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$^{40}Ar/^{39}Ar$ Geochronology Results from Clasts from Late Cretaceous/early Tertiary Units of the Caballo Mountains, New Mexico

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Introduction

Twelve mafic clasts from the Love Ranch and McRae Formations, southern New Mexico were submitted for $^{40}Ar/^{39}Ar$ dating by Dr. Gregory Mack. It is hoped that the $^{40}Ar/^{39}Ar$ ages will help constrain the maximum ages on the McRae and Love Ranch Formations. No dateable material was found in samples Tlr-1, Tlr-3, Kmh-2, Kmh-3 and Kmj-3. Biotite was prepared from the Kmh-1, Tlr-2 and Tlr-4 samples. Groundmass concentrates were prepared from Kmh-4, Kmj-1, Kmj-2 and Kmj-4.

$^{40}Ar/^{39}Ar$ Analytical Methods and Results

Samples were prepared for the $^{40}Ar/^{39}Ar$ dating by using standard minerals separation techniques. Clasts were crushed and sieved to approximately 48-60 mesh (~275 μm). Biotite phenocrysts were hand-picked from crushed samples. For the groundmass concentrate samples, highly magnetic and non-potassium bearing phenocryst phases (e.g. olivine) were removed by the Franz magnetic separator and by hand-picking.

The groundmass concentrate and biotite samples were analyzed by the furnace incremental heating age spectrum $^{40}Ar/^{39}Ar$ method. Abbreviated analytical methods for the furnace sample is given in Table 1, while the analytical data is given in Table 2. Details of the overall operation of the New Mexico Geochronology Research Laboratory are provided in the Appendix. Figures 1-8 show the age spectrum and inverse isochron yielded by the groundmass concentrates (sample Kmj-4 was analyzed twice) and biotites. A summary of the preferred ages yielded in this study is listed in Table 3 and shown on Figure 10.

Table 3. Summary of $^{40}Ar/^{39}Ar$ apparent ages.

Sample	Age±2σ Error (Ma)
Kmj-2 groundmass concentrate	67.3±2.9
Kmj-1 groundmass concentrate	43.3±0.7
Kmh-4 groundmass concentrate	70.82±0.42
Kmj-4 groundmass concentrate	62.3±1.5
Kmj-4 groundmass concentrate	59.6±1.1
Weighted Mean	**60.5±2.6**
Tlr-2 biotite	89.4±2.2
Kmh-1 biotite	89.7±1.0
Tlr-4 biotite	86.47±0.41

The four groundmass concentrate samples yielded moderately to highly discordant age spectra. The age spectrum for the Kmj-2 groundmass concentrate (Figure 1) is best

described as "hump-shaped", where the hump is skewed to the lower temperature steps. The lowest temperature heating steps (<825°C) yield apparent ages of 45 to 62 Ma. Subsequent heating steps initially yield apparent ages of approximately 70 Ma, but then slowly decrease in age to less than 62 Ma. The radiogenic yields are positively correlated to the age spectrum with values ranging from less than 3% (for the lowest temperature steps) to 62.5% (for the oldest steps) to 46% (for the highest temperature step). The K/Ca ratios for Kmj-2 are remarkably consistent over much of the spectrum, yielding values of approximately 1.5. A plateau assigned to steps E through I yields a weighted mean age of 67.3±2.9 Ma (96.1% of the $^{39}Ar_K$ released). The inverse isochron results for Kmj-2 are analytically indistinguishable from the spectrum weighted mean age and atmosphere.

Groundmass concentrate Kmj-1 (Figure 2) yields a discordant age spectrum with two anomalously young low temperature steps and an anomalously old high temperature step. The radiogenic yields for Kmj-1 range from essentially zero to 43%. The K/Ca ratios are initially low for the lowest temperature heating steps (<3), but then climb to values of about 3 before decreasing to less than 2 for the highest temperature steps. The flattest portion of the Kmj-l age spectrum yields a weighted mean age of 43.3±0.7 Ma with 73.4% of the cumulative $^{39}Ar_K$ released. The inverse isochron results for Kmj-l are analytically indistinguishable from the spectrum weighted mean age and atmosphere.

Groundmass concentrate Kmh-4 (Figure 3) yields a discordant age spectrum with two anomalously young low temperature steps and an anomalously old high temperature step. The radiogenic yields for Kmh-4 range from less than 5% for the initial gas released to greater than 75% for the bulk of the age spectrum. K/Ca ratios are consistent throughout much of the age spectrum at approximately 2. The intermediate temperature steps (steps C to H) yield the flattest portion of the age spectrum with a weighted mean or “plateau” age of 70.8±0.5 Ma (52.1% of the $^{39}Ar_K$ released). The inverse isochron for Kmh-4 yielded very discordant results with a MSWD of 65, although the age and $^{40}Ar/^{36}Ar$ intercept were equivalent to the plateau age and atmosphere (295.5), respectively.

Groundmass concentrate Kmj-4 was analyzed twice. Both analyses yielded very similar age spectra. In each case, the first two heating steps (steps A and B) yielded young apparent ages of about 50-60 Ma. The subsequent 4 heating steps (C through F) for both analyses yielded ages climbing to greater than 67 Ma for Kmj-4 #1 (Figure 4) and 64 Ma for Kmj-4 #2 (Figure 5). The final three heating steps (G through 1) for both samples are approximately 4 million years younger than the ages yielded by C through F. As was the case for Kmj-2, the radiogenic yields for Kmj-4 #1 and #2 are positively correlated to the age spectra. Values for both range from less than 1% (earliest gas released) to as high as

59% for the "hump" in the intermediate temperature steps. The K/Ca ratios for each sample are nearly identical and consistent at approximately 1.7. The flattest portion of each age spectrum was used to calculate the weighted mean age. Kmj-4 #1 yielded an age of 62.4±1.5 Ma (79.4% of the $^{39}Ar_K$) and Kmj-4 #2 yielded an age of 59.6±1.1 Ma (75.8% of the $^{39}Ar_K$). The inverse isochrons for the Kmj-4 groundmass concentrates yield ages that are analytically indistinguishable from their respective age spectrums and $^{40}Ar/^{39}Ar$ intercepts that are indistinguishable from atmosphere.

Each of the three biotite samples yielded a continuously climbing (Kmh-1; Figure 6) to hump-shaped (Trl-2 and Trl-4; Figures 7 and 8, respectively) age spectrum. The minimum age for each age spectrum, yielded by the lowest temperature steps, is approximately 20 Ma. From the lowest temperature heating steps, the ages gradually increase to a maximum of 80 to 90 Ma. For the Tlr-4 biotite, the ages of the individual heating steps gradually decrease to approximately 70 Ma at the highest temperature steps. The radiogenic yields for the lowest temperature heating steps (<1100°C) of each age spectra are “normal” for a biotite, the highest temperature steps (>1200°C) yield K/Ca ratios much lower than expected, especially for Kmh-1 and Tlr-2. The isochron results for all three biotite samples were very poor with very high MSWD values (>400). Only the isochron for Tlr-4 has been plotted (Figure 3b).

Discussion

For the four groundmass concentrate samples, the weighted mean ages are inferred to be the best estimate of the ages of these clasts. However, each of the groundmass concentrate age spectra exhibit varying effects of alteration/hydration and/or excess argon and $^{39}Ar_K$ recoil. Groundmass concentrate samples Kmj-2 and Kmj-4 (both analyses) exhibit age spectra characteristic of $^{39}Ar_K$ recoil. $^{39}Ar_K$ recoil occurs when a ^{39}K atom is converted to a ^{39}Ar atom (through the $^{39}K(n,p)^{39}Ar$ nuclear reaction) with an energy sufficient enough to eject the atom from a mineral phase that is being irradiated. The ejected $^{39}Ar_K$ can either be lost from the sample completely or re-implanted into an adjacent phase. The mineral phase that has undergone a net loss of $^{39}Ar_K$ will yield an anomalously old age while a mineral phase that has undergone a net gain of $^{39}Ar_K$ will yield an anomalously young age. A schematic of this affect can be viewed in Figure 9. In the case of the Kmj-2 and Kmj-4 groundmass concentrates, significant quantities of $^{39}Ar_K$ is apparently recoiling out of a low temperature, high potassium mineral phase (e.g. groundmass feldspar) or glass into a high temperature, low potassium mineral phase (e.g. pyroxene or olivine). In cases

where $^{39}Ar_K$ is suspected, the integrated or total gas age is interpreted to be the best estimate for the age of the sample. Therefore, for groundmass concentrate Kmj-2, the preferred age is 65.1±1.7 Ma. The preferred age for Kmj-4 is the weighted mean of the two individual Kmj-4 integrated ages (60.2±1.9 Ma).

For groundmass concentrate Kmh-4 and, to a lesser extent Kmj- 1, the age spectra exhibit clear signs of 1) alteration/hydration for the lowest temperature gas released, as evident by the anomalously young ages and lower radiogenic yields, and 2) excess argon for the highest temperature gas released, as evident by the anomalously old ages and lower K/Ca ratios. The alteration and/or hydration of the groundmass phases can cause varying loss of $^{40}Ar^*$, thus decreasing the apparent age (see Figure 9). Conversely, excess argon will increase the age of a sample due to the incorporation of non-atmospheric ^{40}Ar prior to the cooling of the lava. It is likely that the excess argon present in Kmh-4 and Kmj-1 resides in low potassium pyroxene or olivine phenocrysts contained in the groundmass concentrate. Despite the presence of both alteration/hydration products (argon loss) and excess argon, we are reasonably confident that the weighted mean ages of 70.8±0.5 Ma (Kmh-4) and 43.3±0.7 Ma (Kmj-1) are the best estimate of the ages of eruption for these two samples.

