Available online at www.sciencedirect.com
SCIENCE DIRECT®

Radiation Measurements 39 (2005) 577–583

Radiation Measurements

www.elsevier.com/locate/radmeas

Observations on the geometries of etched fission and alpha-recoil tracks with reference to models of track revelation in minerals

R. Jonckheere*, E. Enkelmann, K. Stübner

Geologisches Institut, Technische Universität Bergakademie Freiberg, Bernhard-von-Cotta-Straße 2, D-09599 Freiberg (Sachsen), Germany

Received 13 February 2004; accepted 3 August 2004

Abstract

The kinetic and atomistic theories of crystal growth and dissolution are used to interpret the shapes and orientations of fission-track, recoil-track and dislocation etch pits in tri-octahedral phlogopite and di-octahedral muscovite. An atomistic approach combined with symmetry considerations lead to the identification of the periodic bond chains that determine the etch pit morphologies and relative etch rates at a chemical level: O–Mg–O in phlogopite, O–Mg–O–Fe in biotite and O–Al–O in muscovite. Using first-order estimates of the bond strengths, it is possible to account for the relative track etch rates in these minerals. The reported, sometimes simultaneous, occurrence of triangular, polygonal and hexagonal etch pit contours in phlogopite, some of which violate the crystal symmetry, suggests that the cohesion of the phlogopite lattice is lost over a much larger radius than that of the track core around the trajectories of particles for which the energy loss exceeds a threshold value. This is interpreted as an indication of pronounced sublattice and anisotropic effects during track registration.

Keywords: Nuclear track etching; Kinetic approach; Atomistic approach; Phlogopite; Biotite; Muscovite

1. Introduction

Despite its practical importance for fission-track dating, nuclear track etching in minerals has, in general, received little attention compared to track revelation in glasses and plastics. Outdated etching models still form the basis of current estimates of the efficiencies with which fission tracks are etched and counted in different minerals and crystallographic planes (Fleischer et al., 1975; Gleadow, 1978, 1981). It has been argued that the existing estimates of the combined etching and counting efficiencies (ηq) are in error (Jonckheere and Van den haute, 1996, 1998, 1999) and that ηq depends on the track length distribution in the sample (Jonckheere and Van den haute, 2002). If this is so, then the calculated fission-track ages could be inaccurate irrespective of the fact whether they are determined using the absolute approach (ϕ-method; Price and Walker, 1963; Jonckheere, 2003) or a standard-based approach (Z and ζ dating methods; Hurford and Green, 1983; Hurford, 1990, 1998).

Etched fission tracks in apatite possess complex, composite geometries, consisting of a track channel and additional facets at its intersection with the surface. The channel is parallel to the latent track and not affected by the orientation of the etched surface. In contrast, the structures at the surface depend on its crystallographic orientation. Surface etch pits in apatite are prominent in basal planes (Fig. 1a), less so in prismatic (Fig. 1b) and absent in most higher index planes (Fig. 1c). Identical etch pits develop where dislocations, small-angle grain boundaries and cracks intersect the surface. These etch pits are well developed at low etchant concentrations and reflect the crystal symmetry with little

* Corresponding author.
E-mail address: raymond.jonckheere@geo.tu-freiberg.de (R. Jonckheere).

1350-4487/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.radmeas.2004.08.008

