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The Kos–Nisyros–Yali Volcanic Field

Olivier Bachmann¹, Sharon R. Allen², and Caroline Bouvet de Maisonneuve³

ABSTRACT

The Kos–Nisyros–Yali volcanic field has produced a range of volcanic products over the last 3 million years. Volumetrically, silicic magma dominates, and activity includes one of the largest known explosive eruptions of the Aegean arc, the >60 km³ (dense-rock equivalent), 161 ka rhyolitic Kos Plateau Tuff. The Kos–Nisyros–Yali volcanic field is situated within an area of active crustal extension, which has greatly influenced magmatic processes and landscape development in the region. Recent seismic unrest, surface deformation and intense geothermal activity indicate that the system remains active, particularly around the Nisyros and Yali edifices. These signs of magmatic activity, together with the fact that the most recent eruptions have become increasingly silicic, would justify detailed monitoring of the area.

Keywords: Kos–Nisyros–Yali volcanic field, Kos Plateau Tuff, caldera cycle, magmatic differentiation

INTRODUCTION

The Kos–Nisyros–Yali volcanic field (Greece – all locations in this article are Greece unless otherwise stated) is the easternmost magmatic complex of the modern South Aegean Volcanic Arc. This volcanic field has developed within a region of E–W crustal

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extension that covers the area from Kos and Tilos (FIG. 1). Over the last 3 My, there have been a variety of eruptive styles, ranging from quiet outpourings of lava to highly explosive eruptions, including the 161 ka Kos Plateau Tuff (KPT) event, and the products of those eruptions have varied between intermediate to silicic in composition. This variation in eruptive style and composition, coupled with the extensional tectonic setting and a dry Mediterranean climate, means that the Kos–Nisyros–Yali volcanic field offers exceptional opportunities for studying petrological, volcanological, and hydrothermal processes in an active subduction zone environment.

Recent notable scientific advances in understanding volcanic and magmatic processes in the Kos–Nisyros–Yali volcanic field include a number of studies summarized in Dietrich and Lagios (2018). In particular, the KPT eruption has been reconstructed in unprecedented detail using textural studies of juvenile pumice clasts, with specific focus on magma–water interaction, the transport of pyroclastic flows across the sea, and conduit flow processes (Allen 2001; Dufek and Bergantz 2007; Bouvet de Maisonneuve et al. 2009). Moreover, the volcanic history and petrological evolution of the whole volcanic field over the last 3 My has been minutely described (Di Paola 1974; Francalanci et al. 1995; Bachmann et al. 2012; Klaver et al. 2017) within the neo-tectonic context (Pe-Piper et al. 2005), while the hazards associated with hydrothermal unrest and phreatic eruptions in the caldera of Nisyros Volcano (a popular tourist destination) has been carefully assessed (Kinvig et al. 2010).

The known volcanic deposits of the Kos–Nisyros–Yali volcanic field can now be ordered chronologically and are grouped according to whether they erupted pre-, syn-, or post-KPT. The earliest exposed, pre-KPT volcanic products (3 Ma–161 ka) include small volume (typically < 1 km³) intermediate-to-silicic lava domes and tuff cones of western Kos (Kefalos dacites and rhyolites), the islands of Pachia and Pyrgousa and, potentially, the lower submarine volcanic succession of pillow lavas and hyaloclastite on Nisyros (FIG. 1). Submarine bathymetry and seismic studies suggest there are pre-KPT submarine domes along a line that extends west of Pachia (Papanikolaou and Nomikou 2001). The KPT, which erupted from a now tectonically extended and submarine caldera centred near Yali, blanketed the surrounded terrain up to a distance of about 50 km from the vents, eroding underlying deposits and depositing pumice, ash and metre-sized lithic fragments. The KPT includes a significant proportion of andesite lava blocks as lithic clasts, indicating destruction of

a large pre-existing volcanic edifice. Post-KPT volcanism has contributed to building Nisyros Volcano, the Yali lava and submarine pumice cone, and Strongyli islet (Di Paola 1974; Dietrich and Lagios 2018).

