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Generation of arc rhyodacites through cumulate-melt reactions in a deep crustal hot zone: Evidence from Nisyros volcano

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A B S T R A C T

The generation of continental crust of intermediate composition occurs predominantly in convergent margin settings, yet the mechanisms by which felsic, calc-alkaline arc magmas are generated remain poorly understood. Magma mixing appears to be a common process in voluminous intermediate arc rocks but the composition of the felsic mixing endmember is typically obscured by the mixing process. We investigate a suite of porphyritic (rhyo)dacitic magmas (65–72 wt.% SiO_2) from Nisyros, a young stratovolcano in the Aegean arc, Greece. These magmas are not affected by shallow process such as hybridisation or crystal-melt segregation and thus offer a valuable insight into the origin of felsic melts at convergent margins. We find that the Nisyros (rhyo)dacites form through a reaction in which earlier-formed wehrlite cumulates in the deep arc crust react with melts to form amphibole. This implies that melt major element compositions are effectively buffered by a low-variance mineral assemblage to follow this peritectic boundary such that the silica content of melts extracted from the deep crustal hot zone is controlled by the amount of amphibole crystallised. The resorption of cumulates is pivotal in imparting a distinct trace element signature that is decoupled from major element systematics. For example, high compatible element contents and a strong amphibole signature (low Y and Dy/Yb) cannot be captured by simple crystallisation models and require cumulate resorption. Variable radiogenic isotope systematics indicate minor crustal contamination although assimilation is not proportional to silica content and hence not a main driving force behind the generation of felsic melts. Instead, the Nisyros (rhyo)dacites formed through melt-cumulate reaction processes prior to emplacement as mush bodies at shallow depth and partial eruption. Magma mixing only becomes an important process in the youngest unit on Nisyros. On a global scale, peritectic boundary melts are rarely sampled in the whole rock or melt inclusion record. Conversely, peritectic boundary melts do form a suitable felsic mixing endmember for the generation of voluminous "*monotonous intermediate*" magmas.

1. Introduction

Rocks of intermediate composition (andesites and dacites; 57–68 wt.% SiO_2) comprise a significant proportion of the extrusive products of continental and mature oceanic arc volcanoes worldwide and are a key component of subduction zone volcanism (e.g., Gill, 1981; Reubi and Blundy, 2009). The strong compositional similarity between arc andesites and the bulk continental crust (e.g., Rudnick, 1995) suggests that the Earth's crust has predominantly formed and evolved at convergent margins. This, in combination with the significant hazards posed by andesitic and dacitic volcanic eruptions and their association with mineral deposits, warrants a clear understanding of the petrogenesis of andesites. Despite decades of research, this is still an unresolved issue and a wide variety of models have been proposed for the generation of intermediate and silicic arc rocks (e.g., Eichelberger, 1975; Gill, 1981; Hildreth and Moorbath, 1988; Annen et al., 2006; Kent, 2014; Lee and Bachmann, 2014; Adam et al., 2016; Blum-Oeste and Wörner, 2016; Blatter et al., 2017; Müntener and Ulmer, 2018). Given the wide textural and compositional variability of intermediate arc rocks, it is unlikely that any single process is dominant. Hence, we will consider the petrogenesis of a subset of global intermediate arc rocks: hybrid, porphyritic andesites and dacites. These magmas are a common and voluminous component of mature arc volcanoes in, for instance, the Cascades, Lesser Antilles and Andean arcs and have been responsible for some of the largest volcanic eruptions of the 20th century (e.g., Mount St. Helens,

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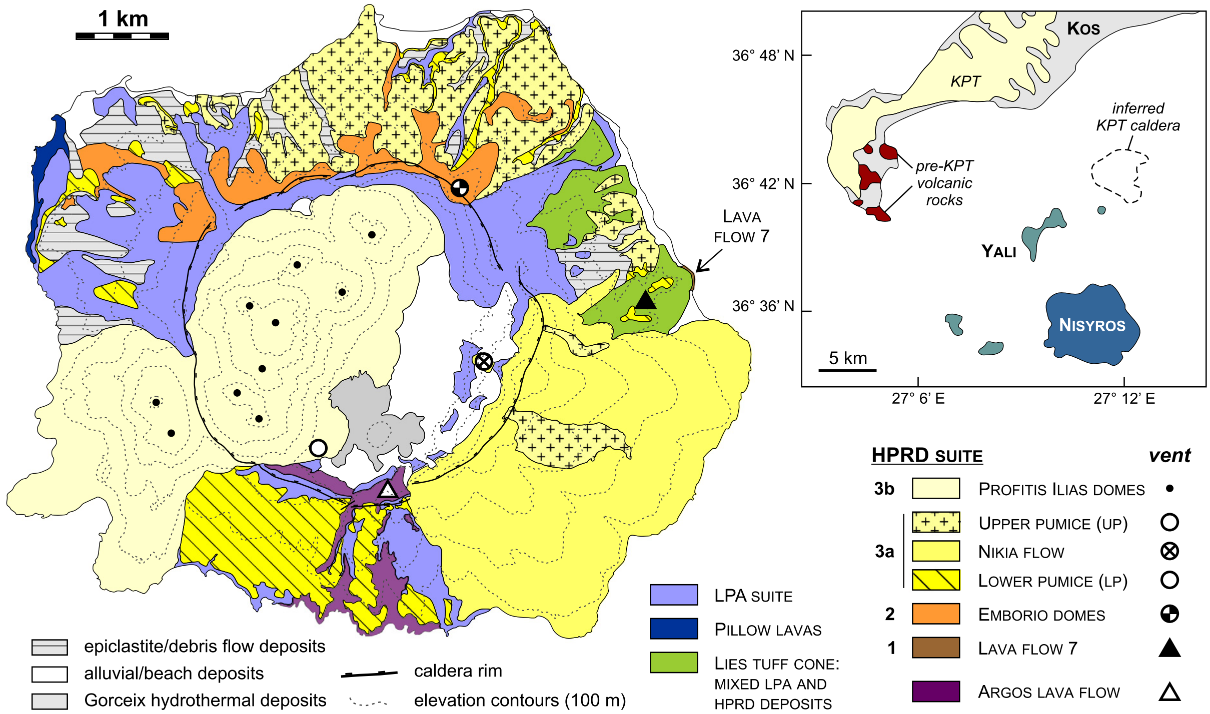

