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MINERALOGICAL, PETROLOGICAL AND GEOCHEMICAL STUDY OF THE AGIOS IOANNIS VOLCANIC ROCKS, KAMENA VOURLA AREA, GREECE

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Abstract

The Plio-Pleistocene volcanic center of Lichades is located in the Northern Euboean Gulf, at the western extremity of the North Anatolian Fault and it is one of the most neo-tectonically active areas in Greece. Volcanic rocks are exposed in the form of lava flows and/or domes mostly in the small islands (Lichades) offshore Kamena Vourla, as well as in a small outcrop in mainland, namely the Agios Ioannis area. Based on the results of the present study, the Agios Ioannis volcanic rocks are characterized as trachyandesites with high-K calc-alkaline affinities, similar to several volcanic rocks from the South Aegean Volcanic Arc. The petrological and mineral-chemical study reveal that the studied volcanic rocks are characterized by vitrophyric texture and a matrix dominated by glass, numerous randomly-oriented microlites of plagioclase and minor sanidine, clinopyroxene and amphibole. Phenocrysts comprise of plagioclase, olivine, quartz, clinopyroxene and amphibole. Plagioclase composition ranges from andesine to bytownite (An_{30}-An_{73}). Olivine cores are typically Mg-rich, and the rims display elevated FeO content. Clinopyroxenes display a narrow compositional range between augite and diopside, with the latter being more common. Amphiboles, are calcic and their composition ranges from tschermakite to tschermakitic hornblende. Mineralogical and geochemical similarities with other volcanic rocks in Greece such as Lesvos lamproites, may be helpful in understanding the genesis of the studied Agios Ioannis volcanics.

Keywords: *Lichades volcanic center, trachyandesite, petrology, mineral-chemistry, geochemistry*

Περίληψη

Στη νοτιοδυτική απόληξη του ρήγματος της Ανατολίας, στο Βόρειο Ευβοϊκό Κόλπο, που είναι μία από τις πιο ενεργές νεοτεκτονικά περιοχές της Ελλάδας, εμφανίζεται το Πλειο-Πλειστοκαινικής ηλικίας ηφαιστειακό κέντρο των Λιχάδων. Αποτελείται από ένα σύμπλεγμα μικρών σε έκταση ηφαιστειογενών νησιών και εμφανίσεις ροών λάβας της περιοχής των Καμένων Βούρλων. Με βάση τα αποτελέσματα της παρούσας μελέτης, τα ηφαιστειακά πετρώματα της περιοχής του Αγίου Ιωάννη (Καμένα Βούρλα) χαρακτηρίζονται ως υψηλού-K ασβεστοαλκαλικής σειράς τραχιανδεσίτες, παρόμοια με πετρώματα που συναντάμε στο ενεργό ηφαιστειακό τόξο του νοτίου Αιγαίου. Η πετρολογική και ορυκτοχημική μελέτη έδειξε ότι τα ηφαιστειακά πετρώματα του Αγίου Ιωάννη παρουσιάζουν υαλοφυρική δομή. Η κύρια μάζα τους κυριαρχείται από ύαλο και πολυάριθμους τυχαία προσανατολισμένους μικρόλιθους αστρίων (σανίδινο, πλαγιόκλαστο), ενώ με μικρότερη συμμετοχή εντοπίζονται κλινοπυρόξενοι και αμφίβολοι. Σαν φαινοκρύσταλλοι εμφανίζονται συνήθως πλαγιόκλαστα, ολιβίνης, χαλαζίας, κλινοπυρόξενοι και αμφίβολοι. Τα πλαγιόκλαστα εμφανίζεται σαν ιδιόμορφοι έως υπιδιόμορφοι κρύσταλλοι και συχνά παρουσιάζουν ζώνωση: οι πυρήνες τους είναι πλούσιοι σε Ca, ενώ η περιεκτικότητα σε Na αυξάνεται σταδιακά προς την περιφέρεια των κρυστάλλων. Η σύσταση τους κυμαίνεται από ανδεσίνη έως βυτοβνίτη (An30-An73). Ο ολιβίνης συνήθως σχηματίζει ιδιόμορφους έως υπιδιόμορφους κρυστάλλους ή περιστασιακά σχηματίζει συσσωματώματα μαζί με κρυστάλλους κλινοπυροξένων. Οι πυρήνες του ολιβίνη είναι τυπικά πλούσιοι σε Mg, ενώ οι περιφέρειες εμφανίζουν χαμηλότερη περιεκτικότητα MgO και αυξημένη περιεκτικότητα σε FeO, η οποία κυμαίνεται από 21,07 έως 28,82 wt.% και ενδεχομένως αντικατοπτρίζει την μείωση του MgO κατά την εξέλιξη της κρυστάλλωσης του μάγματος. Οι κλινοπυρόξενοι παρουσιάζουν περιορισμένο εύρος σύστασης, μεταξύ αυγίτη και διοψίδιου, με τον τελευταίο να είναι συνηθέστερος. Οι αμφίβολοι, παρουσιάζουν επίσης περιορισμένο εύρος σύστασης (κυρίως κεροστίλβη) και χαρακτηρίζονται από σχετικά σταθερή περιεκτικότητα σε Al_2O_3 και FeO. Συνήθως σχηματίζουν ιδιόμορφους κρυστάλλους, με χαρακτηριστική ζώνωση. Τοπικά, οι αμφίβολοι αντικαθίστανται από αδιαφανή ορυκτά. Ο τιτανίτης παρουσιάζεται σπάνια, σαν επουσιώδες ορυκτό, ενώ οι αδιαφανείς ορυκτές φάσεις, που είναι συνήθως σπινέλιος, μαγνητίτης και ρουτίλιο, είναι αρκετά άφθονες, διασκορπισμένες στην υαλώδη κύρια μάζα.