The subaerial part of Nisyros Volcano forms an 8 km wide edifice on the southern edge of the KPT caldera. Nisyros Volcano is the accumulation of numerous alternating episodes of explosive and effusive volcanic eruptions of basaltic-andesite to rhyolite (see stratigraphy and map in Dietrich and Lagios 2018). A 3.8 km wide caldera in the centre of the island largely formed as a result of two 2–3 km³ dense-rock equivalent Plinian eruptions (Lower Pumice and Upper Pumice). The most recent magmatic eruptions on Nisyros (as yet undated) are the extrusions of thick rhyodacite lava domes along the western part of the caldera. Two large sector collapse events from the flanks of the volcano have also been inferred (see summary in Dietrich and Lagios 2018).

In contrast, Yali islet consists of only three different small-volume volcanic events, all erupted post KPT: (1) a submarine pumice breccia (Yali-1); (2) a subaerial obsidian lava flow and associated pyroclastic deposits; (3) a sub-Plinian fall deposit from an unknown vent called Yali-2 (Koutrouli et al. 2018). The submarine pumice succession, capped by a small limestone unit, provides a rare opportunity to study fresh, submarine-erupted pumice in its original stratigraphic context.

Despite the exceptional setting of the Kos–Nisyros–Yali volcanic field, there are challenges to obtaining a well-constrained stratigraphy. The area is an island archipelago with limited terrestrial exposure and there have been many small-volume eruptions of similar composition, which have erupted over relatively short periods of time. Moreover, there is a conspicuous lack of K-bearing phases and a limited number of zircons in most of the deposits (due, in part, to eruption at temperatures close to, or above, zircon saturation). This makes precise geochronology a challenge. For example, an age of 200 ± 50 ka was determined by K–Ar on whole-rock for the Argos Rhyolite (also named the Avlaki Rhyolite in more recent publications), but the same unit was dated at only 66.6 ± 2 ka using K–Ar on plagioclase (see Table 3.2. of Dietrich and Lagios 2018). A few ¹⁴C ages are available, indicating ages younger than ~50 ka for the last large caldera-forming eruption on Nisyros (Upper Pumice), but these tend to have large errors. These geochronological challenges can be tackled by further research, including uranium-series dating of zircons, or by constraining relative ages using marine tephrochronology of ash beds

and interbedded sapropel layers in deep-sea cores (see recent compilations from Tomlinson et al. 2012; Koutrouli et al. 2018).

THE PAROXYSMAL KOS PLATEAU TUFF ERUPTION

The Kos Plateau Tuff (KPT) is comparable in volume to products from the Late Bronze Age eruption of Santorini (Druitt et al. 2019 this issue). More than 60 km³ dense-rock equivalent of crystal-rich, high-SiO₂ rhyolite (with minor andesite and >3 km³ of vent- and conduit-derived lithic debris) were evacuated from a shallow reservoir situated about 5–8 km beneath the surface (Allen 2001; Bachmann 2010). Apart from the opening and final stages, the products are almost exclusively non-welded pyroclastic density current deposits that are well-exposed on the central Kos Plateau in sections up to 20 m thick (FIG. 2).

Isopach (equal thickness) and isopleth (equal grain size) data for the KPT units indicate that the source vent lay offshore of Kos Island, near present-day Yali Island. The nature and volume of the KPT, and the volume of vent-derived lithic clasts, suggest that the eruption formed a caldera with a diameter of 5–10 km. Apart from the post-KPT volcanic islands (Yali, Nisyros, Strongyli), this area now lies below sea-level and has yet to be sampled in detail. Geophysical investigations between Kos and Nisyros revealed an unconformity overlain by an acoustically incoherent layer, which has been interpreted as subaerial KPT and which suggests that part of the depositional basin was not submerged at the time of eruption (Pe-Piper et al. 2005). The opening phase of the KPT eruption was demonstrably phreato-Plinian (Allen and Cas 1998): early KPT floating pumice deposits have been found on Kos (Piper et al. 2010). Hence, shortly before the eruption, seawater must have covered both the opening vent and at least some of the area between the source vent and Kos Island.

