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Fission-Track Geochronology and Geothermometry of Late Cretaceous-Early Tertiary Epizonal Plutons, in and Adjacent to the Lombard Thrust Fault, Southwestern Montana

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Western Michigan University

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FISSION-TRACK GEOCHRONOLOGY AND GEOTHERMOMETRY OF LATE CRETACEOUS-EARLY TERTIARY EPIZONAL PLUTONS, IN AND ADJACENT TO THE LOMBARD THRUST FAULT, SOUTHWESTERN MONTANA

by
Jean Talanda

A Thesis
Submitted to the
Faculty of the Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Science
Department of Geology

Western Michigan University
Kalamazoo, Michigan
June 1988

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FISSION-TRACK GEOCHRONOLOGY AND GEOTHERMOMETRY OF LATE CRETACEOUS-EARLY TERTIARY EPIZONAL PLUTONS, IN AND ADJACENT TO THE LOMBARD THRUST FAULT, SOUTHWESTERN MONTANA

Jean Talanda, M.S.
Western Michigan University, 1988

Thrusting occurred in the central portion of the central Montana salient where the timing of movements is somewhat obscured by the multiple deformations from Archean time to the present. The relationship of this thrusting to the associated plutons has not been established in every case. Fission-track geochronology was employed in dating several plutons associated with the Lombard thrust fault, consequently, defining a time range in which movement along the thrust occurred.

Seven plutons with known structural relationships to the Lombard thrust have ages which suggest that movement along the fault occurred 73.2 +/- 6.7 Ma. Fission-track length distributions suggest that all the plutons studied share a common thermal history. The distributions indicate that the plutons were brought to a shallow depth and cooled rapidly similar to undisturbed volcanic-type rocks. Therefore, the fission-track ages obtained in this study are very likely related to the actual crystallization of rocks.
ACKNOWLEDGEMENTS

Matthew Fisher, my husband: Thanks for your support.

Dorothy and Edmund Talanda, my parents: I hope this paper can appropriately reflect all that I have learned.

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Jean Talanda

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Western Michigan University, 1988

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CHAPTER I

INTRODUCTION

The Problem

Plutonism, volcanism and thrusting occurred between 68 and 78 Ma within the fold and thrust belt of southwestern Montana (Hanna, 1973; Robinson, Klepper, & Obradovich, 1968). During the relatively short time span in which deformation occurred, the Boulder batholith and its satellite plutons were emplaced in and near to the Lombard thrust sheet. Overprinting of thrust belt features in this area by Cenozoic extensional faulting makes uplift history difficult to interpret.

This study sought to define a time limit for the Lombard thrust by dating selected plutons in and adjacent to the Lombard thrust sheet using fission-track geochronology and geothermometry.

The plutons selected for dating were chosen for their presumed structural relationship to the Lombard thrust. Thorough mapping of the Lombard thrust sheet by Robinson (1963), Garihan, Schmidt, Karasevich (1982), Schmidt & O'Neill (1982) and Ludman (1965) has allowed the geologic framework of this area to be comparatively well understood. Some of these selected plutons appear
to have moved with the Lombard thrust sheet where a number of them are inferred to penetrate the sheet. Thus, information regarding the age of these igneous bodies would permit the dating of the Lombard thrust more precisely.

As an example, plutons thought to cut folds or thrust faults are considered post-thrusting; and those cut or folded by a thrust fault have generally been considered to be pre-thrusting. Thus, if the ages of the plutons are known, the time range in which thrusting occurred can be narrowed.

In addition to this dating process, fission track analysis has the unique ability to provide information regarding the thermal history of the samples. By taking measurements of track length distributions, it is possible to date the plutons and to draw inferences about their thermal histories.

The study area is within the Cordilleran fold and thrust belt of southwestern Montana; specifically the southeastern margin of the Boulder batholith and the Central Montana salient (Plate 1). Samples taken from the southwest Montana transverse zone which bounds the southern part of the Lombard sheet include the Butte Quartz Monzonite, the Hell Canyon pluton, the Rader Creek pluton, the 10-N pluton, the Brownback sill (Diamondhead sill), the Gold Hill sill (Bone Basin sill), the Burton
Park pluton, the Pipestone Pass pluton and the Cottonwood Canyon sill. Other samples from the Montana fold and thrust belt are the Lone Mountain pluton, the Rattlesnake Butte pluton, the Townsend pluton, the North Boulder complex and the Mt. Doherty complex (Freeman, Ruppel, & Klepper 1985; Schmidt, Smedes, Suttner, & Vitaliano, 1979; Robinson, 1963; Ludman, 1965). Exact sample locations are given in Table 1.
<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Elevation Feet</th>
<th>Rock Type</th>
<th>Suspected relationship to Lombard Thrust</th>
<th>Sample Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broomback Sill or</td>
<td>5550</td>
<td>Quartz Monzonite</td>
<td>Pre-thrusting; pre-folding;</td>
<td>45° 45': 111 59°</td>
</tr>
<tr>
<td>Diamondhead Sill</td>
<td></td>
<td></td>
<td>intrudes Cambrian Rocks</td>
<td>Central, Sec. 29, T.15, R.3W</td>
</tr>
<tr>
<td>IO-N Pluton</td>
<td>4600</td>
<td>Quartz Monzonite</td>
<td>Post-tectonic if from a late phase</td>
<td>45° 59': 111 37°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>magma (Vitiiano, personal comm.)</td>
<td>SH 1/4, SH 1/4, Sec. 28, T.3N, R.1E</td>
</tr>
<tr>
<td>Butte Quartz Monzonite</td>
<td>5820</td>
<td>Quartz Monzonite</td>
<td>Contemporaneous; intrudes thrust</td>
<td>45° 52°30': 112 21°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fault; cuts Rader Creek Pluton</td>
<td>NE 1/4, NE 1/4, Sec. 4, T.1H, R.6W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>from the main phase of magma</td>
<td></td>
</tr>
<tr>
<td>Hell Canyon Pluton</td>
<td>5200</td>
<td>Quartz Monzonite</td>
<td>Post-thrusting; cuts Camp Creek</td>
<td>45° 30': 112 20°40'</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>thrust; intruded &amp; controlled by</td>
<td>SE 1/4, SE 1/4, Sec. 29, T.25, R.6W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>shape of N.H. fault zone; from</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>late phase of magma</td>
<td></td>
</tr>
<tr>
<td>Rader Creek Pluton</td>
<td>5200</td>
<td>Granodiorite /</td>
<td>Pre-thrustings: separated and sheared</td>
<td>45° 50°40': 112 22°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Quartz Monzonite</td>
<td>by the main plutonic body; possibly</td>
<td>SE 1/4, SE 1/4, Sec. 9, T.1N, R.6W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ascended in fault zone</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rader Creek Pluton</td>
<td>5500</td>
<td>Granodiorite /</td>
<td>Pre-thrustings: separated and sheared</td>
<td>45° 50°20': 112 21°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Quartz Monzonite</td>
<td>by the main plutonic body; possibly</td>
<td>NE 1/4, SH 1/4, Sec. 15, T.1H, R.6W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ascended in fault zone</td>
<td></td>
</tr>
<tr>
<td>Lone Mountain Stock</td>
<td>4500</td>
<td>Quartz Monzonite</td>
<td>Mid to late-thrusting; post-folding;</td>
<td>45° 07': 111 38°30'</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>cuts and shears volcanics; cuts</td>
<td>NE 1/4, NE 1/4, Sec. 7, T.4N, R.1E</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>folded Late Cretaceous rocks</td>
<td></td>
</tr>
<tr>
<td>Rattlesnake Butte Pluton</td>
<td>4860</td>
<td>Granodiorite</td>
<td>Pre-folding; cuts across large</td>
<td>45° 15': 111 41'</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>syncline of Paleozoic rocks;</td>
<td>NE 1/4, NE 1/4, Sec. 26, T.6N, R.1W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>magnetic equivalent of volcanics</td>
<td></td>
</tr>
<tr>
<td>Gold Hill Sill or</td>
<td>5900</td>
<td>Granodiorite</td>
<td>Pre-thrustings: folded &amp; sheared;</td>
<td>45° 46': 112 06°30'</td>
</tr>
<tr>
<td>Bone Basin Sill</td>
<td></td>
<td></td>
<td>intrudes Precambrian Belt series</td>
<td>NE 1/4, NE 1/4, Sec. 8, T.15, R.4W</td>
</tr>
<tr>
<td>Townsend Pluton</td>
<td>5260</td>
<td>Rhyodacite</td>
<td>Contemporaneous; faulted; cuts</td>
<td>45° 17°30': 111 30°10'</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>across large syncline of Paleozoic rocks</td>
<td>NE 1/4, NE 1/4, Sec. 8, T.6N, R.1E</td>
</tr>
<tr>
<td>Lone Mountain Stock</td>
<td>4500</td>
<td>Quartz Monzonite</td>
<td>Mid to late-thrusting; post-folding;</td>
<td>45° 07': 111 38°30'</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>cuts and shears volcanics; cuts</td>
<td>NE 1/4, NE 1/4, Sec. 7, T.4N, R.1E</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>folded Late Cretaceous rocks</td>
<td></td>
</tr>
<tr>
<td>North Boulder Complex</td>
<td>5500</td>
<td>Hornblende Andesite</td>
<td>Pre-thrustings: buttress for thrusts;</td>
<td>45° 56': 111 50'</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>feeder for volcanics</td>
<td>SH 1/4, SE 1/4, Sec. 8, T.2N, R.2W</td>
</tr>
<tr>
<td>Pipestone Pass Pluton</td>
<td>6500</td>
<td>Alaskite</td>
<td>Post-thrusting; latest magma phase</td>
<td>45° 51': 120 28°45'</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NE 1/4, SE 1/4, Sec. 3, T.1H, R.7W</td>
</tr>
<tr>
<td>Cottonwood Canyon Sill</td>
<td>4810</td>
<td>Calc-Alkaline Suite</td>
<td>Pre-folding; walls folded in</td>
<td>45° 53°07': 111 53°10'</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cambrian and Devonian rocks</td>
<td>NE 1/4, SH 1/4, Sec. 32, T.2N, R.2H</td>
</tr>
<tr>
<td>Burton Park Pluton</td>
<td>6800</td>
<td>Quartz Monzonite</td>
<td>Older than the main phase magma</td>
<td>45° 50°: 112 28°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SE 1/4, Sec. 16, T.1H, R.7W</td>
</tr>
<tr>
<td>Mt. Doherty Complex</td>
<td>5200</td>
<td>Granodiorite</td>
<td>Intrudes Precambrian</td>
<td>45° 54°30': 111 52'</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NH 1/4, Sec. 29, T.2N, R.2H</td>
</tr>
</tbody>
</table>
CHAPTER II

