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Fission track and K-Ar dates on the northeastern border zone of the Idaho batholith

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FISSION TRACK AND K-Ar DATES ON THE NORTHEASTERN BORDER ZONE OF THE IDAHO BATHOLITH

By

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Chapter 1

INTRODUCTION

This study used fission track and potassium-argon age dating techniques as an aid in deducing the tectonic and thermal history of a complex plutonic-metamorphic terrain. The area selected for the study is adjacent to the Idaho batholith and was chosen because it is relatively complex geologically and the age or ages of intrusion and metamorphism are questionable. About 100 miles west of the present study area near St. Joe, Idaho, Reid and Greenwood (1968) have recognized four periods of metamorphism; two Precambrian, one Paleozoic, and one Mesozoic. Other geologists consider that the high grade metamorphism surrounding the batholith is Mesozoic, the batholith itself having been derived by anatexis of these rocks. There also exists a fairly consistent pattern of 40-50 million year dates obtained by various workers on rocks of the easternmost portion of the Idaho batholith (Hayden and Wehrenberg, 1960; McDowell and Kulp, 1969; Armstrong and Rychner, unpublished report) (Fig. 1). In this study an attempt was made to date and interpret only the two final events which occurred in this area.

To accomplish this, a broad line of samples was collected starting on the northeast corner of the batholith and extending north into the metamorphic rocks. From these samples, fourteen fission track age determinations were made on apatite and three on sphene. Potassium-argon dates were obtained on biotite from two localities.

In these methods of radiometric dating, the ages determined are a measure only of the time since the particular mineral or rock being dated cooled enough to retain its daughter product. Further, this "clock" may be reset either partially or wholly by subsequent thermal events which tend to remove the daughter product from the system. These thermal events are especially amenable to detection using fission track dates on apatite since this mineral begins to lose fission tracks (i.e., daughter product) if maintained at about 40°C for one million years and can be completely annealed (reset) by maintaining it at about 150°C for the same period of time (Naeser and Dodge, 1969) (Fig. 4). Sphene, on the other hand, must be maintained at temperatures of about 220°C for one million years before a loss of fission tracks will become apparent, and temperatures slightly in excess of 400°C are required to reset completely its radiometric clock. Apatite therefore provides an extremely sensitive indicator of thermal environment and history, whereas sphene gives less sensitive, but equally revealing information of this sort. If, as above, apatite were maintained at temperatures in excess of 150°C through burial (e.g., about six km assuming a geothermal gradient of 25°C/km), it becomes theoretically possible to date tectonic uplift of an area given sufficient vertical movement to bring apatite into a thermal domain compatible with fission track retention. Similar reasoning may be applied to fission track dates on sphene and to potassium-argon dates in general, the only difference being the temperature or depth of burial required to make the mineral an open system with regard to its daughter product. Further, it is possible to show poly-metamorphic events if discordant fission track or fission track K-Ar dates are obtained on different minerals from the same rock (e.g., one metamorphism dated by sphene, and a subsequent "weaker" event which selectively reset the apatite while not affecting the sphene). Note that in order to detect poly-metamorphic events by this method the latter metamorphism must have been less intense than the former.

Chapter 2

PREVIOUS GEOCHRONOLOGICAL AND STRUCTURAL STUDIES

Idaho Batholith

Lead-alpha dates by Larsen et al. (1958), Larsen and Schmidt (1958), and Chapman et al. (1955) seem to indicate at least two stages of intrusion of the Idaho batholith. Nineteen such ages on zircon, xenotime, thorite, and monazite from various batholithic rocks give an average of 108 ± 12 m.y. (Larsen et al., 1958), whereas seven dates on zircon and monazite from a quartz monzonite in Lost Horse Canyon, Montana yield an average age of 57 m.y. (Larsen and Schmidt, 1958). Chapman et al. (1955) dating a gneissic quartz monzonite from this same location report ages of 51 m.y. and 54 m.y. from monazite and sphene respectively. Fifty miles north of this location in Bass Canyon, Hayden and Wehrenberg (1960) report ages of 40.5 m.y. and 39.9 m.y. determined by the potassium-argon method on biotite extracted from a pegmatite of presumed metamorphic origin. McDowell and Kulp (1969) show three distinct age groupings of the batholith rocks (Fig. 1) determined by the potassium-argon method; these three groupings are (1) 44-38 m.y. (Upper Eocene); (2) 77-49 m.y. (Late Cretaceous-Middle Eocene); (3) 156-115 m.y. (Pre and Middle Cretaceous). McDowell and Kulp believe the primary igneous activity to have occured at about 125 m.y. or Early Cretaceous.

Armstrong and Rychner (unpublished report) again using the potassium-argon method show a trend of ages becoming progressively younger from northwest to southeast (Fig. 1). This trend appears to be general for most dates in this area, and may in fact be significant in the final interpretation of this body of data.

Metamorphic Rocks

Reid and Greenwood (1968) through structural considerations and isotopic dates attempt to show four periods of metamorphism in the St. Joe area of Idaho. They suggest the following:

(1) A metamorphism and deformation 1200 m.y. ago as determined by common lead dates on zircon and the age (method unknown) of a diabase dike which postdates the metamorphic rocks.

(2) A metamorphism and deformation 670 m.y. ago as determined by K-Ar dates on hornblende from a diabase injected and metamorphosed late in a structural event that postdates the 1200 m.y. event mentioned above.

(3) A metamorphism and deformation 300 m.y. ago as determined by K-Ar dates on a "metasomatically introduced potassium feldspar" in a bleached fault zone.

(4) A metamorphism and deformation 172 m.y. ago as determined by K-Ar dates on hornblende from an amphibolite.