The widely dispersed KPT deposits are today exposed on several islands and peninsulas of the eastern Aegean region, separated by water channels several hundreds of metres deep (see FIG. 1). This archipelago setting was used to infer that the pyroclastic flows had travelled across significant stretches of water (e.g., Allen and Cas 2001). A possible mechanism to explain such behaviour, together with the observed high concentration of large lithic clasts in the deposits (despite having crossed kilometres of water), involves the blanketing of the sea surface by rafts of floating pumice (Allen and Cas 2001; Dufek and Bergantz 2007). The large areal distribution and massive size of lithic fragments of the KPT were used to infer very

high eruptive fluxes during emplacement, in excess of 2×10^6 m³/s (Dufek and Bergantz 2007).

The dominant juvenile component in the KPT is a white, crystal-rich (25–35 vol%), vesicular (75–85 vol%), and variably sheared “tube” pumice. Its composition is homogeneous and very evolved (high-SiO₂ rhyolite with high volatile content). Additional minor pumice types (also dominantly rhyolitic) include: (a) highly vesicular (≥ 85 vol%), crystal-rich, frothy (non-sheared) pumice; (b) early erupted phreatomagmatic, crystal-poor pumices with a bimodal large/micro-vesicle population; and (c) streaky grey and white pumice (indicating recharge and mingling of a more mafic magma into the reservoir shortly prior to eruption) (Bouvet de Maisonneuve et al. 2009; Piper et al. 2010).

Textural variations between the different pumice populations indicate complex bubble growth mechanisms during magma storage and ascent in the conduit prior to eruption (Bouvet de Maisonneuve et al. 2009). The bimodal distribution of vesicles in the early erupted phreatomagmatic pyroclasts is consistent with bubble accumulation in the more melt-rich part of the magma reservoir; large bubbles represent the exsolved fluid phase in the reservoir, whereas small bubbles record late, rapid nucleation during onset of the Plinian phase of the eruption. Tube pumices are attributed to intense shearing along the conduit margins, while the frothy pumices originated mostly from the low-shear environment at the conduit centre. These two different types of pumice have very different permeabilities, leading to variable outgassing efficiency. The highest permeabilities, found parallel to bubble elongation in tube pumices, must have been subparallel to the conduit walls, constraining outgassing to a dominantly vertical direction, albeit insufficient to prevent explosive fragmentation of the magma. Such non-welded, rhyolitic pumice samples provide a rare opportunity to derive permeability information that can be used to refine conduit flow models and estimate outgassing efficiency from an ascending highly viscous magma.

Crystals found in KPT pumices (mostly quartz and feldspars) are typically large, partly resorbed, and shattered by rapid decompression during eruption (Keller 1969; Bachmann 2010). Feldspars are also commonly compositionally zoned, while Fe–Ti oxides and biotite phenocrysts are more homogeneous (the latter being filled with NaCl-rich inclusions) (Bachmann 2010). Pre-eruptive volatile contents dissolved in the melt (from quartz-hosted melt inclusions) (Bachmann et al. 2010) range from 4.5

to 6.5 wt% H₂O and 15–140 ppm CO₂, yielding crystallization and storage pressures that vary between 150 MPa and 250 MPa, assuming volatile-saturated conditions. Storage temperatures were low (near the water-saturated granitic eutectic, ~700 °C) (Bachmann 2010), and zircons show a long crystallization history, extending from the eruption age at around 160 ka to >400 ka (Guillong et al. 2014). These petrological characteristics are in clear contrast to the subsequent most evolved magmas from Nisyros Volcano (rhyodacitic lavas and pumice clasts), which are hotter, contain no quartz, sanidine nor biotite, and are barely zircon saturated.

