Capo succession. It was alternatively referred to the Panormide units (Broquet and Mascle, 1972; Abate et al., 1991, 1993; Catalano and Di Maggio, 1996; Catalano et al., 1998 a,b; Catalano et al., 2011), to the Trapanese units (Nigro and Renda, 2002), and to the External Thrust System (Lentini et al., 1996; Finetti et al., 2005; Lentini and Carbone, 2014).

The Upper Triassic-Lower Jurassic portion of the Meso-Cenozoic sequence cropping out in the Southern San Vito lo Capo area is formed by carbonate platform strata (from outer ramp to back reef environments) including dololutites, doloarenites, and dolomitic limestones with stromatolitic laminations, followed by coralgal-biolithites, loferitic dolomites and limestones with algae and lamellibranches. The extensional tectonic phase (Dewey et al., 1989; Catalano et al., 2010) occurred during Middle-Late Jurassic led the drowning of the carbonate platform. This event is recorded by the transition from lagoon, tidal to pelagic conditions. The Jurassic sequence consists in reddish limestones, radiolarites and reddish calcilutites with ammonites and beleminites (cfr. Rosso Ammonitico). The restoration of the shallow water setting during the Lower Cretaceous is represented by the deposition of grey oolitic calcarenites alternating with calcirudites and carbonate breccias with fragments of Ellipsactinia, algae, corals and benthic foraminifera. They are followed by carbonate platform sediments composed of rudist and coral-bearing boundstones, calcilutites and biocalcarenites with algae, caprinids, gastropods and hippuritids, which are dated to the Upper Cretaceous. The Paleogene sequence is interpreted as a slope-base deposit and displays calcilutites alternating to marls and marly limestones with intercalations of resedimented calcarenites and calcirudites. The Miocene cover is represented by two different intervals: the former shows biolitites, biocalcarenites and yellow glauconitic biocalcirudites referring to the Burdigalian; the latter is composed of clays and glauconitic brown marls with foraminifera of Middle-Upper Miocene. The San Vito lo Capo succession is unconformably topped by syn- and post-orogenic sediments composed of clays, sands, calcarenites, gravels and conglomerates ranging in age from Upper Miocene to Quaternary.

VOLCANIC OUCROP

The volcanic body studied in this paper is located along the Torrente Forgia Valley between Rocca Rumena and Rocca Presto (Latitude 38°03’54’’N, Longitude 12°39’28’’E; Figure 1). It was firstly reported by Catalano et al. (1984) and Abate et al. (1993). The body is up to three meters thick and it consists in low-medium altered pillow breccias (Figure 2A), formed by stacks of broken pillow fragments and intact pillows (Figure 2B). The volcanic breccia, exposed as a poorly sorted chaotic assemblage, is clast supported, and the single pillow fragments and bulbs contain 1 to 2 mm sized spherical vesicles. Pillow lava fragments show different alteration degrees, and size from ~1 to ~10 cm. They exhibit rectangular, semi-circular, tabular, irregular and pie-like shapes. On the contrary, intact pillows appear as ellipsoidal structures (i.e. sack-

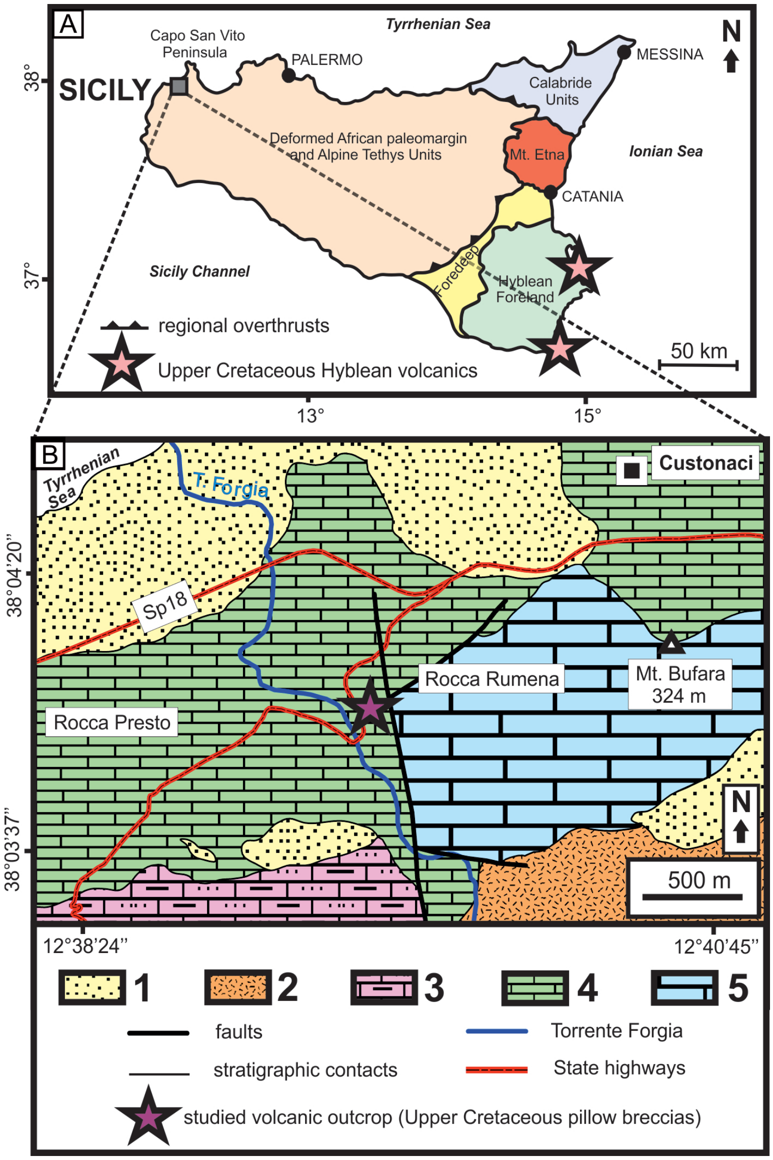

Figure 1. A) Tectonic map of Sicily. B) Geological map with the location of the studied site (modified after Abate et al., 1993) - purple star: volcanic outcrop analysed in this paper; 1: post-orogenic sediments (Plio-Quaternary); 2: terrigenous-carbonate cover and syn-orogenic sediments (Miocene); 3: slope-base deposits (Paleogene); 4: carbonate platform sediments (Upper Cretaceous); 5: carbonate platform, pelagic and carbonate platform margin sediments (Upper Trias-Lower Cretaceous).

like bodies) and result less altered than the fragments. The size of intact pillow bodies is in the decimeter scale. Moreover, the volcanic breccia is cemented by calcite occurring interstitially between pillow fragments, along fractures (Figure 2C) and within vesicles (Figure 2D). No glassy granules, shards and rims were observed.

