$^{40}Ar/^{39}Ar$ dates from alkaline intrusions in the northern Crazy Mountains, Montana: Implications for the timing and duration of alkaline magmatism in the central Montana alkalic province

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ABSTRACT

Intrusive rocks in the Crazy Mountains, Montana, consist of numerous stocks, dike swarms, laccoliths and/or sills of strongly alkaline to subalkaline affinity that have intruded and metamorphosed Tertiary sedimentary strata of the Crazy Mountains Basin. The subalkaline rocks form stocks, sills, and radiating dikes and are located primarily in the southern Crazy Mountains (e.g., Big Timber stock, Loco Mountain stock). With the exception of the Ibex Mountain sill (?), the alkaline rocks are restricted to the northern Crazy Mountains. New $^{40}Ar/^{39}Ar$ dates are reported for alkaline rocks of the northern Crazy Mountains, with results ranging between 50.61 Ma and 50.03 Ma. Five dates from the strongly alkaline nepheline and mafic nepheline syenites of the Ibex Mountain sill (?), Robinson anticline intrusive complex, and Comb Creek stock (?) and dike swarm give tightly clustered dates suggesting that they were emplaced during a restricted time interval at ~50.1 Ma. The dates from the alkaline rocks of the northern Crazy Mountains are slightly older than those previously reported from the subalkaline Big Timber stock in the southern Crazy Mountains (i.e., 49.3–49.2 Ma, biotite $^{40}Ar/^{39}Ar$) (du Bray and Harlan, 1996). However, the limited span of dates (i.e., 50.6–49.2 Ma) and the geographic proximity between the alkaline and subalkaline rocks indicate that the magmas represented by these different geochemical groups were closely associated in both time and space. Furthermore, all the igneous rocks in the Crazy Mountains were emplaced in a narrow time interval of 1–2 m.y. On a regional scale, the 51–49-Ma age span from the Crazy Mountains is similar to that of most of the igneous centers of the central Montana alkalic province and is coeval with the peak of widespread volcanism in the Absaroka-Gallatin volcanic field immediately to the south of the Crazy Mountains Basin.

KEYWORDS: Absaroka-Gallatin volcanic field, alkaline magmatism, Cenozoic, central Montana alkalic province, Crazy Mountains, Cordilleran orogenic belt, disturbed belt, geochronology, intrusive structures, magmatism, Montana, tectonics.

INTRODUCTION

The Crazy Mountains Basin is a structural and physiographic basin located along the eastern margin of the Cordilleran fold-and-thrust belt in west-central Montana (Fig. 1). The basin originated as a foredeep east of the main Cordilleran orogenic belt (Dickinson et al., 1988). The original geometry of the basin has been subsequently modified and partitioned by the encroachment of thin-skinned, decollement-style folds and thrust faults of the Montana disturbed belt (Woodward, 1981; Garrett, 1972) and by basement-involved folds and thrust faults of the Rocky Mountain foreland province (Schmidt and Garihan, 1983; Gries, 1983).

The basin fill consists of Upper Cretaceous–middle Paleocene (?) clastic and volcaniclastic sediments of the Livingston Group and Fort Union Formation (Roberts, 1972). Subalkaline and alkaline stocks, sills, and dikes intrude sedimentary strata in the approximate center of the basin (Figs. 1 and 2). Temporally, these intrusions are part of the central Montana alkalic province, a group of Tertiary intrusive and volcanic rocks that form isolated uplifts east of the main Rocky Mountain front (Fig. 3) (Chadwick, 1972).

