2004

^{40}Ar/ ^{39}Ar Ages of Metamorphic Rocks from the Tobacco Root Mountains Region, Montana

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Geological Society of America
Special Paper 377
2004

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ABSTRACT

Measurements of 60 single-grain, UV laser microprobe $^{40}Ar/^{39}Ar$ total gas ages for hornblende from metamorphic rocks of the Tobacco Root Mountains in southwest Montana yield a mean age of 1.71 ± 0.02 Ga. Measurements of $^{40}Ar/^{39}Ar$ step-heating plateau ages of three bulk hornblende samples from the Tobacco Root Mountains metamorphic rocks average 1.70 ± 0.02 Ga. We believe that these and the K/Ar or $^{40}Ar/^{39}Ar$ ages reported by previous workers are cooling ages from a 1.78 to 1.72 Ga, upper-amphibolite to granulite facies, regional metamorphism (Big Sky orogeny) that affected the northwestern portion of the Wyoming province, including the Tobacco Root Mountains and adjacent ranges. Based on the $^{40}Ar/^{39}Ar$ data, this 1.78–1.72 Ga metamorphism must have achieved temperatures greater than ~500 °C to reset the hornblende $^{40}Ar/^{39}Ar$ ages of samples from the Indian Creek Metamorphic Suite, which was previously metamorphosed at 2.45 Ga, and of the crosscutting metamorphosed mafic dikes and sills (MMDS), which were intruded at 2.06 Ga. Biotite and hornblende from the Tobacco Root Mountains appear to give the same $^{40}Ar/^{39}Ar$ or K/Ar age (within uncertainty), indicating that the rocks cooled rapidly through the interval from 500 to 300 °C. This is consistent with a model of the Big Sky orogeny that includes late-stage tectonic denudation that leads to decompression and rapid cooling. A similar cooling history is suggested by our data for the Ruby Range. Three biotite samples from the Ruby Range yield $^{40}Ar/^{39}Ar$ step-heating plateau ages with a mean of 1.73 ± 0.02 Ga, identical to the best-estimate (near-plateau) age for a hornblende from the same rocks. Two samples of the orthoamphibole, gedrite, from the Tobacco Root Mountains were studied, but did not have enough K to yield a reliable $^{40}Ar/^{39}Ar$ age. Several biotite and three hornblende samples from the region yield $^{40}Ar/^{39}Ar$ dates significantly younger than 1.7 Ga. We believe these samples were partially reset during contact metamorphism by Cretaceous (75 Ma) intrusive rocks. Hydrothermal alteration associated with ca. 1.4 Ga rifting led to growth of muscovite with that age in the Ruby Range, but this alteration was apparently not hot enough to reset biotite and hornblende ages there.

Keywords: Wyoming province, Big Sky orogeny, Proterozoic era.

Brady, J.B., Kovaric, D.N., Cheney, J.T., Jacob, L.J., and King, J.T., 2004, $^{40}Ar/^{39}Ar$ ages of metamorphic rocks from the Tobacco Root Mountains region, Montana, *in* Brady, J.B., Burger, H.R., Cheney, J.T., and Harms, T.A., eds., Precambrian geology of the Tobacco Root Mountains, Montana: Boulder, Colorado, Geological Society of America Special Paper 377, p. 131–149.

INTRODUCTION

The Tobacco Root Mountains of southwestern Montana (Fig. 1) are cored by metamorphic rocks of the Wyoming province that are believed to have a geologic history spanning at least 3 Ga. Sensitive high-resolution ion microprobe (SHRIMP) dating of individual Tobacco Root Mountain zircons by Mueller et al. (1998) yielded detrital zircon core ages of 3.2 to 3.9 Ga, with none younger than 2.9 Ga. Although Rb/Sr studies by Mueller and Cordua (1976) and by James and Hedge (1980) yielded a whole-rock age of 2.7 Ga for the metamorphic rocks of this region, consistent with similar ages reported for the central Wyoming province, recent work on U and Pb isotopes of monazite and zircon (Krogh et al., 1997; Burger et al., 1999; Cheney et al., 1999; Dahl et al., 1999; Roberts et al., 2002; Dahl et al., 2002; Cheney et al., 2004b, this volume, Chapter 8; Mueller et al., 2004, this volume, Chapter 9) has identified metamorphic events in the Tobacco Root Mountains at 2.45 Ga and between 1.78 and 1.72 Ga with no clear evidence for a 2.7 Ga event.

Early K/Ar studies of biotite in southwest Montana by Hayden and Wehrenberg (1959, 1960) demonstrated that the Tobacco Root Mountains rocks experienced a heating event at 1.7 Ga that was not observed in the Archean rocks of the Beartooth Plateau. Giletti and Gast (1961) using Rb/Sr data for micas and Giletti (1966, 1968) using K/Ar and Rb/Sr data for micas and whole rocks showed that the entire northwestern portion of the Wyoming province was heated at 1.6–1.7 Ga, including the Tobacco Root Mountains and adjacent Ruby Range and Highland Mountains. Giletti (1966) presented a map of the Wyoming province showing a line that divided the 1.6–1.7 Ga terrane from the rest of the Wyoming province. Marvin and Dobson (1979) also reported 1.7 Ga K/Ar ages for muscovite in a pegmatite and for hornblende in gneiss from the northern Tobacco Root Mountains. However, because the studies of Mueller and Cordua (1976)

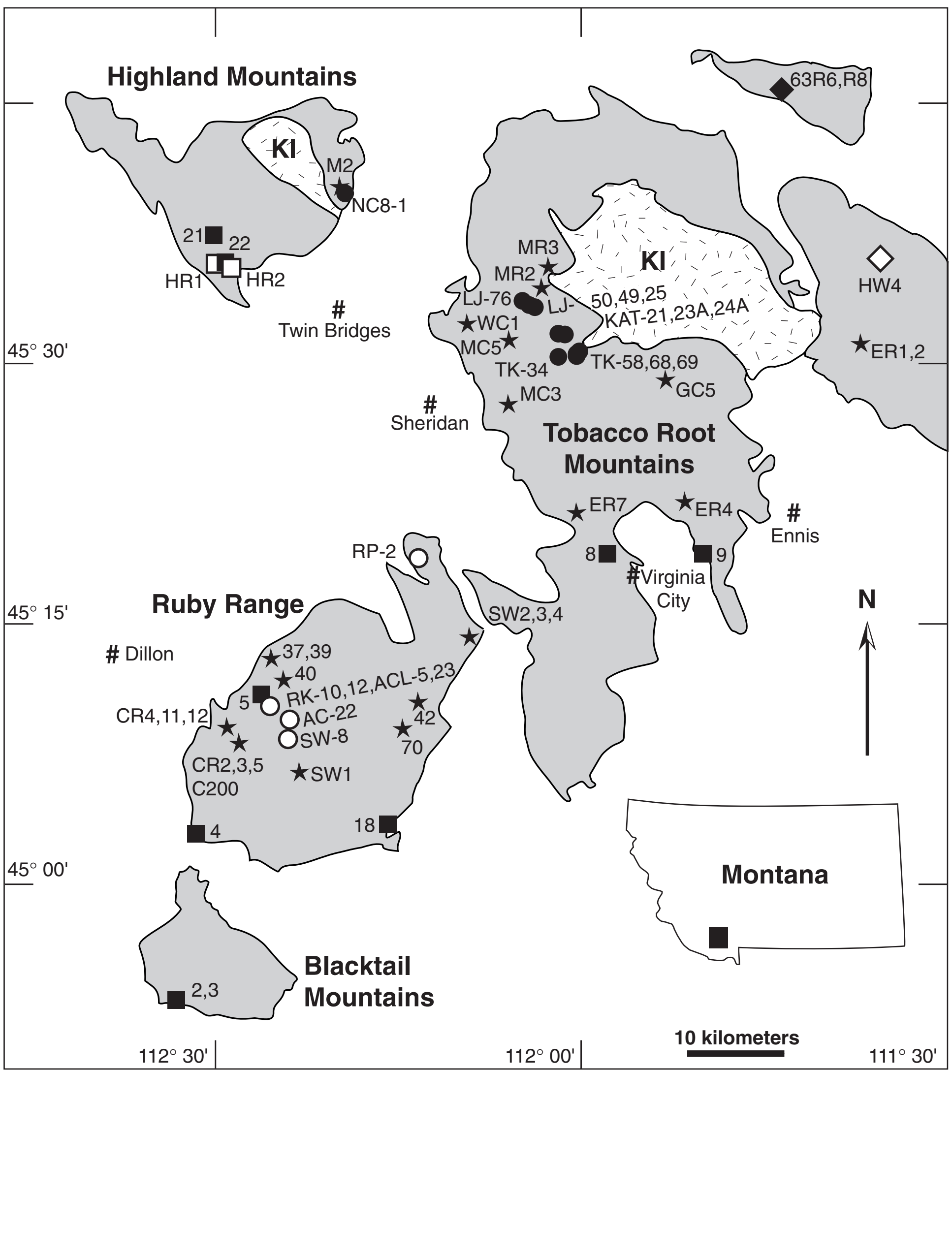

Figure 1. An outline map of the outcrop distribution of Precambrian metamorphic rocks (in gray) and adjacent Cretaceous intrusive rocks (KI) in southwest Montana. Also shown are the locations of samples used for K/Ar and $^{40}Ar/^{39}Ar$ dating. Solid circles—samples newly described in this paper. Open circles—samples of Brady et al. (1998). Solid squares—samples of Giletti (1966). Open squares—samples of Harlan et al. (1996). Solid diamond—samples of Marvin and Dobson (1979). Open diamond—sample of Hayden and Wehrenberg (1960). Stars—samples of Roberts et al. (2002).

and James and Hedge (1980) showed 2.7 Ga Rb/Sr data that were apparently not reset at 1.6–1.7 Ga, it was generally believed that the 1.6–1.7 Ga metamorphism was a low-grade, patchy, greenschist facies event (e.g., Mueller and Cordua, 1976; Berg, 1979; Dahl, 1979) with little accompanying deformation or fabric development. Indeed, most of the data were from micas, which can be crystallized or have their K/Ar clocks reset at relatively low temperatures (300–400 °C, McDougall and Harrison, 1988).

More recently, O'Neill et al. (1988a, 1988b) described 1.8–1.9 Ga euhedral rims on zircon crystals in a Highland Mountains gneiss dome, which they believe demonstrate a significant metamorphism accompanied by penetrative deformation—certainly more significant than a static regional greenschist facies heating. Erslev and Sutter (1990) and Harlan et al. (1996) also argued that the Proterozoic heating recorded by mica and amphibole K/Ar data was a major, regional event involving significant deformation.

It was in this context that we obtained a number of $^{40}Ar/^{39}Ar$ isometric ages that further constrain the tectonometamorphic history of the region as part of an ongoing study of the metamorphic rocks of southwest Montana (Brady et al., 1994; Kovaric et al., 1996; Brady et al., 1998). In the following pages, we present our $^{40}Ar/^{39}Ar$ data and compare them to previously published $^{40}Ar/^{39}Ar$ and K/Ar data, including the extensive $^{40}Ar/^{39}Ar$ data presented by Roberts et al. (2002). We join the other authors cited previously to argue that the 1.7 Ga ages determined for the potassium-bearing minerals of the Tobacco Root Mountains and adjacent ranges date their cooling at the end of a major orogenic event that included regional-scale, granulite facies metamorphism. We argue further that the similar K/Ar and $^{40}Ar/^{39}Ar$ ages obtained for hornblende, biotite, and muscovite are evidence for rapid cooling, consistent with a model of decompression due to tectonic unroofing as suggested by Cheney et al. (2004a, this volume, Chapter 6).

