INTRODUCTION

As we have already noted, a fraction of uranium atoms undergo spontaneous fission rather than alpha decay. The sum of the masses of the fragments is less than that of the parent U atom: this difference reflects the greater binding energy of the fragments. The missing mass has been converted to kinetic energy of the fission fragments. Typically, this energy totals about 200 MeV, a considerable amount of energy on the atomic scale. The energy is deposited in the crystal lattice through which the fission fragments pass by stripping electrons from atoms in the crystal lattice. The ionized atoms repel each other, disordering the lattice and producing a small channel and a wider stressed region in the crystal. The damage is visible as tracks seen with an electron microscope operating at magnifications of 50,000× or greater. However, the stressed region is more readily attacked and dissolved by acid; so the tracks can be enlarged by acid etching to the point where they are visible under the optical microscope. Figure 14.1 is an example.

Because fission is a rare event in any case, fission track dating generally uses uranium rich-minerals. Most work has been done on apatites, but sphene and zircon are also commonly used.

Fission tracks will anneal, or self-repair, over time. The rate of annealing is vanishingly small at room temperature, but increases with temperature and becomes significant at geologically low to moderate temperatures. In the absence of such annealing, the number of tracks is a simple function of time and the uranium content of the sample:

$$F_s = \left(\frac{\lambda_f}{\lambda_\alpha}\right)^{238}U(e^{\lambda_\alpha t} - 1)$$

Equation 14.1 can be solved directly for $t$ simply by determining the number of tracks and number of U atoms per volume of sample. In this case, $t$ is the time elapsed since temperatures were high enough for all tracks to anneal. This is the basis of fission track dating. The temperatures required to anneal fission damage to a crystal are lower than those required to iso-

---

**TABLE 14.1. ETCHING PROCEDURES FOR FISSION TRACK DATING**

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Etching Solution</th>
<th>Temperature (°C)</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apatite</td>
<td>5% HNO$_3$</td>
<td>25</td>
<td>10-30 s</td>
</tr>
<tr>
<td>Epidote</td>
<td>37.5M NaOH</td>
<td>159</td>
<td>150 min</td>
</tr>
<tr>
<td>Muscovite</td>
<td>48% HF</td>
<td>20</td>
<td>20 min</td>
</tr>
<tr>
<td>Sphene</td>
<td>Conc. HCl</td>
<td>90</td>
<td>30-90 min</td>
</tr>
<tr>
<td>Volcanic Glass</td>
<td>24% HF</td>
<td>25</td>
<td>1 min</td>
</tr>
<tr>
<td>Zircon</td>
<td>100M NaOH</td>
<td>270</td>
<td>1.25 h</td>
</tr>
</tbody>
</table>
topically homogenize the crystal. Thus fission track dating is typically used to “date” lower temperature events than conventional geochronometers.

**ANALYTICAL PROCEDURES**

Determining fission track density involves a relatively straightforward procedure of polishing and etching a thin section or grain mount, and then counting the number of tracks per unit area. A number of etching procedures have been developed for various substances. These are listed in Table 14.1. Track densities of up to several thousand per cm\(^2\) have been recorded. A minimum density of 10 tracks per cm\(^2\) is required for the results to be statistically meaningful. A fission track, which is typically 10 \(\mu\) long, must intersect the surface to be counted. Thus equation 14.1 becomes:

\[
\rho_s = F s q = \left(\frac{\lambda_f}{\lambda_a}\right)^{238}\text{U}\left(e^{\lambda_a t} - 1\right)q
\]

where \(\rho_s\) is the track density, \(q\) is the fraction of tracks intersecting the surface, and \(^{238}\text{U}\) is now the concentration of \(^{238}\text{U}\) per unit area.

The second step is determination of the U concentration of the sample. This is usually done by neutron irradiation and counting of the tracks resulting from neutron-induced fission. There are variations to this procedure. In one method, spontaneous fission tracks are counted, then the sample is heated to anneal the tracks, irradiated and recounted (this is necessary because irradiation heats the sample and results in partial annealing). Alternatively, a ‘detector’, either a U-free muscovite sample or a plastic sheet, is place over the surface of the polished surface that has previously been etched and counted. The sample together with the detector is irradiated, and the tracks in the detector counted. This avoids having to heat and anneal the sample. This latter method is more commonly employed.

