Zircon crystallization and recycling in the magma chamber of the rhyolitic Kos Plateau Tuff (Aegean arc)

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ABSTRACT
In contrast to most large-volume silicic magmas in continental arcs, which are thought to evolve as open systems with significant assimilation of preexisting crust, the Kos Plateau Tuff magma formed dominantly by crystal fractionation of mafic parents. Deposits from this ~60 km³ pyroclastic eruption (the largest known in the Aegean arc) lack xenocrystic zircons [secondary ion mass spectrometry (SIMS) U-Pb ages on zircon cores never older than 500 ka] and display Sr-Nd whole-rock isotopic ratios within the range of European mantle in an area with exposed Paleozoic and Tertiary continental crust; this evidence implies a nearly closed-system chemical differentiation. Consequently, the age range provided by zircon SIMS U-Th-Pb dating is a reliable indicator of the duration of assembly and longevity of the silicic magma body above its solidus. The age distribution from 160 ka (age of eruption by sanidine 40Ar/39Ar dating; Smith et al., 1996) to ca. 500 ka combined with textural characteristics (high crystallization content, corrosion of most anhydrous phenocrysts, but stability of hydrous phases) suggest (1) a protracted residence in the crust as a crystal mush and (2) rejuvenation (reduced crystallization and even partial resorption of minerals) prior to eruption probably induced by new influx of heat (and volatiles). This extended evolution chemically isolated from the surrounding crust is a likely consequence of the regional geodynamics because the thinned Aegean microplate acts as a refractory container for magmas in the dying Aegean subduction zone (continent-continent subduction).

Keywords: igneous petrology, rhyolite, zircon geochronology, magma residence time, Aegean arc.

INTRODUCTION
Approximately 160,000 yr ago, one of the largest Quaternary explosive volcanic eruptions of the Mediterranean basin occurred just offshore of the island of Kos (Greece), resulting in ~60 km³ of volcanic ash and pumice emplaced as pyroclastic fall and flow deposits over an area >2000 km² (Keller, 1969; Allen, 2001; Fig. 1). In comparison to the 3500 yr B.P. Minoan eruption, which created a 12-km-diameter caldera on the nearby island of Santorini, the Kos Plateau Tuff is a factor of two larger in volume (Pyle, 1997). These geologically nearly instantaneous events have devastating effects on human infrastructures and populations. Understanding how (and how fast) these highly explosive magmas bodies are generated is of obvious importance.

In the last decades, the vast majority of petrogenetic studies focusing on these evolved (non-basaltic) magma bodies has stressed the complexities that are involved in the generation of such magmas. Although crystal fractionation typically plays a role, open-system behavior, with an important mass contribution from preexisting crust, is a well-established process in generating large-volume (>1 km³) silicic magmas, particularly in continental arcs (e.g., DePaolo, 1981; Halliday et al., 1984; Hildreth and Moores, 1988; Reagan et al., 2003). Earlier work on the Kos Plateau Tuff (Keller, 1969) has suggested that the magma was derived by partial remelting of a pre–Kos Plateau Tuff granitic intrusion in the upper crust. Since such a hypothesis poses mass and thermal balance problems (e.g., Bachmann et al., 2002) and has rarely been suggested for other units, it should be tested further. In contrast to these previous interpretations, our new findings argue that the Kos Plateau Tuff may represent a case of dominantly closed-system fractionation from mafic parents. This chemically closed-system evolution can be tied to the geodynamics of the Aegean arc, and may shed light on the long-standing issue of whether silicic magmas remain for several hundreds of thousands of years in the upper crust above their solidi or whether they rapidly crystallize to solid plutons (e.g., Halliday et al., 1989; Mahood, 1990; Sparks et al., 1990; Reid et al., 1997; Vazquez and Reid, 2004; Bacon and Lowenstern, 2005; Charlier et al., 2005).