For the three biotite samples (Kmh-1. Trl-2 and Trl-4), the plateau or weighted mean ages are inferred to be the best estimate of the ages of these clasts. However, as was the case for some of the groundmass concentrates from this study, each of the biotite age spectra exhibit an age gradient resulting from $^{40}Ar^*$ loss. The event causing the $^{40}Ar^*$ loss is not easily reconciled by the $^{40}Ar/^{39}Ar$ data. Although a thermal event can potentially cause a differential release of $^{40}Ar^*$ within a mica grain, it is unlikely that the age gradient would be so well manifested in the laboratory because of the dehydration of the biotite structure during the step-heating procedure (Giletti, 1974 and Harrison, 1981). The most likely explanation of the age gradient is alteration/chloritization of the biotite lattice, which can cause extensive $^{40}Ar^*$ loss. The very low radiogenic yields for the initial, young ages are also indicative of significant alteration products (i.e. chlorite). This argon loss event has clearly affected a large percentage of each of the biotite spectra. While plateau or weighted mean ages have been assigned to the flattest portions of each spectrum and these are considered the preferred ages of these samples, we are not confident that $^{40}Ar^*$ was not lost from these steps as well. Therefore, the preferred ages must also be considered minimum ages. Although the initial ages for the three biotite samples are coincident at 14-20 Ma, we can only speculate that these ages record any alteration event (e.g. hydrothermal pulse?).

Figure 10 shows a summary of the $^{40}Ar/^{39}Ar$ ages yielded in this study. Taking into account the presumed alteration of the biotite samples, it is possible that the Kmh-1, Tlr-2 and Tlr-4 clasts originated from the same igneous body. Likewise, the Kmh-4 and Kmj-2 clasts are of very similar age to one another and may also be cogenetic. We cannot speculate on whether Kmj-4 is also cogenetic with either Kmh-4 or Kmj-2.

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Table 1. 40Ar/39Ar analytical methods used for the groundmass concentrate samples.

Sample preparation and irradiation:

Geological samples provided by Dr. Greg Mack.
Groundmass concentrates and Biotites were prepared using standard separation techniques (crushing, sieving, franzing and hand-picking).
Samples were packaged and irradiated in machined Al discs for 7 hours in D-3 position, Nuclear Science Center, College Station, TX.
Neutron flux monitor Fish Canyon Tuff sanidine (FC-1). Assigned age = 27.84 Ma (Deino and Potts, 1990)
relative to Mmhb-1 at 520.4 Ma (Samson and Alexander, 1987).

Instrumentation:

Mass Analyzer Products 215-50 mass spectrometer on line with automated all-metal extraction system.
Samples step-heated in Mo double-vacuum resistance furnace. Heating duration 7 minutes.
Reactive gases removed by reaction with 3 SAES GP-50 getters, 2 operated at ~450°C and
1 at 20°C, together with a W filiment operated at ~2000°C.

Analytical parameters:

Electron multiplier sensitivity averaged 2.82×10^{-16} moles/pA.
Total system blank and background for the furnace averaged 4400, 57.0, 1.7, 6.8, 14.1 x 10^{-18} moles
at masses 40, 39, 38, 37, and 36, respectively for temperatures <1300°C.
J-factors determined to a precision of ± 0.1% by CO_2 laser-fusion of 4 single crystals from each of 6 radial positions around the irradiation tray.
Correction factors for interfering nuclear reactions were determined using K-glass and CaF_2 and are as follows:
$(^{40}Ar/^{39}Ar)_K = 0.0002 \pm 0.0003$; $(^{36}Ar/^{37}Ar)_{Ca} = 0.00028 \pm 0.000005$; and $(^{39}Ar/^{37}Ar)_{Ca} = 0.0007 \pm 0.00002$.

Age calculations:

Weighted mean age calculated by weighting each age analysis by the inverse of the variance.
Weighted mean error calculated using the method of (Taylor, 1982).
Total gas ages and errors calculated by weighting individual steps by the fraction of ^{39}Ar released.
Isochron ages, $^{40}Ar/^{36}Ar_i$ and MSWD values calculated from regression results obtained by the methods of York (1969).
Decay constants and isotopic abundances after Steiger and Jäger (1977).
All final errors reported at ±2□, unless otherwise noted.

Table 2. $^{40}Ar/^{39}Ar$ analytical data.

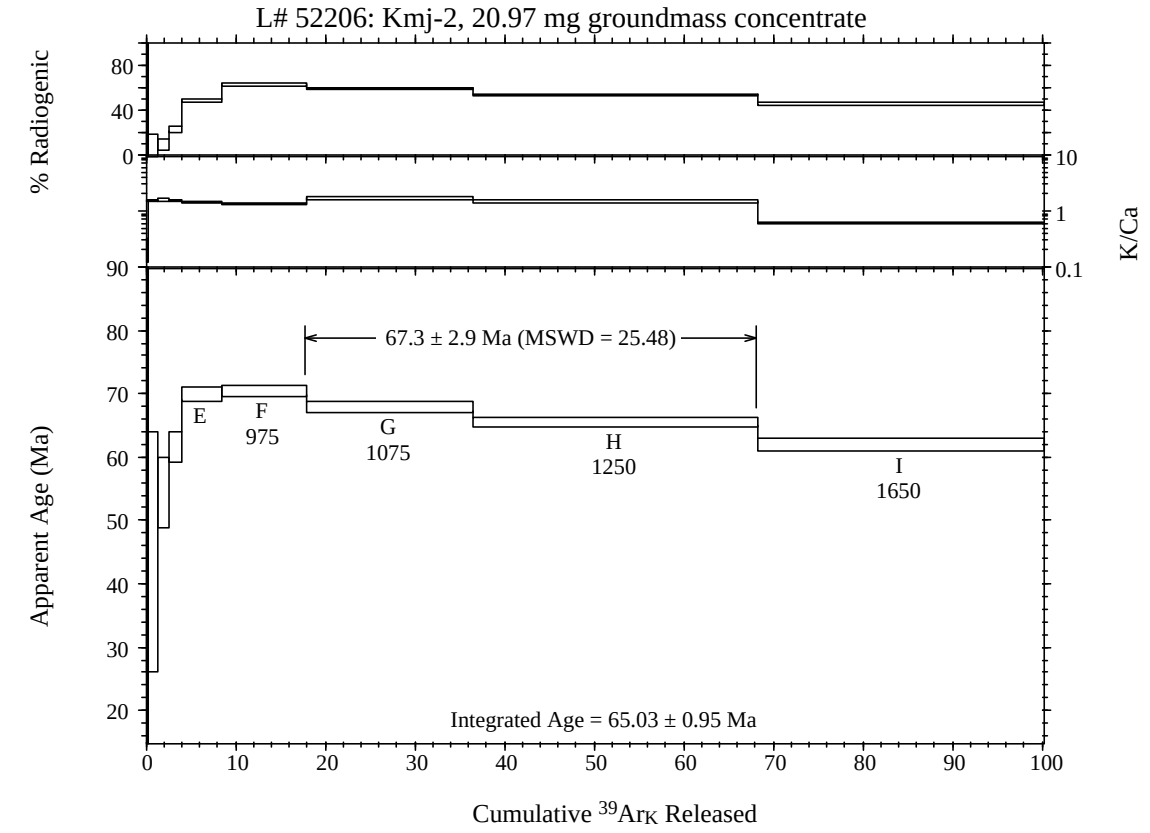
	ID	Power (Watts)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ (x 10^{-3})	$^{39}Ar_K$ (x 10^{-15} mol)	K/Ca	$^{40}Ar^*$ (%)	^{39}Ar (%)	Age (Ma)	±1□ (Ma)
	Kmj-2, 20.97 mg groundmass concentrate, J=0.0006935±0.10%, D=1.00674±0.0011, NM-137, Lab#=52206-01										
#	*A*	*575*	*15029*	*2.592*	*51403.9*	*0.002*	*0.20*	*-1.1*	*0.0*	*-213.6*	*183.6*
#	*B*	*650*	*1649.0*	*0.3322*	*5457.1*	*0.374*	*1.5*	*2.2*	*1.2*	*45.1*	*9.4*
#	*C*	*700*	*489.9*	*0.3236*	*1508.3*	*0.384*	*1.6*	*9.0*	*2.3*	*54.5*	*2.7*
#	*D*	*750*	*223.3*	*0.3340*	*586.3*	*0.501*	*1.5*	*22.4*	*3.9*	*61.6*	*1.2*
	E	825	118.3	0.3616	207.2	1.41	1.4	48.2	8.2	70.01	0.51
	F	925	91.83	0.3740	116.7	3.10	1.4	62.5	17.8	70.41	0.33
	G	1025	93.32	0.3023	128.8	6.06	1.7	59.3	36.4	67.90	0.33
	H	1200	99.61	0.3363	156.8	10.3	1.5	53.5	68.1	65.50	0.34
	I	1600	109.7	0.8495	201.4	10.4	0.60	45.8	100.0	61.87	0.43
	Integrated age ± 2□			n=9		32.5		K2O=0.86 %		65.03	0.95
	Plateau ± 2□	steps E-I		n=5	MSWD=75.65	31.2	1.2		96.1	67.3	2.9
	Isochron±2□			n=7	MSWD=10		$^{40}Ar/^{36}Ar$=289±6			70.2	1.3
	Kmj-1, 22.62 mg groundmass concentrate, J=0.0006923±0.10%, D=1.00674±0.0011, NM-137, Lab#=52204-01										
#	*A*	*575*	*7813.0*	*0.5559*	*26407.2*	*0.071*	*0.92*	*0.1*	*0.2*	*12.1*	*46.3*
#	*B*	*650*	*616.2*	*0.2464*	*1983.3*	*1.13*	*2.1*	*4.9*	*3.2*	*37.3*	*3.5*
#	*C*	*700*	*178.8*	*0.1518*	*495.8*	*0.798*	*3.4*	*18.1*	*5.3*	*39.9*	*1.1*
#	*D*	*750*	*159.8*	*0.1496*	*423.7*	*0.833*	*3.4*	*21.7*	*7.4*	*42.77*	*0.84*
	E	825	135.7	0.1776	338.8	1.65	2.9	26.2	11.8	43.92	0.75
	F	925	109.4	0.1474	249.8	3.24	3.5	32.6	20.3	43.98	0.52
	G	1025	82.09	0.1307	158.6	8.22	3.9	42.9	41.9	43.50	0.36
	H	1200	95.91	0.3893	208.4	14.8	1.3	35.8	80.8	42.44	0.41
#	*I*	*1600*	*175.5*	*1.082*	*465.2*	*7.30*	*0.47*	*21.7*	*100.0*	*47.02*	*0.89*
	Integrated age ± 2□			n=9		38.0		K2O=0.93 %		43.5	1.3
	Plateau ± 2□	steps E-H		n=4	MSWD=2.40	27.9	2.4		73.4	43.3	0.7
	Isochron±2□			n=9	MSWD=5.1		$^{40}Ar/^{36}Ar$=295±4			43.60	0.90
	Kmh-4, 22.14 mg groundmass concentrate, J=0.0006912±0.10%, D=1.00674±0.0011, NM-137, Lab#=52202-01										
#	*A*	*575*	*1815.5*	*0.2485*	*5936.7*	*0.207*	*2.1*	*3.4*	*0.7*	*74.8*	*10.7*
#	*B*	*650*	*157.4*	*0.2645*	*362.5*	*1.53*	*1.9*	*32.0*	*6.1*	*61.69*	*0.72*
#	C	700	84.98	0.2004	88.95	0.734	2.5	69.1	8.6	71.77	0.40
	D	750	77.09	0.2112	64.78	0.818	2.4	75.2	11.5	70.87	0.30
	E	825	78.07	0.2544	68.27	1.47	2.0	74.2	16.6	70.83	0.27
	F	925	79.90	0.2564	73.24	2.56	2.0	72.9	25.5	71.25	0.25
	G	1025	73.71	0.3137	55.22	2.88	1.6	77.9	35.5	70.23	0.23
	H	1200	84.34	0.5281	90.10	6.50	0.97	68.5	58.1	70.65	0.26
#	*I*	*1600*	*90.19*	*0.5053*	*99.68*	*12.0*	*1.0*	*67.4*	*100.0*	*74.26*	*0.27*
	Integrated age ± 2□			n=9		28.7		K2O=0.72 %		71.78	0.64
	Plateau ± 2□	steps D-H		n=5	MSWD=2.48	14.2	1.5		49.5	70.74	0.39
	Isochron±2□			n=8	MSWD=24		$^{40}Ar/^{36}Ar$=300±15			70.9	1.9