Common lead determinations on galena and pitchblende from the Coeur D'Alene mining district of Idaho yield ages of 1035 m.y. (Eckelmann and Kulp, 1957), 1190 m.y. (recalculated from 1952 data of Kerr and Kulp by Eckelmann and Kulp, 1957) and 1400 m.y. (Long, Silverman, and Kulp, 1960). This galena and pitchblende mineralization postdates the deformation and metamorphism in the surrounding

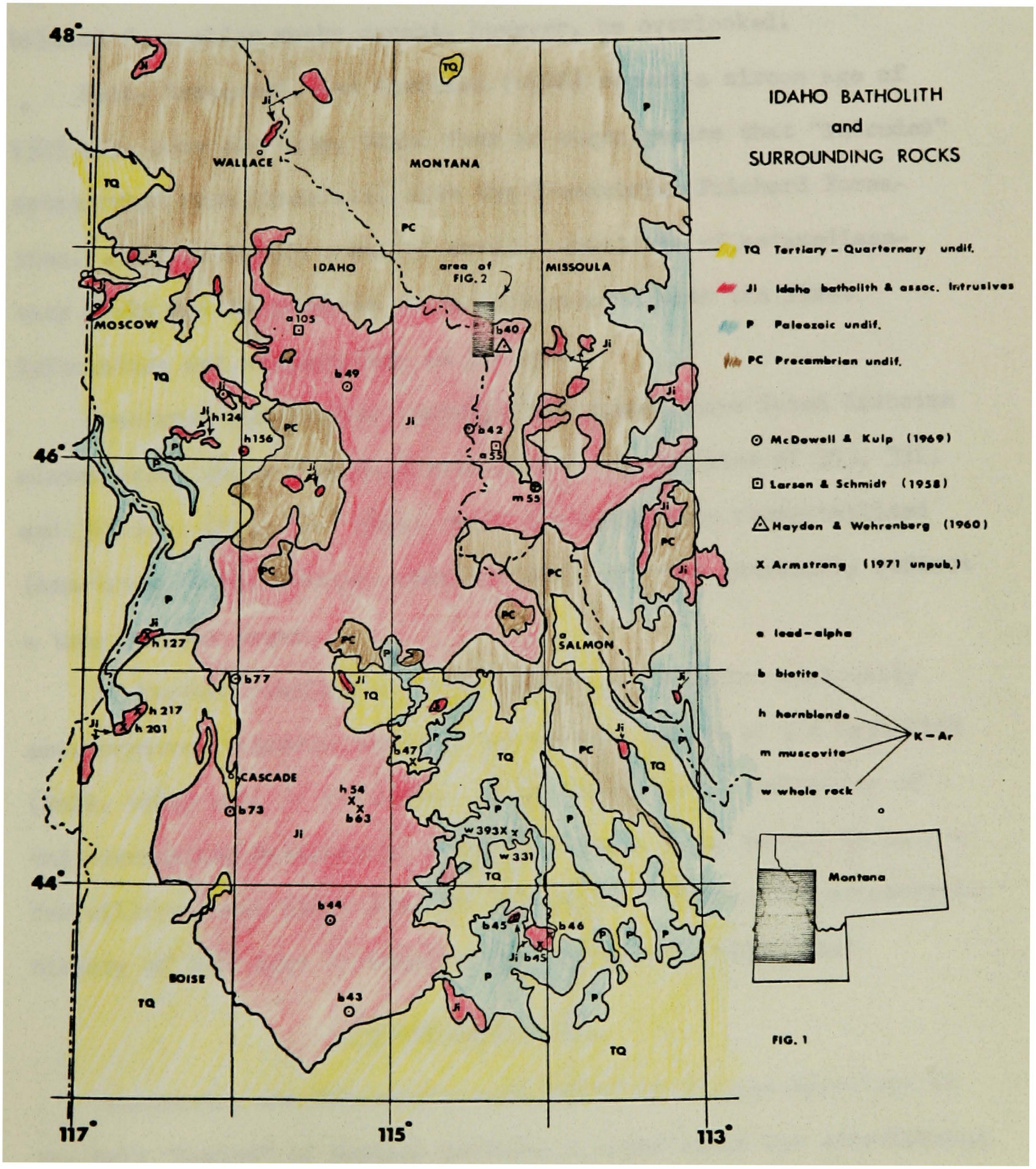

IDAHO BATHOLITH
and
SURROUNDING ROCKS
TQ Tertiary - Quarternary undif.
Ji Idaho batholith & assoc. intrusives
P Paleozoic undif.
PC Precambrian undif.
⊙ McDowell & Kulp (1969)
⊡ Larsen & Schmidt (1958)
△ Hayden & Wehrenberg (1960)
X Armstrong (1971 unpub.)
a lead-alpha
b biotite
h hornblende
m muscovite
w whole rock
K-Ar
Montana
WALLACE
MONTANA
IDAHO
MISSOULA
MOSCOW
SALMON
CASCADE
BOISE
area of FIG. 2
48°
46°
44°
117°
115°
113°

FIG. 1

Belt rocks. The possibility that this is lead more recently remobilized from older rocks cannot, however, be overlooked.

Reid, Greenwood, and Morrison (1970) report a zircon age of 1525 m.y. near Elk City, Idaho from an augen gneiss that "intrudes" metamorphic rock correlated with the Precambrian Prichard Formation. This intrusion contains rotated xenoliths of metasedimentary rocks and is presumed to be synkinematic with the first deformation and metamorphism in the area.

Armstrong and Rychner (unpublished report) have dated Cambrian slates using whole rock K-Ar methods and report dates of 393, 331, and 343 m.y. (Fig. 1). These rocks are completely recrystallized (Armstrong, 1971, written communication) and thus presumably reflect a true thermal event.

