

MAGMA INTERACTION PROCESSES DURING THE LAST PHASE OF ACTIVITY OF NISYROS ACTIVE VOLCANIC SYSTEM (SOUTH AEGEAN, GREECE)

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INTRODUCTION

Understanding the interaction between different magmas is very important for reconstructing the dynamics of the eruptions and the plumbing system configuration of a volcano. One of the best evidence of these processes is represented by mafic enclaves inside evolved host, like lava flow or domes.

Mafic enclaves represent fragment of mafic magma that rapidly crystallize on contact with the cooler more evolved host magma. These two terms are, therefore, considered as the end-members of a system where different liquids interact and generate a variety of characteristics that reflect different condition (P, T, composition). Enclaves are the result of immiscibility processes between two different magmas yielding to mingling.

The work presented here is focused on the understanding of the interaction processes between magmas with different degree of evolution. The aim is to understand how and if these processes can trigger eruptions and if it is possible to find evidence of distinct recharge event of mafic magma inside an evolved shallow reservoir.

The active volcanic system of Nisyros and Yali, in the eastern part of the South Aegean Volcanic Arc, is one of the best place for investigating these processes because its last evolution is characterized by the emplacement of rhyolitic pyroclastic products and extrusion of rhyo-dacitic domes, rich in mafic enclaves.

GEOLOGICAL AND VOLCANOLOGICAL BACKGROUND

Nisyros volcano, near the coast of Turkey, is the easternmost volcanic edifice of the active South Aegean Volcanic Arc. It is the largest of a group of volcanic islands including the islets of Perigusa, Pahia, Strongili and Yali.

Nisyros island is a small entirely volcanic edifice, build up during the last 100 ka. All products have a calc-alkaline affinity varying in composition from basaltic-andesite to rhyolite.

The volcanological evolution can be subdivided into two distinct cycle of activity (Di Paola, 1974): the first cycle includes the cone-building activity with effusive and explosive activity. The second eruptive cycle includes the caldera-forming explosive activity, with two distinct phases, each consisting in rhyolitic phreatomagmatic eruption triggering central caldera collapse and extrusion of dacitic-rhyolitic domes and lava flows. The rocks of this cycle are characterized by the presence of mafic enclaves, with distinct petrographic and chemical features, which testify mixing-mingling processes between variously evolved magmas during the last activity of the volcano (Francalanci *et al.*, 1995). In particular, the last phase of the second cycle, is characterized by the emplacement of six domes after the caldera collapse (probably < 24 ka), associated to the Plinian eruption leading to the formation of a thick pyroclastic

deposit (*Upper Pumice*) (Limburg & Varekamp, 1991). The six post-caldera domes were extruded both inside and outside the caldera along a tectonic lineament aligned NE-SW.

The adjoining island of Yali, younger than 24 ky, has a distinctive assessment composed by two different part characterized by different products. The SW part is completely build up by pyroclastic deposits, whereas the NE portion is formed by lava flow and domes, with a small tuff ring on the eastern corner. All products are calc-alkaline, mostly rhyolitic in composition, with few less evolved products, defining a large compositional gap. The latter are present as dense juvenile material (enclaves) inside the youngest pyroclastic unit named *Yali Upper Pumice* sequence.

RESULTS

Based on field observations, Profitis Elias dome is the oldest one, then the Sterna, Trapesina and Nifios domes were emplaced, followed by Karaviotis and then Boriatico dome. Enclaves show round and irregular shapes with sharp contact and convolute surface. Sizes are variable, ranging from about one meter to few centimeters. Abundance and size of these enclaves show quite evident variation among domes depending on the age: from the older to the younger dome, enclaves increase in percentage (from 5-6 to 10-13%) and decrease in size (from 25-30 cm to 5-10 cm as prevalent size).

The sampling has been performed on domes and mafic inclusions, taking several enclaves for each dome to cover all the variability in size, shape, color and texture, trying also to collect the dome-enclave contacts.

The *Upper Pumice* pyroclastic sequence of Nisyros has been sampled from the base (fallout level) to the top (lag-breccia level) in order to investigate possible compositional changing in the feeding magmas. The basal fallout level is characterized by a double juvenile consisting in white pumice and dense, light grey juvenile, whereas only a dense juvenile is found in the lag-breccia level.