DATA AND METHODS
The main data set that we used to address these questions was composed of zircon 238U-230Th and 238U-206Pb dates from the U.S. Geological Survey–Stanford University sensitive high-resolution ion microprobe–reverse geometry (SHRIMP-RG) (following Bacon and Lowenstern, 2005). The Kos Plateau Tuff eruption occurred at a particularly favorable time for a geochronological study of volcanic processes: it is old enough that precise and accurate 40Ar/39Ar ages on sanidine and U-Pb ages on zircons can be obtained, but young enough that zircons can also be dated by the U-Th disequilibrium method (limited to ages younger than ca. 350 ka; e.g., Turner et al., 2003). Combining these three geochronological methods allows us to determine the eruption age (40Ar/39Ar; Smith et al., 1996), crystallization history (U-Th and U-Pb, this study), and amount of xenocrystic material in the system (U-Pb, this study). New data presented in this paper also include Fe-Ti–oxideo thermometry (using Andersen and Lindsley, 1985) and whole-rock Sr and Nd isotope determinations (following Sallet et al., 2000).

THE KOS PLATEAU TUFF
The nonwelded Kos Plateau Tuff deposits are dominantly fine-grained volcanic ash, tuff pumices, and andesitic lithics of varying sizes (some >2 m in diameter; Keller, 1969; Allen, 2001). They also contain a small proportion of “banded pumices” (pumices with conspicuous white...
and dark bands, which are interpreted as marking the interaction of a mafic magma with the resident rhoditic magma in the reservoir at, or close to, the time of eruption) as well as large (up to 1 m diameter) granitic clasts. Although some are holocrystalline, most of these granitic inclusions contain interstitial melt (5–15 vol% melt; Keller, 1969). These melt-bearing granitic inclusions were one of the main arguments that Keller (1969) used to suggest an anatectic origin for the Kos Plateau Tuff magma (interpreted as partially melted protolith clasts).

The Kos Plateau Tuff magma is rhoditic (74–76 wt% SiO₂, recalculated anhydrous) and crystal-rich (25–35 vol% crystals) with a mineral assemblage consisting of plagioclase, sanidine, quartz, biotite, ilmenite, magnetite, monazite, zircon, and apatite. Texturally, biotite and most plagioclase crystals are euhedral, whereas quartz and sanidine phenocrysts are corroded and contain numerous melt channels (Keller, 1969). The major-element composition of the interstitial glass is slightly more silicic than the whole-rock composition of the magma (SiO₂ content of ~77 ± 0.5 wt, recalculated anhydrous) and is depleted in CaO, FeO, and MgO (due to the presence of plagioclase and biotite in the rock).

Kos Plateau Tuff pumices and associated granitic inclusions have identical mineralogy and whole-rock composition (in terms of major and trace elements; Keller, 1969). Despite the presence of Paleozoic crustal rocks in the area (e.g., Smith et al., 2000) and a Miocene monzonitic intrusion with whole-rock δ⁶⁷Sr/⁶⁶Sr of 0.7065–0.7070 and εNd = ~2 (Juteau et al., 1986; Altherr and Siebel, 2002), whole-rock Nd-Sr isotopic ratios of Kos Plateau Tuff pumices and granitic inclusions (εNd = +0.2 to +1 and δ⁶⁷Sr/⁶⁶Sr = 0.7040–0.7045; Appendix 1) are similar to local young mafic magmas (Francalanci et al., 1995; Buettner et al., 2005).

Prior to eruption, the Kos Plateau Tuff magma was residing at ~8 ± 1 km depth (~2 kbar pressure; estimated by matching the normative composition of the eutectic point in the haplogranitic system at 2 kbar H₂O pressure with the normative composition of the melt; Keller, 1969) and was at ~760–780 °C with oxygen fugacities around NNO +1 to +1.5 (based on co-existing Fe-Ti–oxide composition; all pairs checked for Mg/Mn equilibrium; Bacon and Hirschmann, 1988; Appendix 2 [see footnote 1]). Coexisting oxide temperatures were also determined for the granitic inclusions, which ranged from 710 to 740 °C for the glass-bearing ones to ~580–650 °C for holocrystalline samples.

