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THE AGE AND COOLING HISTORY OF THE CHAIN OF PONDS AND BIG ISLAND POND PLUTONS AND THE SPIDER LAKE GRANITE, WEST-CENTRAL MAINE AND QUEBEC

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ABSTRACT. $^{40}Ar/^{39}Ar$ release spectrum ages have been determined for hornblende, biotite, and K-feldspar from the Chain of Ponds pluton (CPP), Spider Lake Granite (SLG), and Big Island Pond pluton (BIPP) west-central Maine and Quebec. Mean plateau ages of 373.3 ± 2.0, 367.6 ± 1.3, and 367.7 ± 1.3 Ma for hornblendes from the CPP, SLG, and BIPP respectively are interpreted to be intrusive ages for these plutons. A best estimate biotite age of 371.5 ± 2.7 Ma for the CPP is reported. Biotites from the SLG and BIPP have mean total gas ages of 370.3 ± 3.4 Ma. The K-feldspars from the CPP exhibit radiogenic ^{40}Ar loss profiles resultant from an ~170 Ma thermal disturbance and have plateau or terminal ages varying from ~312 to 365 Ma. The discordance in K-feldspar ages are readily interpretable based on variations in closure temperatures with respect to Ar diffusion.

A three dimensional conductive cooling model for the CPP suggest that rapid cooling to ambient conditions occurred within ~3 Ma of intrusion. This model corresponds well with the rapid cooling suggested by the essentially concordant hornblende and biotite ages.

INTRODUCTION

It has been recognized since the early 1960's that various minerals closed with respect to argon diffusion at different temperatures (for example, Hart, 1964). In some geologic settings, cogenetic minerals may have discordant K-Ar ages which can often be directly attributed to different retentivities of radiogenic ^{40}Ar ($^{40}Ar^*$) for different minerals at elevated temperatures. Diffusion experiments (Giletti, 1974a,b; Foland, 1974; Harrison, 1981; Harrison, Duncan, and McDougall, 1985) have confirmed many of the field observations with respect to the mineral closure temperature hiarachy.

Harrison and others (1979) introduced an isotopic cooling curve as a plot of mineral apparent ages versus their respective closure temperature. Subsequent studies using this technique have proven an effective aid in understanding cooling histories of intrusions and metamorphic terranes (Harrison and McDougall 1980a; Dallmeyer, VanBreeman, and Whitney, 1982).

In this study, the $^{40}Ar/^{39}Ar$ technique was used to date hornblende, biotite, orthoclase, and microcline from three plutons located in western Maine and Quebec (fig. 1). The apparent ages of these minerals

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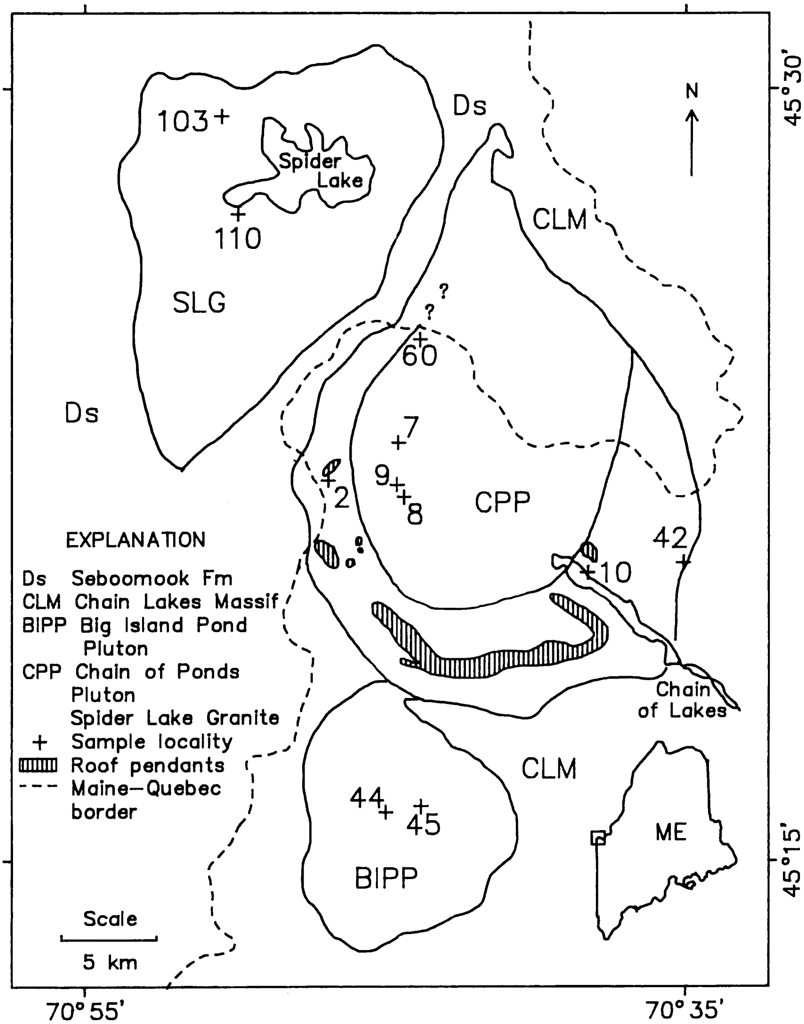

