Geologic and Fission-Track Evidence for Late Cretaceous Faulting and Mineralization, Northeastern Flank of Blacktail Mountains, Southwestern Montana

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Geologic and Fission-Track Evidence for Late Cretaceous Faulting and Mineralization, Northeastern Flank of Blacktail Mountains, Southwestern Montana

By R.G. TYSDAL, R.A. ZIMMERMANN, A.R. WALLACE,
and L.W. SNEE

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CONTENTS

FIGURES

TABLES

Geologic and Fission-Track Evidence for Late Cretaceous Faulting and Mineralization, Northeastern Flank of Blacktail Mountains, Southwestern Montana

By R.G. Tysdal, R.A. Zimmermann, A.R. Wallace, *and* L.W. Snee

Abstract

The Jake Canyon reverse fault trends northwest for more than 18 mi along the northeastern flank of the Blacktail Mountains. Archean metamorphic rocks are displaced over Paleozoic carbonate strata along the northwestern part of the fault and are displaced over other Archean metamorphic rocks along the southeastern part. The Jake Canyon fault is separate and distinct from the Cenozoic Blacktail normal fault that marks the common boundary of the range and the valley to the northeast. Mineralizing hydrothermal fluids caused argillic and propylitic alteration along the Jake Canyon fault in the middle and southeastern parts of the mountain range. Fission-track ages were determined on apatite recovered from nine samples of propylitized gneiss and gneiss beyond the zone of hydrothermal alteration. The combined geologic and geochronologic evidence indicate that the ages of fault movement and the hydrothermal event that produced the mineralized, altered rock are Late Cretaceous.

Silica introduced by the hydrothermal fluids filled voids and (or) replaced some of the Archean gneiss, forming masses of quartz. The quartz forms tabular bodies that commonly are about 50 ft thick and locally are exposed over more than 1,000 ft of relief. The quartz shows multiple episodes of precipitation and fracturing that indicate its deposition was concurrent with fault movement. Fluid-inclusion data indicate that the quartz precipitated at greater than 190 °C; partial argon loss from Precambrian muscovite in a muscovite-chlorite-quartz metaquartzite directly adjacent to a hydrothermal quartz body indicates that temperatures during quartz precipitation were probably less than about 270 °C.

Seven of the nine samples for which fission-track dates were determined yielded ages that range from 60 to 74 Ma. Two ages are considered anomalous. Fission-track ages indicate that the hydrothermally altered gneiss and unaltered gneiss underwent the same thermal history within the area sampled. The ages could reflect the time of the hydrothermal event or the time of cooling during uplift subsequent to the hydrothermal event; a clear choice cannot be made between the two alternatives, but the hydrothermal event can be no younger than the fission-track date. A minimum age for the faulting and mineralization is provided by a $^{40}Ar/^{39}Ar$ plateau date of 48.1±0.3 Ma determined for a whole-rock basalt sample from an unmineralized flow that caps mineralized gneiss and hydrothermal quartz.

Manuscript approved for publication, December 13, 1989.

INTRODUCTION

The Blacktail Mountains lie in a zone of overlap of the Cordilleran thrust belt and the crystalline basement of the Rocky Mountain foreland of southwestern Montana. Westward-dipping Sevier-style (thin-skin) thrust faults of Late Cretaceous age displace Phanerozoic strata in the northwestern half of the mountain range (Pecora, 1981) and form part of a convex-eastward zone that Ruppel and Lopez (1984) named the Blacktail Mountains salient (fig. 1). The Jake Canyon fault, a northwest-trending, northeast-dipping Laramide-style reverse fault, delimits the northern margin of the salient of Phanerozoic strata and extends to the southeast where it is confined to Archean metamorphic rocks (Tysdal, 1988a, b).

The fault, when it formed, separated rocks of the present-day Blacktail Mountains from a structurally high block to the northeast that occupied the present area of the valley of Blacktail Deer Creek and was contiguous with the southern end of Ruby Range (Pecora, 1981). The high block was named the Blacktail Valley block by Tysdal (1988b), who showed that its uplift caused deformation of the north-trending thrust faults and associated folds. During Cenozoic extension, the Black-

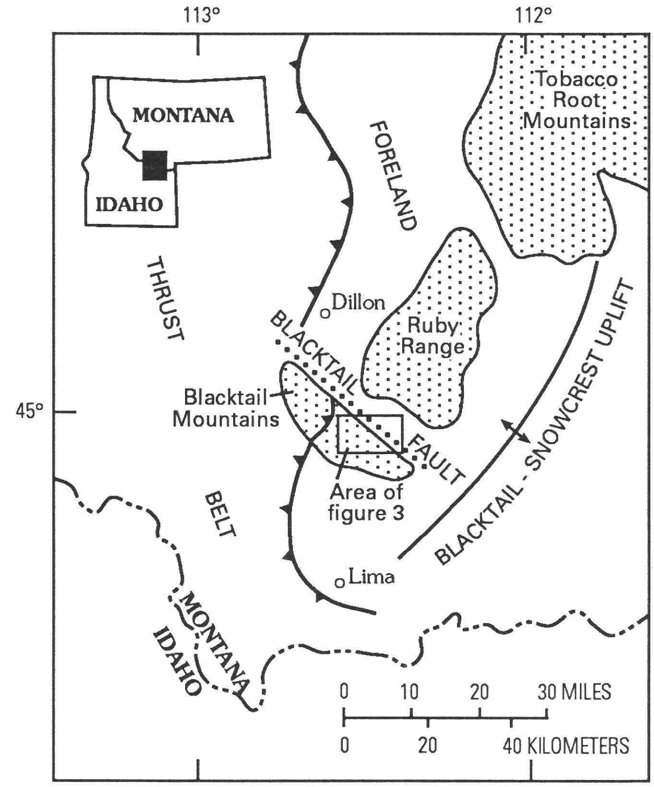

Figure 1. Mountain ranges, location of study area, and major structural features and provinces, southwestern Montana.

tail Valley block was downdropped along the Blacktail fault, which is approximately parallel to the Jake Canyon fault. Along the northwestern part of the mountain range, the Blacktail fault is within the zone of structural weakness associated with the Jake Canyon fault.

In the northwestern half of the mountain range, reverse movement of the Jake Canyon fault is clearly demonstrated by certain rocks and their structural relationships. (1) Slabs of Archean gneiss are preserved locally along the northeastern margin of the range (fig. 2). The gneiss was faulted against Phanerozoic strata during uplift of the Blacktail Valley block, and the slabs are remnants severed from the block during Cenozoic extension and downdropping of most of the block (Tysdal and others, 1987; Tysdal, 1988b). Achuff (1981a) previously recognized these slabs, but believed they were emplaced in the late Tertiary or Quaternary. (2) Masses of quartz occur in a few places, adjacent to Paleozoic rocks, and formed from hydrothermal fluids that altered some of the slabs of gneiss and the Paleozoic strata. In the southeastern half of the mountain range, the Jake Canyon fault is confined to metamorphic rocks. In this area, continuity of the fault pattern and small-scale structural features (folds, slickensides, lineations, and so on) in gneiss of the footwall indicate reverse movement. The fault segment entirely within the metamorphic rocks (fig. 3) has a moderate northeast dip, quartz masses and propylitic and argillic rock are localized along it.

Purpose of Study

Dating was undertaken to determine the time of movement of the Jake Canyon fault and mineralization along it. Rocks adjacent to the fault have not been deformed cataclastically since the hydrothermal event, and datable minerals reset during the event should therefore yield the time of latest movement along the fault. The Jake Canyon fault is demonstrably a reverse fault, but it may have undergone some normal-slip displacement subsequent to reverse movement, and mineralization may have occurred still later. The moderate dip of the southeastern part of the fault offers no clue to the age of the fault. Moderate dips are common in the structurally low parts of northwest-trending faults that cut across the crystalline foreland of southwestern Montana (Schmidt and Garihan, 1983), but moderate to low dips, with or without hydrothermal alteration, also are characteristic of many Tertiary, normal-slip faults of the Basin and Range province of the western-central and southwestern United States (for example, Bartley and Glazner, 1985). The Blacktail Mountains lie within the Basin and Range province and, although north of the Snake River Plain, experienced the same structural history as the southern part of the province (Reynolds, 1979). A Late Cretaceous or early Tertiary age would show that mineralization, including silicification and hydrothermal alteration, occurred during the Laramide orogeny, during a time of regional tectonic shortening. Conversely, a mid-Tertiary or younger age would indicate that the hydrothermal alteration and silicification features are related to Basin and Range extension.

Previous Work

The northeastern flank of the Blacktail Mountains was examined by Pardee (1950) during a study of range-front faults that formed during block faulting in western Montana. The area shown in figure 3 was included in reconnaissance maps of Klepper (1950), Scholten and others (1955), and Heinrich (1960). Keenmon (1950) and Zeigler (1954) studied the range front southeast of Jake Canyon. Zeigler (1954) recognized that quartz masses and chloritic alteration of gneiss are localized along a fault, which he considered to be a strand of the Blacktail normal fault of basin and range style. The northwesternmost part of the map area of figure 3 was examined by Hassemer and others (1986) and Tysdal and