GEOLOGICAL SETTING

The fold and thrust belt (Sevier) structures in the Montana area are characterized by folds and thrusts superimposed on broadly arched and thrusted crystalline basement, (Scholten, 1968).

During the Middle Proterozoic time, when tectonic development occurred along the southern margin of the Belt Basin in southwestern Montana, two fault sets were formed. The two Proterozoic fault zones were: (1) the northwest-trending extensional faults, which may have been related to the opening of the Belt Basin; and, (2) the east-trending Willow Creek-Perry Line, probably a right-normal oblique fault zone. These old, northwest-trending Proterozoic shear zones that extend to the basement appear to have been reactivated from Late Cretaceous to early Paleocene during a second orogenic episode (Schmidt & Garihan, 1983, 1986). Associated folding occurred producing anticlines and synclines with large amplitudes.

Allochthonous sheets were translated eastward along detachment surfaces in Beltian rocks and ramped up and over the craton. As earlier thrusts were folded new
thrusts formed further eastward. Plutonism, associated with thrusting, also developed eastward as evidenced by the intrusive complex called the Boulder batholith.

The thrust belt structures can be generally described as an anastomating and imbricated system of east-trending, north-dipping oblique slip faults, that probably flatten with depth merging with a detachment surface in Precambrian Belt rock. It has been speculated that the faults merge northeastward into north-trending, west-dipping thrust faults (Schmidt & O'Neill, 1982; Woodward, 1981). Schmidt and Garihan (1986) suggest that the east-trending, north-dipping faults of the Jefferson Canyon region (southernmost Montana traverse zone) comprise a large lateral ramp of the Lombard sheet which merges northeastward into the north-trending, west-dipping Lombard thrust. The age of emplacement of this thrust sheet is one of the principal problems dealt with in this report.

Lombard Thrust Fault

The east-trending Jefferson Canyon fault zone (Plate 1) is inferred to connect with the north-trending Lombard thrust just north of Three Forks, Montana, to form a major fault zone within the fold and thrust belt. This appears to connect with the Mayflower and Cave faults as seen in Plate 1. To the north, the Lombard is inferred
to connect with the Eldorado thrust northeast of Helena, Montana (Woodward, 1981). The entire proposed fault zone, the Eldorado-Lombard-Jefferson Canyon zone, marks the pronounced eastward deflection of the Montana fold and thrust belt called the Helena structural salient, and defines the eastern margin of the Lombard thrust sheet. This fault zone has carried allochthonous Middle Proterozoic sedimentary rocks (Belt Supergroup) to the east over Paleozoic and Mesozoic sedimentary layers.

Three other thrust faults between the Lombard and the eastern edge of the thrust belt (Verrall, 1955) also indicate that ramping has occurred. An eastward propagating sequence of thrusts from a single detachment has been inferred by Schmidt and O'Neill (1982).

Between the southernmost trace of the Lombard thrust and the Boulder batholith, larger folds may represent areas where the Lombard sheet has stepped up to higher stratigraphic layers within the Belt Supergroup (Schmidt & O'Neill, 1982).

Boulder Batholith Region

The Proterozoic shear zones formed in the Belt Basin of western Montana became a major influence on the style of deformation during the Late Cretaceous-Early Tertiary time, when the Boulder batholith was emplaced in the Helena structural salient.
The Helena Salient is bounded to the north and south by the Lewis-Clark-Osborn and Willow Creek lineaments respectively (Woodward, 1981). During the Late Cretaceous, thrust faulting was deflected to the north of the Boulder batholith by the Lewis-Clark-Osborn lineament, as reflected by a left-lateral tear zone. Faulting was deflected to the south of the batholith by the portions of the Willow Creek lineament, a right-lateral tear zone.

Eruption of the Elkhorn Mountain Volcanics was followed by north-northeast trending folding. Igneous activity began during the formation of the fold and thrust belt. The northeast-trending Boulder batholith is an epizonal pluton intruded over a 10 million year span between 68-78 Ma (Klepper, Ruppel, Freeman, & Weeks, 1971). The Boulder batholith and surrounding plutons are composed of a succession of calc-alkaline magmas differing in composition and age. Two dissimilar magma series have been proposed as sources: the main series called the Butte Quartz Monzonite, which includes the bulk of the Boulder batholith; and, the sodic series which includes the southern Boulder batholith plutons, Radar Creek and Hell Canyon (Tilling, 1973). Table 1 lists the petrology and structure of the plutons dated.

The western and southwestern portion of the Boulder batholith was later intruded and mantled by the Lowland.
Creek volcanics during the Early Eocene, 48-50 Ma (Smedes, 1962b; Smedes & Thomas, 1965). This second phase of volcanism has obscured many of the structural relationships of the Late Cretaceous - Early Paleocene orogeny, and may even be related to the sodic series (Tilling, 1973).
CHAPTER III

FISSION TRACK ANALYSIS

Problems Involved in Fission Tracking

In geology fission track analysis has many applications. The method of fission track analysis can be used in geochronology to date a variety of rocks as well as geothermometry to provide valuable information about their thermal history. In the following discussions dating methods based on the formation of fission tracks will be treated separately from that of the thermal history which deals with the healing of fission tracks.

Apatite, a common accessory mineral in many rocks, is most often used as a low-temperature geothermometer in the fission track analysis. Apatite crystals, found in igneous rocks, have a sufficient uranium content to allow them to be used in this process. The area chosen for this study was selected because it had an abundance of igneous rock (plutons and sills) associated with the Lombard thrust (See Plate 1 for sample locations).

Because apatite crystals are relatively stable under weathering conditions, they have been studied as paleotemperature indicators in hydrocarbon resource
evaluation (Green, Duddy, Gleadow, & Lovering [in press]); and the post-depositional, thermal evolution of sedimentary basins and orogenic belts (Lakatos & Miller, 1983).