	ID	Power (Watts)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ (x 10^{-3})	$^{39}Ar_K$ (x 10^{-15} mol)	K/Ca	$^{40}Ar^*$ (%)	^{39}Ar (%)	Age (Ma)	±1□ (Ma)
	Kmj-4, 25.00 mg groundmass concentrate, J=0.0007105±0.10%, D=1.00674±0.0011, NM-137, Lab#=52247-01										
#	*A*	*575*	*26386*	*-0.3034*	*90620.9*	*0.003*	*-*	*-1.5*	*0.0*	*-590*	*381*
#	*B*	*650*	*778.6*	*0.2399*	*2496.2*	*1.48*	*2.1*	*5.3*	*3.5*	*51.8*	*4.4*
#	*C*	*700*	*143.4*	*0.2648*	*323.6*	*0.452*	*1.9*	*33.4*	*4.5*	*60.32*	*0.89*
#	*D*	*750*	*113.8*	*0.2875*	*212.6*	*0.771*	*1.8*	*44.8*	*6.3*	*64.17*	*0.60*
#	*E*	*825*	*97.01*	*0.3275*	*148.1*	*1.96*	*1.6*	*54.9*	*10.9*	*67.05*	*0.38*
#	*F*	*925*	*90.44*	*0.3323*	*124.6*	*4.12*	*1.5*	*59.3*	*20.6*	*67.51*	*0.34*
	G	1025	96.81	0.2421	156.9	7.87	2.1	52.1	39.1	63.58	0.37
	H	1200	101.4	0.3300	177.1	12.6	1.5	48.4	68.6	61.93	0.41
	I	1600	100.9	0.8799	177.6	13.4	0.58	48.0	100.0	61.12	0.43
	Integrated age ± 2□			n=9		42.6	K2O=0.92 %			62.38	0.99
	Plateau ± 2□	steps G-I		n=3	MSWD=10.11	33.9	1.3		79.4	62.3	1.5
	Isochron±2□			n=9	MSWD=30		$^{40}Ar/^{36}Ar$=288±12			66.0	1.9
	Kmj-4 wr, 4.86 mg groundmass concentrate, J=0.0007103±0.10%, D=1.00674±0.0011, NM-137, Lab#=52248-02										
#	*A*	*575*	*3978.7*	*0.6471*	*13335.7*	*0.009*	*0.79*	*1.0*	*0.1*	*48.1*	*36.5*
#	*B*	*650*	*732.0*	*0.2039*	*2350.3*	*0.346*	*2.5*	*5.1*	*4.2*	*47.5*	*4.7*
#	*C*	*700*	*131.7*	*0.2300*	*282.2*	*0.194*	*2.2*	*36.7*	*6.5*	*60.9*	*1.2*
#	*D*	*750*	*96.90*	*0.2638*	*159.0*	*0.232*	*1.9*	*51.5*	*9.2*	*62.89*	*0.85*
#	*E*	*825*	*90.24*	*0.2853*	*133.4*	*0.380*	*1.8*	*56.4*	*13.7*	*64.03*	*0.69*
#	*F*	*925*	*89.57*	*0.2694*	*129.9*	*0.888*	*1.9*	*57.2*	*24.2*	*64.46*	*0.45*
	G	1025	97.36	0.2011	166.5	1.38	2.5	49.5	40.5	60.70	0.45
	H	1200	101.9	0.2617	185.8	2.63	1.9	46.1	71.6	59.21	0.45
	I	1600	98.85	0.7450	176.5	2.40	0.68	47.3	100.0	58.96	0.44
	Integrated age ± 2□			n=9		8.47	K2O=0.94 %			59.8	1.1
	Plateau ± 2□	steps G-I		n=3	MSWD=4.39	6.42	1.6		75.8	59.6	1.1
	Isochron±2□			n=9	MSWD=15		$^{40}Ar/^{36}Ar$=290±10			62.3	1.6
	Kmh-1, 1.71 mg biotite, J=0.0007096±0.10%, D=1.00674±0.0011, NM-137, Lab#=52251-02										
#	*A*	*600*	*167.3*	*0.1647*	*528.3*	*0.271*	*3.1*	*6.7*	*14.0*	*14.3*	*1.3*
#	*B*	*700*	*60.77*	*0.0897*	*141.5*	*0.296*	*5.7*	*31.2*	*29.3*	*24.10*	*0.74*
#	*C*	*800*	*62.98*	*0.0817*	*89.92*	*0.272*	*6.2*	*57.8*	*43.4*	*46.03*	*0.56*
#	*D*	*870*	*65.53*	*0.0589*	*66.14*	*0.365*	*8.7*	*70.2*	*62.3*	*57.93*	*0.42*
#	*E*	*950*	*68.91*	*0.1040*	*46.34*	*0.255*	*4.9*	*80.1*	*75.5*	*69.35*	*0.55*
	F	1025	78.50	0.2184	22.75	0.294	2.3	91.5	90.7	89.66	0.53
	G	1060	75.26	0.4366	11.92	0.080	1.2	95.4	94.8	89.6	1.2
#	*H*	*1130*	*91.98*	*4.162*	*87.33*	*0.059*	*0.12*	*72.3*	*97.9*	*83.4*	*1.7*
#	*I*	*1160*	*96.76*	*6.859*	*109.3*	*0.018*	*0.074*	*67.2*	*98.8*	*81.8*	*4.4*
#	*J*	*1200*	*87.28*	*3.996*	*9.201*	*0.008*	*0.13*	*97.3*	*99.3*	*105.8*	*10.2*
#	*K*	*1250*	*129.7*	*5.582*	*205.2*	*0.005*	*0.091*	*53.6*	*99.5*	*87.2*	*14.8*
#	*L*	*1600*	*256.9*	*6.185*	*663.0*	*0.009*	*0.082*	*23.9*	*100.0*	*77.4*	*9.8*
	Integrated age ± 2□			n=12		1.93	K2O=0.61 %			54.18	0.75
	Plateau ± 2□	steps F-G		n=2	MSWD=0.00	0.37	2.1		19.3	89.7	1.0
	Isochron±2□			n=7	MSWD=2.1		$^{40}Ar/^{36}Ar$=266±29			90.1	1.7