### U-Th-Pb RESULTS

SHRIMP-RG U-Th and U-Pb dating on euhedral but complexly zoned zircons (with spot sizes of 30–40 µm; Figs. 2, 3, and Appendix 3 [see footnote 1]) was performed on two pumice samples and four granitic inclusions (three of which were melt-bearing and one holocrystalline). Our strategy was to determine: (1) whether the zircons in the granitic clasts were older than those in pumices, and (2) whether some of the U-Th and/or U-Pb zircon ages were older than the eruption age (161 ± 1 ka by ⁴⁰Ar/³⁹Ar on sanidine; Smith et al., 1996). The first approach was designed to test Keller’s (1969) anatetic hypothesis: if a preexisting granite remelted to form the erupted rhyolite, zircons in granitic inclusions would be older than the zircons in pumices. The second approach was intended to better determine the time scales of magma assembly and residence in the upper crust. A total of 136 U-Th spot analyses was done on zircon rims, and the U-Pb technique (33 ages total) was employed to search for older components in U-rich anhedral cores (present in a significant proportion of crystals).

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Figure 2. Sensitive high-resolution ion microprobe–reverse geometry (SHRIMP-RG) U-Pb ages (and 2σ errors) on cores of zircons from Kos Plateau Tuff (2 pumices and 4 granitic inclusions from different stratigraphic levels in ignimbrite), showing age range in excess of analytical scatter (mean square of weighted deviates [MSWD] >> 1) of ca. 300 ka. All ages are corrected for initial radioactive disequilibrium in ²³⁰Th/²²⁸U using whole-rock values for Th/U melt composition (Appendix 3, see text footnote 1), ²³⁰Th/²²⁸U activity of 0.96, and ²³⁰Th/²²⁸Th from a Nisyros sample (0.834; Gülen, 1989).

Despite representing the oldest component preserved in the magma (anhedral cores), none of the 33 U-Pb ages (from both granitic inclusions and pumices; Fig. 2) was older than ca. 500 ka. If any, xenocrystic zircons were very rare in the erupted volume, implying that preexisting silicic crust was not a significant component in the generation of this rhoditic body. This observation is in agreement with mantle-like whole-rock Sr-Nd isotopic ratios of the Kos Plateau Tuff (Appendix 1, see footnote 1) and ⁴⁰He/³²He ratios for Nisyros volcano (Shimizu et al., 2005), both of which indicate a dominant mantle component in magmas of the Kos-Nisyros volcanic complex. In addition, the U-Pb data for Kos Plateau Tuff samples show a continuous (within the analytical errors) age range from the eruption age (ca. 160 ka) to 340 ka (and a slightly older data point at ca. 500 ka; Fig. 2).

The small errors (down to 10–15 k.y. at 2σ, leading to a high mean square of weighted deviates [MSDW] of 17.8) and the absence of xenocrystic cores (which, when they are present, add some uncertainty as to whether a secondary ion mass spectrometry (SIMS) age older than the eruption age is due to mixing between an old core and a young rim) strongly suggest that zircon crystallization lasted at least 180 k.y. This interpretation is in agreement with other similar studies on longevity of silicic systems (e.g., Reid et al., 1997; Miller and Wooden, 2004; Vázquez and Reid, 2004; Bacon and Lowenstern, 2005; Charlier et al., 2005). The concordance in age between zircons extracted from pumices and granitic clasts implies that the latter do not represent unmelted samples of an older plutonic body, as proposed by Keller (1969), but were excavated either from a high-crystallinity marginal “rind” of a magma chamber (e.g., Brown et al., 1998) or co-genetic plutonic rocks (e.g., Bacon and Lowenstern, 2005).