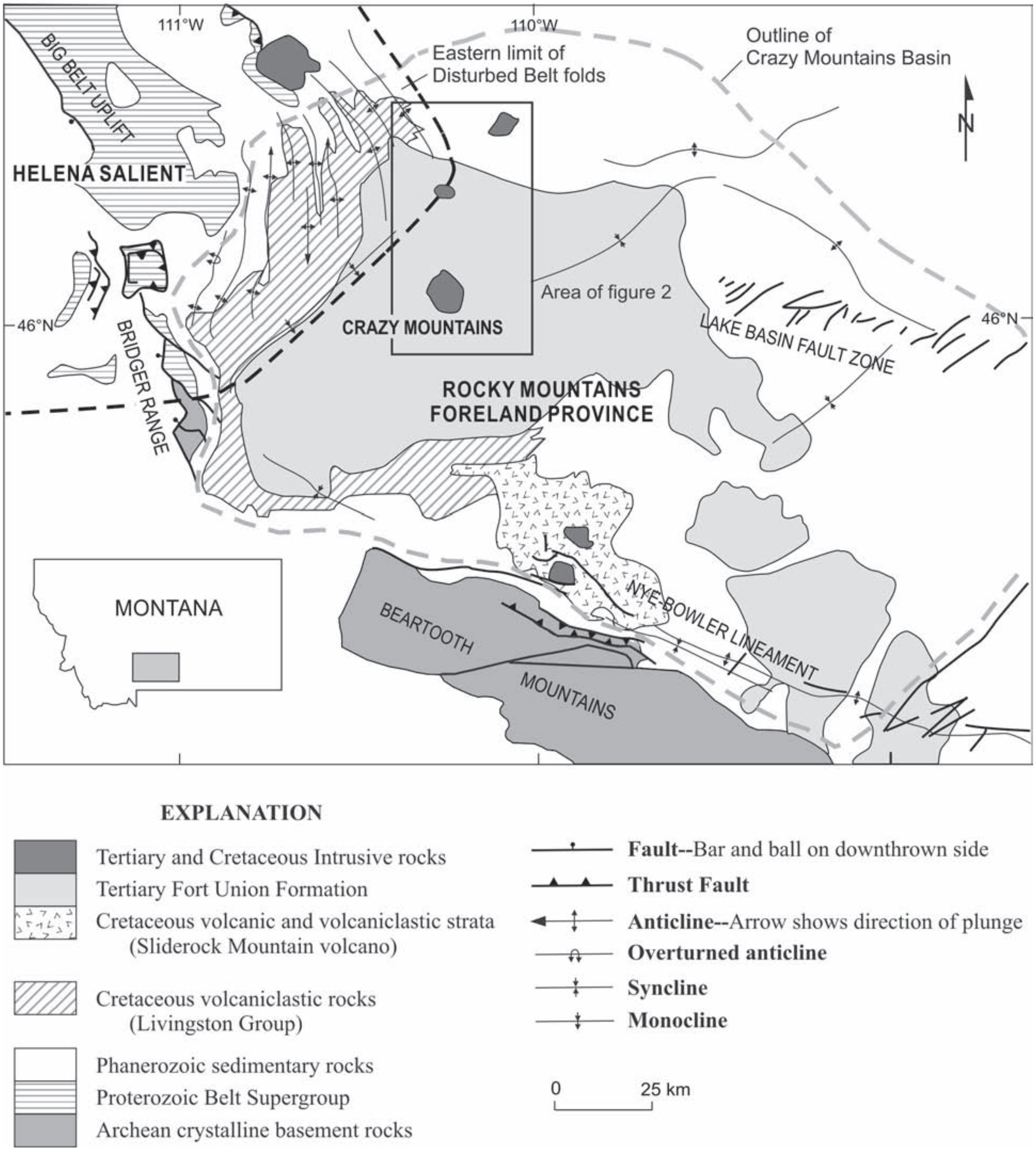

Figure 1. Tectonic map of the Crazy Mountains Basin and surrounding uplifts, west-central Montana. Dashed gray line shows approximate boundaries of the basin. Modified from Roberts (1972) and Harlan et al. (1988). Box shows area of Figure 2.

Within the Crazy Mountains, igneous rocks representing two distinct magma series are present (Dudas et al., 1987; Dudas, 1991; du Bray and Harlan, 1996): (1) sodium-rich, strongly alkaline mafic syenites (also known as malignites), syenites, and trachytes of the Comb Creek stock (?) and dike swarm, the Gordon Butte-Elk Mountain-Coffin Butte sills, the Ibex Mountain sill, and the Robinson anticline intrusive complex (Simms, 1966; Larson and Simms, 1972; Fink, 1975; Emmart, 1985; Harlan et al., 1988; Dudas, 1991); and (2) subalkaline rocks consisting of potassium-rich basalts, diorites, and granodiorites of