Fig. 1. Simplified geological map of Nisyros and its location within the Kos–Nisyros–Yali volcanic centre (inset), modified after Volentik et al. (2005) and Klaver et al. (2017). The volcanic units are grouped into phenocryst-poor andesite (LPA) and phenocryst-rich rhyodacite (HPRD) suites and further subdivided as discussed in the text. Inferred vent locations for the HPRD units are shown, as well as the presumed location of the Kos Plateau Tuff (KPT) caldera to the north of Nisyros.

USA, 1980–1986 and Soufrière Hills, Montserrat, 1995–present). The main characteristic of mature arc magmas is the abundant textural and compositional evidence for magma mixing and mingling, most prominently reflected in bimodal distributions of melt inclusion and amphibole compositions (e.g., Reubi and Blundy, 2009; Kent, 2014). In addition, hybrid andesites commonly have a geochemical signature reflecting amphibole fractionation, irrespective of the presence of amphibole as a phenocryst phase (Davidson et al., 2007). The hybridised nature of these intermediate arc rocks, however, tends to obscure the compositions of mixing components (Blum-Oeste and Wörner, 2016). Quenched mafic enclaves can help constrain the composition of the mafic component, but the nature of the felsic component often remains elusive. Here we present a case-study of Nisyros volcano, Aegean arc, to elucidate the petrogenesis of felsic melts that constitute the dominant component of hybrid arc andesites and dacites. Despite its relatively young age, Nisyros has erupted a wide range of magma compositions that show a temporal transition from tholeiitic andesites to porphyritic, calc-alkaline (rhyo)dacites that lack evidence for extensive hybridisation. Thus, Nisyros offers a unique opportunity to investigate the generation of increasingly felsic melts beneath an embryonic arc stratovolcano, of the type typically buried beneath voluminous hybrid andesites and dacites in more mature volcanoes.

2. Geological background

Nisyros is an island volcano that is part of the Kos–Nisyros–Yali volcanic centre at the eastern edge of the Aegean volcanic arc, Greece. Nisyros is a circular island (~8 km diameter) with a central caldera partly filled with rhyodacitic domes (Fig. 1) and is built on thinned continental crust (~27 km). Following the cataclysmic Kos Plateau Tuff (KPT) eruption at 161 ka (Smith et al., 1996), the locus of volcanism shifted southward and construction of Nisyros began upon distal KPT deposits and non-volcanic basement. Apart from a small exposure of pillow lavas, all volcanic deposits on Nisyros are inferred to postdate the KPT eruption as the KPT was found immediately overlying non-volcanic basement in drill cores inside Nisyros' caldera (Volentik et al., 2005 and references therein). The style of volcanism changed gradually from effusive and mildly explosive to larger Plinian eruptions and the emplacement of viscous lava flows and domes. Based on petrographic features, Klaver et al. (2017) divided the eruptive products into two distinct suites: a phenocryst-poor andesite (LPA) and a phenocryst-rich rhyodacite (HPRD) suite. The LPA suite comprises (basaltic-)andesites and rare dacites with low crystal contents (<10 vol.% on average in the andesites). In contrast, the HPRD suite represents porphyritic rhyodacites that display abundant evidence for magma mingling, including the presence of quenched mafic enclaves and reversely zoned crystals (e.g., Braschi et al., 2014). The rhyodacites have a common texture and mineral assemblage dominated by plagioclase, orthopyroxene, Fe–Ti-oxides and minor clinopyroxene. Amphibole has not been found as a phenocryst phase, despite the clear geochemical signature for residual amphibole in the HPRD suite (e.g., Buettner et al., 2005; Zellmer and Turner, 2007; Bachmann et al., 2012). In addition, the HPRD suite hosts a wide variety of plutonic xenoliths. Several of these cumulate fragments record a high-pressure crystallisation trend of hydrous primitive melts, ranging from (hornblende-)wehrlite to plagioclase-hornblendites (Klaver et al., 2017). Hornblende forms at the expense of clinopyroxene in these cumulates and the role of this reaction in generating the (rhyo)dacites is explored in this study.

3. Analytical techniques

A representative suite of 39 whole rock samples spanning the entire subaerial volcanic history of Nisyros was analysed for major element, trace element and Sr–Nd–Hf–Pb isotope composition. Major element data for 20 of these samples were reported together with mineral major- and trace element compositions in Klaver et al. (2017), whereas trace element and Nd–Pb isotope data for 11 samples have been previously published in Klaver et al. (2016).