SAMPLES

The Tobacco Root Mountains samples were collected by Jacob (1994), King (1994), and Tierney (1994) from amphibolites and gneisses while studying the metamorphism, geochemistry, and structure of the Spuhler Peak Metamorphic Suite and adjacent Indian Creek Metamorphic Suite (see Fig. 1). The Spuhler Peak Metamorphic Suite is a mafic unit—largely of basaltic composition but with significant portions of Ca-poor, Mg-Fe–rich orthoamphibole gneisses and layers of Al-rich quartzite—that outcrops principally along the southwestern margin of the Tobacco Root batholith (see also Burger, 2004, this volume, Chapter 1; Vitaliano et al., 1979a, see reprinted map and text accompanying this volume). The Indian Creek Metamorphic Suite is a quartzofeldspathic gneiss package that also includes marbles, metamorphosed iron formation, and other metasediments as well as felsic meta-igneous rocks, and occupies the southern portion of the Tobacco Root Mountains (see Vitaliano et al., 1979b; Mogk et al., 2004, this volume, Chapter 2). Amphiboles were also dated from weakly foliated and locally folded metamorphosed mafic dikes and sills (MMDS) that crosscut the gneissic layering of the Indian Creek Metamorphic Suite but do not occur in the Spuhler Peak Metamorphic Suite. The goal of our sample collection was to identify differences (if any) in the $^{40}Ar/^{39}Ar$ data for similar minerals in the three rock groups (Spuhler Peak Metamorphic Suite, Indian Creek Metamorphic Suite, MMDS), so our Tobacco Root samples are all from a comparatively small area in the central Tobacco Root Mountains where all three units occur near one another. As a consequence, the Tobacco Root samples studied are all within five kilometers of the Cretaceous Tobacco Root batholith and may have been heated by it. No new samples were dated from the Pony–Middle Mountain Metamorphic Suite, which is believed to have the same Proterozoic geologic history as the Indian Creek Metamorphic Suite because both have gneissic banding cut by the MMDS.

Ruby Range rocks were collected in 1990 by Green (1991), Larson (1991), and Brady et al. (1991) in pursuit of an origin for the talc deposits in the marbles there (see Brady et al., 1998). All of the Ruby Range samples were taken from gneisses, marbles, or amphibolites of the Christensen Ranch Metamorphic Suite within or adjacent to talc deposits (see James, 1990). The Highland Mountains sample was collected by Brady in 1978 from gneisses within a chlorite deposit as part of the Dillon 1° × 2° Sheet study of the U.S. Geological Survey. More detailed sample information can be found in the theses listed above as well as in Table 1.

METHODS

$^{40}Ar/^{39}Ar$ isotopic ages for these samples were determined in three different laboratories (University of California at Los Angeles [UCLA], Massachusetts Institute of Technology [MIT], University of Maine) employing contrasting techniques. Some of the Tobacco Root Mountains samples were analyzed at MIT using UV laser microprobe, single-grain $^{40}Ar/^{39}Ar$ total gas methods on irradiated hornblende grains as described in Hames and Cheney (1997). Other Tobacco Root Mountains samples were dated at UCLA by Kovaric (1996) following standard step-heating procedures of irradiated bulk mineral separates (Quidelleur et al., 1997). The Ruby Range samples (Brady et al., 1998) were analyzed at the University of Maine, also following standard step-heating procedures of irradiated bulk mineral separates (Lux et al., 1989).

RESULTS

Sample information, total gas ages, and plateau ages where available are listed for all samples in Table 1. Errors for the ages in Table 1 are reported as one standard deviation (1σ). Also compiled for comparison in Table 1 are total gas and plateau ages for previously published K/Ar and $^{40}Ar/^{39}Ar$ studies of K-bearing minerals in the Tobacco Root Mountains, the Highland Mountains, the Ruby Range, and the Blacktail Mountains. $^{40}Ar/^{39}Ar$ step-heating release spectra for individual samples are shown in Appendix Figures A1 and A2 along with the original data (Tables A1 and A2). Also in the Appendix are histograms for each sample of UV laser microprobe, single-grain, and total

TABLE 1. K/Ar DATA FOR PRECAMBRIAN ROCKS OF THE TOBACCO ROOT MOUNTAINS AND VICINITY

Data Source	Sample no.	*Latitude (°N)	Longitude (°W)	†Unit	Rock	Mineral	Total gas age (Ma)	±1σ	Plateau age (Ma)	±1σ	Lab	§Method
Tobacco Root Mountains												
Hayden and Wehrenberg (1960)	HW4	45°35'55"	111°35'17"	PMMMS	Biotite Gneiss	Biotite	1620	32	#N.D.	N.D.	Argonne	K/Ar (a)
Giletti (1966)	8	45°19'03"	112°02'10"	ICMS	Pegmatite in Gneiss	Muscovite	1640	33	N.D.	N.D.	Brown	K/Ar (b)
Giletti (1966)	9	45°19'03"	111°50'17"	PMMMS	Granitic Gneiss	Biotite	1700	34	N.D.	N.D.	Brown	K/Ar (b)
Marvin and Dobson (1979)	63R6	45°45'39"	111°43'22"	PMMMS	Pegmatite	Muscovite	1720	50	N.D.	N.D.	USGS	K/Ar
Marvin and Dobson (1979)	63R8	45°45'39"	111°43'22"	PMMMS	Bio-Hbl Gneiss	Hornblende	1740	90	N.D.	N.D.	USGS	K/Ar
Jacob (1994)	LJ-25	45°33'23"	112°04'17"	MMDS	Amphibolite	Hornblende	1694	53	N.D.	N.D.	MIT	LM-10
Jacob (1994)	LJ-49-2	45°33'12"	112°03'53"	SPMS	Amphibolite	Hornblende	1572	57	N.D.	N.D.	MIT	LM-10
Jacob (1994)	LJ-50	45°33'16"	112°03'48"	SPMS	Amphibolite	Hornblende	1730	55	N.D.	N.D.	MIT	LM-10
Jacob (1994)	LJ-76	45°33'38"	112°04'49"	ICMS	Amphibolite	Hornblende	1733	34	N.D.	N.D.	MIT	LM-10
Jacob (1994)	LJ-77	45°33'38"	112°04'49"	MMDS	Amphibolite	Hornblende	1747	80	N.D.	N.D.	MIT	LM-10
King (1994)	TK-34	45°30'24"	112°00'43"	ICMS	Amphibolite	Hornblende	1799	41	N.D.	N.D.	MIT	LM-10
King (1994)	TK-58	45°30'42"	111°59'52"	SPMS	Amphibolite	Hornblende	839	177	N.D.	N.D.	MIT	LM-9
King (1994)	TK-68	45°30'34"	112°00'22"	SPMS	Amphibolite	Hornblende	1228	376	N.D.	N.D.	MIT	LM-9
King (1994)	TK-69	45°30'27"	112°00'22"	ICMS	Amphibolite	Hornblende	1298	257	N.D.	N.D.	MIT	LM-10
Kovaric (1996)	KAT-21	45°31'44"	112°01'53"	SPMS	Bio-Hbl Amphibolite	Biotite	**129	1	N.D.	N.D.	UCLA	$^{40}Ar/^{39}Ar$
Kovaric (1996)	KAT-21	45°31'44"	112°01'53"	SPMS	Bio-Hbl Amphibolite	Hornblende	1639	26	N.D.	N.D.	UCLA	$^{40}Ar/^{39}Ar$
Kovaric (1996)	KAT-23A	45°31'45"	112°01'51"	SPMS	Amphibolite	Hornblende	1697	20	1735	13	UCLA	$^{40}Ar/^{39}Ar$
Kovaric (1996)	KAT-24A	45°31'45"	112°01'50"	SPMS	Ged Amphibolite	Mg-hornblende	1539	74	1665	37	UCLA	$^{40}Ar/^{39}Ar$
Kovaric (1996)	KAT-41	45°31'42"	112°01'29"	SPMS	Bio-Grt-Sil Gneiss	Biotite	**106	0	N.D.	N.D.	UCLA	$^{40}Ar/^{39}Ar$
Kovaric (1996)	KAT-44	45°31'41"	112°01'26"	SPMS	Ged Amphibolite	Gedrite	N.D.	N.D.	N.D.	N.D.	UCLA	$^{40}Ar/^{39}Ar$
Kovaric (1996)	KAT-51B	45°31'41"	112°01'20"	SPMS	Amphibolite	Hornblende	1680	26	1698	27	UCLA	$^{40}Ar/^{39}Ar$
Roberts et al. (2002)	TRER1	45°31'	111°37'	PMMMS	N.D.	Amphibole	1272	16	N.D.	N.D.	Open U.	LM-5
Roberts et al. (2002)	TRER2	45°31'	111°37'	PMMMS	N.D.	Amphibole	**83	4	N.D.	N.D.	Open U.	LM-4
Roberts et al. (2002)	TRER2	45°31'	111°37'	PMMMS	N.D.	Biotite	**72	8	N.D.	N.D.	Open U.	LM-17
Roberts et al. (2002)	TRER4	45°22'	111°51'	ICMS	N.D.	Biotite	1728	12	N.D.	N.D.	Open U.	LM-10
Roberts et al. (2002)	TRER7	45°21'	112°00'	ICMS	N.D.	Biotite	1713	8	N.D.	N.D.	Open U.	LM-15
Roberts et al. (2002)	TRGC5	45°29'	111°53'	ICMS	N.D.	Biotite	1692	8	N.D.	N.D.	Open U.	LM-13
Roberts et al. (2002)	TRMC3	45°28'	112°06'	ICMS	N.D.	Biotite	1752	8	N.D.	N.D.	Open U.	LM-22
Roberts et al. (2002)	TRMC5	45°31'	112°06'	ICMS	N.D.	Amphibole	1803	34	N.D.	N.D.	Open U.	LM-4
Roberts et al. (2002)	TRMR2	45°34'	112°03'	ICMS	N.D.	Biotite	1585	4	N.D.	N.D.	Open U.	LM-26
Roberts et al. (2002)	TRMR3	45°36'	112°03'	PMMMS	N.D.	Amphibole	**248	44	N.D.	N.D.	Open U.	LM-4
Roberts et al. (2002)	TRMR3	45°36'	112°03'	PMMMS	N.D.	Biotite	**80	39	N.D.	N.D.	Open U.	LM-1
Roberts et al. (2002)	TRWC1	45°32'	112°09'	ICMS	N.D.	Amphibole	1634	34	N.D.	N.D.	Open U.	LM-5
Roberts et al. (2002)	TRWC1	45°32'	112°09'	ICMS	N.D.	Biotite	1689	10	N.D.	N.D.	Open U.	LM-10

(continued)

TABLE 1. K/Ar DATA FOR PRECAMBRIAN ROCKS OF THE TOBACCO ROOT MOUNTAINS AND VICINITY (*continued*)