Similar volcanic layer of both fragments and intact pillow lavas are also found for example in the transition zone from pillow lavas to pillow block breccia of the Quaternary subglacial sequence from Mosfell, in Iceland (Furnes and Fridleifsson, 1979), and in the pillow-fragment breccia facies belonging to the Chilcotin Group (Chasm Provincial Park, British Columbia, Canada), where they are correlated to subaerial basalt lavas (Farrell et al., 2008). Concerning the Capo San Vito area, volcanic horizons composed of intact pillow lavas are reported along the southern flank of Mt. Sparagio and near the Custonaci Village, at about 3 km away from the Forgia site (Catalano et al., 1984; Abate et al., 1993; Catalano et al., 2011). These not brecciated pillow lavas lie in identical stratigraphic and geometric position as the studied pillow breccias, therefore we assume that they probably

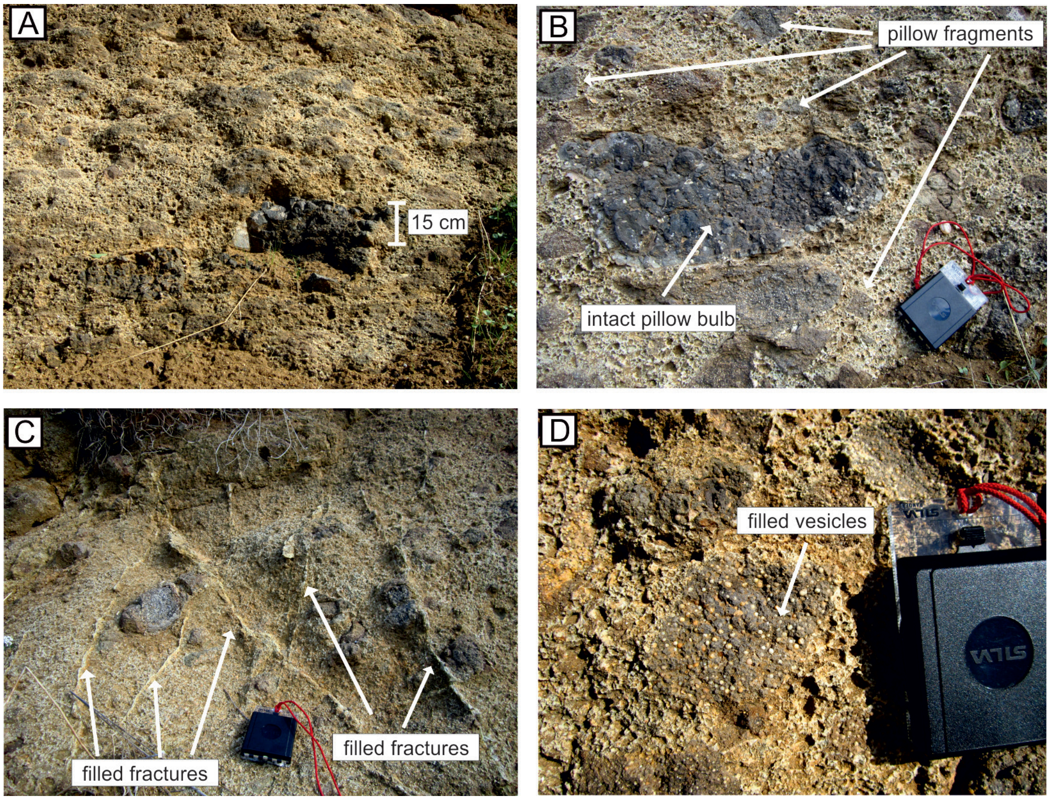

Figure 2. The volcanic outcrop is located along the Torrente Forgia valley and consists of an altered breccia body (A) composed of ellipsoidal intact pillows and pillow fragments of various size and shape (B). Secondary carbonates fill joints (C) and vesicles (D).

represent two different facies of the same volcanic pulses. The pillow breccias here described are very similar to the so-called "ortho-breccias", "broken pillow breccias", "pillow block breccias", and "pillow fragment breccias" already reported in literature by Jones (1970), Carlisle (1963), Furnes and Fridleifsson (1979), and Palinkas et al. (2008) respectively. According to Carlisle (1963) and Jones (1970), the formation of pillow breccias is due to pillows fragmentation during gravitational slides contemporaneous with eruptions. On the contrary, Furnes and Fridleifsson (1979) argue that mechanical movements do not need to take place simultaneously with eruptions, but they may occur any time afterwards. These authors also suggested that fragmentation occurs after freezing of the pillow lava, by the bulldozing effect of the intruding magma or by gravitational slides along spaced slip planes on unstable slopes. We assume that similar processes can be proposed to explain the formation of the Forgia pillow breccia.

The investigated volcanic body is interbedded within the Upper Cretaceous carbonate platform succession (Pellegrino formation) which was referred to reef and fore-reef environments by Di Stefano and Ruberti (1998). During the Upper Cretaceous, the carbonate platform was subjected to alternate marine transgression and regression events due to sea level changes and tectonic processes. The Pellegrino formation is dated to the Upper Albian/Cenomanian - Maastrichtian (Catalano et al., 2013 and references therein), therefore the Forgia volcanics can be ascribed to the Upper Cretaceous.

SAMPLES AND ANALYTICAL METHODS

Fourteen samples of Upper Cretaceous volcanic rocks have been collected at Forgia Valley (FOR1÷FOR14). The analytical measurements were performed using the instruments of the geochemical laboratories of the Messina University. The nucleus of the pillow lava bulbs has been sampled for the analyses. In any case, all samples have been carefully cleaned and treated with diluted acid (HCl 5%).

Chemical composition and variability of the primary and secondary minerals of all the studied volcanics have been investigated by SEM-EDX and XRPD. The analyses have been realized out by an ESEM-FEI Inspect-S electron microscope coupled with Oxford INCA PentaFETx3 EDX spectrometer, an Si(Li) detector equipped by an ultra-thin window ATW2, by using a resolution of 137 eV at 5.9 keV (Mn Kα1). The spectral data were acquired in ESEM (Environmental Scanning Electron Microscope) conditions, operating at working distance of 10 mm with an acceleration voltage of 20 kV, counting times of 60 s and approximately 3000 cps with dead time below 30%. The results were processed by INCA Software Energy that uses the XPP matrix correction scheme developed by Pouchou and Pichoir (1984, 1985).

X-Ray Powder Diffraction analyses were performed using a BRUKER D8 ADVANCE diffractometer, with Cu Kα radiation, on a Bragg-Brentano theta-theta goniometer equipped with a SiLi solid-state detector Sol-X and acquisition conditions are 40 KV and 40 mA. Scans were realized typically from 2 to 80 degrees 2θ, with step size of 0.02 degrees 2θ, with a counting time of 1 second. The data analysis was estimated using the software EVA. The raw diffraction scans were stripped of Kα2 component, the background was corrected and the digital data were smoothed with a Fourier digital filter. The peak positions were matched against the ICDD JCPDS database.