Fig. 1. Geologic map of study area along with location of samples dated by $^{40}Ar/^{39}Ar$ technique. Sample numbers are given a "MH-" prefix in text.

reveal the cooling history of the terrane between the temperatures of ~550° to ~150°C. The Big Island Pond pluton (BIPP) is a relatively uniform body of light gray, medium to coarse grained biotite-hornblende granodiorite and is further characterized by the presence of large subhedral plagioclase. The Spider Lake Granite (SLG) and Chain of Ponds pluton (CPP) are zoned plutons. The SLG rim phase is very similar to the BIPP both in texture and modal mineral composition. The core phase is gray, fine-grained, foliated, porphyritic biotite-hornblende granodiorite. The rim phase of the CPP is gray, medium- to coarse-grained, porphyritic biotite granodiorite, and the core is gray, fine grained, porphyritic biotite-hornblende granodiorite. Sphene, epidote, zircon, and apatite are common accessory minerals in all three plutons. A more detailed description of local geology is given by Harwood (1973), Westerman (1979), and Cheve (1978).

All three plutons distinctly post-date the Acadian deformation of the host rocks. The country rocks are deformed and regionally metamorphosed to lower greenschist facies (Holdaway and others, 1982): the youngest of which is the Gedinian to Siegenian Ironbound Mountain Formation.

A three dimensional conductive cooling model was used to constrain the thermal conduction of the Chain of Ponds pluton using physical parameters, inferred thermal properties, and the isotopic cooling history. The motivation for thermal modeling lay in assessing theoretical cooling rates for plutonic rocks and also for comparison with inferred cooling rates derived from $^{40}Ar/^{39}Ar$ mineral ages.

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ANALYTICAL METHODS

Hornblende, biotite, and K-feldspar were separated from samples from the CPP, BIPP, and SLG using standard techniques. Mafic separates were sized between 90 and 250 μm, and K-feldspar between 250 and 500 μm. Sample purity was estimated to be 99.9 percent or better. Samples were irradiated in the Central Thimble facility of the U.S. Geological Survey TRIGA reactor and the H-5 position of the University of Michigan Ford reactor. MMhb-1 hornblende, whose age given by Alexander, Mickelson, and Lanphere (1978) is 519.4 Ma, was used as a flux monitor for the TRIGA irradiations, and the Australian National University intra-laboratory standard GA1550 biotite was used for the Ford reactor irradiations. GA1550 has a K-Ar age of 97.9 Ma (McDougall and Roksandic, 1974). Ages are calculated using the decay constants recommended by Steiger and Jäger (1977). Isotopic abundances of Ar from the samples were measured on several mass spectrometers: A VG MM-1200B at the U.S. Geological Survey, Reston, Va, and Nuclide 6-60-SGA at the University of Maine, and a Nuclide 4.5-60-RSS at the

State University of New York at Albany. The three K-feldspars (two orthoclase, one microcline) were analyzed at the State University of New York at Albany. Argon extraction at Albany was accomplished in a double vacuum furnace, and temperature was monitored to ±0.5°C with the use of a thermocouple placed within 2 mm of the sample. Argon extraction at Maine and Reston was accomplished in a molybdenum crucible heated by radio-frequency induction. Age calculations and uncertainty estimates (1 sigma) follow procedures described by Dalrymple and others (1981) and also include a 0.5 percent error attributed to uncertainty in the age of the flux monitor (the K-feldspar data do not include this 0.5 percent error; errors are based on the precision of the isotopic ratio measurements only). Plateau ages represent the average age for increments deemed concordant at 2 sigma using the critical value test (Dalrymple and Lanphere, 1969, p. 120). Uncertainties associated with plateau ages are one standard deviation which includes the J-factor error and a 0.25 percent error assigned to the $^{40}Ar^{*}/^{39}Ar_{K}$ ratio.

Geochronologic results.—Ten hornblende, eleven biotite, and three K-feldspar samples were analyzed by the $^{40}Ar/^{39}Ar$ incremental heating technique. Sample locations are shown in figure 1 and listed in table 1 along with their ages. The hornblende samples were incrementally heated in nine to seventeen steps. All samples have plateau ages with most comprising greater than 85 percent of the total ^{39}Ar released. Plateau ages for the CPP ranged from 371.1 ± 2.1 to 375.9 ± 2.1 Ma, with a mean of 373.3 ± 2.0 Ma. Because of the similarity in hornblende release spectra, only the results for the oldest and youngest hornblendes from the CPP are shown in figure 2.

Plateau ages for hornblendes from the SLG were 368.3 ± 2.1 Ma and 366.8 ± 2.1 Ma, with a mean of 367.6 ± 1.3 Ma (fig. 3). The BIPP hornblendes have plateau ages of 367.7 ± 2.1 Ma and 367.6 ± 2.1 Ma, with a mean of 367.7 ± 1.3 Ma (fig. 4). Increments comprising the plateaus for all the hornblende samples had very uniform apparent K/Ca ratios ranging from 0.060 to 0.085 (table 2).