Fission tracking is based on the theory that an atomic parent isotope, $^{238}$U, present in a solid material such as an apatite crystal, is unstable and will decay spontaneously into a pair of fission fragments. Unlike other geochronologic studies which use the daughter products, fission-track dating is based on the crystal lattice distortions created during the fission process. In a fission event, two positively charged nuclei are produced by the decay of $^{238}$U and pass through the solid (e.g. the apatite crystal) in which they are encased. The nuclei recoil from each other in opposing directions forming a damaged zone in the solid, while stripping electrons from the crystal lattice (Fleischer, Price, & Walker, 1965a). A damaged zone is left with positively charged ions that repel each other creating a linear trace within the crystal; this is called a fission track. This new track has a consistent and characteristic cigar shape measuring only 10-20 micrometers long.

Assuming that the amount of parent isotope in a crystal remains constant from the time of its formation, the parent isotope will spontaneously decay at a constant
rate with time. It is the proportion or ratio of original parent $^{238}\text{U}$ to the number of daughter tracks that allows a mineral such as apatite to be dated.

This is a simple concept but there are many questions which must be answered in order to establish the reliability of fission-track geochronology. For example: (a) Is it correct to assume that a mineral with $^{238}\text{U}$ is formed during a geologic event and that at the closing of such an event the age of the mineral is zero? (b) Are there other isotopes present that undergo spontaneous fission creating tracks indistinguishable from those of $^{238}\text{U}$? (c) What are the age limitations of a mineral to be dated by fission tracking? (d) After a crystal has formed, has it been altered in any way physically or chemically to give a false parent-daughter ratio? (e) Has the relationship of parent-isotope to daughter-track remained the same throughout time? (f) Do isotopes decay at a constant rate even under varied geologic conditions? (g) How accurately can the present laboratory techniques determine the parent-daughter ratio?

An attempt is made throughout the rest of this chapter to address these questions.
Effects of Other Fission Track Producing Isotopes

During the formation of a mineral such as apatite it may incorporate trace quantities of $^{238}$U within its crystal lattice; at this time no fission tracks have yet been produced. In this report it is assumed that crystallization occurs at the end of a geologic event; when time is set to zero for those crystals formed during that event. Minerals generally contain other isotopes such as $^{235}$U and $^{232}$thorium ($^{232}$Th). Each of these also has the capability to produce fission tracks identical to those of $^{238}$U. The present known $^{235}$U/$^{238}$U ratio of $7.2527 \times 10^{-3}$ for the vast majority of natural systems, has helped to establish that the number of tracks produced by $^{235}$U is negligible when compared to those from $^{238}$U. In the same manner, fission tracks from $^{232}$Th can also be considered as negligible the effects of $^{235}$U and $^{232}$Th will be ignored (Henderson, 1982).

In addition, $^{238}$U is also known to decay by another process called alpha emission. The proportion of $^{238}$U decay by alpha emission has been calculated and subtracted from the total $^{238}$U; the remaining $^{238}$U is assumed to decay by fission.

Physical and Age Limitations of Apatite Crystals

Fission tracks are distinguished visually under the petrographic microscope. It is very important that
crystals have a sufficient number of tracks to determine the parent-daughter ratio. The track density, the number of tracks per unit surface area, is a function of the age of the material and its uranium content. If too few tracks are present as in a rock with uranium-poor apatite or in a very young rock, fission tracking may be impossible. The same is true if the tracks are too dense and cannot be visually distinguished from each other. This might be the case of a very old Precambrian rock or a rock with uranium-enriched apatites. Fission-track dating has been employed for rocks as old as $20 \times 10^9$ years old.

The chosen apatite crystals must also have very few fractures, dislocations or inclusions which may obstruct or distort tracks and make it difficult to achieve an accurate parent-daughter ratio. The physical and age limitations of the apatites in this fission track analysis did not allow several of the samples collected to be dated.

Changes After Crystal Formation

Information regarding the post-crystallization history of a rock is generally wanting. It has been assumed, therefore, that after a given geologic event the crystals formed have not undergone any chemical or physical alteration resulting in a gain or loss of $^{238}\text{U}$
which would change the parent-daughter relationship. The crystals are assumed to have remained in a closed system after formation; the quantity of uranium is considered to be unchanged except upon fission and alpha emission. It is also assumed that the fission tracks have not been altered or destroyed.

**Laboratory Determinations of the Parent-Isotope/Daughter-Track Ratio**

In order to achieve an accurate parent-daughter ratio, many steps must be properly performed to eliminate erroneous results (Gleadow, 1981). Some common problems stem from careless track counting; the presence of track-like defects in the crystals; inhomogeneous uranium distributions; incomplete etching of tracks; mismatched mica and sample images; discordant ages among grains; varied neutron fluence (flux) among grains; and, different degrees of contact between the mica-sample pairs (Green, 1981). Many laboratory checks were incorporated into this study in order to reduce these kinds of errors. These checks include the dating of a sample previously dated by another technique; including standard samples whose ages are well known; including standards of known uranium concentration; and, having split samples analyzed separately by two analysts.
Age Equation and Zeta Calibration Factor

The apatite crystals are mounted and the crystals are exposed by polishing. The mounts are then etched so the tracks can be counted and the samples and standards are then sent to be irradiated. After that, the tracks are counted under the microscope and eventually, the results are substituted into an age equation.

In this study, age dating was determined using the Zeta Age Equation (Equation 1) described in Hurford and Green (1981a; 1981b):

\[
T_{\text{unknown}} = \frac{1}{\lambda_d} \left( 1 + \lambda_d \cdot Z_{wm} \cdot g \cdot P_d \cdot P_s \right)
\]

where:

- \( g \) = Geometry factor (0.5 for external detector method)
- \( I \) = Natural isotopic ratio, \( \frac{^{235}U}{^{238}U} \)
  
  \( (7.2527 \times 10^{-3}) \)
- \( \lambda_d \) = Total decay constant for \( ^{238}U \)
  
  \( (1.55125 \times 10^{-10} \text{ 1/a}) \)
- \( P_d \) = Measured induced track density for a glass dosimeter of known uranium concentration and isotopic ratio
- \( P_i \) = Measured induced track density for a sample
- \( P_s \) = Measured spontaneous track density for a sample

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Q = Measured thermal-neutron fluence
T std = Age of an age-standard
T unknown = Age of an unknown sample
Z = Individual Zeta Calibration Factor
Z wm = Weighted Mean Zeta Calibration Factor
R = Correlation coefficient

This equation was chosen over the traditional age equation because it eliminates the necessity of using
two, poorly determined parameters; the $^{238}\text{U}$ fission decay constant and the thermal neutron fluence (Hurford &
Green, 1981a; 1981b).

This type of age determination is most dependant on
Z, the Zeta Calibration Factor. Each analyst determines
his own Zeta Factor to correct for his own ability to
reproduce ages of known standards (Equation 2).

\[
Z = \frac{(\exp(\lambda - d \cdot T_{\text{std}}) - 1)}{\lambda \cdot \frac{[\text{Ps}]_{\text{STD}}}{\text{g} \cdot \text{Pd}}} \cdot \frac{[\text{Pi}]_{\text{STD}}}{(\text{Elaboration of these equations can be found in Hurford &
Green, 1983; Fleischer & Price, 1964; Roberts, Gold, &
Armani, 1968; Wagner, Reimer, Carpenter, Paul, Van der
Linden, & Gijbels 1975; Gentner, 1972}).

The Zeta Calibration Factor is dependant on the use
of a specific method of fission track analysis called the
External Detector Method. This involves the exposure of
the sample crystals to thermal neutrons in a nuclear
reactor. As a result of neutron bombardment, $^{235}\text{U}$ fissions to produce a new set of $^{235}\text{U}$ tracks from the sample. Mica placed adjacent to the sample acts as a recorder or external detector of these induced tracks. After irradiation, the mica is etched and the induced tracks are used to determine the present concentration of $^{238}\text{U}$ (the parent) by utilizing the $^{235}\text{U}/^{238}\text{U}$ ratio, $I$, assumed to be constant for most natural systems.

The advantage of this method is that the fossil tracks are counted on the sample grains representing the daughter fraction and the induced tracks are counted on the mica detector for determining the amount of parent isotope. The result is the present parent-daughter ratio, (concentration of $^{238}\text{U}$/concentration spontaneous tracks). Another advantage of this method is that it enables ages to be determined individually on each grain within the mount. (For further discussion of the External Detector Method see Friedlander, Kennedy, Macias, & Miller, 1981; Green, 1981, 1984; Gleadow, 1981).

When "known age standards" go through the same irradiation process as the samples, their ratio of spontaneous to induced tracks, (Ps/Pi) STD, can be used in the Zeta Factor Equation.

A glass standard (or dosimeter) also irradiated along with the samples serves to supply a material of
"known uranium concentration". This is used to measure the induced track density, $P_d$, necessary to solve the Zeta Factor Equation (Hurford & Green, 1981, 1983).

