Fission track age dates from three granitic plutons in the Flint Creek Range western Montana

Joseph Bruce Baty
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FISSION TRACK AGE DATES FROM THREE GRANITIC PLUTONS
IN THE FLINT CREEK RANGE, WESTERN MONTANA

by

Joseph Bruce Baty

B.S., Bowling Green State University, 1967

Presented in partial fulfillment of the requirements for the degree of

Master of Science

UNIVERSITY OF MONTANA

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Approved by:

[Signatures]

Chairman, Board of Examiners
Dean, Graduate School

[Date]
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Chapter 1

INTRODUCTION

Statement of Problem

Recent work by Fleischer and Price (1964), Naeser (1967, 1969), and Wagner (1968) have established the feasibility of fission track dating in many common accessory minerals. The procedures and techniques described in this paper were used to obtain 18 fission track age dates from a cluster of 3 small granitic plutons of Late Cretaceous age. The plutons are in the Flint Creek Range, Montana, and lie about 25 miles west of the Boulder batholith and 80 miles east of the Idaho batholith.

The geologic possibilities for an accurate and inexpensive age determination method are almost unlimited, but there have been no publications completely describing the method to date. This report includes a full explanation of the types of problems that may be encountered by someone who has never done a fission track age determination before.

Areal Geology

Three granitic plutons in the Flint Creek Range are located about 25 miles west of the Boulder batholith and
80 miles east of the Idaho batholith (Fig. 1). The plutons are intruded into non-regionally-metamorphosed rocks ranging in age from Precambrian to Tertiary (Fig. 2). The structure of the area is very complex and often disputed; a general sequence of events (McGill, 1965, p. 134) would be: 1. gentle regional folding; 2. major west-to-east thrusting of Precambrian sediments in the western part of the range; 3. tight isoclinal north-south folding near the center of the range; 4. east-to-west thrusting in the eastern one-third of the range and more folding; 5. forceful intrusion of the plutons; and 6. normal block faulting and uplift of the Flint Creek Range.

There is some disagreement about the origin of the east-dipping thrust faults; Mutch (1961) feels that they are related to a forceful intrusion of the Boulder batholith.

Previous Work

Emmons and Calkins (1913) were the first to map the entire area. Since then, several more detailed studies have been undertaken on specific portions of the Range. Csejtey (1963), Mutch (1960), and McGill (1958) have studied the southeast, northeast, and northwest flanks of the range. Other studies of the structure and petrology of the plutons themselves include: Allen (1962, 1966), Mutch (1962), McGill (1965), Winegar (1970), Ehinger (1971, 1972), Benoit (1972), and Wold (1972).
Figure 1. Location Map, Flint Creek Range.
Figure 2. Generalized Geologic Map of the Flint Creek Range, simplified from Winegar, 1970.

- Sediments and Metasedimentary Rocks
  - Tertiary
  - Cretaceous
  - Carboniferous
  - Devonian
  - Cambrian
  - Precambrian (Belt)

- Volcanic and Plutonic Rocks
  - Tertiary Volcanics
  - Tertiary and Cretaceous Intrusives
  - Thrust fault (teeth on the plate)
  - High angle fault (teeth on down-block)

Royal Stock
Phillipsburg Batholith
Mount Powell Batholith
Chapter 2

METHODS

Field

1:24,000 topographic coverage was available for the area. With these maps, triangulation and altitude readings were used to accurately locate the sample sites. Samples had been collected at 1/4 to 1/2 mile intervals over the entire area by previous field teams. The outcrops were excellent, especially at higher elevations.

Laboratory

Thin sections had been made earlier for many of the rock samples. These thin sections were examined for presence of apatite and sphene. Rocks were taken from the areas that appeared to have abundant apatite, sphene or both. The following procedure was used for making the age determinations:

1. The rocks were crushed and screened, retaining the fraction between 65 and 115 mesh.

2. Mineral separations were run on the samples, first with heavy liquids (bromoform) and then with a magnetic separator, until a fairly pure separate was obtained (95%).
3. The "pure" mineral separates were divided in half. Both halves were mounted on thin sections with epoxy, but one portion was annealed and irradiated before being mounted.