Data Source	Sample no.	*Latitude (°N)	Longitude (°W)	†Unit	Rock	Mineral	Total gas age (Ma)	±1σ	Plateau age (Ma)	±1σ	Lab	§Method
Ruby Range												
Giletti (1966)	4	45°02'55"	112°31'37"	DGG	Bio Gneiss	Biotite	1640	33	N.D.	N.D.	Brown	K/Ar (b)
Giletti (1966)	5	45°10'57"	112°26'15"	CCG	Mus-Bio Schist	Biotite	1580	32	N.D.	N.D.	Brown	K/Ar (b)
Giletti (1966)	5	45°10'57"	112°26'15"	CCG	Mus-Bio Schist	Biotite	1600	32	N.D.	N.D.	Brown	K/Ar (b)
Giletti (1966)	5	45°10'57"	112°26'15"	CCG	Mus-Bio Schist	Muscovite	1670	33	N.D.	N.D.	Brown	K/Ar (b)
Giletti (1966)	6	45°10'57"	112°26'15"	CCG	Bio-Hbl Gneiss	Biotite	1480	30	N.D.	N.D.	Brown	K/Ar (b)
Giletti (1966)	18	45°03'28"	112°15'36"	DGG	Bio Gneiss	Biotite	1540	31	N.D.	N.D.	Brown	K/Ar (b)
Brady et al. (1998)	RK-10	45°10'16"	112°25'32"	CRMS	Amphibolite	Hornblende	1640	9	N.D.	N.D.	Maine	$^{40}Ar/^{39}Ar$
Brady et al. (1998)	ACL-005	45°10'16"	112°25'32"	CRMS	Phlog Marble	Phlogopite	1700	16	1723	15	Maine	$^{40}Ar/^{39}Ar$
Brady et al. (1998)	SW-8	45°08'22"	112°24'03"	CRMS	Talc-Dol Marble	Phlogopite	1670	9	1716	15	Maine	$^{40}Ar/^{39}Ar$
Brady et al. (1998)	RP-2	45°18'48"	112°13'37"	CRMS	Marble	Biotite	1757	8	1764	11	Maine	$^{40}Ar/^{39}Ar$
Brady et al. (1998)	RK-12	45°10'16"	112°25'32"	CRMS	Marble	Biotite	1644	9	N.D.	N.D.	Maine	$^{40}Ar/^{39}Ar$
Brady et al. (1998)	ACL-023	45°10'16"	112°25'32"	CRMS	Marble	Biotite	1659	8	N.D.	N.D.	Maine	$^{40}Ar/^{39}Ar$
Brady et al. (1998)	JBB-AC-22	45°09'30"	112°23'55"	CRMS	Chl-Mus Gneiss	Muscovite	††1330	9	1363	3	UCLA	$^{40}Ar/^{39}Ar$
Roberts et al. (2002)	70-30-2	45°09'	112°15'	DGG	N.D.	Biotite	1744	6	N.D.	N.D.	Open U.	LM-9
Roberts et al. (2002)	RM37	45°13'	112°25'	CRMS	N.D.	Biotite	1731	4	N.D.	N.D.	Open U.	LM-23
Roberts et al. (2002)	RM39	45°13'	112°25'	CRMS	N.D.	Biotite	1784	6	N.D.	N.D.	Open U.	LM-10
Roberts et al. (2002)	RM40	45°12'	112°24'	CRMS	N.D.	Biotite	1772	4	N.D.	N.D.	Open U.	LM-24
Roberts et al. (2002)	RM42	45°10'	112°13'	DGG	N.D.	Biotite	1734	14	N.D.	N.D.	Open U.	LM-6
Roberts et al. (2002)	RMC200	45°08'	112°28'	CRMS	N.D.	Biotite	1742	4	N.D.	N.D.	Open U.	LM-16
Roberts et al. (2002)	RRCR2	45°08'	112°28'	CRMS	N.D.	Biotite	1761	4	N.D.	N.D.	Open U.	LM-35
Roberts et al. (2002)	RRCR3	45°08'	112°28'	CRMS	N.D.	Biotite	1765	6	N.D.	N.D.	Open U.	LM-58
Roberts et al. (2002)	RRCR4	45°09'	112°29'	CRMS	N.D.	Amphibole	1561	60	N.D.	N.D.	Open U.	LM-5
Roberts et al. (2002)	RRCR5	45°08'	112°28'	CRMS	N.D.	Biotite	1741	10	N.D.	N.D.	Open U.	LM-20
Roberts et al. (2002)	RRCR11	45°09'	112°29'	CRMS	N.D.	Amphibole	1557	60	N.D.	N.D.	Open U.	LM-5
Roberts et al. (2002)	RRCR12	45°09'	112°29'	CRMS	N.D.	Amphibole	1566	38	N.D.	N.D.	Open U.	LM-5
Roberts et al. (2002)	RRSW1	45°06'	112°23'	CRMS	N.D.	Amphibole	1708	14	N.D.	N.D.	Open U.	LM-10
Roberts et al. (2002)	RRSW1	45°06'	112°23'	CRMS	N.D.	Biotite	1771	32	N.D.	N.D.	Open U.	LM-6
Roberts et al. (2002)	RRSW2	45°14'	112°09'	DGG	N.D.	Biotite	1738	22	N.D.	N.D.	Open U.	LM-9
Roberts et al. (2002)	RRSW3	45°14'	112°09'	DGG	N.D.	Biotite	1774	12	N.D.	N.D.	Open U.	LM-30
Roberts et al. (2002)	RRSW4	45°14'	112°09'	DGG	N.D.	Biotite	1744	18	N.D.	N.D.	Open U.	LM-9

(continued)

TABLE 1. K/Ar DATA FOR PRECAMBRIAN ROCKS OF THE TOBACCO ROOT MOUNTAINS AND VICINITY (*continued*)

Data Source	Sample no.	*Latitude (°N)	Longitude (°W)	†Unit	Rock	Mineral	Total gas age (Ma)	±1σ	Plateau age (Ma)	±1σ	Lab	§Method
Highland Mountains												
Giletti (1966)	21	45°37'24"	112°30'12"	N.D.	Granite Gneiss	Muscovite	**174	4	N.D.	N.D.	Brown	K/Ar (b)
Giletti (1966)	22	45°35'40"	112°29'10"	N.D.	Biotite Schist	Biotite	**75	2	N.D.	N.D.	Brown	K/Ar (b)
Harlan et al. (1996)	HR1-C	45°34'01"	112°25'19"	N.D.	Hbl-Bio Gneiss	Hornblende	1839	5	1815	10	USGS	$^{40}Ar/^{39}Ar$
Harlan et al. (1996)	HR1-A	45°34'01"	112°25'19"	N.D.	Biotite Gneiss	Biotite	1776	8	1816	10	USGS	$^{40}Ar/^{39}Ar$
Harlan et al. (1996)	HR2-Ja	45°35'46"	112°26'49"	MMDS	Amphibolite	Hornblende	1780	5	1796	12	USGS	$^{40}Ar/^{39}Ar$
Kovaric (1996)	NC8-1	45°39'49"	112°19'21"	N.D.	Chloritized Gneiss	Muscovite	**121	2	N.D.	N.D.	UCLA	$^{40}Ar/^{39}Ar$
Roberts et al. (2002)	HLM2	45°40'	112°20'	N.D.	N.D.	Biotite	1749	6	N.D.	N.D.	Open U.	LM-9
Blacktail Mountains												
Giletti (1966)	2	44°53'20"	112°33'13"	N.D.	Bio Gneiss	Biotite	1590	32	N.D.	N.D.	Brown	K/Ar (b)
Giletti (1966)	3	44°53'20"	112°33'13"	N.D.	Bio Gneiss	Biotite	1320	150	N.D.	N.D.	Brown	K/Ar (b)

Note: Bio—biotite; Hbl—hornblende; Grt—garnet; Sil—sillimanite; Ged—gedrite; Mus—muscovite; Phlog—phlogopite; Dol—dolomite; Chl—chlorite.

* Values for older data from Berg (1979). Roberts et al. (2002) locations approximated from location map.

† Unit—Map unit where known. PMMMS—Pony–Middle Mountain Metamorphic Suite; ICMS—Indian Creek Metamorphic Suite; SPMS—Spuhler Peak Metamorphic Suite; MMDS—metamorphosed mafic dikes and sills; DGG—Dillon Granite Gneiss; CCG—Cherry Creek Gneiss; CRMS—Christensen Ranch Metamorphic Suite.

§ Method of analysis. K/Ar—traditional K/Ar analysis of bulk mineral separate; $^{40}Ar/^{39}Ar$—step heating of bulk mineral separate; LM—UV laser microprobe $^{40}Ar/^{39}Ar$—number of grains. $\lambda_e = 0.581 \times 10^{-10}\ a^{-1}$; $\lambda_\beta = 4.962 \times 10^{-10}\ a^{-1}$. Older data corrected from (a) $\lambda_e = 0.585 \times 10^{-10}\ a^{-1}$; $\lambda_\beta = 4.72 \times 10^{-10}\ a^{-1}$; (b) $\lambda_e = 0.584 \times 10^{-10}\ a^{-1}$; $\lambda_\beta = 4.72 \times 10^{-10}\ a^{-1}$.

\# N.D.—no data.

** Believed to be partially to completely reset by a 75 Ma batholith.

†† Growth during hydrothermal alteration that produced economic talc deposits.

gas ages (Fig. A3), along with the original data (Table A3). Two samples of the orthoamphibole, gedrite, from the Spuhler Peak Metamorphic Suite were studied, but did not have enough K to yield a meaningful $^{40}Ar/^{39}Ar$ age.

As many as ten separate hornblende crystals from each of nine Tobacco Root Mountains samples were dated using a UV laser microprobe $^{40}Ar/^{39}Ar$ total gas method. Data for these 89 crystals are collected in a histogram in Figure 2 (see also Fig. A3). The ages shown in gray are for the 29 crystals of samples TK-58, TK-68, TK-69, which we believe to have been partially reset by Cretaceous intrusions, based on their location and on their scattered ages. The 60 ages shown in black have a mean of 1.71 ± 0.02 Ga. Some of these individual ages are older than the metamorphic maximum that occurred between 1.78 and 1.72 Ga (Cheney et al., 2004b, this volume, Chapter 8; Mueller et al., 2004, this volume, Chapter 9), so they may have accumulated excess ^{40}Ar. Others are as young as 1.50 Ga and appear to have lost some Ar due to reheating.

Measurements of $^{40}Ar/^{39}Ar$ step-heating plateau ages of three bulk hornblende samples from the Spuhler Peak Metamorphic Suite of the Tobacco Root Mountains average 1.70 ± 0.02 Ga. Measurement of three bulk biotite samples from the Ruby Range yielded $^{40}Ar/^{39}Ar$ step-heating plateau ages with a mean of 1.73 ± 0.02 Ga, identical to the best-estimate (near-plateau) age for a hornblende sample from the same rocks. The similarity of the step-heating plateau ages to the mean of the 60 UV laser microprobe total gas ages leads us to believe that 1.71 ± 0.02 Ga is the most recent time the metamorphic rocks in the Tobacco Root Mountains and in the Ruby Range were at temperatures above the Ar closure temperature of hornblende and biotite.

Monazite and zircon studies (Krogh et al., 1997; Burger et al., 1999; Cheney et al., 1999; Dahl et al., 1999; Dahl et al., 2002; Cheney et al., 2004b, this volume, Chapter 8; Mueller et al., 2004, this volume, Chapter 9) show that there was a major, orogenic event (the Big Sky orogeny) that affected the Tobacco Root Mountains region during the Middle Proterozoic. Detailed monazite data on Pb isotopes are interpreted by Cheney et al. (2004b, this volume, Chapter 8) to mean that high-pressure metamorphism with monazite growth beginning at 1780 Ma was followed by low-pressure metamorphism with monazite growth ending at 1720 Ma (see also Cheney et al., 2004a, this volume, Chapter 6). The large cluster of K/Ar and $^{40}Ar/^{39}Ar$ ages observed between 1.73 and 1.71 Ga is consistent with cooling of these rocks through the Ar closure temperatures as part of this metamorphic pressure-temperature path.