The biotite samples were incrementally heated in six to ten steps, and the oldest and youngest flat release spectra are shown in figure 5. Six of the seven samples from the CPP gave plateau ages ranging from 370.0 ± 2.1 Ma to 377.2 ± 2.1 Ma, with a mean of 373.0 ± 3.1 Ma. The total gas ages for these samples ranged from 366.7 to 372.2 Ma. The total gas ages of the two biotite samples (fig. 6) from the SLG were 368.9 and 374.4 Ma. One sample, (MH-103), formed a plateau at 376.3 ± 2.1 Ma. The two biotite samples (fig. 7) from the BIPP yielded total gas ages of 368.3 and 370.0 Ma, and like the SLG, one sample (MH-45) formed a plateau at 373.6 ± 2.1 Ma.

Unlike the hornblende samples, there is a considerable spread in the ages of the biotite samples, and many release spectra are disturbed. Several of the older plateau ages correspond to release spectra that have a characteristic hump-shaped pattern (MH-44, 45, 103, 110). A hump-

TABLE 1

List of samples with respect to their location and age

Sample	Pluton	Location	Mineral	Total Gas Age (Ma)	Plateau Age (Ma)
MH-2	CPP(RIM)	45°21′41″, 70°48′22″	Hornblende	373.3	371.6 ± 2.1
			Biotite	367.9	370.0 ± 2.1
MH-7	CPP(CORE)	45°23′22″, 70°46′01″	Hornblende	369.2	371.1 ± 2.1
			Biotite	369.5	371.2 ± 2.1
MH-8	CPP(CORE)	45°21′58″, 70°45′00″	Hornblende	374.3	375.4 ± 2.1
			Biotite	371.1	N.P.
			Orthoclase	331.1	344.8 ± 2.1*
MH-9	CPP(CORE)	45°22′45″, 70°46′45″	Hornblende	372.6	373.2 ± 2.1
			Biotite	372.2	376.5 ± 2.1
MH-10	CPP(RIM)	45°21′03″, 70°41′03″	Hornblende	371.9	372.5 ± 2.1
			Biotite	370.3	372.9 ± 2.1
			Orthoclase	346.1	365.0 ± 2.0
MH-42	CPP(RIM)	45°21′21″, 70°38′48″	Biotite	368.6	377.2 ± 2.1
			Microcline	279.6	311.8 ± 2.1*
MH-60	CPP(CORE)	45°25′18″, 70°46′05″	Hornblende	373.9	375.9 ± 2.1
			Biotite	366.7	370.3 ± 2.1
MH-44	BIPP	45°15′59″, 70°47′07″	Hornblende	365.2	367.7 ± 2.1
			Biotite	368.0	N.P.
MH-45	BIPP	45°16′03″, 70°45′23″	Hornblende		367.6 ± 2.1
			Biotite	370.0	373.6 ± 2.1
MH-103	SLG(RIM)	45°29′25″, 70°51′20″	Hornblende	371.3	368.3 ± 2.1
			Biotite	374.4	376.3 ± 2.1
MH-110	SLG(CORE)	45°27′32″, 70°50′52″	Hornblende	365.8	366.8 ± 2.1
			Biotite	368.9	N.P.

N.P. = no plateau
*Terminal age

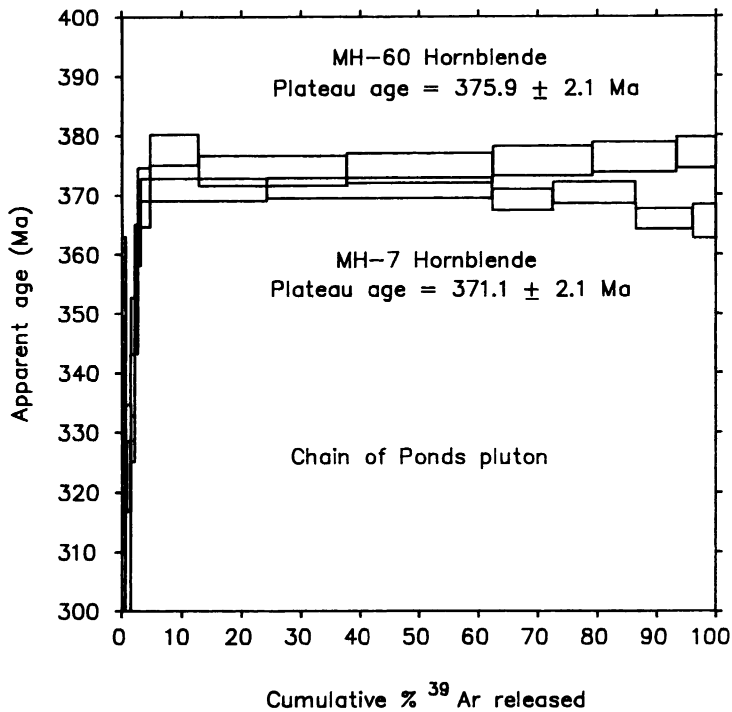

Fig. 2. Release spectra for youngest and oldest hornblendes from the Chain of Ponds pluton.

shaped release spectrum is defined by samples with intermediate temperature increment ages older than the low and high temperature increments; examples are shown in figures 6 and 7. The hump-shaped nature of the biotite spectra is not severe. In fact, within analytical uncertainty, many of the release spectra have plateaus but have higher apparent ages than those of coexisting hornblendes (table 1). This is inconsistent with the relative hornblende and biotite closure temperatures (Harrison, 1981; Harrison, Duncan and McDougall, 1985).