4. That portion of the sample that was not annealed was mounted on a glass microscope slide with clear epoxy cement. For convenience, a mounting procedure was developed so that most of the grains lay in the same plane. This was especially important for those samples of limited quantity. The technique was to spread a small amount of epoxy on a slide to a thickness approximately equal to or less than the thickness of the grains. The slide was heated to approximately 100°C to decrease the viscosity of the epoxy, the grains were then sprinkled homogeneously over the surface. The slide was heated for a few more minutes to allow the grains to settle through the epoxy and come to rest on the slide surfaces. If the samples were large enough, additional grain mounts were made in case any slides were damaged in later handling. The irradiated sample is especially difficult to replace if destroyed.

5. The epoxy surface was ground until the grains were dissected and then the surface was polished, using
a procedure that was similar to that for polishing ore minerals. The final polishing compound was in the neighborhood of 1/4 micron in size. The fission tracks were 10 microns long, or less; in order for them to be observed, the surface has to be polished with a grit finer than the size of the track (Naeser, 1967).

6. The sample was etched by immersing the thin section in the proper etchant for the required length of time. A list of etchants and etch times for various minerals is given by Naeser and Dodge (1969), Fleischer and Price (1964), and Lal et al. (1968). Fifty seconds in 10% nitric acid was used for the apatite in this report. Etch time does vary with different areas, so the proper time of etching was determined for this specific set of samples before actual work commenced.

7. The polished grain mounts were covered with an index oil having a refractive index slightly lower than that of the mineral to be studied. Oil 1.584 was used for apatite. This removes many of the distortions caused by differences in relief, giving a much clearer field. Index oils can be corrosive and were covered with a cover glass to prevent damage to the microscope lenses. A drop of
immersion oil was placed on top of the cover glass (for observation with oil immersion lenses) and the fission tracks were counted using 800 to 1,000 power magnification. A grid or constant-area eyepiece was used. Although it was not necessary to know the exact area of the field, it was necessary that equal areas be counted on each grain.

Note: If the thermal neutron dose is determined by counting the tracks in a glass of known uranium content (Step 11), then the area of the field of view needs to be calibrated.

Fission tracks were counted on a sufficient number of grains, so that a legitimate average for each sample was obtained. Where the track density varied considerably among grains, more grains were counted than where the track density was fairly constant. When selecting a counting area on a grain, one was chosen that appeared to have a typical concentration of tracks for that grain. Counting was avoided in areas that contained inclusions, cracks, and other distortions. (Imperfections in the grains will obscure some of the fission tracks, giving a faulty count.) Where feasible, the selection of grains was kept as random as possible, and only features that were
Plate 1

A. This is an exceptionally clear grain of apatite showing a high density of fission tracks. Scale, 10 microns; sample number, S16-7a.

B. This is a different apatite grain on the same slide as A (above). Again, this is an exceptionally clear grain. Note the low fission track density. The track density was variable on all the samples; pictures A and B show the typical extremes that were observed in this study. Scale, 10 microns; sample number, S16-7a.

C. This apatite grain shows an abnormally high concentration of fission tracks radiating from a single point. Anomalous areas such as these were avoided. Scale, 10 microns; sample number, S16-7a.

D. This is a view of a typical grain that was counted. Note that this grain has more fractures in it than A or B. Grains with too many fractures were avoided. Scale, 10 microns; sample number, S16-7a.
A. This picture shows the variation in crystal clarity. The top grain shows abundant inclusions, while the lower grain is virtually inclusion free. Both grains are apatite from the same sample. Scale, 1/10 mm.; sample number, S16-7a.

