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Synthesizing uniform ^{3}He concentrations in accessory minerals for ^{4}He/^{3}He thermochronology: Current status, complications, and prospects

Cody Colleps, Peter van der Beek, Julien Amalberti, and Maxime Bernard
University of Potsdam, Institute of Geosciences, Potsdam-Golm, Germany (colleps@uni-potsdam.de)

High-resolution ^{4}He/^{3}He thermochronometry involves stepped-heat degassing of U and Th-bearing accessory minerals with simultaneous measurement of natural ^{4}He (non-uniform bulk distribution) and synthetically produced ^{3}He (uniform bulk distribution) at each step. The ratio evolution of ^{4}He/^{3}He measured across all heating steps reflects the spatial distribution of ^{4}He within a single crystal, which can be coupled with its (U-Th)/He date to model high-resolution low-temperature thermal histories. Although an exceptionally powerful tool to elucidate disputed drivers of crustal exhumation in various geologic settings (e.g., climatic vs. tectonic mechanisms), the ^{4}He/^{3}He method is commonly hindered by the necessity to uniformly synthesize ^{3}He within crystals at concentrations >1x10^{9} atoms/mg for single grain analysis. This high concentration is required to ensure that the ^{3}He released at initial heating steps—where the most important geological information is preserved—is sufficiently above blank-detection limits of modern, highly-sensitive noble gas mass spectrometers. Synthesis of high ^{3}He concentrations is conventionally achieved via the spallation of targeted nuclei during high-energy proton irradiations to fluences >1x10^{15} protons/cm^{2}; however, facilities capable of, or willing to, efficiently carry out such anomalously high-fluence irradiations using previously defined methods remain few and far between. Here, we summarize the current state-of-the-art of synthesizing uniform distributions of ^{3}He in geologic materials, and present preliminary ^{4}He/^{3}He measurements on gem-quality Durango apatite using conventional and alternative approaches to induce ^{3}He to sufficient concentrations. Alternative approaches include (1) in-vacuum proton-irradiation with a narrowly focused proton beam to maximize intensities for short-duration experiments, and (2) direct uniform ^{3}He implantation via sample exposure to an energy-modulated ^{3}He beam. We discuss the advantages and disadvantages of both conventional and alternative methods in regards to ^{3}He uniformity, concentration limitations, crystal lattice damage, efficiency, post-experiment 'cool-down' times, and accessibility. Both alternative approaches are considerably less demanding on particle accelerator facilities, and can significantly reduce the post-experiment waiting time required to safely handle activated samples. Accordingly, these approaches, if proven successful, yield great promise to improve the accessibility and efficiency of routine ^{4}He/^{3}He analyses for geologic applications.