Substitution of the parameters, $(P_s/P_i)_{STD}$ and $P_d$, into Equation 2 yields a single Zeta Calibration Factor. Repeating the whole process with many different 'known standard' allows the analyst to produce a personal Weighted Mean Zeta Factor, $Z_{wm}$, to correct for his ability to reproduce the known age of a standard. After evaluation of the Weighted Mean Zeta, the unknown ages of samples may be determined by substitution of the measured track densities $P_s, P_i, P_d$, in Equation 1.

Geothermometry Effects of Heat and Time on Resultant Ages

Fission track analysis is also a relatively new method of geothermometry, which takes advantage of the fact that fission tracks respond to prevailing temperatures.

Once the fission-track age has been ascertained for a given rock, it can be evaluated further by geothermetric techniques. Information about the thermal history of a vertical suite of samples is unique to fission-track dating. It is possible to date samples on a mountain from its lowest to highest elevations; or through the depths of a deep core and learn about the thermal or burial history.
Fission tracks are metastable, meaning they are gradually annealed under certain combinations of heat and time (Fleischer et al., 1965a; Gleadon & Duddy, 1980). It has been discovered that fission tracks in apatite will remain stable for extended periods of time, if once cooled (solidified below 125°C and never subjected to temperatures greater than 70°C (Dodson, 1973). If the crystals are heated above 70°C, tracks will begin to disappear. Apparently, the ions that were displaced during track formation gradually diffuse back into the track and seal it. In fission-track geothermometry the term annealing is used for this partial to complete erasure of tracks. How fast and how much they fade depends not only on temperature but the amount of exposure time at a given temperature.

In such cases, where loss of tracks has occurred, the fission-track clock will not date the original formation of the crystal but some later stage of its thermal history. As temperature increases the tracks begin to fade and eventually disappear, effectively resetting the age.

As determined experimentally, the resultant age from the Zeta Age Equation will be accepted as the time before present when the given sample is cooled through the 110°C isotherm for the last time in its history. If, however, the movement of isotherms is large such as in a period of
rapid uplift and erosion, the apatite ages from depths above the annealing zone may actually record the age of their formation while those below the isotherm record a later thermal event. It is, therefore, desirable to sample vertically as well as horizontally. Above 125°C fission tracks will be completely annealed in apatites such that no tracks remain and the age of a sample is reset to zero. From that time on any tracks formed will result in the age of the event that annealed the previous tracks but will not indicate anything about the time of rock formation (Naeser & Faul, 1969; Fleischer, Price, Walker, 1975; Faure, 1977; Gleadow & Duddy, 1981; Harrison, 1984; Green, 1985; Gleadow, Duddy, & Lovering, 1983).

Apatite is the most sensitive fission tracking mineral to temperatures that normally occur in the upper several kilometers of the earth's crust. Other minerals, however, can be used for fission tracking and can aid the understanding of the thermal history when used in addition to apatites. Minerals such as sphene and zircon are also valuable because of their ability to resist annealing at temperatures greater than apatite.

Dating several minerals by sampling over a large horizontal distance can reveal important thermal information about the site. If apatite and sphene were present in a granite that had quickly cooled but was
later intruded by a basaltic sill, their fission-track ages might reveal the following. Close to the granite-basalt contact the ages of both minerals were reset by heat from the intrusion to the age of the intrusion. A distance away from the intrusion, both minerals revealed the older age of the cooled granite showing they were not affected by the intrusion. In between these areas, the ages of the two minerals would be different. Apatite, due to its lower annealing tolerance, would have its age reset to that of the intrusion, but the age of the sphene would remain unchanged by the heat, giving the age of the granite. As in this example, it is possible to estimate the effect of temperatures in a thermal event. (For further information see Fleischer & Price, 1964b; Green, 1985).

Unfortunately, this project could not take into consideration the vertical sampling technique or the use of additional minerals so that the age and thermal history of the samples could be further evaluated.

There is another aspect to track fading, however, that has given some insight into the thermal history of the rocks studied in this project. This is the degree of track fading which occurs between 70 and 125°C and results in unique fission-track length distributions (Green, 1985).
Fission-Track Length Distributions

Important information about thermal histories can be obtained from different track lengths within a crystal. Generally, all tracks are created with the same length even though they may have been formed at different times. Track length distributions are controlled by and representative of the cooling or thermal history of a sample; this includes the effects of time as well as temperature.

Between the temperatures of 70 and 125°C, fission tracks in apatites are metastable and subject to partial annealing. Therefore, if a given proportion of tracks in a crystal are distinctly shorter than the rest of the tracks (having been partially annealed), that proportion has been influenced by a thermal event before the other tracks were formed. The degree of shortening reflects the range of thermal conditions that the shorter tracks experienced before the longer tracks were created. Regardless of the amount of shortening, the faster a crystal is cooled through its metastable zone, the more uniform the track lengths will be. The slower a crystal is cooled, the more divergent its length distribution becomes. Five types of track length distributions have been observed in crystals which are highly distinctive of their thermal histories (see Figure 1):

1. All the tracks are freshly induced by irradiation and are of maximum lengths.
2. All the tracks naturally have a uniform length exhibiting <20% shortening; e.g., undisturbed volcanics and related rocks which have cooled very rapidly and have never been significantly heated above 50°C.

3. All the tracks have been considerably shortened; e.g., undisturbed basement rocks which have not been heated above the 125°C isotherm since emplacement.

4. The tracks have a bimodal length distribution; e.g., a two stage history with alternate high and low temperature phases.

5. The tracks are of many mixed length distributions; e.g., the effects of continuous production of tracks through time.

<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>Induced</td>
</tr>
<tr>
<td>02</td>
<td>Undisturbed Volcanic</td>
</tr>
<tr>
<td>03</td>
<td>Undisturbed Basement</td>
</tr>
<tr>
<td>04</td>
<td>Bimodal</td>
</tr>
<tr>
<td>05</td>
<td>Mixed</td>
</tr>
</tbody>
</table>

Figure 1. Fission-Track Length Distributions: Five Cases Observed.


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Because of the sensitivity of apatite to moderately elevated temperatures, its fission-track ages rarely reflect the actual age of host rock formation. An exception to this, as determined by the track length distributions, is the case of 2, rapidly cooled volcanics or epizonal intrusives which have not been buried deeply (< 1 km). In this case only, the length distributions seem to be independent of ages; characterizing only the thermal history (Gleadow et al., [in press]). In order to determine whether the fission-track ages reflect the age of host rock formation, it is recommended that any age determination be complimented by a track length distribution study.

There is still much to be learned about fission-track length distributions because the concept is relatively new. There are problems which have not been solved; such as unavoidable counting bias in measuring the lengths and anisotropic annealing of tracks (Laslett, Gleadow & Duddy 1983; Green, 1981). Until this topic is more thoroughly studied, its implications will not be completely understood.
CHAPTER IV

ANALYTICAL METHODS AND RESULTS

Sampling Techniques

For a study such as this to be of maximum utility, it is important that the study area be sampled properly and that excellent laboratory techniques be maintained. These factors are extremely important in order to achieve representative samples for petrologic analysis.

In southwestern Montana, surrounding the eastern and southern margins of the Boulder batholith, horizontal sampling was employed to more fully understand the time frame of the igneous and structural evolution of the area.

Vertical sampling at each locality, however, was not undertaken and therefore the regional thermal evolution could not be fully addressed. This study did, however, successfully produce fission-track ages as well as geothermal histories for several of the igneous bodies sampled and each has been analyzed in its respective structural context.

Samples taken across the study area came from fourteen distinct igneous bodies: one from the main igneous complex called the Butte Quartz Monzonite; and,
fourteen from satellite plutons, sills and dikes (Plate 1). Some samples could not be utilized for this study. Some of them had too few apatites to date, whereas others had an abundance of apatites but too many dislocations or inclusions to make them useful for dating (Refer to Table 2 for explanations).