Whereas \(^{238}\text{U}\) is the isotope that fissions in nature, it is actually \(^{236}\text{U}\), produced by neutron capture by \(^{235}\text{U}\), that undergoes neutron-induced fission. The number of \(^{235}\text{U}\) fission events induced by thermal neutron irradiation is:

\[
F_i = ^{235}\text{U}\phi\sigma
\]

where \(\phi\) is the thermal neutron dose (neutron flux times time) and \(\sigma\) is the reaction cross section (about 580 barns for thermal neutrons). The induced track density is:

\[
\rho_i = F_i q = ^{235}\text{U}\phi\sigma q
\]

Dividing equation 14.2 by 14.4 we have:

\[
\frac{\rho_s}{\rho_i} = \frac{\lambda_f}{\lambda_a} \frac{137.88}{\phi\sigma} \left(e^{\lambda_a t} - 1\right)
\]

In the detector method, equation 14.5 must be modified slightly to become:

\[
\frac{\rho_s}{\rho_i} = \frac{\lambda_f}{\lambda_a} \frac{137.88}{2\phi\sigma} \left(e^{\lambda_a t} - 1\right)
\]

The factor of two arises because surface-intersecting tracks produced by spontaneous fission originate both from U within the sample and from that part of the sample removed from etching. However,
tracks in the detector can obviously only originate in the remaining sample. This is illustrated in Figure 14.2.

One of the most difficult problems in this procedure is correctly measuring the neutron dose. This is usually done by including a gold or aluminum foil and counting the decays of the radioisotope produced by neutron capture. Nevertheless, the neutron flux can be quite variable within a small space and it remains a significant source of error.

We can readily solve equation 14.6 for $t$:

$$ t = \frac{1}{\lambda_a} \ln \left( 1 + \frac{\rho_i}{\rho_s} \frac{\lambda_a}{\lambda_f} \frac{2\phi\sigma}{137.88} \right) $$

and thus determine the time since the tracks last annealed.

Yet another alternative method is the zeta method, which involves comparison of spontaneous and induced fission track density against a standard of known age. The principle involved is no different from that used in many methods of analytical chemistry, where comparison to a standard eliminates some of the more poorly controlled variables. In the zeta method, the dose, cross section, and spontaneous fission decay constant, and $U$ isotope ratio are combined into a single constant:

$$ \zeta = \frac{\phi\sigma}{\lambda_f} \frac{^{235}U}{^{238}U} \rho_d = \frac{\phi\sigma}{\lambda_f, 137.88} \rho_d $$

where $\rho_d$ is the density of tracks measured in a glass standard. The value of $\zeta$ is determined by analyzing standards of known age in every sample batch. $\zeta$ is determined from:

$$ \zeta = \frac{e^{\lambda_f t} - 1}{\lambda_a (\rho_s / \rho_i) \rho_d} $$

The age is then calculated from:

$$ t = \frac{1}{\lambda_a} \ln \left( 1 + \frac{\zeta \lambda_a \rho_i \rho_d}{\rho_s} \right) $$

Standards used in the zeta method include zircon from the Fish Canyon Tuff (27.9 Ma), the Tardree rhyolite of Ireland (58.7 Ma), and South African kimberlites (82 Ma).

Usually, fission track ages on a number of grains must be measured for the results to be significant. The results are often presented as histograms. Alternatively, when the errors are also considered, the results may be presented as a probability density

Figure 14.3. Probability density plot of fission track ages of 30 detrital zircon grains from the reworked El Ocote tephra from Mexico. The data show a bimodal distribution.

Figure 14.4. Spontaneous track density vs. induced track density for the same set of zircon grains as in Figure 14.3. On this plot, the slope of the correlation is proportional to time.
diagram, such as Figure 14.3. Yet another approach is to plot the spontaneous track density ($\rho_s$) vs the induced track density ($\rho_i$), such as Figure 14.4. From equation 14.6, we see that the slope on such a diagram is proportional to time. Thus these kinds of plots are exactly analogous to conventional isochron diagrams. There is a difference, however. On a plot of $\rho_s$ vs. $\rho_i$, the intercept should be 0.