Although analytical errors are larger, the U-Th data corroborate the U-Pb data. They also show a continuous age range (for zircons extracted from both granitic inclusions and pumices) from the eruption age (ca. 160 ka) to the equilibrium (older than 350 ka; Fig. 3). On the basis of the low probability of fit for the isochrons (calculated with Isoplot; Ludwig, 2003), we interpret the isochron “ages” reported in Figure 3 (194 ± 10 ka for the granitic inclusions and 228 ± 14 ka for the pumices; both significantly older than the eruption age) as the most common crystallization ages of a zircon population that was crystallized over more than 200 k.y. (the same meaning is attributed to the mean U-Pb age; Fig. 2). Although one could expect that zircon rims dated by...
U-Th should all yield similar ages, a spread is anticipated because (1) not all zircon rims crystallized at the same time (some crystals become isolated from melt when included in other mineral phases and/or crystallized in areas of the magma chamber with different zircon saturation characteristics), and (2) the SIMS spot size was generally larger than a single growth band and therefore provided a mixed age between different crystallization episodes.

A LINK BETWEEN MAGMA GENESIS AND GEODYNAMICS?

The Aegean arc embodies a destructive margin in its dying stages; the low-density continental crust of Africa is thought to have reached the trench at present (e.g., Meier et al., 2004), slowing down the subduction process (convergence rate ~1 cm/yr; Jackson, 1993). As a result, the magma production rate in the mantle should be low, leading to small thermal energy input into the overlying crust. This low magma productivity is illustrated by (1) the low silicic magma output rate of the system (erupting ~60 km³ of rhyolite in at least 200~300 k.y. gives a maximum output rate of 2~3 × 10⁻⁴ km³/yr, which is an order of magnitude smaller than the rhyolite volcanic output given by White et al., 2006), and (2) the volumetrically small amount of volcanic products (in particular mafic magmas) preserved prior to the Kos Plateau Tuff eruption (even when considering the fact that some mafic volcanic rocks may be submersed at present). In comparison, most continental arcs (e.g., Andes or San Juan volcanic field) show a major input of hot, mafic magma over 10⁷~10⁸ yr prior to the assembly and eruption of large silicic magma chambers (e.g., Lipman, 2000). In addition, thin continental crust leads to unfavorable conditions for crustal melting (Dufek and Bergantz, 2005; Annen et al., 2006). In the Aegean setting (thin crust and low crustal heat input), the preexisting crust acts as a refractory container, and should not contribute much to magma generation. We therefore hypothesize that magmatic evolution can be dominated by closed-system fractionation in areas of thin crust and/or slow convergence. In contrast, subduction zones where convergence is rapid and the crust is thick (typically, the central Andes at present) receive more heat in the crust, leading to more efficient crustal melting and generation of large amounts of silicic magmas (batholiths) and magmatic evolution dominated by mixture of both crustal and mantle melts.

CONCLUSIONS

New SIMS zircon U-Th-Pb ages and whole-rock isotopic results support the following model for the Kos Plateau Tuff: (1) The near-eutectic rhyolitic magma was generated dominantly by closed-system fractionation of mafic parents (partial melting of young mafic intrusive rocks is not likely in a area of thin crust and low heat input; Dufek and Bergantz, 2005). A similar conclusion can be reached for the post–Kos Plateau Tuff evolved volcanic products on Nisyros volcano, in light of their Sr and Nd isotopic ratios within the range of European mantle composition (Francalanci et al., 1995; Downes, 2001) and decoupling of Sr, Nd, Pb, and Hf isotopic systems (Buettner et al., 2005). (2) The magma was emplaced in the upper crust and built a large (>60 km³) body at 7~9 km depth. (3) Magma was stored for at least 200 k.y. During this extended period, the crystallinity fluctuated in the reservoir (due to changes in temperature and/or pressure), as evidenced by complex mineral zoning and disequilibrium textures. However, the magma chamber never reached complete crystallization, because this would have precluded remobilization by eruption due to mass and energy balance constraints (Bachmann et al., 2002) and would have led to gaps in the zircon crystallization record. The magma was most likely stored as a crystal mush kept above its solidus by periodic influxes of hot intermediate to mafic magmas at the base of the system (the latest of these rejections of mafic magma is preserved as stripes of andesite in the banded pumices).

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