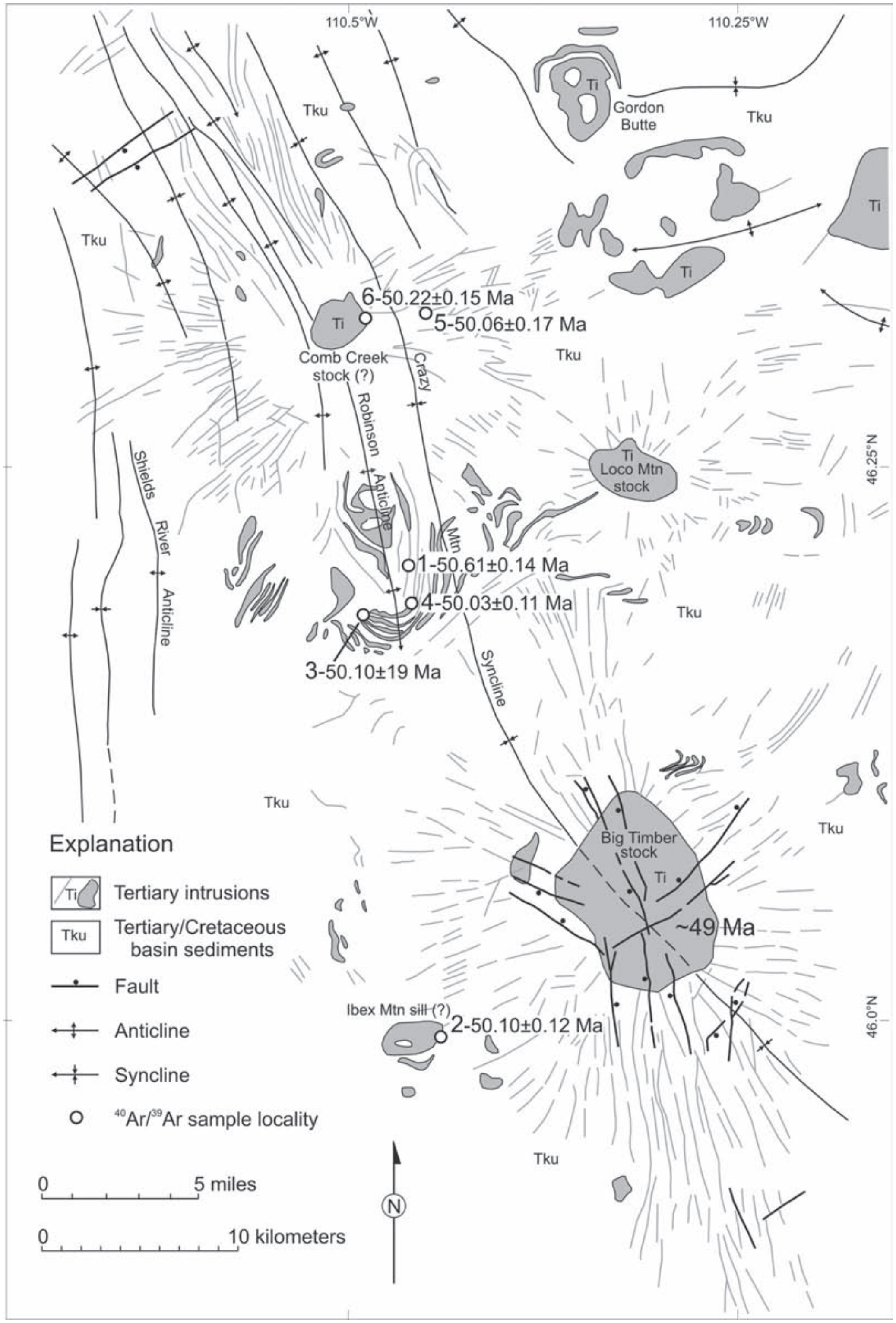

Figure 2. Tectonic map showing distribution of Tertiary intrusions in the central part of Crazy Mountains Basin, west-central Montana. Also shown are locations of samples dated by $^{40}Ar/^{39}Ar$ method and their apparent ages as described in the text and as listed in Table 1. Approximate date cited for the Big Timber stock is based on $^{40}Ar/^{39}Ar$ dates reported by du Bray and Harlan (1996). Figure modified from Roberts (1972).

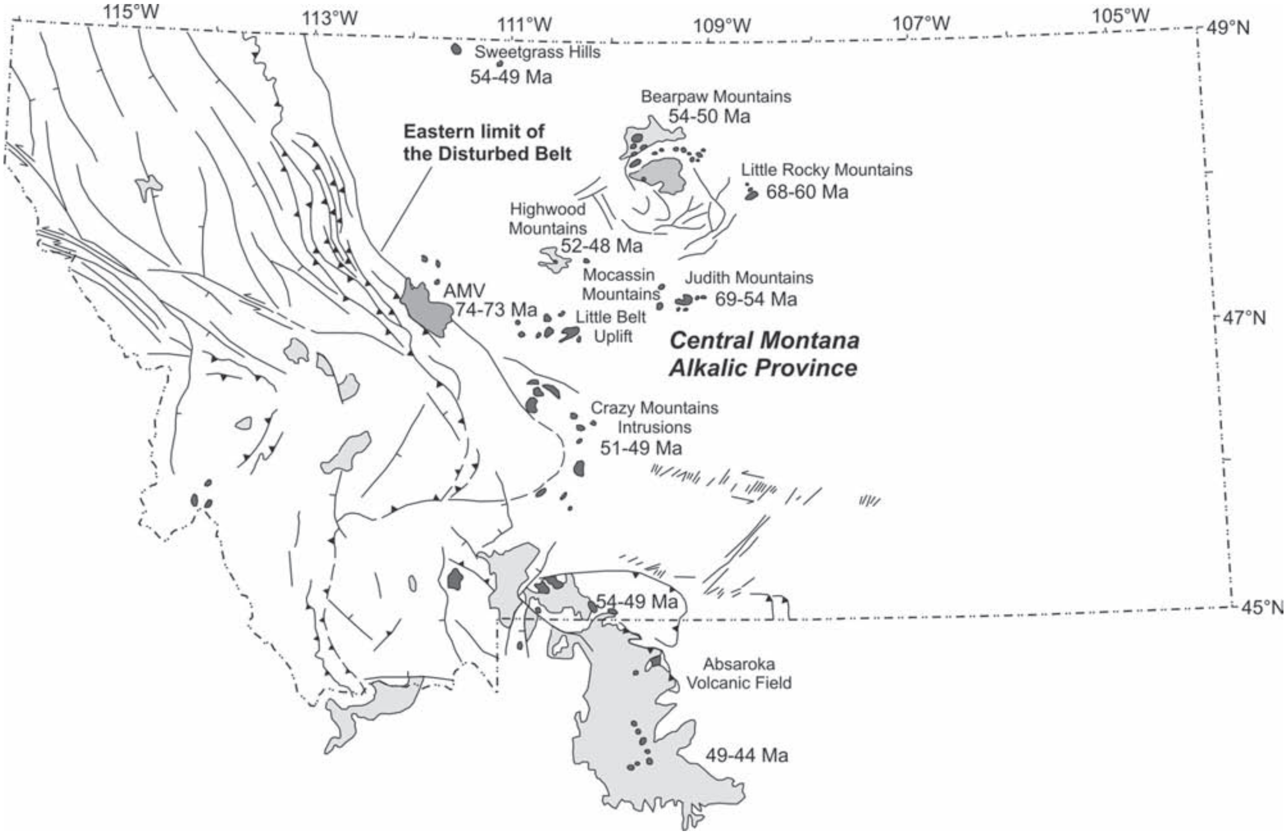

Figure 3. Tectonic map of Montana showing location and age of Tertiary volcanic (light gray) and intrusive (dark gray) rocks, including the central Montana alkalic province and volcanic rocks of the Absaroka volcanic field. Isotopic dates indicate a Tertiary age for most central Montana alkalic province rocks. Also shown is the location of the Adel Mountain volcanic field (AMV; medium gray), which has been considered by some workers to be part of the central Montana alkalic province. Recent $^{40}Ar/^{39}Ar$ dating indicates that the field is Late Cretaceous in age (Harlan et al., 2005). Sources for isotopic dates from Marvin et al., 1973; Marvin and Dobson, 1979; Marvin et al., 1980; Chadwick, 1981; Harlan, 1996; Harlan et al., 1996; Feeley and Cosca, 2003; Harlan et al., 2005; this study. Figure modified from a map by D. R. Lageson in Taylor et al. (1984).