To further complicate the situation, there exist regionally metamorphosed Triassic rocks on the western margin of the batholith (Nold, 1968) and, if the batholith is an anatectic derivative of the surrounding metamorphic rocks then these rocks should be only a few million years older than the batholith. Clearly the metamorphic history of this area is complicated and not well understood.

Sedimentary Rocks

Obradovich and Peterman's work (1968) on the geochronology of the Belt "Series" of Montana provides a sound basis for establishing the age of sediments in the area. An age of about 1100 m.y. (determined by Rb-Sr whole rock, mineral isochron, and K-Ar techniques) is used in this paper to establish the time of deposition of the Wallace Formation (the youngest formation in the study area). A minimum age of 1330 m.y. is assumed to be the time of deposition of the Precambrian Prichard and Ravalli Formations. This date was determined using K-Ar techniques on metamorphic biotite from the oldest formation in the area, the Precambrian Prichard.

According to Obradovich and Peterman, a 200 m.y. hiatus exists somewhere between deposition of the Prichard and deposition of the Wallace, but problems of correlation in the study area make it impossible to fix the exact stratigraphic location of this hiatus. Structural and geochronologic data by Reid, Greenwood, and Morrison (1970) suggest that the Wallace should perhaps be placed in the lower Belt along with the Prichard and Ravalli Formations.

Structural Sequence

The northeastern border zone of the Idaho batholith has a fairly complex structural history. The interpretation of this history is hampered by the fact that various deformations, obvious in one area, may be absent or extremely subtle a few miles distant. It is possible, however, to put together a generalized structural sequence based on the work of Chase (1968), Nold (1968), Wehrenberg (1972), and White (1969). This sequence is (early to late):

(1) A high grade metamorphism and the development of schistosity that was sub-parallel to bedding. Similar style folding predominated.

(2) The occurence of southwest-trending similar style and flexural slip folding.

(3) The development of northwest-trending similar style folding followed by intrusion of the Idaho batholith and subsequent steep-axis folding. Following this was intrusion of granitic sheets to the east of the study area. These granitic sheets are possibly related to the intrusion of the Skookum Butte stock.

(4) The formation of a gneiss dome due to diapiric uplift of the Bitterroot Range. Plastic deformation predominated on the eastern margin of the dome, while thrusting predominated on the more brittle northern margin.

(5) Deformation on the eastern margin of the dome changed from a plastic to a brittle character. Ensuing north-south high angle, en echelon faulting delineated the front range.

Chapter 3

PETROGRAPHY OF ROCKS USED FOR DATING

Thin-section Descriptions

The various rocks used in this study are from the northeasternmost portion of the Idaho batholith, extending northward through the metamorphic rocks, and crossing a small stock about midway in the traverse (Fig. 2).

Thin section mineral contents of typical igneous rocks of the Idaho batholith and Skookum Butte stock are shown in Table 1; similarly Table 2 shows the mineral contents of metamorphic and sedimentary rocks.

The quartz diorite orthogenesis has been grouped with the metamorphic rocks since, though originally igneous, it is considered to have been regionally metamorphosed prior to intrusion of the Idaho batholith and Skookum Butte stock (Nold, 1968). The Precambrian Ravalli rocks are thought to be the less metamorphosed equivalent of the quartzite, and a similar relationship is thought to exist between the Precambrian Prichard (not present in the study area) and what is mapped as pelitic schist. Of the metamorphic rocks, the pelitic schist and quartzite units are found only in the amphibolite facies, whereas the Precambrian Ravalli Formation is found in both the upper greenschist and lower amphibolite facies. Samples from the Idaho batholith contact zone (K3), the amphibolite (K112), and the quartz diorite orthogneiss (XK3) are in the sillimanite zone of the amphibolite facies.

Sample #	I_b B650+	I_b K42+	SB_s K4, K7, K8
Quartz	30	22	12
Plagioclase	50(An36)	33(An32)	68(An30)
K-spar	10	33	10
Biotite	10	10	5
Muscovite	Tr	Tr	-
Chlorite	Tr	Tr	Tr
Hornblende	-	-	5
Zircon	Tr	-	Tr
Apatite	Tr	Tr	Tr
Sphene	-	Tr	Tr
Rutile	-	Tr	-
Opaques	1	Tr	Tr
No. Sections	1	1	5