Hump-shaped age spectra for biotite has been observed by several workers (Tetley and McDougall, 1978; Foland 1983; Hubacher and Lux, 1986; York and Lopez-Martinez, 1986). Though the cause of this release spectrum is uncertain and has yet to be satisfactorily explained, it is generally observed that the total gas age for these biotites is consistent with coexisting mineral ages. This being the case, for the biotites exhibiting the hump-shaped release spectra, the total gas age is considered as the best estimate age for the sample.

A biotite age of 371.1 ± 2.7 Ma for the CPP is given by the mean of the plateau ages from MH-2, 7, 10, and 60. These samples have flat

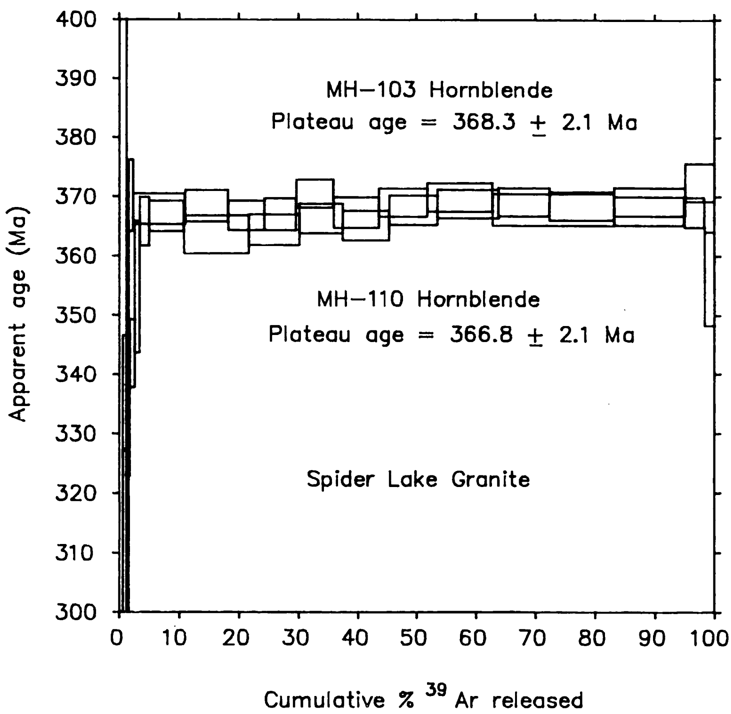

Fig. 3. Release spectra for the Spider Lake Granite hornblendes.

release spectra and yield ages younger than their hornblende pairs and are therefore interpreted to be the best estimate of the CPP biotite age.

The biotites from the SLG and BIPP all exhibit hump-shaped release spectra (figs. 6, 7) and have plateau ages significantly older than their coexisting, well constrained, hornblende pairs. This age difference does not imply that the biotites have higher closure temperatures than the hornblendes, but rather is due to problems in the biotite argon systematics. The total gas ages for these biotites are nearly concordant with their hornblende pairs, and thus, as borne out in the literature and here, the total gas age is considered as the best estimate biotite age for these plutons (370.3 ± 3.4 Ma).

Three K-feldspars from the CPP were analyzed, and their release spectra are shown in figure 8. These release spectra provide evidence of $^{40}Ar^*$ concentration gradients within the crystals. Low temperature increments have ages ranging from 175 to 275 Ma followed by a monotonic age increase until a plateau or terminal age is reached at between 312 to 365 Ma. As the K-feldspar samples are all from the CPP, the contrast in ages seems remarkable. This discordance will be discussed in detail in a later section.

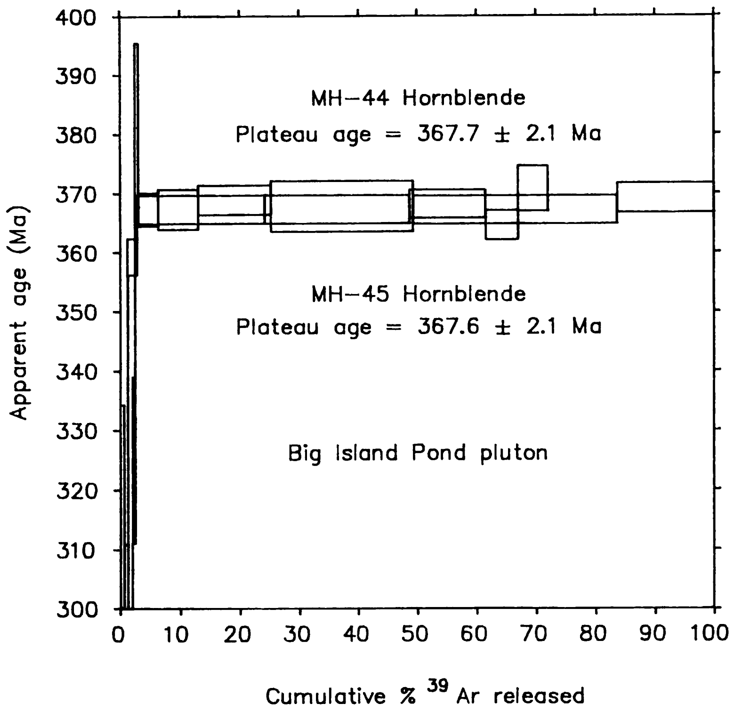

Fig. 4. Release spectra for the Big Island Pond pluton hornblendes.