Major (SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MgO, MnO, CaO, Na_2O, K_2O, P_2O_5) and minor elements (Nb, Zr, Y, Sr, Rb, Ba, Co, Cr, V, Ce, La, Ni) have been analysed through X-ray fluorescence spectrometry (XRF) on powder pellets. To define the chemical composition of samples in terms of major, minor and trace elements, the WDXRF method with Bruker model S8 Tiger setup (Bruker, 2015 a,b) has been used. The excitation source is a tube of Rh at 4 kW, and major and minor elements contents have been calculated through the use of the software package GEO-QUANT M (Bruker, 2015 a,b) using more than 20 certified materials as standards. To determine trace elements concentrations were used the software GEO-QUANT T, a solution for the measurements of these elements in natural and geological materials (see Bruker, 2015 a,b). It is a pre-calibrated and standardized method by the manufacturer, and was validated by using two standard samples GBW07103 and GBW07406. Performing the quality control, the analysis must meet the narrow analytical range provided by the standards certificates.

RESULTS AND DISCUSSION

The purpose of this paper is to give new information about the poorly studied Upper Cretaceous magmatism occurred at the San Vito Lo Capo area. Petrographic observations highlighted that the studied samples suffered variable degrees of secondary alteration, that frequently led to the development of mineral phases replacement and generated different structures (Figure 3A, B and C).

Primary mineralogy

Despite the secondary alteration processes, some samples such as FOR1, FOR2, FOR3, FOR4, FOR5, FOR6 and FOR13 retain the original porphyritic texture (Figure 3A) and are characterized by the lowest values of LOI (2.59-3.56 wt%; Table 1). The main mineral assemblage includes phenocrysts of prevalent olivine and clinopyroxene set in a cryptocrystalline groundmass composed of plagioclase microlites and opaque grains (Figure 3A). All the phenocrysts, microphenocrysts and microlites have been analysed. According to IMA pyroxene classification, microphenocrysts of the analysed samples are mainly characterized by diopside and augite compositions (Figure 3D) with high amount of Al_2O_3 (5-7 wt%). XRPD analyses identified pyroxene as Al-bearing diopside (Figure 3E and F). Unaltered portions of olivine, both phenocrysts and microphenocrysts, have been analysed. Generally, the composition ranges from Fo_{75} to Fo_{84} with a slight enrichment in fayalitic component towards the rim (Fo contents between 75 and 79 in cores and between 79 and 84 in rims).

All the phenocryst types, both euhedral and subhedral, are similar in composition and characterized by relatively high CaO content (1.6-3 wt%). The variable CaO content may depend by secondary alteration processes. Plagioclase occurs in microlites showing a composition range from An_{30} to An_{50} and falling in the andesine field (Figure 3G). Opaque minerals are mainly ilmenites with skeletal habit probably due to the relative rapid cooling during crystallization.

Secondary alteration

In the most altered samples (FOR7, FOR8, FOR9, FOR10, FOR11, FOR12 and FOR14), the XRPD pattern identified calcite and smectite-like phases (Figure 3F). Calcite occurs as vesicles, fractures and veins filler (Figure 3B), whereas clay minerals occur as replacement of mafic minerals. Bowlingite was broadly identified after olivine and pyroxene. This phase consists of a smectite-chlorite mixture with minor amounts of talc and serpentine (Delvigne et al., 1979). Bowlingite is variable in composition and displays a predominance of smectite minerals identifiable with saponite (Caillère and Henin, 1951). Bowlingite is extensively developed along fractures and lines outer shape, and occasionally can be observed as a complete pseudomorph of mafic minerals. In the less altered samples, olivine and pyroxene are relatively preserved, and the alteration process is slightly restricted only along fractures.

In some samples (e.g. FOR4), Fe-Ti oxides were observed as void and vein infillings (Figure 3C). Moreover, field and petrographic observations evidence the transformation of volcanic glass into clay minerals.

The presence of secondary minerals highlights the significant effect of secondary processes on the studied