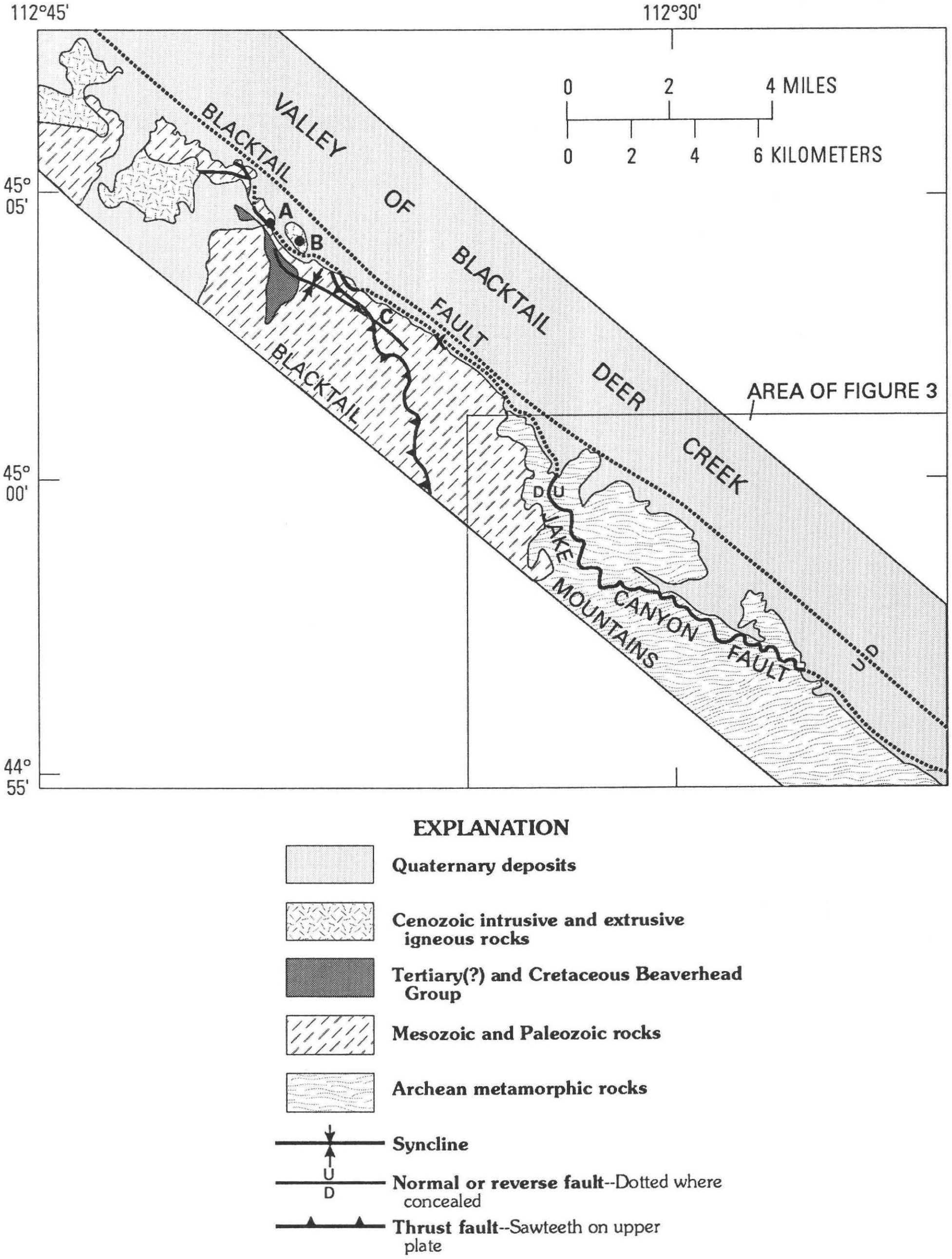

Figure 2. Generalized geology of Blacktail Mountains. The dot near letter A shows location of deformed mixed-clast conglomerate of Beaverhead Group; dot near letter B marks location of sample from rhyolite dated at 44±1.6 Ma; area near letter C shows where Jake Canyon fault dips about 70° NE.; X marks location of Nevada mine.

others (1987) during a mineral-resource study of lands under consideration for inclusion in the National Wilderness system. Archean rocks in the northwestern half of the map area of figure 3 were examined by Clark (1987) as part of a larger areal study of metamorphic rocks in the southeastern part of the Blacktail Mountains. The entire area under study here was included by Tysdal (1988a) within a geologic strip map of the 22-mi-long northeastern flank of the Blacktail Mountains. Several thesis studies have been conducted in the northwestern part of the Blacktail Mountains, northwest of the area under concern here, and are cited in Tysdal (1988a, b).

BEDROCK OF BLACKTAIL MOUNTAINS

Bedrock that is important to the interpretations presented in this paper is described in some detail in this

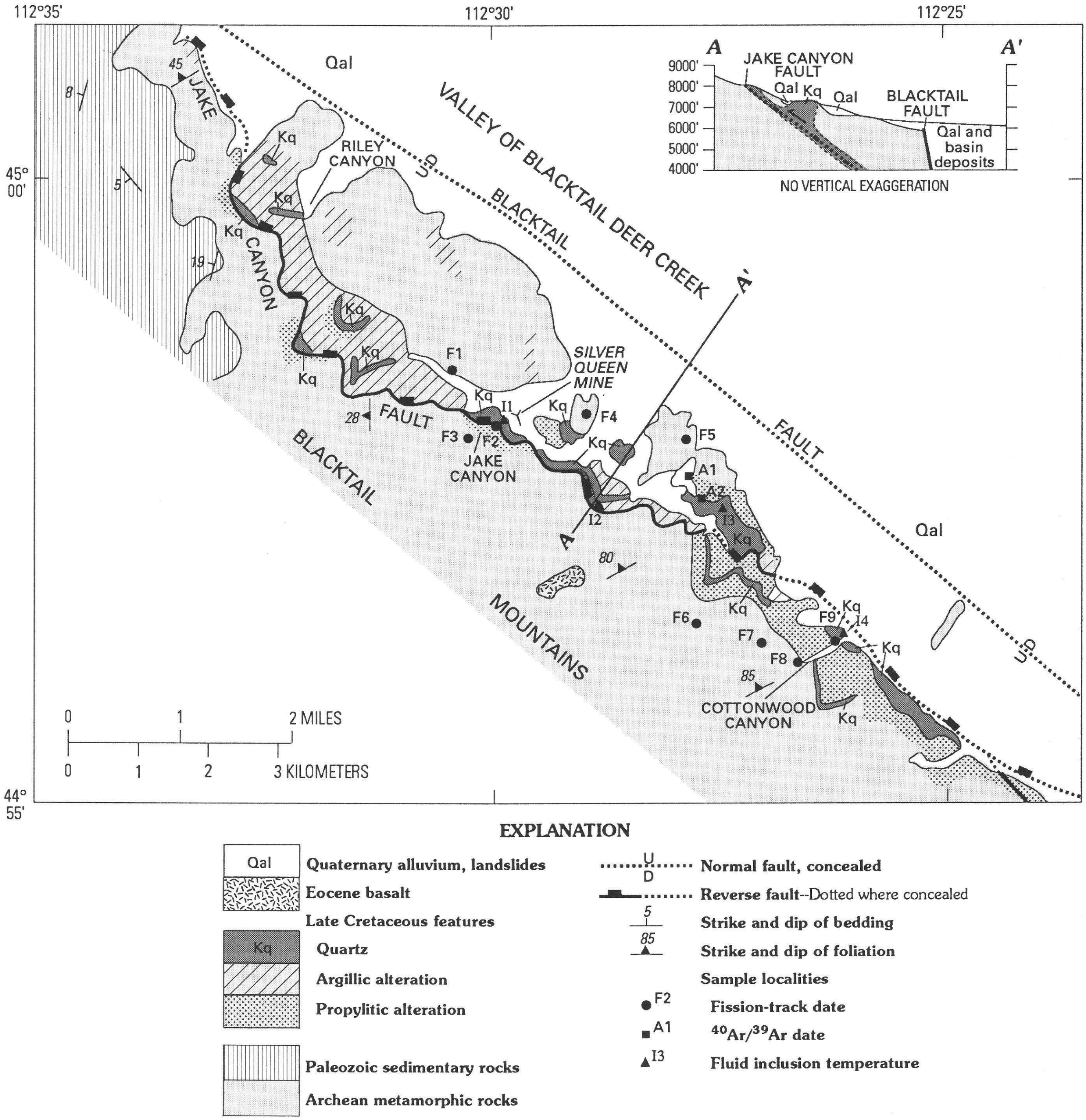

Figure 3. Geologic features and sample localities, southeastern half of Blacktail Mountains and adjacent valley. Location of map area shown on figure 2.

section. Other rock units are shown in figures 2 and 3. Much of the bedrock flanking the Jake Canyon fault in the southeastern half of the Blacktail Mountains is Archean quartzofeldspathic gneiss. Our mapping and that of Clark (1987) distinguish two widespread varieties. One variety is pink to pale-orange, medium- to coarse-grained quartz-plagioclase-microcline gneiss that contains sparse biotite. Scholten and others (1955) and Heinrich (1960, fig. 7) mapped rocks of this description as the Dillon Granite Gneiss, but the rocks form many tabular units interlayered with other kinds of metamorphic rocks described below rather than one uniform body. Another common variety of gneiss is light gray, well foliated, and medium to coarse grained; it consists of quartz, plagioclase, microcline, and biotite and locally contains hornblende. Layers of hornblende-rich gneiss a few tens of feet thick are within the light-gray gneiss in some areas and range in composition from quartz-plagioclase-hornblende gneiss to hornblende-rich gneiss. Ultramafic rocks composed of biotite, plagioclase, and clinopyroxene are present in a few places. Some of these ultramafic rocks are layered, a few tens of feet thick, and concordant with the gneissic country rock (Sinkler, 1942; Heinrich, 1960). Near the range front, just north of Jake Canyon, are irregularly shaped intrusions of gabbro; these rocks have been metamorphosed and show foliation concordant with that of the surrounding gneiss. Clark (1987) reported Archean marble southeast of the area shown in figure 3, but none was found by us within the map area. Foliation of the metamorphic rocks of the Blacktail Mountains generally strikes northeast, about normal to the range front.

Metamorphic rocks in the Blacktail Mountains have been correlated with those in the Ruby Range (fig. 1) (Klepper, 1950; Heinrich, 1960; Clark, 1987). Rock units and foliation trends in the two ranges are similar, but the ranges are separated by a Cenozoic basin beneath the valley of Blacktail Deer Creek. A Rb/Sr whole-rock isochron age shows that quartzofeldspathic gneisses of the Ruby Range were originally metamorphosed at about 2,750 Ma, a common age of metamorphism in southwestern Montana (James and Hedge, 1980). A whole-rock sample from the Blacktail Mountains, southwest of the area of figure 3, yielded a Rb/Sr age of 3,080 Ma (Giletti, 1966). K/Ar dating of rocks from both the Ruby Range and the Blacktail Mountains shows that the rocks underwent a second regional metamorphism about 1,600 Ma (Giletti, 1966; James and Hedge, 1980).