Λέξεις-κλειδιά: *Ηφαιστειακό κέντρο Λιχάδων, τραχιανδεσίτης, πετρολογία, ορυκτοχημεία, γεωχημεία*

1. INTRODUCTION

Greece is a well-known example of a relatively small geographical area that exhibits an extreme variety of igneous rocks, in terms of composition, age and tectonic setting, and has been characterized as a microcosm of tectonic and igneous processes (Pe-Piper and Piper, 2002). This is due to the complex orogenetic processes that have taken place in the Hellenides and continue until today. In its present state, the Hellenic orogen is characterized by the subduction of the African plate below the Eurasian margin, along the north-dipping Hellenic subduction zone (e.g. Mountrakis, 2006). This process gives birth to a series of volcanic centers, known as the South Aegean Volcanic Arc (SAVA).

The targeted study of Greek igneous rocks began with the study of Santorini by Fouqué (1879). During the first half of the 20th century, Prof. Georgalas (e.g. 1938, 1940) made considerable amount of studies all over Greece concerning the igneous rocks. In the second half of the 20th century and in the 21th century, several studies described the Greek igneous rocks, but mainly focused in Santorini and the volcanos of SAVA. The book of G. Pe-Piper and D.J. Piper (2002), entitled "*The igneous rocks of Greece: The anatomy of an orogen*" has been rightfully considered a milestone for the studies of igneous rocks in Greece. A set of papers concerning the volcanism of SAVA were recently published in the journal "Elements" (June 2019, vol. 15, num. 3), special issue under the name "*South Aegean Volcanic Arc*", by the guest editors T.H. Druitt and G. Vougioukalakis. Many recent, igneous rocks and volcanic centers, scattered throughout Greece, which are unrelated to the SAVA, have attracted limited attention, leaving several questions unanswered. A characteristic case is the greater Volos-Atalanti area, where several small volcanic centers occur (e.g. Pe and Panagos, 1976; Pe-Piper and Piper, 2002; Innocenti et al., 2010). One of occurrences is the volcanic center of Lichades, located in the Northern Euboea Gulf (Fig. 1). Many different theories that have been proposed about its geotectonic setting. Additionally, the Lichades volcanic center has been related to the presence of hot springs both in the Kamena Vourla area and the adjacent Euboea island (i.e. Aedipsos, Gialta and Ilia) (Kanellopoulos et al., 2017a, 2017b, 2018).

The aim of this paper is to investigate the mineral chemistry, petrography and geochemistry of the volcanic rocks at the Agios Ioannis outcrop, Kamena Vourla area, central Greece.

2. GEOLOGICAL SETTING

In the Northern Euboean Gulf and at the western extremity of the southwestern end of the Anatolia fault, occurs the volcanic center of Lichades. It comprises a complex of small volcanic islands and a nearby lava outcrop at Agios Ioannis, Kamena Vourla area, in mainland (Fig. 1 and 2; Georgalas, 1938; Georgiades, 1958; Pe-Piper and Piper, 2002). Available geochronological data for the Lichades islands lava flows yielded an age of 0.5 Ma (whole rock K-Ar, Fytikas et al., 1976), and for the nearby lavas in the Kamena Vourla area an age of 1.7 Ma (K-Ar, Bellon et al., 1979). Several different theories have been proposed about the genesis of the Lichades volcanic center. Ninkovich and Hays (1972), Pe (1975) and Pe and Panagos (1976) proposed that the Lichades volcanic center could be the western continuation of the South Aegean active volcanic arc. Pe-Piper and Piper (1989) suggested that the Lichades volcanic center together with trachytes and sodic basalts elsewhere in the Aegean, could be related to the "aseismic subducted slab" at greater depths than the arc volcanoes. Fytikas et al. (1985) and Pe-Piper and Piper (2007) proposed a possible genetic relation with the North Anatolia fault continuation. Innocenti et al. (2010) based on Sr–Nd–Pb isotopic data, related this volcanic center with the large volcanic belt that developed north of the Pelagonian–Attic–Cycladic–Menderes massifs, which is widespread over a large area from NW Greece–Macedonia to the Aegean–western Anatolia, encompassing a 35 Ma timespan. According to the above authors, the Euboea-Kamena Vourla (including Lichades) volcanic products display an orogenic character and are partially contemporaneous with the south Aegean active volcanic arc, but with different geochemical features, related to distinct magma sources (e.g. lithospheric mantle wedge and a depleted asthenospheric mantle wedge north and south of the Pelagonian–Attic–Cycladic–Menderes massifs, respectively).