	ID	Power (Watts)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ (x 10^{-3})	$^{39}Ar_K$ (x 10^{-15} mol)	K/Ca	$^{40}Ar^*$ (%)	^{39}Ar (%)	Age (Ma)	±1σ (Ma)
	TIr-2, 1.52 mg biotite, J=0.00071±0.10%, D=1.00674±0.0011, NM-137, Lab#=52249-02										
#	*A*	*600*	*1442.7*	*0.0690*	*4733.3*	*0.012*	*7.4*	*3.1*	*0.7*	*55.5*	*17.8*
#	*B*	*700*	*92.44*	*0.0760*	*275.9*	*0.166*	*6.7*	*11.8*	*10.8*	*14.0*	*1.3*
#	*C*	*800*	*72.68*	*0.0824*	*148.1*	*0.180*	*6.2*	*39.8*	*21.8*	*36.68*	*0.84*
#	*D*	*870*	*60.83*	*0.1035*	*37.53*	*0.137*	*4.9*	*81.8*	*30.1*	*62.63*	*0.74*
#	*E*	*950*	*73.87*	*0.0725*	*19.47*	*0.287*	*7.0*	*92.2*	*47.6*	*85.22*	*0.45*
	F	1025	79.23	0.0813	22.71	0.242	6.3	91.5	62.3	90.60	0.61
	G	1060	79.73	0.0602	24.74	0.216	8.5	90.8	75.5	90.47	0.56
	H	1130	79.99	0.1187	34.29	0.284	4.3	87.3	92.8	87.36	0.55
#	*I*	*1160*	*78.43*	*0.3647*	*49.00*	*0.047*	*1.4*	*81.6*	*95.6*	*80.2*	*2.2*
#	*J*	*1200*	*75.73*	*0.3326*	*55.91*	*0.025*	*1.5*	*78.2*	*97.2*	*74.3*	*3.6*
#	*K*	*1250*	*92.46*	*0.6642*	*111.4*	*0.018*	*0.77*	*64.5*	*98.2*	*74.8*	*5.3*
#	*L*	*1600*	*168.9*	*3.479*	*373.9*	*0.029*	*0.15*	*34.8*	*100.0*	*73.9*	*3.6*
	Integrated age ± 2σ			n=12		1.64		K2O=0.59 %		72.02	0.76
	Plateau ± 2σ	steps F-H		n=3	MSWD=10.64	0.74	6.2		45.2	89.4	2.2
	Isochron±2σ			n=8	MSWD=18		$^{40}Ar/^{36}Ar$=270±68			88.6	3.4
	TIr-4, 3.62 mg biotite, J=0.0007098±0.10%, D=1.00535±0.00031, NM-137, Lab#=52250-02										
#	*A*	*600*	*236.1*	*0.0867*	*742.4*	*0.279*	*5.9*	*7.1*	*4.6*	*21.3*	*1.4*
#	*B*	*700*	*137.4*	*0.0571*	*390.3*	*0.292*	*8.9*	*16.1*	*9.5*	*28.06*	*0.94*
#	*C*	*800*	*76.09*	*0.0494*	*142.5*	*0.347*	*10.3*	*44.7*	*15.2*	*43.02*	*0.61*
#	*D*	*870*	*64.50*	*0.0730*	*42.93*	*0.408*	*7.0*	*80.3*	*22.0*	*65.17*	*0.36*
#	*E*	*950*	*69.01*	*0.0396*	*20.53*	*0.731*	*12.9*	*91.2*	*34.1*	*78.87*	*0.23*
#	*F*	*1025*	*72.46*	*0.0515*	*22.58*	*0.753*	*9.9*	*90.8*	*46.5*	*82.35*	*0.19*
	G	1060	77.12	0.0632	26.48	0.429	8.1	89.9	53.6	86.63	0.31
	H	1130	75.95	0.1016	23.24	0.976	5.0	91.0	69.8	86.38	0.24
#	*I*	*1160*	*69.05*	*0.1009*	*16.32*	*0.770*	*5.1*	*93.0*	*82.6*	*80.44*	*0.21*
#	*J*	*1200*	*65.62*	*0.0954*	*11.63*	*0.454*	*5.3*	*94.8*	*90.1*	*77.94*	*0.27*
#	*K*	*1250*	*61.54*	*0.0524*	*11.12*	*0.509*	*9.7*	*94.7*	*98.5*	*73.10*	*0.45*
#	*L*	*1600*	*98.97*	*0.3965*	*156.7*	*0.091*	*1.3*	*53.2*	*100.0*	*66.3*	*1.0*
	Integrated age ± 2σ			n=12		6.04		K2O=0.90 %		72.52	0.30
	Plateau ± 2σ	steps G-H		n=2	MSWD=0.41	1.41	6.0		23.3	86.47	0.41
	Isochron±2σ			n=8	MSWD=250		$^{40}Ar/^{36}Ar$=427±253			78.3	19.0

Notes:

Isotopic ratios corrected for blank, radioactive decay, and mass discrimination, not corrected for interferring reactions.
Ages calculated ralative to FC-1 Fish Canyon Tuff sanidine interlaboratory standard at 27.84 Ma.
Errors quoted for individual analyses include analytical error only, without interferring reaction or J uncertainties.
Integrated age calculated by recombining isotopic measurements of all steps.
Integrated age error calculated by recombining errors of isotopic measurements of all steps.
Plateau age is inverse-variance-weighted mean of selected steps.
Plateau age error is inverse-variance-weighted mean error (Taylor, 1982) times root MSWD where MSWD>1.
Plateau and integrated ages incorporate uncertainties in interferring reaction corrections and J factors.
Decay constants and isotopic abundances after Steiger and Jaeger (1977).
# symbol preceding sample ID denotes analyses excluded from plateau age calculations.
Discrimination = 1.00535 ± 0.00031
Correction factors:
$(^{39}Ar/^{37}Ar)_{Ca}$ = 0.0007 ± 2e-05
$(^{36}Ar/^{37}Ar)_{Ca}$ = 0.00028 ± 5e-06
$(^{38}Ar/^{39}Ar)_{K}$ = 0.01077
$(^{40}Ar/^{39}Ar)_{K}$ = 0.0002 ± 0.0003



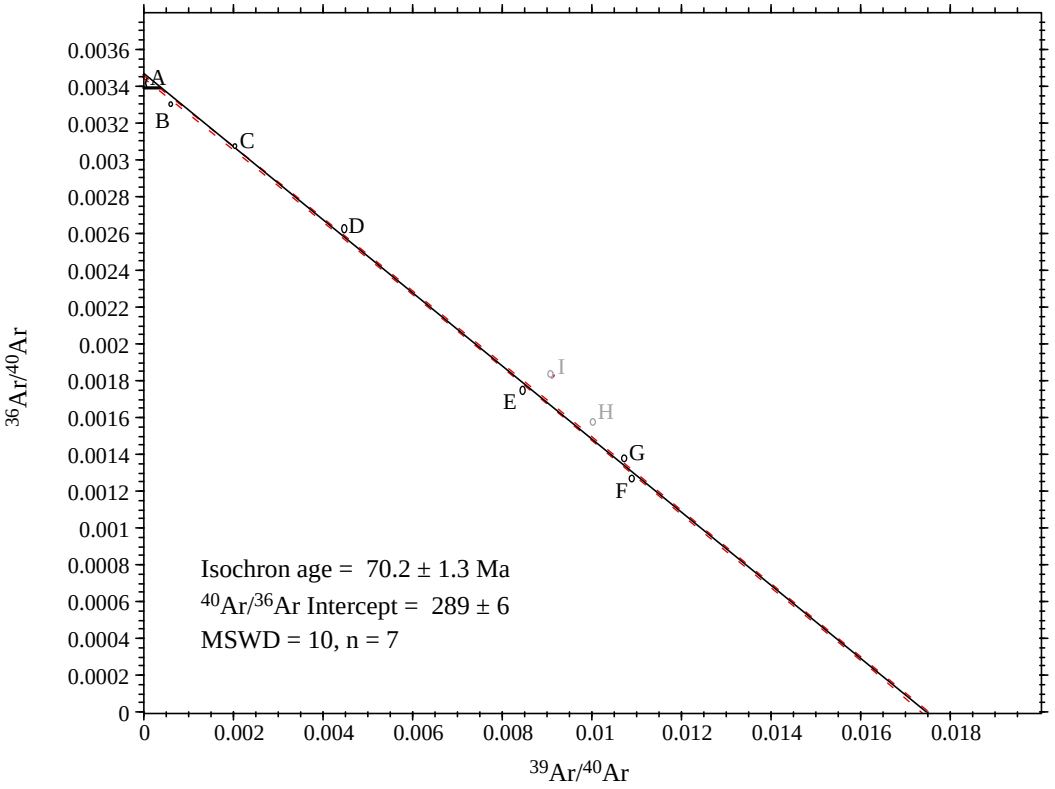


Figure 1. $^{40}Ar/^{39}Ar$ age spectrum and inverse isochron for the Kmj-2 groundmass concentrate sample. The preferred age of this sample is the spectrum weighted mean age of 67.3 ± 2.9 Ma. All errors are two-sigma.

