A West-East Traverse along the magmatism of the south Aegean volcanic arc in the light of volcanological, chemical and isotope data

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ABSTRACT

The volcanic rocks of the South Aegean arc (SAAVA) form a chain from the Gulf of Saronikos (Susaki, Egina, Poros, Methana) at West, to an area close to the Anatolian coast at East (Kos, Nisyros and minor islands), through the central part (Milos and Santorini island groups). The volcanic activity began in the Lower Pliocene at Egina (4.7 Ma) and lasted until present days, with the still active Methana, Milos, Santorini and Nisyros volcanoes. The beginning of volcanism is younger in the central sector of the arc.

Volcanic center location was controlled by large tectonic lineaments, most of them still active, trending E-W to NW-SE for the western part and mainly NE-SW for the central and eastern parts of the arc. Volcanic fields developed along ellipse shaped areas with the longest axis oriented perpendicular to the subduction front.

In the western volcanic fields (Susaki, Egina-Poros-Methana and Milos), volcanic centers are mostly monogenetic and no composite volcanic structures are present. In the eastern sector of the arc, Santorini and Nisyros are important composite volcanoes with caldera structures.

Volcanic rocks belong to the calc-alkaline and high-K calc-alkaline (mainly Pliocenic in age) series. Basalts are mainly present in Santorini island group. Magmas underwent to complex differentiation processes, dominated by crystal fractionation, often associated to crustal contamination and mixing-mingling. Large compositionally

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zoned magma chambers often fed highly explosive eruptions, especially in the central and eastern sectors of the arc.

In the western and eastern parts, potassium content of erupted magmas decreased with time, probably due to the increase of partial melting degree of the mantle source. Trends of evolution tend to pass from calc-alkaline to tholeiitic from West to the Santorini volcanic field, back again to calc-alkaline toward the Nisyros volcanic field. Incompatible trace element contents are lower in Santorini mafic magmas. From West to East, Sr and Pb isotope ratios decrease, whereas Nd isotope ratios increase.

Partial melting of a MORB-like astenospheric mantle, metasomatised by prevailing subducted sediments, is thought to produce the entire spectrum of parental magmas of SAAVA. Slab-derived fluids are generally reduced. Low Ba/La values suggest the occurrence of even lower fluid contents during magma genesis at Santorini. Total amount of subducted sediments involved in the magma genesis decreases from West to East. Alternatively, the West-East ^{87}Sr/^{86}Sr and ^{144}Nd/^{143}Nd variation of the Mediterranean sediments leads to suggest a similar variation in the subducted sediment composition. Most of the geochemical characteristics of the Santorini magmas can be explained by higher partial melting degrees of the mantle source, probably triggered by the greater lithosphere extension, inducing adiabatic upwelling of the mantle. The higher lithosphere extension also caused Santorini magmas to stop at shallower levels, thus preventing amphibole crystallisation and allowing a higher amount of mafic magmas to reach the surface.

From the beginning of SAAVA magmatism, occurred in the external parts of the arc, the partial melting degrees of the magma mantle source seem to have increased with decreasing time and going towards the central sector of the arc.

Keywords: Magmatic arc, volcanology, geochemistry, magma genesis, Aegean Sea.

1. INTRODUCTION

The Aegean area is one of the most rapidly deforming parts of the Alpine - Himalayan mountain belt, pointed out by the extremely high number of the seismic events occurring in this area. Geophysical data record a thinned continental crust in all the Aegean area and an anomalous heat flow, implying a complex geodynamic - geotectonic setting (Papazachos et al., this volume, Mountrakis et al., this volume, Pe-Piper and Piper, this volume and references therein). Deformation seemed to be dominated by the effects of the westward motion of the Anatolian block (~20 $^{mm}/_{y}$), the southwestward motion of southern Aegean (~30-35 $^{mm}/_{y}$) and the vertical movements of big lithosphere portions. Alternatively, differential convergence rates between the northeastward directed subduction of Africa relative to the hangingwall disrupted Eurasian lithosphere (faster motion of Greece relative to Cyprus-Anatolia), however, have been recently proposed in order to determine the Aegean extension (Doglioni et al., 2002 and references therein).

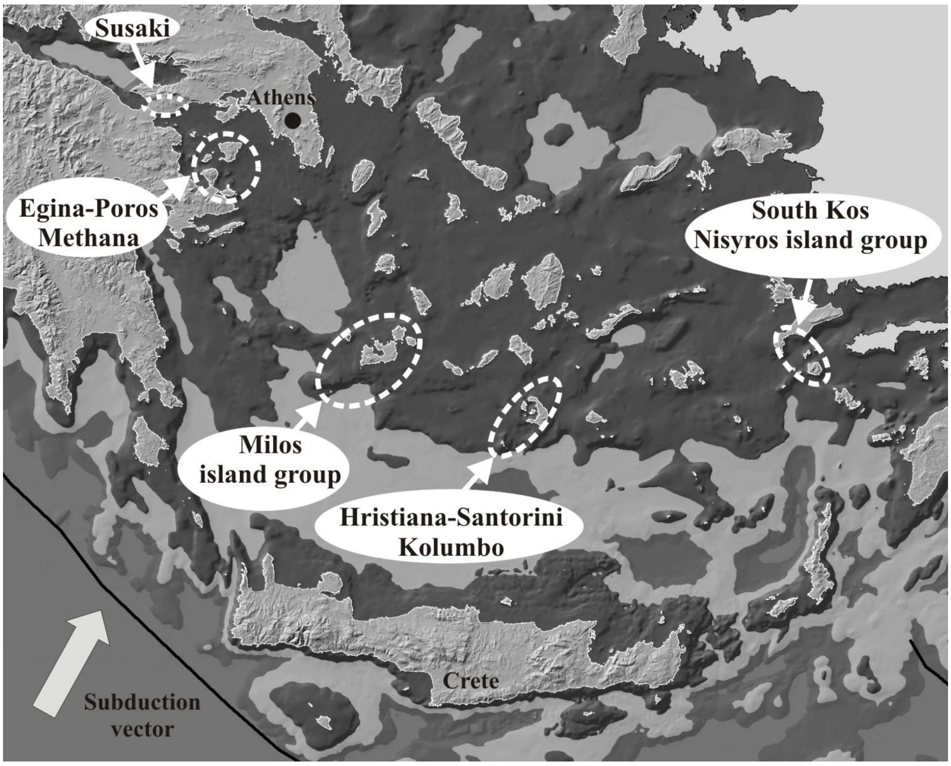


Fig. 1. The South Aegean active volcanic arc fields (dashed white curves).

Calc-alkaline (CA) and high-K (HK) calc-alkaline volcanic activities were manifested in Plio-Quaternary along a restricted belt, which extends in an arc form from Susaki to the west to Nisyros island to the east, the so-called South Aegean Active Volcanic Arc (SAAVA) (Fig. 1). This arc hosts the active (Methana and Santorini) and potentially active (Milos and Nisyros) Hellenic volcanic centers. The correspondence of the active volcanic arc over a Benioff zone at a depth of about 110-130 km is an evidence for the role of subduction in the genesis of the arc (e.g., Innocenti et al., 1981; Manetti, 1997; Pe-Piper and Piper, 2002).

The volcanism is voluminous, with subaerial volumes for the volcanic fields up to 100 km^3. Volcanic field and volcanic center shapes and distribution appear to be associated with big tectonic lineaments and active faults whose trending changes from West to East of the arc. The central and eastern sectors of the arc are characterised by large composite volcanoes, with caldera structures (Santorini and Nisyros), whereas the western sector is mainly characterised by small, often monogenic, eruptive centers.

The products of this volcanism form a typical calc-alkaline association, which displays a continuous evolution from basalts to rhyolites. Their chemical characteristics are closely comparable with those of the volcanics of island arcs sited on thin continental margins. Andesites and dacites are dominant, but less evolved members (basalts and basaltic andesites) are also common (about 25% of the total erupted products) in the central-south part of the arc.

In this paper, we summarise the main geological-volcanological characteristics of the SAAVA fields. We also discuss the available chemical, isotopic and petrological dataset, based on more than 1500 analyses, in an attempt to highlight both common features and differences and try to interpret them in the known geodynamic context of the South Aegean area.

2. VOLCANOLOGICAL AND GEOCHEMICAL CHARACTERISTICS OF THE SAAVA FIELDS

The South Aegean Volcanic Arc Province, intended in the classical meaning of the term as petrologically broadly homogeneous rock association, consists of five different volcanic fields: a) Susaki, b) Egina-Methana-Poros, c) Milos island group, d) Santorini island group and e) Nisyros island group-South Kos island (Fig. 1).

2.1. Susaki

For Susaki area (Fig. 2), the term volcanic field is not probably the most appropriate, as volcanic outcrops are of limited extension (total volume less than 1 km^3) and scattered in a large area. Volcanic centers are monogenetic, comprising dacitic lava domes and associated lava flows. Outcrops are found in two subgroups: the western one gather the oldest centers (3,6-4,05 Ma, Bellon et al., 1979, Collier and Dart, 1991), whereas the eastern one comprise the youngest lavas (2,7-2,3 Ma, Fytikas et al., 1976; Schroder, 1976). Both the vent distribution and the shape of the edifices are controlled by the E-W and the NW-SE tectonic lineaments of the area, which were present since Pliocene and continue to be active up to the present. The NW trending extensional tectonic lines, which are considered also as the youngest ones, mostly seems to control the eastern group (Mettos et al., 1988; Pavlides, 1993; Stiros, 1995). In the coeval lacustrine deposits, which surround the volcanic outcrops, a few layers of tuffs and tuffites are found, documenting a subordinate explosive activity related with the emplacement of the lava domes (Mettos et al., 1988).

The Susaki area host today a low enthalpy geothermal field, with a max temperature of 80 ^{o}C at a depth of 200 m, as well as a weak fumarolic activity with low temperature, CO_2-H_2S rich, hot gasses (30-40 ^{o}C). Both hydrothermal fluid circulation and hot gas outpouring lead to an extensive argilization-

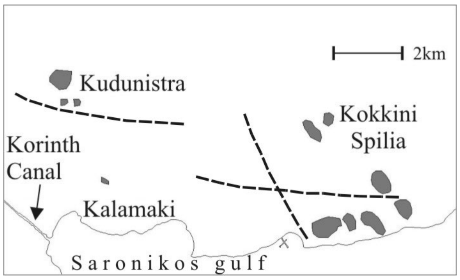


Fig. 2. The Susaki volcanic area. Gray areas: volcanic outcrops. Dashed lines: main tectonic lineaments.

silicification of the rocks in the area.

The volcanic products are HK dacites and rhyolites (Fig. 3) with a glassy groundmass and phenocrysts of plagioclase, biotite and quartz. $^{87}Sr/^{86}Sr$ ratios are high, with values around 0.713 (Fytikas et al., 1986a; Pe-Piper and Hatzipanagiotou, 1997).

2.2. Egina-Poros-Methana volcanic field

This magmatism occurs in the Gulf of Saronikos, a tectonic depression which started to form in the Pliocene. The volcanic activity developed in three limited areas starting from lower Pliocene (Egina) to historical time (Methana) (Fig. 4).

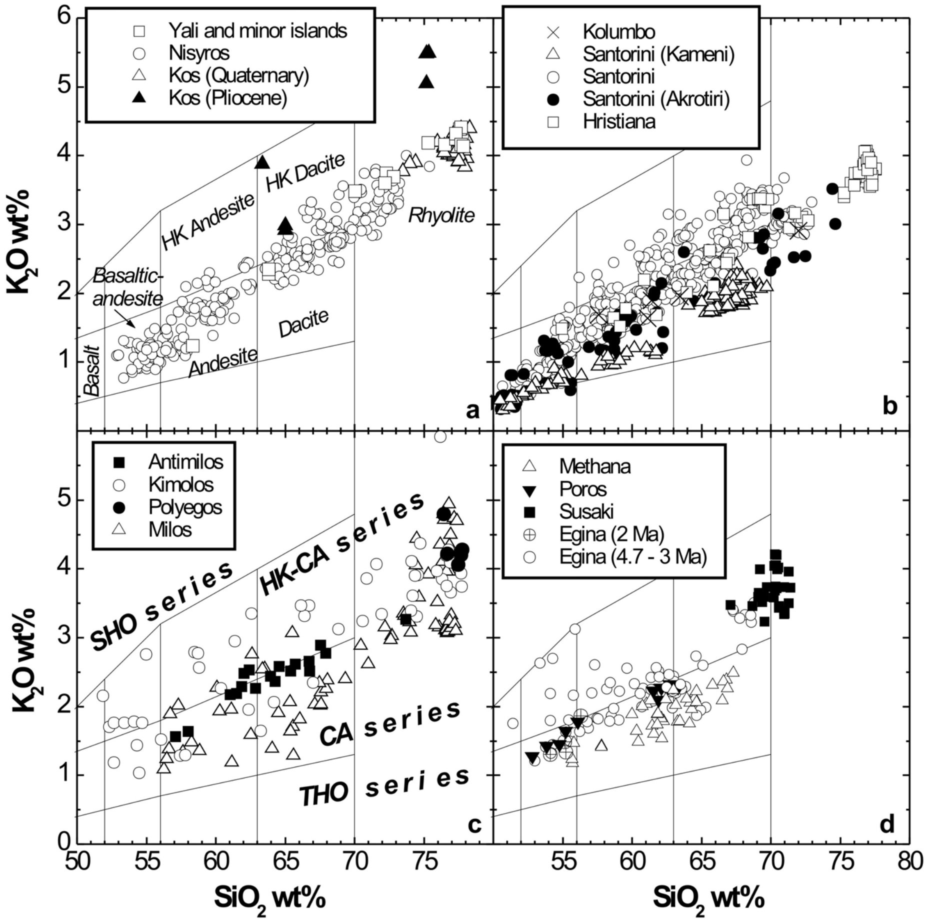


Fig. 3. K_2O versus silica classification diagrams (Peccerillo and Taylor, 1976) for all the SAAVA fields. Data are reported on water-free bases. SHO: shoshonitic, HK-CA: high-K calc-alkaline, CA: calc-alkaline, THO: tholeiitic. See text for the data font.

2.2.1. Egina

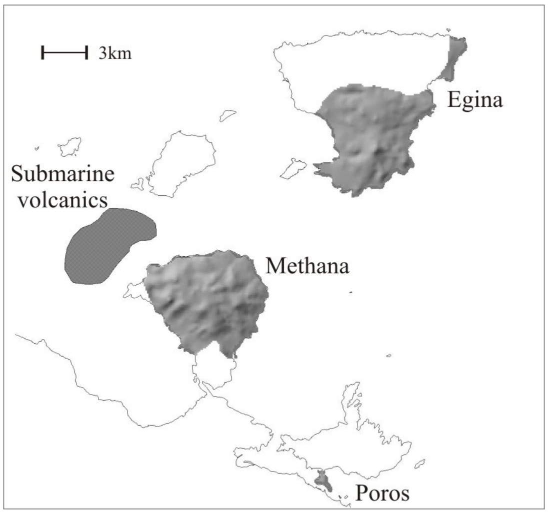


Fig. 4. The Egina-Poros-Methana volcanic field.

Egina island (Fig. 5) is formed by volcanic products for about 2/3 (about 55 km^2) of its area. Volcanic activity started in the Lower Pliocene (Muller et al., 1979; Pe-Piper et al., 1983; Fytikas et al., 1986a). Between 4,7 and 4,3 Ma a variety of volcanic products, from rhyodacitic pumice flows and tuffites to andesitic pillow lavas and hyaloclastites, were deposited by different centers in a shallow submarine environment. From 3,9 to 3,0 Ma the main phase of the volcanic activity was manifested, building up the central and southern Egina island. Extrusion of dacitic to andesitic magmas built up lava domes and dome complexes with associated lava flows, in mainly subaerial environment.