B. These are inclusions and not fission tracks. The mineral is apatite. Scale, 10 microns; sample number, S16-7a.

C. This grain shows oriented etch pits in apatite. They could be confused with fission tracks, so counting in areas showing these features was avoided. Scale, 10 microns; sample number, S16-7a.

D. This is a view perpendicular to the 'C' axis of apatite. Numerous cleavages or inclusions mask the actual fission tracks, which can be seen in the background. Grains with this orientation were counted only if the fission tracks were readily recognizable. Scale, 10 microns; sample number, S16-7a.
definitely fission tracks were counted. Often, due to undulations in a grain, sections of it remained coated with epoxy and therefore not etched. These areas were void of tracks and were thus avoided.

Note: A grain with a low uranium content also shows few tracks. It must not be confused with a grain that is partially covered with epoxy. For information on recognizing fission tracks, see Fleischer and Price (1964).

8. The portion of each sample to be irradiated with neutrons was first annealed at 600°C for one day (Naeser, 1967). After the samples were annealed, some of the grains were mounted, polished, etched and observed to insure that the annealing was complete.

9. Several hundred to one thousand grains from each annealed sample were packaged and taken to the neutron source. As many as fifteen samples (depending on the reactor) can be irradiated at one time if they are packaged correctly. Naeser (1967) packages samples in aluminum foil; small heat-sealed plastic pouches also work. The method for making pouches is described below:

a. A plastic strip was folded in half lengthwise.
b. With heat, vertical pouches were sealed in the folded plastic strip. The tops were left open for the addition of the samples.

c. After adding each sample, the air was squeezed out of each pouch and the tops heat sealed closed.

d. Notches were cut in the end of the strip to identify the whole sequence. Foreign material was avoided on or in the samples as this may increase the possibility of it becoming "hot" when irradiated.

10. The thermal neutron dose at which to irradiate the samples was determined from: \( \phi = 1.6 \times 10^7 \, T \), where \( \phi \) = the thermal neutron dose (neutrons/cm\(^2\)), and \( T \) = estimated age of the sample in years (Fleischer, Price and Walker, 1964).

11. Two methods may be used to determine the thermal neutron dose (\( \phi \)) that the samples received.

a. Include a small piece of microscope slide glass in each reactor package, Fleischer et al. (1965). Each slide in a box of ordinary microscope slides has an extremely
uniform uranium content, and a very close
determination of $\phi$ can be made by multiplying
$2.66 \times 10^{11}$ by the induced areal track density
of the glass after neutron irradiation

$$\left( \frac{\text{Number of tracks}}{\text{cm}^2} \right).$$

A box of slides can be accurately calibrated by irradiating several pieces from
the slides and comparing the induced fission track density with that from some known standards that were included in the same reactor package (Fleischer et al., 1965).

Naeser and Fleischer used calibrated slides.

b. Because the ratio of slow to fast neutrons for the MTR reactor at the National Reactor Testing Station (NRTS) in Idaho Falls (the one used in this study) was high, an alternate method was used for neutron flux determinations. This method involves a pure cobalt wire, which, during neutron bombardment captures neutrons and becomes $^{60}$Co instead of $^{59}$Co. $^{60}$Co is unstable, emitting two gamma rays per disintegration in cascade with energies of 1.17 and 1.33 Mev, and having a half-life of 5.27 years. Neutron irradiation of cobalt also produces a ten
minute $^{60m}$Co which decays to 5.27 year $^{60}$Co with the emission of a single 0.59 Mev gamma per disintegration.

The absolute gamma ray emission from the irradiated cobalt was measured at NRTS by a multi-channel differential pulse height analyzer which is connected to a sodium iodide crystal and a photomultiplier tube. The sodium iodide crystal gives off light energy when irradiated with gamma rays. The photomultiplier tube was monitored at several energy levels and the intensities of the 1.17 and the 1.33 Mev peaks for $^{60}$Co were determined. Larger neutron fluxes will cause greater 1.17 and 1.33 Mev intensity levels.