Assignment of closure temperature.—Harrison (1981) conducted an isothermal-hydrothermal diffusion study of hornblende and also studied hornblende from a contact aureole that had been thermally affected (Harrison and McDougall, 1980b). These studies revealed an activation energy (E) of 64.1 kcal/mol, a frequency factor (D_0) of 0.024 cm^2/sec, and an effective radius of diffusion (a) of approx 80 μm. For a cooling rate of 100°C/Ma, a closure temperature of ~550°C is calculated. Caution should be used in assigning this temperature to amphiboles in all cases as Harrison and Fitz Gerald (1986) showed that exsolution phenomenon can result in a significantly lower closure temperature. The hornblendes from this study have simple flat release spectra and uniform K/Ca ratios in contrast to the very complex release spectrum and non-uniform K/Ca ratios for the amphibole analyzed by Harrison and Fitz Gerald (1986). Therefore the 550°C closure temperature is used for these hornblendes.

The most reliable estimate for the closure temperature of biotite is given by Harrison, Duncan and McDougall (1985). Their work suggests the closure temperature for biotite is compositionally dependent, with Mg-rich biotite being signficiantly more retentive than Fe-rich biotite.

TABLE 2

$^{40}Ar/^{39}Ar$ *age spectrum results*

Temp (°C)	$^{40}Ar/^{39}Ar$[1]	$^{37}Ar/^{39}Ar$[2]	$^{36}Ar/^{39}Ar$[1] ($\times 10^{-3}$)	^{39}Ar ($\times 10^{-14}$ mol)	% $^{39}Ar_K$ released	$^{40}Ar^*$[3] (%)	K/Ca	Age ± 1 s.d. (Ma)
MH-2 Hornblende (Reston)		J = .008476						
700	82.67	0.97	176.00	1.35	1.80	37.20	0.535	417.6 ± 2.1
850	53.78	1.27	93.82	1.22	3.60	48.60	0.408	361.2 ± 3.0
900	51.75	5.20	85.01	1.17	5.30	52.20	0.996	372.1 ± 2.1
950	36.31	9.28	32.29	3.54	10.5	75.70	0.056	377.8 ± 1.8
1000	31.61	8.93	17.20	8.84	23.4	86.10	0.058	374.4 ± 1.8
1025	32.12	8.82	19.01	8.11	35.3	84.60	0.059	374.0 ± 1.7
1050	58.27	9.36	108.50	1.41	37.4	46.20	0.055	371.0 ± 2.4
1075	49.08	9.09	77.20	2.53	41.1	55.00	0.057	371.3 ± 1.9
1100	38.38	8.71	40.77	6.17	50.1	70.40	0.059	371.8 ± 1.8
1125	35.08	8.50	29.48	12.00	67.7	77.00	0.061	372.1 ± 1.8
1150	54.16	8.53	94.07	6.46	77.2	49.90	0.061	372.0 ± 2.1
1175	45.47	8.80	64.75	9.53	91.2	59.40	0.059	371.9 ± 1.7
FUSION	72.80	8.92	157.80	5.99	100.	36.90	0.058	370.1 ± 2.0
PLATEAU AGE								371.6 ± 2.1
MH-7 HORNBLENDE (Reston)		J = .008813						
700	150.3	2.46	41.79	0.18	.024	18.0	0.211	385.4 ± 21.
850	81.41	1.59	201.2	0.52	.794	27.1	0.325	320.7 ± 3.5
900	58.60	1.32	123.4	0.57	1.48	37.9	0.393	322.7 ± 5.9
950	70.15	3.00	161.3	0.56	2.11	32.4	0.173	329.0 ± 3.9
1000	66.26	7.24	140.9	0.88	3.11	38.0	0.071	361.6 ± 3.5
