Thermal annealing mechanisms of latent tracks: Apatite *versus* zircon*

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Etched tracks of apatite and zircon are both widely used for the determination of the thermal history of Earth's crust. The present understanding of the annealing process is largely limited to mathematical fits to data for etched track-lengths as a function of temperature and time. Details of the annealing of unetched, latent tracks at the atomic scale have remained elusive, as the original track is destroyed during chemical etching. In the absence of actual observations of the atomic-scale process, tracks in apatite and zircon have been considered to anneal by the same mechanism, essentially epitaxial recrystallization. In this study, direct, atomic-scale observations of thermal annealing of latent tracks at elevated temperatures by transmission electron microscopy (TEM) demonstrate that the annealing behavior of tracks in apatite is entirely different from that of the amorphous tracks in zircon [1]. This is a direct result of differences in the internal structure of the track, consisting of an amorphous domain in zircon but of low atomic density void in apatite [2].

Parallel tracks were produced in natural zircon (Beaune-sur-Arzon, France) by exposing the single crystals to 2.2 GeV Au ions from the UNILAC accelerator of GSI. Randomly oriented tracks in Durango fluorapatite were produced by thermal neutron-induced fission of ^{235}U. *In situ* thermal annealing experiments were performed in a TEM equipped with a hot-stage holder, which enables us to directly observe track thermal annealing behavior during the TEM analysis.

The dynamic process of thermal annealing of tracks in apatite was observed by heating the sample in TEM at 700 ^{o}C (Figs. 1a-d). Between image recording, the electron beam was moved away to reduce the effects of electron-induced annealing. Initially, the track radius either shrinks or grows along the ion trajectory without much periodicity in the intervals. After annealing times in excess of 53 min, the fission track breaks into segments, randomly fragmented along the ion trajectory. The track segmentation and the Brownian motion of track segments can be ascribed to the high mobility of atoms at the surface within the highly porous track structure. This is in clear contrast to the annealing behavior of amorphous tracks in zircon, which gradually shrink and eventually disappear at 830 ^{o}C after 90 min due to defect elimination (Figs. 1e-h). No track segmentation or Brownian motion of track segments in zircon was observed. This is because the surface tension and the diffusivity of atoms on the surface of amorphous tracks are too low for track segmentation into separate droplets.

These TEM observations of *in situ* thermal annealing of tracks provide a bridge between the current empirical models of annealing and a fundamental understanding of the atomic-scale process [1]. Remnants of the latent tracks in apatite can be seen after *in situ* heating at 700 ^{o}C for 130 min, in clear contrast to the complete disappearance of etchable tracks heated at 360 ^{o}C for 1 hr. The thermally-induced discontinuity of porous tracks in apatite prevents solutions from entering into the porous tracks for further etching, thus reducing the etched track length. This accounts for the complete disappearance of etchable tracks in apatite at much lower temperatures, as compared to that of the latent tracks observed by TEM. In contrast, the amorphous tracks in zircon do not segment or move randomly due to the low surface energy and low diffusivity of atoms at the track-matrix boundary. This explains the similarity between the complete disappearance of latent tracks in zircon at 830 ^{o}C after 90 min and that of etchable tracks at 800 ^{o}C after 1 hr.

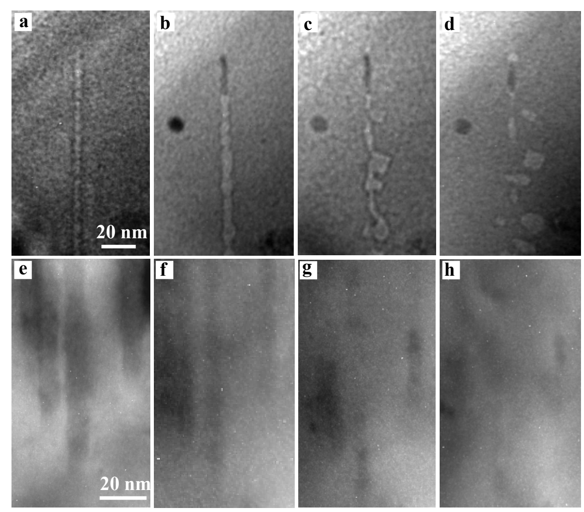

Figure 1: *In situ* isothermal annealing of latent tracks in apatite and zircon observed by TEM. (a-d) At 700 ^{o}C, a porous fission track in apatite gradually segments into shorter lengths; (a) before heating, and (b) after 1, (c) 53 and (d) 130 min. (e-h) At 830 ^{o}C, the amorphous tracks created by 2.2 GeV ions in zircon gradually disappear without track segmentation; (e) before heating, and (f) after 10, (g) 53, and (h) 90 min.

References

[1] W.X. Li, L.M. Wang, M. Lang, C. Trautmann, and R.C. Ewing, Earth Planet. Sci. Lett. (2010) In press, doi:10.1016/j.epsl.2010.12.016.

[2] W.X. Li, L.M. Wang, K. Sun, M. Lang, C. Trautmann, and R.C. Ewing, Phys. Rev. B 82(2010) 144109.

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