The volcanic center of Lichades is located along the major tectonic structures in the area (Ganas, 1997; Kranis, 1999). Karastathis et al. (2011) showed that there is a magma chamber under the North Euboean Gulf area estimated at about 7-8 km depth, by combining a three-dimensional travel time inversion of microseismic data recorded by an on/offshore local seismic network and a Curie Point Depth analysis based on aeromagnetic data. Kanellopoulos et al. (2017a, 2017b, 2018) suggested that the volcanic center of Lichades and the associated magmatic chamber is the heating source and contributes with a portion of deep magmatic fluid to the geothermal fluid of Euboea-Sperchios system, along with seawater and only limited meteoric water contribution. Northern Euboea and the neighbouring part of the mainland in eastern Central Greece (Sperchios area) are recognized as areas with high geothermal gradient following the areas occupied by the South Aegean active volcanic arc (Fytikas and Kolios, 1979).

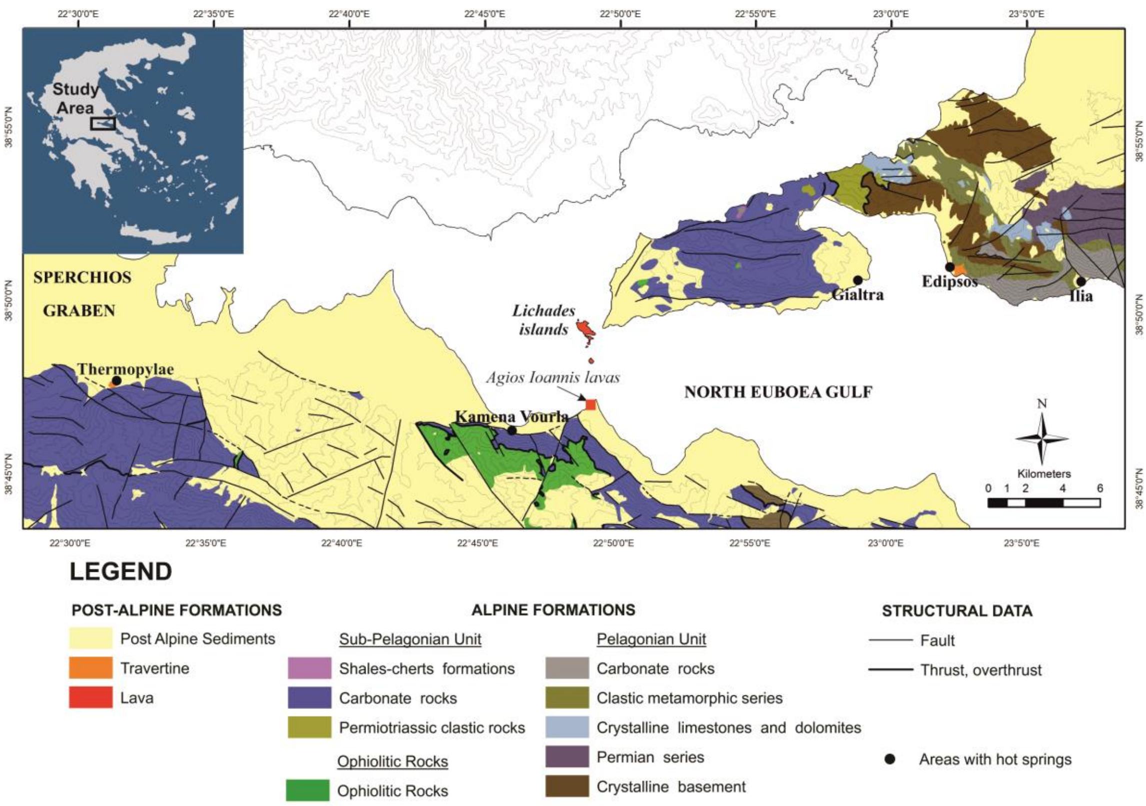

Fig. 1: Simplified geological map of the Kamena Vourla and NW Euboea area (North Euboea Gulf, modified after Kanellopoulos, 2011). Red square marks the studied outcrop.

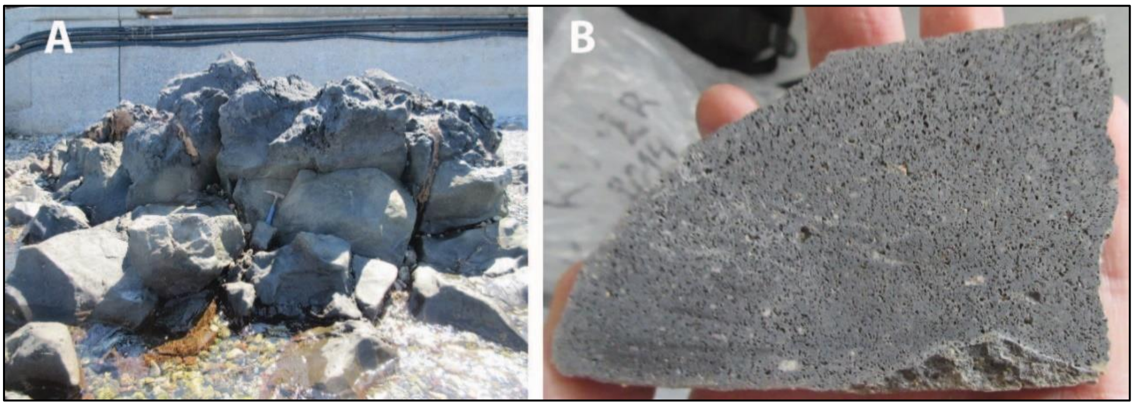

Fig. 2: Field (A) and hand-specimen (B) photographs of the volcanic rocks from the Agios Ioannis area at Kamena Vourla.