Overall, our data are similar to the results of other investigators. A histogram of all 71 total gas $^{40}Ar/^{39}Ar$ and K/Ar ages in Table 1 is presented in Figure 3 with our data (23 samples) shown in the gray pattern. Most (55) of the ages in Figure 3 fall in a group between 1.54 and 1.84 Ga with a mean of 1.70 ± 0.07 Ga. Nine ages form a group between 72 and 248 Ma. Another seven ages fall between these two groups. Based on the data in Figure 3, there is no significant or systematic difference in age between the various Precambrian rock suites (Indian Creek

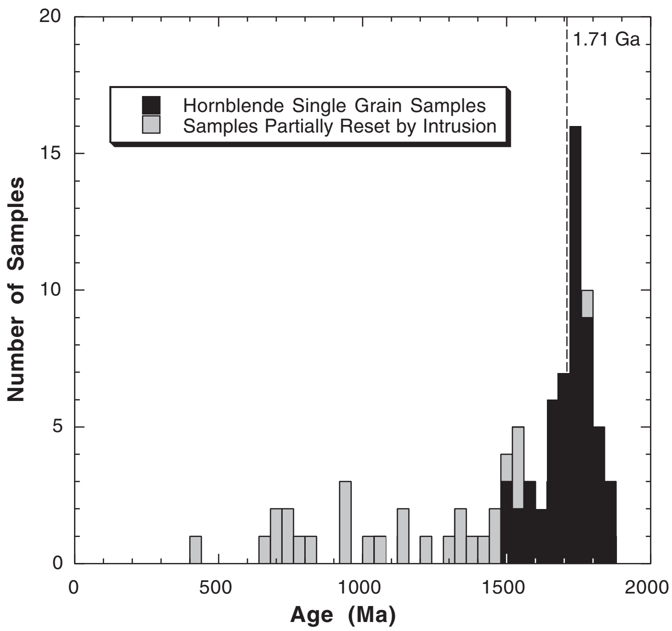

Figure 2. A histogram of 89 UV laser microprobe $^{40}Ar/^{39}Ar$ ages for single hornblende crystals from nine Precambrian metamorphic rocks of the Tobacco Root Mountains. Ten individual hornblende crystals were dated for each sample, save one. Ages in gray (29) are in rocks that are believed to have lost ^{40}Ar due to reheating by Cretaceous intrusions. Ages in black (60) cluster about a mean of 1.71 ± 0.02 Ga. Bin size is 40 m.y.

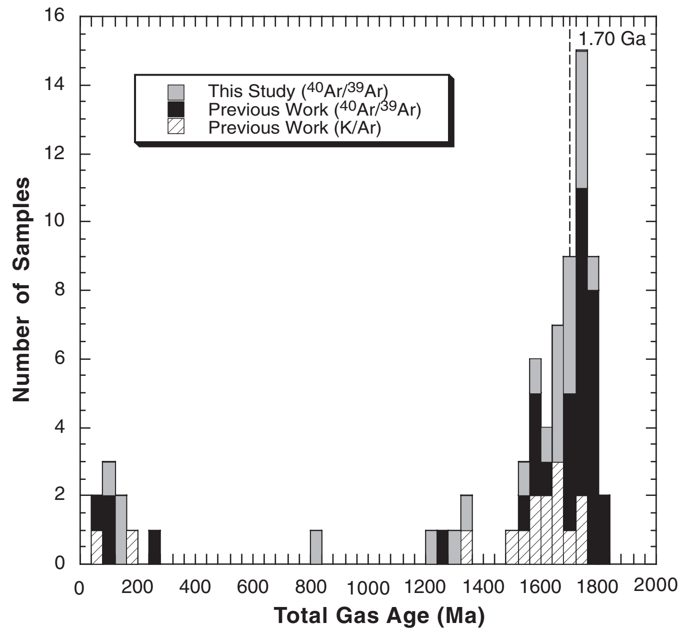

Figure 3. A histogram of the K/Ar and $^{40}Ar/^{39}Ar$ total gas ages for Precambrian metamorphic rocks of the Tobacco Root Mountains and vicinity listed in Table 1. Samples in gray are $^{40}Ar/^{39}Ar$ total gas ages determined as part of this project. Samples in black are $^{40}Ar/^{39}Ar$ total gas ages from the literature, mostly Roberts et al. (2002). Samples in stripes are K/Ar total gas ages from the literature. Bin size is 40 m.y. The large cluster of ages with a mean of 1.70 ± 0.07 Ga is believed to record cooling from a 1.78 to 1.72 Ga regional metamorphism of upper-amphibolite or granulite facies. Younger ages are believed to reflect various degrees of ^{40}Ar loss due to later heating by Late Cretaceous intrusive rocks.

Metamorphic Suite, Pony–Middle Mountain Metamorphic Suite, Spuhler Peak Metamorphic Suite, and MMDS) in the Tobacco Root Mountains. However, the scatter among the total gas ages is too large (300 m.y.) to reasonably attribute to differences in cooling age from a single orogenic event. Clearly, some samples must have been disturbed by subsequent heating to lose Ar, while other samples must have acquired excess Ar.

We interpret the nine 72–248 Ma ages to be the result of partial to complete Ar loss due to heating by nearby 75 Ma intrusive igneous rocks (Tobacco Root batholith, Hells Canyon pluton, and smaller igneous bodies). Two of these nine ages, for Highland Range micas, were reported by Giletti (1966), who first recognized this Cretaceous resetting. Eight of these nine samples are mica separates (biotite or muscovite), which can lose their Ar if heated to between 300 and 400 °C (McDougall and Harrison, 1988). In our study, both biotite and hornblende were separated and dated from one Tobacco Root Mountains Spuhler Peak Metamorphic Suite sample (KAT-21). Both minerals have disturbed $^{40}Ar/^{39}Ar$ step-heating spectra (Fig. 4) and no good age plateau (adjacent steps including >50% of the ^{39}Ar, all within 2σ of the plateau age). The hornblende yields a total gas age of 1639 ± 26 Ma, whereas the biotite gives a total gas age of 129 ± 6 Ma. Because the biotite age is close to the Tobacco Root batholith intrusion age (75 Ma, Vitaliano et al., 1980), we believe this sample was heated above 300 °C by that intrusion. Because the hornblende is only slightly

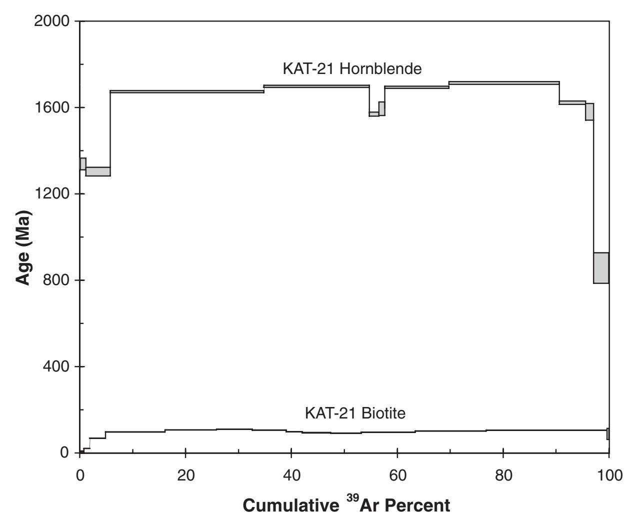

Figure 4. $^{40}Ar/^{39}Ar$ step-heating age spectra for hornblende and biotite separated from the same Tobacco Root Mountains Spuhler Peak Metamorphic Suite sample (KAT-21). The young age of the biotite is due to ^{40}Ar loss resulting from heating by Late Cretaceous (75 Ma) intrusive rocks. The hornblende gives much older age steps, with a best-estimate age of 1700 ± 9 Ma that would be a plateau without steps five and six.

disturbed, the host rock was probably not heated above 500 °C, but the hornblende total gas age may be a minimum age. Indeed, there is a "near plateau" at 1700 ± 9 Ma that is our best estimate of the metamorphic cooling age of this sample, so there may have been some Ar loss due to heating by the intrusion. Sample KAT-21 was collected approximately one kilometer from the surface exposure of the Tobacco Root batholith. Using simple thermal models for batholith emplacement (Jaeger, 1964), Kovaric (1996) demonstrated that temperatures between 300 and 500 °C are reasonable contact metamorphic temperatures for the size of the batholith and the position of the samples.

Several samples give ages between the main group with the 1.70 ± 0.07 Ga mean and the young group clearly reset by the Cretaceous intrusions. One of these (JBB-AC-22) is a muscovite sample from a zone of hydrothermal alteration that formed a talc deposit in the Ruby Range. Brady et al. (1998) argue that this age (total gas = 1.33 ± 0.01 Ga, plateau = 1.36 ± 0.01 Ga) represents the growth of muscovite during formation of the talc as part of ca. 1.4 Ga rifting. Indeed, this sample was collected in an attempt to learn the age of talc formation. Because samples of biotite (RP-2, RK-12, ACL-023), phlogopite (ACL-005, SW8), and hornblende (RK-10) near the talc deposits were not reset, the hydrothermal alteration and growth of mica must have occurred at temperatures below 300 °C. The three amphibole samples (TK-58, TK-68, TK-69) that give intermediate mean ages (839, 1228, 1298 Ma) were collected near one another about one kilometer from the Tobacco Root batholith contact and even closer to several satellite intrusions. We believe that these three samples were heated enough to lose some, but not all, of their Ar. The heating of these samples was probably due to the batholith, but these and other intermediate-age samples may have been affected by the intrusion of (unmetamorphosed) mafic dikes during the Proterozoic era at 1450 Ma (Wooden et al., 1978) or at 780 Ma (Harlan et al., 2003).

DISCUSSION

K/Ar and $^{40}Ar/^{39}Ar$ data for hornblende, biotite, and muscovite of the northwestern portion of the Wyoming province present a consistent temporal pattern, whether measured by traditional bulk K/Ar methods, by $^{40}Ar/^{39}Ar$ step heating of bulk, irradiated mineral separates, or by total gas $^{40}Ar/^{39}Ar$ UV laser spot heating of irradiated single crystals, and in a number of different labs (Fig. 3). As first observed by Hayden and Wehrenberg (1959) and more fully documented by Giletti (1966), the K/Ar systems of the metamorphic rocks of the Tobacco Root Mountains and adjacent areas record Early Proterozoic ages, unless reset by thermal effects such as those due to Late Cretaceous plutons. $^{40}Ar/^{39}Ar$ data reported here further document the nature of the Proterozoic event. The Indian Creek Metamorphic Suite, which was previously metamorphosed at 2.45 Ga (Cheney et al., 1999; 2004b, this volume, Chapter 8), and the MMDS, which were intruded at 2.06 Ga (Burger et al., 1999; Mueller et al., 2004, this volume, Chapter 9), must have achieved temperatures greater than ~500 °C (McDougall and Harrison, 1988) during the 1.78–1.72 Ga metamorphism to reset their hornblende $^{40}Ar/^{39}Ar$ ages and to record cooling by 1.71 ± 0.02 Ga. The fact that similar $^{40}Ar/^{39}Ar$ ages are obtained for hornblende from the Ruby Range and the Highland Mountains is consistent with a high-temperature, tectonothermal event of regional extent.