The sampling on Yali island has been performed on the *Yali Upper Pumice* sequence (Yup), lava flows and tuff ring products.

Petrographic and geochemical studies were performed on whole rocks of all the samples collected, whereas mineral chemistry and isotope analyses were performed on a selected number of samples.

Finally *in situ* micro-sampling technique, for micro-Sr isotope determinations, has been also applied on three most significant enclave samples.

Petrography

Domes have porphyritic and glomeroporphyritic textures, with criptocrystalline to glassy groundmasses. They show high phenocryst contents (*ca.* 20-30 vol.%) which are constituted by plagioclase, quartz, orthopyroxene, Fe-Ti oxides and rare clinopyroxene, olivine and amphibole. Microlites of plagioclase are present in the glassy groundmass.

Magmatic enclaves have hypocrySTALLINE textures with variable and generally low porphyritic index (< 10 vol.%). They frequently have diktytaxitic voids in the groundmasses and show variable vesicle contents. The dome-enclave contacts are usually characterized by chilled margins in the enclaves, with smaller size of the microlites and/or higher glass content. Chilled margin insure their origin from a magmatic liquid and their inclusion into the cooler dome magmatic bodies. Phenocrysts are constituted by plagioclase, clinopyroxene, and rare amphibole, olivine, Fe-Ti-oxides and orthopyroxene, whereas the groundmasses are formed by a microcrystalline network of acicular plagioclase and amphibole with interstitial clinopyroxene, oxides and small amount of glass. Several enclaves show mega-phenocrysts of

plagioclase with rounded shape and several sieved zones. These crystals are often present near the contact surfaces between the enclaves and the host domes. This characteristic suggests that mega-phenocrysts of plagioclase move from the dome host magma to the enclave body, giving rise to an intense crystal exchange between the two magmas (micro-scale mingling).

Pumices of the *Upper Pumice* sequence have low porphyritic texture (up to 5 vol.%), with glassy, highly vesicular groundmass. Crystals are mostly plagioclase and Fe-Ti oxide with rare pyroxene crystals. The dense juvenile component (both from fallout and lag breccia levels) are similar to the magmatic enclaves, but show a higher vesicular texture. Pyroxene, Fe-Ti oxide and olivine micro-phenocrysts are also present.

Pumices from *Yali Upper Pumice* sequence (Yup) are low porphyritic with glassy, high vesicular groundmass. Plagioclase (micro-phenocrysts) is the main mineral phase together with Fe-Ti oxides. Dense juvenile samples are similar to the Nisyros magmatic enclaves. Lavas and pyroclastic juvenile forming the tuff ring are very low porphyritic (< 1%) with glassy, variously vesiculate, groundmass. Plagioclase represent the main mineralogical phase together with oxides.

Mineral chemistry

Mineral chemistry has been analyzed in 12 representative samples of domes and enclaves.

Mg# ($\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$) in clinopyroxene range between 0.58-0.85 and in orthopyroxene between 0.70-0.85, while anorthite contents in plagioclase vary between 20-95%.

Among the enclaves, minerals are characterized by distinct features: plagioclase xenocrysts coming from the host magma show oscillatory zoning and range in composition between An% 25-60, whereas plagioclase of the enclaves magma are mainly micro-phenocrysts and have An% between 70-90. Few intermediate compositions are also present suggesting complex interaction processes.

Amphiboles are classified as tschermakite and are quite homogeneous in composition, with Mg# ranging between 0.70-0.80. The amphiboles of the Profitis Elias enclaves show small, but consistent, variations in Mg#, aluminum content and $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratio in respect with those of the Boriatico enclaves.

Two *Upper Pumice* samples have been selected for the mineral chemistry analysis. Pumice, have orthopyroxene with homogeneous Mg# of about 0.59, whereas dense juvenile (from the same fallout level) have Mg# of 0.55. On the contrary, plagioclase shows anorthite contents between 25-40% among the pumice and 45-51% among the dense juvenile.

Among the Yali samples, only few analyses were performed on pumice and dense juvenile samples belonging to the pyroclastic sequence of Yup. Clinopyroxene are exclusively present in the dense juvenile sample and show a variation in Mg# between 0.72-0.90. Plagioclase of the pumice shows anorthite contents between 60-75%; those of dense juvenile are wide zoned, ranging from An% 35 in the core to 80 in the rim.

