Geophysical Research Abstracts
Vol. 20, EGU2018-6812, 2018
EGU General Assembly 2018
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Zircon petrochronology reveals the mechanism of crustal anatectic magma formation

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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 scatter, 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 granitoid rocks, hence allowing the linking of rock-forming processes with the rate at which they operate.

In this study, zircon crystals from the Larderello-Travale (Italy) shallow-level buried granites were investigated combining in-situ oxygen isotope analysis, high-precision U-Pb ages, and whole-grain Hf isotope measurements. The granites are peraluminous two-mica, tourmaline-bearing bodies whose emplacement is associated with the formation of the steam-dominated Larderello-Travale geothermal field. Generated in a post-collisional extensional setting, these granites represent pure crustal anatectic magma, which are good candidates to provide valuable insights into the mechanism and timing of crustal recycling.

Magmatic zircon crystals from the Larderello-Travale granites display δ^{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 show ε_{Hf} ranging between -7.4 and -12.4, with moderate, intra-sample ε_{Hf} isotope variability. All ^{206}Pb/^{238}U zircon ages range from 4.5 to 1.6 Ma and reveal the occurrence of three main pulses of magmatic activity at ca. 3.6, 2.7 and 1.6 Ma. More importantly, zircon crystals from individual samples typically exhibit an age spreads as large as 300–500 ky. This age dispersion, more than one order of magnitude greater than the uncertainty on a single date, suggests that most of the zircon did not crystallize at the emplacement level. Most zircon grains are therefore antecrysts that crystallized at depth and were subsequently recycled and juxtaposed during ascent followed by emplacement at shallow level. When plotted against high-precision U-Pb ages, 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 were assembled into single shallow-level intrusions generated during three major magma pulses.

This project has received funding from the European Union's Horizon 2020 research and innovation program under the Marie SkŁ odowska-Curie grant agreement No 701494.