Interestingly, the K/Ar and $^{40}Ar/^{39}Ar$ ages of amphiboles and micas are very similar in these rocks (Fig. 5), even though the amphibole ages are believed to be set as the rock cools through ~500 °C and the mica ages are believed to be set as the rock cools through ~300 °C (McDougall and Harrison, 1988). Cooling rate, grain size, and mineral composition can affect the value of the closure temperature, but the available K/Ar and $^{40}Ar/^{39}Ar$ data appear to reflect fairly rapid cooling through the 500–300 °C temperature interval. Cheney et al. (2004a, this volume, Chapter 6) argue on the basis of mineral assemblages and reaction textures that the pressure-temperature path followed by Tobacco Root Mountains rocks during the Big Sky orogeny includes a nearly isothermal decompression segment, possibly caused by tectonic unroofing during late extension. If their model is correct, then one would expect rapid cooling to follow the removal of overburden. The observed similarity in amphibole and mica ages from the Tobacco Root Mountains lends support to this model.

Plateau ages for the three Highland Mountains samples reported by Harlan et al. (1996) are slightly older (averaging 1.81 ± 0.01 Ga) than the ages reported here for the Tobacco Root

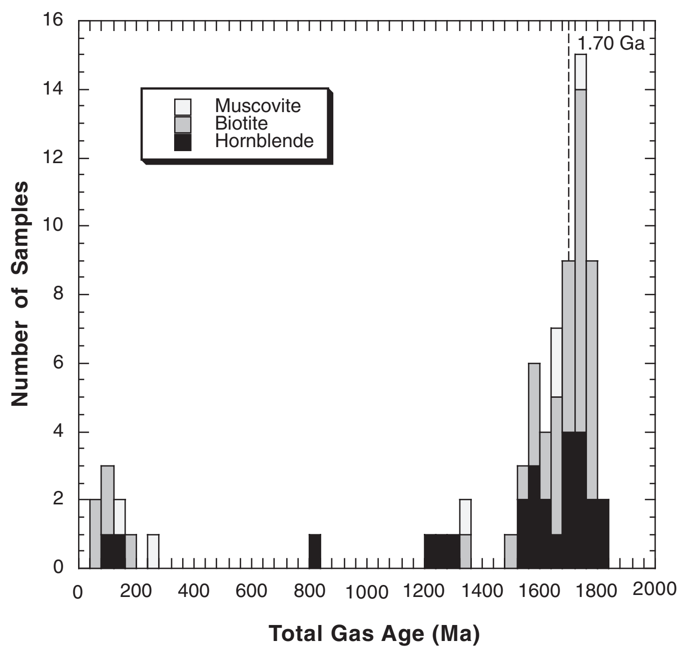

Figure 5. A histogram of K/Ar and $^{40}Ar/^{39}Ar$ total gas ages for Precambrian metamorphic rocks of the Tobacco Root Mountains and vicinity. This figure is similar to Figure 3, except that the ages are sorted by mineral rather than by investigator. Bin size is 40 m.y.

Mountains and the Ruby Range. Our three plateau ages for the Tobacco Root Mountains average 1.70 ± 0.02 Ga, whereas our three plateau ages for the Ruby Range average 1.73 ± 0.02 Ga. It is possible that some of the Harlan et al. (1996) samples held excess ^{40}Ar, giving them apparently older ages. However, it is also likely that, in an event as large as the 1.78–1.72 Ga Big Sky orogeny, rocks with different cooling histories can be found, due to their different locations in the orogen. Indeed, different levels of the crust might be juxtaposed by the extensive Cenozoic block faulting. Clearly, there is much to learn from additional isotopic studies in this region.

Recently, Roberts et al. (2002) presented $^{40}Ar/^{39}Ar$ UV laser microprobe ages for 18 samples from the Ruby Range, 13 samples from the Tobacco Root Mountains, and two samples from the Highland Mountains, examining at least ten single crystals of biotite (23 samples) or hornblende (10 samples) for each sample. This large data set, which nearly doubled the number of samples with measured $^{40}Ar/^{39}Ar$ total gas ages from this region, is included in the histograms of Figures 3 and 5. Alone, the Roberts et al. (2002) biotite data define a histogram similar to Figure 2, but with a mean age of 1.76 ± 0.02 Ga, older than the 1.71 ± 0.02 Ga $^{40}Ar/^{39}Ar$ cooling age adopted in this paper. Roberts et al. (2002) argue that all measured ages younger than 1700 Ma are for samples that have lost Ar due to the Cretaceous intrusions, and only use ages older than 1700 Ma to date cooling from the Proterozoic metamorphism, possibly biasing their results to older values. They also suggest that some of their amphibole ages that are older than 1780–1740 Ma are due to the presence of excess ^{40}Ar and, therefore, focus on their biotite data. As a consequence, they argue from their selected biotite data that these rocks cooled through the temperature interval of 350–300 °C during the interval 1780–1740 Ma.

The Roberts et al. (2002) interpretation of their data is in conflict with the abundant evidence of monazite growth in the Tobacco Root Mountains as late as 1720 Ma reported by Cheney et al. (1999; 2004b, this volume, Chapter 8), who correlate late monazite growth with a lower-pressure portion of the metamorphic pressure-temperature path at temperatures of 650–700 °C (see also Cheney et al., 2004a, this volume, Chapter 6). The Roberts et al. (2002) 1780–1740 Ma age is also somewhat in conflict with the $^{40}Ar/^{39}Ar$ plateau ages obtained in our study. Roberts et al. (2002) presented ^{207}Pb-^{206}Pb garnet step-leaching ages, probably dating monazite inclusions in the garnet, of 1820–1780 Ma for samples from this region (also in conflict with the results of Cheney et al., 2004b, this volume, Chapter 8). They argue that their 1780–1740 Ma $^{40}Ar/^{39}Ar$ total gas ages were set during cooling from 1820 to 1780 Ma regional metamorphism. One possible explanation for the conflict between the data and interpretations of this paper along with the data of Cheney et al. (2004b, this volume, Chapter 8) and that of Roberts et al. (2002) is that some of the Roberts et al. (2002) biotite samples may contain excess ^{40}Ar. Another possibility is that there may be systematic differences in the dates obtained from two or more $^{40}Ar/^{39}Ar$ labs.

ACKNOWLEDGMENTS

The authors thank the W.M. Keck Foundation and the colleges of the Keck Geology Consortium for their financial support of this work. Kovaric thanks Smith College for a Schultz Foundation summer fellowship. Dan Lux, Bill Hames, Mark Harrison, and Marty Grove all graciously shared their facilities and expertise to help us complete this project, but bear no responsibility for the errors in interpretation that remain. We thank Hazel Roberts and Pete Dahl for providing drafts of their work in progress. The manuscript was significantly improved due to excellent and helpful reviews by Steve Harlan and Pete Dahl.

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Manuscript Accepted by the Society September 12, 2003

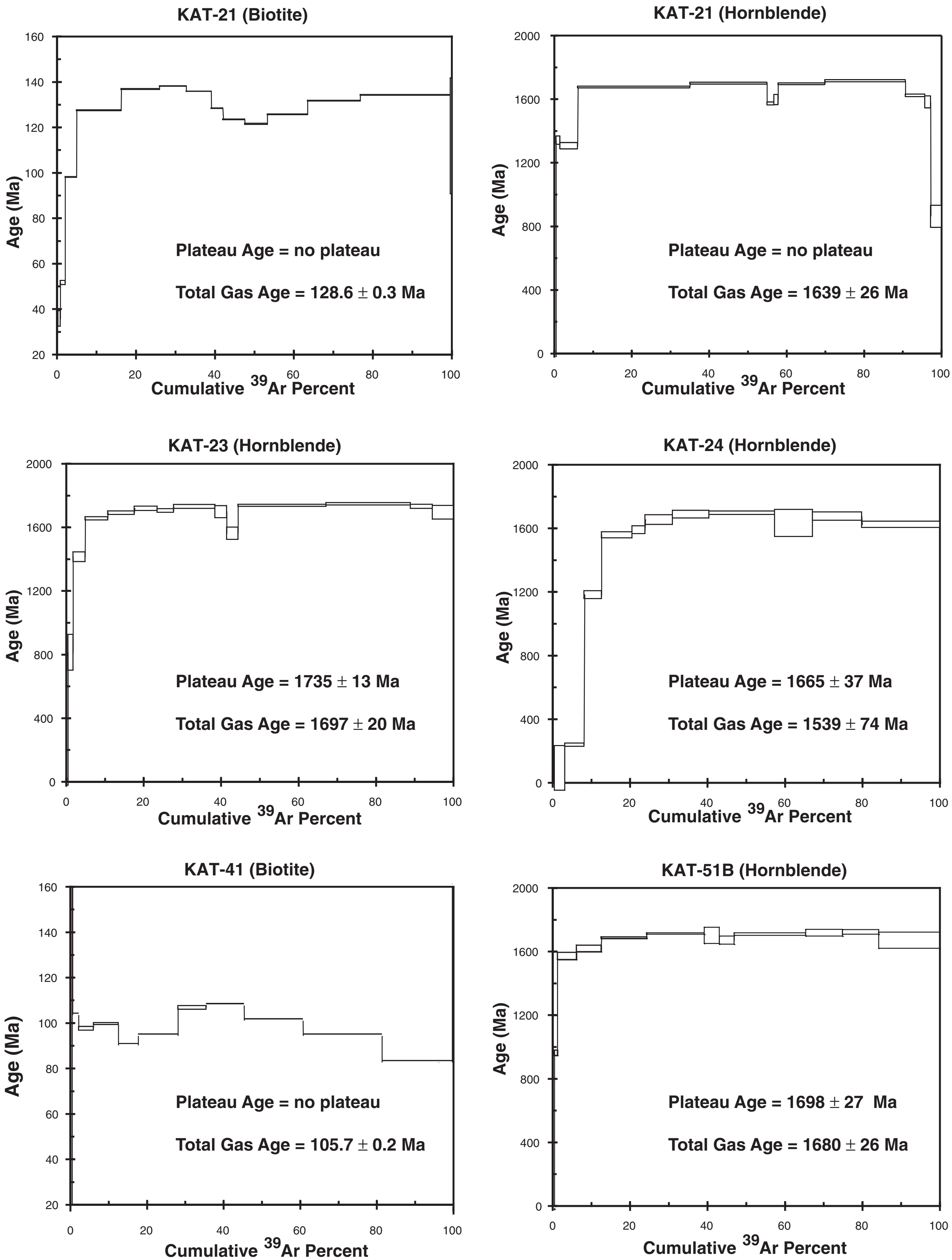

Figure A1. $^{40}Ar/^{39}Ar$ step-heating age spectra determined at University of California at Los Angeles.