Muscovite from muscovite-chlorite-quartz metaquartzite within the Archean gneiss directly adjacent to a hydrothermal quartz body (fig. 3, locality A2) was dated by the $^{40}Ar/^{39}Ar$ method. (Experimental details are discussed in the appendix; data are given in table 1.) Because the muscovite was thought to have been a product of the hydrothermal event, based on geologic constraints, a Tertiary or Cretaceous age was expected. A relatively large amount (35.8 mg) of pure muscovite was irradiated under conditions appropriate for material of Mesozoic age. During argon analysis, it became obvious that this muscovite was not hydrothermal, and the experiment was terminated at 875 °C (fig. 4). A smaller aliquant of muscovite was irradiated under conditions more appropriate for samples of Precambrian age (fig. 5). Within analytical error the two age spectra are identical. Age spectra that step up in age from low to high temperatures during argon extraction, as these do, may be characteristic of partial argon loss resulting from incomplete thermal resetting of a sample after it has cooled below its closure temperature for argon diffusion (Turner, 1968). This type of behavior in muscovite and an argon-closure temperature for muscovite of 270–325 °C, depending on cooling rate, have been quantified by Snee and others (1988). Considering the character of these age spectra, several conclusions can be drawn from the argon data for the muscovite sample from locality A2. First, the total-gas dates for both spectra, which are analogous to conventional K/Ar dates, are similar and have no geologic meaning. The difference in total-gas dates is due to incomplete extraction of argon from the apparently younger muscovite. Second, original cooling of these muscovites below 270–325 °C occurred at 1,268±3 Ma or earlier, and partial argon loss took place since 443±2 Ma. If the original closure occurred at 1,268 Ma, then only 6 percent of the total argon was lost during younger thermal activity. This argon loss may have occurred during hydrothermal activity along the fault zone during the Tertiary or Cretaceous. In any case, the muscovites were not heated above 270 °C after Proterozoic cooling.

Phanerozoic strata that overlie the Archean crystalline rocks in the northern half of the Blacktail Mountains (fig. 2) are composed of 3,500–4,500 ft (depending on structural interpretations) of Paleozoic rocks that are mainly limestone and dolomite (Pecora, 1987; Tysdal and others, 1987) and about 2,500 ft of Mesozoic strata that are mostly limestone and conglomerate. The uppermost Mesozoic unit is the nonmarine Beaverhead Group of Late Cretaceous and early Tertiary(?) age (Haley and Perry, in press), which is mainly a synorogenic conglomerate. Rocks of the Beaverhead are described here because their deformation into a syncline adjacent to the Jake Canyon fault (fig. 2) (Tysdal, 1988a, b) helps to constrain the time of movement along the fault to the Laramide.

The Beaverhead in the Blacktail Mountains consists of two units. The lower unit is composed of clasts of limestone, eroded chiefly from Mississippian formations, and has a matrix of reddish-orange to maroon sandstone and siltstone. It also contains a bedded unit of finely crystalline limestone several tens of feet thick that locally contains oncolites (Pecora, 1987). The upper unit of the Beaverhead consists of a mixture of (1) well-rounded quartzite and siltite clasts eroded from the Middle Proterozoic Belt Supergroup, which crops out in thrust sheets several miles west of the Blacktail Mountains, and (2) rounded limestone clasts derived from Phanerozoic formations.

The age of the Beaverhead in the Blacktail Mountains is not constrained by fossils. Palynological dating of the Beaverhead near Lima, Mont., about 25 mi south of the study area (fig. 1), yielded a Coniacian (about 88 Ma) to mid-Campanian (about 78 Ma) age for strata that comprise much of the group in that area (Nichols and others, 1985). Nichols and others concluded that the overlying strata, from which they recovered no fossils, probably were no younger than Maastrichtian. Perry and others (1988) and Haley and Perry (in press)

Table 1. $^{40}Ar/^{39}Ar$ age-spectrum data
[See appendix for definitions and discussion of methods]

Sample number: 85MTz319A muscovite (irradiated at University of Michigan at 2 MW for 75 hours)
Sample weight: 35.8 mg Atmospheric $^{40}Ar/^{36}Ar$: 298.9 J-value: 0.006150±31

Temperature (°C)	$^{40}Ar_R$	$^{39}Ar_K$	F	Radiogenic yield (percent)	^{39}Ar (percent of total)	Apparent age and error (Ma at 1σ)
375	1.79724	0.03973	45.240	85.7	1.5	442.83±2.30
475	0.32917	0.00533	61.743	85.9	0.2	580.67±9.47
575	5.96495	0.06634	89.911	98.6	2.4	794.05±3.30
675	39.59931	0.32940	120.218	98.8	12.1	998.52±4.81
725	88.38884	0.62319	141.833	99.7	23.0	1,131.38±4.80
775	110.47730	0.72280	152.846	100.0	26.7	1,195.49±5.08
825	72.06723	0.45584	158.097	99.8	16.8	1,225.28±5.28
875	77.28850	0.46913	164.750	100.0	17.3	1,262.32±4.77
Total gas			145.999			1,155.90±4.90

No plateau.

Sample number: 85MTz319A muscovite (irradiated at U.S. Geological Survey at 1 MW for 100 hours)
Sample weight: 16.2 mg Atmospheric $^{40}Ar/^{36}Ar$: 298.9 J-value: 0.023560±59

Temperature (°C)	$^{40}Ar_R$	$^{39}Ar_K$	F	Radiogenic yield (percent)	^{39}Ar (percent of total)	Apparent age and error (Ma at 1σ)
400	1.45023	0.09948	14.578	84.8	1.4	532.64±1.34
500	4.00484	0.15269	26.229	99.2	2.2	868.03±1.91
600	16.31648	0.49811	32.757	98.4	7.1	1,031.84±2.18
700	41.31311	1.12071	36.863	99.8	16.1	1,127.74±2.33
750	42.05935	1.06381	39.536	99.8	15.3	1,187.55±2.41
800	43.32997	1.05637	41.018	99.7	15.2	1,219.85±2.46
850	52.46576	1.23498	42.483	99.9	17.7	1,251.25±2.50
900	36.20205	0.83694	43.255	99.6	12.0	1,267.57±2.53
950	26.44885	0.61515	42.996	99.9	8.8	1,262.11±2.52
1,000	9.75355	0.22948	42.502	99.6	3.3	1,251.65±2.53
1,050	1.74207	0.04160	41.879	97.5	0.6	1,238.38±5.18
1,100	0.49472	0.01059	46.697	96.1	0.2	1,338.62±18.05
1,200	0.42454	0.00755	56.221	96.5	0.1	1,521.74±21.86
Total gas			39.613			1,189.24±2.45

No plateau.

Sample number: 84MTz208 basalt whole rock (irradiated at University of Michigan at 2 MW for 75 hours)
Sample weight: 419.4 mg Atmospheric $^{40}Ar/^{36}Ar$: 298.9 J-value: 0.006335±32

Temperature (°C)	$^{40}Ar_R$	$^{39}Ar_K$	F	Radiogenic yield (percent)	^{39}Ar (percent of total)	Apparent age and error (Ma at 1σ)
300	0.11224	0.02952	3.802	8.9	0.2	42.93±1.95
400	0.08959	0.01954	4.585	19.0	0.1	51.65±3.42
500	0.65870	0.14113	4.667	37.0	0.8	52.56±0.36
600	2.37061	0.53379	4.441	79.8	3.1	50.05±0.26
700	6.61790	1.51757	4.361	86.4	8.7	49.16±0.25
800	18.45807	4.31888	4.274	94.3	24.9	48.19±0.24
900	15.25304	3.56484	4.279	96.5	20.5	48.25±0.24
1,000	15.46797	3.65298	4.234	95.3	21.0	47.75±0.24
1,100	9.07738	2.17829	4.167	94.8	12.5	47.01±0.24
1,450	5.97742	1.40874	4.243	90.0	8.1	47.85±0.24
Total gas			4.266			48.11±0.25

Plateau date: 48.07±0.24.
Plateau on 800, 900, and 1,000 °C steps (66.4 percent of ^{39}Ar).

believed that uppermost strata of the group in an area 15–20 mi south of Beaverhead outcrops in the Blacktail Mountains may be as young as early Tertiary. Their conclusion of an early Tertiary(?) age is based on

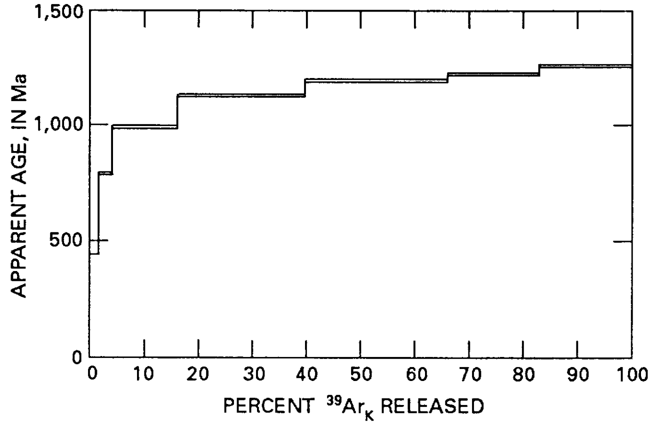

Figure 4. Truncated $^{40}Ar/^{39}Ar$ age-spectrum diagram for muscovite from gneiss from sample locality A2. Sample was irradiated for 75 hours at the University of Michigan, Ann Arbor, Mich.

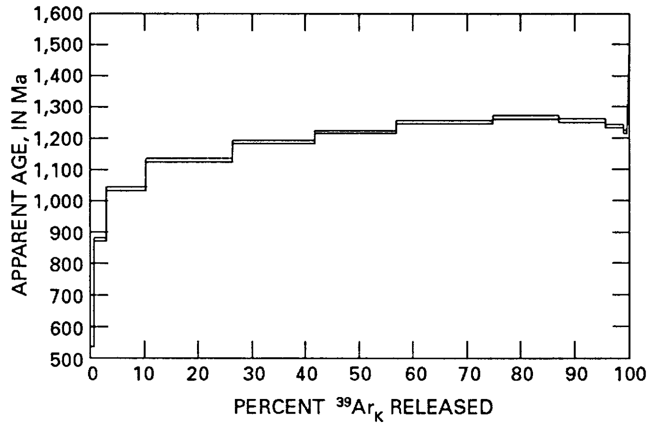

Figure 5. $^{40}Ar/^{39}Ar$ age-spectrum diagram for muscovite from gneiss from sample locality A2. Sample was irradiated for 100 hours at the U.S. Geological Survey, Denver, Colo.

structural and stratigraphic arguments but on no additional faunal data beyond those at reported by Nichols and others (1985).