**INTERPRETING FISSION TRACK AGES**

Fission tracks will anneal at elevated temperatures. As is the case for all chemical reaction rates, the annealing rate depends exponentially on temperature:

$$A = ke^{-E_A/RT}$$

where $T$ is thermodynamic temperature (kelvins), $k$ is a constant, $R$ is the gas constant (some equations use $k$, Boltzmann’s constant, which is proportional to $R$), and $E_A$ is the activation energy. Thus, as is the case for conventional radiometric dating, fission track dating measures the time elapsed since some high temperature event. The constants $k$ and $E_A$ will vary from mineral to mineral, so that each mineral will close at different rates. In laboratory experiments, apatite begins to anneal around 70°C and anneals entirely on geologically short times at 175°C. Sphene, on the other hand, only begins to anneal at 275°C and does not entirely anneal until temperatures of 420°C are reached. At higher temperatures, these minerals anneal very quickly in nature: no fission tracks are retained. Figure 14.5 shows the experimental relationship between the percentage of tracks annealed, temperature, and time.
Consider a U-bearing mineral cooling from metamorphic or igneous temperatures. At first, tracks anneal as quickly as they form. As temperature drops, tracks will be partially, but not entirely preserved. As we discussed in the context of K-Ar dating, the apparent closure temperature is a function of cooling rate. This cooling rate dependency is summarized in Figure 14.6. Because different methods of etching attack partially annealed tracks to different degrees, etching must be done in the same way for closure temperature determination.

In general, closure temperatures for fission tracks are below those of conventional isotope geochronometers, so they are particularly useful in analysis of low temperature events and in determining cooling histories. When combined with estimates of geothermal gradients, fission track ages, particularly if ages for a variety of minerals are determined, are a useful tool in studying uplift and erosion rates.

For example, the average fission track age for 3 apatites from the Huayna Potosi batholith in the Bolivian Andes is 12.5 Ma. We chose 10°C/Ma for a first order estimate of cooling rate and determine the closure temperature from Figure 14.6 to be 95°C. Assuming an average surface temperature of 10°C, we calculate the cooling rate to be:

\[
\frac{dT}{dt} = \frac{95 - 10}{12.5} = 6.8 \degree C / Ma
\]

We could refine this value by re-estimating the closure temperature based on our result of 6.8°C/Ma. If we assume the geothermal gradient to be 30°C/km, we can calculate the exhumation rate to be:

\[
\frac{dz}{dt} = \frac{dT}{dt} / \frac{dT}{dz} = \frac{6.8 \degree C / Ma}{0.030 \degree C / m} = 226 m / Ma
\]

Using this approach, exhumation rates have been estimated as 500 m/Ma over the past 10 Ma for the Alps and 800 m/Ma for the Himalayas. Figure 14.7 shows an example of the results of one such study of the Himalayas from northern India (Kashmir). Fission track ages of apatites from high grade metamorphic rocks of the Higher Himalaya Crystalline complex. A plot of ages vs. the altitude at which the samples were collected (Figure 14.7) indicates an exhumation rate of 0.35 mm/a or 350 m/Ma over the last 7 million years.

**Interpreting Track Length**

As fission tracks anneal, they become shorter. Thus when a grain is subjected to elevated temperature, both the track density and the mean track length will decrease. As a result, problems of partial annealing of fission tracks can to some degree be overcome by also measuring the length of the tracks. Because (1) tracks tend to have a constant length (controlled
by the energy liberated in the fission), (2) become progressively shorter during annealing, and (3) each track is actually a different age and has experienced a different fraction of the thermal history of the sample, the length distribution records information about the thermal history of the sample. Uniform track lengths suggest a simple thermal history of rapid cooling and subsequent low temperature (such as might be expected for a volcanic rock), while a broad distribution of track lengths suggests a reheating event. A skewed distribution suggests initial slow cooling and subsequent low temperatures. Figure 14.8 illustrates how track lengths are expected to vary for a variety of hypothetical time-temperature paths.

One problem with the approach is that both etching rates and annealing rates, and therefore track lengths, depend on crystallographic orientation. As a result, track length measurements should be only on tracks having the same crystallographic orientation.

REFERENCES AND SUGGESTIONS FOR FURTHER READING