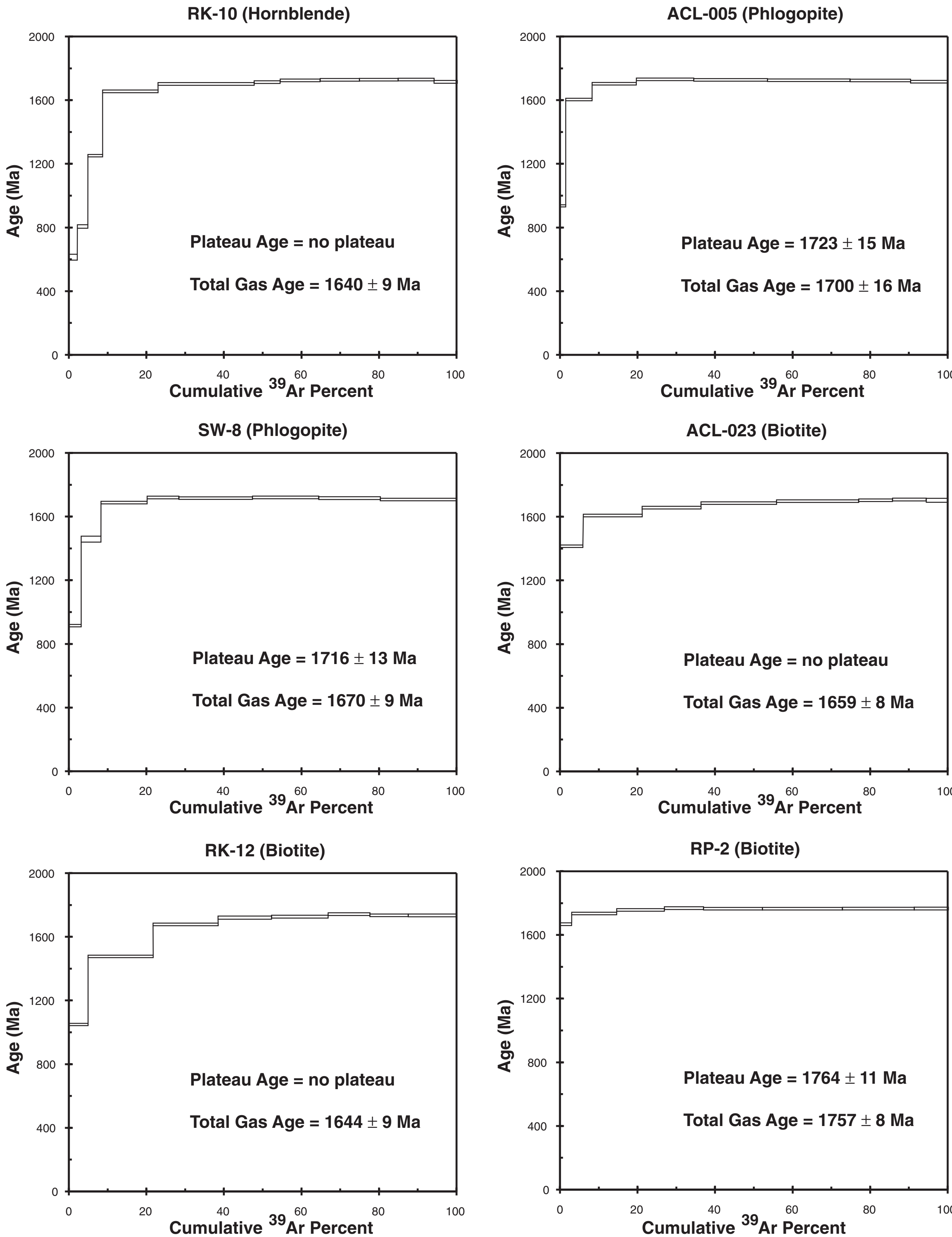

Figure A2. $^{40}Ar/^{39}Ar$ step-heating age spectra determined at the University of Maine.

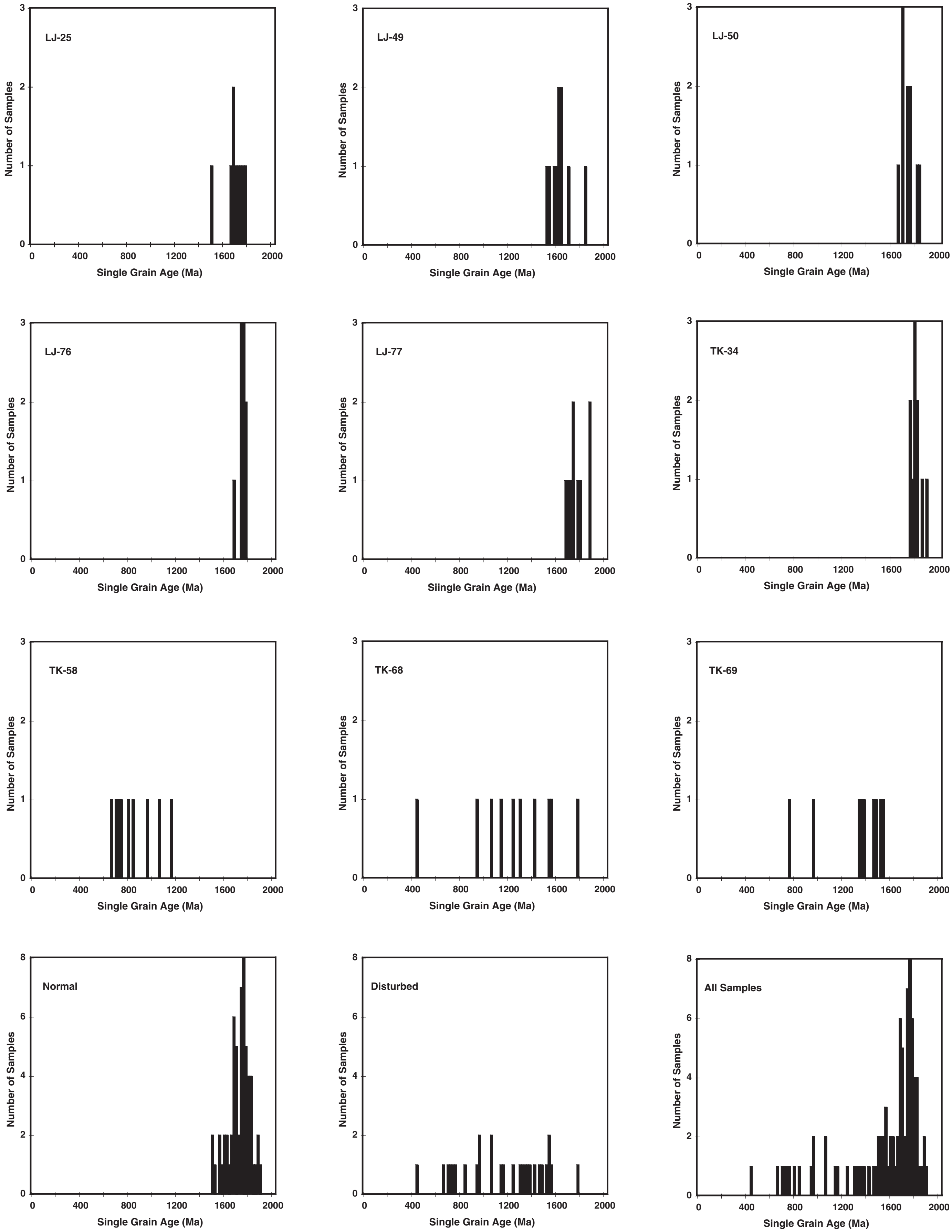

Figure A3. Single-grain UV laser microprobe $^{40}Ar/^{39}Ar$ total gas ages determined at Massachusetts Institute of Technology.

TABLE A1. UCLA Ar DATA

T (°C)	$^{40}Ar/^{39}Ar$	$^{40}Ar^*/^{39}Ar_K$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	K/Ca	$\%^{39}Ar$	$\%^{40}Ar^*$	Age (Ma)	± 1σ
KAT-21 (Biotite, 19.8 mg) J = 0.006614 (± 0.000023)†									
500	21.82	3.140	5.43E-02	6.31E-02	9.1	0.6	14.4	37.1	3.9
600	12.70	4.485	3.49E-02	2.77E-02	14.2	1.8	35.3	52.7	1.0
680	12.66	8.490	8.40E-03	1.40E-02	58.9	4.7	67.1	98.5	0.5
750	12.20	11.07	6.86E-03	3.74E-03	72.1	16.0	90.7	127.4	0.7
800	12.31	11.90	7.05E-03	1.32E-03	70.2	25.8	96.6	136.5	0.7
840	12.33	12.01	6.21E-03	1.01E-03	79.7	32.6	97.4	137.8	0.7
880	12.22	11.81	6.85E-03	1.29E-03	72.2	38.9	96.7	135.6	0.7
920	11.58	11.15	5.76E-03	1.37E-03	85.9	41.9	96.3	128.3	0.6
960	11.27	10.71	6.35E-03	1.80E-03	77.9	47.4	95.1	123.4	0.6
990	11.03	10.54	5.71E-03	1.58E-03	86.7	53.1	95.6	121.5	0.6
1020	11.28	10.91	5.29E-03	1.17E-03	93.6	63.4	96.7	125.6	0.6
1000	11.64	11.44	7.66E-03	5.89E-04	64.6	76.8	98.3	131.5	0.6
1150	11.79	11.67	2.12E-02	3.45E-04	23.3	99.6	98.9	134.0	0.7
1350	165.1	10.07	7.19E-01	5.25E-01	0.7	100.0	6.10	116.2	29.5
Total Gas		11.18						128.6	0.3
Plateau								(no plateau)	
KAT-21 (Hornblende, 25.2 mg) J = 0.006613 (± 0.000023)									
800	195.0	167.0	8.32E-01	9.52E-02	0.588	1.1	85.6	1342.4	36.3
950	166.0	160.9	4.19E+00	1.99E-02	0.118	5.6	96.6	1307.3	28.4
1000	230.4	230.5	5.38E+00	3.59E-03	0.092	34.8	99.7	1670.8	8.8
1020	235.7	235.7	5.36E+00	4.30E-03	0.092	54.7	99.6	1695.2	9.3
1040	224.8	209.8	5.01E+00	5.43E-02	0.098	56.5	93.0	1569.9	13.7
1060	236.4	214.6	5.39E+00	7.78E-02	0.092	57.6	90.4	1593.9	44.0
1100	237.7	234.7	5.82E+00	1.47E-02	0.085	69.8	98.3	1690.2	9.0
1150	240.7	238.9	5.73E+00	1.07E-02	0.086	90.6	98.8	1709.9	9.2
1200	233.8	220.0	5.29E+00	5.06E-02	0.093	95.7	93.8	1620.3	13.5
1250	305.1	211.6	5.14E+00	3.20E-01	0.096	97.2	69.1	1579.0	50.7
1350	425.0	93.7	2.44E+00	1.12E+00	0.204	99.5	22.0	870.1	86.0
1450	5429	-86.4	2.03E+00	1.87E+01	0.244	100.0	−1.6	−1527.5	17131
Total Gas		223.8						1639	26
Plateau								(no plateau)	
KAT-23A (Hornblende, 22.5 mg) J = 0.006612 (± 0.000017)									
800	198.0	87.25	2.49E+00	3.76E-01	0.200	1.3	44.0	821.8	146.7
950	195.8	180.1	9.23E+00	5.94E-02	0.053	4.4	91.4	1414.8	43.0
980	232.7	226.6	1.15E+01	2.97E-02	0.043	10.3	96.6	1651.8	14.7
1000	241.3	234.1	1.17E+01	3.38E-02	0.042	17.3	96.2	1687.3	16.6
1010	249.3	239.6	1.21E+01	4.23E-02	0.041	23.2	95.3	1713.2	20.8
1020	245.7	237.0	1.20E+01	3.90E-02	0.041	27.4	95.7	1700.8	15.5
1040	245.3	242.6	1.24E+01	1.94E-02	0.040	38.2	98.0	1726.6	17.8
1060	253.6	235.3	1.24E+01	7.19E-02	0.040	41.2	92.0	1692.9	52.4
1100	232.9	207.9	1.11E+01	9.25E-02	0.044	44.1	88.6	1560.5	54.3
1150	245.8	244.0	1.27E+01	1.65E-02	0.038	66.9	98.4	1733.1	12.4
1200	251.7	246.0	1.26E+01	2.97E-02	0.039	88.8	96.9	1742.3	11.4
1250	300.1	242.7	1.24E+01	2.04E-01	0.040	94.6	80.2	1727.2	19.6
1350	396.5	234.6	1.21E+01	5.57E-01	0.041	100.0	58.7	1689.9	57.3
Total Gas		236.1						1697	20
Plateau						50.5		1735	13
KAT-24A (Hornblende, 19.9 mg) J = 0.006612 (± 0.000017)									
800	89.05	9.8	2.03E+00	2.68E-01	0.244	2.7	11.0	113.8	170.5
950	40.10	23.1	3.38E+00	5.85E-02	0.147	7.8	57.4	256.2	13.1
980	154.9	140.4	1.78E+01	5.94E-02	0.027	12.2	89.5	1184.4	33.4
1000	219.5	207.2	2.37E+01	5.88E-02	0.021	20.1	92.9	1556.8	26.5
1015	240.4	213.4	2.39E+01	1.09E-01	0.020	23.6	87.3	1587.9	34.5
1030	249.3	226.2	2.53E+01	9.79E-02	0.019	30.6	89.1	1649.9	42.9
1045	263.2	233.3	2.65E+01	1.22E-01	0.018	40.1	87.0	1683.8	33.6
1080	260.4	235.2	2.71E+01	1.07E-01	0.018	57.1	88.6	1692.6	17.8
1120	914.0	74.5	1.29E+01	2.85E+00	0.038	58.4	8.1	722.4	4698.8
1160	529.3	222.1	2.81E+01	1.06E+00	0.017	66.9	41.1	1630.0	108.6
1200	413.9	231.0	2.69E+01	6.40E-01	0.018	79.8	54.8	1672.6	34.9
1350	467.7	220.2	2.47E+01	8.56E-01	0.020	100.0	46.3	1621.2	25.6
Total Gas		203.7						1539	74
Plateau						76.4		1665	37