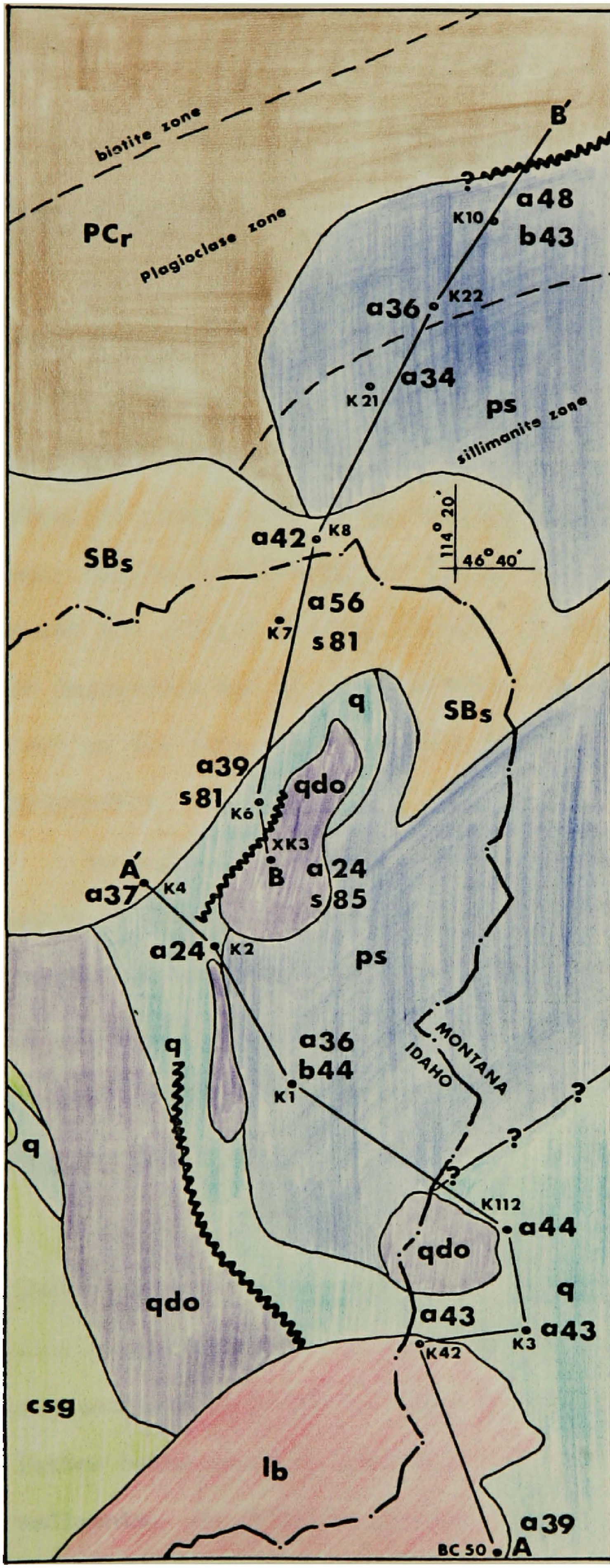
*Nold (1968)
+Chase (1968)

Table 1. Mineral content of the Idaho batholith and Skookum Butte stock.

	p_r*	q*	ps*	qdo*	K3+	K112+
Quartz	70	70	44	11	22	14
Plagioclase	12	14	30	73	36	11
K-spar	6	8	6	1	-	-
Biotite	4	4	11	6	-	7
Muscovite	7	4	7	-	-	1
Hornblende	-	-	-	9	-	64
Chlorite	Tr	Tr	Tr	Tr	Tr	Tr
Diopside	-	-	-	Tr	42	-
Sillimanite	-	Tr	Tr	-	-	-
Apatite	Tr	Tr	Tr	Tr	-	-
Sphene	Tr	Tr	-	Tr	Tr	1
Opaques	-	-	-	Tr	-	3
No. Sections	20	27	25	8	1	1

*Nold (1968)
+Chase (1968)

Table 2. Mineral content of the sedimentary and metamorphic rocks.



Geology and Sample Locations

Geology by Nold (1968) and Chase (1968)

FIG. 2

General

Idaho Batholith

Rocks of the Idaho batholith are generally medium to coarse-grained quartz monzonites and granodiorites with minor amounts of quartz diorite. Commonly a weak to very well developed foliation is present. This is manifested in the interior of the pluton by a parallel arrangement of biotite and by migmatites and feldspar augen near the batholith margins. Large inclusions of metasedimentary rocks are present in many places. Potassium feldspar occurs both as megacrysts and as crystals about the same size as those in the rest of the rock. Quartz shows moderate to strong undulose extinction.

Contacts of the batholith with the country rocks are, on the scale of an outcrop, sharp and concordant, but on a larger scale consist of an alternating series of igneous sills and sheets of metamorphic rock, which in places extend for several miles along strike. Contact breccias occur locally.

Skookum Butte Stock

The Skookum Butte stock is mainly medium to coarse-grained granodiorite, diorite, and quartz diorite. A fair to poor foliation is delineated by both biotite and hornblende. Inclusions of metasedimentary rocks and diorite are present, the boundaries of the latter being somewhat indistinct in contrast to those of the metasediments. No definite evidence exists that this stock is a multiple injection, but the possibility is suggested by a distinct mineralogical variation from east to west (Nold, 1968). The contact of the stock with the country rock is sharp, both concordant and discordant relationships being present.

On the northern border of the Skookum Butte stock, the contact with biotite zone rocks in the Wallace Formation shows a contact metamorphic effect that extends, in some places, for two miles beyond the contact. This contact effect is not as apparent where the stock intrudes higher grade metamorphic rocks (amphibolite facies), probably because the higher grade minerals were more stable under the conditions of contact metamorphism. However, in sample K6 biotite altering to hornblende was observed in thin section, due presumably to contact metamorphism of the quartzite unit.

Pelitic Schist

The pelitic schist unit is composed of about equal amounts of pelitic schist and mica quartzofeldspathic gneiss with minor amounts of calc-silicate gneiss and micaceous quartzite layers. These rocks fall in the plagioclase and sillimanite zones of the amphibolite facies. The plagioclase zone as used by Nold (1968) includes those rocks having no sillimanite but containing plagioclase with an An content greater than 15. The rocks are medium to coarse-grained and weather to a characteristic reddish brown color. They correspond to the "red weathering gneiss" of Groff (1954) and the "sillimanite gneiss" of Chase (1968).

Quartzite-Quartzitic Gneiss

This unit is composed mainly of micaceous quartzite and mica quartzofeldspathic gneiss. Locally calc-silicate gneiss and micaceous quartzofeldspathic schist may be found. The rocks are fine to medium-grained and are generally well bedded. They have a well developed schistosity and, like the pelitic schist unit, exist in both the plagioclase and sillimanite zones of the amphibolite facies. This unit corresponds to the "grey-weathering gneiss" of Chase (1968).