the Big Timber and Loco Mountain stocks and associated dike swarms (Tappe, 1966; Larsen and Simms, 1972; Starmer, 1972; du Bray and Harlan, 1996). With the exception of the sill (?) at Ibex Mountain, the strongly alkaline rocks are largely restricted to the northern Crazy Mountains, whereas the subalkaline rocks are found mostly in the southern Crazy Mountains.

The strongly alkaline rocks intrude the easternmost folds of the Montana disturbed belt. The arcuate and concordant nature of some sills with fold structure has suggested that at least some of the igneous activity may have preceded folding (Simms, 1966; Harlan and Lageson, 1983). Paleomagnetic and structural analysis, however, demonstrated that intrusion of the sills in the Robinson anticline intrusive complex postdated thin-skinned, fold-and-thrust-belt deformation (Harlan, 1986; Harlan et al., 1988). Geochronologic data from the Crazy Mountains intrusions indicate that they were emplaced during the Eocene at ~52–48 Ma, during the height of magmatic activity of the Challis magmatic flare-up (Harlan, 1986; Harlan et al., 1988; Dudas, 1991). This paper presents new, high-precision $^{40}Ar/^{39}Ar$ geochronologic data obtained from the strongly alkaline intrusions from the northern Crazy Mountains that complement previously published $^{40}Ar/^{39}Ar$ geochronologic data from the subalkaline Big Timber stock (du Bray and Harlan, 1996).

ANALYTICAL METHODS

The samples used in $^{40}Ar/^{39}Ar$ dating were crushed, sieved, and separated using standard gravi-

Table 1. ^{40}Ar/^{39}Ar incremental heating data for samples of alkaline intrusive rocks from the Crazy Mountains, west-central Montana.