In the Grasshopper Creek area, about 10 mi west of the northwestern end of the Blacktail Mountains, deformed limestone-clast conglomerate of the Beaverhead is overlain by a 1,300-ft-thick sequence of volcanic rocks that has a strike length of more than 10 mi (Lowell, 1965; Thomas, 1981; Johnson, 1986; Johnson and Sears, 1988; Ivy, 1989; Pearson and Childs, 1989). Rocks from the volcanic sequence yielded $^{40}Ar/^{39}Ar$ dates of 72–80 Ma (Meyer, 1980; Snee, 1982; analyses by L.W. Snee, *in* Ivy, 1989). A conglomerate composed of a mixture of Phanerozoic limestone clasts and Belt Supergroup clasts overlies the Cretaceous volcanic rocks to within 5 mi of the northwestern end of the Blacktail Mountains. In the Grasshopper Creek area, this conglomerate is considered part of the Beaverhead by Thomas (1981), Johnson (1986), and Johnson and Sears (1988) and tentatively so by Lowell (1965). All of these workers consider the mixed-clast conglomerate to depositionally overlie the dated volcanic rocks. Johnson (1986) and Johnson and Sears (1988) also interpreted the volcanic rocks to be thrust over the mixed-clast conglomerate in one area.

The mixed-clast conglomerate of the Beaverhead in the northwestern part of the Blacktail Mountains was first mapped by Lowell (1949) and O'Connor (1949) and later by Achuff (1981a, b), Pecora (1981, 1987), and Tysdal (1988a). Both it and the older limestone-clast conglomerate (which lacks Belt clasts) are deformed within the Jake Canyon fault system near the mouth of Small Horn Canyon (locality A, fig. 2), where both units display near vertical dips (Tysdal, 1988a). Because geologic relationships in the area of Grasshopper Creek indicate that the mixed-clast conglomerate there is entirely younger than the 72–80 million-year-old volcanic rocks and because the Belt clasts in the Beaverhead in the northwestern part of the Blacktail Mountains most likely came originally from a western source, the apparently correlative mixed-clast conglomerate in the Blacktail Mountains also should be younger than the volcanic rocks. We consider this conclusion to be tentative, however, because conglomerates within orogenic settings commonly are subjected to repeated recycling and the Small Horn Canyon site is about 10 mi east of the dated volcanic rocks. Nevertheless, fission-track dates discussed in a later section of this report area are consistent with this tentative conclusion.

An undeformed biotite-bearing rhyolitic body intruded the Jake Canyon fault zone in the northwestern part of the mountain range (fig. 2, locality B). Biotite from the intrusive rock yielded a middle Eocene K/Ar date of 44±1.6 Ma (Tysdal, 1988a) that provides a minimum age for movement on the fault.

Two small outcrops of basalt are in the southeastern part of the Blacktail Mountains. One is on top of the range and the other is on the flank, about 1,800 ft lower than the first (fig. 3). A whole-rock $^{40}Ar/^{39}Ar$ isotopic determination on the basalt near the mouth of Jake Canyon (fig. 3, locality A1; table 1) yielded a plateau date of 48.1±0.2 Ma (figs. 6, 7) that is interpreted to be the age of extrusion. The basalt flowed over mineralized gneiss and quartz but is not mineralized itself; hence, the basalt provides a minimum age constraint for the mineralization.

JAKE CANYON FAULT

The Jake Canyon fault was named for a fracture zone that is prominent near the mouth of the canyon of the same name (figs. 3, 8) (Tysdal and others, 1987). The fault trends northwest across the crystalline foreland of

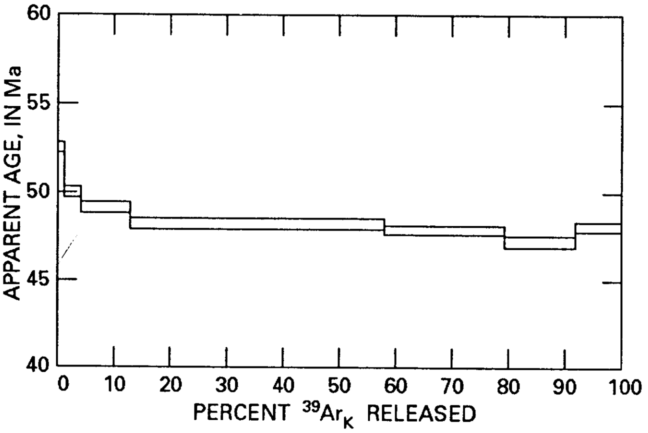

Figure 6. $^{40}Ar/^{39}Ar$ age-spectrum diagram for basalt from sample locality A1. Plateau date of 48.1 ±0.2 Ma is defined by the 800, 900, and 1,000 °C temperature steps, which comprise 66.4 percent of the $^{39}Ar_K$ released from the sample. Initial 12.9 percent of the argon displays relatively older dates probably due to excess ^{40}Ar. Final 20.6 percent of the argon is influenced by low K/Ca ratio minerals in the whole-rock sample and probably does not reflect the true extrusion age.

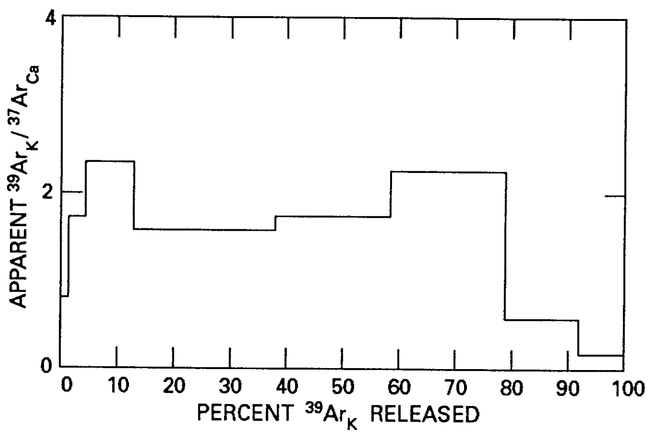

Figure 7. $^{39}Ar_K/^{37}Ar_{Ca}$ diagram for basalt from sample locality A1. Approximate K/Ca ratio of each temperature step can be obtained by multiplying the $^{39}Ar_K/^{37}Ar_{Ca}$ ratios by 0.5. Dates of the last two temperature steps comprising 20.6 percent of the total ^{39}Ar released from the sample are controlled by low K/Ca ratio minerals in the basalt whole-rock sample. Dates of intermediate temperature steps having higher K/Ca ratios are interpreted to be better representatives of the extrusion age of the basalt.

southwestern Montana and is one of many such faults that were active during the Laramide orogeny. These faults commonly show moderate to steep dips, and where Phanerozoic strata are preserved on top of the Archean metamorphic rocks, the faults are flanked by an anticline on the upthrown side and a syncline on the downthrown side. Characteristics of the northwest-trending faults and folds in southwestern Montana are summarized in regional syntheses by Schmidt and Garihan (1983) and Schmidt and others (1988) and by Brown (1988) for the Wyoming province as a whole. Schmidt and Garihan (1986) discussed the role of recurrent movement along the northwest-trending faults that began in the Proterozoic.

A composite downstructure view from southeast to northwest along the entire length of the Jake Canyon fault (fig. 2) shows that the dip of the fault changes along strike. In the southern half of the mountain range, the structurally lowest part of the fault dips 30°–40° NE.; it steepens to as much as 70° along the middle part of the range, about halfway between the letters B and C in figure 2 and farther northwest it flattens somewhat in the higher structural level. This pattern is characteristic of the northwest-trending faults of the foreland of southwestern Montana (Schmidt and Garihan, 1983).

Structures in Phanerozoic strata along the northwestern half of the Jake Canyon fault show a continuous pattern of features that resulted from localized shortening in a northeast-southwest direction related to uplift of the Blacktail Valley block. Phanerozoic strata become progressively more deformed northwestward: the number of northwest-trending faults is greater, the complexity of the fault pattern increases, strata are overturned, and rocks are more brecciated. Progressively younger strata are deformed toward the northwest where the highest structural level is exposed (Tysdal, 1988b). Conversely, in the structurally lower southeastern part of the mountain range, only Archean metamorphic bedrock remains in the footwall (figs. 2, 3).

In the southeastern half of the mountain range, within the metamorphic rocks, precise location of the Jake Canyon fault is not always readily apparent because of argillic alteration and silicification of the fault zone. The following criteria were used to trace the fault. The fault generally concides with the southwest limit of argillically altered rock (figs. 3, 8) and forms a markedly planar boundary that delimits fractured rock observed locally in the footwall. Between Riley and Jake Canyons (fig. 3), the zone of argillic alteration is wide and the fault generally coincides with an abrupt change from argillic rock to unaltered or propylitically altered gneiss. Southeast from Jake Canyon to Cottonwood Canyon, argillically altered rock locally occurs between masses of quartz and the mapped trace of the fault, but in other places quartz is adjacent to the mapped trace. Location of the fault trace for this segment in part differs from that shown by Zeigler (1954), who placed it on the northeast side of the quartz masses. We found no evidence of faulting on the northeast side of these masses. Southeast from near Cottonwood Canyon, the fault is concealed by alluvium, no prominent zone of brecciation was evident in the nearby metamorphic rocks, and the fault is inferred to lie northeast of the quartz, as mapped by Zeigler (1954).