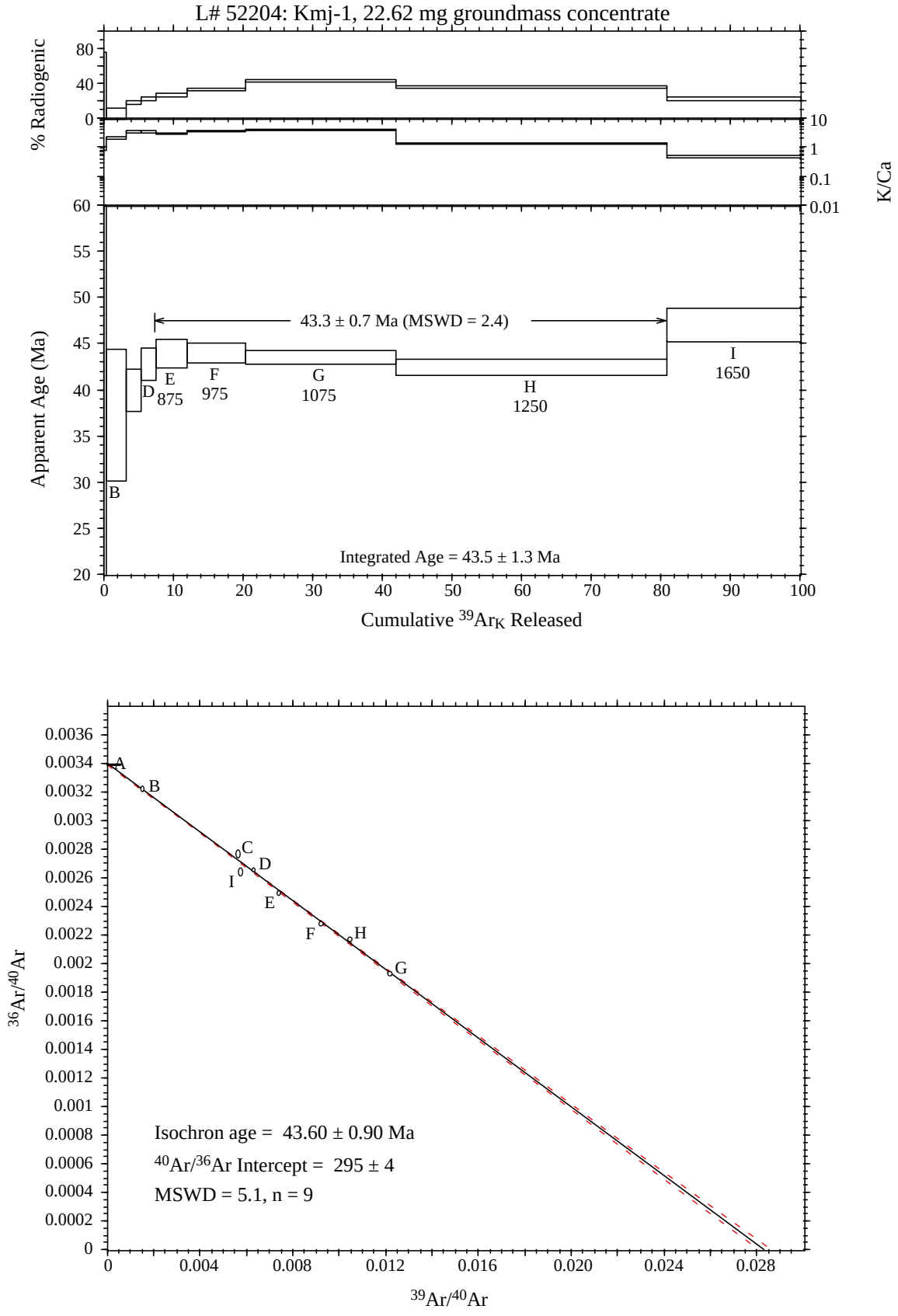


Figure 2. $^{40}Ar/^{39}Ar$ age spectrum and inverse isochron for the Kmj-1 groundmass concentrate sample. The preferred age of this sample is the spectrum weighted mean age of 43.3 ± 0.7 Ma. All errors are two-sigma.

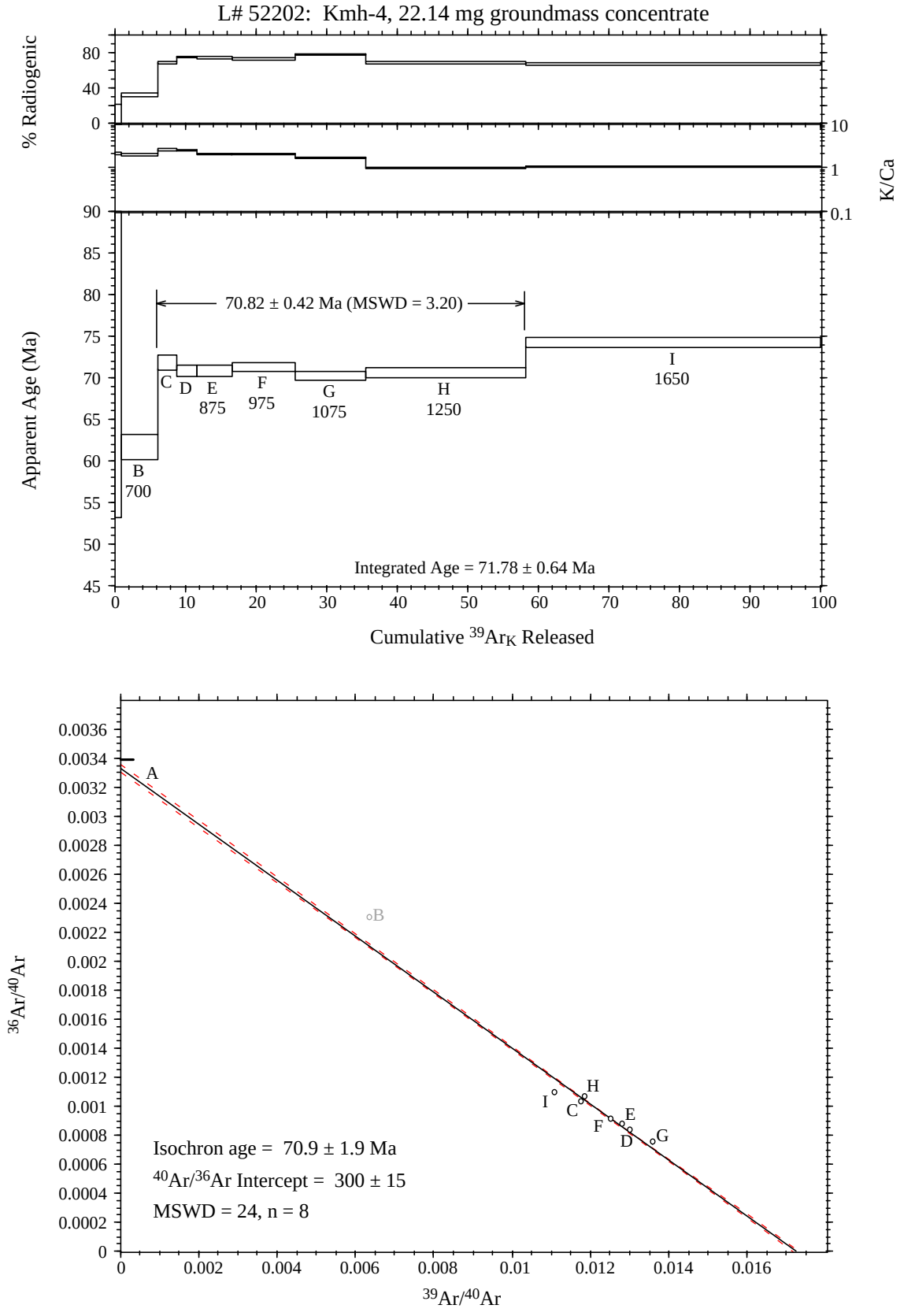


Figure 3. $^{40}Ar/^{39}Ar$ age spectrum and inverse isochron for the Kmh-4 groundmass concentrate sample. The preferred age of this sample is the spectrum weighted mean age of 70.82 ± 0.42 Ma. All errors are two-sigma.