Between 3,0 and 2,1 Ma a low rate eruption period probably occurred: two samples coming from debris flows gave K-Ar ages of 2,5 and 2,2 Ma (Matsuda et al., 1999). At 2,1-2,0 Ma the last eruptive period on Egina occurred, producing subaerial andesitic and basaltic andesitic lava domes and associated flows.

The distribution of the volcanic centers and the shape of the edifices is mainly controlled by the active tectonic lines trending E-W and ENE-WSW In some cases, NW-SE trending lineaments had also an important role.

Egina hosts a hot spring (25 ^{o}C) in its north coast, and low temperature (30-40 ^{o}C) geothermal reservoirs at a depth of a few hundred meters.

The rocks composition ranges from basaltic andesites to dacites of CA and HK-CA serial affinities (Fig. 3).

Lavas are generally porphyritic; basaltic andesites and andesites have phenocrysts of plagioclase, augite, hornblende, magnetite and minor olivine and hypersthene, whereas dacites contain phenocrysts of plagioclase, hornblende, magnetite and minor clinopyroxene.

Mg-values [molecular Mg/(Mg+Fe)*100] are up to 70. TiO_2 (0.6-0.9 wt%) and K_2O (1.2 – 3 wt%) contents are quite scattered among basaltic andesites. The youngest rocks tend to have lower potassium contents, being CA basaltic andesites (Fig. 3). $^{87}Sr/^{86}Sr$ ratios range from about 0.704 to 0.7067 in rocks with silica less than 56 wt% and remain around 0.706 in the most evolved rocks (Pe, 1975; Pe-Piper and Piper, 1979; Fytikas et al., 1986a; Mitropoulos et al., 1987; Gulen, 1989).

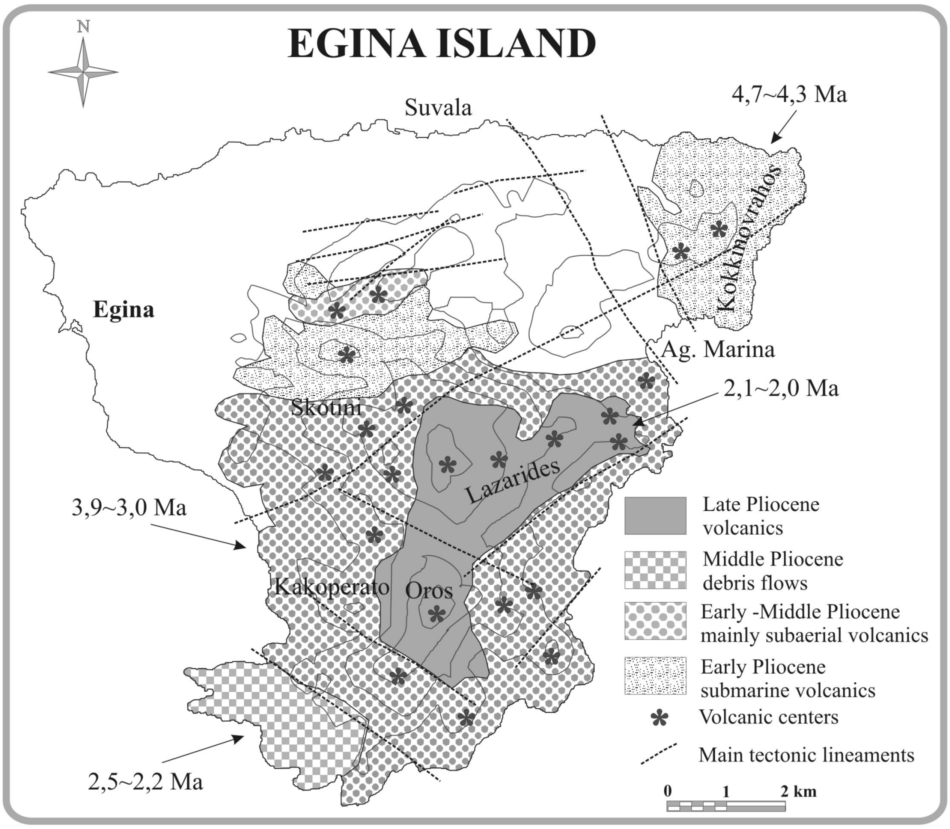


Fig. 5. Egina island geological sketch map (modified from Fytikas et al., 1986a).

2.2.2. Poros

On Poros island one limited outcrop (about 1 Km^2) of a lava dome and associated lava flows, with a K-Ar age of 3,1-2,6 Ma is found (Fytikas et al., 1986a; Matsuda et al., 1999). This volcanic center is located in the eastern edge of the ENE-WSW trending active Trizina graben.

The rocks are evolved andesites with silica between 60.7 - 63.5 wt% and Mg-values around 55. They are porphyritic with phenocrysts of plagioclase and clinopyroxene. The magmatic enclaves found in the lavas are basaltic andesites with Mg-values up to 67, thus a compositional gap (silica between 56 - 61 wt%) is present between the compositions of the host rocks and the enclaves (Fig. 3). The available three data of $^{87}Sr/^{86}Sr$ on andesites are variable and quite high, ranging from 0.7058 to 0.7074 (Pe, 1975; Fytikas et al., 1986a; Mitropoulos et al., 1987).

2.2.3. Methana

Methana peninsula (Fig. 6) is characterised by the youngest volcanic products of the whole Saronikos area: the oldest K-Ar dated products are of 0,9 Ma and older volcaniclastics were also probably deposited in Quaternary. The youngest volcanic event built up the Kameno Vuno andesitic dome and the associated flow at about 230 BC (Strabo, Geographica).

Volcanic edifices are lava domes and dome complexes, with associated lava flows, block and ash flows and related debris flows. The presence of distinctive lithosomes and the absence of guide levels do not permit an accurate reconstruction of Methana volcanic history. Different data agree for a nearly continuous low rate production activity for the whole active period. Vent distribution and edifices shape seems to be

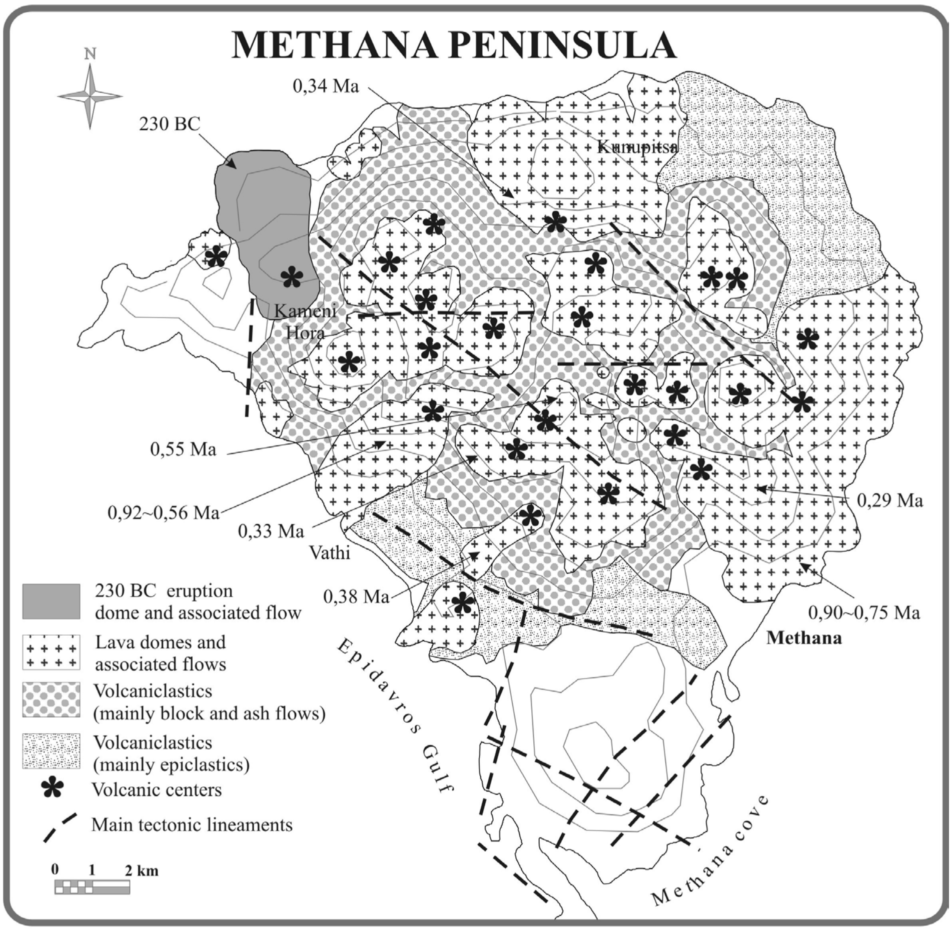


Fig. 6. Methana peninsula geological sketch map (modified from Fytikas et al., 1986a).

controlled by both E-W and NW-SE trending tectonic lineaments.

A few km NW offshore of the Kameno Vuno center, submarine volcanics have been identified (Fig. 4) (Papanikolaou et al., 1988). The age of these volcanics has been estimated at about 1,0 Ma, based on the thickness of the sedimentary cover (Pe-Piper and Piper, 2002).

The volcanic rocks are mainly CA andesites and dacites, with rare basaltic andesites (Fig. 3), and generally show a lower potassium content than those of Egina and Poros.

Plagioclase, clino- and orthopyroxene, and magnetite constitute the phenocryst paragenesis of andesites, whereas in the dacites, plagioclase and magnetite are associated with horneblende and biotite.

Major and trace element contents are generally well correlated with silica and Mg-values are up to 65. TiO_2 contents of the most mafic rocks are around 0.8 wt%. Sr isotope ratios range from about 0.7057 to 0.7066; they do not show a clear correlation with the degree of magma evolution (Pe, 1975; Fytikas et al., 1986a; Mitropoulos et al., 1987; Gulen, 1989).

2.3. Milos volcanic field

Milos, Kimolos, Polyegos and Antimilos islands, as well as Ananes islets, are almost entirely constituted by volcanic products (Fig. 7). The activity started about 3.5 Ma ago in Milos and Kimolos and continued up to recent time with hydrothermal explosions in Milos.

Milos island group is the third SAAVA field with no important central volcano structure. Only Antimilos center could be considered a composite volcano, built up by lava flows and volcaniclastics, as well as acid lava domes and associated flows (Marinos, 1960; Fytikas et al., 1986b).

Milos, Kimolos and Polyegos islands are compound volcanoes constituted by different volcanic edifices, mainly lava domes resulting from limited vent migration, which intrude thick volcaniclastic deposits (Fytikas et al., 1986b; Fytikas and Vougioukalakis, 1993; Francalanci et al., 1994, 2003; Stewart and McPhie, 2003).

The oldest K-Ar date on the lowest volcanic outcrops in the SW coast of Milos island, gave an age of 3,5 Ma (Fytikas et al., 1986b). Biostratigraphic - magnetostratigraphic data and astronomical polarity time scales (APTS) correlations from the marine sediments deposited before the onset of the volcanic activity in South Milos (Van Hinsbergen et al., 2004) gave similar results (4,5-3,7 Ma). It is not clear if the volcanic ash layers of older ages (between 6 and 4,6 Ma) intercalated in these sediments are early volcanic events from Milos centers or they have

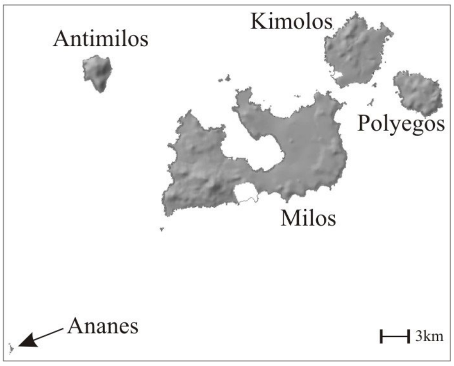


Fig. 7. Milos volcanic field.

been deposited as distal ash from Northern Aegean centers (Antiparos, Patmos).

From 3,5 to 1,6 Ma, alternation of explosive and extrusive activity built up Kimolos, Polyegos and most of the present Milos island (Figs. 8-10). Ananes islets volcanic center is probably one of the earliest in the area. Extensive hydrothermal alteration of the outcropping volcanic rocks does not permit any dating or stratigraphic correlation with the rest of the Milos island group outcrops.

During most of this period, Milos volcanites were deposited in submarine environment, while Kimolos was partly emerged since about the middle of Pliocene. The presence of a large intrusive body in the subsurface of Kimolos area was detected by geophysical exploration, by very limited outcrops, as well as by numerous lithic fragments in the pyroclastic deposits. This is probably the cause of the rapid uplift of this part of the volcanic field.

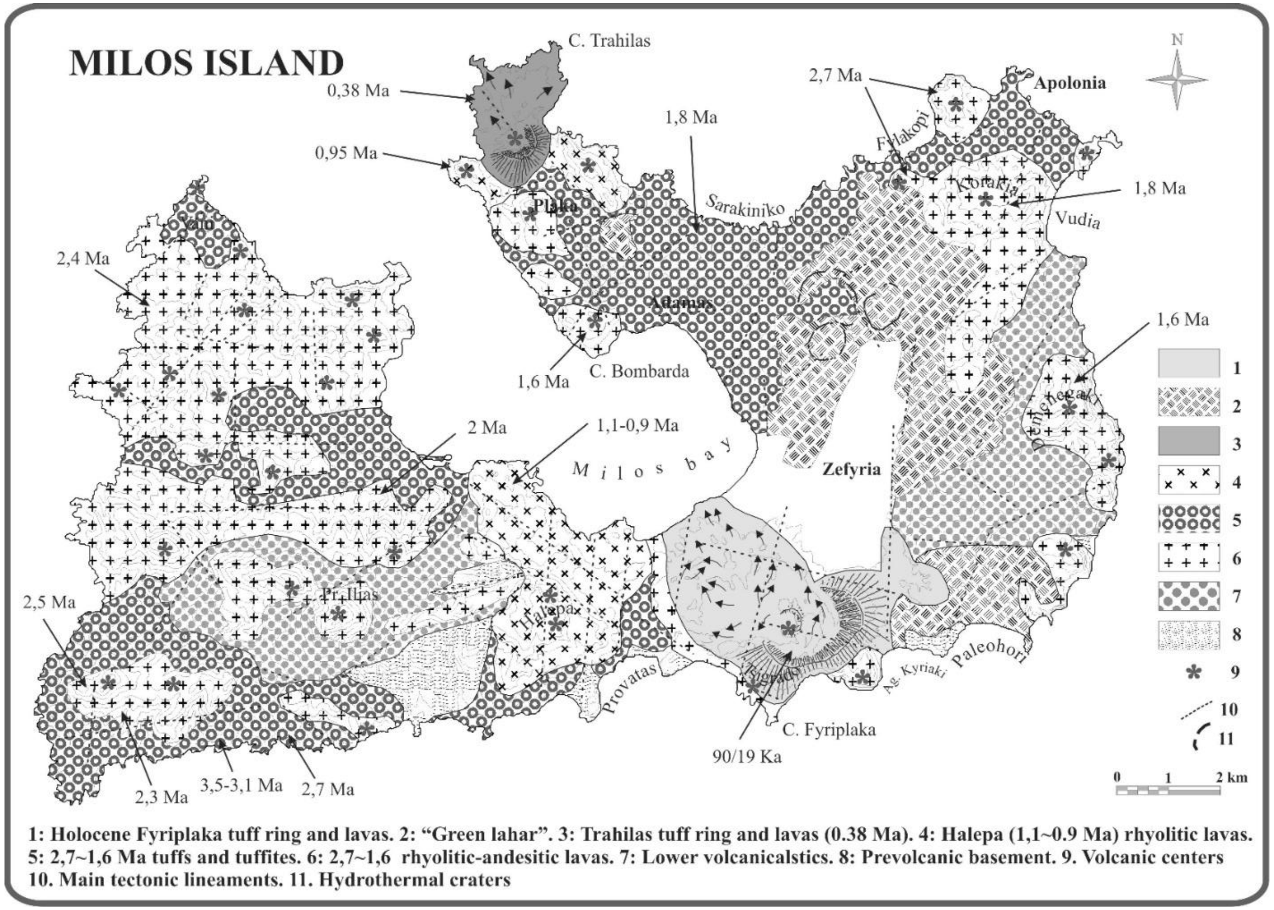
Volcanic vent distribution and shape of the edifices is clearly controlled in the whole area by NE-SW to E-W trending lineaments, with a subordinate role of the N-S lineaments.