3. MATERIALS AND METHODS

XRD analyses were conducted on powders of all samples using a Siemens Model 5005 X-ray diffractometer in combination with the DIFFRAC plus software package. The diffractometer was operated using Cu Kα radiation at 40 kV and 40 mA and employing the following scanning parameters: step size 0.020° and step time from 1 sec to 20 sec. The raw files were evaluated using the DIFFRACplus EVA (Bruker-AXS, USA) software based on the ICDD Powder Diffraction File (2006 version). Thin and polished sections were studied through transmitted-light microscopy and a JEOL JSM 5600 scanning electron microscope, equipped with automated OXFORD ISIS 300 energy dispersive analysis system (SEM-EDS), and back-scattered electron (BSE) imaging capabilities, at the Department of Geology, University of Patras, Greece, with the following operating conditions: accelerating voltage 20 kV, beam current 0.5 nA and beam diameter 1–2 microns. The spectra were processed using the ZAF software. For the bulk-rock geochemical analyses, four representative samples were pulverized to <200 mesh in an agate mill. Then they were digested with a mixture of $HCl–HNO_3–HF$ acids and were analyzed for major elements by X-ray fluorescence (XRF) and for a series of trace elements by Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) and Inductively Coupled Plasma-Mass Spectrometry (ICP-MS), at the laboratories of the Hellenic Survey of Geology and Mineral Exploration (H.S.G.M.E., ex-I.G.M.E.).

4. RESULTS AND DISCUSSION

4.1. Petrography and mineral chemistry

Petrography

The studied volcanic rocks are characterized by vitrophyric texture (Figs 3 and 4). Their matrix is dominated by glass, numerous, randomly oriented microlites of plagioclase and minor sanidine, clinopyroxene, amphibole grains (Fig, 3a-b, 4a). Phenocrysts are commonly plagioclase, olivine, clinopyroxene and amphibole, while quartz is uncommon. Plagioclase occurs as large euhedral to subhedral grains, displaying patchy or concentric zonation. At places, plagioclase phenocrysts are rimmed by a thin rind of K-rich feldspar (sanidine, Figs3c, 4e-f), which can rarely be found as phenocryst as well. Olivine is usually found as large, euhedral to subhedral grains (Figs3d, 4a) or it can form glomerophyric aggregates along with clinopyroxene crystals (Fig. 3f). Sometimes, crystal zoning indicate normal chemical differentiation as crystallization was evolving through time (Fig. 4d). Amphiboles, mostly hornblende, is usually forming euhedral grains with characteristic zoning. Locally, replacement by opaque phases suggest minor opacitization processes. Resorbed quartz phenocrysts, always rimmed by clinopyroxene rims are uncommon (Fig. 3e). Vesicles are abundant and in some cases are filled with euhedral clinopyroxene (Figs 4a-b). Clinopyroxene is also present as euhedral to subhedral isolated phenocrysts (Fig. 4c) or even as glomerophyric aggregates (Fig. 3f). Titanite may occur as a rare accessory mineral. Finally, opaque phases, commonly hematite and or ilmenite are quite abundant, scattered in the vitreous matrix.