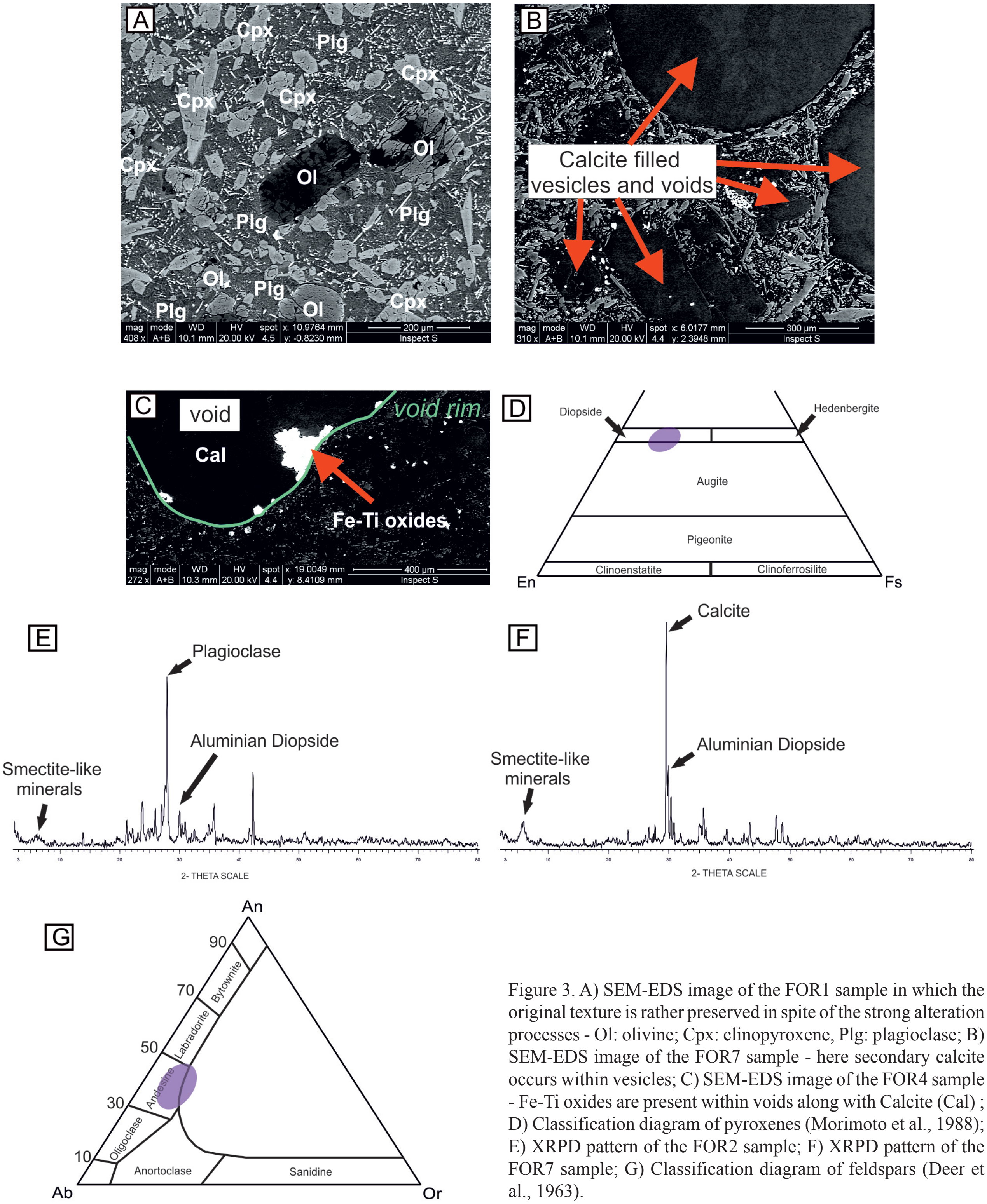

Figure 3. A) SEM-EDS image of the FOR1 sample in which the original texture is rather preserved in spite of the strong alteration processes - Ol: olivine; Cpx: clinopyroxene, Plg: plagioclase; B) SEM-EDS image of the FOR7 sample - here secondary calcite occurs within vesicles; C) SEM-EDS image of the FOR4 sample - Fe-Ti oxides are present within voids along with Calcite (Cal) ; D) Classification diagram of pyroxenes (Morimoto et al., 1988); E) XRPD pattern of the FOR2 sample; F) XRPD pattern of the FOR7 sample; G) Classification diagram of feldspars (Deer et al., 1963).

volcanic rocks. Calcite can precipitate from CO_2-rich fluids at temperatures ranging from below 50 °C (Ding et al., 2017) up to ~300 °C (Simmons and Christenson, 1993, 1994). Smectite-like minerals (e.g. Bowlingite) usually formed by replacement of mafic minerals under reducing conditions (Stucki et al., 1988) at temperatures

Table 1. XRF chemical analyses of major (wt%) elements of the studied samples.

Sample	FOR 1	FOR 2	FOR 3	FOR 4	FOR 5	FOR 6	FOR 7	FOR 8	FOR 9	FOR 10	FOR 11	FOR 12	FOR 13	FOR 14
wt%														
SiO_2	44.84	44.34	46.66	43.92	45.00	41.85	29.37	32.39	40.42	42.20	40.28	40.53	42.97	35.92
CaO	11.16	12.62	9.87	10.71	10.03	18.12	32.61	27.37	16.11	15.35	19.85	20.04	15.37	20.96
Fe_2O_3	12.81	12.43	12.75	12.62	13.17	10.82	7.03	7.61	11.55	11.81	10.44	11.10	10.52	4.82
Al_2O_3	11.15	10.84	10.03	11.16	10.46	12.01	9.52	10.85	13.21	12.71	12.63	12.34	12.39	14.75
MgO	8.97	9.01	9.72	9.37	10.74	5.96	3.34	3.51	6.04	5.46	5.37	5.41	5.63	1.97
TiO_2	2.94	2.78	2.98	3.04	3.17	2.80	2.17	2.56	2.96	2.96	2.86	2.86	2.76	3.49
P_2O_5	0.64	0.80	1.02	1.32	0.79	1.31	1.28	1.47	1.42	1.62	1.61	1.58	1.33	1.10
Na_2O	2.68	2.32	3.06	3.73	3.12	2.27	1.16	1.02	1.31	2.58	0.40	0.45	3.32	1.02
K_2O	1.46	1.34	0.81	0.81	0.72	1.05	0.77	0.96	0.82	1.01	1.02	0.97	2.05	4.07
MnO	0.10	0.10	0.10	0.11	0.11	0.08	0.04	0.05	0.09	0.08	0.09	0.09	0.09	0.07
L.O.I.	3.16	3.24	2.95	3.16	2.59	3.56	13.43	12.84	5.99	4.12	5.32	4.47	3.50	12.65
Total	99.91	99.82	99.96	99.94	99.92	99.83	100.72	100.64	99.92	99.91	99.87	99.84	99.93	100.82

between 50-100 °C and 250-300 °C (Cann, 1979). At those temperatures, plagioclase is partly replaced by smectite-like minerals such as saponite (Cann, 1979). According to Jakobsson and Moore (1986), Olivine is hydrothermally altered to smectite at temperatures >120 °C. Moreover, the occurrence of smectites and smectite-rich mixed-layers in the temperature range of 120-300 °C has been reported for several active geothermal systems (Inoue et al., 1992; Patrier et al., 1996; Gianelli et al., 1998).

As a result, the detected assemblage of secondary minerals is consistent with alteration processes acted by hydrothermal fluids at low temperatures in the range of 100-120 °C up to 250-300 °C max.

In order to quantify the intensity of alteration, the Ishikawa alteration index (AI; Ishikawa et al., 1976) and the chlorite-carbonate-pyrite index (CCPI; Large et al., 2001), both based on ratios of mobile major elements, were tentatively used. Although they are strictly dedicated to measure the hydrothermal alteration of volcanic rocks proximal to ore bodies (especially with reference to volcanic-hosted massive sulfide deposits), they can provide rough estimations on the degree of secondary alteration phenomena affecting Forgia volcanics. The CCPI $[100*(MgO+FeO)/(MgO+FeO+Na_2O+K_2O)]$ reflects the Fe and Mg alteration due to chlorite, carbonate and pyrite replacements of feldspars and glass (Large et al., 2001). Forgia products have CCPI values between 55 and 92 (mean value 82), indicating an important role of secondary processes. The AI $\{[100*(K_2O+MgO)]/(K_2O+MgO+Na_2O+CaO)\}$, is used to investigate chlorite and sericite alteration, and it is characterized by two limitations: i) it does not discriminate the chlorite and sericite relative roles; ii) it does not consider carbonate alteration. For hydrothermally altered rocks, the AI varies between 50 and 100. On the contrary, AI values obtained for Forgia samples are typical of unaltered rocks, ranging from 11 to 47 (mean value 30); this discrepancy might be connected to the secondary calcite precipitation observed in the studied rocks, since carbonate alteration is not considered by the Ishikawa alteration index.

Geochemical features and rocks signature

Tables 1 and 2 list the XRF data of major and trace elements showing how all samples have LOI values

Table 2. XRF chemical analyses of trace (ppm) elements of the studied samples.