During Quaternary, volcanic activity fed by acid magmas was concentrated in central Milos island and in Antimilos. It developed in three distinctive periods. Between 1,1-0,9 Ma huge rhyolitic extrusive activity was focused in a N-S trending area of central Milos, building up a huge lava field and some lava domes. At about 0,38 Ma the perlitic Trachylas tuff ring and associated rhyolitic flows were built up in the northern extent of previous N-S trending lineament. The rhyolitic domes intruding the southern part of Antimilos volcano have the same age. The last volcanic event on Milos occurred in Holocene (90 Ka according to a K-Ar dating by Fytikas et al., 1986b; 19 Ka according to fission track dating by Principe et al., 2003) building up the perlitic Fyriplaka tuff ring and associated rhyolitic flows, in the South edge of the N-S trending Zephyria active tectonic graben.

The installation in the East-Central Milos area of a huge geothermal field (320 ^{o}C in 1 km depth nowadays) and the high seismicity of the area since Holocene, had the result of triggering of many large hydrothermal explosions, both before and after the last volcanic eruption. These events deposited in the central-eastern Milos area a vast mantle of debris and mud flows rich in basement schist fragments which was mapped as the "Green Lahar" formation (Fytikas et al., 1986b). Hydrothermal explosions continued up to historic time (80-200 AD, Traineau and Dalabakis, 1989) in the Agia Kyriaki area, where a fumarolic activity with gas temperatures of 100-101 ^{o}C is also present nowadays.

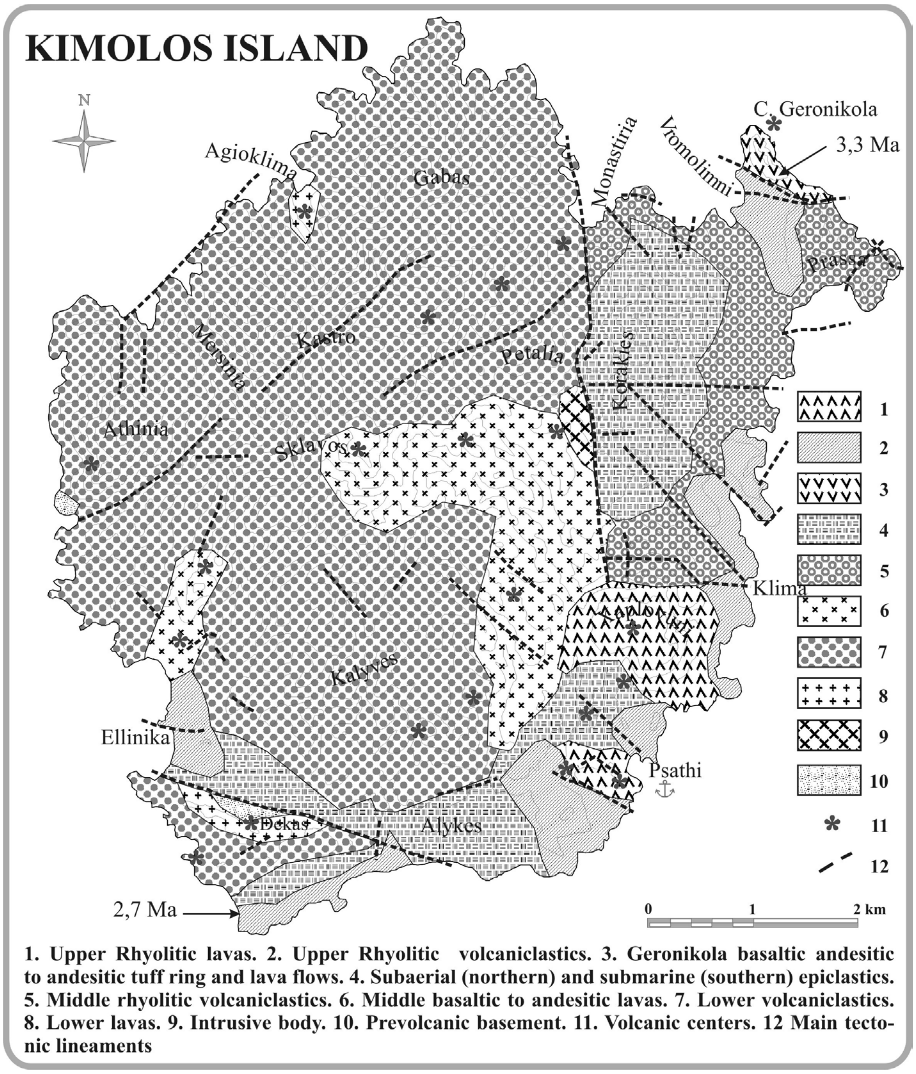
The composition of Milos rocks is mainly CA, with only few samples falling in the HK-CA field of the K_2O versus silica classification diagram (Fig. 3). The most mafic rocks have 56 wt% of silica and Mg-values around 55. They are found together with abundant andesites, dacites and rhyolites. The youngest rhyolites appear to have higher K_2O contents than the oldest rocks.

Most of the rocks are porphyritic with holocrystalline to glassy groundmasses; only some rhyolites are completely glassy (obsidians). Andesites contain phenocrysts of plagioclase, augite, orthopyroxene and magnetite; rare unstable olivine and hornblende



1: Holocene Fyriplaka tuff ring and lavas. 2: “Green lahar”. 3: Trahilas tuff ring and lavas (0.38 Ma). 4: Halepa (1,1~0.9 Ma) rhyolitic lavas. 5: 2,7~1,6 Ma tuffs and tuffites. 6: 2,7~1,6 rhyolitic-andesitic lavas. 7: Lower volcanicalstics. 8: Prevolcanic basement. 9. Volcanic centers 10. Main tectonic lineaments. 11. Hydrothermal craters

Fig. 8. Milos island geological sketch map (modified from Fytikas et al., 1986a).



1. Upper Rhyolitic lavas. 2. Upper Rhyolitic volcaniclastics. 3. Geronikola basaltic andesitic to andesitic tuff ring and lava flows. 4. Subaerial (northern) and submarine (southern) epiclastics. 5. Middle rhyolitic volcaniclastics. 6. Middle basaltic to andesitic lavas. 7. Lower volcaniclastics. 8. Lower lavas. 9. Intrusive body. 10. Prevolcanic basement. 11. Volcanic centers. 12 Main tectonic lineaments

Fig. 9. Kimolos island geological sketch map (modified from Francalanci et al., 2003).

are present. In the dacites, the phenocryst paragenesis is constituted by plagioclase, ortho- and clinopyroxene associated to hornblende, rare biotite and corroded quartz. In the rhyolites, plagioclase, biotite and quartz are invariably present, but amphibole and sanidine only sometime occur.

TiO_2 contents are generally lower than 0.9 wt%. The HK-CA samples generally contain higher TiO_2, Rb, Sr and Zr abundances than the CA samples. Sr isotope ratios largely vary, passing from 0.7037 to 0.7076. This large range is found among rocks

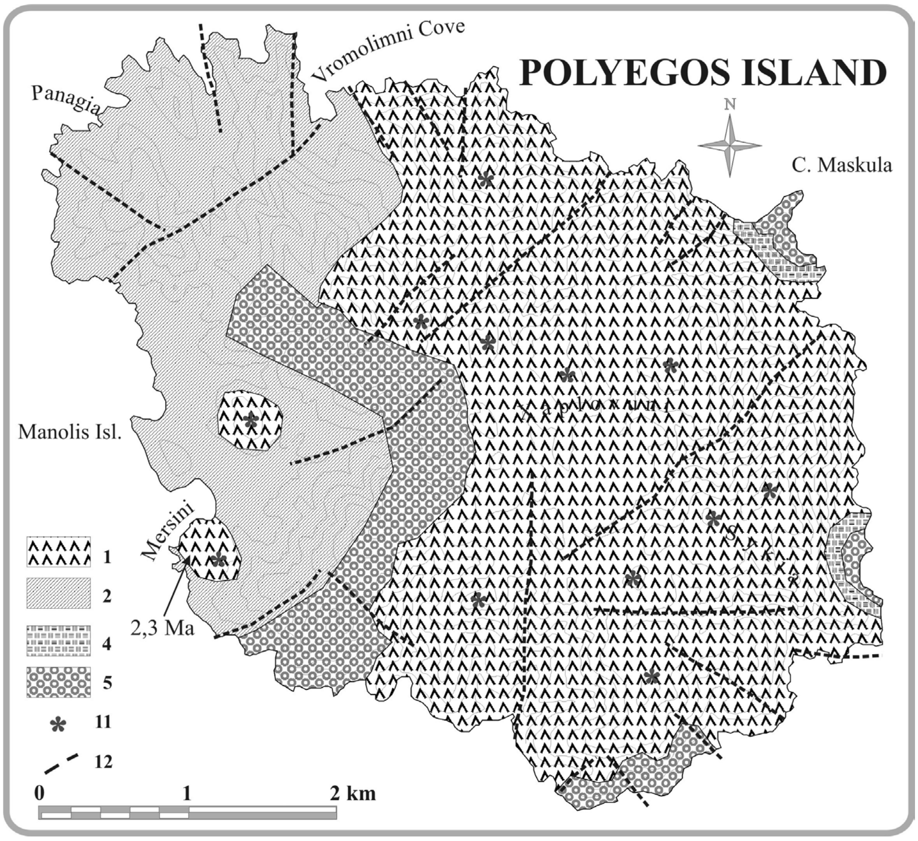


Fig. 10. Polyegos island geological sketch map (modified from Francalanci et al., 2003).

with silica <68 wt%; for rocks with higher silica contents, $^{87}Sr/^{86}Sr$ values generally show a narrower variation, from 0.7051 to 0.7065. $^{143}Nd/^{144}Nd$ values range from 0.51247 to 0.51275 and are negatively correlated with Sr isotope ratios (Innocenti et al., 1981; Barton et al., 1983; Briqueu et al., 1986; Fytikas et al., 1986b, Mitropoulos et al., 1987; Gulen, 1989)

The Kimolos rocks belong to the CA and HK-CA series, ranging from basalts (only few) to rhyolites (Fig. 3). The rocks are variably porphyritic with hypo-crystalline to glassy groundmasses. Olivine is only present in the oldest basalts, where orthopyroxene is lacking. The latter phase is, however, always present in the other rocks becoming accessory in the rhyolites. Clinopyroxene is only lacking in some rhyolites. Plagioclase is ubiquitous and abundant in all the rocks. Hornblende is abundant in dacites and some rhyolites. Biotite, magnetite, sanidine and quartz are also found as accessory minerals in rhyolites.

Mg-values are quite variable also among the most mafic rocks ranging between 65-42. TiO_2 contents of mafic rocks are quite high, varying between 0.9-1.4 wt%. The

Kimolos rocks, except for the youngest ones, generally display higher TiO_2, K_2O and incompatible element contents and lower Sr abundances and Mg-values than the Milos and Antimilos rocks. The youngest products, however, are more similar to the Milos and Antimilos rocks with the same degree of evolution. As for potassium contents, the Kimolos rhyolites are similar to the youngest rhyolites of Milos. The $^{87}Sr/^{86}Sr$ values are between 0.7045-0.7064, displaying a narrower range in respect with the Sr isotopes of Milos (Fytikas et al., 1986b; Francalanci et al., 1994, 2003).

The Polyegos rocks are all rhyolites similar in composition to the Kimolos rhyolites (Fig. 3). Even the Sr isotope ratios are in the range of the most evolved rocks of Kimolos. The Polyegos rocks have glassy, often perlitic, groundmasses with abundant plagioclase and accessory amount of orthopyroxene, hornblende, biotite, magnetite, sanidine and quartz (Fytikas et al., 1986b; Francalanci et al., 1994, 2003).

In the K_2O – silica classification diagram the Antimilos rocks fall at the boundary between the CA and HK-CA series. They are mainly andesites and dacites, with rare rhyolites (Fig. 3).

These rocks are variably porphyritic with hypo-crystalline to glassy groundmasses. Olivine is rarely present in the less evolved members. Orthopyroxene is present only in the evolved rocks becoming accessory in the rhyolites. Clinopyroxene is only lacking in some rhyolites. Plagioclase is ubiquitous and abundant in all the rocks. Hornblende is abundant in dacites and some rhyolites. Accessory abundances of biotite, magnetite, sanidine and quartz are also found in rhyolites.

Major and trace element characteristics of Antimilos rocks more strictly resemble those of Milos rocks (Fytikas et al., 1986b).

2.4. Santorini volcanic field

Santorini volcanic field (Hristiana islets, Santorini island group and Kolumbo submarine volcano) (Fig. 11) is found in the central part of the SAAVA. This volcanic field was built up on the thinnest continental crust (~25 km thick) in comparison with the rest of the SAAVA fields and nearest to the max extension area of the Aegean Sea (Cretan basin).

Santorini volcanic field has developed on the northern margin of a basement horst called the Santorini-Amorgos ridge. If extrapolated, the fault defining the northern margin of the horst passes through the centre of Santorini caldera, where it gives rise to a NE-SW zone of surface faulting, vent

Fig. 11. Hristiana-Santorini-Kolumbo volcanic field.

alignments, and gas emission known as the Kameni Line (Heiken and McCoy, 1984; Druitt et al., 1989; Fytikas et al., 1990; Barberi and Carapezza, 1994). Basement rocks which crop out in the south-eastern half of Thira island lie on a continuation of the Santorini-Amorgos ridge. The north-western half of the volcanic field lies within the Anydros graben. The Kameni Line splits the caldera in two halves and played a fundamental role in the structural development of the volcanic field. Historic subaerial vents of the Kameni Islands lie on the Kameni Line and are confined to a 600m-wide elongate zone trending N65°E parallel to it. Vents for at least six prehistoric plinian eruptions also lay on the Kameni Line. The Amorgos 1956 earthquake (Ms 7,5), the largest shallow seismic event of the Aegean area in the past century, was generated along the same tectonic lineament. Present shallow seismic events, which are registered in the area, are also located along the same lineament, mostly concentrated near to the Kolumbo submarine volcano (Dimitriadis et al. this volume).