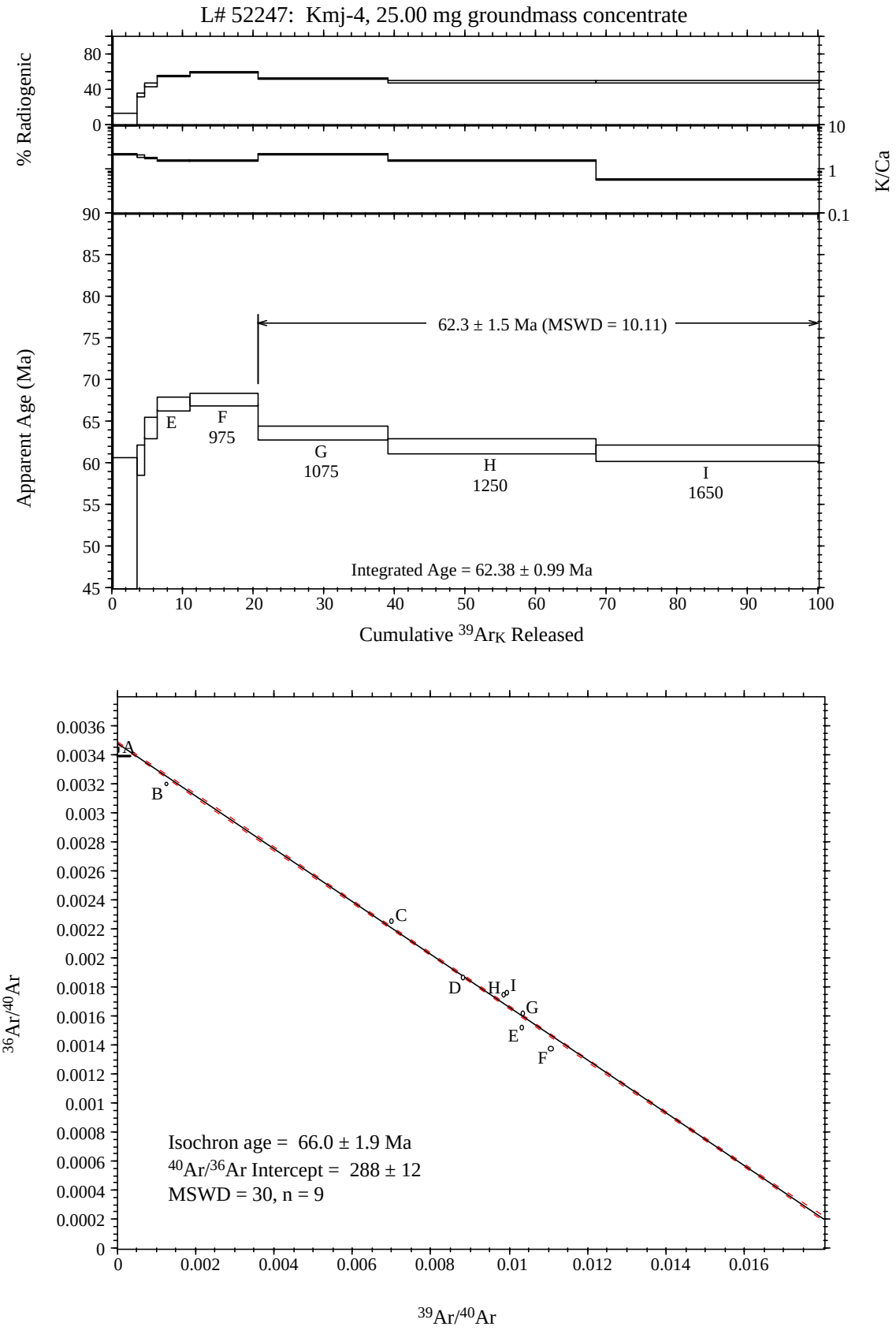


Figure 4. $^{40}Ar/^{39}Ar$ age spectrum and inverse isochron for the Kmj-4 groundmass concentrate sample. The preferred age of this sample is the spectrum weighted mean age of 62.3 ± 1.5 Ma. All errors are two-sigma.

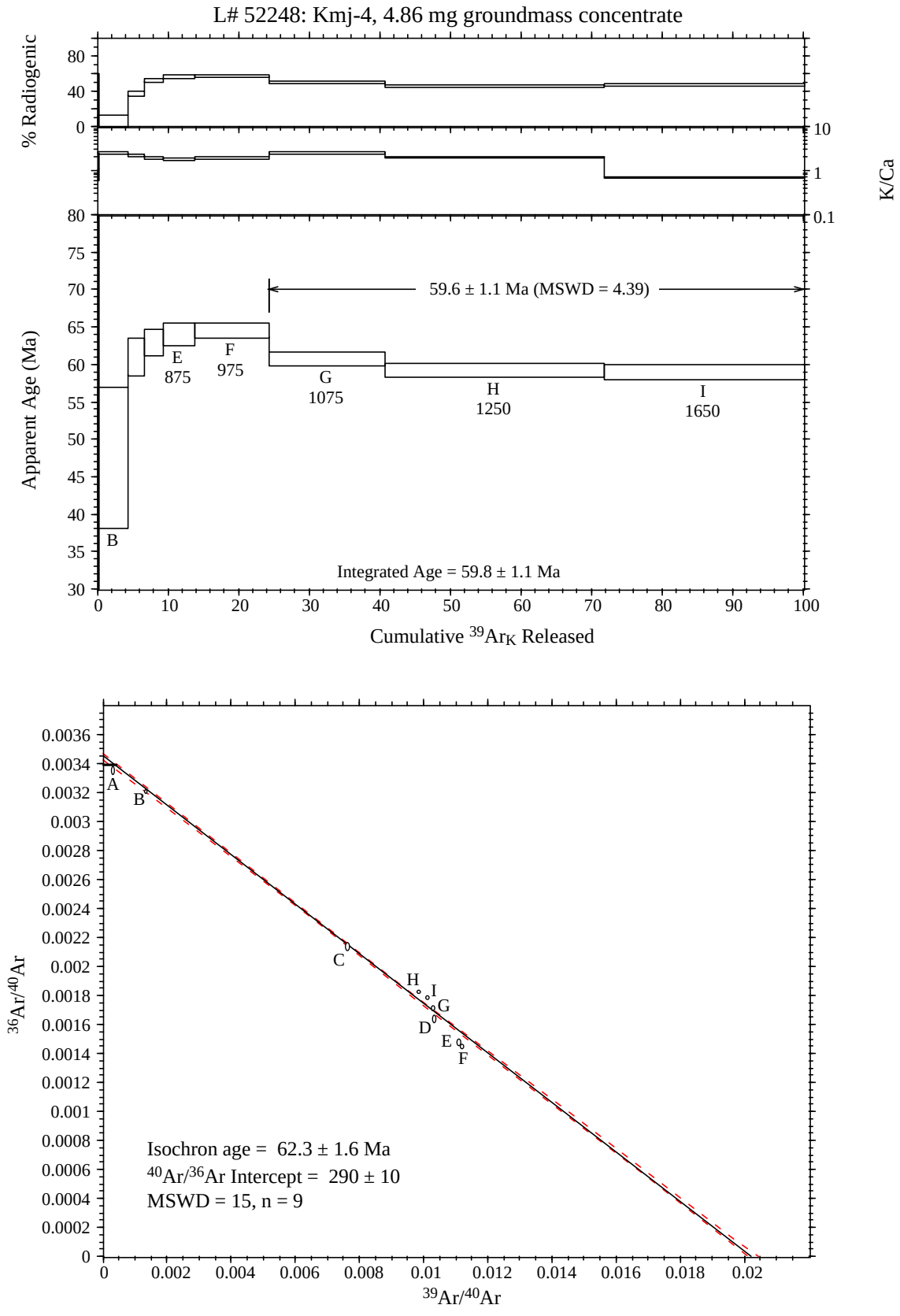


Figure 5. $^{40}Ar/^{39}Ar$ age spectrum and inverse isochron for the Kmj-4 groundmass concentrate sample. The preferred age of this sample is the spectrum weighted mean age of 59.6 ± 1.1 Ma. All errors are two-sigma.