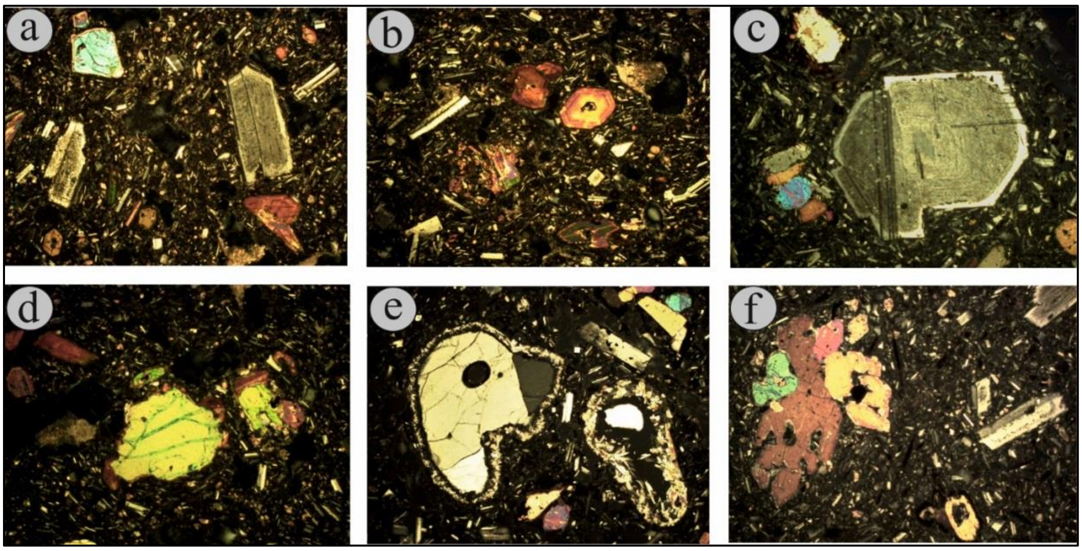

Fig. 3: Photomicrographs of the Agios Ioannis volcanic rocks, taken under cross-polarized light: (a, b) The studied volcanic rocks are composed on various phenocrysts (sanidine, olivine, clinopyroxene) and numerous microlites set in a vitreous matrix (x5 magnification). (c) Zoned plagioclase phenocryst rimmed by K-feldspar (x5 magnification). (d) Anhedral olivine phenocryst (x10 magnification). (e) Resorbed quartz phenocrysts rimmed by fine-grained laths of clinopyroxene (x2.5 magnification). (f) Glomerocryst composed of clinopyroxene and olivine (x5 magnification).

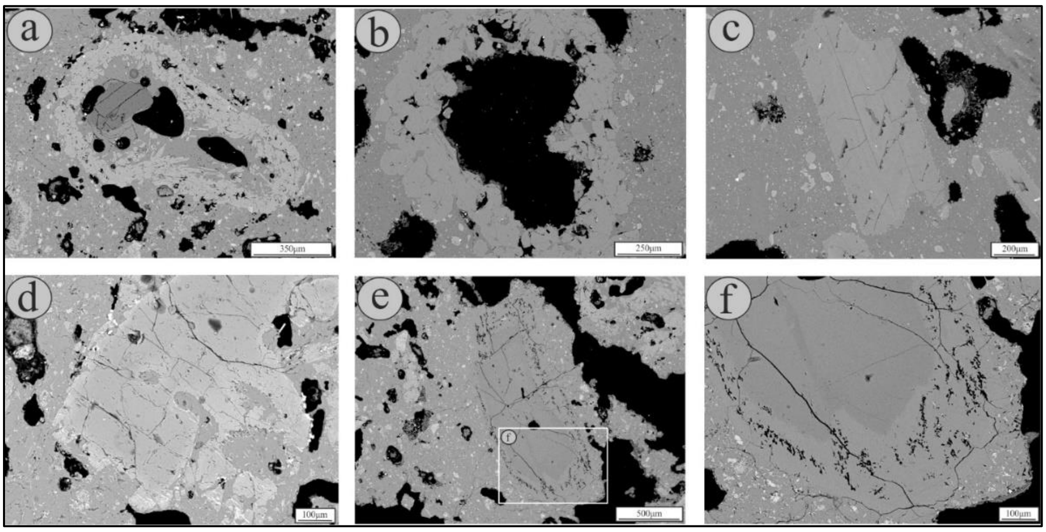

Fig. 4: SEM-BSE images of the major mineralogical constituents of the Agios Ioannis volcanic rocks: (a, b) Vesicles rimmed by euhedral, fine-grained clinopyroxene crystals. (c) Subhedral clinopyroxene crystal. (d) Olivine phenocryst displaying an embayed

crystal shape and compositional differentiation indicated by a bright, Fe-rich peripheral zone (e, f) Plagioclase rimmed by K-feldspar.

Mineral chemistry

Feldspar group minerals

Chemical analyses displayed significant variations (Table 1) between Ca, Na and K, in the analyzed feldspar group minerals from the studied samples. Plagioclase composition ranges from andesine to labradorite (An_{30}-An_{69}), while few analyses yielded higher anorthitic component, corresponding to the field of bytownite (An_{73}, Fig. 5a). A zonation is commonly observed: cores are Ca-rich, while Na content is gradually increasing towards the rims of the crystals. In some cases, plagioclase crystals are rimmed by a thin K-feldspar rind (Figs 4e-f), corresponding to sanidine composition which shares the same chemistry with isolated sanidine phenocrysts which are embedded in the matrix.

Clinopyroxene

Analyzed clinopyroxene crystals revealed a relatively narrow compositional range between augite and diopside, with the latter composition being more common (Table 1, Fig. 5b). Al_2O_3 content is varying significantly (up to 4.52 wt. %), while FeO and MgO content display a quite significant variation, from 5.45 wt.% to 6.95 wt.% and from 13.98 wt.% to 16.39wt.%, respectively, which is reflected in zoned clinopyroxene phenocrysts. CaO values range between 21.46 wt.% and 23.39 wt.%, while traces of TiO_2 were also detected (up to 0.9 wt.%) in some crystals.

