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Temperature-sensitive trapping of helium in apatite: insights from $^{4}He/^{3}He$ diffusion experiments

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Observations from continuous ramped heating (CRH) experiments of a large array of apatite samples have confirmed that the diffusion of radiogenic helium cannot be completely explained by radiation-damage-modified volume diffusion. A hypothesis stemming from these observations is that helium can be trapped in some type(s) of diffusion sinks in addition to the widely known control from radiation damage across various timescales.

We test the hypothesis through step-heating experiments of proton-irradiated apatite samples that contain a spatially uniform ^{3}He distribution but varying ^{4}He distribution owing to the different nature of the samples (e.g., internal fragments of large crystals versus entire small crystals, and samples with distinctive thermal histories). We evaluate the results using two kinds of data presentation: (1) the step-wise ^{4}He and ^{3}He fractional loss as a function of temperature, which allows a direct examination of overall diffusion behavior; (2) the ratio of $^{4}He/^{3}He$ released from each heating step relative to the bulk $^{4}He/^{3}He$ (referred to as the Rs/Rb) as a function of cumulative ^{3}He release, which allows a closer look at how a sample's thermal history impacts the proposed trapping.

The results from fragments of Durango apatite consistently show volume diffusion behavior of ^{4}He and ^{3}He step-losses, and the Rs/Rb equals to 1. The results from single-crystal KTB (German Continental Drilling Borehole) and TAM (Transarctic Mountains) analyses show either volume diffusion or additional trapping behaviors of ^{4}He and ^{3}He step-losses, and the Rs/Rb ratios reach values that are forbidden under simple volume diffusion behavior and are in fact consistent with trapping.

Our results for the first time confirm that (1) the widely reported trapping of ^{4}He also occurs for ^{3}He and that (2) samples with different thermal histories have distinguishable trapping of ^{4}He and ^{3}He. Several critical implications emerge from these observations. Helium trapping can occur at various timescales, both geologically and through lab-heating. Lab-observed ^{3}He diffusion is a proxy for trapping dynamics, and combined with observations from ^{4}He, which is controlled by both geological thermal history and lab-heating, should resolve additional thermal-history information.