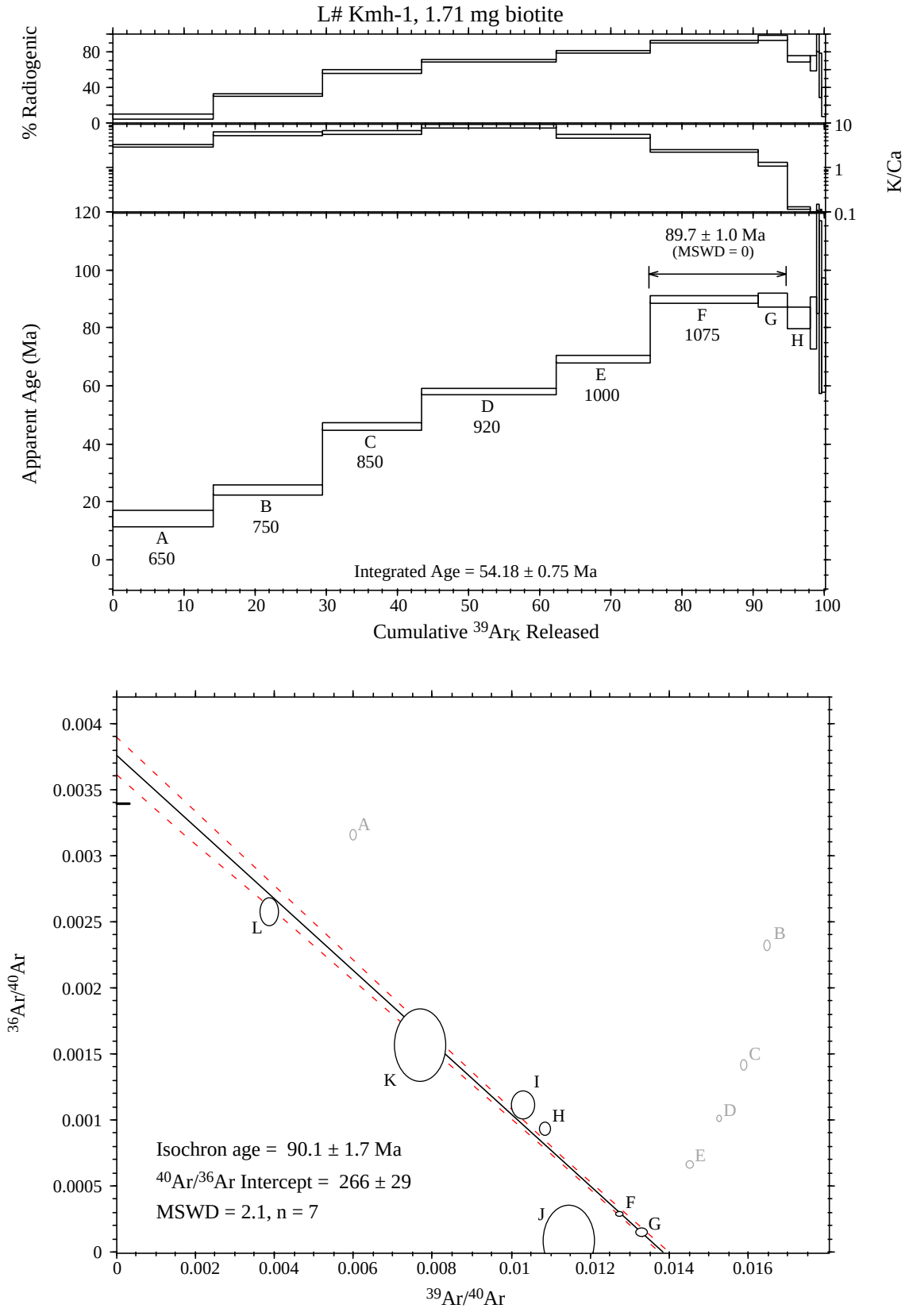


Figure 6. $^{40}Ar/^{39}Ar$ age spectrum and inverse isochron for the Kmh-1 biotite sample. The preferred age of this sample is the spectrum weighted mean age of 89.7 ± 1.0 Ma. All errors are two-sigma.

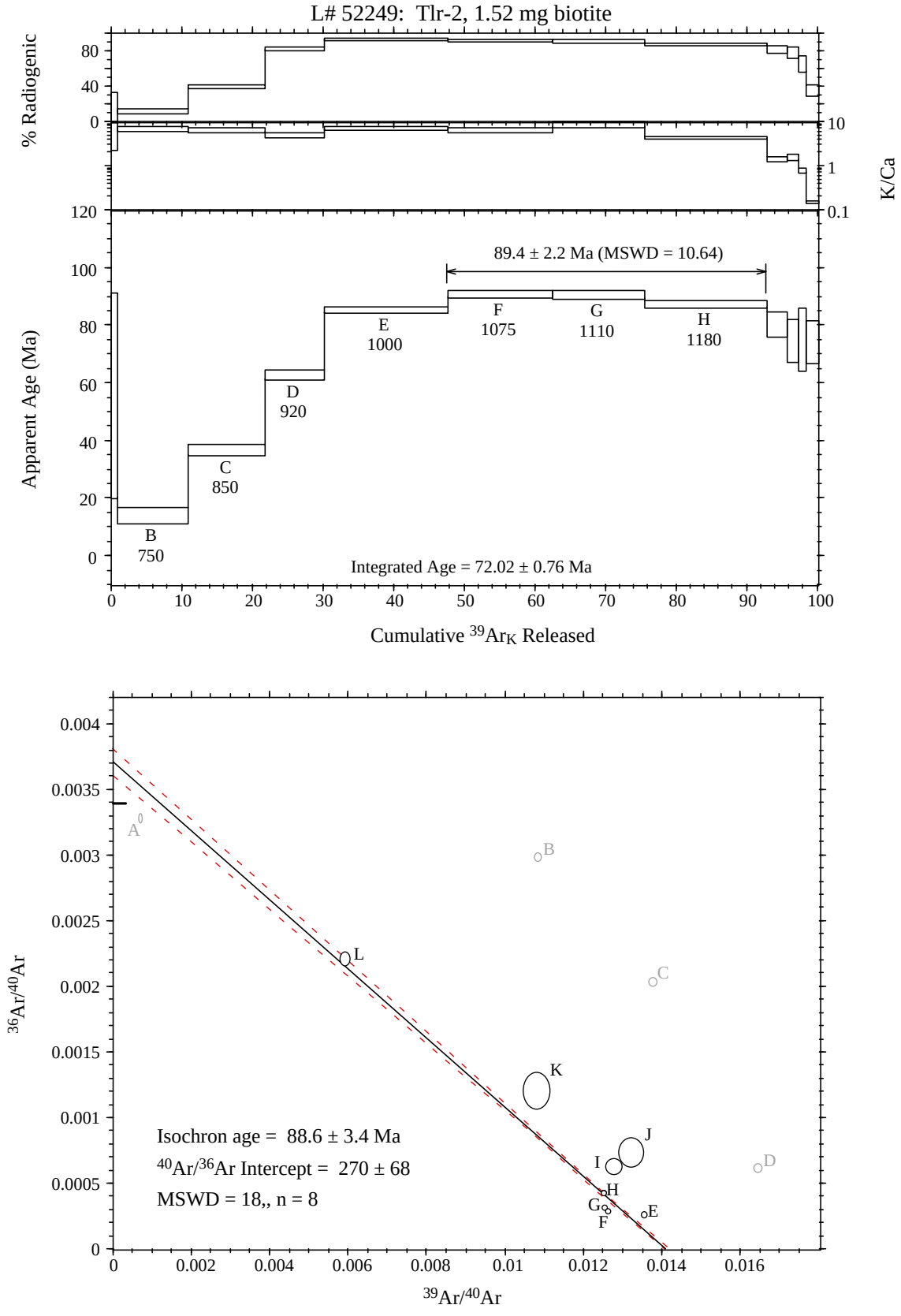


Figure 7. $^{40}Ar/^{39}Ar$ age spectrum and inverse isochron for the Tlr-2 biotite sample. The preferred age of this sample is the spectrum weighted mean age of 89.4 ± 2.2 Ma. All errors are two-sigma.

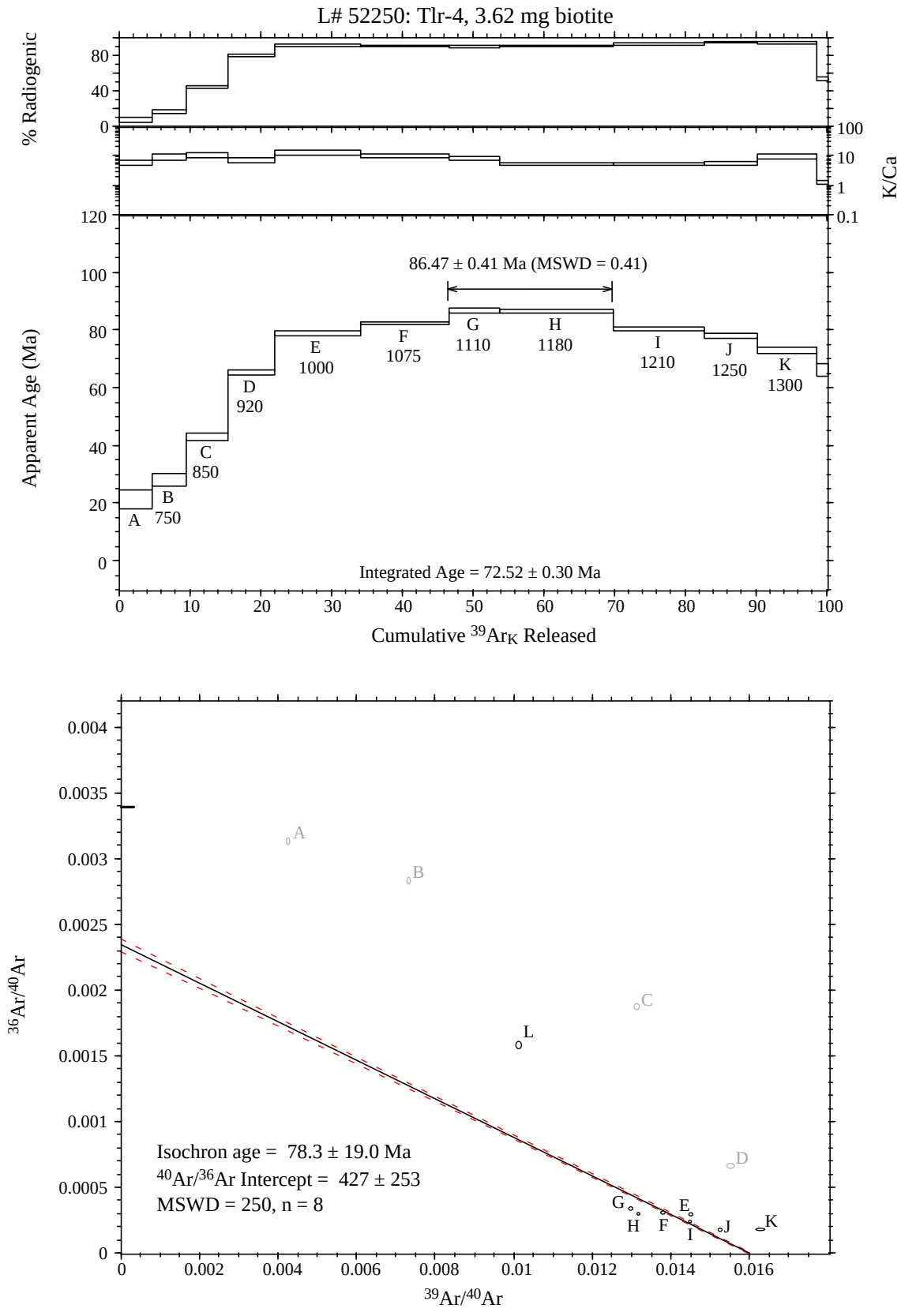


Figure 8. $^{40}Ar/^{39}Ar$ age spectrum and inverse isochron for the Tlr-4 biotite sample. The preferred age of this sample is the spectrum weighted mean age of 86.47 ± 0.41 Ma. All errors are two-sigma.