The climax of the KPT eruption ejected large fragments of nearly fully crystallized granitoids (Keller 1969), representing the near-solidus margins of the magma reservoir. Zircons present in these clasts have the same age range as those extracted from pumices (Bachmann 2010). Quartz and feldspar in these clasts contain abundant fluid inclusions, providing a unique window into primary magmatic fluids in the subvolcanic reservoirs. Such saline (some up to >35 wt% NaCl_{equiv}), high-temperature fluids (up to 600–700 °C) may, ultimately, feed hydrothermal systems and nurture shallow ore deposits that are common around and above large magmas reservoirs.

GENERATION OF VISCOUS, WET ARC MAGMAS AT THE KOS-NISYROS-YALI VOLCANIC FIELD

On the basis of bulk-rock geochemical and isotopic data on the volcanic products (FIG. 3), as well as mineral chemistry, the chemical evolution trend observed in the Kos–Nisyros–Yali volcanic field (including the KPT rhyolite) suggests a dominant role of fractional crystallization from basaltic parents within the relatively thin Aegean crust (~30 km in the Kos–Nisyros area), accompanied by some assimilation of surrounding crust (Klaver et al. 2017). Overall, however, interactions with pre-existing crustal rocks were relatively limited, e.g., little to no inherited zircons (Guillong et al. 2014), and limited isotopic variability (Buettner et al. 2005), but may have involved some carbonate assimilation (FIG. 3) (Spandler et al. 2012). This assimilation and fractional crystallization-dominated evolution appears to be the main differentiation mechanism throughout the modern South Aegean Volcanic Arc (Francalanci and Zellmer 2019 this issue). It is likely to have occurred in at least two main magma storage regions located at different depths: one in the lower crust, and the other in the upper crust. This type of magmatic evolution is typically ascribed to polybaric differentiation within a transcrustal column of magmatic mush (see Klaver et al. 2017 for Nisyros).

REJUVENATION OF LARGE SILICIC RESERVOIRS

Silicic, crystal-rich ignimbrites, such as the KPT, develop from some of the most viscous magmas on Earth. Two key questions are: (1) How can such magmas leave their shallow magmatic hearths to generate such large volcanic cataclysms?; (2) Why are they so homogeneous in bulk-rock composition? An event of “rejuvenation” of the crystal-rich (“mushy”) reservoir that was powered, for example, by hot recharge from deeper in the system seems to be required to reduce the bulk viscosity of the magma and allow it to erupt. There are clear petrological and textural signs that thermal rejuvenation happened in the case of the KPT. Hot recharge magma mingled with the silicic endmember (grey-banded pumices and mafic enclaves) (Bachmann 2010; Piper et al. 2010), while partial melting/resorption of lower temperature mineral phases (feldspars and quartz) has been noted since the early work of Keller (1969). The exact process by which “mush rejuvenation” takes place remains keenly debated, but it likely involves a thermo-mechanical process induced by partial melting of pre-existing crystals following the injection of heat and/or mass (including volatiles) from below. This leads to local pressure increase, viscosity reduction, and convective stirring, all of which can generate the observed hand-sample-scale homogeneity (Parmigiani et al. 2014) prior to the catastrophic evacuation of the shallow reservoir.

Whether this rejuvenation process ultimately triggered the KPT eruption is a matter of debate. However, it is likely that such an event can, *if fast enough*, generate sufficiently large overpressures in the magma reservoir to fracture wall rocks and propagate the mobile (i.e., <50 vol% crystals) magma towards the surface. The precise duration of the rejuvenation event is not known for the KPT, but many systems of similar sizes around the world, based on diffusion chronometry in minerals, yield timescales of decades to centuries (Parmigiani et al. 2014).

A PETROLOGICAL CALDERA CYCLE?