Table 2
List of the Samples Not Dated

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Reasons sample not dated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold Hill sill</td>
<td>Too many dislocations; too few tracks</td>
</tr>
<tr>
<td>Townsend pluton</td>
<td>Too many dislocations; too few tracks</td>
</tr>
<tr>
<td>Lone Mountain stock</td>
<td>Poor contact between mica and slide due to pinholes</td>
</tr>
<tr>
<td>North Boulder complex</td>
<td>Too many dislocations; too few tracks; highly zoned uranium</td>
</tr>
<tr>
<td>Pipestone Pass pluton</td>
<td>Poor mounts; sparse apatite</td>
</tr>
<tr>
<td>Cottonwood Canyon sill</td>
<td>Too few tracks to align mica with slide</td>
</tr>
<tr>
<td>Buton Park pluton</td>
<td>Sparse apatite</td>
</tr>
<tr>
<td>Mt. Dohtery complex</td>
<td>Sparse apatite</td>
</tr>
</tbody>
</table>

Methods of Fission-Track Dating

The first procedure in the fission-track dating is to obtain apatite separates, 90-300 um in size, from
crushed, pulverized, sieved and washed sample rock. Two heavy organic liquids, diodomethane and tetrabromoethane, in conjunction with a Franz Electromagnetic Separator were employed to separate apatites from other minerals by using density differences and magnetic properties. The apatite grains were then mounted on 27 x 46 mm slides and polished to a smooth and flat finish with a 0.3 micron Aluminum Oxide slurry to expose the internal portions of the grains. These surfaces were then etched in 5M Nitric Acid for five to ten seconds at room temperature to reveal the fission tracks within the apatites.

The crystal mounts were trimmed to 10 x 15 mm, covered with a low-uranium mica detector of the same size, and held together tightly in a small bag made of heat-shrink plastic. Individual slides were strategically stacked and packaged for irradiation. Uranium-containing glass dosimeters (SRM612) from the U.S. National Bureau of Standards were placed at the top and bottom of the stack to test for a non-uniform radiation dose. Two other tectonically unrelated but well dated age standards from Durango, Mexico and Renfrew, Canada were placed among the Montana slides.

The stack was wrapped in aluminum foil and irradiated at the Phoenix Memorial Reactor at the University of Michigan in Ann Arbor, Michigan. The wrapped slides were placed in pneumatic tubes and placed
within a few inches from the core to obtain the maximum bombardment of thermal neutrons ($2 \times 10^{13}$ neutrons/cm$^2$/second). The samples were then sent to Rensselaer Polytechnic Institute (RPI) for acid etching and microscopic analysis.

After irradiation, all slides and their complimentary mica detectors were carefully separated (see Figure 2).

Figure 2. Sample-Mica Pairs; Before and After Radiation.
The micas were then etched in 39 percent aqueous hydro­fluoric acid for about 18-20.5 minutes at room temperature. The mica, acting as a recorder (detector), revealed the fission tracks induced by irradiation of the uranium in the apatite. In this manner a comparison can be made between the spontaneous fission tracks revealed on the sample mounts and the induced fission tracks recorded on the complimentary mica detector.

The slide and mica pairs were then remounted on a standard petrographic slide, 27 x 46 mm, as mirror images and analyzed petrographically (see Figure 3).

Figure 3. Petrographic View of Sample-Mica Pairs.

For complete details on the methods used in this fission-track study refer to Gleadow, 1984.
Results: Relative Thermal-Neutron Fluence Measurements

Induced track density for the glass dosimeter standards (Pd) were counted at 1000x under dry conditions on a Leitz Ortholux TM microscope. A 5 x 5 ocular grind was produced for counting tracks by calibrating the eyepiece to a 600 lines/mm diffraction grating. Fission tracks were counted on the glass standards using a combination of transmitted and reflected light. The results are summarized on Table 3.

It was apparent from the results that the irradiated package was not uniformly irradiated. The density of tracks (Pd) in tracks/cm² is given for the glass standards at both the top and bottom of the irradiated package. A 4.2% flux per cm of package height had been induced and this thermal-neutron fluence (Q) was corrected for in the analysis of the samples (see Figure 4). Q values were adjusted accordingly for fission-track age determinations. Table 3 lists the corrected values assigned to various ample positions in the irradiated package.
<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Sample Code</th>
<th>Slide</th>
<th>Spontaneous-fission track density $P_0$ Tracks/cm$^2$</th>
<th>Induced-fission track density $P_1$ Tracks/cm$^2$</th>
<th>Thermal neutron fluence $Q$ Neutrons/cm$^2$</th>
<th>Tracks$^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brownback Sill or Diamondhead Sill</td>
<td>M01-1 / B2</td>
<td>Apatite Sample</td>
<td>8.36 x 10$^5$ 146</td>
<td>2.17 x 10$^6$ 379</td>
<td>1.397 x 10$^6$ (Pd) 4008</td>
<td>1.349 x 10$^6$(Pd) 4005</td>
</tr>
<tr>
<td></td>
<td>M01-5 / K</td>
<td>Apatite Standard</td>
<td>2.22 x 10$^5$ 105</td>
<td>1.56 x 10$^6$ 739</td>
<td>1.383 x 10$^6$ 8013</td>
<td>4.290 x 10$^6$ 8353</td>
</tr>
<tr>
<td>10-N Pluton</td>
<td>M01-6 / 10-1</td>
<td>Apatite Sample</td>
<td>3.56 x 10$^5$ 313</td>
<td>7.56 x 10$^5$ 665</td>
<td>1.380 x 10$^6$ 8013</td>
<td>4.330 x 10$^6$ 8353</td>
</tr>
<tr>
<td>Butte Quartz Monzonite</td>
<td>M01-8 / 4</td>
<td>Apatite Sample</td>
<td>9.90 x 10$^5$ 421</td>
<td>3.01 x 10$^6$ 1280</td>
<td>1.373 x 10$^6$ 8013</td>
<td>4.380 x 10$^6$ 8353</td>
</tr>
<tr>
<td>Renfrew, Canada</td>
<td>M01-9 / 62</td>
<td>Apatite Standard</td>
<td>3.15 x 10$^5$ 621</td>
<td>3.86 x 10$^6$ 761</td>
<td>1.369 x 10$^6$ 8013</td>
<td>4.380 x 10$^6$ 8353</td>
</tr>
<tr>
<td>Hell Canyon Pluton</td>
<td>M01-14 / H-1</td>
<td>Apatite Sample</td>
<td>6.19 x 10$^5$ 286</td>
<td>2.08 x 10$^6$ 962</td>
<td>1.353 x 10$^6$ 8013</td>
<td>4.410 x 10$^6$ 8353</td>
</tr>
<tr>
<td>Rader Creek Pluton</td>
<td>M01-15 / R</td>
<td>Apatite Sample</td>
<td>1.48 x 10$^6$ 864</td>
<td>4.56 x 10$^6$ 2671</td>
<td>1.350 x 10$^6$ 8013</td>
<td>4.350 x 10$^6$ 8353</td>
</tr>
<tr>
<td>Rader Creek Pluton</td>
<td>M01-4 / 10-8</td>
<td>Apatite Sample</td>
<td>9.36 x 10$^5$ 75</td>
<td>3.28 x 10$^6$ 263</td>
<td>4.310 x 10$^6$ 8353</td>
<td>4.310 x 10$^6$ 8353</td>
</tr>
<tr>
<td>Lone Mountain Stock</td>
<td>M01-16 / L-2</td>
<td>Apatite Sample</td>
<td>3.56 x 10$^5$ 161</td>
<td>1.15 x 10$^6$ 504</td>
<td>1.347 x 10$^6$ 8013</td>
<td>4.470 x 10$^6$ 8353</td>
</tr>
<tr>
<td>Rattlesnake Butte Pluton</td>
<td>M01-11 / T-1</td>
<td>Apatite Sample</td>
<td>3.21 x 10$^5$ 58</td>
<td>6.53 x 10$^5$ 118</td>
<td>1.363 x 10$^6$ 8013</td>
<td>4.460 x 10$^6$ 8353</td>
</tr>
<tr>
<td>Sample Name</td>
<td>Sample Code</td>
<td>Slide</td>
<td>Fission Track</td>
<td>2s T</td>
<td>2s T</td>
<td>2s T</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>-------------</td>
<td>-----------------</td>
<td>---------------</td>
<td>------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>SRM612-1  Neutron Dosimeter</td>
<td>---</td>
<td>---</td>
<td>88.6</td>
<td>17.4</td>
<td>71.7</td>
<td>106</td>
</tr>
<tr>
<td>SRM12-2  Neutron Dosimeter</td>
<td>---</td>
<td>---</td>
<td>102.0*</td>
<td>48.2</td>
<td>53.8</td>
<td>150.2</td>
</tr>
<tr>
<td>Brownback Sill or Diamondhead Sill</td>
<td>M01-1 / B-2  Apatite Sample</td>
<td>---</td>
<td>102.0*</td>
<td>48.2</td>
<td>53.8</td>
<td>150.2</td>
</tr>
<tr>
<td>Durango, Mexico</td>
<td>M01-5 / K  Apatite Standard</td>
<td>31.2</td>
<td>6.8</td>
<td>24.4</td>
<td>38.0</td>
<td>177</td>
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<tr>
<td>10-N Pluton</td>
<td>M01-6 / 10-1 Apatite Sample</td>
<td>110.0</td>
<td>15.4</td>
<td>94.6</td>
<td>125.4</td>
<td>428</td>
</tr>
<tr>
<td>Butte Quartz Monzonite</td>
<td>M01-6 / 4  Apatite Sample</td>
<td>75.5</td>
<td>8.6</td>
<td>66.9</td>
<td>84.1</td>
<td>306</td>
</tr>
<tr>
<td>Renfrew, Canada</td>
<td>M01-9 / 62 Apatite Standard</td>
<td>195.0</td>
<td>21.6</td>
<td>173.4</td>
<td>216.6</td>
<td>96</td>
</tr>
<tr>
<td>Hell Canyon Pluton</td>
<td>M01-14 / H-1 Apatite Sample</td>
<td>68.5</td>
<td>9.4</td>
<td>59.1</td>
<td>77.9</td>
<td>225</td>
</tr>
<tr>
<td>Rader Creek Pluton</td>
<td>M01-15 / R  Apatite Sample</td>
<td>75.7 Mean Age*</td>
<td>8.8</td>
<td>66.9</td>
<td>84.5</td>
<td>287</td>
</tr>
<tr>
<td>Rader Creek Pluton</td>
<td>M01-4 / 10-B Apatite Sample</td>
<td>73.5*</td>
<td>19.4</td>
<td>54.1</td>
<td>92.9</td>
<td>39</td>
</tr>
<tr>
<td>Lone Mountain Stock</td>
<td>M01-16 / L-2 Apatite Sample</td>
<td>73.2</td>
<td>13.4</td>
<td>59.8</td>
<td>86.6</td>
<td>214</td>
</tr>
<tr>
<td>Rattlesnake Butte Pluton</td>
<td>M01-11 / T-1 Apatite Sample</td>
<td>114.0</td>
<td>36.6</td>
<td>77.4</td>
<td>150.6</td>
<td>93</td>
</tr>
</tbody>
</table>