Sample	FOR 1	FOR 2	FOR 3	FOR 4	FOR 5	FOR 6	FOR 7	FOR 8	FOR 9	FOR 10	FOR 11	FOR 12	FOR 13	FOR 14
ppm														
Sc	20	17	14	15	15	16	10	13	16	15	15	13	16	19
V	194	180	176	180	184	189	155	175	190	190	189	188	188	197
Cr	298	313	364	380	391	394	386	430	308	321	285	294	266	173
Co	47	45	44	45	46	59	46	49	58	46	89	74	50	36
Ni	113	111	275	300	291	313	162	128	230	197	181	196	191	64
Cu	57	55	71	71	74	88	62	69	92	97	84	85	109	74
Zn	119	114	128	132	132	121	116	205	138	134	155	156	107	149
Ga	22	20	23	23	21	21	20	19	23	24	20	20	23	17
As	6	5	2	3	5	7	6	4	7	6	7	7	9	2
Rb	10	9	10	11	10	11	20	22	16	16	18	18	25	21
Sr	593	578	719	794	651	603	741	668	521	730	508	613	788	547
Y	25	25	28	28	25	28	26	29	29	31	32	32	26	25
Zr	229	217	322	333	338	268	269	310	316	325	310	312	244	292
Nb	60	56	87	88	90	72	72	83	85	87	82	83	63	63
Mo	6	6	9	8	8	6	6	6	6	7	6	6	6	6
Cs	34	31	34	35	35	36	39	41	37	37	39	39	35	51
Ba	294	276	332	343	334	311	539	884	469	408	334	385	437	836
La	24	25	35	47	27	57	65	73	49	61	64	70	41	43
Ce	71	71	87	110	79	98	116	117	106	121	134	128	79	70
Pb	4	6	5	7	8	5	5	4	6	6	7	5	5	5
Th	8	8	10	10	9	8	10	10	9	10	10	10	10	8
U	10	10	11	12	10	10	11	10	9	11	9	10	11	9

exceeding 2.5% due to secondary alteration processes. FOR7, FOR8 and FOR14 samples are characterized by very high LOI values (>10%) and therefore were excluded from the geochemical discussion.

In order to set a comparison with the coeval volcanic products from Hyblean Plateau, geochemical data by Avanzinelli et al. (2012) have been also plotted on the geochemical diagrams. The two groups of rocks display different alteration degrees: Hyblean lavas are less to mildy altered, exhibiting LOI values in the range of 0.32-2.91% (mean value 1.42%), whereas samples collected at Forgia show higher degrees of alteration since LOI ranges from 2.59 to 13.43% (mean value 5.79%). For this reason, during discussion of geochemical data, considerable attention will be given to elements such as Zr, Y, Nb, and Ti, considered geochemically immobile during secondary processes (*e.g.* Rollinson, 1993). The considered sites both experienced Mesozoic volcanism, before the onset of the compressive tectonics related to the continental collision that involve European and African plates. Due to this common geodynamic framework, evaluating differences and similarities between the two sample suites, is fundamental to better understand the processes responsible for the Upper Cretaceous anorogenic magmatism in Sicily. According to Avanzinelli et al. (2012), the Hyblean volcanics were generated in response to the asthenospheric passive upwelling connected to an extensional tectonic episode. Alkaline and mildly alkaline products, ranging in composition from picro-basalts to hawaiites, were originated by different degrees of partial melting of a recycled mafic oceanic crust within the mantle source. Their assumption is based on the high radiogenic isotope ratios, the high TiO_2 content, and the high MREE/HREE ratios.

Figure 4A plot the studied volcanic rocks on the Nb/Y vs SiO_2 diagram (Winchester and Floyd, 1977) showing how the rocks from Forgia Valley fall in the fields of alkaline basalts and basanites/nephelinites. The geochemical immobile elements ratios Nb/Y=2.23-3.69; Zr/Nb=3.70-4.79; La/Nb=0.30-0.84; Ti/Zr=56.44-79.02 are typical

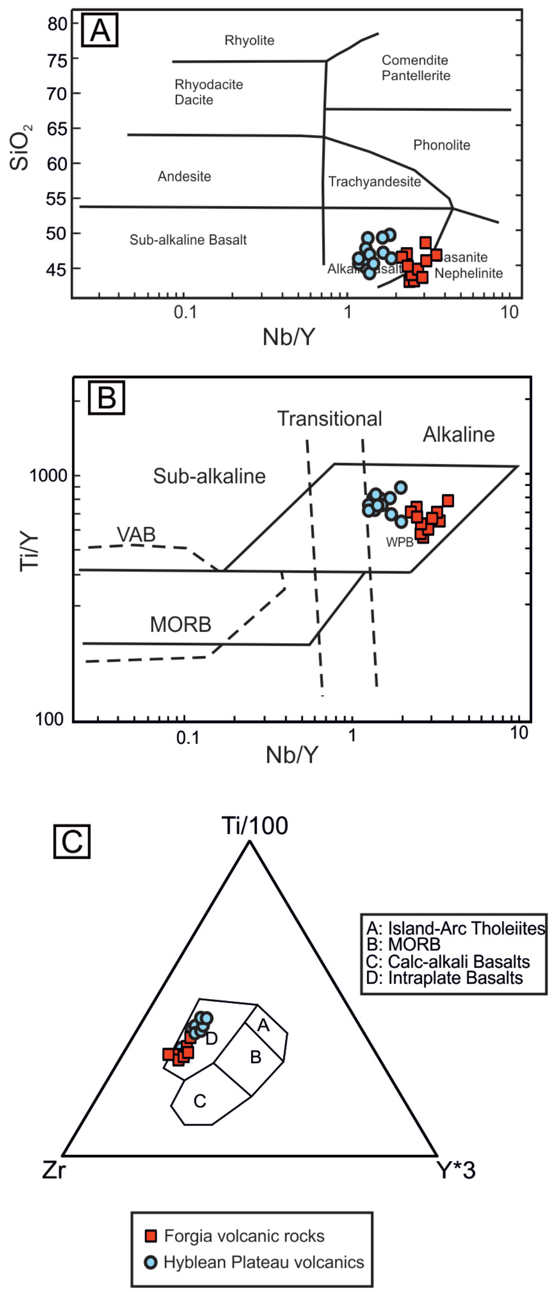

Figure 4. Classification of the rocks from the Forgia valley: A) Nb/Y vs SiO_2 plot of Winchester and Floyd (1977); B) Nb/Y vs Ti/Y plot of Pearce (1982) - WPB: Within-plate basalts, MORB: Mid ocean Ridge Basalts, VAB: Volcanic Arc Basalts; C) Ti-Zr-Y diagram of Pearce and Cann 1973. For comparison, data from Hyblean Plateau (after Avanzinelli et al., 2012) are plotted.

of alkaline basalts. Since alkaline elements Na and K might be heavily modified during alteration, it is difficult to define the affinity (K or Na) of these rocks. However, the less-altered samples show a Na_2O/K_2O weight ratios >2, denoting the sodic nature of the Forgia volcanism according to Le Maitre et al. (2002). Contrastingly, the Hyblean samples have slightly lower Nb/Y values, thus indicating an alkali-basaltic composition (Figure 4A). The Nb/Y vs Ti/Y and the Ti-Zr-Y diagrams of Figures 4B and C (Pearce, 1982 and Pearce and Cann, 1973 respectively) discriminate the tectonic setting of the studied volcanism. The Forgia volcanics as well as the coeval products from Hyblean Plateau exhibit an intraplate character since samples fall in the within plate field.