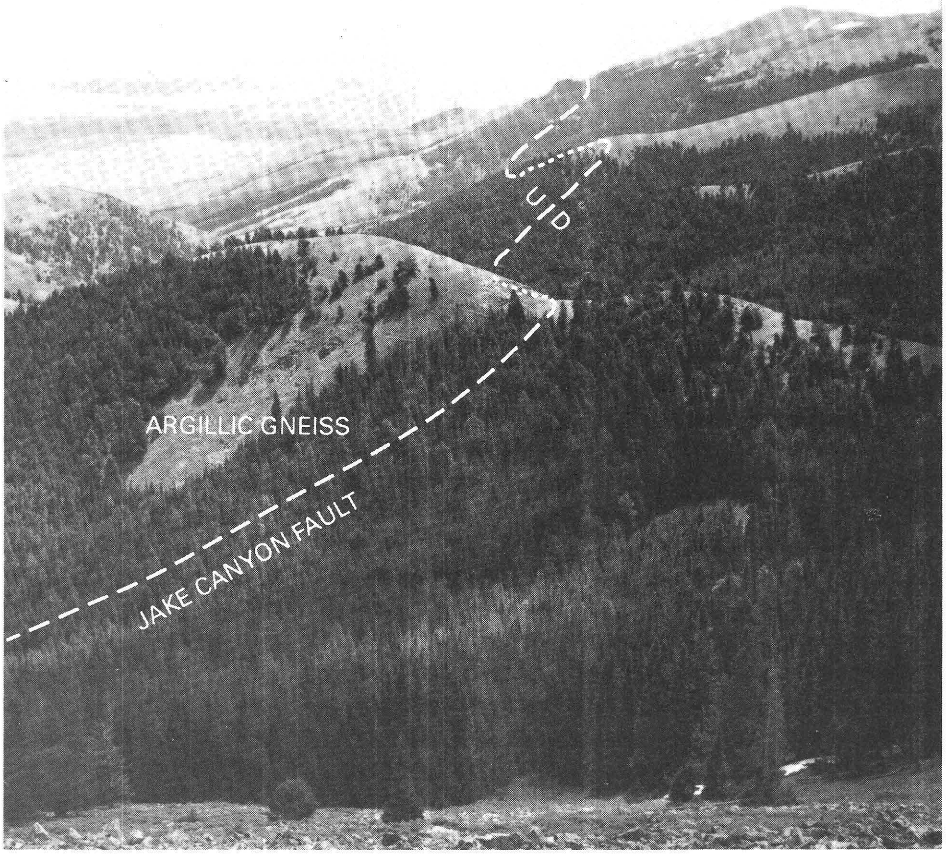

Figure 8. Trace of Jake Canyon fault. Photograph taken facing southeast along front of Blacktail Mountains.

From 0.5 mi northwest of Riley Canyon to the northwestern limit of figure 2, the fault is not exposed but is inferred to exist where drawn for two reasons. (1) The alluvial fan in this area is composed almost entirely of clasts of reddish-brown to ochre, argillically altered metamorphic rock. (2) Some of the metamorphic rocks of the footwall along the projected trace show propylitic alteration.

Part of the Jake Canyon fault may have undergone normal slip during the mid- to late Cenozoic, but the movement is localized, took place after the mineralizing hydrothermal event, and does not alter the interpretations or conclusions reached in the study. At the southeasternmost part of the map (fig. 3), chatter marks along small faults and in rhyolite (neither shown in figure) indicate down-to-the-basin movement for hanging-wall rocks. Zeigler (1954) pointed out that quartz at the range front in the same area, near the trace of the Jake Canyon fault, also is highly fractured and contains slickensides.

About 0.25 mi southeast of the Silver Queen mine (fig. 3), gouge and cataclasite formed from quartz occur on the dump of a small prospect pit northeast of the Jake Canyon fault. Only alluvium is exposed in the area of the prospect pit, thus no fault is evident. The area of basalt near sample locality A1 (fig. 3) is about 1 mi northeast of basalt that crops out about 1,800 ft higher, atop the mountains. We found no evidence to indicate that the two outcrops of basalt are offset by a normal fault; the basalt is believed to have flowed northeastward down the mountain front.

HYDROTHERMAL FEATURES

In the southeastern two-thirds of the Blacktail Mountains, the Jake Canyon fault served as a conduit for hydrothermal fluids subsequent to major movement on the fault. Propylitic and argillic alteration is widespread

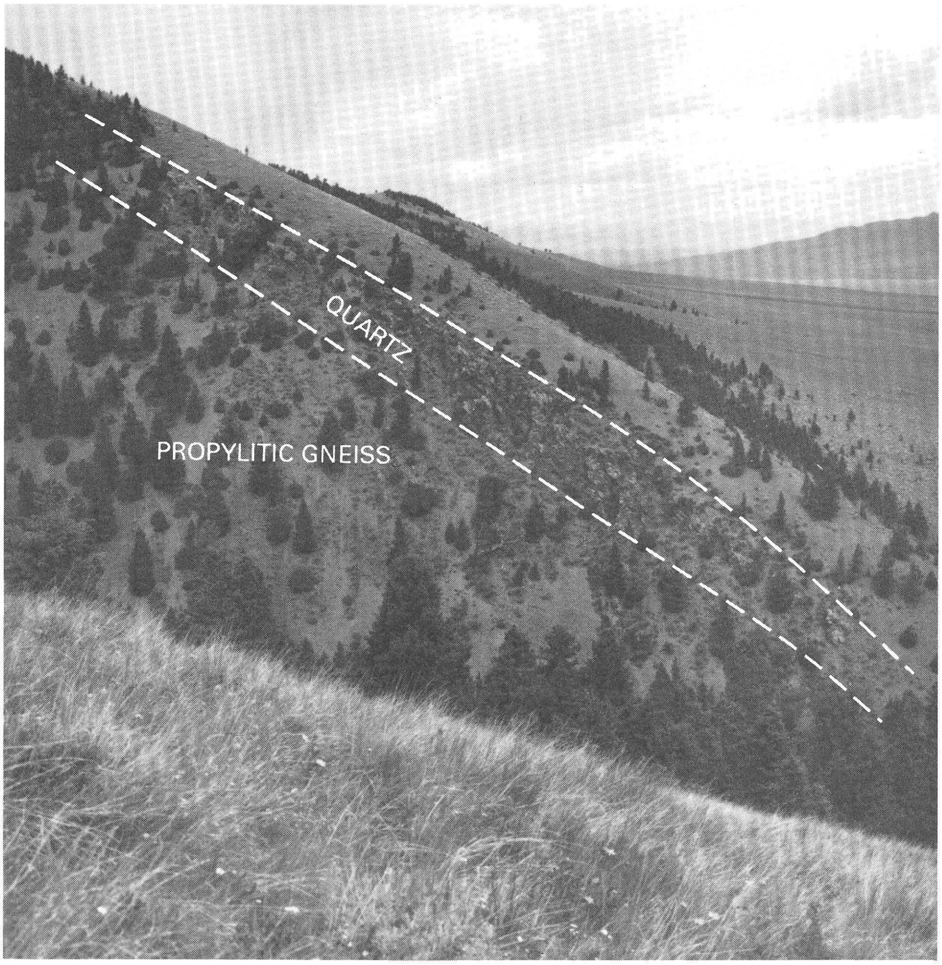

Figure 9. Tabular quartz body and propylitic gneiss on north side of Cottonwood Canyon. From valley bottom (lower right) to high part of slope (upper left) represents about 400 ft change in elevation.

in gneiss adjacent to the fault. Quartz has replaced gneiss and filled voids to form tabular and irregular masses. The hydrothermal fluids carried anomalous concentrations of arsenic, barium, copper, lead, zinc, cobalt, nickel, chromium, and silver; gold is not anomalous (Tysdal and others, 1987). According to Benham (1986), the Silver Queen mine, near the mouth of Jake Canyon (fig. 3), produced silver (8,214 ounces) and copper (988 pounds) in 1934–35. Geach (1972) believed the production came from the Nevada mine (fig. 2, point X).

Silicification

Quartz commonly forms tabular bodies several tens of feet thick (fig. 9), but near the range front, about halfway between Jake and Cottonwood Canyons (fig. 3), it forms masses as thick as several hundreds of feet. Hydrothermal fluids that precipitated the quartz along the mountain front probably moved through the most porous rocks available, and because the Archean rocks of high metamorphic grade are not porous, the favored path would have been along a zone of structural weakness, such as the Jake Canyon fault. At Cottonwood Canyon, about 0.25 mi southwest of the mountain front, a tabular quartz body as thick as 50 ft is exposed for about 1,000 ft of elevation (fig. 3). Quartz also filled fractures and minor faults in the metamorphic rocks of the footwall of the Jake Canyon fault, forming veins and pods. The quartz was called jasperoid by Tysdal and others (1987) and Tysdal (1988a), but further study shows that most of it is coarser grained than true jasperoid.

Relationships within the brecciated gneiss and crosscutting quartz veins that make up part of the tabular masses indicate that silicified rock was repeatedly fractured and cemented with additional silica. The textural evidence suggests that faulting, brecciation, and silicification were concurrent processes. Quartz has replaced brecciated metamorphic rocks at least locally. Zeigler (1954) reported orthoclase (adularia?) within quartz masses in the southeasternmost part of the area. We found potassium feldspar in only 3 of 20 thin sections and rock samples of quartz stained for potassium feldspar, where it occurred only in remnant fragments of gneiss. Pyrite is preserved locally, but more commonly sulfide minerals have been destroyed and only a boxwork texture with limonite and secondary copper minerals remains.

Argillic Alteration

Argillically altered rocks are mainly in the hanging wall of the Jake Canyon fault. Some feldspar grains have been altered to kaolinite and sparse tiny grains of sericite. Hematite is widespread. Oxidation of sulfide minerals to limonite gives the rocks a rusty-brown color that contrasts sharply with nearby green propylitic gneiss and light-gray quartz masses. Remnant sulfide grains include pyrite and chalcopyrite. Texturally these rocks are breccias. Fractures that delimit the breccia fragments are emphasized by dark-reddish-brown hematite that is concentrated along them. Interior parts of the fragments commonly are pale yellowish brown or bleached to light gray.

Propylitic Alteration

Local replacement of metamorphic rocks in the footwall rocks of the Jake Canyon fault by chlorite and epidote forms a zone of green propylitic alteration that ranges from a few tens of feet to a few hundreds of feet wide. This alteration was first observed by Zeigler (1954) in the southeasternmost part of the study area. Zeigler reported chloritic alteration only on the southwest side of the quartz masses, but we have found chloritic rock on both sides. Chlorite and epidote also are associated with hydrothermal quartz in the tabular quartz masses.

The zone of propylitic alteration on the hanging wall of the Jake Canyon fault is much wider than that on the footwall, most notably in the area surrounding the tabular quartz body southeast of Cottonwood Canyon. Archean gneiss of the hanging wall northeast of the tabular quartz body is entirely propylitized, whereas gneiss in the footwall directly southwest of the quartz shows no propylitic alteration in outcrop. Propylitic rocks are zoned at least locally. Directly southwest of the quartz bodies at the mouth of Jake Canyon, the propylitized rocks contain epidote within a zone that is tens of feet wide, but epidote is absent from chloritic propylitized rocks farther to the southwest.

