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DATING, FISSION-TRACKS

Fission-track (FT) dating is a powerful and relatively simple method of radiometric dating that has made a significant impact on understanding the thermal history of the upper crust, the timing of volcanic events, and the source and age of archeological artifacts. Unlike most other dating techniques, FT dating is uniquely suited to dating low-temperature thermal events with common accessory minerals over a very wide geological range (as much as 0.004–4,000 Ma and typically 0.1–2,000 Ma). The method involves using the number of fission events produced from the spontaneous decay of ^{238}U in common accessory minerals to date the time of rock cooling below closure temperature. Most current research using FT dating focuses on: (a) thermochronological studies of orogenic belts, (b) provenance and thermal analysis of basin sediments, (c) age control of poorly dated strata including tephrochronology, and (d) archeological applications.

FT dating relies on the formation of damage zones, or fission tracks, in a crystal from the spontaneous decay of uranium. Unlike other isotopic dating methods, the daughter used in FT dating is an effect in the crystal rather than a daughter isotope. As such, the technique requires measurement of the parent isotope (^{238}U) and the daughter-like effect (fission tracks shown in Figure D17). Note that uranium and thorium also disintegrate through the process of α-decay through decay series that result in lead isotopes; this forms the basis of U-Pb dating. Both processes of nuclear disintegration (α-decay and fission) occur simultaneously, but the rate of fission decay ($\lambda_f = \sim 7 \times 10^{-17}$ yr^{-1} for ^{238}U) is about 1 million times less frequent than that of α-decay ($\lambda_a = 1.5 \times 10^{-10}$ yr^{-1} for ^{238}U). The vast majority of fission events in typical Phanerozoic rocks are from ^{238}U, due to its abundance and spontaneous fission decay rate.

Fission tracks are produced and retained in a number of minerals and solid materials (Fleischer et al., 1975), but currently the only routinely dated minerals are apatite, zircon, and to a lesser extent titanite (sphene). Fission-track dating is possible in garnet, pyroxene, and epidote among other common rock forming minerals, but these are rarely exploited. The nearly exclusive use of apatite and zircon in current studies stems from their very common occurrence as accessory minerals in sedimentary rocks and granites and their metamorphic equivalents. Fission tracks are also routinely measured in volcanic glass (Westgate, 1989).

Fission tracks form when two sub-equal fission fragments recoil and create end-to-end zones of disorder in the crystal lattice. This zone, long considered a result of the charged fission fragments stripping electrons from adjacent atoms (i.e., the "ion spike" mechanism of Fleischer et al., 1975), is a narrow zone, or trail, in the crystal. Once enlarged by chemical etching, typical tracks in apatite are ca. 14 μm and ca. 12 μm long in zircon, although they shorten when brought to elevated temperatures. While these zones of disorder were recognized in the late 1950s (Silk and Barnes, 1959), it was not until the early 1960s when researchers at General Electric in Schenectady, NY realized that these tracks were susceptible to chemical attack, and as such could be etched large enough to be visible with an ordinary optical microscope (i.e., 200x to 1,500x – Fleischer et al., 1975). Thus the technique of FT dating was born and the first reported fission track ages on ordinary minerals were reported soon thereafter (Fleischer et al., 1964).

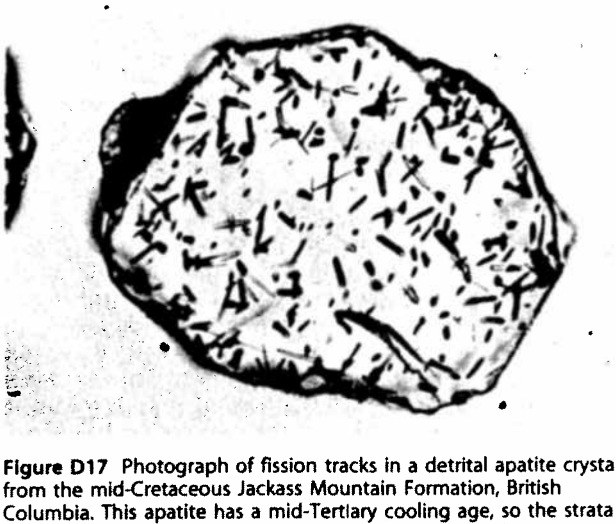

Figure D17 Photograph of fission tracks in a detrital apatite crystal from the mid-Cretaceous Jackass Mountain Formation, British Columbia. This apatite has a mid-Tertiary cooling age, so the strata were buried, heated, and then cooled in the Eocene. This apatite is about 150 μm across and horizontal tracks are about 12 μm long. This apatite crystal is mounted in epoxy, polished so an internal surface is exposed, and the chemically etched tracks are oriented in all directions, so some are short vertical track tips, while others are nearly horizontal and a full length can be seen. (Photo: J. I. Garver.)