1050	29.72	7.13	14.78	18.6	24.2	87.2	0.073	370.9 ± 1.9
1075	28.49	6.87	10.46	33.6	62.3	91.0	0.075	371.2 ± 1.7
1100	36.10	6.98	36.76	8.99	72.5	71.4	0.074	369.2 ± 1.8
1125	34.43	7.23	30.87	12.2	86.4	75.1	0.071	370.4 ± 1.8
1175	42.94	7.41	60.84	8.4	96.0	59.5	0.070	366.0 ± 1.7
FUSION	88.23	7.19	214.2	3.5	100.	28.9	0.072	365.6 ± 2.8
PLATEAU AGE								371.1 ± 2.1
MH-8 Hornblende (Maine)		J = 0.008853						
400	385.6	3.81	1241.	1.11	0.070	4.89	0.128	283.2 ± 142.
540	81.61	2.07	185.4	3.37	0.290	32.8	0.236	386.9 ± 23.
650	68.32	1.39	157.0	5.58	0.660	32.0	0.352	321.6 ± 11.
710	35.87	0.89	44.04	6.79	1.11	63.7	0.547	333.4 ± 11.9
810	30.87	1.31	30.45	9.63	1.74	70.8	0.372	320.9 ± 5.0
890	32.83	2.89	32.74	9.95	2.39	70.5	0.169	339.9 ± 4.0
935	33.52	5.45	30.62	11.12	3.12	73.0	0.089	360.6 ± 7.7
980	28.99	6.78	12.65	43.23	5.96	87.1	0.072	372.3 ± 2.7
1040	27.20	6.33	5.84	317.85	26.9	93.6	0.077	374.7 ± 3.5
1080	26.79	6.51	4.71	473.58	58.0	94.8	0.075	373.9 ± 2.4
1110	26.95	6.43	4.31	352.07	81.2	95.2	0.076	377.4 ± 2.4
1130	26.99	6.77	4.88	160.79	91.8	94.6	0.072	376.2 ± 2.5
1140	27.58	6.90	6.44	59.81	95.7	93.1	0.071	378.0 ± 2.6
1150	29.70	6.88	12.91	25.64	97.4	87.1	0.071	380.7 ± 2.9
1175	31.57	6.79	22.69	9.09	98.0	78.7	0.072	367.3 ± 13.
FUSION	31.22	6.72	18.28	30.89	100.	82.7	0.073	379.6 ± 3.1
PLATEAU AGE								375.4 ± 2.1
MH-9 Hornblende (Reston)		J = .008213						
700	107.78	2.14	262.2	0.30	0.40	28.3	0.243	402.9 ± 7.0
850	68.41	1.13	149.0	0.75	1.30	35.8	0.461	330.4 ± 2.5
950	59.54	5.41	113.0	1.74	3.40	44.6	0.096	356.1 ± 2.5
1000	46.73	6.66	63.78	4.46	8.70	60.8	0.078	378.1 ± 2.0
1025	32.18	6.62	15.63	18.00	30.2	87.2	0.078	374.2 ± 1.8
1050	30.75	6.41	11.26	24.10	59.0	90.8	0.081	372.4 ± 1.8
1075	37.28	6.30	33.77	7.57	68.0	74.5	0.082	370.8 ± 1.7
1100	43.35	6.37	53.30	5.79	74.9	64.8	0.081	374.4 ± 1.8
1125	42.19	6.75	49.91	8.14	85.0	66.3	0.077	372.9 ± 1.8
1175	45.89	6.81	62.10	9.64	96.5	61.2	0.076	374.1 ± 1.7
FUSION	125.42	6.51	332.6	2.94	100.	22.0	0.080	369.0 ± 2.6
PLATEAU AGE								373.2 ± 2.1
MH-10 Hornblende (Reston)		J = .008349						
700	109.66	1.45	279.70	0.35	0.30	24.7	0.036	368.3 ± 8.8
850	50.81	0.90	87.93	0.98	1.40	49.0	0.577	340.6 ± 1.9
950	38.22	5.90	39.02	4.62	6.40	71.0	0.088	368.5 ± 1.7
1025	31.20	6.21	14.31	16.40	24.0	88.0	0.083	372.2 ± 1.7
1050	29.99	6.14	10.04	23.70	49.4	91.7	0.084	372.8 ± 1.7
1075	31.43	6.00	15.01	17.30	67.9	87.4	0.086	372.3 ± 1.7
1125	32.27	6.33	17.84	17.20	86.4	85.2	0.082	372.7 ± 1.7
1175	39.08	6.26	40.88	11.60	98.9	70.3	0.083	372.6 ± 1.8
FUSION	177.91	6.24	513.40	1.02	100.	15.0	0.083	362.5 ± 7.1
PLATEAU AGE								372.5 ± 2.1

TABLE 2
(continued)