2.4.1. Hristiana islands

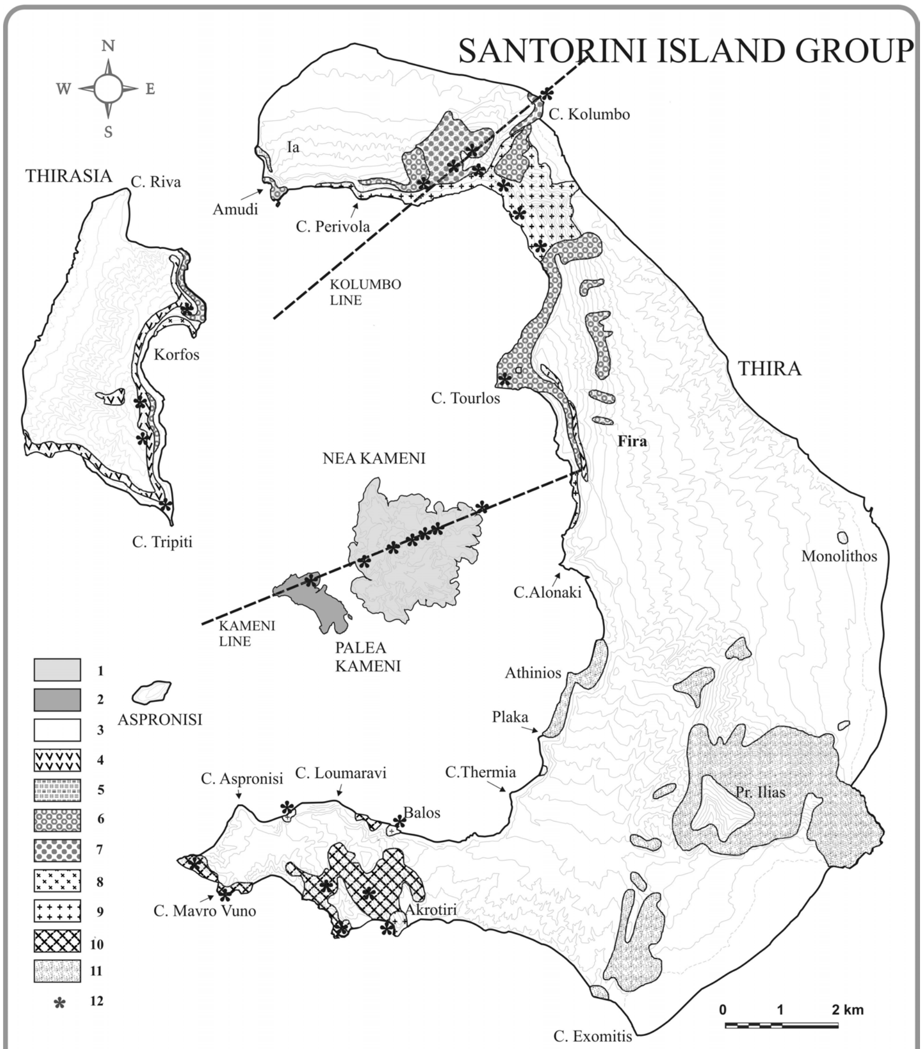
Hristiana islet group (Hristiani, Askania and Eschati) are constituted by lava domes and flows, with some relevant volcaniclastics intercalations (Puchelt et al., 1977; Aarbourg 1998, Aarbourg and Frechen, 1999). Bathymetric and tectonic data (Mountrakis et al., 1998) suggest that the islets are the remnants of a large volcano that has been dissected and submerged. No dating has been carried out on the Hristiana volcanics. Correlation of the Hristiani in situ pyroclastic tuffs with the oldest ash layers mantling the pre-volcanic basement on Santorini (1 Ma, Seward et al., 1980) suggest that Hristiana volcanic activity is the earliest in the area.

The Hristiana rocks are andesites, dacites and rhyolites, with rare basaltic andesites. They belong mainly to the CA series and only some dacites plot in the HK-CA field (Fig. 3). Few rhyolites have around 72 wt% of silica, but most of the rhyolites show silica between 75-78 wt%.

Mg-values are quite variable with a maximum up to 50. The trace element composition of the Hristiana samples generally overlaps that of the Santorini rocks, a part from a slightly higher Nb content of the former samples. The HK-CA dacites and the least evolved rhyolites display higher incompatible trace element contents than the other Hristiana rocks. The most silicic rhyolites are less enriched in Zr, Nb and Rb and seem to more closely resemble the oldest (Akrotiri) Santorini rocks (Aarburg, 1998; Aarburg and Frechen, 1999).

2.4.2. Santorini island group

Santorini is composed of five islands. Thira, Thirasia, and Aspronisi are arranged in a dissected ring around a flooded caldera containing the post-caldera islands of Palea Kameni and Nea Kameni. The caldera is a composite structure resulting from at least four collapse events (Druitt and Francaviglia, 1992), the last of which was triggered by the Minoan eruption (3,6 ka BP). It is bounded by cliffs up to 300 m high and extends to as much as 390 m below sea level. The islands of Palea and Nea Kameni postdate the



1. Nea Kameni lavas (1570.1950). 2. Palea Kameni lavas (46-726 AD). 3. First / second cycle tephra deposits. 4. Thirasia lava shield. 5. Ia andesites (~30 ka). 6. Skaros lava shield (~80-50 ka). 7. North Thira cinder cones and Kolumbo tuff ring (~80-50 ka). 8. Simandiri lava shield (170 ka). 9. Peristeria lava shield and SW Thira cinder cones (530-350 ka). 10. Early submarine Akrotiri centers. 11. Prevolcanic basement. 12 Volcanic centers.

Fig. 12. Santorini island group geological sketch map (modified from Druitt et al., 1999).

Minoan caldera collapse and are the subaerial expressions of a dominantly submarine dacitic shield ~2 km^3 in volume. Complessively, the whole Santorini structure could be defined as a composite volcano (Fig. 12).

Santorini is one of the most violent caldera-forming volcanoes of the world. During the last 360 ka, over a hundred explosive eruptions were manifested. Twelve of these discharged volumes of magma exceeding a few cubic kilometres, and triggered, at least, four caldera collapses. The last of them was the Minoan eruption of the late Bronze Age.

The volcanic evolution of Santorini can be divided into six main stages (Druitt et al., 1989): (1) early centres of the Akrotiri peninsula, (2) cinder cones of the Akrotiri Peninsula, (3) Peristeria Volcano, (4) products of the first eruptive cycle, (5) products of the second eruptive cycle, (6) the Kameni shield.

Among these six stages, the products of the two eruptive cycles are volumetrically the most important. Together they contain the deposits of 12 major explosive eruptions, as well as remnants of at least five large lava shield volcanoes. Deposits of the twelve main pyroclastic eruptions reach 200 m in thickness, eight of them are compositionally bimodal with compositional gaps. Accurate volume estimation is possible only for the Minoan Tuff (30±3 km^3; Pyle, 1990), but the considerable thicknesses, coarse grain sizes, and wide dispersals of the other 11 deposits suggest individual volumes in the range km^3 to tens of km^3 (Druitt et al., 1989).

The two eruptive cycles (4 and 5, above) are recognised on the basis of long-term trends in magma composition. Each cycle commenced with the eruption of mafic to intermediate magmas and terminated with a pair of major rhyodacitic eruptions accompanied by caldera collapse.

The chronostratigraphic evolution of Santorini is mainly based on extensive whole-rock K-Ar and ^{40}Ar/^{39}Ar age determinations (Table 1 in Druitt et al., 1998). Submarine tuffs and tuffites, which outcrop in SW Thira, yield early Quaternary ages (Ferrara et al., 1980; Seidekrantz and Friedrich, 1992) and probably were deposited from both Hristiana and Akrotiri centers. Subaerial volcanic activity on Thira began about 650 ka ago, and continued without significant break until the present day. The onset of major explosive volcanism (cycles 1 and 2) at Santorini took place around 360 ka. Apparent intervals between the twelve explosive eruptions vary between 17 and ~ 40 ka, based on available data. The average recurrence time is 30 ka. The duration of each cycle of explosive activity was about 180 ka.

After the Minoan eruption, volcanic activity continued mainly localised in the intracaldera area. Extrusive, effusive and slightly explosive activity produced the dacitic lava domes, flows and pyroclasts that built up Palea- and Nea Kameni, between 197 BC and 1950 AD (Fouqué, 1879; Washington, 1926; Ktenas, 1927; Reck, 1936; Georgalas, 1953; Georgalas and Papastamatiou, 1953).

The composition of lavas and pyroclastic rocks of Santorini shows a continuous variation from basalts to rhyolites. Basalts plot on the boundary between CA and tholeiitic series, basaltic andesites are all CA, andesites and dacites are mainly CA, but several samples are also found in the HKCA field of the classification diagram (Fig. 3). Basalts are mainly found among lavas and magmatic enclaves whereas, among pyroclastics, basaltic scoriae only occur in one level known as Lower Pumice 2.

Rocks show a variable porphyritic index, which ranges between 5-40 vol%, with the highest values found in the least evolved magmas. Phenocryst assemblages are nearly always dominated by plagioclase. Clinopyroxene follows in order of abundance, becoming less important only in the rhyolites. Olivine is present up to dacites, whereas orthopyroxene appears in the andesites. Magnetite, as microphenocryst, is ubiquitous for rocks with silica > 55 wt%. Rhyolites bearing amphibole, biotite and zircon were only erupted from the early centres of the Akrotiri Peninsula. Amphibole occurs abundantly in cognate mafic inclusions hosted in silicic lavas and tuffs of the early centres of the Akrotiri Peninsula.

Mg-values are up to 70 and, among intermediate and most evolved rocks, they are generally higher in the Akrotiri samples. TiO_2 of the most mafic rocks is between 0.7-1.1 wt% and decreases in Akrotiri rocks. Instead, in Kameni and in the other Santorini rocks, TiO_2 contents tend to increase up to intermediate rocks (1-1.5 wt%) for decreasing again towards more evolved magmas. Kameni and Akrotiri samples have generally lower K_2O, Rb, Zr, Th and Nb contents than the other Santorini rocks. $^{87}Sr/^{86}Sr$ values are between 0.7036 and 0.7054, with rare higher ratios of about 0.7062. They correlate positively with silica and Rb/Sr ratio also among the samples of the same volcanic unit. Kameni magmatic enclaves have higher Sr isotope ratios than the other mafic rocks. $^{143}Nd/^{144}Nd$ values vary from 0.5126 to 0.5129 and show a negative correlation with silica (Barton et al., 1983; Barton and Huijsmans, 1986; Briqueu et al., 1986; Mitropoulos et al, 1987; Huijsmans et al., 1988; Puchelt et al., 1990; Vitaliano et al., 1990; Giovannetti, 1994; Francalanci et al., 1995, 1998; Petrone, 1995; Davis et al., 1998; Druitt et al., 1999; Gulen, 1989, Zellmer et al., 2000).

2.4.3. Kolumbo submarine volcano

Outside the Santorini caldera depression, volcanic activity was manifested historically only once, during 1649-1650 AD building up Kolumbo submarine volcano (Fig. 13). The volcano has been formed by initial submarine extrusion of ~ 2 km^3 mixed andesitic-dacitic lavas. After the emergence of the edifice, hydromagmatic explosive activity built up a tuff ring, which isolated the vent from the sea. The final paroxysmal event occurred in 30/9/1650 and was mainly magmatic of sub-plinian to plinian type, triggering a caldera collapse. The volume of the explosively ejected magma is estimated ~ 1km^3, based on the caldera collapse volume. This was the most hazardous and powerful historic volcanic eruption in the Hellenic territory (Fytikas and Vougioukalakis, 1995; Vougioukalakis et al., 1995). During this eruption more than 70 people dead, volcanic ash covered all the Aegean area, and a big tsunami was triggered.

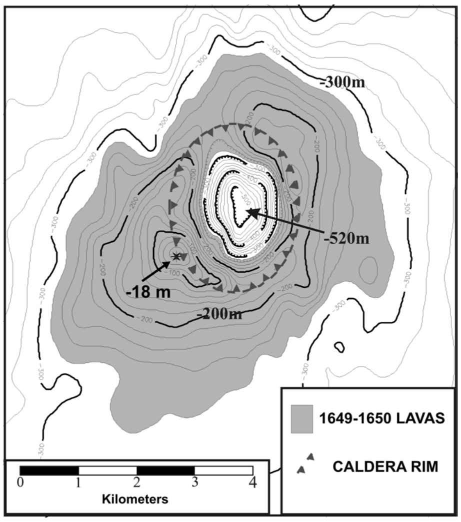


Fig. 13. Interpretative geological sketch map of Kolumbo submarine volcano (from Vougioukalakis et al., 1995).

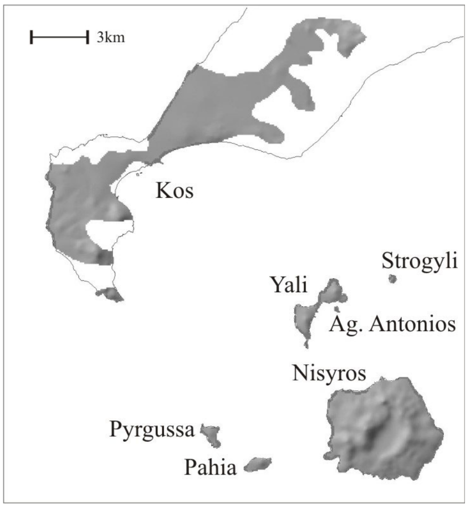


Fig. 14. South Kos-Nisyros volcanic field.

Kolumbo volcanics are typical CA andesites and rhyolites, similar to most of the Santorini rocks, but with higher K_2O content than Kameni rocks (Fig. 3). The mineralogical paragenesis is constituted by plagioclase, clinopyroxene, orthopyroxene, hornblende, biotite, magnetite and ilmenite. Magmatic, more mafic, enclaves are also included in Kolumbos lavas.

Kolumbo rocks have TiO_2 always lower than 0.8 wt% and display higher Sr, Ba, Nb and lower Y than Kameni volcanics. Andesites also have higher light rare earth element contents and lower Sr isotope ratios than Kameni rocks (Vougioukalakis et al., 1995).

2.5. South Kos – Nisyros volcanic field

South Kos, Nisyros and the surrounding islets of Yali, Pahia, Pyrgussa and Strogyli are the easternmost volcanic edifices of the SAAVA (Figs. 1, 14).

The distribution of volcanic centers in South Kos – Nisyros volcanic field indicate that the NW-SE lineaments are prominent on South Kos, controlling both the vent position as well as the shape of the domes. Also Pahia and Pyrgussa islets are located along the SE extention of these lineaments. On Nisyros, both NE and NW trending tectonic and volcanotectonic lineaments are prominent, but the vent distribution is mainly controlled by the NE trending lineaments (Vougioukalakis, 1993).

2.5.1. South Kos

In the South Kos area (Fig. 15), Pliocene volcanic activity built up different scattered dacitic-rhyolitic domes from 3,4 to 1,6 Ma (Bellon et al., 1979; Keller, 1982; Dalabakis, 1986; Keller et al., 1990; Davis et al., 1993). The dacitic domes and related volcaniclastics (about 64 wt% of silica; Fig. 3) of Pyrgussa and Pahia islets, sited west of Nisyros island, are overlain by the Kos Plateau Tuff. There are no dating on these rocks, but their petrological and structural characteristics well correlate with the Pliocene South Kos magmatism.

At about 0,5 Ma, in the Kefalos area, rhyolitic magmas fed firstly hydrovolcanic explosive and later extrusive activities which formed the Kefalos tuff ring and the Zini perlitic obsidian dome. This activity triggered a small caldera collapse in the Kamari bay area (Dalabakis, 1986; Dalabakis and Vougioukalakis, 1993).