The FT methodology is technically simple and requires little in the way of specialized equipment (Naeser, 1976). Fission-track ages are now routinely determined in many academic laboratories and several commercial labs throughout the world. The most common approach to FT dating is through the external detector method using a *zeta* calibration factor, which is based on repeated measurements of standards of known age (Fleischer and Hart, 1972; Hurford and Green, 1983). For an age to be calculated, the spontaneous track density (or fossil track density – ρ_s) and the uranium concentration in a single crystal need to be determined. Together these measurements are accomplished by mounting the crystals in a solid medium (epoxy or Teflon®), polishing to expose crystal interiors, and then enlarging the tracks with a chemical etchant. The measurement of uranium is typically accomplished by neutron irradiation, but other methods could in principle be used. In this step, the mount is covered with an external track detector (mica or plastic), and irradiated in a nuclear reactor with slow neutrons. This thermal neutron irradiation causes uranium to fission in the minerals of interest, and some fission fragments are ejected into the overlying external track detector. Because the thermal cross-section for fission of ^{235}U is large relative to that for ^{238}U, the track density on the external detector is a function of the thermal neutron flux (or fluence) and the concentration of ^{235}U. To determine total uranium, the ratio of U^{235}/U^{238} is assumed to be constant. In practice, therefore, an age is determined by measuring the spontaneous track density (ρ_s), the induced track density (ρ_i), and the thermal fluence as determined from a dosimeter with known uranium concentration (ρ_d).

Fission tracks are constantly formed through the spontaneous fission of uranium, but only the ^{238}U isotope contributes significantly to the total accumulated fission tracks due to its abundance and relative decay rate (Roberts et al., in Fleischer et al., 1975). Tracks are only preserved in the crystal when temperatures fall below the annealing temperature (similar to the closure temperature of other isotopic systems), which varies from mineral to mineral and is the basis for determining low-temperature vs. time histories. While the details of closure temperatures are complicated, they are approximately 100–110 °C for typical apatite, ca. 230–250 °C for zircon, and ca. 300 °C for titanite. As with other isotopic systems, closure temperature is affected by the rate of cooling (Gallagher et al., 1998).

Tracks anneal by shortening or disappearing if they reside at elevated temperatures for an appreciable time. As such, it was discovered that the statistical distribution of track lengths could be used to understand the amount of time a sample spent at temperatures sufficient to anneal or partially anneal tracks. The partial annealing zone (PAZ) is generally regarded as the temperature range at which fission tracks are progressively shortened. Quantitatively this is regarded as the temperatures between 90% annealing and 10% annealing. At temperatures below the PAZ, fission tracks are more or less fully retained. At temperatures above the PAZ, fission tracks are formed, but then fully erased over geological times.

The relationship between track-length distributions and annealing rates is well established for apatite, but no other minerals (Gallagher et al., 1998). For apatite, crystal composition controls annealing rates and the relative proportions of Cl, F, and OH appear to be most important. In laboratory and geological experiments, F-rich apatite is more resistant to annealing than Cl-rich apatite. For zircon, radiation damage appears to be the major influence on annealing rates and temperatures (Brandon et al., 1998).

The FT technique is widely used in understanding the thermal structure of the upper crust, especially in orogenic settings. Studies include understanding the offset of faults, the local exhumation of rock and regional denudation, the relationship between exhumation and orogenic relief, and the large-scale movement of rock in deforming orogenic wedges. These exhumation studies of the tectonic evolution of orogenic belts are perhaps the most widely used application of the FT technique. FT dating is also widely applied to understanding sedimentary basins and specific applications are aimed at deciphering the thermal history of sedimentary basins in the context of the thermal maturation of oil generation, and the provenance of sedimentary detritus (Naeser et al., 1989; Garver et al., 1999). Fission-track dating has also seen a variety of other uses including dating burnt coal seams, diatreme eruption, volcanic ash deposition, meteoritic impacts, tektite strewn fields, and the formation of precious metal deposits (Wagner and Van den Haute,1992; Fleischer, 1998). In archeological applications, FT dating has been used understand the age and source of obsidian artifacts, and fire-heated implements and hearthstones. The technique has also been used to date uranium-doped glasses and vases that are less then 200 year old (Fleischer et al., 1975; Wagner and Van den Haute, 1992).

John I. Garver

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Cross-references

Dating, Radiometric Methods
Uranium-Series Dating