Temp (°C)	$^{40}\mathrm{Ar_R}$	$^{39}\mathrm{Ar_K}$	$^{40}\mathrm{Ar_R}/^{39}\mathrm{Ar_K}$	$^{39}\mathrm{Ar}/^{37}\mathrm{Ar}$	$\%^{40}\mathrm{Ar_K}$	$\%^{39}\mathrm{Ar}$	Apparent age (Ma ± 1σ)
82VP-2: Hornblende, trachyte, sill; 70.9 mg; $^{40}\mathrm{Ar}/^{36}\mathrm{Ar}_a$ = 298.9; J-value =0.00769 ± 0.1% (1σ)							
700	0.12645	0.03153	4.011	2.62	21.6	0.6	54.87±1.37
800	0.11665	0.02694	4.329	1.56	20.2	0.5	59.15±1.29
900	0.22156	0.05643	3.926	1.07	62.3	1.0	53.73±1.05
975	0.27472	0.06863	4.003	0.84	74.7	1.2	54.76±0.35
1050	0.78274	0.20420	3.833	0.43	75.7	3.6	52.47±0.29
1075	1.1540	0.30934	3.730	0.37	86.1	5.4	51.09±0.15
1100	1.73822	0.47043	3.695	0.36	91.1	8.3	50.61±0.15
1125	4.9527	1.3374	3.703	0.35	93.7	23.5	50.72±0.08
1150	6.4046	1.7318	3.698	0.35	94.6	30.4	50.67±0.08
1200	2.1640	0.58862	3.676	0.34	92.5	10.3	50.36±0.13
1250	1.9220	0.52223	3.680	0.29	93.8	9.2	50.41±0.14
1350	1.1035	0.29962	3.683	0.27	92.3	5.3	50.45±0.21
1450	0.20734	0.05506	3.766	0.28	82.5	1.0	51.56±0.47
Total Gas			3.712				50.84±0.14
202338(Ibex Mountain): Biotite, mafic nepheline syenite, sill, 50.9 mg; $^{40}\mathrm{Ar}/^{36}\mathrm{Ar}_a$ = 298.9; J-value = 0.007781 ± 0.1% (1σ)							
600	0.05104	0.04121	1.238	20.70	0.7	0.7	17.30±0.99
700	0.42849	0.16230	2.640	53.49	56.6	2.6	36.68±0.17
750	1.14790	0.32306	3.564	102.33	70.8	5.2	49.35±0.13
800	1.65660	0.45697	3.265	137.22	86.0	7.4	50.18±0.08
850	1.93705	0.53609	3.613	183.78	87.9	8.7	50.02±0.09
900	2.05721	0.56998	3.609	250.85	89.1	9.2	49.96±0.14
950	2.07748	0.57350	3.622	174.92	90.3	9.3	50.14±0.10
1000	1.74716	0.48279	3.619	137.74	88.7	7.8	50.10±0.08
1050	1.66418	0.46037	3.615	104.29	90.3	7.5	50.04±0.24
1100	2.90917	0.80330	3.622	71.88	86.7	13.0	50.13±0.08
1150	2.38796	0.66073	3.614	53.21	82.7	10.7	50.03±0.08
1350	3.98206	1.09858	3.625	15.99	79.7	17.8	50.18±0.08
Total Gas			3.574				49.49±0.12
83VP-75: Biotite, mafic nepheline syenite, sill; 70.9 mg; $^{40}\mathrm{Ar}/^{36}\mathrm{Ar}_a$ = 298.9; J-value =0.007825 ± 0.1% (1σ)							
600	0.35848	0.10247	3.498	51.92	48.4	1.1	48.72±0.37
700	0.97747	0.26818	3.645	93.60	87.9	2.8	50.73±0.15
750	1.84141	0.51303	3.589	128.80	84.9	5.3	49.97±0.08
800	2.83212	0.78754	3.596	190.88	92.0	14.5	50.06±0.11
850	3.64399	1.01482	3.594	333.53	94.8	10.5	49.99±0.09
900	4.53069	1.23591	3.589	293.40	94.7	13.0	49.97±0.08
950	4.44170	1.23591	3.594	187.92	93.9	12.8	50.03±0.08
1000	3.54210	0.98650	3.591	122.61	91.8	10.2	49.99±0.09
1050	4.39253	1.22284	3.592	115.85	86.3	12.6	50.01±0.08
1100	3.49982	0.97170	3.602	73.45	77.4	10.0	50.14±0.08
1150	2.09815	0.58376	3.594	32.27	69.0	6.0	50.04±0.11
1200	1.38955	0.38493	3.610	14.50	52.9	4.0	50.25±0.14
1350	1.22904	0.34308	3.591	3.85	57.8	3.5	49.87±0.49
Total Gas			3.594				50.03±0.10
83VP-65: Biotite; mafic nepheline syenite, sill; 59.7 mg; measured $^{40}\mathrm{Ar}/^{36}\mathrm{Ar}_a$ = 298.9; J-value = 0.00623 ± 0.1% (1σ)							
600	1.05374	0.23180	4.546	99.29	58.1	4.5	50.38±0.14
700	1.91901	0.42471	4.518	161.74	78.0	8.3	50.08±0.16
800	6.54108	1.44775	4.518	352.04	93.4	28.3	50.08±0.19
850	3.51108	0.77686	4.520	745.20	93.5	15.2	50.09±0.33
900	3.32483	0.73430	4.528	340.31	93.2	14.4	50.18±0.26
950	2.78227	0.61316	4.538	308.36	92.2	12.0	50.29±0.42
1000	1.72834	0.38260	4.517	160.59	80.4	7.5	50.07±0.14
1050	1.09643	0.24175	4.535	78.10	65.3	4.7	50.27±0.65
1100	0.70177	0.15125	4.640	37.65	51.0	3.0	51.41±1.00
1300	0.48709	0.10349	4.707	5.06	41.5	2.0	52.14±1.07
Total Gas			4.532				50.22±1.07
83VPCC-1: Biotite, mafic nepheline syenite, dike, 61.3 mg; $^{40}\mathrm{Ar}/^{36}\mathrm{Ar}_a$ = 298.9; J-value = 0.006138 ± 0.1% (1σ)							

Table 1. (continued).

600	0.08828	0.02069	4.266	15.21	7.7	0.4	46.63±1.22
700	1.00596	0.21530	4.672	35.74	65.4	4.0	51.01±0.30
800	5.94678	1.29290	4.600	78.82	88.4	24.0	50.23±0.14
900	6.14365	1.34352	4.573	116.17	92.0	25.0	49.94±0.14
950	3.31741	0.72587	4.570	50.47	88.8	13.5	49.91±0.29
1000	2.68422	0.58519	4.587	34.54	86.2	10.9	50.09±0.14
1025	1.21498	0.26520	4.581	23.58	80.1	4.9	50.03±0.20
1050	0.83467	0.18252	4.573	14.05	77.5	3.4	49.94±0.43
1100	1.17611	0.25662	4.583	10.11	77.6	4.8	50.05±0.22
1250	2.26306	0.48965	4.622	2.55	70.5	9.1	50.46±0.16
Total Gas			4.589				50.11±0.18
83VPCC-12: Biotite, nepheline syenite, stock (?), 53.2 mg; $^{40}Ar/^{36}Ar_a$ = 298.9; J-value = 0.006151 ± 0.1% (1σ)							
600	0.18041	0.04671	3.862	37.26	35.6	0.9	42.35±0.78
700	0.74269	0.16672	4.455	113.97	52.8	3.2	48.76±0.25
800	5.20549	1.13237	4.597	322.98	94.3	22.0	50.30±0.20
850	3.35254	0.73051	4.589	385.09	96.3	14.2	50.22±0.14
900	1.41193	0.30669	4.604	268.53	94.5	5.9	50.38±0.19
950	1.36432	0.29800	4.578	131.95	89.4	5.8	50.10±0.19
1000	2.44198	0.53064	4.602	143.76	93.6	10.3	50.36±0.15
1050	3.73626	0.81358	4.592	138.51	95.7	15.8	50.25±0.14
1100	3.45184	0.75335	4.582	100.21	96.1	14.6	50.14±0.14
1250	1.72665	0.37730	4.576	4.75	94.7	7.3	50.08±0.16
Total Gas			4.580				50.12±0.16