Major and trace element geochemistry

Domes are dacitic and rhyolitic with silica content ranging from 66 wt.% to 72 wt.%. Sterna and Profitis Elias domes have the highest silica contents, whereas Boriatico dome has the lowest silica content. Al_2O_3 , TiO_2 , CaO and FeO contents are negatively correlated with SiO_2 (Fig. 1), whereas Na_2O and K_2O abundances form positive correlations with silica.

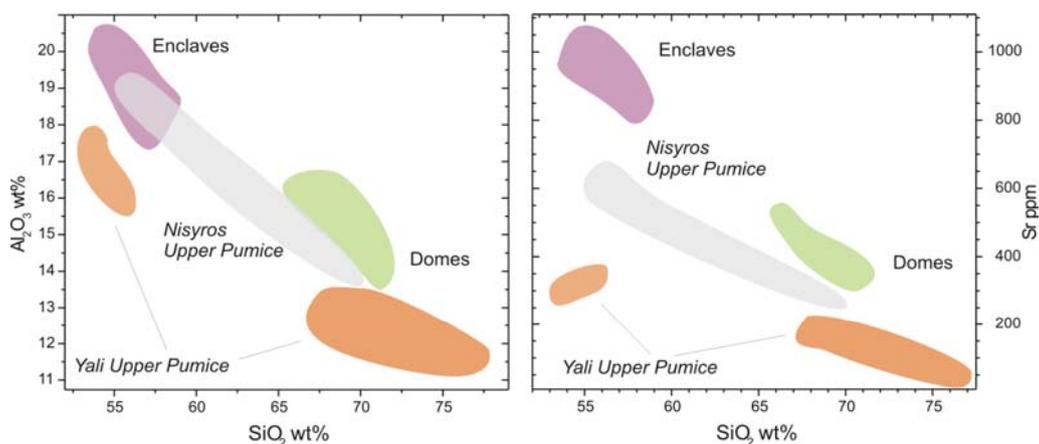


Fig. 1 - Al_2O_3 (wt.%) and Sr (ppm) vs. SiO_2 (wt.%) contents for Nisyros and Yali younger products. Light green: domes; violet: enclaves; light grey: Upper Pumice pyroclastics; orange: Yali products.

Enclaves are basaltic-andesites and andesites with silica contents ranging between 54-59 wt.%. A large silica gap between domes and their enclaves is thus present. Among major elements (Fig. 1), Al_2O_3 contents of enclaves show the highest variation and are well negatively correlated with silica, with Karaviotis and Boriatico enclaves having the highest alumina contents. At the same silica content, Boriatico, Karaviotis and some Trapesina enclaves also show lower FeO and TiO_2 abundances than the other enclaves. On the whole, among both the enclaves and domes, the silica content decreases from the oldest to the youngest.

Both major and trace elements of the whole rocks show clear differences between domes and enclaves. For example, K_2O in the enclaves vary from 0.9 to 1.5% and from 2.4 to 3% in the domes. Enclaves show higher contents in compatible elements and lower amounts in incompatible trace elements than domes: Sr contents in the enclaves vary from 850 to 1000 ppm and from 320 to 530 in the domes (Fig. 1), V and Rb contents in the enclaves are 105-155 and 5-25 ppm, respectively, whereas in the domes they are 35-70 and 45-75 ppm, respectively.

The Upper Pumice samples cover a wide compositional range from basaltic-andesite to rhyodacite. They show a small compositional gap between 65% and 69% of silica. This gap discriminates between pumice (69-73% SiO_2) and dense juvenile components (56-65% SiO_2). Among the dense juvenile samples, major and trace element contents are quite homogenous in the lag-breccia samples, whereas they show much more variability in the fallout samples. The latter are intermediate between pumice and lag-breccia dense juvenile.

The Yali products show a wide compositional gap, with rhyolitic lavas and pumices (silica from 67 up to 76%) and basaltic-andesite dense juvenile components.

On the basis of major elements, it is hard to discriminate between pre- and post-caldera products of Nisyros as well as between Nisyros and Yali products. On the contrary, trace elements, especially Sr, highlight systematic differences among the products of the three eruptive events. At same silica content, the Nisyros post-caldera dome-enclave samples are characterized by the highest Sr content, whereas the lowest are found in the Yali products (Fig. 1).