The total neutron flux was determined from the equation (Hogg, 1960):

$$A = N \cdot \phi \cdot \sigma \cdot \lambda \cdot t,$$

or

$$\phi = \frac{A}{N \cdot \sigma \cdot \lambda \cdot t}$$

Where:

- $A$ = activity of sample in disintegrations per second (determined from the multi-channel differential pulse height analyzer),

- $N$ = number of atoms of cobalt,

- $\phi$ = neutron flux (total) ($\text{neutrons/cm}^2/\text{min}$).
\[ \sigma = \text{cross section for } ^{59}\text{Co} \ (36.3 \times 10^{-24} \text{ cm}^2), \]
\[ \lambda = \text{decay constant } ^{60}\text{Co} \]
\[ \frac{(.693)}{5.3 \times 3.5 \times 10^7 \text{ year}} = 4.15 \times 10^{-9} / \text{year}, \]
\[ t = \text{length of irradiation in minutes}. \]

The thermal neutron dose is needed to determine the age of the samples; however, the above equation gives the total neutron dose (both slow and fast neutrons). Fast neutrons must be avoided because they will cause fission of \(^{238}\text{U}\) which would add additional fission tracks to the sample and give an erroneous age. However, at the MTR Reactor, the ratio of slow to fast neutrons was sufficiently high (300:1) and the cross section for fission of \(^{238}\text{U}\) was low enough so that the number of fissions caused by \(^{238}\text{U}\) was negligible (0.3%) (Dr. Elton Turk, personal communication).

12. The age was determined from the following formula (Fleischer, Price and Walker, 1965):
\[ T = \frac{1}{\lambda_D} \ln \left[ 1 + \left( \frac{\rho s \lambda_D \sigma I F}{\rho I_F \lambda_F} \right) \right] \text{ years} \]
Where:

\[ T = \text{age in years before present}, \]
\[ \rho_s = \text{spontaneous (natural) fission areal track density}, \]
\[ \rho_i = \text{induced fission areal track density}, \]
\[ \lambda_D = \text{total decay constant for } ^{238}\text{U} \]
\[ (1.54 \times 10^{-10} \text{ yr.}^{-1}), \]
\[ \sigma = \text{thermal neutron cross section for fission of } ^{235}\text{U} \]
\[ (582 \times 10^{-24} \text{ cm}^2), \]
\[ \phi = \text{total thermal neutron dose (neutrons/cm}^2\text{)}, \]
\[ I = \text{isotopic ratio } ^{235}\text{U}/^{238}\text{U} \]
\[ (7.26 \times 10^{-3}) \]
\[ \lambda_F = \text{fission decay constant of } ^{238}\text{U} \]
\[ (6.85 \times 10^{-17} \text{ yr.}^{-1}) \]
\[ \text{(Fleischer and Price, 1964)}. \]

By substituting the constants in the formula, it becomes:

\[ T = 6.49 \times 10^9 \ln [1 + (9.45 \times 10^{-18} \frac{\rho_s}{\rho_i} \phi)] \text{ years.} \]

13. When counting the tracks, both the irradiated and non-irradiated samples were counted within an hour of each other. This procedure compensated for counting errors caused by boredom or fatigue (see Appendix II).

Because apatite fission tracks anneal out at fairly low geologic temperatures as shown in Figure 4, (apatite heated to 175°C for one million years will lose all its fission tracks, Naeser and Faul, 1969), it is desirable to have some dates from minerals that have high annealing temperatures, that is, sphene or zircon.
Minerals with low uranium concentrations may only be used to date older rocks, whereas those with higher uranium concentrations are used to date younger rocks (Fleischer et al., 1964), so the spontaneous track density was checked at the outset to determine if the uranium concentration of the apatite from the Flint Creek Range was suitable for age determinations. One thousand power, or higher, had to be utilized when observing minerals with high track densities (i.e., sphene and zircon). The higher the track density, the smaller the area that needed to be counted in each grain.