Variation of major and trace elements have been estimated on the binary diagrams reported in Figures 5 and 6 where Al_2O_3 and CaO are negatively correlated with SiO_2. K_2O, TiO_2 and MgO are rather constant, while Na_2O shows a positive correlation with SiO_2. The poorly variable values of MgO against SiO_2 can be attributed to a slight Mg mobilization during hydrothermal circulation. Generally, slight enrichments in MgO occur under non-oxidative conditions reflecting the additions of Mg-rich secondary minerals, whereas oxidative conditions induce MgO depletion (Scheidegger and Corliss, 1981). On the same variation diagrams of Figure 5 the Hyblean samples show an increase in TiO_2, Al_2O_3, and Na_2O with increasing SiO_2, whereas K_2O and CaO are almost constant. Concerning the variation of trace elements vs SiO_2 of study samples (Figure 6), Co shows a "L" shape correlation, whereas Cr is constant. REE (La, Ce and Y) outline similar trends against SiO_2 showing overall negative correlations. Conversely, Zr and Nb are characterized by roughly constant values. Moreover, LILE (Rb, Ba and Sr) show scattered concentrations (not shown). Hyblean volcanics display scattered concentration of Cr, Co and Y vs SiO_2, while Zr, Nb, La and Ce are roughly constant.

Major and trace element trends of the Forgia samples indicate an evolution by fractional crystallization with separation of mafic minerals (*i.e.* olivine and clinopyroxene) during the first stage of magma crystallization. A role of clinopyroxene fractionation is suggested by Al_2O_3/CaO ratio increase with increasing SiO_2 and by the "L" shape of Co vs SiO_2 (Figures 5 and 6).

Figure 7 shows the pattern for the primordial mantle-normalized incompatible element of the mafic samples (MgO>5%; McDonough et al., 1992). Although some trace elements lack, the Forgia Valley rocks show patterns very similar to those of the OIB. In fact, the analysed rocks are enriched in HFSE such as Nb, Th and Zr and exhibit negative anomalies of Rb, Sr and K making them consistent with an anorogenic volcanism. Additionally, they show positive spikes of Cs, Pb and U, which are related to low temperature seawater-rock interactions during hydrothermal processes (Jochum and Verma, 1996). Samples from the Hyblean Plateau show a typical OIB-type primordial mantle-normalized incompatible

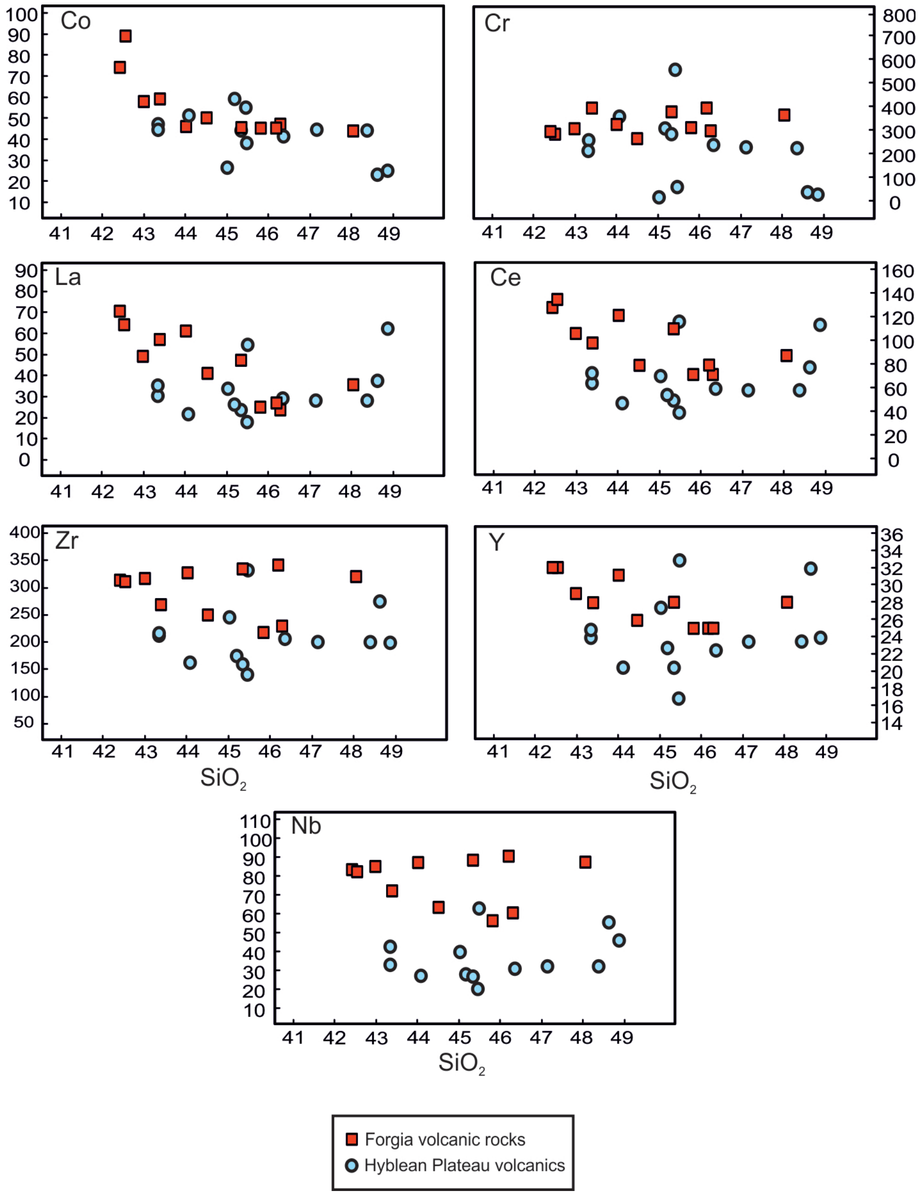

Figure 5. Variation diagrams of major element (wt%) and the Al_2O_3/CaO ratio vs SiO_2 (wt%). For comparison, data from Hyblean Plateau (after Avanzinelli et al., 2012) are plotted.

element (Avanzinelli et al., 2012). Despite a few differences (*i.e.* Cs and U) clearly related to the secondary processes occurred along the Forgia Valley, the patterns of the two rock suites appear quite comparable (Figure 7). They show similar concentration of HFSE (Th, Nb, Zr, Ti), REE (La, Ce, Y) and some LILE (*i.e.* Rb, Ba, K).