Quartz Diorite Orthogneiss

This unit outcrops between the Idaho batholith and the Skookum Butte stock and occurs only in the sillimanite zone of the amphibolite facies. It consists of medium-grained quartz diorite having a moderate to strong schistosity and contains inclusions of pelitic schist, quartzite, and calc-silicate gneiss. Most of the plagioclase shows normal zoning. The highly deformed nature and strong schistosity of this rock are used as criteria for concluding that it has undergone regional metamorphism. The uniform quartz diorite composition, lack of banding, and presence of inclusions support the contention that this rock was originally igneous.

Amphibolite

Sample K112 is from an amphibolite layer in the quartzite unit (grey-weathering gneiss of Chase). These layers are described by Chase as being medium-grained, lenticular, two to three feet wide and ten to fifty feet long. The rock has a weak lineation as shown by the hornblende. The amphibolite-gneiss contacts are sharp, the lineation of the amphibolite paralleling both the long dimension of the amphibolite and the foliation of the gneiss.

<u>Idaho Batholith Contact Zone</u>

Sample K3 is from the Idaho batholith contact zone. It is a medium-grained, calc-silicate inclusion described as being sharply bounded and lying within an area resembling a "contact breccia" (Chase, 1968).

<u>Precambrian Ravalli</u>

These rocks are predominantly quartzite, which weathers to a gray color and commonly shows sedimentary structures. Bedding thickness ranges from a few inches to a few feet. Rocks of this formation fall into the biotite zone of the greenschist facies and the plagioclase zone of the amphibolite facies. They are fine-grained, predominantly quartz and include the accessory minerals zircon, apatite, and tourmaline.

Chapter 4

METHODS AND TECHNIQUES

Separation

The sample was crushed and sieved, the fraction between 65 and 115 mesh being retained for further separation. The mafic minerals in this size fraction were separated using heavy liquid (1, 1, 2, 2-tetrabromoethane). This heavy separate was run first on a shaker table to remove mica and finally on a magnetite separator to extract apatite and sphene.

Sample Preparation and Dating

After obtaining pure separates, the apatite and sphene samples were divided into halves, one half being annealed at 600°C for 24 hours, packaged and sent to the reactor for irradiation. The neutron dose was determined at the reactor by including two Co_{59} wires in the reactor package along with the samples. After irradiation the absolute disintegration rate of Co_{60} (formed during irradiation) was measured and converted to a reading in nvt (neutrons/cm^2). Accuracy of the dose determination was estimated at ± 5%.[1]

Of the remaining half sample 50-100 grains were mounted on a glass slide with epoxy resin, ground to expose an interior surface of the grain and polished in stages using 0.3 micron alumina for the final polish. Following this the slides were etched to enlarge

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[1] Dr. Elton Turk, verbal communication.

the fission tracks; apatite for 100 seconds in 10% HNO_3 at 20°C; sphene for four minutes in $6H_2O:3HCl:2HNO_3:1HF$ at 20°C (Naeser and McKee, 1969, modified from Pellas and Poupeau, unpublished data).

After etching, the samples were thoroughly washed, and fossil fission tracks were counted using 1250X magnification (oil immersion) and a grid eyepiece to allow determination of the number of tracks per unit area. The irradiated half of the samples from the reactor were also mounted, ground, polished, etched, and counted as above. A complete discussion of fission track dating techniques may be found in Naeser and Dodge (1969), Naeser (1967), Fleischer, Price, and Walker (1965), and Fleischer and Price (1964b).

Ages are determined from the following equation (Fleischer and Price, 1964b).

$$A = \frac{1}{\lambda_d} \ln\left[1 + \left(\frac{P_s \lambda_d I \sigma \phi}{P_i \lambda_f}\right)\right]$$

P_s = spntaneous tracks

P_i = induced tracks

λ_d = total decay constant of uranium (1.54×10^{-10} yr^{-1})

λ_f = fission decay constant for U^{238} (6.85×10^{-17} yr^{-1}) (Fleischer and Price, 1964a)

σ = cross section for thermal neutron induced fission of U^{235} (582×10^{-24} cm^2)

I = isotopic ratio of U^{235} to U^{238} (7.26×10^{-3})

A = age of sample in years

ϕ = neutron dose (neutrons/cm^2)

Chapter 5

RESULTS

Values Obtained

Shown in Tables 3 and 4 are the results of 14 fission track dates on apatite, three fission track dates on sphene, and two K-Ar dates on biotite. The sphene and K-Ar dates are from rocks which have also been dated using apatite and thus provide sphene-apatite and K-Ar-apatite dating pairs, respectively. Fig. 2 shows these dates in relation to the areal geology and Fig. 3 shows two cross sections through the area with the ages plotted above.

Discussion

It will be noted that the apatite-sphene pairs are discordant, the sphene dates averaging 82 m.y., the apatite, 39 m.y. The reason for this discordance is the different annealing temperatures of sphene and apatite (Fig. 4).

Note that apatite can be completely annealed by maintaining it at 160°C for one m.y., whereas to accomplish the same thing in sphene the temperature must be kept at 400°C.