Olivine

Available mineral-chemical data from olivine crystals (Table 1) display a normal zonation in the crystals. Fo values are varying significantly, and reflect the increase of FeO content which characterizes the rims of the grains. The cores are typically Mg-rich, with MgO content ranging from 43.08 wt.% to 47.49 wt.%, corresponding to forsteritic component between Fo82 and Fo88. On the other hand, rims display lower MgO values followed by elevated FeO content, which range from 21.07 wt.% to 28.82 wt.% (Fo77 and Fo67 respectively, Fig. 5c) and reflect normal disequilibrium crystallization processes. Analogous high-Fo olivine have been described from lamproites in Lesvos island, that include both trachyandesite and basalt compositions and have been interpreted as direct supply from a mantle source (Pe-Piper et al., 2014).

Amphibole

Analytical data from amphibole grains revealed small compositional differences (Table 1). They are characterized by relatively stable Al_2O_3 and FeO content (13.89 wt.% - 14.47 wt. % and 11.20 wt.% -12.01 wt. %, respectively) and variable amounts of TiO_2, Na_2O and K_2O (up to 1.86 wt.%, 2.45 wt.%, and 1.08 wt. % respectively). All amphiboles are classified as calcic and more specifically, according to the diagram proposed by Leake et al., 1997 they plot in the fields of tschermakitic hornblende and tschermakite (Fig. 5d).

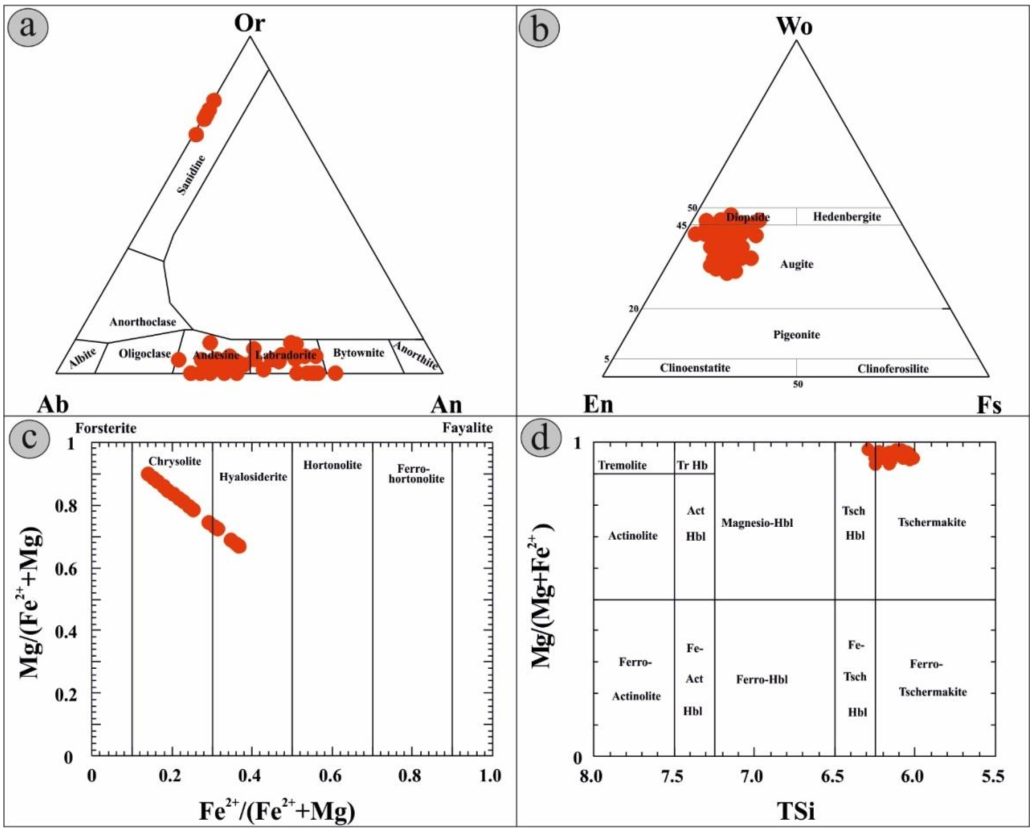

Fig. 5: Mineral classification diagrams of (a) Feldspar group minerals (after Deer et al., 1992), (b) Clinopyroxene (after Morimoto, 1989), (c) Olivine, and (d) Amphibole (after Leake et al., 1997) from the Agios Ioannis volcanic rocks.

Table 1. Representative SEM-EDS analyses from the major mineralogical constituents of the Agios Ioannis volcanic rocks.

No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Wt.%	Feldspar					Olivine				
SiO2	48.04	45.73	56.83	65.3	60.10	38.78	36.89	37.24	39.37	41.28
TiO2	-	-	-	-	-	-	-	-	-	-
Al2O3	29.97	29.84	29.88	16.86	29.2	-	-	-	-	-
FeO	-	-	-	0.96	-	13.53	21.67	24.59	28.32	15.95
MgO	-	-	-	-	-	46.55	40.74	36.95	33.13	43.08
CaO	14.49	19.01	8.88	-	6.12	-	-	-	-	-
Na2O	4.80	3.84	6.05	2.58	7.56	-	-	-	-	-
K2O	-	-	0.79	12.89	0.75	-	-	-	-	-
Total	98.89	98.64	99.05	98.57	98.60	98.86	98.70	98.78	100.82	100.31
	32 (O)					4 (O)				
Si	8.935	8.673	10.229	12.158	10.859	0.981	0.970	0.992	1.034	1.029
Ti	-	-	-	-	-	-	-	-	-	-
Al	6.918	6.730	5.789	3.692	5.125	-	-	-	-	-
Al^{VI}	-	-	-	-	-	-	-	-	-	-
Fe	-	-	-	0.149	-	0.286	0.463	0.548	0.633	0.333
Mg	-	-	-	-	-	1.752	1.597	1.468	1.298	1.604
Ca	2.887	3.861	1.712	-	2.648	-	-	-	-	-
Na	1.731	1.397	2.111	0.931	2.648	-	-	-	-	-
K	-	-	0.181	3.061	0.174	-	-	-	-	-