The Kos–Nisyros–Yali volcanic field seems to follow a cyclic evolutionary pattern (FIG. 4), as is the case in many active volcanic regions (e.g., Forni et al. 2018; Druitt et al. 2019 this issue; Francalanci and Zellmer 2019 this issue). This volcanic field evolved slowly over 10^5 – 10^6 years to highly silicic compositions in shallow storage zones, building up to a large-magnitude eruption. When the KPT eruption occurred, the magma plumbing system likely changed drastically. A large amount of magma vented into the atmosphere and so significantly decompressed the magmatic column which led to intense outgassing and associated crystallization of the upper-crustal mush zone (Bachmann et al. 2012). Following this cataclysmic volcanic event, post-caldera

activity was distinctively more mafic, hotter, and drier for a certain period of time, and sourced from the deeper roots of the system. Interestingly, the latest eruptions (Nisyros post-caldera domes and Yali rhyolites) are very silicic, and progressively more water-rich, suggesting that a shallow, evolved magma reservoir may be building again in the area. A change from *post*-caldera to a new cycle of *pre*-caldera volcanism may have occurred in the last 20-30 ky (FIG. 4) (Bachmann et al. 2012).

PRESENT STATE OF THE NISYROS AND YALI MAGMA RESERVOIR(S)

Coeval magmatic activity at Nisyros and Yali over the last 20–30 ky (as volcanic activity shifted to a potential pre-caldera mode) suggests that at least two upper-crustal zones (“pockets”) of eruptible magma are now present beneath this area. The fact that the recently erupted products are so different (strongly mixed, crystal-rich magmas in the post-caldera domes of Nisyros; more silicic, crystal-poor material in Yali) indicates that the present-day reservoir is not fully unified, and so not yet homogeneous and voluminous enough to produce another KPT-like eruption. However, the crystal-poor, high-SiO₂ rhyolite of Yali clearly demonstrates that parts of the storage system have reached a cool, hydrous state, and the long dormancy of the system points towards a potential period of magma reservoir growth that could ramp up to an eruption of silicic magma in the (potentially far) future [see a similar case for the other large restless calderas of the Mediterranean region, Campi Flegrei (Italy), in Forni et al. (2018)]. Whether such potential future eruptions will form a slow-moving lava dome (as in the post-caldera domes) or a new caldera-forming explosive event (like the Upper Pumice) with significant regional hazards warrants further investigation.

In order to better image the present-day magma reservoir(s) below the whole Kos–Nisyros–Yali volcanic field, seismic tomography and deformation studies have been conducted (see Dietrich and Lagios 2018). However, these typically lack the spatial resolution necessary to image any individual pockets of eruptible magma. Obtaining the requisite resolution remains extremely challenging and costly. Other techniques, such as magneto-telluric and gravity surveys, could be extremely useful in complementing seismic and deformation studies to better constrain the state, geometry and conditions in the present-day magmatic plumbing system and the sizes of eruptible magma pockets.

Analyzing compositions of fumaroles/gases escaping from the edifice is less costly and easier to do than large-scale geophysical experiments. Existing models of

hydrothermal activity within the Nisyros caldera (Dietrich and Lagios 2018) propose the presence of a deep aquifer containing hot (>300 °C) hydrothermal brine that is part magmatic and part seawater in origin. The magmatic component, indicating the presence of an actively degassing magma body below the edifice, has been varying over time and has significantly increased following the seismic crisis of 1996–1997. Such an increase suggests that some magmatic recharge of the volcanic plumbing system occurred at the end of the 1990s (Dietrich and Lagios 2018).

FUTURE DIRECTIONS

Whether or not the Kos–Nisyros–Yali volcanic field will produce another large volcanic eruption depends on the configuration of the magma reservoir(s). Without better constraints of the shape, size, and state of such reservoir(s), it is difficult to predict the magnitude of any future eruption. This volcanic complex is certainly active and is undergoing seismic crises (with more than 1,600 earthquakes between 1995 and 1997), strong surface deformation, and outgassing of fluids that have a clear magmatic flavour (Dietrich and Lagios 2018). Pushing the boundaries of our understanding to obtain more detailed images of the upper crustal reservoir(s), and monitoring continuously deformation and fumarole chemistry, should be a priority in the coming years. The Kos–Nisyros–Yali volcanic system is certainly capable of producing further eruptions which, whether phreatic or magmatic, could have profound implications for local populations and aviation routes.