Note: $^{40}Ar/^{36}Ar_a$ is measured atmospheric argon used for mass-discrimination at time of analysis; $^{40}Ar_R$ is radiogenic ^{40}Ar in volts signal; $^{39}Ar_K$ is potassium-derived ^{39}Ar in volts signal; $^{40}Ar_R/^{39}Ar_K$ is the ratio of $^{40}Ar_R$ to $^{39}Ar_K$ after correction for mass-discrimination and interfering isotopes; $^{39}Ar/^{37}Ar$ = ratio of $^{39}Ar_K$ to $^{37}Ar_{Ca}$ (this value can be converted to the approximate K/Ca by multiplying by 0.52); $\%^{40}Ar_K$ and $\%^{39}Ar$ are the percentage of radiogenic ^{40}Ar and percentage of total $^{39}Ar_K$ released in each temperature step. Temperature steps in bold are those used in calculation of plateau age. Conversion of volts signal to moles Ar can be made using a conversion factor of 1.252×10^{-13} moles argon per volt of signal. Steps denoted by bold font are those used in calculation of the plateau dates as described in the text. Analytical details are available in Snee (2002).

metric methods. Individual samples were handpicked to greater than 99.9% visual purity prior to irradiation for $^{40}Ar/^{39}Ar$ dating. The sample and flux monitors were loaded in aluminum foil capsules, placed in quartz vials, and irradiated for 30 hours in the central thimble of the U.S. Geological Survey TRIGA reactor. Vertical and horizontal variations in neutron flux in the irradiated package were monitored by 8 to 12 standards distributed along the length of each vial; the geometry of the package was arranged such that each unknown sample was adjacent to at least one standard during irradiation. The flux monitor used was hornblende MMHb-1, which has an assigned K-Ar age of 520.4 ± 1.7 Ma (Samson and Alexander, 1987). Following irradiation, the samples were progressively degassed in a double-vacuum resistance furnace for 20 minutes in 10 to 12 steps from 500° to 1550°C. Five naturally occurring and radiogenic argon isotopes were measured at each step using a Mass Analyzer Products MAP-215 mass spectrometer operated in the static mode. Corrections for reactor-produced interfering reactions were made using argon isotopes of K_2SO_4 and CaF_2 irradiated in each package. $^{40}Ar/^{39}Ar$ analytical data are listed in Table 1.

Apparent ages for each temperature step were calculated using the decay constants recommended by Steiger and Jäger (1977). The argon data were evaluated using age-spectrum, apparent K/Ca, and $^{39}Ar/^{40}Ar$ vs. $^{36}Ar/^{40}Ar$ inverse correlation diagrams. The determination of whether the apparent ages in the age spectrum constituted a plateau was made using the criteria of Fleck et al. (1977). Following these criteria, a plateau is defined as comprising two or more contiguous gas fractions that yield apparent ages that are statistically identical at 95% confidence (using the critical value test of Dalrymple and Lanphere, 1969) and which together constitute greater than 50% of the total potassium-derived ^{39}Ar released in the incremental heating experiment. The plateau age and associated error were calculated using a weighted mean, where weighting is by the inverse of the analytical variance (Taylor, 1982), following the procedure of Ludwig (2003). Calculation of total gas, plateau, and correlation ages includes the analytical uncertainty in

Table 2. Summary of isotopic dating results from alkaline intrusive rocks exposed in the northern Crazy Mountains, west-central Montana.

Figure 2	Sample No.	Locality	Latitude (°N)	Longitude (°W)	Rock Type	Material Dated	K-Ar Date (Ma)	^{40}Ar/^{39}Ar Date (Ma)
1	82VP-2	Robinson anticline, Davey Butte	46.2023	110.4592	Trachyte sill	Hornblende	48.5±4.5	Tw = 50.61 ± 0.14
2	202338	Ibex Mountain sill	46.9943	110.4479	Mafic nepheline syenite sill	Biotite	50.5±0.6	Tp = 50.10 ± 0.12
3	83VP-65	Robinson anticline	46.1873	110.4918	Mafic nepheline syenite sill	Biotite	50.3±1.9	Tp = 50.10 ± 0.19
4	83VP-75	Robinson anticline	46.1875	110.4637	Mafic nepheline syenite sill	Biotite	49.3±1.9	Tp = 50.03 ± 0.11
5	83VPCC-1	Comb Creek stock	46.2984	110.4453	Mafic nepheline syenite dike	Biotite	52.3±2.0	Tp = 50.06 ± 0.17
6	83VPCC-12	Comb Creek stock	46.307	110.499	Nepheline syenite stock	Biotite	48.0±1.9	Tp = 50.22 ± 0.15

Tp, plateau date; Tw, weighted mean date, for which the strict plateau criteria have not been met, as described in the text. Analytical error for the K-Ar dates is ± 1σ; the error in the ^{40}Ar/^{39}Ar dates is given at ± 2σ. All ^{40}Ar/^{39}Ar dates are from mineral separates used in original K-Ar dating reported by Harlan (1986) and Harlan et al. (1988), with the exception of the sample from the Ibex Mountain sill (?). For this intrusion, a new sample was collected, processed, and dated by the ^{40}Ar/^{39}Ar technique.

the determination of the flux parameter *J*. Summary analytical data are listed in Table 2.