Diagrams of Figures 8A and 8B are useful to identify the geochemical signature of the mantle source. The Ti vs V diagram (Shervais, 1982) of Figure 8A is based on the principle that the fractionation of V and Ti during partial melting and fractional crystallization is a function of oxygen fugacity, and the Ti/V ratio increases from island-arc to MORB to OIB basalts. The studied rocks show a Ti/V ratio of about 100, falling on the separation line between OIB and alkaline basalts. The lower Ti/V ratio (between 50 and 100) of the Hyblean volcanics suggests their derivation from a source with an OIB composition. On the plot of the Zr/Nb vs Ce/Y diagram (Figure 8B; Göncüoglu et al., 2010) which discriminates among OIB, E-MORB, N-MORB and SSZ (supra-subduction-zone) source compositions, the samples from both Forgia Valley and Hyblean Plateau lie within the OIB field. Moreover,

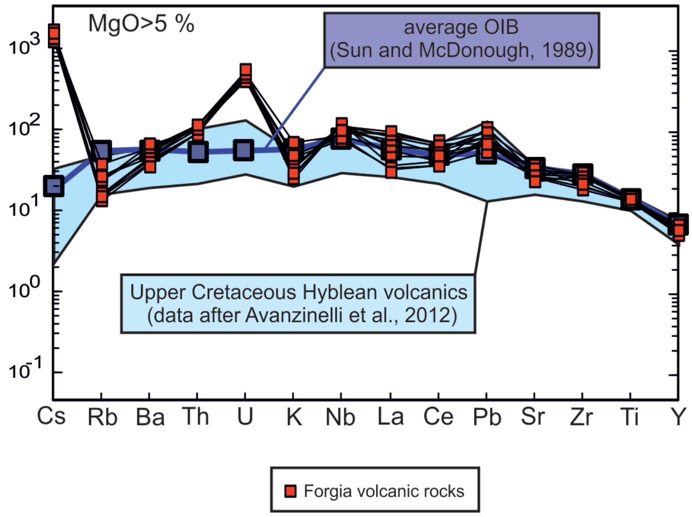

Figure 6. Variation diagrams of some trace element (ppm). For comparison, data from Hyblean Plateau (after Avanzinelli et al., 2012) are plotted.

the Zr/Nb vs Nb/Y discrimination diagram (Figure 8C; Harangi, 2001) indicates that Forgia volcanic rocks might have been generated by low degrees (from ~1% to ~1.5%) of partial melting of a source region located within the intermediate zone between garnet- and spinel-lherzolite mantle. Accordingly, the Hyblean volcanism could derive from a similar mantle region, but with higher partial melting degrees.

Consequently, because of the similarities regarding the trace elements composition, we can carefully speculate that the Upper Cretaceous volcanism in the Hyblean Plateau and in the Forgia area could have sampled a rather common mantle source. However, lacking in isotope data from the Forgia volcanic rocks does not allow to verify this hypothesis. The speculation of a rather common reservoir beneath the Capo San Vito area (Western Sicily) and the Hyblean Plateau (Eastern Sicily) is in agreement with the previous works which identify a common mantle source component beneath the Circum-Mediterranean province (*e.g.* Wörner et al., 1986; Wilson and Downes, 1991, 1992; Cebrià and Wilson, 1995; Granet et al., 1995; Hoernle et al., 1995; Goes et al., 1999; Lustrino and Wilson 2007). In this framework, the slight geochemical discrepancy between the volcanic products from Forgia Valley and Hyblean Plateau should be addressed to the different partial melting degree and to secondary alteration processes.

Origin of magmas

To investigate the magmatogenesis and the probable geodynamic setting in which the Forgia volcanism occurred, we have to consider that from Albian to Late Cretaceous, a large portion of the African-Adria paleomargin underwent tectonic extension. Evidences for transtensional and extensional deformation have been recorded in the Central Apennines carbonate platforms (Bigi and Costa Pisani, 2005), along the Sorrento Peninsula (Tavani et al., 2013), in the Apulian foreland (Festa, 2003; Carannante et al., 2009; Santantonio et al., 2013), in the Hyblean plateau (Patacca et al., 1979; Carbone et al., 1982; Avanzinelli et al., 2012; Neri et al., 2018), in the Panormide platform of the Madonie Mountains (Renda et al., 1999, 2000), along the Rocca Busambra culmination of the Central Sicily (Martire and Montagnino, 2002; Basilone, 2009), in the Sirte Basin of Lybia (Gumati et al., 1991; Roohi, 1996; Abadi et al., 2008; Frizon de Lamotte et al., 2011) and in the Hammamet, Gabes and Chotts basins of Tunisia (Patriat et al., 2003). Tavani et al. (2013) proposed that the Albian to Late Cretaceous extensional pulse recorded in the Sirte basin may have extend northwestward, where Sicily and Southern Apeninnes were located. In this model, the Cretaceous distension represents a pervasive tectonic event involving the Southern Adria and the northeastern portion of the Africa plate with NE-SW to NNE-SSW oriented extensional trends. After these remarks, we can assume that the Upper Cretaceous extensional deformation might easily have affected also the San Vito lo Capo region. Due to the absence of robust constraints regarding to the Upper Cretaceous tectonics of the San Vito lo Capo and taking into account the extensional/transtensional deformation occurred throughout a very wide section of African-Adria paleomargin, we propose that the Forgia volcanism might have been originated from partial melting occurred in response to the passive mantle upwelling caused by lithospheric stretching and wrenching.

