Radiation damage and helium diffusion kinetics in apatite

D.L. Shuster1,2, R.M. Flowers1, K.A. Farley1

1 Geological and Planetary Science, Caltech, CA 91125, USA
2 Berkeley Geochronology Center, 2455 Ridge Road, Berkeley, CA 94709, USA; dlshuster@bgc.org

Experimentally determined diffusion coefficients for 39 different samples of apatite demonstrate that the closure temperature \( T_c \) for helium retention in apatite spans a wider range than previously recognized: from \( 44 \pm 4 \) °C to \( 116 \pm 18 \) °C (for \( 10 \) °C/Myr) and correlates with the radiogenic \(^4\)He concentration \([\text{^4He}]\) in a given sample. We find no correlation between helium diffusion kinetics and apatite chemistry, including the F/Cl ratio. We argue that \([\text{^4He}]\) is a measurable proxy for the radiation damage which accumulated within each crystal over geologic time. As the volume density of lattice damage sites increases, apatite becomes more helium retentive. This implies that helium retentivity, and hence the effective helium diffusion kinetics, is an evolving function of time. Measured diffusivities thus reflect a snapshot in time and cannot alone be applied to the thermochronometric interpretation of a given sample.

Calibrated with diffusion kinetics of 39 different samples of apatite, we present a simple, quantitative trapping model which relates diffusivity to both temperature and \([\text{^4He}]\). This previously proposed model [1] consists of two Arrhenius relations: one for volume diffusion through undamaged mineral lattice and one for the release of helium from the damage traps back into the undamaged lattice. The model predicts much of the observed log-linear correlation between \( T_c \) and \([\text{^4He}]\). By inserting this function into a \(^4\)He production-diffusion calculation, the trapping model predicts: (i) that the effective \(^4\)He closure temperature of apatite will vary with cooling rate and effective U concentration \( eU \) and may differ from \( 70 \) °C by up to \( \pm 15 \) °C, (ii) the depth of the \(^4\)He partial retention zone will depend on accumulation time and on \( eU \), and (iii) samples subjected to reheating after the accumulation of substantial radiation damage will be more retentive than previously expected. These predictions are consistent with recent observations of unexpected apatite (U-Th)/He ages in some settings, most notably [2].

References