Note: Sphene can easily be confused with monazite, (both occur in granitic rocks) and, because of its exceptionally high thorium content monazite could not be used for fission track age determinations. Thorium will decay by spontaneous fission, and in the process will produce its own fission tracks. The thorium tracks are indistinguishable from $^{238}$U tracks, and if the thorium content is high, as in monazite, enough additional tracks would be counted to make the spontaneous track density erroneous. Index oils were used to distinguish sphene from monazite; x-ray patterns or density differences could also be used.
Note: When the irradiated samples were ground and polished, the residue was monitored and disposed of correctly if it was overly radioactive.
Chapter 3

RESULTS AND DISCUSSION

The granitic rocks in the Flint Creek Range have an average fission track age of 64.7 m.y., with a standard deviation of 4.5. The dates for each pluton are: 65.9 m.y. for the Philipsburg batholith (standard deviation, 1.4); 66.4 m.y. for the Royal stock (standard deviation, 3.1); and 62.1 m.y. for the Mount Powell batholith (standard deviation, 5.6). Table I shows the ages from each sample, while Figure 3 shows the sample locations.

The data presented in this thesis are consistent with other research conducted in the same area, especially with that of Benoit (1972). He concludes that the Mount Powell batholith is the last of the three intrusions, and that it is a partial differentiate of the Royal stock. As the Royal stock was cooling, its molten central core broke through the margins and intruded the country rock. The younger dates on the Mount Powell batholith are compatible with such an origin.

Both Ehinger (1971) and Benoit (1972) conclude that the plutons (Philipsburg batholith and Royal stock) have differentiated in situ and that the cores were the last
<table>
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<tr>
<th>Sample No.</th>
<th>Total Tracks ($\rho_s$)</th>
<th>Grains Counted</th>
<th>Density of ($\rho_s$) Per Unit Area</th>
<th>Total Tracks ($\rho_i$)</th>
<th>Grains Counted</th>
<th>Density of ($\rho_i$) Per Unit Area</th>
<th>$\phi(x10^{15})$</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Philipsburg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>H29-14</td>
<td>1189</td>
<td>40</td>
<td>29.7</td>
<td>1347</td>
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<td>33.7</td>
<td>1.29</td>
<td>64.8 m.y.</td>
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<tr>
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<td>1256</td>
<td>40</td>
<td>31.4</td>
<td>1404</td>
<td>40</td>
<td>35.1</td>
<td>1.32</td>
<td>65.9 m.y.</td>
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<tr>
<td>S30-5</td>
<td>629</td>
<td>26</td>
<td>24.2</td>
<td>754</td>
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<td>27.0</td>
<td>1.35</td>
<td>68.2 m.y.</td>
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</tr>
<tr>
<td></td>
<td>Average = 65.9 m.y.</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Royal</td>
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</tr>
<tr>
<td>H31-1</td>
<td>452</td>
<td>48</td>
<td>9.4</td>
<td>423</td>
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<td>10.6</td>
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<td>69.3 m.y.</td>
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<td>5.9</td>
<td>286</td>
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<td>7.1</td>
<td>1.32</td>
<td>66.9 m.y.</td>
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<tr>
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<td>12.2</td>
<td>398</td>
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<td>16.6</td>
<td>1.32</td>
<td>60.1 m.y.</td>
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<td>8.1</td>
<td>389</td>
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<td>9.7</td>
<td>1.29</td>
<td>65.4 m.y.</td>
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<td>S31-10</td>
<td>546</td>
<td>40</td>
<td>13.7</td>
<td>684</td>
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<td>17.1</td>
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<td>11.7</td>
<td>1.32</td>
<td>66.7 m.y.</td>
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<td>Average = 66.4 m.y.</td>
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</tr>
<tr>
<td>Mount Powell</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>H14-2</td>
<td>283</td>
<td>48</td>
<td>5.9</td>
<td>226</td>
<td>32</td>
<td>7.1</td>
<td>1.29</td>
<td>65.7 m.y.</td>
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<td>48</td>
<td>21.6</td>
<td>1072</td>
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<td>26.8</td>
<td>1.29</td>
<td>63.6 m.y.</td>
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<td>32</td>
<td>22.7</td>
<td>1164</td>
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<td>1.32</td>
<td>62.9 m.y.</td>
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<td>40</td>
<td>7.2</td>
<td>351</td>
<td>40</td>
<td>8.8</td>
<td>1.29</td>
<td>65.4 m.y.</td>
</tr>
<tr>
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<td>597</td>
<td>48</td>
<td>12.4</td>
<td>793</td>
<td>40</td>
<td>19.8</td>
<td>1.32</td>
<td>50.7 m.y.</td>
</tr>
<tr>
<td>H6-8</td>
<td>199</td>
<td>40</td>
<td>5.0</td>
<td>251</td>
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<td>6.3</td>
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<td>62.0 m.y.</td>
</tr>
<tr>
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<td>238</td>
<td>48</td>
<td>5.0</td>
<td>277</td>
<td>40</td>
<td>5.9</td>
<td>1.35</td>
<td>69.7 m.y.</td>
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<td>8.5</td>
<td>497</td>
<td>40</td>
<td>12.4</td>
<td>1.35</td>
<td>56.4 m.y.</td>
</tr>
<tr>
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<td>Average = 62.1 m.y.</td>
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</tr>
</tbody>
</table>