At 161 ka BP the last volcanic event on Kos occurred, being the most powerful explosive eruption in the Quaternary Hellenic arc, which emplaced the Kos Plateau Tuff

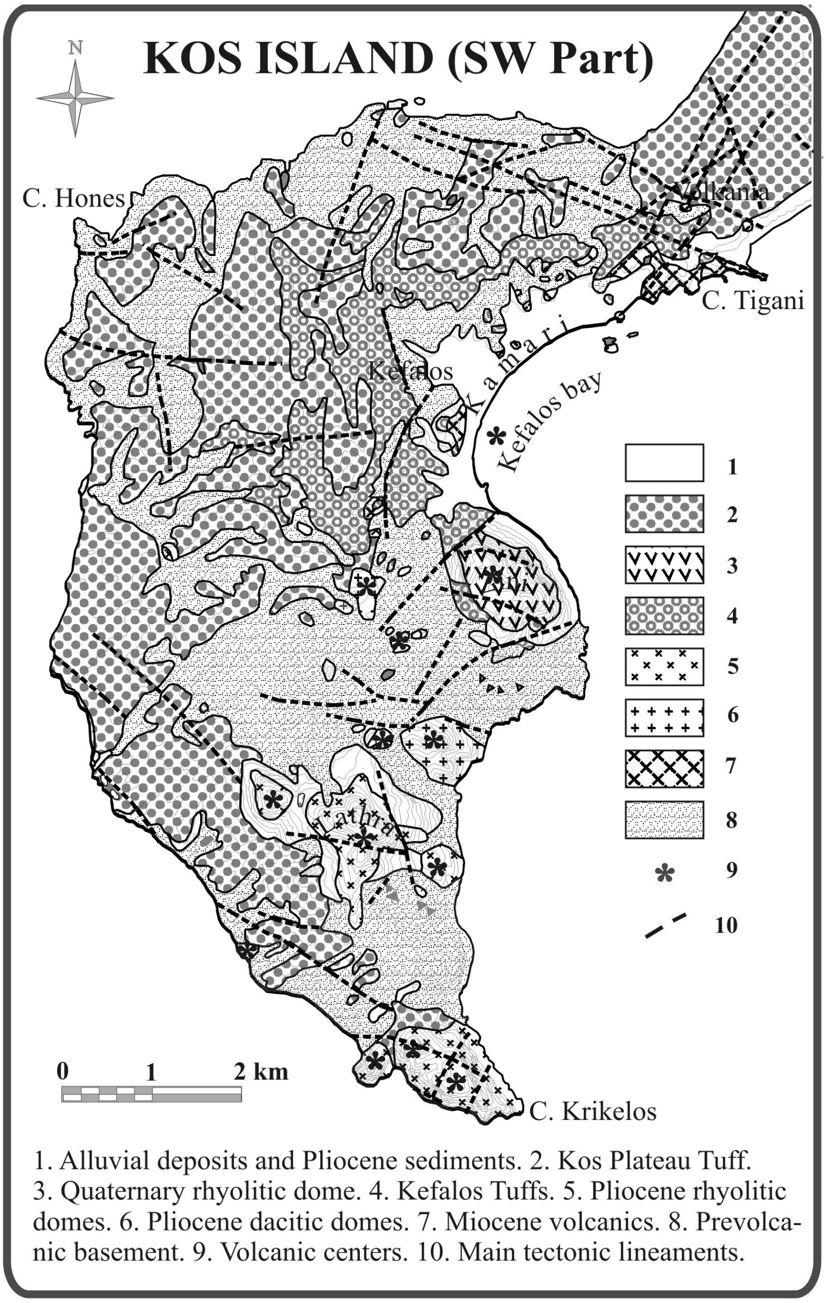


Fig. 15. South Kos geological sketch map (modified from Triantaphylis, 1994).

(Keller, 1969; Dalabakis, 1986; Keller et al., 1990; Smith et al., 1996; Allen and Cas, 1998). More than 100 km^3 of rhyolitic magma was ejected in the atmosphere, which covered with pumice flows an area of ~ 5000 km^2. Kos Plateau Tuff deposits are found on Kalymnos, Pserimos (north of Kos), Pyrgousa, Pahia and Tilos islands (south of Kos), as well as on the adjacent Turkish mainland (east of Kos). Co-ignimbrite ash-layers are found in deep sea sediments 500 km Southeast of Kos, near Cyprus (W-3 deep sea ash layer, Federman and Carey, 1980). The vent of this eruption was localized near to the present south Kos coast, as indicated by extensive lag deposits. A lot of discussion and hypothesis have been formulated for a probable caldera structure and for travelling of the dense pyroclastic flows over the seawater, but both subjects continue to be controversial.

A presumed large flooded caldera in this area has been probably obliterated by post caldera activity. Yali, Strogyli and partially Nisyros volcanic centres are sited in a position which could correspond to post-caldera centres.

The Plio-Quaternary Kos volcanic rocks are mainly acidic products, being mostly constituted by rhyolites and HK dacites. The Quaternary volcanics are only rhyolites, whereas the Pliocene rocks are both HK dacites and rhyolites with higher K_2O contents than younger rocks (Fig. 3).

Pyrgussa-Pahia lavas are strongly porphyritic. Phenocrysts, in order of abundance, are: plagioclase, clinopyroxene, horneblende, biotite, orthopyroxene and magnetite. Groundmass consists of little glass and microliths of plagioclase, pyroxene and magnetite.

Rhyolites have a large variation in all incompatible trace elements and Ni. Pliocene HK dacites tend to have higher La, Ba, Mg-value, Ni and Sr and lower Zr and Nb contents than Nisyros pre-caldera dacites. Sr isotope ratios of HK dacites are around 0.7042 being the only isotope data available in literature (Mitropoulos et al., 1987; Davis et al., 1993)

2.5.2. Nisyros island

Nisyros island is a small (42 km^2) young composite volcano with a central caldera (Keller, 1971, 1980, 1982; Di Paola, 1974; Bond, 1976; Vougioukalakis, 1984, 1989, 1993; Limburg, 1986; Limburg et al., 1986; Bohla and Keller, 1987; Lodise, 1987; Seymour and Vlassopoulos, 1989, 1992; Wyers and Barton, 1989; Keller et al., 1990; Papanikolaou et al., 1991; Limburg and Varekamp, 1991; Gansecki, 1991; Varekamp, 1992; Francalanci et al., 1995; Hardiman, 1996; Volentik et al., 2002) (Fig. 16). The topography resembles the shape of a truncated cone with a basal diameter of 8 km and a central caldera depression of 4 km diameter. The post-caldera domes (youngest volcanic products) excel the caldera rim (~ 450 m high) at a maximum height of 698 m. The whole island is entirely build up of volcanic products, deposited on a basement consisting of Mesozoic limestone and Neogene sediments (Barberi et al., 1988; Varekamp, 1992; Nis-1 drillhole report - Geotermica Italiana, 1983).

Two eruptive cycles are distinguished in the history of Nisyros volcanic activity: the first cycle includes the cone-building eruptive activity and the second one the caldera-

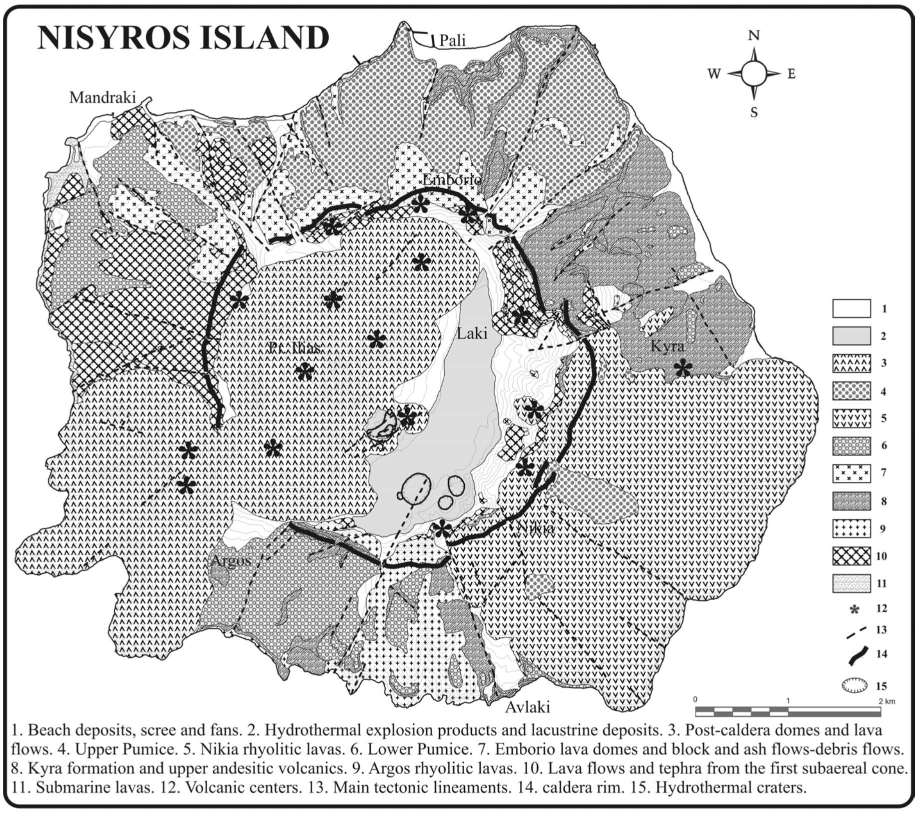


Fig. 16. Nisyros island geological sketch map (modified from Vougioukalakis, 1989).

forming eruptive activity. The second cycle consists of two different phases. Each phase commenced with a low intensity - low magnitude phreatomagmatic explosion fed by rhyolitic magmas. This triggered a central calderic collapse that was followed by extrusion of rhyolitic-dacitic domes and lava flows.

The existing radiometric ages (K-Ar, ^{14}C), tephrostratigraphy and the absence of the Kos Plateau Tuff deposits suggest that the subaerial part of Nisyros was built up during the last 160 ka.

The available radiometric ages of Nisyros rocks are difficult to correlate and still leave some open questions about the time frame of volcanic eruption. K/Ar ages of 66,4 and 24 ka were obtained on the uppermost products of the cone building activity (Rehren, 1988; Keller et al., 1989). According to these data, the earliest caldera collapse should have an age <24 ka. Nevertheless, ages >44 ka were obtained with different methods for the Nisyros Upper Pumice deposits, whereas the age of the Yali Upper Pumice that postdate the last Nisyros caldera collapse is 31 ka (Yali C deep ash layer of Federman and Carey, 1980).

All the historically registered explosions at Nisyros (1873-1887) are hydrothermal and created three small craters in the west area of the remaining caldera floor (Gorceix, 1873, 1874; Martelli, 1917). The presence of more than 8 older hydrothermal explosion craters in the caldera floor, with a maximum diameter of 300m, indicate that this type of activity was frequent in the past few thousand years. The island is today a site of intense hydrothermal activity which feed many fumaroles in the caldera floor area and hot springs along the coast, hosting a high enthalpy geothermal field (fluids with more than 500°C at 1800m depth) (Chiodini et al., 1993).

Active tectonics is prominent on the Nisyros island group. Some of the active faults have been reactivated during seismic crisis manifested in the last century. During the last 1995-1997 shallow earthquake activity, two of these fractures trending N-S and NW-SE were opened on Nisyros and Yali, respectively (Vougioukalakis et al., 1998).

Nisyros is characterised by a nearly continuous series of volcanic rocks, from basaltic andesites to rhyolites. Basaltic andesites and most of andesites are CA, whereas dacites and rhyolites plot along the boundary between CA and HKCA series (Fig. 3).

Rocks have a variable porphyritic index, ranging from nearly aphyric to highly porphyritic (up to 60 vol%). Plagioclase, clino- and orthopyroxene and opaques are ubiquitous, but present in different amount. Plagioclase is always higher than 70 vol%, whereas the others are always lower than 20 vol% of phenocryst content. Olivine is found up to andesites, whereas amphibole is present in dacitic and rhyolitic lavas and in andesitic enclaves. Biotite is rarely present.

TiO_2 contents of the most mafic rocks range between 0.6-1.0 wt%, but tend to increase up to 1.2 wt% in rocks with about 60 wt% of silica. Mg-values are up to 70. Some elements, like K_2O, Rb and Ba, form single and smooth trends with silica, whereas other elements, such as Sr, Zr, Nb, show more scattered variations, with the samples of the post-caldera domes forming nearly distinct trends. The latter rocks tend to have lower Zr, Nb and LREE and higher Sr and Mg-values than the other Nisyros rocks with the same degree of evolution. $^{87}Sr/^{86}Sr$ ratios are mostly between 0.7034-0.7051, with a higher value of 0.7064. Sr isotope ratios are negatively correlated with Nd isotope ratios (0.51258 –0.51282) (Mitropoulos et al., 1987; Wyers and Barton, 1989; Gansecki, 1991; Vougioukalakis, 1993; Francalanci et al., 1995; Innocenti, 1998).

2.5.3. Yali and Strogyli islets

Yali islet is the youngest volcanic centre of Nisyros island group. It is an Upper Quaternary rhyolitic volcanic edifice. Two small hills, with a maximum height of 165m, are connected with a narrow isthmus of alluvial and seashore deposits. The SW part consists entirely of volcaniclastic deposits. The NE part consists of obsidian lava domes and flows with subordinate pyroclastic deposits. Agios Antonios islet emerge between the two hills of Yali and consist of dacitic lavas.

Two volcanic cycles are distinguished, both characterised by an initial explosive eruption that emplaced rhyolitic pumice fall (Lower Pumice - submarine and Upper Pumice - subaerial), followed by extrusions of obsidian-perlitic lava domes and flows. A marine terrace deposit separate these two cycles. Reliable absolute dating are lacking and chronostratigraphy is not well constrained. In any case, Lower Pumice post-date the Kos Plateau Tuff as pumice of this eruption is found as lithics in the Yali Lower Pumice deposits. Moreover, the probable age of 31 ka for the Yali Upper Pumice and 24 ka for the following obsidian domes suggest a quite young age for the second eruptive cycle of Yali (Wagner et al., 1976). This young age leads us to consider this centre as a potentially active volcano.

Strogyli is a steep andesitic cone, lying on a 500 m deep sea bottom and with a top of 120 m above sea level. The Yali Upper Pumice cover the floor of its small central crater, postdating the Strogyli cone formation to an age >31 ka.

Yali volcanics are all rhyolites with silica between 70-78 wt%, whereas Strogyli rocks are less evolved, being andesites with about 57 wt% of SiO_2. In the potassium-silica diagram all the previous rocks follow the same trend of Nisyros and Quaternary rocks from Kos (Fig. 3).

Agios Antonios dacite is porphyritic, with phenocrysts of plagioclase, clinopyroxene, orthopyroxene and magnetite. The Yali pyroclastites are aphyric with rare microphenocrysts of plagioclase and corroded quartz in the Lower Pumice and of plagioclase, hornblende, clinopyroxene and magnetite in the Upper Pumice. The obsidian lavas have rare phenocrysts similar to the previous minerals, but biotite is also present. Strogyli andesites are porphyritic with phenocrysts of plagioclase, clinopyroxene, orthopyroxene and magnetite.

Strogyli andesites have the highest Mg-value of 58. TiO_2 is always lower than 0.6 wt%. Strogyli, Pahia and Pyrgussa rocks have lower Nb and Zr and higher Sr, Ni and Mg-values than the main Nisyros rocks with the same silica contents. Yali rhyolites show higher Zr, Rb and lower Ba and Ni than the Kos youngest rhyolites.

3. PETROCHEMICAL VARIATIONS ALONG THE SAAVA

In spite of the generally similar calc-alkaline character of all the SAAVA magmas, several systematic mineralogical and geochemical variations in space and time occur.

Mitropoulos and Tarney (1992) found several mineralogical differences between Santorini rocks and those from the other volcanic fields. The most evident are those occurring in olivine, amphibole and opaques. Olivine is more commonly present in Santorini, whereas in the rocks of the other volcanic field, it occurs only in the most mafic basalts. Hornblende is usually found as phenocryst in all the volcanic centres except for Santorini, where it is mainly restricted to the Akrotiri lavas, erupted during the early stages of the volcano history. The opaques in Santorini have higher Ti content and Fe^{2+}/Fe^{3+} values, indicating lower oxygen fugacity.

In the external sectors of the arc a general decrease with time of potassium and incompatible trace element contents is observed, contrarily to what is expected for the volcanic arcs. Indeed, in the western part, among the youngest rocks (2 million years old Egina products and Methana peninsula) only CA compositions are found, whereas the older volcanics are CA and HK-CA (Figs. 3, 17a). At East, the only HK-CA rocks are the Pliocene rocks from Kos, but all the younger samples have lower K_2O contents.

At Milos volcanic field this tendency is not clear, even if the youngest rocks of Kimolos are clearly CA. In the central sector of the arc, on the other hand, Hristiana and Akrotiri rocks follow the same trend of the younger Santorini rocks. Only the more evolved Kameni lavas have lower K_2O contents, probably due to different processes of evolution (Francalanci et al., 1998). It is noteworthy, however, that all the volcanics from this central group are Quaternary in age (Figs. 3, 17a), thus suggesting a general more depleted character for all the youngest rocks of the arc.