RESULTS AND INTERPRETATION

Sample 82VP-2 was collected from a trachyte sill exposed along the eastern flank of the Robinson anticline intrusive complex (Fig. 2; locality 1). Hornblende from the sill previously yielded a K-Ar date of 48.5 ± 4.5 Ma (1σ) (Harlan et al., 1988). ^{40}Ar/^{39}Ar analysis of the same mineral concentrate gives a somewhat discordant age spectrum with a total gas age of 50.84 ± 0.14 Ma (1σ) (Table 1). The spectrum is somewhat U-shaped with older ages released in the lower temperature steps, but yields a fairly flat profile over ~90% of the ^{39}Ar$_K$ released (Fig. 4). The sample does not yield a plateau using the strict criteria of Fleck et al. (1977), but the intermediate temperature steps, which give a reasonably flat release pattern, define the best estimate for the age of the sample. These steps give a weighted-mean age of 50.61 ± 0.14 Ma (2σ) (Table 2). I interpret this date to best represent the emplacement age of the trachyte sill.

Five biotite mineral separates were dated from strongly alkaline intrusions, with intrusion compositions ranging from mafic nepheline syenite to nepheline syenite. These intrusions include the sill (?) at Ibex Mountain, just west of the subalkaline Big Timber stock; sills of the Robinson anticline intrusive complex, previously shown by paleomagnetic methods to have post-dated folding (Harlan et al., 1988); and the Comb Creek stock (?) with an associated radial dike (Fig. 2). Previous K-Ar dates from the mineral concentrates obtained from these intrusions gave ages ranging from 52.3 ± 2.0 (1σ) to 48.0 ± 1.9 Ma (1σ) (Table 2). The interpretation of the ^{40}Ar/^{39}Ar results from these samples is reasonably straightforward. Although individual age spectra show minor complications in low- or high-temperature steps (Fig. 4), all samples yielded well-defined plateau-like segments over ~90% of the ^{39}Ar$_K$ released in the step-heating experiments. The plateau dates are tightly grouped and range from 50.22 to 50.03 Ma, with 2σ errors ranging from ± 0.11 to 0.19 Ma (Fig. 4; Table 2). Because most of the samples are from small, hypabyssal intrusions that must have cooled very quickly, these dates represent the best estimate of the emplacement age of these intrusions. These data indicate that strongly alkaline syenites were emplaced during a short interval of time at ~50.10 Ma.

The ^{40}Ar/^{39}Ar dates presented here yield ages that are within the range of previously determined