**TABLE I**

Ages and information needed to compute the age of each sample (spontaneous track density, induced track density, and thermal neutron dose).
Figure 3 Sample Locations with Fission Track Age Dates (dates in millions of years).
parts to crystallize. If this were so, then younger dates would be expected toward the center of the plutons. Examination of Figure 3 suggests that this is possibly the case, but only very generally. A possible reason for the poor correlation of younger dates toward the center of the plutons is that the apatite fission track date does not set the time of crystallization, but sets only the time of cooling, below about 50°C.

The dates for the plutons are nearly 10 m.y. younger than the dates established by Obradovitch, using Potassium-argon methods. His results on both biotite and hornblende in samples AA-4 and BB-7 in the Philipsburg batholith gave an average age of 72.7 m.y. and 75.3 ± 2.3 m.y., respectively (Hyndman, Obradovitch, and Ehinger, 1972). This difference in ages between the two different methods indicates that there has been some natural annealing of the spontaneous fission tracks as the plutons cooled.

It has been established by Naeser and Faul (1969) that fission tracks in apatite are very temperature sensitive; thus, in order to establish a cooling history for the area, it is necessary to determine the normal temperature of the country rock at the depth the plutons were intruded. Ehinger (1971) found miarolitic cavities in the central region of the Philipsburg batholith. He believes the miarolitic cavities indicate a minimum pressure during
crystallization of around 450 bars, and a maximum pressure of 700 bars. These rock pressures would be expected at depths of 1.74 km. and 2.45 km., respectively. Assuming a geothermal gradient of 25°C per km., the temperature of the country rock at the depth of emplacement of the exposed part of the Philipsburg batholith would have been between 44°C and 61°C. (In the preceding calculations of the temperatures and the depth of emplacement, loss of heat due to the removal of the batholithic cover by erosion has been neglected.) If the rocks were held at these temperatures (44°C to 61°C) for 10 m.y., about 20% of the natural fission tracks in apatite would be annealed (Fig. 4).

The intrusion temperature for the Philipsburg batholith is set by Ehinger (1971) at around 700°C. According to the experimental work of Naeser and Paul (1969), rocks would have to cool below 175°C before any tracks could be retained, and below 110°C before 50% of the tracks would be preserved (Fig. 4). This latter temperature is only 57°C above the normal temperature that would be expected at the depth of emplacement of the Philipsburg batholith.