The lowest silica contents (47-51 wt%), highest Mg-values and compatible trace element abundances (e.g., Sc and V up to 40 and 400 ppm, respectively) are found in the Santorini volcanic field rocks (Figs. 3, 17b). The most abundant and highest silica rocks (up to about 78 wt%) are present at the Milos and South Kos – Nisyros volcanic fields. Quite high silica samples (> 75 wt%) are, anyway, also observed at Hristiana, whereas in the western part, silica contents remain always lower than 72 wt% (Figs. 3, 17b).

Passing from the western to the eastern sectors of the arc, there is a general decrease of Sr isotope ratios, both in the lowest and highest values. This variation is evident either among all the samples or in the rocks with silica <60 wt% (Fig. 18). In the same direction, among variably evolved samples an increase of Nd isotope ratios is also generally observed. From Santorini to Nisyros island groups, however, Nd isotope ratios tend to slightly decrease again. This leads to a general correlation of $^{87}Sr/^{86}Sr$ versus $^{143}Nd/^{144}Nd$ of the most mafic rocks (silica <60 wt%), with the Santorini samples having the highest Nd isotope ratios but not the lowest Sr isotope ratios (Fig. 19). Fig. 19 also shows that the general correlation of SAAVA samples points to the isotope compositions of marine sediments and, in particular, to those of the Eastern Mediterranean sediments (Weldeab et al., 2002).

Pb isotope ratios also show a general tendency to decrease from the western to the eastern volcanic fields. $^{206}Pb/^{204}Pb$ values range from about 18.65 to 18.95, falling in the field of mid ocean ridge basalts (MORB), whereas $^{207}Pb/^{204}Pb$ (15.62-15.70) and $^{208}Pb/^{204}Pb$ (38.5-39.2) are generally higher than MORB values. Only the Pb isotopes of Nisyros are very close to those of MORB (Fig. 20).

According to the variation of FeO/MgO along the magmatic evolution series, there is an increase of the tholeiitic character of SAAVA magmas from west to Santorini island group, for decreasing again toward the eastern magmas (Fig. 21). However, based on the Al_2O_3 versus alkali index diagram for the mafic rocks (Fig. 22) most of the SAAVA magmas fall in the calc-alkaline field, with the exception of some basalts from Santorini island group.

Incompatible trace element patterns for the most mafic rocks are typical of calc-alkaline magmas, with high LILE/HFSE and REE/HFSE ratios. They have quite similar shapes for all the SAAVA sectors, even if the rocks of Santorini island group have lower incompatible element contents (Fig. 23). Rare earth element patterns are similar, with $La_N/Sm_N > 1$ and Tb_N/Yb_N mostly around 1. La_N/Sm_N is usually > 3, reaching lower values (up to 1.5) only in Santorini rocks.

4. DISCUSSION

The SAAVA rocks show large volcanological, geochemical and petrological variations within each volcanic fields and going from the western to the eastern sectors of the arc.

Some systematic correlations seem to exist with age of volcanism. Indeed, the onset of subaerial activity started at West on Egina island (at about 4.7 Ma), then occurred on Milos island group and in the eastern part and, finally, it appears in the central sector, on the Santorini island volcanic field (Fig. 17a). Thus, in a time span of about 1-2 Ma, subaerial activity appeared shifting from the external to the central area of the SAAVA. The end of volcanism, however, does not occur with a similar systematic time sequence, because active or potentially active volcanoes are present in most of the volcanic fields.

Correlations between age and compositional characteristics of rocks in the volcanic fields of the external sectors of the arc are also found, with a general shift from HK-CA to CA magmatisms.

Most of the volcanological, geochemical and isotopic characteristics follow geographical trends, changing along the arc from the western to the eastern part. At West, the volcanic fields are mainly constituted by small, monogenic eruptive centers, whereas in the central and eastern sectors, large composite volcanoes with caldera collapses dominates. From a geochemical point of view, a decoupling between the behaviour of isotope ratios (especially Sr and Pb isotopes) and the other petrochemical characteristics is observed. Indeed, isotope ratios mostly change from West to East of the arc, whereas element contents and ratios vary passing from the central to the external sectors of the SAAVA (Figs. 3, 17-23).

Several magma differentiation processes can be responsible for the compositional variability in the SAAVA rocks. Many petrochemical variations, especially those occurring within a single volcanic center, are clearly determined by shallow level evolutionary processes, whereas the West-East compositional changes are more probably due to magma source variations.

4.1. Magma differentiation processes at shallow levels

Large compositional variations are present in all the volcanic fields, where magmas generally range from basalts or basaltic andesites to rhyolites (Fig. 3), with highly variable Mg-values ranging between 80-15. Silica contents and Mg-values are also usually well correlated with the other major and trace element abundances. This large spread of compositions is mostly caused by fractional crystallisation (FC) of the main mineral phases found in the variably evolved magmas. Sr, Nd and Pb isotope ratios, on the other hand, also show quite large variations within the single volcanoes (Figs. 18-20) and they are usually positively correlated with the degree of magma evolution. These isotopic characteristics have been usually ascribed to processes of crustal assimilation, which are often associated to fractional crystallisation (AFC). The FC and AFC processes acted at more extent for producing the large amount of rhyolitic magmas erupted from the SAAVA volcanic centers. Most of the SAAVA rhyolites, in fact, can

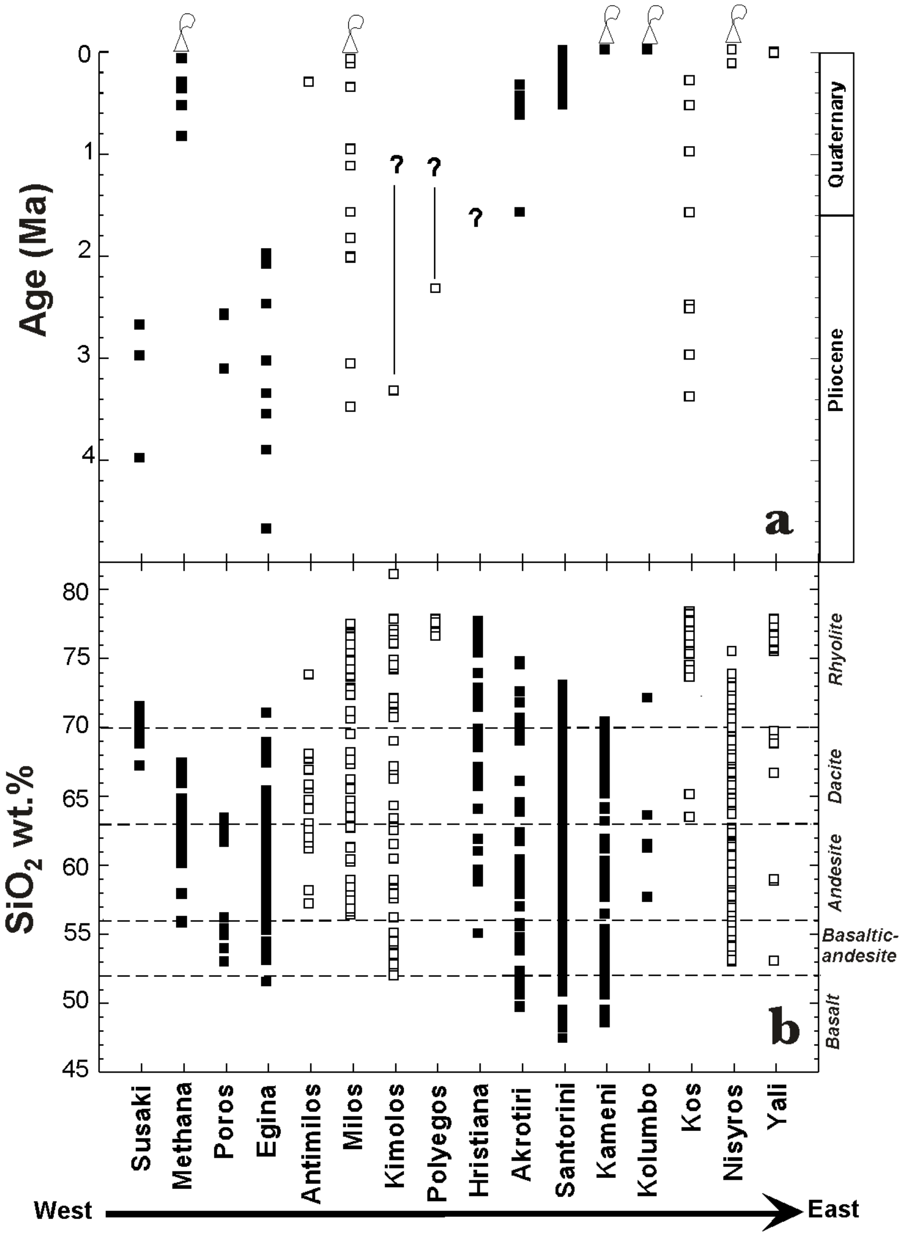


Fig. 17. West - East variations of ages (a) and silica contents (b) of rocks along the SAAVA. Volcanoes indicate the still or potentially active volcanic centers. See text for the data font.

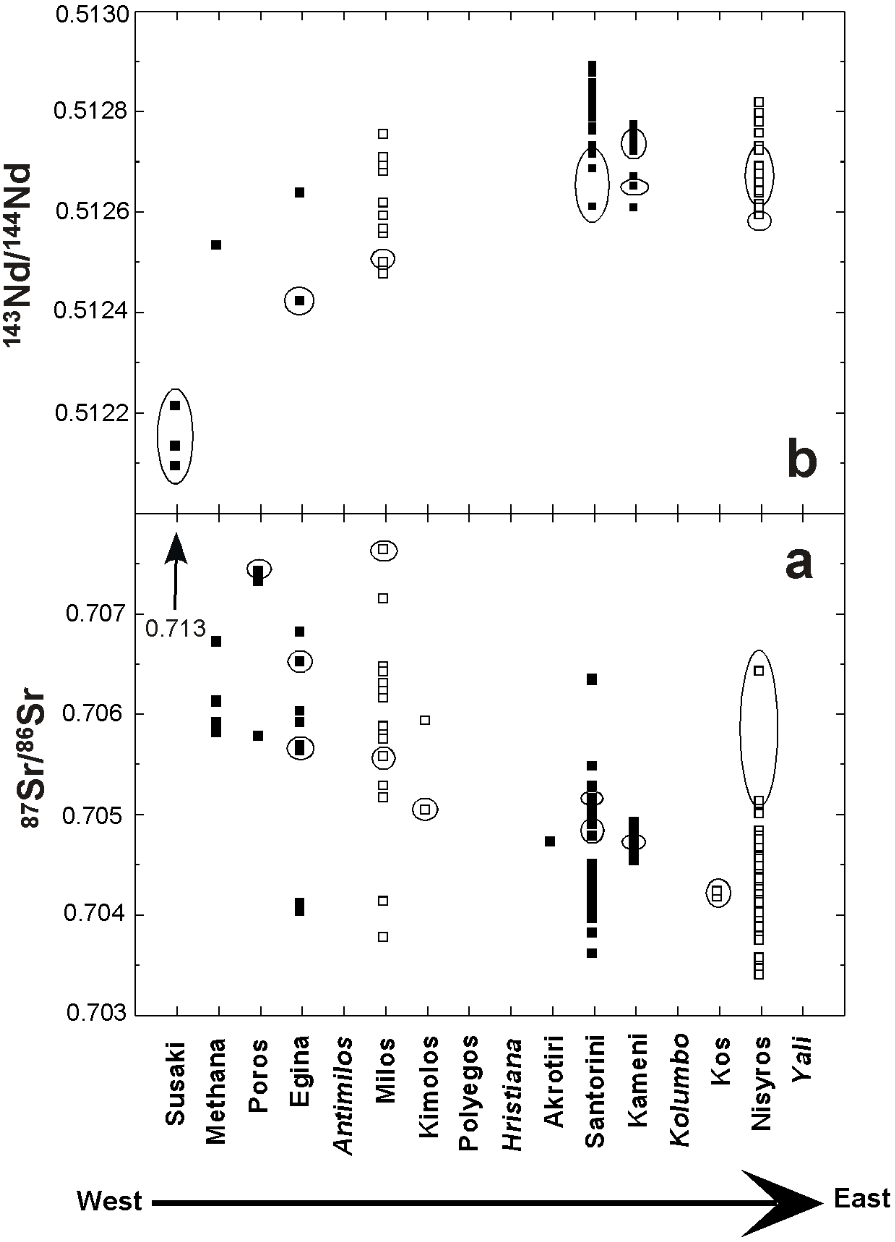


Fig. 18. West - East variations of Sr (a) and Nd (b) isotope ratios of rocks along the SAAVA. The encircled data are referred to samples with silica higher than 60 wt%. See text for the data font.

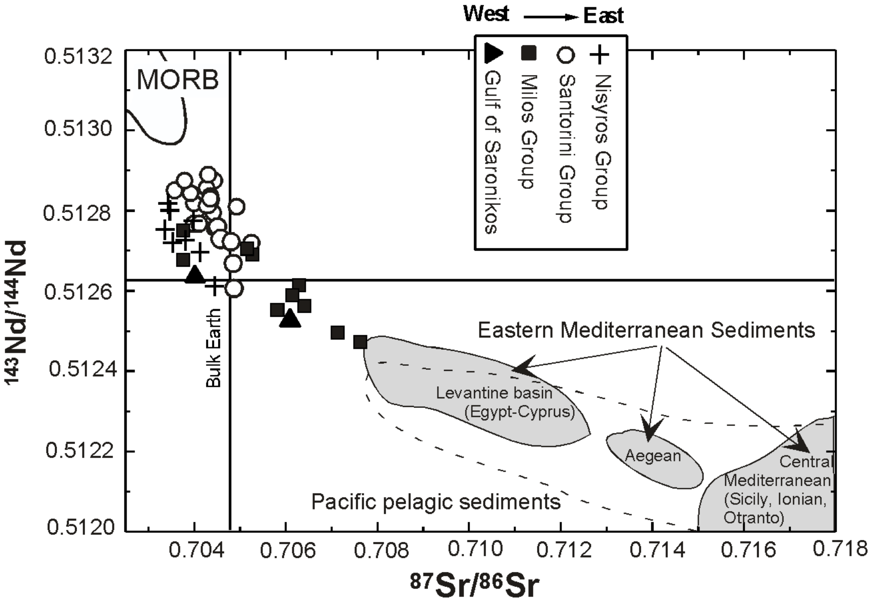


Fig. 19. $^{87}Sr/^{86}Sr$ versus $^{143}Nd/^{144}Nd$ diagram for the most mafic rocks ($SiO_2 < 60$ wt%) of the SAAVA fields. See text for the SAAVA data font. Data font of Eastern Mediterranean and Pacific pelagic sediments from Weldeab et al. (2002) and White et al. (1985), respectively.

be considered to be generated by evolutionary processes starting from more mafic magmas, rather than by crustal anatexis. Indeed, in most of the volcanoes, rhyolites plot at the most acidic extreme of continuous series of evolution (Figs. 3, 21) and their Sr isotope ratios are lower than those of continental crust. Furthermore, isotope ratios show a similar variation from West to East of the arc in the acidic and mafic rocks, thus suggesting a strict link between their lowest and highest values by AFC processes. Some doubts may arise for the Susaki rhyolites, because they are not associated with more mafic magmatism and have quite high Sr isotope ratios (around 0.713) (e.g., Pe, 1975; Pe-Piper and Piper, 1979; Innocenti et al., 1981; Barton and Huijsmans, 1986; Briqueu et al., 1986; Fytikas et al., 1986a,b; Mitropoulos et al., 1987; Huijsmans et al., 1988; Gulen, 1989; Wyers and Barton, 1989; Vougioukalakis, 1993; Francalanci et al., 1994, 1995, 1998, 2003; Vougioukalakis et al., 1995; Pe-Piper and Hatzipanagiotou, 1997; Davis et al., 1998; Aarburg, 1998; Aarburg and Frechen, 1999; Druitt et al., 1999; Zellmer et al., 2000).