Isotope geochemistry

Sr and Nd isotope data show important variations among the post-caldera samples (domes and enclaves) as well as between products of Nisyros Upper Pumice and Yali samples (Fig. 2).

$^{87}\text{Sr}/^{86}\text{Sr}$ data show little but significant differences between the enclaves (from 0.70383 to 0.70386). This variation becomes more evident among the domes, where values from 0.70402 to 0.70418 are measured.

$^{143}\text{Nd}/^{144}\text{Nd}$ values vary from 0.51269 to 0.51273 among the enclaves and from 0.51264 to 0.51266 among the domes. Like silica contents, $^{87}\text{Sr}/^{86}\text{Sr}$ values decrease, among the enclaves, from the oldest to the youngest ones, whereas among domes, Sr isotope ratios is considerably higher for the oldest domes. The Boriatico system is, therefore, less Sr radiogenic both for enclaves and host-dome, in respect with all the other dome-enclave systems, showing composition closer to those of the enclaves. Nd isotope ratios, are well negatively correlated with Sr isotope ratios (Fig. 2).

Upper Pumice samples show $^{87}\text{Sr}/^{86}\text{Sr}$ values ranging from 0.70425 to 0.70456 for lag breccias dense juvenile and pumice respectively, whereas $^{143}\text{Nd}/^{144}\text{Nd}$ values vary from 0.51255 to 0.51261 in the fallout dense juvenile and pumice, respectively. Among these samples, the Nd and Sr isotope ratios are not well correlates, pointing out the occurrence of complex evolutionary processes inside the pre-caldera plumbing system.

Among the Yali samples, the evolved pumice shows a $^{87}\text{Sr}/^{86}\text{Sr}$ value of 0.70450 and a $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.51261, whereas the more mafic dense juveniles have $^{87}\text{Sr}/^{86}\text{Sr}$ of about 0.70400 and $^{143}\text{Nd}/^{144}\text{Nd}$ ranging from 0.51273 to 0.51277.

Micro-Sr isotope data

In order to investigate the origin of the plagioclase mega-phenocrysts found in several enclaves, which probably belong to the host-domes, three representative samples from enclaves are selected for *in situ* Sr isotope determinations. They have been chosen from Trapesina, Karaviotis and Boriatico samples.

The results from this forefront technique give important information for the understanding of post-caldera plumbing systems.

Cores of all mega-plagioclase crystals selected for *in situ* determinations (characterized by low anorthite content of 30-35%) show high $^{87}\text{Sr}/^{86}\text{Sr}$ (ranging from 0.7044 to 0.70452), whereas rims (where anorthite content is up to 70%) show $^{87}\text{Sr}/^{86}\text{Sr}$ values that range from 0.70415 to 0.70398. The latter

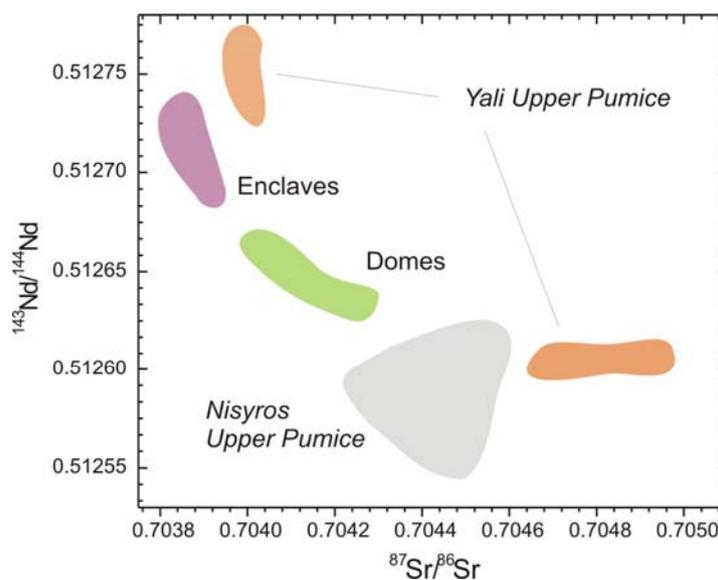


Fig. 2 - $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $^{143}\text{Nd}/^{144}\text{Nd}$ for Nisyros and Yali younger samples. Field colours as in Fig. 1.

show, therefore, a wider range than cores, and have an isotopic composition similar to that of the domes. Cores have, instead, an isotopic composition that fall inside the Sr isotope range of the *Upper Pumice* products.