Temp (°C)	$^{40}Ar/^{39}Ar$[1]	$^{37}Ar/^{39}Ar$[2]	$^{36}Ar/^{39}Ar$[1] ($\times 10^{-3}$)	^{39}Ar ($\times 10^{-14}$ mol)	% $^{39}Ar_K$ released	$^{40}Ar^{*}$[3] (%)	K/Ca	Age ± 1 s.d. (Ma)
MH-60 HORNBLENDE (Maine)		J = .010242						
650	73.70	1.64	189.90	4.2	0.658	23.8	0.297	301.1 ± 62.6
850	30.41	0.93	40.19	5.2	1.47	60.9	0.524	314.7 ± 20.5
935	31.93	2.20	38.35	7.5	2.62	64.5	0.222	348.3 ± 4.8
1000	29.68	6.07	27.20	13.3	4.68	72.9	0.080	369.6 ± 5.0
1040	25.17	7.75	10.67	52.7	12.8	87.4	0.063	377.6 ± 2.6
1080	23.74	7.79	6.65	160.8	37.7	91.7	0.063	374.1 ± 2.5
1100	23.60	7.68	6.05	160.3	62.4	92.4	0.063	374.5 ± 2.5
1150	23.57	7.79	5.73	108.0	79.1	92.8	0.063	375.7 ± 2.5
1185	23.58	7.92	5.65	92.1	93.3	92.9	0.061	376.3 ± 2.5
FUSION	25.43	8.04	11.76	43.2	100.	86.3	0.061	377.1 ± 2.6
PLATEAU AGE								375.9 ± 2.1
MH-44 HORNBLENDE (Maine)		J= .010882						
650	34.62	1.11	74.24	13.4	1.61	36.6	0.441	234.7 ± 6.8
750	35.47	1.44	69.61	3.6	2.04	42.0	0.338	273.1 ± 18.
850	37.22	2.57	65.29	3.5	2.46	48.1	0.190	325.3 ± 14.
935	39.32	4.56	61.22	5.2	3.08	53.9	0.107	381.6 ± 14.
1000	25.32	7.08	17.63	27.3	6.36	79.4	0.069	367.3 ± 2.8
1040	22.94	6.81	9.51	55.5	13.0	87.7	0.072	367.3 ± 3.4
1065	22.12	6.64	6.35	100.8	25.2	91.5	0.073	368.9 ± 2.5
1100	21.59	6.47	4.75	200.1	49.3	93.5	0.075	367.8 ± 4.3
1150	21.36	6.29	4.04	285.2	83.6	94.4	0.078	367.2 ± 2.4
FUSION	22.70	6.40	8.16	136.3	100.	89.3	0.076	369.2 ± 2.5
PLATEAU AGE								367.7 ± 2.1
MH-45 HORNBLENDE (Maine)		J = .009297						
535	77.09	1.70	194.8	10.6	0.595	25.3	0.286	303.3 ± 31.
650	37.25	2.32	60.47	11.3	1.24	52.0	0.210	301.8 ± 9.0
710	28.28	5.65	17.25	29.1	2.86	81.9	0.086	359.3 ± 3.1
890	25.12	6.34	4.84	383.1	24.2	94.3	0.077	367.3 ± 2.4
935	24.84	6.30	3.85	439.0	48.7	95.4	0.077	367.3 ± 2.4
950	24.98	6.30	4.10	229.7	61.5	95.1	0.077	368.2 ± 2.4
965	25.23	6.29	5.85	96.2	66.9	93.1	0.078	364.6 ± 2.5
980	25.32	6.29	4.61	91.8	72.0*	94.6	0.078	370.8 ± 3.8
PLATEAU AGE								367.6 ± 2.1

* - remaining gas fractions lost due to vacuum leak - concentration based of K content of MH-44

Temp (°C)	$^{40}Ar/^{39}Ar$[1]	$^{37}Ar/^{39}Ar$[2]	$^{36}Ar/^{39}Ar$[1] ($\times 10^{-3}$)	^{39}Ar ($\times 10^{-14}$ mol)	% $^{39}Ar_K$ released	$^{40}Ar^{*}$[3] (%)	K/Ca	Age ± 1 s.d. (Ma)
MH-103 HORNBLENDE (Maine)		J = .009237						
520	77.00	1.66	84.93	15.1	0.94	67.4	0.294	708.6 ± 23.
650	99.40	1.65	227.6	3.8	1.18	32.3	0.296	471.1 ± 39.
750	44.82	1.89	80.83	5.5	1.52	46.7	0.258	321.3 ± 36.
850	41.19	4.29	57.31	12.5	2.30	58.8	0.114	370.2 ± 6.0
935	25.87	6.18	6.64	140.4	11.0	92.4	0.079	367.9 ± 2.6
965	25.84	6.22	6.41	115.1	18.2	92.6	0.078	368.4 ± 2.7
980	25.69	6.27	6.34	99.5	24.3	92.7	0.078	366.8 ± 2.5
990	25.71	6.29	6.34	84.1	29.6	92.7	0.078	367.0 ± 2.7
1010	25.54	6.31	4.92	101.8	35.9	94.3	0.077	370.5 ± 2.4
1025	25.49	6.30	5.54	122.6	43.5	93.5	0.077	367.3 ± 2.6
1040	25.42	6.31	4.85	133.4	51.8	94.3	0.077	369.0 ± 2.4
1055	25.30	6.34	4.26	177.7	62.8	95.0	0.077	369.9 ± 2.4
1080	25.02	6.33	3.84	328.6	83.2	95.4	0.077	367.8 ± 2.7
1100	25.05	6.27	3.94	187.5	94.9	95.3	0.078	367.6 ± 2.4
1120	25.80	6.38	6.58	55.1	98.3	92.4	0.076	367.4 ± 2.5
FUSION	26.93	6.63	13.24	27.7	100.	85.4	0.074	356.2 ± 7.9
PLATEAU AGE								368.3 ± 2.1
MH-110 HORNBLENDE (Maine)		J = .009398						
540	64.31	2.39	170.3	9.6	0.58	21.7	0.204	226.0 ± 49.
650	49.77	1.06	94.81	9.5	1.15	43.7	0.462	336.9 ± 9.7
710	28.64	0.60	23.66	9.4	1.72	75.5	0.805	334.8 ± 12.
810	28.07	1.64	19.96	14.2	2.57	78.9	0.298	343.5 ± 5.8
890	29.59	3.06	22.85	14.3	3.43	77.1	0.160	354.7 ± 11.
935	27.85	5.36	14.99	26.3	5.01	84.1	0.091	365.8 ± 4.1
980	25.53	6.26	7.22	96.3	10.8	91.6	0.078	366.7 ± 2.6
1010	24.91	6.31	5.89	180.2	21.6	93.0	0.077	363.6 ± 3.2
1025	24.87	6.28	5.54	143.0	30.1	93.4	0.078	364.4 ± 2.6
1040	24.91	6.29	5.22	122.2	37.4	93.8	0.077	366.3 ± 2.5
1055	24.81	6.31	5.18	133.7	45.4	93.8	0.077	365.1 ± 2.5
1065	24.79	6.34	4.48	135.3	53.5	94.6	0.077	367.7 ± 2.5
1080	24.66	6.34	3.80	171.6	63.8	95.4	0.077	368.8 ± 2.4
1090	24.65	6.32	3.66	144.3	72.4	95.6	0.077	369.1 ± 2.4
1110	24.58	6.35	3.61	181.4	83.2	95.6	0.077	368.4 ± 2.4
1165	24.54	6.67	3.42	198.7	95.1	95.8	0.073	369.1 ± 2.4
FUSION	25.96	6.64	7.38	82.1	100.	91.6	0.073	372.4 ± 3.2
PLATEAU AGE								366.8 ± 2.1