* R.P.I. analysis by R.A. Donelick; CN1 dosimeter; Zeta = 120.
* R.P.I. analysis by D.S. Miller; CN1 dosimeter; Zeta = 120.6 +/- 1.3.
* Number of tracks counted to determine the reported track density.

Ppm Parts per million.
Myr Million years.
Figure 4. Determination of Gradient on Irradiation Cylinder

Results: Individual and Weighted Mean Zeta Calibration Factor

All individual zetas and track counts were made at 1600X under dry conditions on a Leitz Ortholux TM microscope. Tracks were counted using both transmitted and reflected light.

From the individually calculated zetas a Weighted Mean Zeta Factor, Zwm, of 342.26 +/- 9.98 was obtained. This corresponds to a 2.92% error, from the theoretical ideal of 350. The personal Zwm of the investigator was used in calculating the apatite fission-track ages in Table 3 (Hurford & Green, 1981, 1983).
Results: Measurements of Uncertainty

All zeta and age determinations were calculated using the statistical techniques as developed by Green (1981). See Hurford and Gleadow, 1977; Hurford and Green 1981a, 1981b, 1982, 1983 for additional information on other fission-track parameters.

Methods of Fission-Track Length Distributions

The length of individual fission tracks was measured on the same sample slides used in the dating process. A Zeiss, MOP-3 TM, digitizing pad and a tracing tube affixed to a Leitz 12 TM microscope allowed the simultaneous observation and measurement of confined tracks (completely enclosed) at 1250X under dry conditions.

Results: Fission-Track Length Distributions

Annealed standards contain apatite crystals with completely annealed (healed) fission tracks. After being annealed, spontaneous fission will occur from the apatite's uranium and produce new tracks. Fresh tracks are a maximum length to which other samples with partially annealed tracks (shorter in length) can be compared.

Two annealed standards as well as four other commonly studied standards were compared with the Montana
fission-track length distributions (FTLD's). Because of the different methods employed in these length measurements as opposed to fission-track age determinations, two Montana samples were used in the track length study which were not dated. These two exceptions are samples from the Gold Hill sill and the Townsend pluton.

The orientation of the mounted crystals as viewed under the microscope is an important factor in track-length measurements. According to Gleadown et al, (in press) and Donelick (1986), distributions measured parallel to the c-axis exhibit the longest and most consistent average track lengths within a crystal. Because of the anisotropy associated with track lengths at various crystallographic orientations, only those crystals viewed with tracks roughly parallel to the c-axis were studied.

The resultant data for fission-track length distributions is shown on Table 4.
<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Track Length Average UM</th>
<th>Track Length Average +/- 1s UM</th>
<th>Skewness of tracks UM</th>
<th>Kurtosis of tracks UM</th>
<th>Number of tracks counted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brownback Sill or Diamondhead Sill</td>
<td>15.52</td>
<td>1.01</td>
<td>-0.387</td>
<td>3.636</td>
<td>101</td>
</tr>
<tr>
<td>10-N Pluton</td>
<td>14.63</td>
<td>1.17</td>
<td>-0.075</td>
<td>2.179</td>
<td>40</td>
</tr>
<tr>
<td>Butte Quartz Monzonite</td>
<td>14.82</td>
<td>0.86</td>
<td>-0.014</td>
<td>2.798</td>
<td>101</td>
</tr>
<tr>
<td>Hell Canyon Pluton</td>
<td>14.56</td>
<td>0.92</td>
<td>+0.203</td>
<td>3.127</td>
<td>101</td>
</tr>
<tr>
<td>Rader Creek Pluton (R)</td>
<td>14.47</td>
<td>0.81</td>
<td>+0.194</td>
<td>2.770</td>
<td>112</td>
</tr>
<tr>
<td>Rader Creek Pluton (10-B)</td>
<td>14.45</td>
<td>0.75</td>
<td>+0.279</td>
<td>3.587</td>
<td>104</td>
</tr>
<tr>
<td>Long Mountain Stock</td>
<td>14.62</td>
<td>1.11</td>
<td>-0.105</td>
<td>3.052</td>
<td>79</td>
</tr>
<tr>
<td>Rattlesnake Butte Pluton</td>
<td>15.02</td>
<td>0.85</td>
<td>-0.261</td>
<td>3.539</td>
<td>70</td>
</tr>
<tr>
<td>Gold Hill Sill or</td>
<td>14.35</td>
<td>1.15</td>
<td>-0.535</td>
<td>4.343</td>
<td>102</td>
</tr>
<tr>
<td>Townsend Pluton</td>
<td>14.65</td>
<td>0.70</td>
<td>-0.347</td>
<td>2.239</td>
<td>13</td>
</tr>
<tr>
<td>Annealed Durango (8122-3)</td>
<td>16.49</td>
<td>0.91</td>
<td>+0.127</td>
<td>3.080</td>
<td>100</td>
</tr>
<tr>
<td>Annealed Renfrew (8462-1)</td>
<td>16.47</td>
<td>0.91</td>
<td>+0.415</td>
<td>3.610</td>
<td>100</td>
</tr>
</tbody>
</table>
CHAPTER V

DISCUSSION OF RESULTS

Fission-Track Length Distributions

As discussed earlier, the Montana samples were compared to freshly induced fission tracks of natural apatites. Results from Table 4 show that tracks that are induced have a narrow and symmetrical track length distribution; mean length = 16.5 um and standard deviation = +/- 0.9 um. This is in good agreement with that measured by Gleadow et. al., (in press) where the mean length = 16.3 um and standard deviation = +/- 0.9 um.

The Montana fission-track length distributions are all very similar to those described by Gleadow et. al., (in press) as volcanic and related rocks which have cooled very rapidly, never having been significantly reheated above 50°C (Figure 5).

Statistical analysis of the Montana FTLD's show a mean length of 14.4 um and a standard deviation, +/- 0.9 um. The FTLD's are narrow, unimodel and symmetrical but the mean length is up to 21% shorter than that for induced tracks from annealed standards (Figure 6, statistical data on FTLD's). Twenty percent reduction in
Figure 5. Fission-Track Length Distributions.
A.- Five Cases Observed by Gleadow et al. (in press)
B.- Montana Samples.
maximum amount determined before there is any measurable reduction in fission-track ages (Gleadow et. al., 1983). This, and the fact that the standard deviation is less than one, lends confidence to the ages of the Montana samples.