Some euhedral plagioclase, with anorthite of 80-90% has been also analyzed. The results give $^{87}\text{Sr}/^{86}\text{Sr}$ values lower than those of the aforesaid mega-plagioclase rims, down to values lower than the whole isotopic range of the enclaves (0.70380).

DISCUSSIONS AND CONCLUSIONS

Concerning the domes-enclaves interaction, field observations and petrographic examinations tell us that, from the oldest to the youngest domes, the degree of mingling processes increases enhancing the emulsion of mafic magmas (the enclaves) inside the host magma (lava domes). During mingling, several exchange processes also take place at the micro-scale, allowing intense transfer of mineral phases from dome to enclaves (plagioclase and glassy groundmass portions) and vice versa (pyroxenes, olivine and plagioclase microlites due to the crumbling of enclaves).

The latter observation is consistent with the compositional characteristics revealed by mineral chemistry analysis. For example, the evaluation of equilibrium-disequilibrium conditions of the mafic phases (pyroxene and olivine), in respect to the whole host rocks, highlight that several crystals are out of the equilibrium conditions, both in domes and enclaves.

Geobarometric determinations, based on amphibole composition, allow us to suppose a slight decrease in pressure conditions with time, from Profitis Elias to Boriatico dome systems. This means that, probably the level of contact surface between the two magmas rise up during the emplacement of the six post-caldera domes.

Geochemical and isotopic data show variation that can be explained by the concomitance of several processes. Major and trace element compositions indicate a mixing trend between two end-members (rhyolitic and basaltic-andesite magmas), but the real hybrid magmas are lacking.

For the post-caldera domes, rhyo-dacitic rocks show, in effect, evidence of hybridization with the mafic magma of the enclaves (increasing with time). This hybridization is mostly due to the dispersion inside the host magma of micro-enclaves and mineral phases, like a micro-scale mingling.

The generation and differentiation of the enclave magmas, seem mainly due to fractional crystallization, with the concomitance of less contamination processes with the host evolved magma (probably due to small amount of evolved, residual liquid that slip into the enclave body).

Little geochemical variations among the enclaves, belonging to different dome body, have been interpreted as the evidence of different inputs of new magma (at least two different input) inside the shallow magma chamber, before the post-caldera activity. This causes a zoning inside the more primitive magma reservoir underlying the rhyo-dacite magma. Dispersion starts consequently to the instauration of strong convective motions inside the magma chamber (due to the heating and density contrast) and brings up different portions of the mafic magma, generating a complex, variously zoned system. The emplacement of domes allows sampling different portions of the magma chamber, which result in the different characteristics of enclaves.

Finally, micro-Sr results show that most, if not all, the macro-plagioclase are xenocrysts in respect to the enclaves magma and come from the dome evolved magma, but they crystallize from the previous magmatic system that formed the evolved Upper Pumice product.

In this interpretation, the *Upper Pumice* represents the parental system for the post-caldera evolved portion.

Summarizing, all the characteristics of the magmatic enclaves suggest that they represent mafic magmas intruded in the more evolved dome magmas. The presence of a compositional gap between domes and enclaves demonstrates that generation of hybrid magmas, did not really occur, and seems to indicate that the two magmas remained in contact for a short period of time.

The plumbing system of the last magmatic activity of Nisyros can be figure out as a complex system with a zoned magma chamber where several events of renewed intrusion of mafic magma took place, with a clear tendency of the system towards more mafic composition.

Furthermore, it is also evident that Quaternary tectonics play an important role on the volcanic activity of Nisyros volcanic system. Tectonic movements can cause closure or opening of new way out for the deep magma, allowing jumping on the volcanic activity (from explosive to effusive). Indeed, *Upper Pumice* pyroclastics and domes-enclaves systems cover the same silica range (that means same degree of evolution) and undergo similar mingling process, but they are emplaced by different type of activity. This indicates the importance of the tectonic assessment variation from the caldera-forming and post-caldera periods of activity.

Regarding to Yali, the obtained data suggest that it represents an independent volcanic center, fed by a different plumbing system, marginal in respect with the main volcanic area of Nisyros.

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