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Zircon petrochronology reveals the timescale and mechanism of anatectic magma formation

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ABSTRACT

Igneous rocks of intermediate to acidic composition commonly exhibit considerable degrees of isotope variability preserved at the crystal and sub-crystal scale, as well as a significant U–Pb age range, reflecting protracted timescales of zircon crystallization and long magma residence times. The association of high-precision U–Pb zircon dates with stable and radiogenic isotope data represents a powerful tool to unravel the petrological evolution of granitic rocks, hence allowing a better understanding of the processes that led to the formation and reworking of the continental crust.

In this case study, we combine high-precision U–Pb dates with stable and radiogenic isotope data from zircon crystals in the Larderello–Travale (Italy) shallow-level granites. These rocks are peraluminous two-mica, cordierite-bearing granites and represent pure crustal anatectic magmas, generated in a post-collisional extensional setting. As such, they are ideal candidates to investigate the timing, rates and mechanisms of melt production during anatectic magma formation, giving insights into the process of intracrustal differentiation. Magmatic zircon crystals from the Larderello–Travale granites contain $\delta^{18}O$ values ranging from 8.6 to 13.5‰ and crystals from individual samples exhibit inter- and intra-grain oxygen isotope variability exceeding 3‰. The analysed crystals have ε_{Hf} values ranging between −7.4 and −12.4, with moderate, intra-sample ε_{Hf} isotope variability. All CA-ID-TIMS (chemical abration isotope-dilution thermal ionization mass spectrometry) $^{206}Pb/^{238}U$ zircon ages range from 4.5 to 1.6 Ma and suggest four pulses of magmatic activity at ∼3.6, 3.2, 2.7 and 1.6 Ma. More importantly, zircon crystals from individual samples typically exhibit an age spread as large as 300–500 ka. This age dispersion suggests that most of the zircon did not crystallize at the emplacement level but in the middle crust and were subsequently recycled and juxtaposed during ascent and emplaced at shallow level. When plotted against age, stable and radiogenic isotope data suggest the co-existence of multiple and isotopically distinct magma batches produced by partial melting of different crustal domains. This requires coeval magma batches that are physically separated and evolve independently for hundreds of thousands of years before coalescing during ascent and emplacement. The involvement of multiple sources in the production of crustal anatectic magmas reflects the inherent heterogeneous nature of the continental crust and result from the interplay between the rise and evolution of the geotherms through the crust and the composition of the fertile source rocks. Finally, the isotopically diverse zircon-bearing magma batches mixed and assembled into shallow-level intrusions generated during the four major magma pulses.

1. Introduction

In the continental crust, magmas with broadly granitic composition are formed by partial melting of a variety of different sources under water-fluxed and fluid-absent melting conditions (Brown, 2013). The removal of granitic magmas from middle and deep crustal levels and their emplacement at shallower depths has shaped the structure of the crust, enriching its upper part in incompatible and heat-producing elements and leaving its lower portion relatively mafic and refractory (Petford et al., 2000). Although crustal reworking (i.e. melting of pre-existing crustal rocks) followed by melt extraction, ascent and granite emplacement is the main agent that caused the chemical differentiation of the continental crust, the timescale of melt production and the processes controlling the chemical composition of crustally-derived granites are still poorly constrained (e.g. Clemens and Stevens, 2012).