No.	**11**	**12**	**13**	**14**	**15**		**16**	**17**	**18**	**19**
Wt.%	Pyroxene						Amphibole			
SiO2	52.81	54.75	54.02	53.36	55.73		45.02	41.98	42.40	43.15
TiO2	-	-	-	0.88	-		-	1.75	1.86	1.17
Al2O3	3.77	-	-	4.52	-		14.77	14.40	13.89	14.01
FeO	5.45	5.67	6.95	5.56	5.97		7.95	8.55	8.76	9.02
MgO	15.43	16.27	16.16	13.98	16.39		15.51	15.50	15.42	14.96
CaO	22.19	23.39	22.34	21.69	21.46		11.20	11.49	11.29	12.01
Na2O	-	-	-	-	-		2.45	1.80	1.83	1.78
K2O	-	-	-	-	0.23		0.89	1.08	0.96	0.87
Total	99.65	100.08	99.47	99.35	100.32		97.79	96.55	96.41	96.97
				Formulae based on						
	6 (O)						23 (O)			
Si	1.945	2.013	2.003	1.974	2.004		6.348	6.029	6.092	6.165
Ti	-	-	-	0.025	-		-	0.189	0.201	0.213
Al	0.164	-	-	0.197	-		1.652	1.971	1.908	1.835
Al^{VI}	-	-	-	-	-		0.802	0.466	0.445	0.524
Fe	0.168	0.174	0.216	0.172	0.183		1.047	1.027	1.051	1.078
Mg	0.847	0.892	0.893	0.772	0.924		3.260	3.318	3.303	3.186
Ca	0.876	0.921	0.888	0.861	0.842		1.692	1.768	1.738	1.839
Na	-	-	-	-	-		0.393	0.501	0.510	0.493
K	-	-	-	-	0.011		0.160	0.198	0.176	0.159

Table 2. Major, trace and rare earth elements content of the Agios Ioannis volcanic rocks.

Major Elements (wt. %)				
	KV-1R-2	KV-1R	KV-2R	KV-3R
SiO_2	58.24	57.27	58.85	58.38
TiO_2	0.74	0.68	0.74	0.71
Al_2O_3	17.01	16.99	17.29	17.53
$FeO_{(tot)}$	6.07	6.04	5.93	5.86
MnO	0.12	0.12	0.11	0.11
MgO	4.10	4.10	4.43	4.35
CaO	5.76	5.76	6.01	6.15
Na_2O	3.60	3.59	3.24	3.45
K_2O	3.16	2.86	3.02	3.01
P_2O_5	0.18	0.18	0.21	0.21
LOI	1.60	2.00	1.03	1.75
Total	100.58	99.65	100.86	101.54
Trace Elements (ppm)				
Ba	570	620	670	625
Cs	bd	bd	bd	bd
Nb	20	22	23	21
Rb	114	121	123	110
Sr	390	418	445	405
Ta	4	3	3	2
Th	14	13	14	13
V	123	132	140	125
Zr	208	234	258	224
Y	19	18	19	17
Sc	23	30	37	31
Rare Earth Elements (ppm)				
La	34	32	33	30
Ce	77	74	76	72
Pr	9	8	9	8
Nd	32	30	31	29
Sm	6	6	6	6
Eu	2	1	2	1
Gd	6	6	6	6
Tb	1	1	1	1
Dy	4	4	4	4
Er	2	1	2	1
Tm	bd	bd	bd	bd
Yb	2	2	2	1
Lu	bd	bd	bd	bd

4.2. Whole-rock geochemistry

Both major and trace elements in the studied samples (Table 2) show a limited range of variation. SiO_2 values range between 57.27wt.% and 58.85 wt.%. Al_2O_3 (16.99 to 17.53 wt.%), $FeO_{(tot)}$ (5.86 to 6.07 wt.%), TiO_2 (0.68 to 0.74 wt.%), MgO (4.1 to 4.43wt.%), CaO (5.76 to 6.14 wt.%) Na_2O (3.24 to 3.6 wt.%), K_2O (2.86 to 3.16 wt.%). MnO and P_2O_5 are present in minor amounts (up to 0.12wt.% and 0.21 wt.%, respectively).