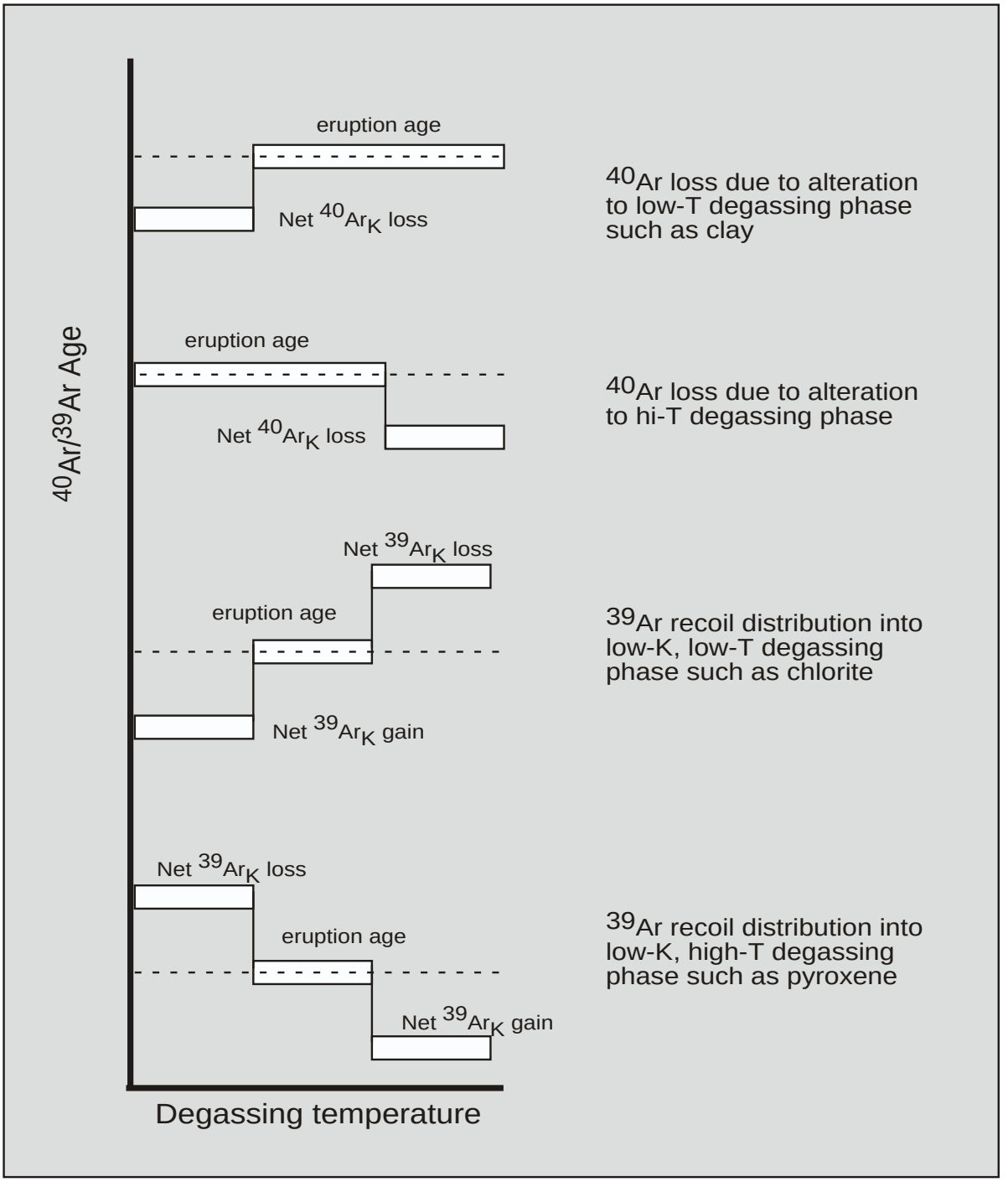


Figure 9. Cartoon showing potential effects of ^{39}Ar recoil and alteration induced ^{40}Ar loss on an otherwise flat age spectrum.

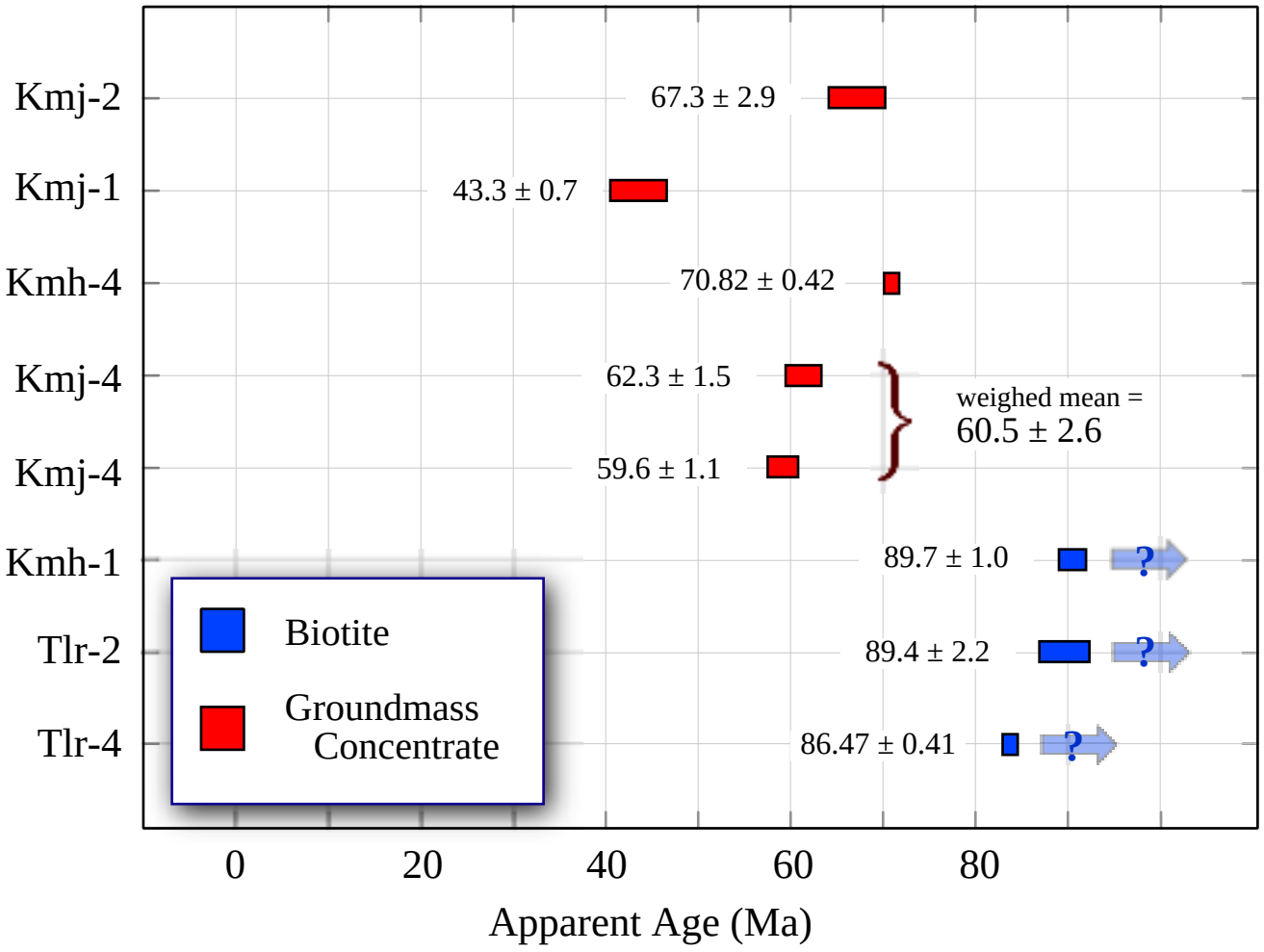


Figure 10. Age summary for the biotite and groundmass concentrate samples dated in this study. The arrows indicate those samples that are to be considered minimum ages. All errors are two-sigma.