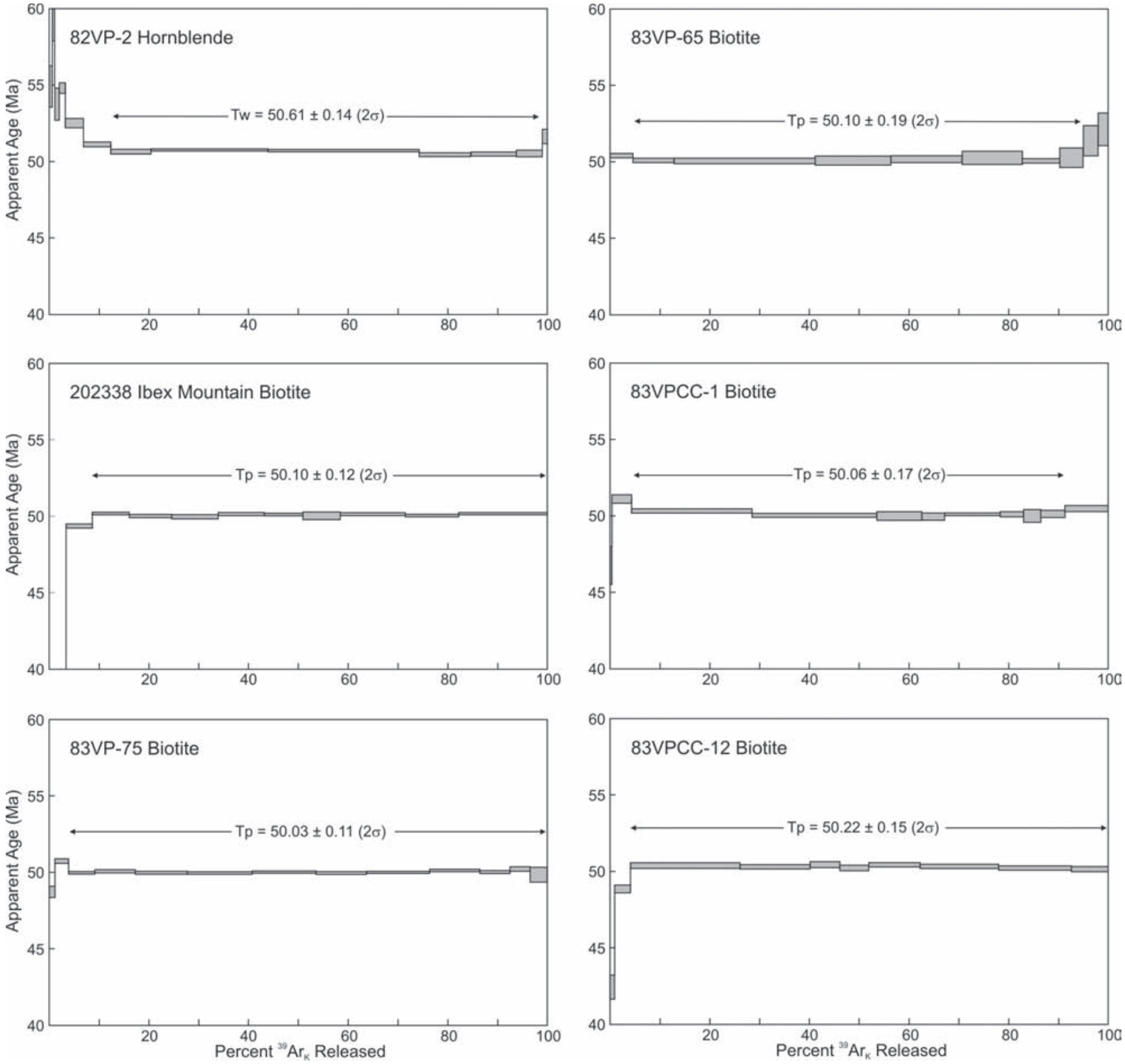

Figure 4. $^{40}Ar/^{39}Ar$ age spectra for intrusive rock samples from the Crazy Mountains. The length of each rectangle is proportional to the amount of $^{39}Ar_K$ released in each incremental heating step. The height of the rectangle represents the analytical error in each apparent age at ± 1σ. Tw or Tp is the calculated weighted mean or plateau age as described in the text. The associated error is reported at ± 2σ.

K-Ar dates reported by Harlan et al. (1988), but are analytically more precise. The $^{40}Ar/^{39}Ar$ hornblende and biotite dates are somewhat older than the Rb-Sr mineral isochron reported by Dudas (1991) for the Comb Creek stock, which yielded an age of 48.3 ± 1.25 Ma (error recalculated from Dudas (1991) assuming an ^{87}Rb decay constant of 1.42×10^{-11} (Steiger and Jäger, 1977) and a 2% error in that value). Dudas (1991) noted that the mineral isochron from the northern Crazy Mountains rocks essentially represents a two-point fit between clusters of low-Rb minerals and Rb-rich biotite and that potential problems with modification of Rb/Sr of biotite due to alteration or weathering could significantly affect the calculated age, resulting in an apparent age that could be too young. However, this difference is not significant when uncertainties in errors for the decay constants for the Rb-Sr and $^{40}Ar/^{39}Ar$ systems and uncertainties in the age of the neutron flux monitor used in this study are fully propagated into the absolute errors for the isotopic dates (Renne et al., 1998). Similarly, a whole rock isochron from a variety of the alkaline rocks of the northern Crazy Mountains yielded a somewhat older apparent age of 51.4 ± 1.3 Ma (error calculated as above), but this age is also not statistically distinguishable from the ^{40}Ar/^{39}Ar dates presented here when decay constant errors and flux-monitor uncertainties are considered. However, because of the potential complications in the Rb-Sr systematics and the consistency of the of the ^{40}Ar/^{39}Ar dates from the syenites, the dates presented here are considered to be the most reliable estimates of the age of the intrusion for this group of rocks.

The ^{40}Ar/^{39}Ar dates from the alkaline rocks of the northern Crazy Mountains are somewhat older than the ~49.3–49.2-Ma biotite ^{40}Ar/^{39}Ar dates from the subalkaline Big Timber stock (du Bray and Harlan, 1996). The older dates from the alkaline rocks of the northern Crazy Mountains could be interpreted to indicate that their emplacement predated intrusion of the subalkaline rocks exposed largely in the southern Crazy Mountains. Such an interpretation would be problematic, however, because the biotite dates from the Big Timber stock represent cooling ages through closure temperatures of ~350°C and thus represent minimum ages for emplacement of the stock. Field relationships bearing on the relative ages of the two distinct geochemical groups are rare and typically ambiguous (Simms, 1966; Dudas, 1991), and hence cannot be used to distinguish the relative intrusive history between the two groups. Still, the limited span of ^{40}Ar/^{39}Ar ages between the subalkaline and alkaline rocks (ca. 50.6–49.2 Ma), and their geographic proximity, indicate that the rocks of these two distinctly different geochemical groups were closely linked in both time and space and may indicate that the entire mass of intrusive rocks was emplaced in as little as 1–2 m.y.

On a regional scale, the 51–49-Ma age span is similar to the range of dates from most of the igneous centers of the central Montana alkalic province and is coeval with the peak of widespread volcanism in the Absaroka-Gallatin volcanic field immediately to the south of the Crazy Mountains Basin (Fig. 3) (Smedes and Protska, 1972; Harlan et al., 1996; Feeley and Cosca, 2003) and the peak of magmatism of the Challis magmatic event (Armstrong, 1978). High-precision ^{40}Ar/^{39}Ar dating of intrusive rocks elsewhere in the central Montana alkalic province is needed to further refine the timing, duration, and migration of magmatic activity in this region during the Tertiary. These studies are key to understanding processes that gave rise to magmatism during the transition between subduction- and extension-dominated tectonics in the evolution of the Cordilleran orogenic belt.

CONCLUSIONS

Isotopic dating of mineral separates from the strongly alkaline intrusive rocks from the Crazy Mountains yields well-defined age spectra and represents substantial improvement in our understanding of the intrusive history of this area. The new dates indicate emplacement of a trachyte sill at 50.61 Ma and that mafic and felsic nepheline syenites from five separate intrusions were emplaced during a short period of time between 50.22 and 50.03 Ma. Because of the shallow nature of these intrusions, these dates represent the age of emplacement of the individual intrusions. Overall, the geochronologic data from the Crazy Mountains indicate that the intrusions from the alkaline and subalkaline groups were emplaced at approximately the same time and may have spanned an interval of time on the order of 1–2 m.y.

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