SAAVA magmas also underwent to important processes of mixing-mingling between different evolved melts. These processes are particularly evident either when mafic (basaltic to andesitic) magmatic enclaves are included in more evolved (usually dacitic and rhyolitic) lavas and domes or when pyroclastic deposits are characterised by compositionally different juvenile materials. In both cases, they indicate the presence of large zoned magma chamber, which can feed energetic pyroclastic explosions, as

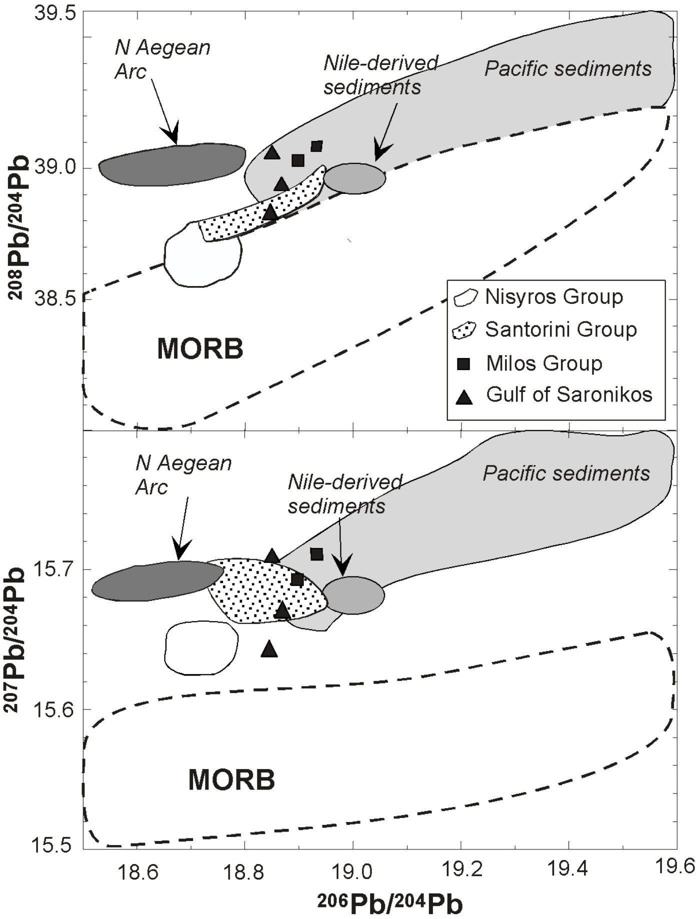


Fig. 20. ^{206}Pb/^{204}Pb versus ^{207}Pb/^{204}Pb and ^{208}Pb/^{204}Pb diagrams for the rocks of the SAAVA fields. See text for the data font.

mainly occurred at Santorini and Nisyros. Re-filling by mafic magmas of these shallow reservoirs may also trigger the eruptions. More complex processes of evolution have been also pointed out for Nisyros magmas, where crystal retention and re-cycling are also associated to AFC. Finally, a polybaric evolution occurring in reservoirs sited at different levels in the crust, has been also suggested for Santorini and Nisyros (e.g., Huijsmans et al., 1988; Wyers and Barton, 1989; Francalanci et al., 1995, 1998; Vougioukalakis et al., 1995; Davis et al., 1998; Aarburg, 1998; Aarburg and Frechen, 1999; Druitt et al., 1999; Zellmer et al., 2000; Mortazavi and Sparks, 2004).

It is noteworthy that the variation from CA to tholeiitic trend in the FeO/MgO versus SiO_2 of Fig. 21, can be also determined by shallow level differentiation processes and, in particular, by the minor role of hornblende and Fe-Ti oxides in Santorini island

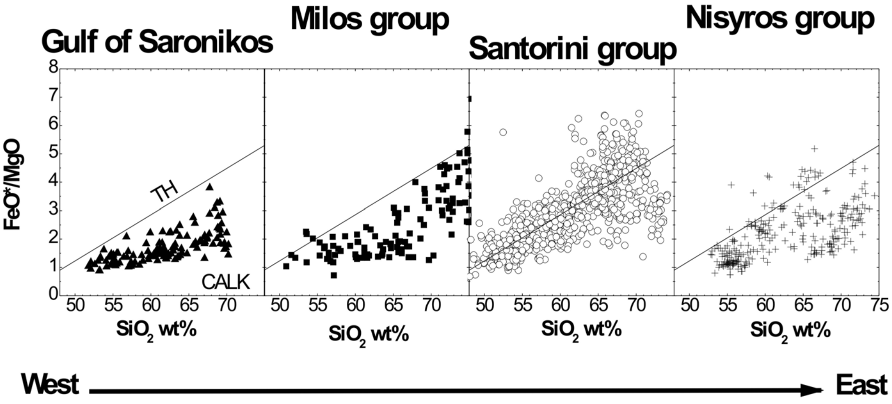


Fig. 21. Variations of FeO/MgO versus silica from West to East of the SAAVA. See text for the data font.

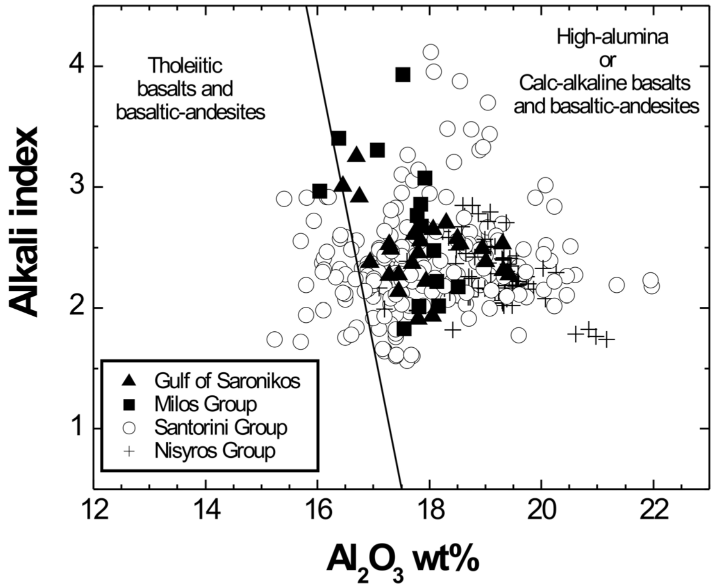


Fig. 22. Alkali index (=(Na_2O+K_2O)/[(SiO_2-43)*0.17] versus alumina for basalts and basaltic-andesites of the SAAVA. See text for the data font.

group, whose crystallisation leads to decrease the FeO/MgO value of the residual magmas. Hornblende is an important crystallising phase in most of the SAAVA fields, including the early volcanic centers of Santorini, at Akrotiri, but it is practically absent in the younger volcanics of Santorini. The Y variation versus silica points out the different role of amphibole in the different sector of the arc (Fig. 24). Indeed, because the solid/liquid partition coefficients of Y for amphibole is always > 1, only when hornblende does not crystallise, Y contents will increase with the degree of magma

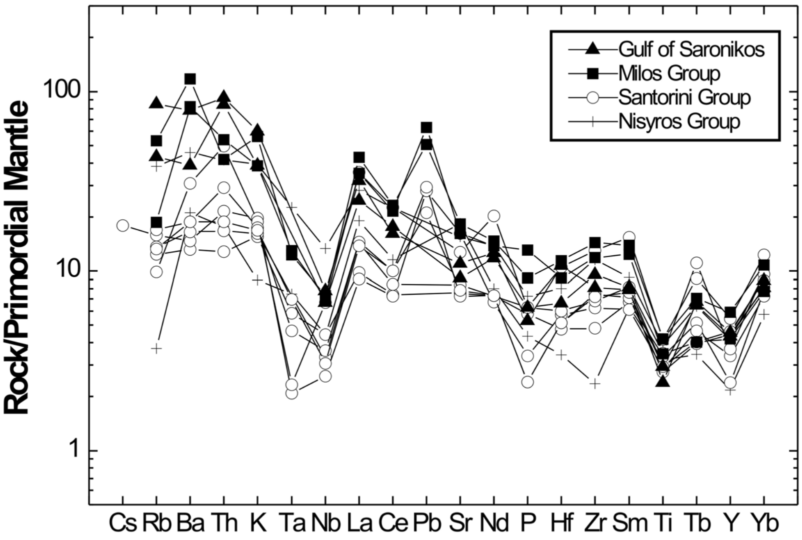


Fig. 23. Patterns of incompatible trace element contents normalised to the Primordial Mantle composition (Sun and McDonough, 1989) for the SAAVA most mafic rocks. See text for the data font.

evolution. The latter case is, in fact, only found for the youngest series of Santorini, where hornblende is not present. Along the same series, moreover, TiO_2 contents increase from basalts to basic andesites for decreasing at higher silica levels. On the contrary, in most of the magmatic series from the other volcanic fields, TiO_2 abundances start to decrease from basalts to more evolved compositions. On the other hand, lower oxygen fugacity has been hypothesised for the Santorini youngest magmas, based on the presence of Ti-rich titanomagnetites (Mitropoulos and Tarney, 1992). A lower oxygen fugacity can prevent the early crystallisation of Fe-Ti oxides, leading to increase FeO in the residual liquids.

It can be also argued that the absence of hornblende crystallisation in the youngest Santorini magmas is probably linked to a higher lithospheric extension in this zone of the arc, which lead magma to rest at shallower levels where amphibole is not stable. Furthermore, a possible lower aqueous fluid content in the youngest Santorini magma could also explain the lack of hornblende in these rocks.

A higher lithosphere extension below Santorini could be also the cause for a greater abundance of basalts occurring at this volcano (Innocenti et al., 1981). Indeed, mafic magmas more easily reach the shallow levels, thus increasing their possibility to be erupted.

4.2. Magma differentiation processes in the mantle source

The genesis of subduction-related magmas can be influenced by many factors, which include the composition of the subducting lithosphere, the type of mass transfer

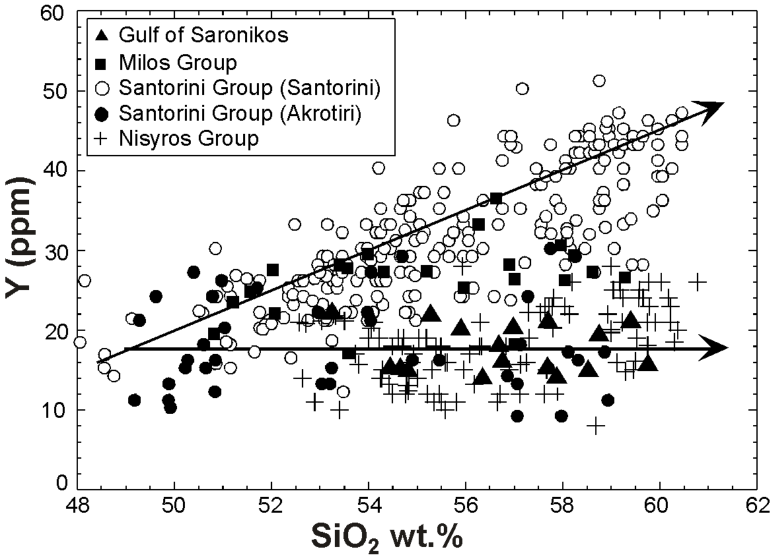


Fig. 24. Y versus SiO_2 diagram for the SAAVA rocks having <60 wt% of silica. See text for the data font.

of crustal material into the mantle wedge (fluids or melts, amount of metasomatising material added to the mantle) and the partial melting process of the metasomatised mantle (e.g., degree of partial melting). Also the nature of the mantle wedge before the event of metasomatism, e.g., lithosphere, asthenosphere, is of primary importance in determining the characteristics of the subduction-related magmas.

Several geochemical and isotopic variations occurring along the SAAVA from West to East seem to be due to differentiation processes in the mantle source during the magma genesis. Indeed, evolutionary processes along the pathway to the surface would have caused less systematic compositional variations. Even the decrease of Sr and Pb isotope ratios towards East is not correlated with the thickness variation of continental crust, which is lower in the central part of the arc, thus ruling out the possibility that this general trend is due to a decrease of crustal contamination.

Furthermore, the general decrease of K_2O with time in the external volcanic fields of the arc seems also to be related to mantle processes, because, in some cases (Milos and Saronikos Gulf), the K_2O decrease occurs among mafic rocks and it is not correlated with the decrease of Sr isotope ratios (Figs. 3, 18). A lower potassium content in orogenic magmas can be generated either: 1) by a lower amount of subducted material added to the mantle wedge, or 2) by higher partial melting degrees of the mantle wedge, or 3) by a major role of astenosphere as pre-metasomatism mantle source, in respect to the continental, possibly re-enriched, lithosphere.

The process (1), however, can be excluded again on the basis of Sr isotope ratios that should be systematically lower in CA magmas, strictly depending on the amount of crustal material brought into the mantle by subduction. Even geodynamic considerations lead to invalidate this process, because evidence of higher degrees of metasomatism are usually expected in younger orogenic magmas, erupted in an evolved phase of subduction, and not in the older magmas, as it occurs in SAAVA. Regarding to the process (3) several authors, based on spatial petrochemical trends, have hypothesised a higher implication of upwelling asthenospheric mantle in the genesis of Santorini magmas, due to a greater lithosphere extension (Mitropoulos et al., 1987; Mitropoulos and Tarney, 1992; Pe-Piper and Piper, 2002, 2004). This implicates the involvement of lithosphere as a pre-metasomatism mantle wedge in most of the SAAVA magma genesis. It is difficult to understand if the mantle involved in the magma genesis above the subducted slab is an asthenospheric or lithospheric mantle. Lithosphere, however, normally constituted by residual peridotite (usually harzburgite), is difficult to be melted. Even if the old continental lithospheric mantle can have suffered several events of incompatible element re-enrichment, the magmas generated by this mantle should have acquired some geochemical characteristics (e.g., high MgO and compatible element contents, low La/Sm values) indicating the residual character of their mantle source. At SAAVA neither the Pliocene HK-CA rocks nor all the rocks from the external parts of the arc show these kind of characteristics. Instead, higher Mg-values and lower La/Sm are found in the central part of the arc. Furthermore, Papazachos et al. (2004) found that SAAVA magmas derive from a “low velocity layer” sited at a depth of 60-90 km along the arc, which is probably the asthenosphere. Thus, different partial melting degrees of a similar and metasomatised mantle source (process 2) seem to be more suitable for explaining the compositional trend with time of the external parts of the arc.

Similar considerations arise in accounting for the lower alkali and incompatible element contents of Santorini magmas in respect with the magmas from the external sectors of the arc (Figs. 22, 23). Indeed, a higher involvement of astenospheric mantle in respect with the continental lithosphere might explain the geochemical characteristics of Santorini rocks. On the other hand, higher partial melting degrees of a similar astenospheric metasomatised mantle can originate primary magmas with a more tholeiitic character, as the mafic rocks of Santorini.

Evidences from the diagram of Fig. 25 could also indicate the involvement of subcontinental lithosphere in the petrogenesis of the magmas from the external sector of the arc, due to the higher Ta/Yb ratios, plotting in the field of active continental margins. In any case, lower Ta/Yb for the Santorini rocks can be explained again by higher degrees of source partial melting, taking in mind that Ta is greatly more incompatible than Yb for the peridotite mineralogical assemblage. This hypothesis can be also corroborated by the lower La/Sm values of Santorini rocks, considering a mantle partial melting where lower abundance of clinopyroxene remains as residue.

Isotope ratios of orogenic magmas are usually considered to indicate the amount of subducted crustal material added to the mantle wedge. This can be represented by both aqueous fluids from a subducted oceanic crust or subducted pelagic sediments.