The Agios Ioannis volcanic rocks plot at the field of trachyandesite on the total alkalis-silica (TAS) diagram (Fig. 6a; Le Bas et al. 1986). On the K_2O vs SiO_2 classification diagram (Fig. 6b; Peccerillo & Taylor 1976), they plot at the field of the high-K calc-alkaline series. Similar to many SAVA volcanic rocks (Francalanci and Zellmer, 2019). The studied volcanic rocks are depleted in High Field Strength Elements (HFSE), such as Ta and Nb (Fig. 6c) and in heavy-REE (HREE, Fig. 6d), as Innocenti et al. (2010) also noted. Based on the incompatible trace-element patterns, normalized to the primordial mantle composition (after McDonough and Sun 1995; Fig. 6c) and taking under consideration the limited set of the analyzed elements, it could be inferred that the studied samples are presenting the typical pattern of arc-related volcanic rocks (see Ta, Nb and Ti negative anomalies), which is in accordance to Innocenti et al. (2010). Light-REE (LREE) are enriched compared to HREE. They display moderate negative Er and Eu anomalies, which may be due to plagioclase fractionation, changes in fO_2 conditions or crustal contamination of the source.

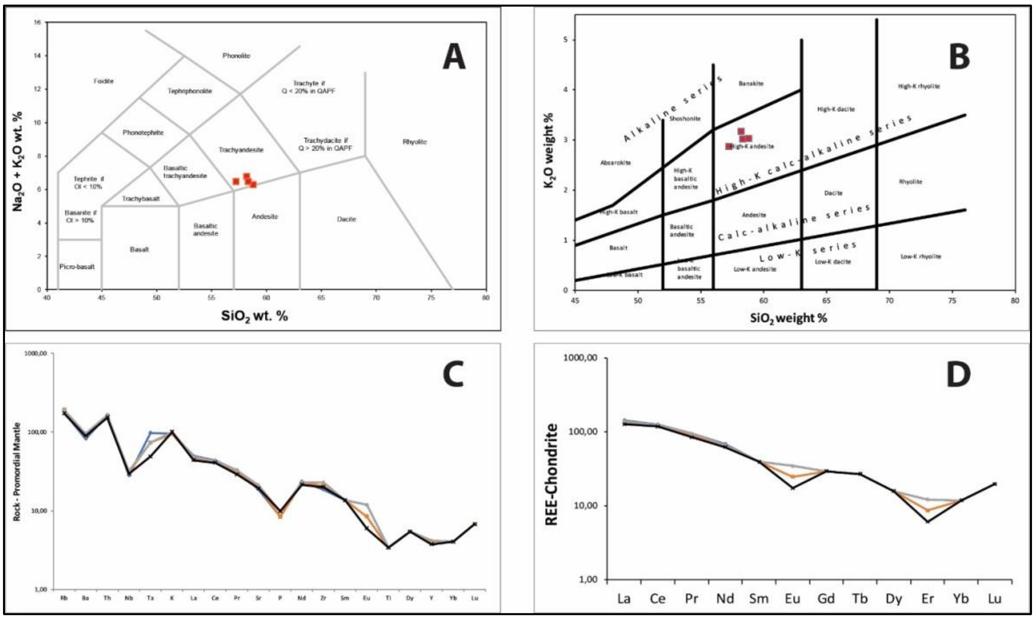

Fig. 6: Geochemical classification diagrams: (A) Na_2O+K_2O versus SiO_2 plot (after Le Bas et al., 1986); (B) K_2O versus SiO_2 plot (after Peccerillo and Taylor, 1976); (C) Primordial mantle-normalized incompatible trace element (after McDonough and Sun, 1995), and (D) chondrite-normalized rare earth element (after McDonough and Sun, 1989) patterns of the Agios Ioannis volcanic rocks. In cases of below detection, the value of half the detection limit was used.

5. CONCLUSIONS

The Agios Ioannis volcanic rocks are characterized as trachyandesites with high-K calc-alkaline affinities, similar to several volcanic rocks from the South Aegean Volcanic Arc. Light-REE are enriched compared to Heavy-REE and moderate negative Er and

Eu anomalies were identified. These could be related to plagioclase fractionation, changes in fO_2 conditions or crustal contamination of the source.

Based on petrological and mineral-chemical results reveal that the Agios Ioannis volcanic rocks are characterized by vitrophyric texture and a matrix dominated by glass, numerous randomly-oriented microlites of plagioclase and minor sanidine, clinopyroxene and amphibole. Phenocrysts comprise plagioclase, olivine, quartz, clinopyroxene and amphibole. Plagioclase composition ranges from andesine to bytownite (An_{30}-An_{73}). Olivine cores are typically Mg-rich, and the rims display elevated FeO content. Analogous high-Fo olivine have been described from lamproites in Lesvos island, and have been interpreted as direct supply from a mantle source (Pe-Piper et al., 2014). Clinopyroxenes display a narrow compositional range between augite and diopside, with the latter being more common. Amphiboles, are calcic and their composition ranges between tschermakite and tschermakitic hornblende.

The Agios Ioannis volcanic rocks comprise a small part of the Lichades volcanic center. A systematic sampling in all outcrops of the Lichades volcanic center, coupled with petrological, mineral-chemical and geochemical analyses are ongoing. The forthcoming results will allow us to study in further detail the Lichades volcanic center in order to compare it to other Greek volcanic rocks of similar age and to integrate them with the geological processes that took place in the area.

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