(continued)

TABLE A1. UCLA Ar DATA (*continued*)

T (°C)	$^{40}Ar/^{39}Ar$	$^{40}Ar^*/^{39}Ar_K$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	K/Ca	$\%^{39}Ar$	$\%^{40}Ar^*$	Age (Ma)	± 1σ
KAT-41 (Biotite, 20.3 mg) J = 0.006608 (± 0.000017)									
500	170.4	100.51	1.62E-01	2.37E-01	3.1	0.1	59.0	918.9	26.2
680	15.97	9.594	1.19E-02	2.15E-02	41.5	1.7	60.1	110.9	0.7
750	11.20	9.101	4.65E-03	7.03E-03	106.4	5.6	81.2	105.4	0.5
800	10.25	9.311	2.65E-03	3.11E-03	186.9	12.1	90.8	107.7	0.5
840	9.175	8.562	1.96E-03	1.99E-03	251.9	17.3	93.3	99.3	0.5
880	9.483	8.881	2.11E-03	1.95E-03	234.7	27.7	93.7	102.9	0.5
920	10.37	9.861	1.91E-03	1.66E-03	258.4	35.2	95.0	113.9	0.6
960	10.54	9.996	1.71E-03	1.75E-03	289.9	45.1	94.9	115.4	0.6
1020	9.868	9.460	2.14E-03	1.30E-03	231.5	60.5	95.9	109.4	0.5
1060	9.083	8.837	2.30E-03	7.51E-04	215.1	81.1	97.3	102.4	0.5
1120	8.096	7.904	3.41E-03	5.67E-04	144.9	95.9	97.6	91.8	0.5
1200	8.202	7.871	4.02E-03	1.04E-03	123.2	99.6	96.0	91.5	0.5
1350	17.15	14.77	6.88E-02	8.00E-03	7.2	100.0	86.1	168.0	2.4
Total Gas		9.13						105.7	0.2
Plateau								(no plateau)	
KAT-51 (Hornblende, 19.5 mg) J = 0.006603 (± 0.000017)									
800	194.5	107.9	4.08E+00	2.95E-01	0.120	0.8	55.3	970.3	20.8
950	215.7	210.0	1.41E+01	2.95E-02	0.035	5.7	96.4	1569.4	31.9
980	223.0	219.5	1.28E+01	2.13E-02	0.038	12.1	97.6	1616.2	28.8
1000	234.0	233.4	1.33E+01	1.25E-02	0.037	23.9	98.8	1682.7	8.5
1020	239.0	239.0	1.36E+01	1.10E-02	0.036	38.9	99.0	1708.4	8.3
1040	245.0	236.4	1.35E+01	4.01E-02	0.036	42.8	95.6	1696.4	69.8
1080	240.2	230.1	1.38E+01	4.50E-02	0.035	46.7	94.9	1666.9	34.7
1120	239.8	238.0	1.37E+01	1.72E-02	0.036	65.3	98.3	1703.9	13.0
1160	248.5	239.8	1.34E+01	4.01E-02	0.037	74.7	95.6	1712.4	30.1
1200	258.0	241.1	1.34E+01	6.81E-02	0.036	84.1	92.6	1718.2	21.0
1350	697.1	230.0	1.28E+01	1.59E+00	0.038	100.0	32.7	1666.6	63.5
Total Gas		232.8						1680	26
Plateau						87.9		1698	27
JBB-AC-22 (Muscovite, 1.0 mg) J = 0.006598 (± 0.000049)									
500	155.6	148.2	7.42E-02	2.49E-02	6.7	6.1	95.3	1225.4	16.3
550	169.7	167.9	1.70E-02	6.05E-03	29.2	15.6	98.9	1339.6	12.3
600	168.9	167.3	1.66E-02	5.34E-03	29.9	46.1	99.1	1336.3	9.4
650	177.5	176.5	1.11E-02	3.33E-03	44.8	66.4	99.4	1387.5	12.1
700	177.1	176.1	4.31E-03	3.03E-03	114.7	79.8	99.5	1385.6	9.8
800	176.8	174.8	1.10E-02	6.49E-03	45.0	92.6	98.9	1378.3	12.0
900	133.8	130.1	3.35E-02	1.25E-02	14.7	97.2	97.2	1113.4	18.0
1100	92.99	85.80	5.02E-01	2.45E-02	1.0	100.0	92.2	805.5	16.0
Total Gas		166.2						1330	9
Plateau								(no plateau)	

†Fish Canyon sanidine standard (27.8 Ma) used for all samples.

TABLE A2. UNIVERSITY OF MAINE Ar DATA

T (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	K/Ca	$\%^{39}Ar$	$\%^{40}Ar^*$	Age (Ma)	± 1σ
RK-10 (Hornblende) J = 0.00847†								
730	126.84	2.5840	0.2702	0.19	2.2	37.2	607.6	19
850	115.40	3.8860	0.1678	0.13	2.7	57.3	804.0	11
940	139.76	11.2900	0.0809	0.04	3.8	83.6	1247.7	8
1030	180.77	20.0740	0.0263	0.02	14.3	96.7	1653.4	9
1080	186.62	21.1150	0.0207	0.02	24.8	97.7	1700.7	9
1110	187.01	21.5850	0.0163	0.02	6.7	98.4	1711.5	8
1140	188.82	21.5630	0.0165	0.02	10.3	98.4	1722.1	8
1170	189.87	21.5020	0.0181	0.02	10.1	98.2	1725.5	8
1200	190.21	21.5170	0.0185	0.02	10.0	98.1	1726.8	8
1230	190.00	21.4560	0.0173	0.02	9.3	98.3	1727.5	8
Fused	189.49	21.2260	0.0232	0.02	6.0	97.4	1713.7	9
Total Gas					100.0		1640	9
Plateau							(no plateau)	
ACL-005 (Phlogopite) J = 0.00833								
700	87.99	0.0909	0.0240	44.75	1.5	91.9	929.2	7
820	172.86	0.0099	0.0055	49.59	6.8	99.0	1599.0	8
940	188.40	0.0093	0.0014	52.96	11.4	99.8	1700.0	8
1020	192.86	0.0112	0.0004	43.67	14.8	99.9	1727.5	8
1100	192.96	0.0171	0.0001	28.66	19.0	100.0	1724.0	8
1160	191.79	0.0110	0.0002	44.68	21.3	100.0	1721.8	8
1220	191.59	0.0098	0.0001	49.96	15.6	100.0	1720.7	8
Fused	190.58	0.0254	0.0014	19.30	9.6	99.8	1712.6	8
Total Gas					100.0		1700	16
Plateau					70.7		1724	15
SW-8 (Phlogopite) J = 0.00830								
700	85.29	0.0341	0.0215	14.39	3.2	92.5	908.9	8
820	150.74	0.0289	0.0046	16.96	5.1	99.1	1454.9	19
940	187.19	0.0162	0.0033	30.32	11.9	99.5	1685.8	8
1020	191.98	0.0151	0.0010	32.44	8.2	99.8	1717.6	8
1100	191.13	0.0176	0.0004	27.84	19.0	99.9	1713.7	8
1160	191.87	0.0362	0.0004	13.54	17.1	99.9	1718.0	8
1220	191.11	0.0236	0.0003	20.77	15.9	99.9	1713.8	9
Fused	189.63	0.0241	0.0004	20.34	19.7	99.9	1704.9	8
Total Gas					100.0		1670	9
Plateau					60.2		1716	13

(continued)

TABLE A2. UNIVERSITY OF MAINE Ar DATA (*continued*)

T (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	K/Ca	$\%^{39}Ar$	$\%^{40}Ar^*$	Age (Ma)	± 1σ
ACL-0023 (Biotite) J = 0.00841								
700	144.04	0.0311	0.0087	15.74	5.9	98.2	1413.6	8
820	171.53	0.0271	0.0030	18.10	15.2	99.5	1605.1	8
940	178.82	0.0203	0.0003	24.16	15.2	99.9	1654.9	8
1020	183.56	0.0174	0.0003	28.14	19.5	99.9	1683.4	8
1100	185.76	0.0222	0.0006	22.12	21.2	99.9	1695.9	8
1160	186.82	0.0334	0.0010	14.69	8.7	99.8	1701.5	8
1220	187.43	0.0268	0.0006	18.26	8.7	99.9	1705.7	9
Fused	188.62	0.0466	0.0009	10.51	5.6	99.8	1712.3	13
Total Gas					100.0		1659	8
Plateau							(no plateau)	
RK-12 (Biotite) J = 0.00836								
700	96.76	0.0608	0.0102	8.06	4.9	96.9	1044.0	7
820	152.50	0.0498	0.0046	9.83	16.8	99.1	1473.8	8
940	183.62	0.0340	0.0016	14.42	16.8	99.7	1675.5	8
1020	190.55	0.0310	0.0004	15.78	13.8	99.9	1718.3	10
1100	191.58	0.0190	0.0004	25.82	14.6	99.9	1724.3	9
1160	194.30	0.0212	0.0004	23.16	10.8	99.9	1740.0	9
1220	193.20	0.0218	0.0005	22.46	9.9	99.9	1733.5	8
Fused	193.16	0.0338	0.0009	14.49	12.5	99.8	1732.5	9
Total Gas					100.0		1644	9
Plateau							(no plateau)	
RP-2 (Biotite) J = 0.00843								
700	183.93	0.0243	0.0131	20.18	3.0	97.9	1665.8	9
820	192.28	0.0243	0.0030	20.18	11.6	99.5	1733.1	8
940	195.40	0.0491	0.0004	9.98	12.3	99.9	1755.5	8
1020	197.55	0.0359	0.0010	13.65	10.1	99.8	1766.8	9
1100	196.77	0.0421	0.0003	11.64	15.2	99.9	1763.6	8
1160	196.74	0.0470	0.0003	10.43	20.6	99.9	1763.4	8
1220	196.84	0.0413	0.0003	11.86	18.5	99.9	1764.0	8
Fused	196.88	0.0939	0.0003	5.22	8.8	99.9	1764.3	9
Total Gas					100.0		1757	8
Plateau					64.4		1764	11

[†]Muscovite SBG-7 standard (240.9 Ma), calibrated to MMhb-1(520.4 Ma), used for all samples.