Because two variables are involved in fission track annealing, both time and temperature, it is impossible to determine an exact cooling history. Having the rocks at 110°C for 1 m.y. will anneal as many tracks in apatite as having the rocks maintained at a temperature of 80°C for
Figure 4. Amount of Fission Track Annealing in Apatite in Relation to Temperature and Time (Naeser and Faul, 1969).
100 m.y. However, the rocks must have cooled below 175°C (the temperature above which no tracks will be retained over a million year period) by 70 m.y. ago (oldest date). Assuming the potassium-argon dates by Obradovich to be correct, (a reasonable assumption because both hornblende and biotite in each sample gave concordant dates) an age of 74 ± 2 m.y. can be used for the time of the cooling of the plutons to about 300°C (approximate temperature for the retention of argon). It can therefore be established that samples with dates close to 74 m.y. had to cool fairly quickly from 300°C to 50°C (temperature for 100% track retention over a million year period); samples with younger dates took longer to cool.

It is difficult to explain the variation in ages across the plutons (range 71-51 m.y.), but, if one considers the situation at Yellowstone Park, and assumes that the Yellowstone Plateau is a typical batholithic cover, he can find it is quite possible for hot rising solutions to maintain thermal zones at high enough temperatures to anneal half of the fission tracks in apatite (110°C over a million year period). Conversely, descending surface solutions could produce zones of cooler rocks. A variation of 57°C above or below the normal rock temperatures at the depth of intrusion (44°C to 61°C) will either raise the temperature enough to erase half of the fission tracks or lower it enough to allow complete retention.
It may also be possible that the age variation reflects a difference in elevation across the plutons, with the older dates being closer to the top and hence cooling faster. All the sample locations were checked against elevation, with no apparent effect being due to vertical differences in the plutons.

It was originally planned to have fission track age dates from sphene as well as apatite. The sphene tracks are much more stable under thermal conditions than apatite, and it was hoped that an accurate cooling history could be derived for the plutons. However, it was extremely difficult to separate the sphene grains, so this plan had to be abandoned.

Tertiary stratigraphers, working in the southwestern Montana basins, find that fine-grained silt and mudstones were being deposited in the center of the basins during the Eocene. By Early Oligocene (about 40 m.y. ago), parts of the Boulder batholith were unroofed (Kuenzi and Fields, 1971). Granitic detritus from the Boulder batholith was deposited on an erosional surface of the Boulder batholith. East of the Continental Divide from Butte, is a pronounced Middle Tertiary unconformity that occurred sometime between Middle Oligocene and Upper Miocene (Kuezi and Richard, 1969).

Rasmussen (1969, 1973) describes a thick sequence of Miocene sediments which unconformably overlies Cretaceous
in the Drummond Basin, just north of the Flint Creek Range. These mid-Tertiary unconformities probably mark a period of uplift for the ranges in southwestern Montana. With major uplift and erosion, the plutons would cool faster and more fission tracks would be preserved. Dissection and cooling of the elevated plateau had to occur sometime before the youngest dates, 51 m.y. (about Middle Eocene).

There is also the possibility that tectonic denudation could have occurred in the area and that this rather than erosion could have removed the sedimentary cover. With tectonic denudation however, one would expect the batholithic cover to move as a unit, cooling the underlying rocks at essentially the same time. If this happened, the dates across the plutons should be fairly uniform. Figure 3 shows that the dates range from 71 m.y. ago to 51 m.y. ago with no consistent pattern to the variation. It is also possible that the Flint Creek Range is too small an area for gravity sliding, and that the amount of uplift was too little (2.5 km.). From these arguments, it can be concluded that tectonic denudation was probably not responsible for the unroofing of the Flint Creek plutons.

