Improved modeling of fission-track annealing in apatite

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ABSTRACT

Two abiding issues impact the reliability of apatite fission-track analysis and thermal history inversion in particular: reproducibility of track-length measurements and variability of annealing kinetics. In the companion to this paper, we addressed the first by demonstrating that using e-axis projection to normalize track lengths for crystallographic angle improves reproducibility among measurements acquired by Barbarand et al. (2003a, 2003b). We continue here by looking at the effect of e-axis projection on extrapolation of laboratory measurements to geological time scales. We find that e-axis projection improves agreement between predictions of empirical annealing models fit to measurements by Barbarand et al. (2003b) analysts 1 and 3, further corroborating its effectiveness in ameliorating observer bias. Furthermore, these annealing models closely match predictions from the Carlson et al. (1999) annealing data set, which was obtained by a different analyst using a different etching protocol. Normalizing for angle thus allows us to create a single annealing model that encompasses both data sets and etching techniques. By combining the different compositional varieties of apatite in the two data sets, the resulting model provides an improved basis for estimating apatite kinetic properties in unknowns using proxies such as composition, etch-figure dimension, and unit-cell parameters. Predictions from a fanning curvilinear model form accord with conventional expectations of annealing at high and low temperatures, and its use for thermal history inversion will not introduce spurious late cooling events.

Keywords: Fission-track, apatite, annealing, anisotropy, thermochronology, fanning point

INTRODUCTION

Apatite fission-track thermochronology is a well-established technique in its fourth decade of useful application to geological problems. However, two still unresolved issues impact the reliability of this method and its use for thermal history inversion in particular: variable annealing kinetics and reproducibility of length measurements.

Variations in apatite fission-track annealing kinetics are known to cause changes in closure temperature of at least 40 °C, and perhaps more than double that amount (Ketcham et al. 1999; Kohn and Foster 1996). Various avenues for estimating apatite kinetics have been proposed, including Cl content (Green et al. 1986); a function of multiple compositional variables (Carlson et al. 1999); etch-pit length (D_{et}) (Burtner et al. 1994); and unit cell parameters (Barbarand et al. 2003b). High Cl content has long been known to increase resistance to annealing, but it is well documented that other compositional factors are influential as well, including various cation substitutions (Barbarand et al. 2003b; Carlson et al. 1999; Crowley et al. 1991; Ravenhurst et al. 2003). The prevalence and thus practical importance of these other substitutions is not known, primarily because the relevant compositional measurements are seldom obtained and published.

Further complicating matters is the limited pool of appropriate laboratory annealing experiments useful for characterizing kinetic effects, the results of which are not straightforward to cross-reference owing to differing track etching protocols.

In a detailed study of length measurement reproducibility, Barbarand et al. (2003a) documented multiple instances in which variation among analysts and for a single analyst over time exceeded predictions by standard statistical treatments. In the companion to this paper, we demonstrated that normalizing for angle using e-axis projection eliminates or ameliorates the problems they documented.

We here continue this effort by seeing how e-axis projection impacts consistency of geological time-scale predictions of empirical annealing models fit to the Barbarand et al. (2003a, 2003b) and Carlson et al. (1999) data sets. We begin by fitting models for single apatite varieties measured by single analysts (“single-apatite models”). We then create combined (“multiple-apatite”) models that incorporate both data sets, and use them to improve characterization of the effects of composition on annealing kinetics.

SINGLE-APATITE ANNEALING MODELS

Following Ketcham et al. (1999), we consider the empirical problem to be fitting the equation

\[ g(l; l_0, \alpha, \beta) = f(t; T, C) \]  

where \( g \) is a function that transforms measured mean length \( l \), which can be non-projected or e-axis projected, using the initial...