TABLE A3. MIT SINGLE-GRAIN Ar DATA†

Sample	$^{40}Ar/^{39}Ar$	$^{40}Ar^{*}/^{39}Ar_{K}$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	K/Ca	$\%^{39}Ar_{K}$	$\%^{40}Ar^{*}$	Age (Ma)	± 1σ
LJ-25	114.8	114.4	4.06E-05	1.135E-03	0.1265	0.192	99.71	1725.3	2.4
LJ-25	114.2	113.7	5.01E-05	1.135E-03	0.1032	0.326	99.71	1719.6	6.0
LJ-25	91.9	91.2	7.83E-05	1.771E-03	0.1281	0.545	99.43	1486.1	7.0
LJ-25	117.1	116.5	1.13E-04	2.472E-03	0.0975	0.769	99.38	1744.3	1.9
LJ-25	102.2	102.0	5.58E-05	1.129E-03	0.1030	0.927	99.67	1599.4	0.1
LJ-25	109.5	108.8	9.47E-05	2.579E-03	0.1292	1.092	99.30	1669.2	2.3
LJ-25	121.4	119.4	2.89E-04	6.049E-03	0.0897	1.161	98.53	1774.4	6.9
LJ-25	111.6	110.8	2.99E-04	3.465E-03	0.0540	1.258	99.08	1687.4	7.3
LJ-25	109.1	108.3	8.13E-05	2.018E-03	0.1182	1.373	99.45	1666.5	5.3
LJ-50	116.8	116.7	3.52E-05	6.178E-04	0.0780	1.565	99.84	1746.6	6.5
LJ-50	111.9	111.9	1.73E-05	3.119E-04	0.0838	1.600	99.92	1699.5	7.5
LJ-50	107.2	105.9	2.32E-04	4.025E-03	0.0843	1.704	98.89	1641.8	15.1
LJ-50	116.2	115.9	–2.93E-05	–5.907E-04	0.0903	1.766	100.15	1743.7	13.1
LJ-50	125.0	125.2	–3.65E-05	–6.897E-04	0.0787	1.821	100.16	1826.4	16.2
LJ-50	115.0	115.9	–8.55E-05	–1.451E-03	0.0768	1.890	100.37	1734.7	13.1
LJ-50	114.0	114.1	–1.94E-05	–3.354E-04	0.0790	1.932	100.09	1722.0	7.7
LJ-50	122.4	122.7	–1.29E-05	–2.388E-04	0.0788	2.078	100.06	1801.7	6.5
LJ-50	111.4	111.4	3.02E-05	5.073E-04	0.0784	2.222	99.87	1693.9	3.0
LJ-50	110.8	110.5	6.17E-05	1.070E-03	0.0813	2.398	99.71	1686.7	4.2
LJ-76	117.6	117.3	2.11E-05	6.325E-04	0.1323	2.592	99.84	1753.9	6.3
LJ-76	109.9	109.2	8.70E-05	2.272E-03	0.1236	2.726	99.39	1673.5	7.3
LJ-76	115.0	114.5	6.77E-05	1.940E-03	0.1294	2.910	99.50	1725.6	10.2
LJ-76	117.9	117.1	6.77E-05	1.980E-03	0.1291	3.179	99.50	1753.1	4.0
LJ-76	115.8	115.6	1.37E-05	4.096E-04	0.1340	3.367	99.90	1737.2	4.5
LJ-76	115.9	115.5	3.55E-05	1.114E-03	0.1408	3.666	99.72	1736.0	2.4
LJ-76	117.9	117.6	3.89E-05	1.137E-03	0.1288	3.877	99.72	1755.7	1.7
LJ-76	118.4	118.3	1.88E-05	5.433E-04	0.1271	4.118	99.86	1761.7	1.9
LJ-76	118.9	118.4	5.29E-05	1.470E-03	0.1215	4.306	99.63	1763.5	12.4
LJ-77	116.1	115.6	9.15E-05	1.809E-03	0.0885	4.553	99.54	1736.4	5.8
LJ-77	130.5	130.2	3.06E-05	7.076E-04	0.0920	4.855	99.84	1872.8	12.1
LJ-77	111.7	110.7	1.65E-04	3.159E-03	0.0891	5.057	99.16	1689.6	10.6
LJ-77	120.9	120.1	1.34E-04	2.903E-03	0.0931	5.206	99.29	1778.4	8.4
LJ-77	109.2	109.2	4.11E-05	6.641E-04	0.0769	5.380	99.82	1672.1	3.2
LJ-77	112.2	111.9	4.00E-05	7.239E-04	0.0838	5.573	99.81	1701.5	56.0
LJ-77	114.7	114.2	6.30E-05	1.159E-03	0.0834	5.718	99.70	1724.9	0.3
LJ-77	131.0	130.3	8.60E-05	1.756E-03	0.0811	5.851	99.60	1874.5	4.2
LJ-77	121.1	120.7	8.34E-05	1.582E-03	0.0815	6.097	99.61	1784.7	0.5
LJ-49	98.1	96.7	5.50E-04	5.522E-03	0.0532	6.222	98.34	1542.0	6.5
LJ-49	124.9	123.3	4.17E-04	4.580E-03	0.0458	6.313	98.92	1811.2	0.3
LJ-49	105.3	103.1	6.22E-04	7.330E-03	0.0582	6.408	97.94	1612.5	17.3
LJ-49	98.7	97.9	2.48E-04	2.593E-03	0.0551	6.512	99.22	1557.5	26.6
LJ-49	110.6	109.1	4.86E-04	5.080E-03	0.0491	6.576	98.64	1672.6	10.8
LJ-49	94.5	92.0	7.94E-04	8.399E-03	0.0582	6.637	97.37	1493.3	7.5
LJ-49	104.7	103.0	5.14E-04	5.590E-03	0.0540	6.678	98.42	1611.4	31.1
LJ-49	95.2	92.6	8.06E-04	7.891E-03	0.0535	6.750	97.55	1503.1	19.7
LJ-49	115.8	101.3	6.70E-04	6.235E-03	0.0470	6.841	98.41	1593.7	4.3
LJ-49	99.4	99.0	1.29E-04	2.536E-03	0.0577	6.911	99.25	1565.3	7.0

(continued)

TABLE A3. MIT SINGLE-GRAIN Ar DATA (*continued*)

Sample	$^{40}Ar/^{39}Ar$	$^{40}Ar^*/^{39}Ar_K$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	K/Ca	$\%^{39}Ar_K$	$\%^{40}Ar^*$	Age (Ma)	± 1σ
TK-68	122.2	118.2	2.02E-03	1.313E-02	0.0276	99.156	96.82	1762.3	19.0
TK-68	148.6	83.9	2.64E-03	1.770E-02	0.0401	99.200	96.48	1401.7	3.6
TK-68	98.2	97.1	6.57E-04	4.631E-03	0.0373	99.279	98.61	1545.2	0.5
TK-68	52.4	48.6	2.32E-03	1.284E-02	0.0550	99.319	92.75	935.9	10.6
TK-68	77.4	74.6	1.48E-03	9.237E-03	0.0420	99.387	96.47	1290.3	15.5
TK-68	63.0	61.8	5.75E-04	3.654E-03	0.0524	99.550	98.29	1126.5	1.8
TK-68	19.7	19.3	2.17E-04	1.569E-03	0.1906	99.925	97.65	431.0	7.1
TK-68	63.2	55.7	6.13E-03	2.533E-02	0.0340	99.943	88.16	1040.3	31.2
TK-68	70.4	69.3	6.42E-04	3.975E-03	0.0457	99.982	98.33	1222.7	7.1
TK-68	100.7	94.5	2.97E-03	2.038E-02	0.0354	100.000	94.02	1522.1	38.8
TK-58	42.6	39.9	2.14E-03	9.573E-03	0.0545	0.000	93.36	798.0	14.7
TK-58	39.3	34.3	4.99E-03	1.707E-02	0.0453	4.077	87.16	706.4	9.2
TK-58	72.1	64.4	5.24E-03	2.602E-02	0.0358	5.240	89.34	1159.8	23.3
TK-58	39.1	33.1	8.00E-03	2.030E-02	0.0337	6.977	84.66	687.1	18.5
TK-58	52.9	49.8	1.56E-03	1.040E-02	0.0655	7.824	94.19	954.8	35.4
TK-58	32.9	30.9	1.73E-03	6.459E-03	0.0589	10.120	94.21	650.8	14.9
TK-58	39.0	35.1	2.31E-03	1.321E-02	0.0762	14.724	89.99	721.2	6.4
TK-58	58.9	55.9	1.28E-03	1.021E-02	0.0706	19.211	94.88	1043.2	9.5
TK-58	44.0	41.7	1.13E-03	7.848E-03	0.0823	24.219	94.72	828.5	4.8
TK-69	80.7	79.2	5.09E-04	4.895E-03	0.0620	26.832	98.21	1346.1	8.6
TK-69	49.7	49.1	1.67E-04	2.286E-03	0.1432	35.915	98.64	943.4	1.0
TK-69	88.5	87.6	2.06E-04	2.516E-03	0.0718	38.851	99.16	1446.2	9.9
TK-69	95.5	94.5	1.65E-04	3.077E-03	0.1018	44.295	99.05	1521.7	0.1
TK-69	36.6	36.2	8.56E-05	1.228E-03	0.2037	54.171	99.01	740.6	2.8
TK-69	91.1	90.5	1.95E-04	2.610E-03	0.0764	57.572	99.15	1474.6	9.4
TK-69	94.7	94.2	9.48E-05	1.374E-03	0.0796	63.103	99.57	1518.2	2.6
TK-69	78.6	77.4	3.42E-04	3.809E-03	0.0738	67.420	98.57	1325.5	3.9
TK-69	81.4	80.5	2.26E-04	2.999E-03	0.0850	73.365	98.91	1361.5	2.0
TK-34	123.6	121.0	1.01E-03	8.801E-03	0.0368	75.604	97.90	1788.1	11.7
TK-34	120.7	117.6	1.52E-03	1.217E-02	0.0346	77.939	97.02	1750.6	12.9
TK-34	122.8	122.1	2.84E-04	2.412E-03	0.0360	83.393	99.42	1797.7	3.7
TK-34	124.5	123.2	4.18E-04	3.861E-03	0.0386	86.435	99.08	1809.5	1.1
TK-34	125.0	122.8	9.46E-04	8.610E-03	0.0378	89.159	97.96	1801.2	12.5
TK-34	128.8	127.6	6.43E-04	5.646E-03	0.0355	91.925	98.70	1844.6	2.9
TK-34	124.2	120.8	1.27E-03	1.159E-02	0.0382	93.160	97.24	1786.1	20.3
TK-34	124.3	120.0	1.62E-03	1.462E-02	0.0377	94.717	96.53	1778.6	17.7
TK-34	122.0	116.6	2.03E-03	1.797E-02	0.0377	97.665	95.65	1747.3	21.6

†Hornblende, J = 0.014, Standard MMHB-1 = 520.4 Ma.

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