The biotite (K-Ar)-apatite (fission track) pairs show complete concordance in one case (K10) and discordance in sample K1. Possible reasons for this discordance are less obvious but somewhat analogous to the sphene-apatite pairs. Evidently the argon loss from the biotite was less, relatively, than the fission track annealing of the apatite or alternatively the biotite, upon cooling, was able to retain argon at a higher temperature than the apatite was able to retain

Sample	P_s X 10^5 *	Counts	P_i X 10^5 *	Counts	ø X 10^{15} +	Age (m.y.)
K1A	4.78	418	15.00	375	1.833	36 ± 3
K2A	2.08	286	9.60	264	1.833	24 ± 2
K3A	5.94	297	15.40	385	1.833	43 ± 4
XK3A	7.45	134	37.10	382	1.833	24 ± 3
XK3S	11.70	247	15.30	281	1.833	85 ± 9
K4A	3.57	223	10.84	271	1.833	37 ± 4
K6A	22.10	566	62.63	476	1.833	39 ± 3
K6S	47.58	571	65.60	446	1.833	81 ± 7
K7A	4.27	267	8.53	320	1.833	56 ± 5
K7S	34.10	410	46.80	374	1.833	81 ± 7
K8A	3.65	274	9.66	290	1.833	42 ± 4
K10A	8.00	400	18.60	465	1.833	48 ± 4
K21A	3.84	336	12.77	382	1.833	34 ± 3
K42A	6.38	676	16.72	418	1.833	43 ± 3
BC50A	5.56	292	16.16	403	1.833	39 ± 4
K112A	4.10	256	10.46	340	1.833	44 ± 4

* Tracks/cm^2
\+ Neutrons/cm^2

Table 3. Fission track age dates.

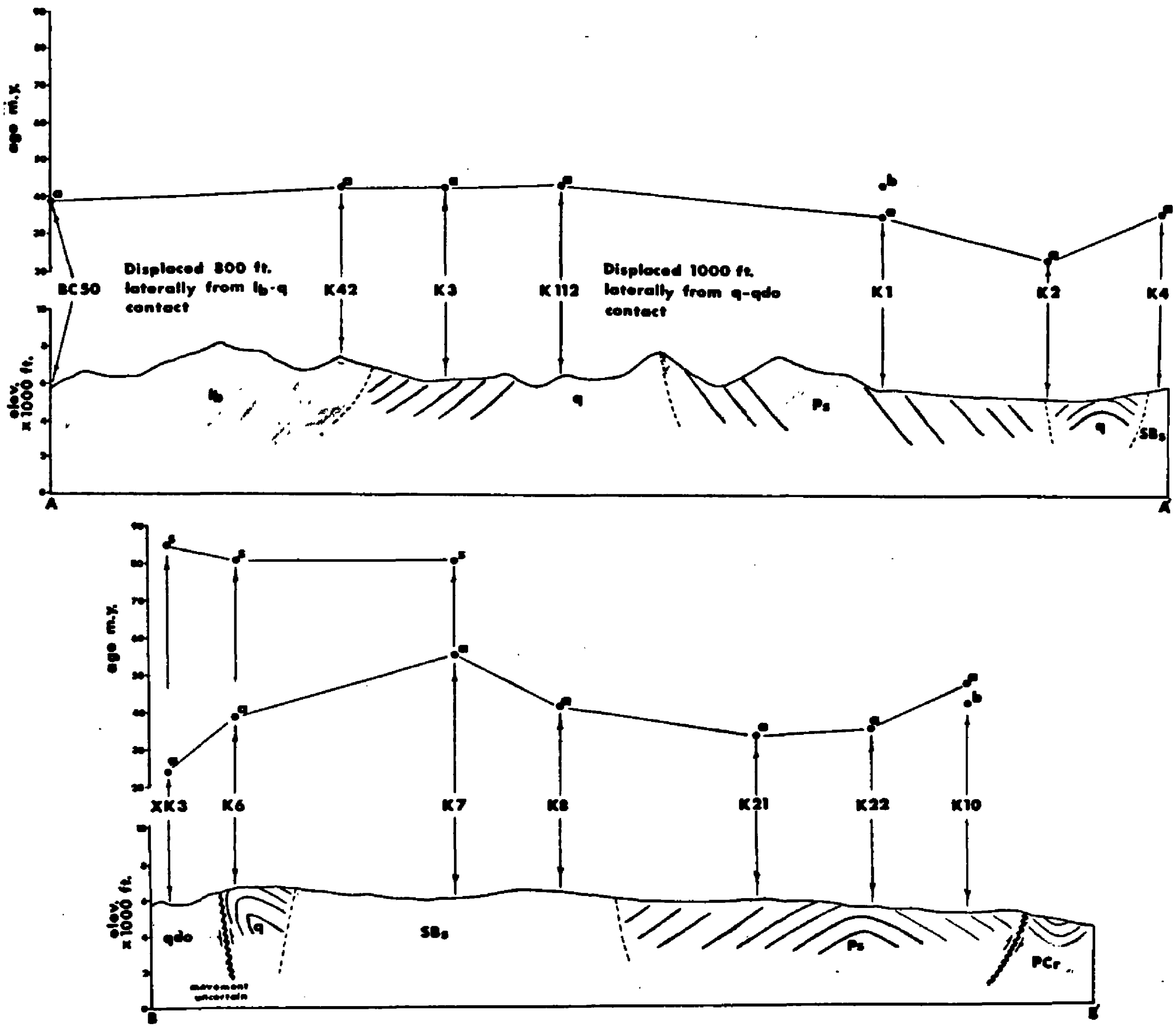
Sample	%K	STP cc Ar^{40} X 10^6	%Air correction	Age (m.y.)
K1	6.99	12.3	26	43.6 ± .9
K10	7.18	12.7	24	43.2 ± .9

Table 4. K-Ar dates. (Analysis by R. L. Armstrong)

fission tracks.[2] The possible geologic significance of these discordant pairs and condordant pair is discussed in the next section.