Zonation of Hydrothermal Alteration

Lateral variation in the abundance of quartz and argillic rock along strike of the Jake Canyon fault may reflect vertical zonation. Extending for 6 mi southeast of Jake Canyon, quartz masses are most extensive between about 7,000 and 7,400 ft in elevation, and argillic rock forms only a narrow zone adjacent to the fault. For 2 mi northwest of Jake Canyon, quartz is generally absent, outcrops are between about 7,400 and 8,000 ft in elevation, and the zone of argillic rock is much broader. Viewing the Jake Canyon fault along strike, the wide zone of argillic rock lies structurally higher than the zone bearing abundant quartz. Optimum conditions for deposition of quartz from the hydrothermal fluids may have existed at what is now the 7,000–7,400-ft elevation. At Riley Canyon (fig. 3), the presence of small masses of quartz at about 7,000 ft elevation suggests that, between Jake and Riley Canyons, quartz may lie concealed within the Jake Canyon fault zone at the 7,000–7,400-ft elevation. Alternatively, hydrothermal fluids may have been generally absent from the area north of Jake Canyon.

The masses of quartz show a close spatial relationship with the propylitized metamorphic rocks. Southeast of the mouth of Jake Canyon metamorphic rocks of the footwall are almost entirely propylitically altered, but northwest of the canyon no propylitic alteration is evident in outcrops except near the Riley Canyon area. Furthermore, quartz forms veins and pods in fractures and small faults in the propylitized gneiss of the footwall and hanging wall. As expected from this correlation, propylitized metamorphic rocks are absent from the footwall of the segment of the Jake Canyon fault between Jake and Riley Canyons.

TEMPERATURE DURING ALTERATION

The maximum temperature attained by the hydrothermal fluids during alteration of the metamorphic rocks can be estimated by the occurrence of certain minerals. In the propylitized rocks, epidote is such a mineral. Epidote in modern hydrothermal systems, which is the genetic model envisioned for the mineralization along the fault zone, commonly is stable from about 200 to 350 °C (Henley and Ellis, 1983). Thus, the presence of epidote gives an approximate lower temperature for alteration within the propylitic zone. Epidote was found only sparingly in thin sections, however, and only in some areas of propylitic alteration. The absence of epidote could imply temperatures below the stability field of epidote, inappropriate chemistry or fluid pressures, or sluggish kinetic reaction. Therefore, homogenization temperatures of fluid inclusions in the hydrothermal quartz were measured as an independent approach to determine the temperature of the mineralizing event.

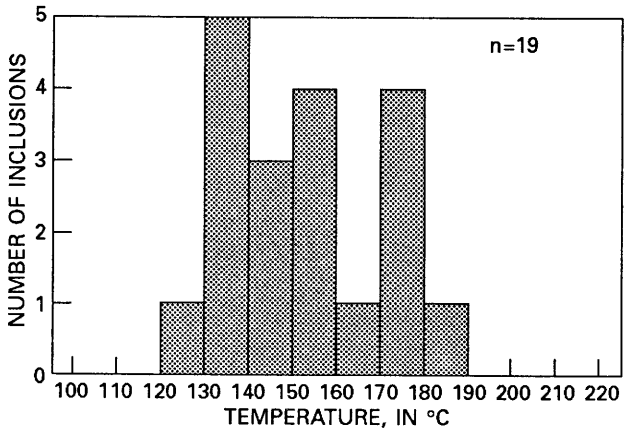

Figure 10. Histogram of homogenization temperatures for primary and secondary fluid inclusions in quartz.

Fluid-Inclusion Data

In the thin sections examined for fluid inclusions, quartz generally is very fine grained, but it is coarser grained in succeeding generations. Some of the later quartz is faintly zoned, but most of it forms a mosaic of small, interlocking grains. Doubly polished thick sections were prepared from four samples of fault-filling quartz. All four samples were from localities adjacent to those collected for fission-track studies (fig. 3, sample localities I1–I4). Care was taken to minimize preparation-related thermal damage of the samples. The sections were heated and frozen using a Fluid, Inc., modified U.S. Geological Survey gas-flow heating-freezing stage. Replicate homogenization temperature measurements indicate an accuracy of about ±0.3 °C.

Few usable inclusions were found in the samples, mostly because of the extremely fine grain size of the quartz. The later stage quartz contained the most inclusions, but the vast majority of the inclusions were too small (<2 microns) to be optically resolvable. Two samples (from localities I1 and I3) had no resolvable inclusions. Measured inclusions were between 4 and 15 microns in diameter.

All of the measured inclusions were liquid-dominant, two-phase aqueous inclusions, in which the vapor phase occupied 10–15 volume percent of the inclusion. No daughter minerals were observed. Homogenization temperatures are shown in figure 10. Primary inclusions were trapped mostly between 170 and 183 °C, whereas secondary inclusions along microfractures had somewhat lower homogenization temperatures, between 128 and 157 °C. All inclusions homogenized to a liquid phase.

The small size of the inclusions precluded detailed freezing studies. Melting temperatures of two inclusions, however, indicate salinities of approximately 2-weight percent NaCl equivalent, and the temperature of first melting (eutectic) on one indicates that sodium was the dominant cation. Based upon geologic considerations, a reasonable depth of formation for the quartz veins sampled is about 5,000 ft, equivalent to a hydrostatic pressure of approximately 150 bars. At a depth of 5,000 ft and a temperature of 175 °C, 2-weight percent NaCl solution requires a pressure correction of about +10 to +15 °C (Potter, 1977). The fluid-inclusion data indicate that the fluids from which the quartz precipitated had a temperature of about 190 °C. Therefore, the homogenization temperatures are just slightly lower than the actual trapping temperatures.

In summary, the fluid-inclusion data indicate a temperature of 190 °C for late-stage mineralization. This is probably a minimum temperature for the mineralizing event because late-stage minerals are typically deposited at cooler temperatures than earlier main-stage minerals. The presence of epidote suggests a temperature greater than 200 °C, as does the minor argon loss in muscovite. The lack of major argon loss, however, indicates that the hydrothermal system did not exceed the muscovite argon retention temperature of 270 °C. Therefore, a reasonable temperature range estimate for the hydrothermal system is 190–270 °C.

FISSION-TRACK STUDIES

Sampling was designed to answer two questions. (1) What is the age of the quartz and associated mineralization? Samples from the propylitically altered rocks were collected for dating the hydrothermal event. Apatite was chosen for dating because of the low temperature at which the fission-track dates are reset (well below the temperature of mineralization, as confirmed by fluid inclusion studies). (2) Did the gneissic terrane on opposite sides of the Jake Canyon fault experience similar uplift-erosion histories prior to the hydrothermal event? Slivers of gneiss emplaced above Paleozoic strata along the northwestern half of the Blacktail Mountains could have undergone as much as 5,000–10,000 ft of reverse movement along the Jake Canyon fault during the Laramide orogeny, based on displacement on comparable faults in the Ruby Range to the north (Tysdal, 1976). Given the probable depth of burial and the associated temperature of the sampled rocks prior to removal of the sedimentary section, it is possible that the fission-track dates of the apatite could record the erosional history in areas beyond the thermal effects of the mineralogical alteration. Samples of rock from which apatite was recovered were collected initially from about equal elevations on both sides of the Jake Canyon fault, outside the obviously hydrothermally altered rocks of the propylitic and argillic zones. Other samples of gneiss, farther from the fault and at greater elevation, also were collected.

Table 2. Fission-track analytical data for apatite

[Track density given in 10^5 tracks per cubic centimeter. Tracks counted given in parentheses. Age at 95 percent confidence interval]

Locality no.	Sample	Latitude (north)	Longitude (west)	Elevation (feet)	No. of grains	Track density: Fossil	Track density: Induced	Track density: Monitor	Age (Ma)
F1	84MTz254	44°58'25"	112°30'18"	7,050	9	19.3 (649)	39.4 (1,325)	0.260 (1,508)	69±7
F2	84MTz161B	44°58'02"	112°29'59"	6,840	11	12.0 (764)	26.3 (1,669)	0.263 (1,508)	65±7
F3	85MTz719	44°57'53"	112°30'18"	7,040	10	10.0 (861)	17.9 (1,538)	0.237 (1,508)	72±7
F4	84MTz214	44°58'05"	112°28'58"	6,975	8	22.9 (844)	43.6 (1,606)	0.252 (1,508)	72±7
F5	85MTz720	44°57'51"	112°27'52"	6,860	10	15.4 (946)	33.9 (2,078)	0.233 (1,508)	57±5
F6	85MTz713	44°56'24"	112°27'45"	8,850	10	13.6 (854)	25.6 (1,609)	0.256 (1,508)	74±7
F7	85MTz715	44°56'16"	112°27'01"	7,950	13	14.8 (1,093)	32.1 (2,363)	0.248 (1,508)	60±7*
F8	85MTz716	44°56'05"	112°26'40"	7,050	10	11.2 (1,064)	25.8 (2,442)	0.263 (1,526)	62±6
F9	85MTz717B	44°56'18"	112°26'16"	6,950	10	3.5 (254)	4.9 (354)	0.240 (1,508)	93±16

*Sample failed chi-square statistical test, as explained in text.

Methods

Apatite concentrates from nine samples were dated by the fission-track method, and these dates are presented in table 2. Details of the fundamentals and specific techniques employed are described in Fleischer and others (1975) and Naeser (1976). The samples were dated by using the external detector technique. Two irradiations were performed in the U.S. Geological Survey TRIGA reactor lazy-susan facility at a power of 200 kW. The irradiations were monitored with National Bureau of Standards glass SRM 614 using muscovite detectors. Apatite fission-track dates were calibrated relative to the age-standard apatite from the Fish Canyon Tuff, from which biotite yields an $^{49}Ar/^{39}Ar$ plateau date of 27.79±0.14 Ma (Kunk and others, 1985). The "zeta" calibration technique of Hurford and Green (1983) was employed using a zeta value of 10,830±190, an average value and standard deviation of the mean of four independent determinations.

Apatite samples were etched in 6-percent nitric acid at 20 °C for 40 seconds. Muscovite detectors placed over the apatite samples during neutron irradiation were etched in 48-percent hydrofluoric acid at 20 °C for 20 minutes. Both apatite and detector tracks were counted using an oil immersion objective at about ×1500 magnification. Track lengths in three of the samples were measured after etching in 6-percent nitric acid at 20 °C for 60 seconds. Horizontal, confined, bladelike tracks were measured using an electronic digitizer and microscope drawing-tube arrangement.