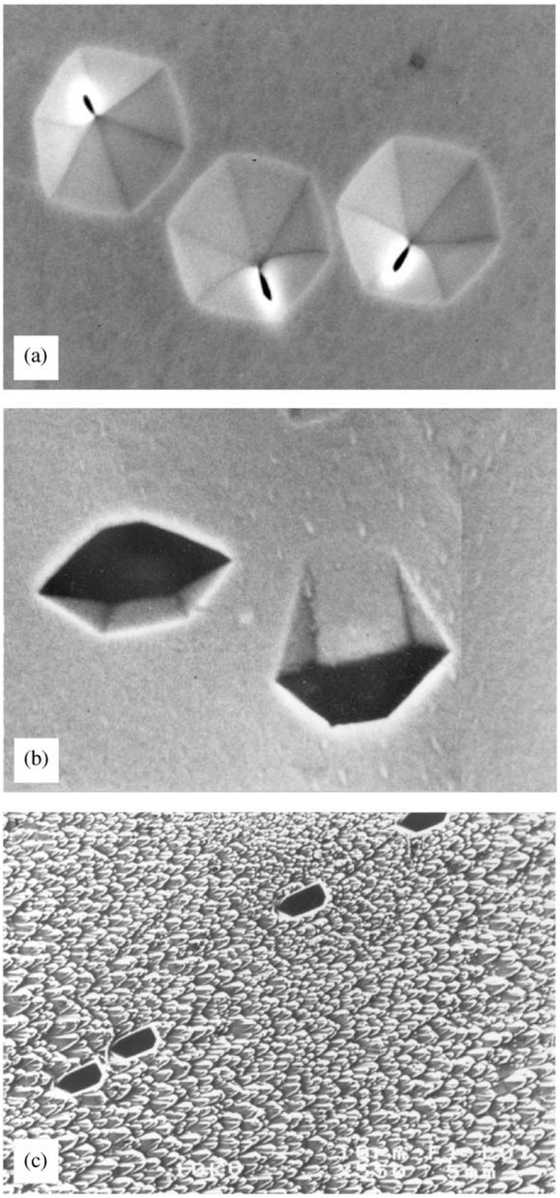

Fig. 1. Etched fission tracks (a, b) and dislocations (c) in pitted (a; basal), scratched (b; prism) and textured (c) surfaces of apatite.

influence of the track orientation. They are less well-developed and their shape is to some extent influenced by the orientation of the track at higher concentrations (Jonckheere and Van den haute, 1996). According to the law of mass action, the chemical reaction between the etchant and the crystal surface is, at all stages, further from equilibrium for a more concentrated than for a less concentrated etchant, and the etch rate is consequently greater. This suggests that the different development and geometries of surface etch pits is determined by the reaction rate. The preceding leads us to conclude that the complex track geometries result from the *superposition* of two entirely independent etch pits: (1) a *track etch pit* (channel) and (2) a *surface etch pit*, which has *nothing* whatsoever to do with the defect properties along the nuclear track.

This has a number of significant consequences: (1) the composite geometries of etched nuclear tracks in minerals *cannot* be described by an etch model based on the two traditional etching velocities, $\boldsymbol{v}_t$ (track etching velocity) and $\boldsymbol{v}_b$ (bulk etching velocity); this accounts for the limited success of attempts to predict track geometries in minerals based on extensions of the $(\boldsymbol{v}_b, \boldsymbol{v}_t)$-model appropriate for isotropic detectors (Wagner, 1968; Gleadow, 1978; Thiel and Külzer, 1978; Somogyi, 1980); (2) the geometry of the surface etch pit is not only independent of the defect properties along a nuclear track, but also of the nature of the defect, and therefore holds no information on $\boldsymbol{v}_t$; this implies that studies aimed at particle identification based on etched-track profiles in minerals should disregard the surface etch pit; based on an alternative model for track revelation in minerals (Jonckheere and Van den haute, 1996), it is doubtful whether even the track-channel profile allows one to make inferences about $\boldsymbol{v}_t$, and therefore about the track forming particle; this leaves the etch-anneal-etch method (Green et al., 1978) as the only method for the identification of the track forming particle based on track etching in minerals.

Progress in our understanding of track revelation in minerals has been hindered by confusion about the meaning of "etching velocity". It is clear that, in models derived from those for isotropic detectors, an etching velocity is understood to be the rate of displacement of a *point on a surface* in a given direction. It follows from this definition that the track (channel) *cross-section* is a direct reflection of the variation of the etching velocity with orientation (Yamada et al., 1994). Although such a definition works for isotropic detectors, it is important to note that it is in conflict with the kinetic theories of crystal growth and dissolution (Frank, 1958; Irving, 1962; Jaccodine, 1962), wherein an etching velocity (radial shift velocity; $\boldsymbol{v}_r$) is a property of a *crystallographic plane*. The radial shift velocity $\boldsymbol{v}_r$ is a *vector* normal to a crystallographic plane equal in magnitude to its rate of translation parallel to itself. Even before Frank (1958) published his kinetic theory, Hartman and Perdok (1955a–c) had published an atomistic theory of crystal growth and dissolution based on the concept of *periodic bond chains*. Here, we attempt to interpret the geometries of etched recoil tracks in phlogopite and muscovite in terms of these theories.

2. Regular etch pits

The fact that phlogopite ($KMg_3[(OH)_2AlSi_3O_{10}]$) and muscovite ($KAl_2[(OH)_2AlSi_3O_{10}]$) are sheet silicates reduces the problem of correlating the etch figures in different crystallographic planes to one in two dimensions. The phlogopite lattice is made up of a stack of tetrahedron and