Figure 6. Track Length Distributions for Annealed Standards and Samples
The uniformity among the Montana samples suggests a similar thermal relationship between them. It is, therefore, probable that all the samples experienced one and the same tectonic event in which the magma rose quickly to a very shallow depth and cooled rapidly. This is a significant finding in this study because it is only among the undisturbed volcanic-type FTLD's that the fission-track ages can be assumed to actually represent the age of rock formation and not some secondary thermal event (Gleadow et. al., in press).

This idea gives credibility to the fission-track ages obtained. It also implies that the ages will be concordant with those of other isotopic studies (Table 5).

One last point of interest, the FTLD study clearly shows the samples from the Boulder batholith, namely Rader Creek and Butte Quartz Monzonite, and the nearby Hell Canyon pluton have distributions positively skewed. Those further away from the batholith, the samples; 10-N, Lone Mountain, Rattlesnake, Townsend, Brownback and Gold Hill; are negatively skewed. Although the implication is unclear, the mean length of the fission tracks appear to be slightly less in samples farthest away from the Boulder batholith.
Table 5

Fission-Track Ages and K-Ar References

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Fission Track Dates</th>
<th>Nearby K-Ar Dates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T unknown</td>
<td>Pooled Ages</td>
</tr>
<tr>
<td></td>
<td>Myr</td>
<td>Myr</td>
</tr>
<tr>
<td>Brownback Sill</td>
<td>80.0</td>
<td>8.7</td>
</tr>
<tr>
<td></td>
<td>102.0</td>
<td>24.1</td>
</tr>
<tr>
<td>10-M Pluton</td>
<td>81.6</td>
<td>17.5</td>
</tr>
<tr>
<td>Butte Quartz Monzonite</td>
<td>75.5</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>70.4</td>
<td>7.2</td>
</tr>
<tr>
<td>Hell Canyon Pluton</td>
<td>69.5</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>67.6 Mean Age</td>
<td>14.4</td>
</tr>
<tr>
<td>Rader Creek Pluton</td>
<td>75.7 Mean Age</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>74.0</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td>60.9</td>
<td>5.6</td>
</tr>
<tr>
<td>Rader Creek Pluton</td>
<td>76.5</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>73.0</td>
<td>7.7</td>
</tr>
<tr>
<td></td>
<td>94.4</td>
<td>10.7</td>
</tr>
<tr>
<td>Rattlesnake Butte Pluton</td>
<td>114.0</td>
<td>18.3</td>
</tr>
</tbody>
</table>

Nearby K-Ar Dates

- Tobacco Rost Batholith: zircon=68 (Pb-alpha) [K5]
- Tobacco Rost Batholith: biotite=75 [K6]
- Sand Creek Sill: biotite=106 +/- 6 [K7]
- Sampled area: biotite=72.9, hornblende=71.2; +/- 3.6
- Hell: biotite=72.7 +/- 3.0, hornblende=75.5 +/- 2.4 [K8]
- General pluton: 73.2 +/- 1.0 [K3]
- Sampled area: biotite=70.0 +/- 3.5 [K2]
- General pluton: 72.0 +/- 2.7 [K2]
- Sampled area: biotite=72.0 +/- 3.6 [K2]
- General pluton: 75.0 +/- 3.3 [K2]
- Sampled area: biotite=73.9 +/- 3.7 [K2]
- Elkhorn Mt. Volcanics north of pluton: biotite=73.5 +/- 2.9 [K2]

# R.P.I. analysis by R.A. Donelick; CnI dosimeter
# R.P.I. analysis by O.E. Miller; CnI dosimeter
# Reported by Tilling, Klepper, and Erb (1963)
# Reported by Hsu (1960) and MDow (1966)
# McCandless (1964)
# Jeffs and Carothers, 1959
# Jaffe (1965)
# Daugherty and Vitaliano (1969)
# Myr, Million years
Fission-Track Ages

Because of the volcanic-like FTLD's observed in the samples, the resultant fission-track ages are assumed to reflect the formation age of the plutons. The tight grouping of ages and the fact that all but one passed Galbrith's chi squared test (Green, 1981) indicates the ages are reliable (Table 3).

Resultant ages of the selected plutons are given in Table 5. They range in age from 68.5 to 114.0 Ma. These plutons are either part of the Boulder batholith or satellites of the batholith, which were emplaced 69-78 Ma (Robinson, Klepper, Obradovich, 1968; Tilling, Klepper, Obradovich, 1968), 68-78 Ma (Hanna, 1973), 70-78 Ma. (Knopf, 1964) with the majority being crystallized between 72-78 Ma.

Measured ages are only significant within the range of two standard deviations. This means that an exact date of formation can not be produced with this method, but, the confidence interval in which the date lies, can be.

Four controlling factors were interwoven in this study, and, as discussed below, they each lend credibility to the ages obtained. First, the analyst's personalized Weighted Mean Zeta Factor used to correct for analytical errors, was 342. This was achieved after 23 analyses of age standards and is considered very good.
when compared to the theoretical ideal of 350. Essentially it lends confidence to the petrographic results.

Secondly, both age standards, Renfrew and Durango, irradiated with the Montana samples and analyzed with the Weighted Mean Zeta of 342 are in excellent agreement with those dated at RPI. This indicates the Montana samples have not been processed in any significantly different manner than those of RPI's.

Thirdly, RPI took separates from the Montana samples and packaged, irradiated and analyzed them independently. Their results are in agreement with this study except for the age of 10-N pluton. The only noticeable difference is that the RPI ages have a much larger standard deviation because they are based on fewer grain counts.

Lastly, knowing that Butte Quartz Monzonite has been previously dated several times by Potassium-Argon (K-Ar) Methods (Table 5), it was intentionally placed among the samples and used as a standard or reference with which the samples could be compared.

In conclusion, all of the Montana age analyses seem reliable except that of Rattlesnake Butte which is discussed in the following section.

**Individual Pluton Ages**

For sample rock types and their inferred relationship to thrusting refer to Table 1. See Figure 7 for a fission-track age comparison among the Montana samples.
Figure 7. Montana Fission-Track Ages

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Brownback Sill

The Brownback sill is a uniform, silicic quartz monzonite that intruded into Cambrian rocks. It appears to be tectonically folded with the surrounding rock, but this is unproven (Schmidt, 1976; Smith, 1970). If it has been folded, then it was emplaced before folding and thrusting, and therefore, before the Lombard thrust sheet was emplaced. This means the age of the Brownback sill probably provides a pre-thrusting age limitation.

The fission-track age is 88.6 +/- 17.4 Ma (all dates are given with 2 standard deviations) suggesting that this sill was emplaced before or during Late Cretaceous deformation (68-78 Ma). The samples analyzed at RPI also confirm this.

10-N Pluton

The quartz monzonite sample taken from the 10-N pluton (a composite pluton) extends beneath 10-N highway near Three Forks (Schmidt & O'Neill, 1982; Robinson, 1963). Its close proximity to the leading edge of the Lombard thrust sheet is interesting but inconclusive. The fission-track age for this rock is 110 +/- 15.4 Ma, which implies that it was emplaced prior to deformation. The age from RPI (81.6 +/- 35.0 Ma), however, expands from pre-deformation through the deformation period. The
fission-track ages of the 10-N pluton are therefore considered to be ambiguous.

Butte Quartz Monzonite

The Butte Quartz Monzonite sample is part of the main magma series making up the majority of the Boulder batholith. Its emplacement has been dated 72-75 Ma by K-Ar studies (Tilling et al., 1968; McDowell, 1966, 1971). Its relationship to the Lombard thrust is uncertain but according to Knopf (1968), it is at least post-volcanic. This sample was chosen as a standard to which the Montana sample results could be compared. The fission-track age, 75.5 +/- 8.6 Ma, closely corresponds to the K-Ar age and is also supported by that of RPI. If this age is reasonable then it means this sample was emplaced while deformation was taking place.

Hell Canyon Pluton

The Hell Canyon pluton is a homogeneous, leucocratic, quartz monzonite, derived from a late phase magma (Lambe, 1981). It was emplaced into the Camp Creek fault which is the westward continuation of the Jefferson Canyon fault zone and is the southwestern trace of the Lombard thrust sheet (Schmidt & O'Neill, 1982). The Hell Canyon pluton, therefore, provides a post-Lombard age limitation needed for this study.
The fission-track age is 68.5 +/- 9.4 Ma. This date is comparable with 70-74 Ma from McMannis (1963) and Tilling et al., (1968). It agrees with the magmatic information from Lambe (1981) as well as the fission-track ages from RPI, 67.6 +/- 28.8 Ma. This pluton is apparently post-deformation.