An interesting facet of this research is that the uranium concentration in apatite was not constant from pluton to pluton or in some cases, across the same pluton. The relative abundance of uranium in the samples can be
determined approximately by comparing the average track densities from Table I. Samples in the Philipsburg batholith have two to six times more uranium than the other samples. All samples in the Philipsburg batholith were difficult to count because of this anomalously high uranium content. In the Mount Powell batholith, the rocks adjacent to samples H10-6 and H10-8 are fairly high in uranium content, whereas the Royal stock seems to show no distinct uranium distribution pattern.
Chapter 4

CONCLUSIONS

The apatite fission track dates from the three plutons in the Flint Creek Range are: 65.9 m.y. for the Philipsburg batholith (standard deviation, 1.4); 66.4 m.y. for the Royal stock (standard deviation, 3.1); and 62.1 m.y. for the Mount Powell batholith (standard deviation, 5.6). These data are consistent with other research that suggests that all three plutons were injected at about the same time.

The range of individual dates across the plutons varied from 51 m.y. to 71 m.y. Areas with dates close to 71 m.y. cooled from 300°C to 50°C within a few million years, and areas with younger dates took much longer to cool. It is felt that this variation can be caused by ascending or descending solutions. Heating the rocks 50°C above their normal geothermal temperatures for a million years would anneal 50% of the fission tracks. Conversely, cooling the rocks 50°C below their normal geothermal temperatures would allow complete retention of the fission tracks. The uplift and dissection of the plateau must have occurred before 51 m.y. ago (the youngest date).
APPENDIX I

Reasons for omission of samples:

1. During shipping and handling of the irradiated samples, some of the heat-sealed joints between the pouches separated and parts of the samples in the pouches mixed, thus rendering both samples unusable. These samples were discarded at the outset.

2. When the samples were recounted a year after the first counts, the grains were extremely cloudy and the tracks almost impossible to see. Scrubbing the slides was not successful, whereupon the slides were reground and repolished to expose a new surface. In doing so, some of the samples were inadvertently ground too far. These slides are identified in the following list of slides that were omitted:

H30-5  This sample had a high uranium content which made it hard to count. For some reason the irradiated portion was filled with fractures and in the non-irradiated portion, the grains were very clear. This may have been caused in the polishing or grinding procedure.

H15-8  The non-irradiated slide was ground too far.

H15-1  The grains were small (ground too far) and it appeared as if many were partially covered with epoxy.

H31-6  The grains were larger on the irradiated sample and it was very easy to find suitable locations on each grain of the sample. The non-irradiated grains were smaller (ground too far) and had to settle for the portion of the grain that was exposed. Because of the lack of selection available in the non-irradiated slide, this sample was omitted.
S29-4  Ground too far on the second grinding.
S26-14 Ground too far on the second grinding.
S26-12 A poor separation with heavy liquids was made; this sample contained mostly quartz.
S26-9  A poor separation with heavy liquids was made; this sample was mostly quartz.
S24-10 A poor separation with heavy liquids was made; this sample was mostly quartz.
S24-4  A poor separation with heavy liquids was made; this sample was mostly quartz.
S22-5  Ground too far in the second grinding.
Originally, fission tracks were counted on all samples during the summer of 1970. The procedure used then was purposely random. Slides were counted in whichever order they were picked up. This figured to be a good method because it was fairly random, and didn't lend itself to personal bias.

During the winter of 1971, the slides that had previously been completed (summer, 1970) were recounted, and the dates didn't correspond to the original dates. The samples were then counted by slide pairs and it was found that the results were reproducible. In this way, each sample pair was treated similarly. The apatite grains in the Flint Creek Range tend to have abundant inclusions and an excessive number of fractures which tend to obscure fission tracks. By counting slide pairs together, one is better able to compare the two slides for differences that may affect the accuracy of the count. Also, it tends to eliminate errors that result from fatigue or boredom since one is essentially in the same frame of mind for each count.
BIBLIOGRAPHY