Each sample was evaluated statistically to determine not only the uncertainty in the mean ages reported but also the internal consistency of dates for individual grains within a particular sample. The assumptions tested are as follows: (1) the sample is age homogeneous, and (2) the only significant source of scatter between individual grain ages is due to Poisson-distributed decay-activation probability. Squared deviations from the mean sample age for individual grains in the sample were evaluated by a chi-square test. Samples failing this test (less than 5 percent X^2 probability) are interpreted as possessing excessive experimental scatter. Only the sample from locality F7 failed this test. Its age and uncertainty were calculated as the weighted-mean grain age by using the observed scatter of grain ages (noted with an asterisk in table 2). For all other samples, the age and its uncertainty were calculated by summing individual grain counting data and using the Poisson estimate of error for the summed fossil, induced, and neutron fluence monitor counts. These three uncertainties were then combined to produce an age uncertainty by using a first-order approximation for variance in the age (Kendall and Stuart, 1963, p. 232) for these random variables that have no correlation between them. The uncertainties cited in table 2 represent 95-percent confidence intervals. Neither individual grain dates nor sample dates were calculated until data for the entire study had been collected in order to eliminate one source of experimenter bias.

Fission tracks in apatite, as in other minerals, are affected by elevated temperatures applied over time. The chemical etching that makes the tracks optically visible reveals fewer tracks (lower track densities) and shorter tracks as both temperature and duration of heating increase. There is considerable debate as to the appropriate mathematical model relating time, temperature, and track fading in apatite (Green and others, 1988). The interpretation used here is that originally proposed by Zimmermann (1977) and Zimmermann and Gaines (1979), a first-order kinetic model to explain the fading (disappearance) of fission tracks. This approach is geologically accurate in predicting fission-track dates in well-defined geological settings (Zimmermann, 1977, unpublished data).

The concept used to interpret the temperature significance of these dates is that of closure temperature, the temperature at which the apparent age is zero (Dodson, 1973). The closure temperature has a direct geological significance as a time-temperature datum because it is a function of the kinetics of track fading in the apatite and additionally of the rate of cooling around the closure temperature. The model used here predicts closure temperatures of from 87 to 129 °C for cooling rates between 0.1 and 100 °C/m.y. Rather than using more detailed modeling procedures, a closure temperature interpretation is allowed here because all tracks existing at the time of the mineralizing event were removed. This is known because corrected homogenization temperatures in fluid inclusions of about 190 °C provide evidence of a temperature sufficiently high to rapidly anneal preexisting tracks. Furthermore, the track length measurements (fig. 11) discussed below show no evidence of a population of short tracks such as would result from only a partial removal of premineralization tracks.

Interpretation

Fission-track ages determined on apatite from the nine samples are shown in table 2. Seven of the nine samples yielded ages in the range of 74–60 Ma; that is, latest Cretaceous (Maastrichtian) to middle Paleocene. One-way analysis of variance of the individual grain ages of all samples supports the interpretation that these seven samples are from a single population of age 68±4 Ma (all sample errors are cited at the 95-percent confidence level). The sample from locality F5 yielded an age of 57±6 Ma, which is significantly younger than the other ages, and the sample from locality F9 yielded an age of 93±16 Ma, considerably older than the other ages. On geologic grounds we consider the ages from localities F5 and F9 to be anomalous, as explained later.

Track lengths in the samples that yielded the anomalous ages (localities F5, F9) were compared with track lengths in a sample (locality F2) considered representative of the non-anomalous population of seven samples that has a mean age of 68 Ma. Only the sample from locality F2 shows a significant number of extremely short tracks (<9 μm) but no statistically significant differences exist between these distributions (largest Kolmogorov-Smirnov statistic, 0.33). Within the limits of these measurements, samples from localities F5 and F9 show no evidence of significant partial resetting. On statistical grounds alone, this suggests that the low and high ages are due to causes other than reheating, such as real, albeit extreme statistical variation in the age determinations or, in the case of F9, an artifact of the poor quality of the sample (low track density and high inclusion and defect background).

One possible geological explanation for the young age of apatite from locality F5 is that the sampled rock was affected by heat from the basalt dated at 47.9±0.3 Ma. The apatite fission-tracks of the gneiss could have been annealed by heat from the flow, an effect we are unable to detect in our track-length measurements. The outcrop area of the gneiss may have been in direct contact with the basalt flow, which has been partly eroded and the remainder now is about one-eighth of a mile from the sample locality.

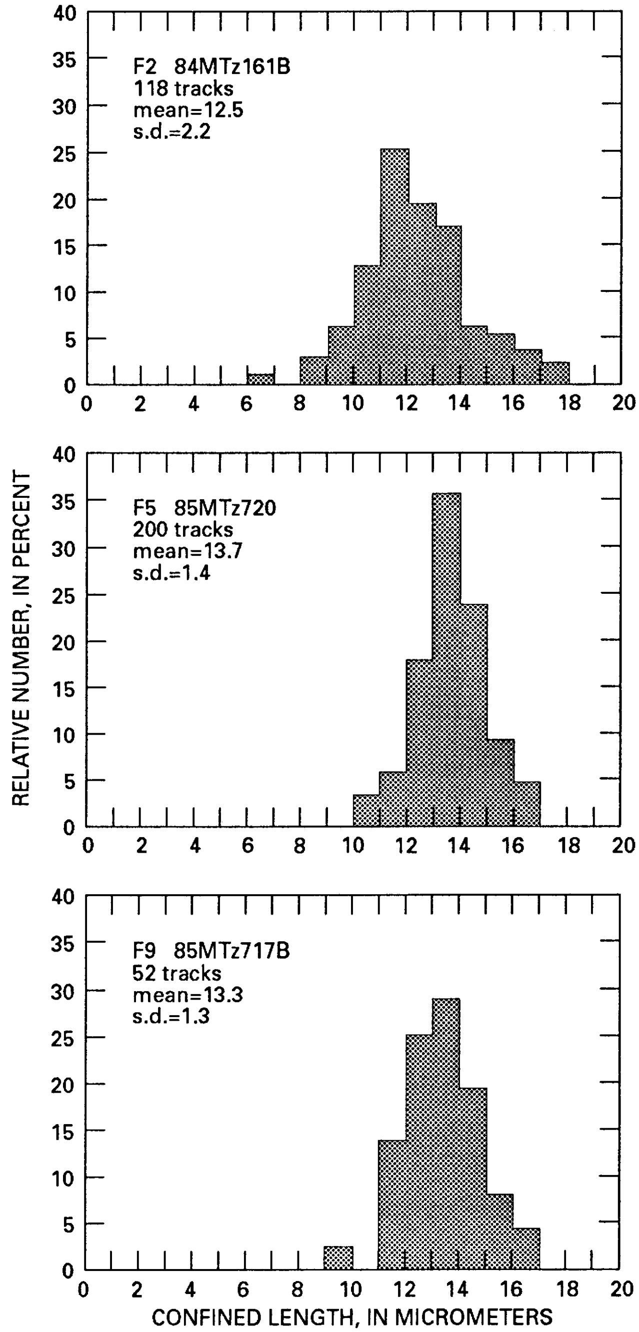

Figure 11. Track-length distributions of apatite from localities F2, F5, and F9. The distributions are statistically identical and suggest a simple but rapid cooling history.

The 93±16-Ma date on apatite of locality F9, from propylitically altered rock, is considered erroneous as an age of hydrothermal alteration and faulting for the following geological reasons. The Beaverhead Group in the northwestern part of the Blacktail Mountains was deformed into a syncline during this movement (fig. 2). Deformed mixed-clast conglomerate of the Beaverhead in the Blacktail Mountains and directly to the west contains quartzite clasts from the Belt Supergroup that generally occur in upper strata of the Beaverhead and, as discussed previously, in the general region are known only in conglomerate younger than 72-Ma volcanic rocks. These ages for strata of the Beaverhead are considerably younger than the age obtained for the sample from locality F9.

Two lines of reasoning permit us to place constraints on the age of hydrothermal alteration and hence movement in the Jake Canyon fault. Geological evidence constrains mineralization between the time of initial deposition of the Beaverhead Group at 88 Ma, based on the paleontological age (72 Ma, if the appearance of Belt Supergroup clasts in the upper part of the Beaverhead in the Blacktail Mountains is coeval with their appearance in mountains a few miles to the west) (Meyer, 1980; Snee, 1982; Ivy, 1989; Pearson and Childs, 1989), and 48 Ma, the age of the unaltered basalt overlying the mineralized gneiss.

The $^{40}Ar/^{39}Ar$ date of the basalt, homogenization temperatures of the fluid inclusions produced during the mineralizing event, and the apatite fission-track cooling date provide three reference points of the cooling history from which interpretation of the age of mineralization can be made (fig. 12). First, we know the minimum temperature, 190 °C, but not the age of mineralization. Second, we know the apatite fission-track date of 68±4 Ma and can estimate the closure temperature it represents if we have an estimate of cooling rate after the mineralization. Last, we know that the present surface was exposed before the basalt flowed across it at 48.1±0.2 Ma. Because cooling probably was most rapid just after the mineralizing event (the fluids were hotter than ambient temperature), a linear extrapolation among these data provides a maximum estimate for the age of mineralization. At about 48 Ma, the apatite grains dated were at a temperature of about 20 °C and already would have yielded a date of about 18 Ma. From this information, a closure temperature of 110 °C can be calculated (after Dodson, 1973, and Zimmermann and Gaines, 1979). Linear extrapolation back to the 190 °C minimum temperature shows that mineralization could have occurred as long ago as 86 Ma. As explained previously, deformation of the Beaverhead Group during movement along the Jake Canyon fault indicates that the hydrothermal event is younger than the maximum age of 86 Ma suggested by linear extrapolation. The hydrothermal event would be only slightly older than that indicated

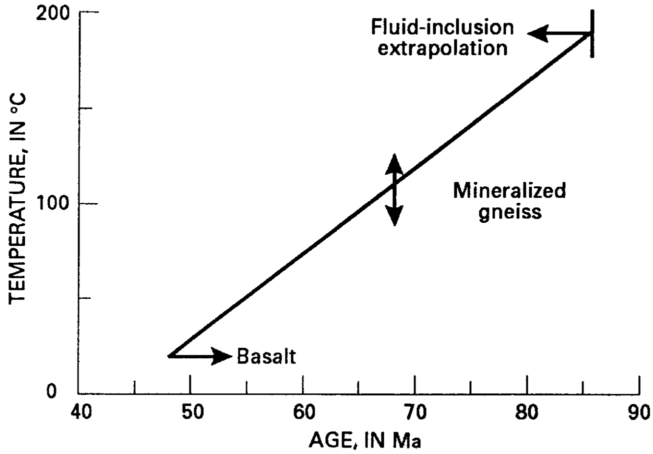

Figure 12. Schematic cooling history of hydrothermal event derived from (1) $^{40}Ar/^{39}Ar$ plateau date of the basalt, which represents the minimum age of exposure of the crystalline basement rocks, (2) apatite fission-track cooling age, (3) post-mineralization cooling reference, and (4) fluid-inclusion homogenization temperature of late-stage mineralization, based on temperatures of late-stage mineralization. The maximum age of mineralization is 86 Ma. See text for explanation.

by the cooling age. In summary, we consider the hydrothermal event and cessation of movement along the Jake Canyon fault to be of Late Cretaceous age.