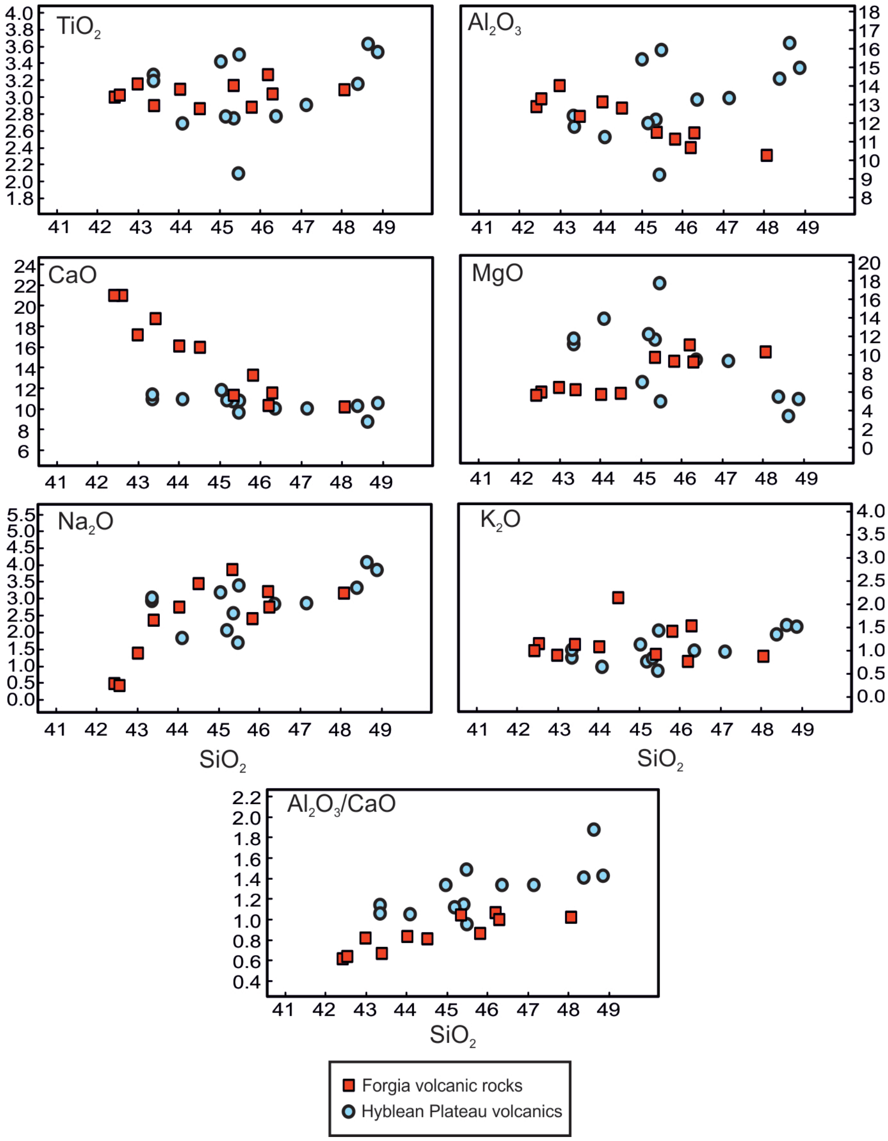

Figure 7. Patterns of incompatible elements normalized to primordial mantle composition (McDonough et al., 1992) for mafic (MgO>5%) rocks from Forgia Valley.

CONCLUDING REMARKS

This paper focuses on the petrographic and geochemical study of a volcanic body outcropping along the San Vito lo Capo Peninsula. It records a distensive or transtensive tectonic event affecting the African-Adria paleomargin during the Upper Cretaceous, at least from Lybia to the Central Apennines. The lithospheric stretching led to the development of alkaline volcanism in the Forgia area. Mafic volcanics emplaced over a shallow submarine environment characterizing the wide carbonate platform of the southern margin of the Alpine Tethys realm.

The geochemical analyses highlight the intraplate signature of the volcanic rocks probably derived from a OIB-type reservoir. The primordial mantle-normalized incompatible element patterns, in fact, resemble those of the OIB besides some incompatible element ratios (*e.g.* Ce/Y, Zr/Nb, Ti/V) that are typical of oceanic island magmas. In turn, the Upper Cretaceous volcanics from Capo San Vito Peninsula show geochemical features in terms of trace element composition similar to the coeval products from the Hyblean Plateau. We may speculate that the similarities possibly reflect an almost synchronous partial melting occurred in two different but relatively close areas, of a rather common mantle source extended at least from Eastern to Western Sicily. Future investigations, including isotopic analyses that represent a key tool to

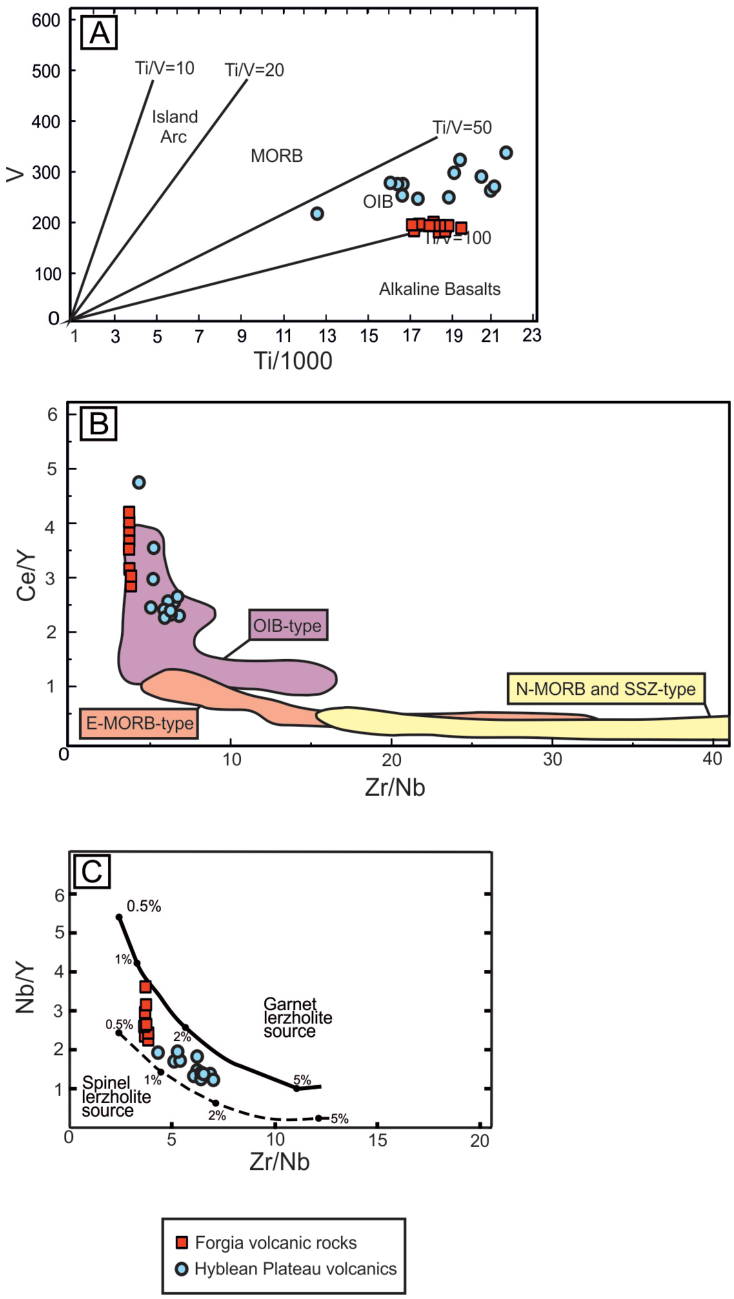

Figure 8. Discrimination diagrams of the Forgia volcanics: A) V vs Ti plot from Shervais (1982); B) Zr/Nb vs Ce/Y diagram after Göncüoglu et al., 2010 - Fields for the OIB-, E-MORB, N-MORB, and SSZ-type basaltic rocks are taken from Maheo et al. (2004), and Aldanmaz et al. (2008). C) Zr/Nb vs Nb/Y diagram (after Harangi, 2001). For comparison, data from Hyblean Plateau (after Avanzinelli et al., 2012) are plotted.

better constrain the magmatogenic processes operating in Sicily (and with a more general view in the Circum-Mediterranean area), may provide further indications on the existence of a common magmatic source just before the onset of the Alpine Orogeny.

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