On growth and form of etched fission tracks in apatite: A kinetic approach

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ABSTRACT

We discuss differences between the bulk etch rate ($v_B$) and an alternative radial etch rate ($v_R$) model for fission-track etching in apatite. A skeletal $v_R$-model, based on the inferred orientations of the $v_R$ minima and maxima, accounts for the main geometrical features of etched fission tracks, including the track-surface intersections, track channels and their terminations, and the outlines of confined tracks. It unifies the diverse appearances of etched tracks as variations of a basic plan, governed by the orientation of the etched surface and that of the track. The $v_R$-model also embeds fission-track etching in the mainstream theories of crystal growth and dissolution. However, in contrast to the $v_R$-model, the $v_B$-model does not provide bottom-up criteria for discriminating between tracks that are counted by an observer or a computer program and those that are not. Moreover, abandoning the $v_R$-model implies that basic assumptions of fission-track dating must be reconsidered, in particular that track counting efficiencies depend only on a critical dip angle, and are thus independent of the track registration geometry and the length distribution.

Keywords: Apatite, fission track, etching, fission-track dating

INTRODUCTION

Our understanding of fission-track etching has progressed little since the earliest studies. The still-current bulk etch rate model explains etched-track geometries in terms of the etch rate $v_B$ along the latent-track core and the bulk etch rate(s) $v_T$ of the undamaged detector (Fig. 1a; Fleischer and Price 1963a, 1963b, 1964; Tagami and O’Sullivan 2005; Hurford 2019). This model underlies equations relating the number of counted tracks to the undamaged detector (Fig. 1a; Fleischer and Price 1963a, 1963b, 1964; Tagami and O’Sullivan 2005; Hurford 2019). This model underlies equations relating the number of counted tracks to the number whose etchable section intersects the unetched surface, involving a complex function of $v_B$ and $v_T$ (e.g., Tagami and O’Sullivan 2005):

$$\rho_B = \rho_L \left\{ 1 - \frac{v_T L}{v_B g R_L \left( 1 - \frac{v_T}{v_T} \right)} \right\} \tag{1}$$

wherein $\rho_B$ and $\rho_L$ are the observed- and unetched-track densities, $R_L$ the etchable track length, $g$ the geometry factor ($\frac{1}{2}$ for external and 1 for internal surfaces), and $t_E$ the etch time. Equation 1 implies that all tracks are counted in surfaces with low bulk etch rates ($\rho_B \approx \rho_L$ for $v_B \ll v_T$ and $v_B L << R_L$). Equation 1 also has more troubling implications for non-negligible $v_B$. Because it is linear in $t_E$, it implies an unlimited increase of $\rho_B$ with increasing etch time. In contrast, the corresponding equation of Jonckheere and Van den haute (1999) has $\rho_B$ constant for an internal surface ($g = 1$):

$$\rho_B = \rho_L \left\{ 1 - \frac{v_T t_M}{R_L} \right\} \left( \frac{v_B t_M}{2 R_L} \right)^2 \tag{2}$$

wherein $t_M$ is the minimum duration that an added track has to be etched to be identified and counted; if $t_M = 0$ then $\rho_B = \rho_L$.

Equations 1 and 2 differ because the former assumes that a track, once etched, is forever retained and counted, whereas in the latter, a track is eliminated when its lower termination is overtaken by the surface. This illustrates how a wrong assumption can mislead us concerning the relationship between “what is” ($\rho_B$) and “what is observed” ($\rho_L$).

This is of some practical interest. The standardless dating methods, based on neutron activation (Jonckheere 2003; Enkelmann et al. 2005; Danhara et al. 2013; Jonckheere et al. 2015; Iwano et al. 2018) and on LA-ICP-MS (Hasebe et al. 2004; Hadler et al. 2009; Abdullin et al. 2014; Soares et al. 2014; Gleadow et al. 2015), require an estimate of the counting efficiency $\eta_B = \rho_B/\rho_L$. In contrast, the standard-based dating methods (Hurford and Green 1983; Green 1985; Hurford 1998) are not affected if the counting efficiencies $\eta_B$ of the samples and age standards are identical. However, Equation 1 implies that $\rho_B/\rho_L$ increases with decreasing track length $R_L$. $R_L$ appears in the term that accounts for the addition of tracks due to surface etching (Fig. 1c). Of equal concern is the fact that $R_L$ does not appear in the terms referring to tracks intersecting the original surface. This implies that these tracks are counted with efficiencies determined by the critical angle $\phi_C = \arcsin(v_B/v_T)$ (Fig. 1b), independent of the track-length distribution or the track-registration geometry. This contradicts experimental evidence that $\eta_T$ depends on both these factors (Jonckheere and Van den haute 2002; Jonckheere 2003). Jonckheere (2003) and Enkelmann et al. (2005) also presented experimental evidence that the track counting efficiencies in external ($\eta_T \approx 1.0$) and internal ($\eta_B \leq 0.9$) prism faces of apatite are not identical, and in the latter case well below the prediction of Equation 1 for a surface with low $v_B$.

Despite the absence of experimental support and disconcerting mathematical properties, the $v_B$-model underpins core assumptions of practical fission-track dating, i.e., that almost