So far, our discussion has assumed that all of the isotopic dates are directly related to cooling of rock heated during the hydrothermal event. The dates, however, may reflect cooling due to denudation that accompanied uplift. If the dates do reflect uplift and denudation, then the hydrothermal event that produced the quartz and mineralization took place at a depth greater than the closure temperature and earlier than the dates recorded in the apatites. The apatite dates were then set when overlying rocks were eroded and the hydrothermally altered rocks passed through the closure temperature. The age of the hydrothermal event would be older than the age of uplift and erosional stripping of overlying rock, but not by much because the Campanian to Maastrichtian to Tertiary(?) Beaverhead Group was deformed during movement along the Jake Canyon fault and the brecciation and silicification observed in the mineralized rock indicate active deformation during mineralization.

Fission-track sample localities F6 and F7 are farthest from the Jake Canyon fault and are outside the alteration zone, but they did not yield dates significantly different from those obtained from the other localities. If the apatite dates do represent resetting due to thermal effects associated with the Jake Canyon fault, then one would expect the apatite dates of samples distant from the fault to be less affected, if at all, by this event. In plan view, sample localities F6 and F7 are distant from the

Jake Canyon fault and outside the zone of hydrothermal alteration; however, if cross section *A–A′* (fig. 3) is used to project the Jake Canyon fault above the present erosional surface, it can be seen that the terrane containing sample localities F6 and F7 was, in fact, close to the fault and, therefore, to any thermal effects localized along the fault. The thermal effects, however, are not recorded by chemical alteration of minerals. One could argue that the zone of alteration is controlled by the availability of fluids and by accessibility of the rocks to fluid flow, in this case along the fault plane itself, and that the thermal effects sufficient to reset the apatite dates (significantly less than 190 °C) extended beyond the zone of mineralogic alteration.

If the Jake Canyon fault zone was mineralized when its presently exposed trace was at a depth where equilibrium temperatures were greater than the apatite closure temperature, then the apatite dates would be recorded only as denudation proceeded, eventually leading to the present level of exposure. Apatite dates would decrease with decreasing elevation. Given the mean age of the apatites and the fact that the present surface was exposed prior to extrusion of basalt at about 48 Ma and assuming a steep geothermal gradient (30 °C/km), we can estimate that the greatest age difference expected over the range of elevations sampled here is 4 m.y. This difference is well within the scatter of the data set and could not be detected. An argument against uplift and denudation subsequent to mineralization as a cause of resetting can be made based on the maximum depth of the basement prior to mineralization. As previously stated, we estimated a thickness of only about 5,000 ft of Phanerozoic cover above the Archean basement rocks at the time of the thermal event. Additional strata, in particular those of (pre-Beaverhead) Cretaceous (?) age, may have been present and thus increased the maximum depth of burial at the time of the thermal event. But we question that the depth of burial would have been adequate at the Archean-Phanerozoic unconformity to have raised temperatures sufficiently to cause resetting and then to register uplift in the Mesozoic. In fact, one might suspect that apatite dates in the upper part of the crystalline Archean basement should still record the pre-Phanerozoic exposure history of the basement (that is, ages older than the oldest overlying sedimentary formations). In retrospect, the ideal sampling locality for differentiating between the mineralization and uplift models, as well as testing for depth of burial required to establish viability of an uplift interpretation, is at a lower elevation west of the range crest. There, basement rocks are far removed from the thermal effects associated with mineralization along the Jake Canyon fault but not too far beneath the original basement-Phanerozoic unconformity.

CONCLUSIONS

In the southeastern half of the Blacktail Mountains, the Jake Canyon reverse fault juxtaposed Archean metamorphic rocks, mainly gneiss, against other Archean gneiss. Circulation of hydrothermal fluids within the fault zone produced propylitic and argillic alteration of gneiss and introduced silica that replaced gneiss, forming tabular bodies of quartz. Repeated fracturing and annealing of the quartz indicates that emplacement of the silica was concurrent with faulting. The temperature of quartz formation and hydrothermal alteration along the fault zone was between 190 °C, based on fluid-inclusion data, and 270 °C, based on muscovite $^{40}Ar/^{39}Ar$ age spectra. The data are interpreted to indicate that the hydrothermal event and movement along the Jake Canyon fault took place before the end of the Cretaceous. The fission-track dates could be either uplift ages, reflecting the time of uplift of the mountain range and cooling of the gneiss and hydrothermally altered rock, or cooling ages, reflecting the age of cooling of the altered rocks associated with the hydrothermal event, in which case the mountain range already would have been uplifted through the closure temperature for apatite. We believe the second alternative is the more likely of the two.

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APPENDIX

Appendix. Procedures and techniques for $^{40}Ar/^{39}Ar$ dating of samples from localities A1 and A2

The isotopic composition of argon was measured in the $^{40}Ar/^{39}Ar$ laboratory at the U.S. Geological Survey, Denver, Colo., using a MAP 215 Series rare gas mass spectrometer made by Mass Analyzer Products Limited. Radiogenic ^{40}Ar is total ^{40}Ar derived from natural radioactive decay of ^{40}K after all corrections for non-decay-derived ^{40}Ar have been made. K-derived ^{39}Ar is total ^{39}Ar derived from the epithermal neutron-induced reaction $^{39}K(n,p)^{39}Ar$ after corrections for non-^{39}K-derived ^{39}Ar are made. *F* is the quantity resulting from the division of the amount of radiogenic ^{40}Ar by the amount of K-derived ^{39}Ar. Quantities for radiogenic ^{40}Ar and K-derived ^{39}Ar are given in volts of signal measured on a Faraday detector by a digital voltmeter. Mass spectrometer sensitivity at time of measurement was 9.736×10^{-13} moles Ar per volt of signal. The measured atmospheric $^{40}Ar/^{36}Ar$ ratio used for mass discrimination correction is 298.9. Basalt sample 84MTZ208 and muscovite sample 85MTZ319A were irradiated at 2 MW for 75 hours in the University of Michigan Phoenix nuclear reactor facility in Ann Arbor, Mich.; the muscovite sample also was irradiated for 100 hours at 1 MW in the U.S. Geological Survey TRIGA reactor in Denver, Colo. The neutron flux monitor used in this study was hornblende MMhb–1, the age of which is 519.4 Ma (Alexander and others, 1978); errors of 0.5 percent (68-percent confidence level) in the calculated *J*-value for samples irradiated at the University of Michigan and 0.25 percent for the sample irradiated at the U.S. Geological Survey were determined experimentally by calculating the reproducibility of multiple monitors. Corrections for irradiation-produced, interfering isotopes of argon were made by measuring production ratios for the interfering isotopes of argon produced in pure K_2SO_4 and CaF_2 irradiated simultaneously with the samples of this study. Those ratios for the irradiation at the University of Michigan as determined from five measurements of each salt with errors at 68-percent confidence level are $(^{36}Ar/^{37}Ar)_{Ca} = 2.73 \pm 0.01 \times 10^{-4}$, $(^{39}Ar/^{37}Ar)_{Ca} = 6.92 \pm 0.03 \times 10^{-4}$, $(^{38}Ar/^{37}Ar)_{Ca} = 5.11 \pm 0.18 \times 10^{-5}$, $(^{40}Ar/^{39}Ar)_K = 3.391 \pm 0.366 \times 10^{-2}$, $(^{37}Ar/^{39}Ar)_K = 1.70 \pm 0.57 \times 10^{-4}$, and $(^{38}Ar/^{39}Ar)_K = 1.229 \pm 0.002 \times 10^{-2}$. The average production ratios for samples irradiated at the U.S. Geological Survey as determined from two measurements of each salt are $(^{36}Ar/^{37}Ar)_{Ca} = 2.57 \times 10^{-4}$, $(^{39}Ar/^{37}Ar)_{Ca} = 1.25 \times 10^{-3}$, $(^{38}Ar/^{37}Ar)_{Ca} = 6.84 \times 10^{-5}$, $(^{40}Ar/^{39}Ar)_K = 1.20 \times 10^{-2}$, $(^{37}Ar/^{39}Ar)_K = 4.48 \times 10^{-4}$, and $(^{38}Ar/^{39}Ar)_K = 1.3 \times 10^{-2}$. Corrections were made for additional interfering isotopes of argon produced from irradiation of chlorine using the method described by Roddick (1983). Quantities of ^{37}Ar and ^{39}Ar were corrected for radioactive decay. $^{39}Ar/^{37}Ar$ ratios used on the diagram were corrected for radioactive decay of ^{37}Ar and ^{39}Ar and for interfering isotopes. *Relative*, approximate K/Ca distribution of the samples may be obtained by multiplying the $^{39}Ar/^{37}Ar$ ratios by approximately 0.5. Constants used in age calculations are those of Steiger and Jäger (1977). Error estimates for apparent ages of individual temperature steps were assigned by using the equations of Dalrymple and others (1981); however, the equations were modified to allow the option of choosing the larger of separately derived errors in the *F*-value—either a calculated error from differential equations or an experimentally determined error determined from the reproducibility of identical samples. Age plateaus were determined by comparing contiguous gas fractions using the Critical value test described by Dalrymple and Lanphere (1969), and the error was determined by the equations of Dalrymple and others (1981). All raw data are available from the authors.

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