Within the group of apatite ages there also exists some discordance. Samples K2 and K3 have ages of 24 m.y., and samples K10 and K7 have ages of 48 m.y. and 46 m.y., respectively (note that one of the anomalous apatite dates (K10) is part of the concordant K-Ar

[2]In this paper a temperature of 300°C is considered sufficient to prevent the retention of argon in the biotite crystal lattice (Evernden *et al.*, 1960). This value probably represents a maximum temperature of that phenomenon.



GENERALIZED GEOLOGIC CROSS SECTIONS and AGES

Refer to figure 2 for explanation of symbols

FIG. 3

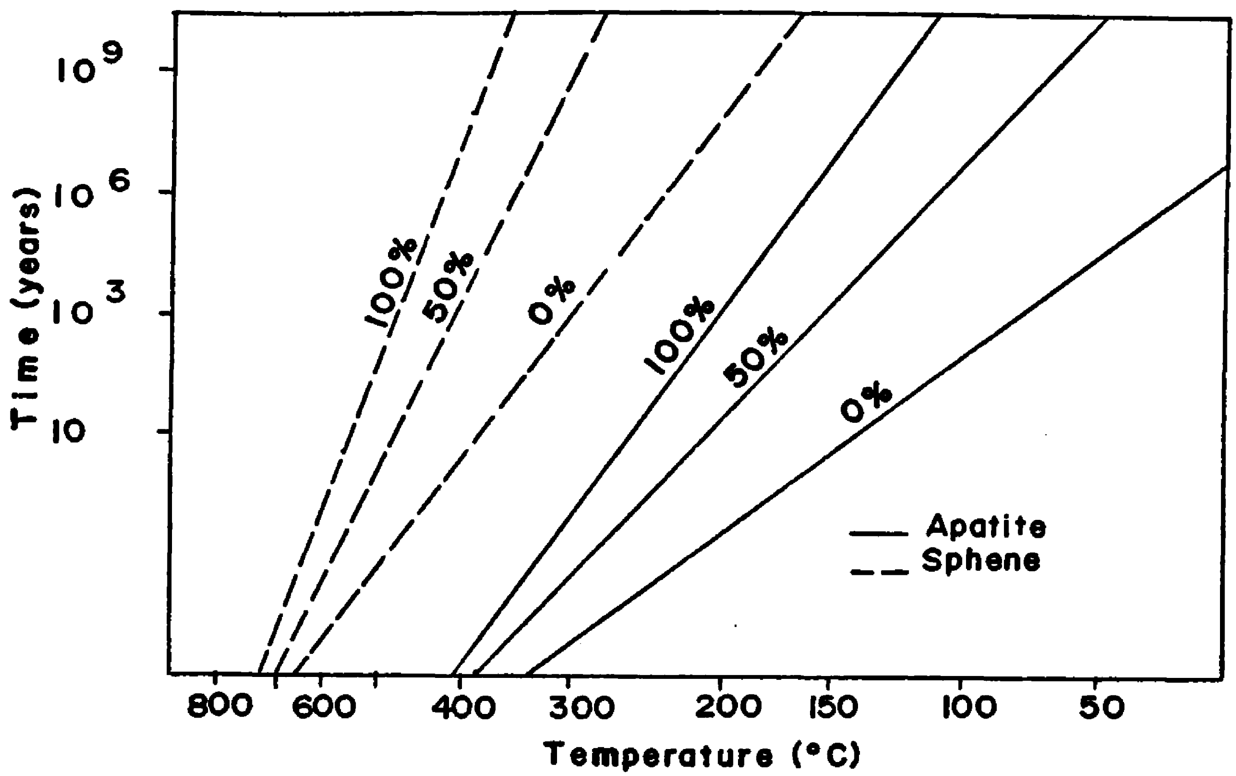


Figure 4. Track-loss curves for sphene-apatite (after Naeser and Dodge, 1969).

pair). Taken as a group the apatite dates average 39 m.y. and omitting the above mentioned four dates leaves this average unchanged. Also, as previously stated the apatite dates which form half of the sphene-apatite pairs average 39 m.y. In this paper no attempt will be made to explain this discordance in the apatite dates except to say that they possibly reflect localized thermal conditions.

Geologic Significance

There are three main ways by which the observed ages can be explained, all of which have certain features and assumptions in common. Briefly stated these hypotheses are:

(1) Intrusion of the Skookum Butte stock at fairly shallow depths, the sphene dates (82 m.y.) reflecting the time of cooling of this intrusion. A subsequent thermal event at about 39 m.y. caused fission track annealing of the apatite and argon loss in the biotite. There are, in fact, rhyolitic plugs of presumed Tertiary age 5-10 miles east of the study area (Wehrenberg, 1972), and the Lolo batholith, about ten miles west of the area also appears to be of Tertiary age (Nold, 1968). The Lolo batholith also contains abundant miarolitic cavities indicative of intrusion at fairly shallow (one or two km) depths.

(2) Intrusion of the Skookum Butte stock at greater depths (>50,000 ft), the 82 m.y. sphene ages reflecting uplift of the area which brought the sphene into a thermal domain compatible with fission track retention. Following this uplift a thermal event as before would be required to produce the apatite and K-Ar dates. Scholten (1968) states "...by early Upper Cretaceous time at least the northern part of the Idaho batholith region had been uplifted so rapidly and highly that many thousands of meters of its roof had been removed by erosion and Belt strata were widely exposed."

(3) Intrusion of the Skookum Butte stock at moderate depths, the 82 m.y. sphene ages reflecting a minimum age of cooling of the stock. In this case the apatite and biotite ages

are assumed to record later uplift of the area, and no major subsequent thermal event need be called upon to produce the 38-49 m.y. dates.

In considering these three hypotheses the following data must be taken into account:

(1) Early Tertiary ages of the batholithic rocks are quite widespread (Fig. 1) and thus are likely not a local "contact effect" of shallow plutonism.