Rader Creek Pluton

The Rader Creek pluton is made of granodiorite but grades to quartz monzonite. It is compositionally related to the pre-batholith volcanics and actually contains mafic pipes within it. It is probably one of the earliest, less felsic plutons to be emplaced (Lambe, 1981; Tilling et al., 1968). Because it is also intruded by the Butte Quartz Monzonite it is considered pre or syn Lombard in age.

The Rader Creek pluton was dated once in this study and twice by RPI using rocks from different locations. All analyses were agreeable and confirmed the fission-track age of 75.7 +/- 8.8 Ma. Other isotopic studies gave ages that lie between 74 and 75 Ma (Lambe, 1981). This means the Rader Creek pluton was emplaced early in the deformation sequence and was most likely emplaced prior to or during thrusting.
Lone Mountain Stock

The Lone Mountain stock, between Radarsburg and Three Forks, is a quartz monzonite with a fine grained equivalent around its margin, indicative of rapid cooling. It intrudes the pre-batholithic volcanics and is believed to intrude Paleozoic rocks which were previously subjected to the main phase of folding. This indicates they were probably emplaced sometime during or after movement of the Lombard thrust.

The fission-track age is 73.2 +/- 13.4 Ma which is backed by the analysis at RPI. There are no other studies with which to compare this date, but the data suggests the stock was emplaced at some time during or after deformation, perhaps while movement occurred along the Lombard thrust plane.

Rattlesnake Butte Pluton

The Elkhorn Mountain volcanics are intruded by Rattlesnake Butte pluton, a compositional equivalent of the volcanics (Tilling, 1974). Its fine grained texture is a result of its emplacement at shallow depths followed by rapid cooling. It could be a feeder for the volcanics but the evidence to confirm this is lacking. It is post-volcanic and most likely pre-deformation and pre-thrusting in age. There is no evidence that it has been folded or faulted but it was intruded into the post-
The fission-track date for this pluton is 114 +/- 18.3 Ma, (77.4-150.6 Ma) suggesting a pre-thrusting age, but certainly too general to base any conclusions. According to Chardwick (1971) the volcanics erupted from 84 to 74 Ma with the majority extruded at 78 Ma (Robinson et al., 1968). There are no other radiometric studies available to which this fission-track age can be compared. The fission-track age was difficult to achieve on this particular sample and will not be used to address the age of the Lombard thrust.

**Gold Hill Sill**

The Gold Hill sill, a uniformly porphyritic granodiorite appears to be magmatically related to the Tobacco Root batholith dated at 75 Ma. The sill was emplaced concordantly along a plane of weakness within the Middle Proterozoic LaHood Formation. It was later folded along with the surrounding rocks into an anticline (Capozza, 1967; Burfield, 1967). There is textural evidence that it cooled slowly at great depth and then was quenched rapidly near the surface. It is pre-thrusting in age. This pluton was too difficult to evaluate for age by fission-tracking methods but the track length distributions confirm its cooling history and relationship to the plutons sampled.
**Townsend Pluton**

Like Rattlesnake Butte, the Townsend pluton is a compositional equivalent of the volcanics (Tilling, 1974). It was emplaced as a sill in Paleozoic rocks before the culmination of Late Cretaceous - Early Paleocene folding and faulting. It has been faulted and is assumed to be pre-thrusting in age. Jaffe, Gottfried, Waring, Worthing (1959) have dated it to be 72-76 Ma.

As with Gold Hill, sill, the Townsend pluton was much too difficult to date by fission tracking. The track length distributions do, however, infer that this sample is thermally related to the other plutons and was brought to a shallow depth and cooled quickly.

**Other Plutons**

Fission-track age dating was attempted on several other plutons. Unfortunately, for the various reasons given in Table 3, they were eliminated throughout the process.

**Determination of the Timing of Movement Along the Lombard Thrust**

As discussed earlier, by obtaining the age of several plutons with known relationships to the Lombard thrust, it is possible to narrow the time range in which movement occurred along its fault plane. Constraints on
the timing of movement were made by plutons known to be pre or post thrusting (deformation). Timing for movement along the Lombard thrust plane was bracketed between the pre-thrusting and post-thrusting plutons, and, by averaging the ages of the plutons thought to be intruded while thrusting took place. The timing of movement was determined to be 73.2 +/- 6.7 Ma or 66.5 - 79.9 Ma. This indicates that thrusting along the Lombard thrust plane occurred approximately the same time the Boulder batholith was being intruded (68-78 Ma).
CHAPTER VI

SUMMARY

The objectives of this study have been met. Several plutons in and adjacent to the Lombard thrust have been dated by fission track analysis and the timing of movement along the Lombard thrust plane has been narrowed using the resultant ages.

The resultant FTLD's of the Montana samples indicate that all the samples are thermally related and fit the "undisturbed volcanic-type" rocks as discussed in Gleadow et al., (in press). This specific type of FTLD implies these igneous bodies ascended quickly to a shallow depth of the earth's crust and cooled rapidly.

Statistical treatment of the data indicates that the results are reliable. The fact that the Montana samples were determined to be the "undisturbed volcanic-type" means their fission-track ages probably represent the age of rock formation and not some later thermal event. One point of interest in the FTLD study shows the samples from the Boulder batholith have positively skewed distributions while those further away from the batholith are negatively skewed. The mean length of the fission tracks also appears to be slightly less in samples farthest away from the Boulder batholith.
Results of the fission-track dating analyses correlate well with those of other earlier radiometric studies. The ages of the Montana plutons range from Early Cretaceous to middle Paleocene time; five of which extend from Late Cretaceous to Early Paleocene and two of which are dated from Early to Late Cretaceous (Figure 6). Clearly, the relationships of the ages to the structural features of the plutons delineate a time frame in which movement along the Lombard thrust sheet took place. The data indicate the Lombard thrust was emplaced 73.2 +/- 6.7 Ma (66.5-79.9 Ma).

The similar timing of thrusting and the crystallization of the Butte Quartz Monzonite (68-78 Ma) suggests a close association between the two. Apparently some plutonic activity preceded thrusting but also continued after thrusting as proposed by Schmidt and O'Neill (1982).

The results of this study exemplify the manner in which tectonic features, like the Lombard thrust fault can be dated indirectly using fission-track geochronology. In addition to this the fission-track method has the ability to give some additional information about the thermal history of the samples which other dating processes do not.
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**LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS**

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EXPLANATION

ROCK UNITS

PLEISTOCENE SEDIMENTARY UNITS
TERTIARY SEDIMENTARY UNITS
TERTIARY INTRUSIVES
TERTIARY EXTRUSIVES

CRETACEOUS INTRUSIVES
(Quartz Monzonite & Granodiorite)

CRETACEOUS EXTRUSIVES

CRETACEOUS SEDIMENTARY UNITS

JURASSIC SEDIMENTARY UNITS

PENNYSYLVANIAN - PERMIAN SED. UNITS

MISSISSIPPIAN SEDIMENTARY UNITS

CAMBRIAN - DEVONIAN SED. UNITS

PRECAMBRIAN BELT SUPERGROUP
PRECAMBRIAN BE  
SEDIMENTARY UNITS

PRECAMBRIAN CRYSTALLINE BASEMENT  
AND METAMORPHICS (Pre-Beltian)

--- Township and Section Lines
--- Formation Contact
--- Fault
--- Fault - u, upthrown side
d, downthrown side
--- Fault, Thrust - Sawtooth on upper plate

10 Interstate Highway
20 State Highway
30 U.S. Highway

Town

Sample Location:
1 - Townsend Pluton
2 - Rattlesnake Butte Pluton
3 - Lone Mountain Pluton

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PLATE I - GENERALIZED GEOLOGIC
Sample Location:

1 - Townsend Pluton
2 - Rattlesnake Butte Pluton
3 - Lone Mountain Pluton
4 - North Boulder Complex
5 - IO-N Pluton
6 - Mt. Dohtery Complex
7 - Cottonwood Canyon Sill
8 - Pipestone Pass Pluton
9 - Burton Park Pluton
10 - Butte Quartz Monzonite
11 - Radar Creek Pluton
12 - Hell Canyon Pluton
13 - Gold Hill Sill
14 - Brownback Sill