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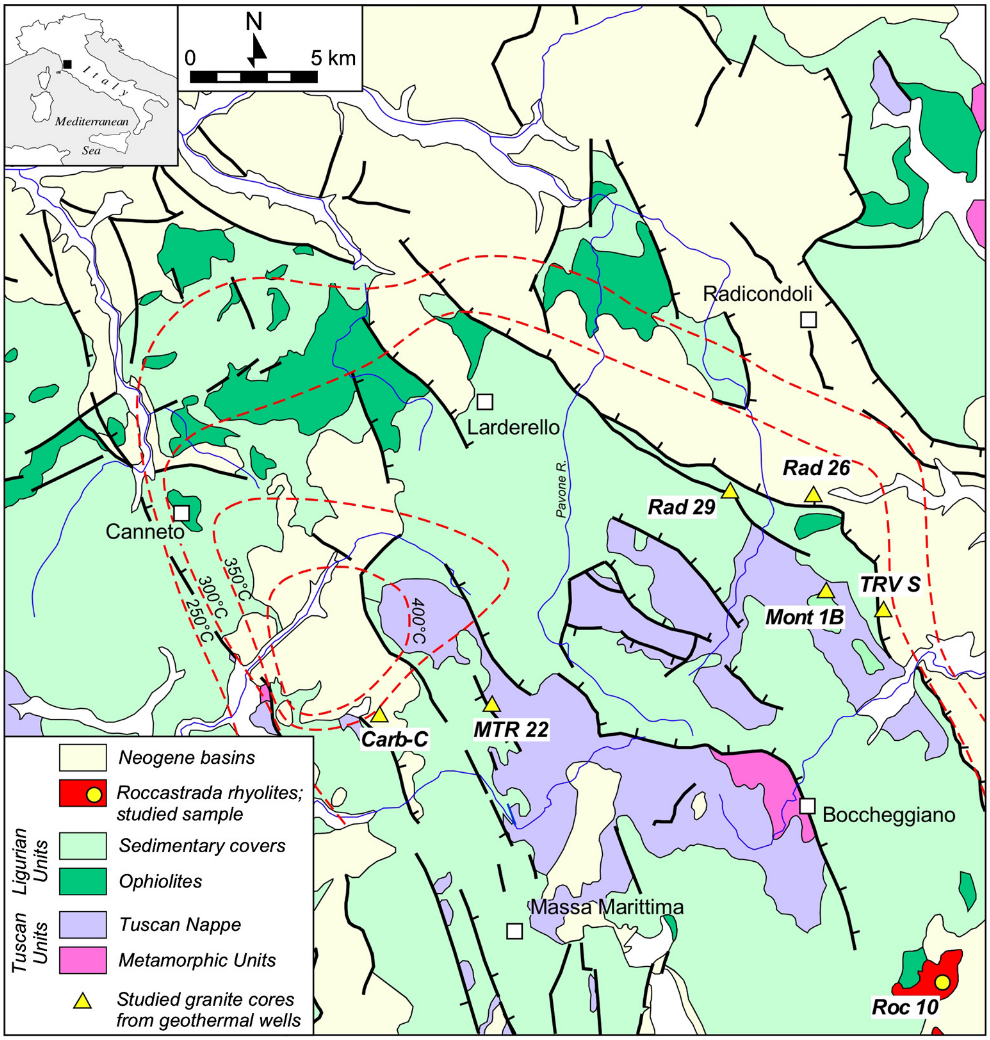

Fig. 1. Geological map of the Larderello–Travale area and location of the six wells where granite core samples were collected. Red dashed lines indicate the temperature (in °C) at 3 km below the surface. (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

In the last decade, the increased utilization of spatially resolved isotope analyses in igneous petrology has revealed that granitoid rocks are far less homogeneous than previously thought and are commonly characterized by large degrees of small-scale isotopic variability (Wotzlaw et al., 2014; Farina et al., 2014a, 2014b). Also, the achievement of unparalleled high-precision in CA-ID-TIMS zircon geochronology (i.e. better than 0.1% on ^{238}U–^{206}Pb dates; Schaltegger et al., 2015) has shown the common occurrence of significant U–Pb age scatter in populations of zircon crystals from individual samples of granitoids and felsic volcanic rocks (Wotzlaw et al., 2013; Barboni and Schoene, 2014; Samperton et al., 2015). This new generation of high spatial resolution isotopic data and bulk-grain high-precision U–Pb dates has strongly contributed to the emerging view that magma reservoirs are incrementally built regions in the crust where melt, crystals, and volatiles are heterogeneously distributed in space and time (Cashman et al., 2017). The vast majority of these studies are focussed on granitoids and felsic volcanic rocks that were formed in continental and oceanic arcs and in within-plate continental settings (Wotzlaw et al., 2014; Samperton et al., 2015; Schmitt et al., 2017), where felsic igneous rocks are mostly produced by mixing between mantle- and crustally-derived magmas (e.g. Szymanowski et al., 2015). Less attention has been paid to the genesis of felsic rocks originating from direct melting of pre-existing crustal material, even though from the end of the Archean such processes are predicted to have been important (Hawkesworth et al., 2018). To gain a comprehensive understanding of processes leading to the internal reworking of the continental crust, we investigated the Plio–Pleistocene shallow-level peraluminous granites from the Larderello–Travale intrusive system (Tuscany, Italy; Fig. 1), which represent crustal anatectic magmas (Dini et al., 2005). We use high precision CA-ID-TIMS zircon dating combined with stable and radiogenic zircon isotope data to shed light on the rates and mechanisms of melt production as well as on the processes that generate the chemical variability observed in many S-type granitoids. Ultimately, these data will help to better understand the formation and evolution of the upper continental crust.

2. The Larderello–Travale magmatic system

The development of the northern Apennine orogenic wedge culminated at the Oligocene–Miocene boundary and was followed by widespread lithosphere extension and asthenosphere upwelling caused by the rollback and delamination of the Adriatic microplate below the European margin (Malinverno and Ryan, 1986). From Miocene to Present, post-collisional extensional tectonics led to the opening of a continental back-arc basin (i.e. the northern Tyrrhenian Sea) and to the emplacement and eruption of rocks of the Tuscan Magmatic Province (Lustrino et al., 2011). The igneous rocks of this province are exposed across an area of about