(2) Temperatures of about 300°C are required to "reset" K-Ar dates in biotite.

(3) By Early Tertiary time the area was not covered very deeply since the apparently Early Tertiary Lolo batholith contains miarolitic cavities.

The hypothesis that is best able to account for this data seems to be number three since it does not require an extensive area to have undergone a "thermal event" where temperatures of 300°C would be fairly common. While reheating may have played a significant role locally, causing perhaps the discordance in the apatite dates and in the apatite (fission track)-biotite (K-Ar) pair, uplift of the area is thought to be the major factor in producing the observed apatite and K-Ar ages. The question immediately arises as to how much uplift would be required to produce these ages, and what evidence there is to support the occurence of such an uplift.

Consider first the sphene-apatite pairs. In order to account for the observed discordance and have the 82 m.y. sphene dates reflect the time of cooling of the Skookum Butte stock, the apatite would have to have been maintained at temperatures of between 140°C and 200°C for about 40 m.y., then rapidly uplifted. These temperatures correspond to depths (assuming a geothermal gradient of 25°C/km)[3] of six to eight km or about 20,000 to 26,000 ft. The apatite dates, however, cannot be used to set this minimum limit. Instead the K-Ar dates, because of their higher temperature of daughter product retention must be used to establish the probable amount of uplift. If biotite must cool to about 300°C (Evernden et al., 1960) before it begins to retain argon then the minimum depth of burial (assuming again 25°C/km) must be twelve km or about 39,000 ft. In that case the sphene ages reflect only a minimum, not true, time of cooling of the Skookum Butte stock since at these temperatures the sphene would be retaining only about 50-60% of its fission tracks (Fig. 4). It may be recalled that McDowell and Kulp (1969) believe the primary igneous activity in this area to have occured at about 125 m.y.

It is possible to arrive at similar figures for burial by different approaches. Hornblende hornfels facies contact metamorphism can be observed at the contact of the Skookum Butte stock with the country rock. This contact metamorphism is most obvious where the stock intrudes rocks of biotite zone regional metamorphism but is also discernible in thin section where the stock

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[3]A geothermal gradient of 25°C/km is based on the "average" of 20°C/km used by Hyndman (1972, in press) for the geothermal gradient in a "normal" geosyncline. This figure was modified upward because of the proximity of the study area to the Idaho batholith.

intrudes higher grade regionally metamorphosed rocks (e.g., sample K6). These contact effects should not be obvious at pressures greater than about three kb which corresponds to a depth of about 37,000 ft. It is of course possible by this reasoning that the depth of intrusion was considerably less than that (Turner and Verhoogen, 1960).

Another method is to try to reconstruct the stratigraphic column. Assuming about 10,000 ft. of Wallace, 15,000 ft. of Missoula Group, and 10,000 ft. of Paleozoic and Mesozoic section (interpolated from Mudge, 1970) one arrives at a figure of 35,000 ft. which probably represents a minimum depth of burial. Indeed if the correlation of Precambrian Prichard Formation with the pelitic schist is valid, one can add about 6000 ft. of Ravalli in many parts of the study area.

While uplift of this magnitude may at first seem unreasonable, Mudge (1970) claims that at least 45,000 ft. of rock were eroded from the area of maximum uplift in northwestern Montana in Early Tertiary time.

Significant information concerning the time if not magnitude of uplift may be inferred from the Tertiary stratigraphy and paleontology of southwest Montana. Several locations of Late Eocene fauna have been found in the intermontane valleys in this area (Petkewich, 1971). In fact the assumption can be made that these valleys share a similar geologic history and mode of formation (Kuenzie and Fields, 1971), and further that this mode of formation is related to tectonism which encompasses the present study area, then a minimum age of this tectonism corresponding to the age of the basal Tertiary valley fill may be assigned (i.e., Late Eocene or 47-37 m.y.). This correlates well with the K-Ar and fission track data obtained. The Bitterroot Valley, westernmost of the intermontane valleys, is about 20 miles east of the study area.

Chapter 6

SUMMARY AND CONCLUSIONS

The Skookum Butte stock was intruded a minimum of 82 m.y. ago, most likely somewhat more than 100 m.y. ago at a depth of about 35,000 to 40,000 ft. Biotite and apatite were, at this time, depressed too far into the geothermal gradient to retain their argon and fission tracks, respectively. Sphene at this time was retaining about 50 to 60% of its fission tracks.

In the Early Tertiary, the area underwent rapid, vertical uplift bringing the biotite and apatite into a thermal domain where they could retain the daughter product. The discordant apatite (fission track)-biotite (K-Ar) dates (K1) could be indicative of a relatively slow uplift in this region or, less likely, could reflect a subsequent regional reheating of this area which selectively affected only the apatite dates. Temperatures of only 60° to 70°C would be sufficient if maintained for about one m.y. The concordant apatite pair may reflect more rapid uplift along the fault shown in Figs. 2 and 3, but without a great deal more work such an uplift would be difficult to establish. During this proposed uplift, sphene would begin to retain 100% of its fission tracks.

Subsequent to uplift, or during the latter stages of uplift, some igneous activity occurred along the eastern part of the Idaho batholith, i.e., the Lolo batholith intrusion to the west of the study area and the Challis Volcanics to the south. This activity is thought to have had only a minor and local effect on the ages.

The 82 m.y. fission track dates on sphene are the first pre-Tertiary dates reported that might reflect a minimum age of igneous activity in this area. For this reason it is suggested that fission track dating techniques may provide, in part, a method for future workers to use in establishing a pre-lift geochronology on the eastern margin of the Idaho batholith.

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