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FIGURES

Figure 1 Map of the Kos–Nisyros–Yali volcanic field (Greece) highlighting the extent and distribution of volcanic deposits produced prior to, during, and after the paroxysmal caldera-forming eruption of the Kos Plateau Tuff (KPT). Distribution of the volcanic deposits is after Allen and McPhie (2001), Pe-Piper et al. (2005), and Dietrich and Lagios (2018); bathymetry is from EMODnet; black dashed-lines indicate major faults (see Lagios et al. 2005); white rectangle on Kos outlines area shown in FIGURE 2. (**INSET**) Map showing the location of the Hellenic trench and the Kos–Nisyros–Yali volcanic field within the Southern Aegean Volcanic Arc.

Figure 2 The Kos Plateau Tuff (KPT); location shown on FIGURE 1. **(LEFT)** Generalized stratigraphic log of the Kos Plateau Tuff (KPT). Four eruptive phases (1-4) generated six major stratigraphic units: where unit A is at the base to unit F is at the top. Phase 1 comprises Units A and B; phase 2 comprises units C and D; phase 3 comprises unit E; phase 4 comprises unit F. The units D, E and F are further subdivided as follows: unit D = lower (Dl), intermediate (Di) and main ignimbrite (Dm); unit E = the basal lithic breccia (Ebx), main ignimbrite (E) and the upper ignimbrite (Eu); unit F = pyroclastic density current deposit (Fs) and vitric ash (Ff). The lapilli grain scale letters f, m, and c stand for fine, medium and coarse. **(RIGHT)** Photo of the most proximal KPT on central Kos, ~11 km from source, showing the thick lower units (A-D) of the KPT. The erosive boundary at the contact between Ebx and ignimbrite Dm was created during the eruption climax. Vertical section is ~15 m (photo by O Bachmann).

FIGURE 3 Major and trace element compositions of magmas from the Kos–Nisyros–Yali volcanic field. The probable liquid line of descent (LLD) is indicated with an arrowed black line on most plots; black arrowed lines also indicate differentiation trends at temperatures above and below that of zircon saturation ($T_{\text{sat. zircon}}$); “sat.” = saturation. Mafic magmas affected by carbonate assimilation are circled. Abbreviations in the classification and nomenclature diagram at top left (for the plot of Na + K versus Si) are as follows: tb. = trachybasalt; bas-ta. = basaltic trachyandesite; ta. = trachyandesite; trach. = trachyte; bas-and. = basaltic andesite; and. = andesite. DATA FROM DI PAOLA (1974), FRANCALANCI ET AL. (2005), ZELLMER AND TURNER (2007), PE PIPER AND MOULTON (2008), BACHMANN ET AL. (2012), AND SPANDLER ET AL. (2012).

Figure 4 Evolution of the Kos-Nisyros-Yali volcanic field (see FIGURE 1), illustrating a possibly cyclic trend with the reconstruction of a large upper crustal reservoir bearing cool and oxidized, high-SiO₂ rhyolite akin to the KPT magma. 1. Early magmatic history with the production mafic to intermediate magmas erupted at Pachia and Pyrgoussa. 2. Evolution to more silicic magma compositions erupted in Kefalos. 3. Growth of a large, volatile-rich, silicic magma reservoir at the origin of the paroxysmal caldera-forming eruption (highlighted with the yellow star). 4. Gradual re-growth of a reservoir and differentiation of magmas erupted in Nisyros and Yali. Abbreviations are as follows: BA = Basaltic-Andesites; KPT = Kos Plateau Tuff; AM = Agios Mammas dome; PCD = Post-Caldera Domes of Nisyros.