The U-Th isotope ratio disequilibria suggest some role of slab-derived fluids for the

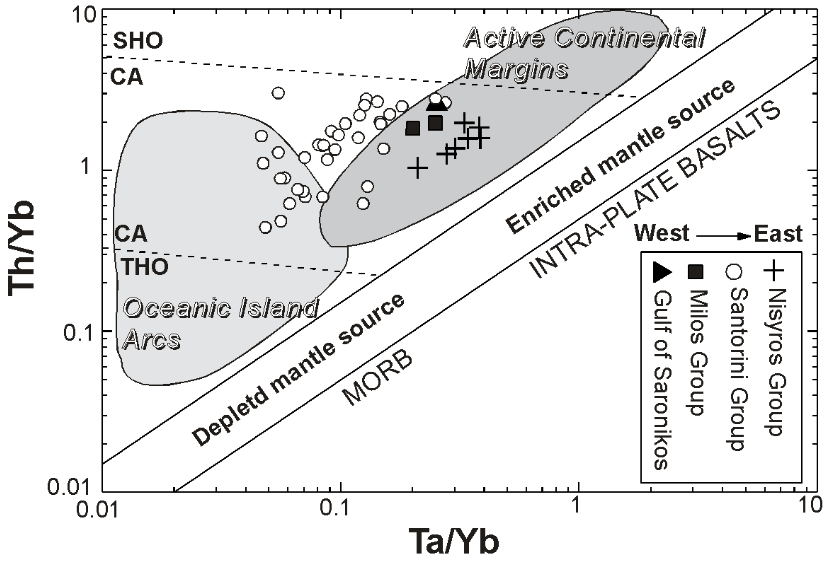


Fig. 25. Th/Yb vs Ta/Yb discrimination diagram for the least evolved SAAVA rocks. Fields for Oceanic Island Arcs and Active Continental Margins from Wilson (1989). See text for the other data font.

genesis of Kameni parental magmas (Zellmer et al., 2000). On the other hand, the diagram of Fig. 26 seems to indicate a low amount of fluids involved in the genesis of SAAVA magmas. Indeed, all the SAAVA mafic rocks plot at the lower Ba/La values of the island arc basalt (IAB) field, with the lowest values found in the Santorini magmas. The latter evidence could also account for the lack of amphibole crystallisation and the lower oxygen fugacity found for the youngest Santorini magmas.

On the other hand, the involvement of melts from slab-derived pelagic sediments is pointed out by the variations of Sr and Nd isotope ratios and B/Be ratios. Indeed, the former plot at the more radiogenic extreme of the SAAVA mafic rock trend (Fig. 19), whereas the high B/Be values measured by Clift and Blusztajn (1999) were considered as an evidence for a flux of sedimentary material from the subducted slab (Plank and Langmuir, 1998). A small amount of sediment melts added to the mantle wedge is also proposed by Zellmer et al. (2000) for the genesis of Santorini parental magmas, on the basis of incompatible trace element budget calculations.

Accordingly, the decrease of Sr and Pb isotope ratios from West to East of the arc can be due to a decreased amount of metasomatising sediments added to the mantle. Alternatively, based on the variations of Sr and Nd isotope ratios of the Eastern Mediterranean sediments from West (Aegean of Fig. 19) to East (Levantine basin of Fig. 19) (Weldeab et al., 2002), a smooth change in the isotopic composition of the subducted sediments can be suggested (Fig. 19).

Nd isotope ratios tend to decrease passing from Santorini to Nisyros island groups, showing a different variation in respect with the other isotope ratios and making

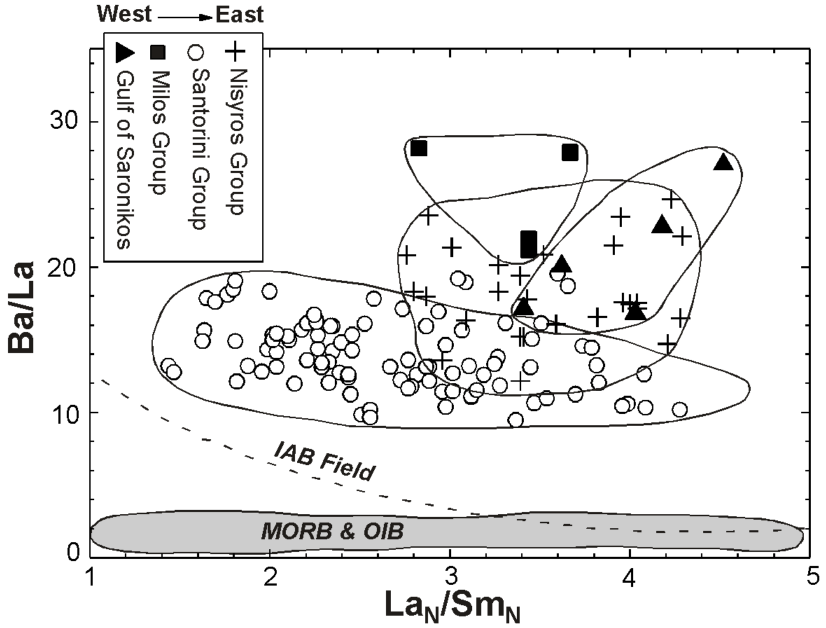


Fig. 26. La$_N$/Sm$_N$ vs Ba/La ratios plot for the SAAVA rocks. Fields for MORB, OIB and IAB from Wilson (1989). See text for the other data font.

Santorini the volcanic center with the highest ^{143}Nd/^{144}Nd (Fig. 19). This characteristic could lead again to hypothesize for the Santorini magma genesis a major role of depleted, MORB-like, asthenospheric mantle, enriched in radiogenic Nd. Nevertheless, an other explanation can be searched in the possible different composition of sediments, which could contain lower Nd abundances in the central part of the arc. Indeed, keeping constant the sediment content added to the mantle, a lower Nd abundance in the slab-derived sediments leads to maintain higher the ^{143}Nd/^{144}Nd of the metasomatised mantle. Since now, however, this can be only an inferred hypothesis, due to the lack of available Sr and Nd content data for the Mediterranean sediments (Weldeab et al., 2002). On the other hand, the West-East Sr and Nd isotope variations in the same sediments may suggest a possible bulk compositional variation.

4.3. Magmatism and tectonics

The presence of Pliocene volcanism in all but the central (Santorini) SAAVA area is not easy to understand. Both subducting slab geometry and tectonic regime of the overlying Aegean lithosphere do not have an evident relation with the time onset of the volcanism. On the other hand, as already suggested by Innocenti et al. (1981), the presence of composite volcanoes with central calderas can be related to the thinned lithosphere in the Santorini area and the higher extension in both Nisyros and Santorini areas resulted from the palinspastic models (Le Pichon and Angelier, 1979). Indeed, the tensional tectonics would favour the formation of large shallow magma chambers. Present day extension rates, however, measured by modern geodetic satellite techniques (Reilinger, 1997) do not indicate any important difference along the arc.

In Fig. 27 the main characteristics of the Plio-Quaternary volcanic fields of the SAAVA are schematically resumed. Different Pliocene and Quaternary volcanic areas, trends and polarity of the lineaments controlling the volcanic vents are pointed out (Fig. 27). It is clearly evident that:

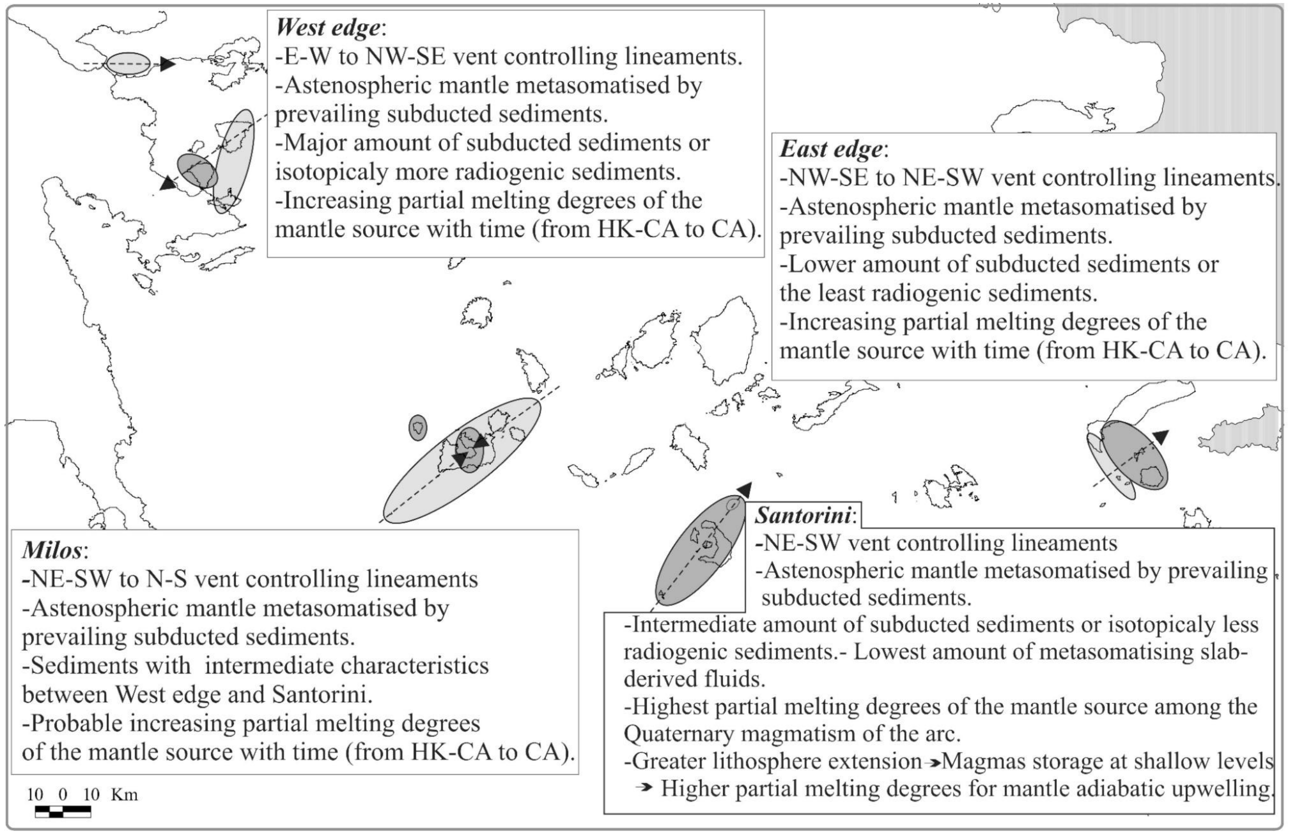
- The distribution of the volcanic centers over the zone of the 110-130 km dipping African lithosphere (see Papazachos et al. this volume) is restricted to five very limited areas.
- The trending of these areas is roughly perpendicular to the subduction front: from E-W at Susaki, to ENE-WSW at Milos, NE-SW at Santorini and NW-SE at South Kos-Nisyros.
- The active tectonic lineaments, which control the vent distribution, are not generally concordant with the general, previously mentioned, trending of these areas. In Susaki, Santorini and at some extent in Milos, both areal distribution and vent controlling lineaments are concordant.
- Vent controlling lineaments shift in space and time. In Milos and South Kos-Nisyros fields, where both Pliocene and Quaternary activity coexist, there is a clear change in the direction of the vents controlling lineaments with time: from NE-SW to N-S in Milos, from NW-SE to NE-SW in South Kos-Nisyros. This is not so clear at Susaki and Egina-Methana, but it seems to exist a shifting in the controlling lineaments from E-W to NW-SE.
- Vent migration with time in each field has not an univocal polarity: in Susaki they move from W to E, in Saronikos from ENE to WSW, in Milos from both NE and SW to the center of the field, in South Kos-Nisyros from SW to NE.
- There are large portions over the zone of the 110-130km dipping African lithosphere that are not affected by volcanic activity, even if active faulting, crustal thickness and extension are the same or even more prominent than in the volcanic field areas (see Fig. 7 of Pe-Piper and Piper this volume). Taking into account that most of these areas are submarine, the presence of some small Plio-Quaternary submarine volcanoes is possible, but the marine geology research carried out in the area excludes the presence of extensive volcanic fields.

5. SUMMARY

Several volcanological, geochemical and mineralogical variations occur along the SAAVA volcanic fields.

Many compositional characteristics are determined by differentiation processes during the pathway to the surface, which are dominated by crystal fractionation associated to crustal contamination and mixing-mingling processes.

General systematic variations are generated by differentiation processes occurring at the magma mantle source. SAAVA parental magmas are generated by partial melting of



West edge:
-E-W to NW-SE vent controlling lineaments.
-Astenospheric mantle metasomatised by prevailing subducted sediments.
-Major amount of subducted sediments or isotopicaly more radiogenic sediments.
-Increasing partial melting degrees of the mantle source with time (from HK-CA to CA).

East edge:
-NW-SE to NE-SW vent controlling lineaments.
-Astenospheric mantle metasomatised by prevailing subducted sediments.
-Lower amount of subducted sediments or the least radiogenic sediments.
-Increasing partial melting degrees of the mantle source with time (from HK-CA to CA).

Milos:
-NE-SW to N-S vent controlling lineaments
-Astenospheric mantle metasomatised by prevailing subducted sediments.
-Sediments with intermediate characteristics between West edge and Santorini.
-Probable increasing partial melting degrees of the mantle source with time (from HK-CA to CA).

Santorini:
-NE-SW vent controlling lineaments
-Astenospheric mantle metasomatised by prevailing subducted sediments.
-Intermediate amount of subducted sediments or isotopicaly less radiogenic sediments.- Lowest amount of metasomatising slab-derived fluids.
-Highest partial melting degrees of the mantle source among the Quaternary magmatism of the arc.
-Greater lithosphere extension ➔Magmas storage at shallow levels ➔ Higher partial melting degrees for mantle adiabatic upwelling.

Fig. 27. Main characteristics of the SAAVA. Light gray areas: Pliocene volcanism. Dark gray areas: Quaternary volcanism. Arrows: Time polarity of the volcanism.

a depleted, MORB-like, athenospheric mantle, metasomatised by prevailing subducted sediments and low amount of aqueous fluids (e.g., low Ba/La values, Fig. 26). The latter seems also to be lower in the genesis of Santorini magmas, thus representing a possible explanation for the lower oxygen fugacity and the lack of amphibole crystallisation (probably associated to the higher lithosphere extension, see below) in these magmas.

The abundances of slab-derived sediments added to the mantle probably decrease from West to East (Sr and Nd isotope variations). Alternatively, the West-East $^{87}Sr/^{86}Sr$ and $^{144}Nd/^{143}Nd$ variations of the Mediterranean sediments lead to suggest a similar variation in the subducted sediment composition (Fig. 19). The slightly higher Nd isotope ratios of some Santorini magmas may also lead to hypothesise an inferred lower Nd content of the subducted sediments in the central part of the arc.

The degrees of mantle partial melting are generally high, but variable along the SAAVA or in a same sector of the arc. They seem to increase with time in the magmatism of the external parts (Gulf of Saronikos, Kos-Nisyros and probably Milos) and, among Quaternary volcanism, they are higher during the genesis of Santorini parental magmas.

The greater lithosphere extension below Santorini volcanic field may be responsible of several petrological processes characterising the magmatism in this sector of the arc. Magmas can stop at shallower levels, thus preventing amphibole crystallisation and allowing a higher amount of mafic magmas to reach the surface without undergoing to extensive processes of evolution. The greater lithosphere extension is also able to trigger a higher partial melting degrees observed for the Santorini magma source, due to the adiabatic upwelling of the asthenospheric mantle.

It has been also pointed out that from the beginning of SAAVA magmatism, occurred in Pliocene in the external parts of the arc, the partial melting degrees of the magma mantle source have increased with time and going towards the central sector of the arc.

It can be also concluded that volcanic activity along the South Aegean area is clearly controlled by both the active tectonic lineaments (Papazachos and Panagiotopoulos, 1993) and the subduction kinematics dynamics (Pe-Piper and Piper this volume). Nevertheless, it is difficult to apply a simple evolutionary model, as the whole area is a patchwork of fragmented crustal blocks which move one respect to the other in a very complex relationship, not predictable by any simple general model.

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Discussion on the SAAVA characteristics with Prof. M. Fytikas, F. Innocenti and G. Pe-Piper greatly enhanced the authors ideas and conclusions.

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