Effect of orientation on ion track formation in apatite and zircon

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ABSTRACT

Fission track (FT) thermochronology is essentially based on empirical fits to annealing data of FTs revealed by chemical etching, because, until now, unetched latent FTs could not be examined analytically at the atomic-scale. The major challenge to such an analysis has been the random orientation of FTs and their extremely small diameters. Here we use high-energy ions (2.2 GeV Au or 80 MeV Xe) to simulate FT formation along specific crystallographic orientations. By combining results from transmission electron microscopy (TEM) of single tracks and small-angle X-ray scattering (SAXS) for millions of tracks, a precise picture of track morphology as a function of orientation is obtained. High-resolution analysis reveals that orientation affects the shape of tracks in apatite and zircon through the preferential creation of damage along directions with highest atomic density. However, track radius does not depend on orientation, contradicting previous reports. Independent of track orientation, track radii, as measured at each point along the entire length of 80 MeV Xe ion tracks in apatite, can be understood using the thermal spike model of Szénes. Thus, the well-known track annealing anisotropy of apatite is not due to track radius anisotropy. The combination of ion-irradiations with TEM and SAXS analysis provides a unique opportunity to understand and model track formation and annealing under various geologic conditions.

Keywords: Ion tracks, fission tracks, apatite, zircon, orientation effects, thermal spike, TEM, SAXS

INTRODUCTION

Swift heavy ions (SHIs) create a narrow track of damage in an irradiated solid along the trajectory of the ion. Such SHI irradiations have widespread applications in nanoeengineering (Akcoltekin et al. 2007; Mara et al. 2004), and particle damage in electronics (Dodd and Massengill 2003). More interestingly, SHI irradiations can be used to simulate the formation of fission tracks (FTs), damage trails that were caused by spontaneous fission events of uranium impurities in minerals that have been widely used for age dating and thermochronology (Donelick et al. 1999; Gleadow et al. 2002; Jonckheere and Chadderton 2002; Yamada et al. 1995). Generally, tracks in transverse cross section are circular, but in a few cases (Bursill and Braunschwein 1990; Hebert et al. 1998; Paul and Fitzgerald 1992; Vetter et al. 1994), they have a tendency to facet along specific crystallographic directions, with an important indication that orientation may play a role in track formation. However, details of how orientation affects track formation remain elusive, because there are very few systematic studies of the shape and radius of latent, unetched tracks as a function of orientation at the atomic-scale. According to a highly cited transmission electron microscopy (TEM) study (Paul and Fitzgerald 1992), the mean radius (4.5 ± 3.7 nm) of latent FTs || c (or the c axis) of the hexagonal apatite [Ca9.6(PO4)6F2] is significantly larger than that (2.5 ± 2.8 nm) of FTs perpendicular to c. The anisotropy of track radii in apatite has gained general acceptance (Carlson 1993; Jaskierowicz et al. 2004; Rabone et al. 2008; Schouwink et al. 2010), and has been used to explain (Carlson 1993; Paul and Fitzgerald 1992) the well-known track annealing anisotropy (Donelick et al. 1999; Gleadow et al. 2002; Green and Durrani 1977), i.e., tracks || c anneal more slowly than tracks perpendicular to c, however, a molecular dynamics simulation concluded that track size was insensitive to orientation (Rabone et al. 2008). Because of the random orientation of FTs, TEM imaging of the track radius requires considerable effort to accurately determine the orientation of any individual track that is measured, essentially requiring the alignment of the electron beam parallel to major zone axes of the grain. In this study, we overcome this problem by investigating parallel tracks produced by the irradiations of SHIs (2.2 GeV Au or 80 MeV Xe) along known zone axes of apatite (P6/m) and zircon (ZrSiO₄ Ih/amd), two minerals that have anisotropic structures and figure prominently in FT thermochronology. By combining the results from TEM analysis of single tracks and small-angle...