TABLE 2
(continued)

Temp (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ ($x10^{-3}$)	^{39}Ar ($x10^{-14}$ mol)	% $^{39}Ar_K$ released	$^{40}Ar^*$ (%)	Age ± 1 s.d. (Ma)
MH-2 BIOTITE (Maine) J = .009332							
520	33.60	6.09	60.69	9.5	0.400	46.6	246.8 ± 25.3
625	24.03	0.09	4.79	125.9	5.67	94.1	345.4 ± 2.4
770	24.66	0.03	1.55	514.0	27.1	98.1	367.3 ± 2.4
920	24.94	0.04	1.34	379.2	43.0	98.4	372.0 ± 2.4
1010	24.60	0.05	0.74	712.4	72.8	99.1	369.8 ± 2.4
1110	24.60	0.14	0.80	538.0	45.3	99.0	369.5 ± 2.4
1175	25.44	0.87	3.17	97.3	49.3	96.3	371.6 ± 2.8
FUSION	31.42	139.	22.72	12.0	100.	78.60	374.4 ± 8.7
PLATEAU AGE							370.0 ± 2.1
MH-7 BIOTITE (Reston) J = .008619							
550	32.28	0.82	69.71	1.4	0.300	36.2	173.0 ± 1.4
750	26.48	0.00	2.79	59.1	11.7	96.9	360.4 ± 1.7
850	26.56	0.06	0.54	104.0	31.8	99.4	369.8 ± 1.7
950	27.03	0.02	1.45	77.1	46.7	98.4	372.3 ± 1.7
1000	27.02	0.02	1.31	87.5	63.6	98.6	372.7 ± 1.7
1050	27.56	0.00	3.43	3.9	71.2	96.3	371.6 ± 1.7
FUSION	27.51	0.40	3.52	14.9	100.	96.2	370.7 ± 1.7
PLATEAU AGE							371.2 ± 2.1
MH-8 BIOTITE (Reston) J = .008069							
550	35.27	0.44	76.84	1.4	0.343	35.6	174.1 ± 1.2
750	27.48	0.07	5.28	38.1	7.34	94.3	342.7 ± 1.6
850	28.53	0.01	1.10	78.7	24.2	98.8	369.8 ± 1.7
950	29.30	0.03	1.63	74.7	46.0	98.3	377.1 ± 1.7
1000	29.43	0.04	1.56	76.1	64.1	98.4	378.9 ± 1.8
1050	29.30	0.50	2.34	83.5	84.0	97.6	374.7 ± 1.7
FUSION	31.01	0.61	8.74	67.2	100.	91.7	372.5 ± 1.7
MH-9 BIOTITE (Reston) J = .008193							
550	38.59	0.31	99.69	1.9	0.446	23.6	130.1 ± 1.1
750	27.51	0.09	4.30	53.9	13.0	95.4	351.2 ± 1.6
850	28.49	0.02	1.33	78.1	31.3	98.6	373.6 ± 1.7
950	29.17	0.09	2.14	74.3	48.7	97.8	379.0 ± 1.7
1050	29.03	0.11	2.19	147.0	83.0	97.7	377.1 ± 1.7
FUSION	31.21	0.79	10.08	73.0	100.	90.5	375.3 ± 1.7
PLATEAU AGE							376.5 ± 2.1
MH-10 BIOTITE (Reston) J = .008283							
550	39.74	0.26	69.53	3.9	0.834	48.3	266.1 ± 1.3
750	28.07	0.01	3.47	77.5	17.3	96.3	364.6 ± 1.7
850	28.12	0.01	1.95	81.4	34.7	97.9	370.7 ± 1.7
950	28.37	0.10	2.05	73.2	50.3	97.8	373.4 ± 1.7
1000	28.70	0.03	3.17	55.8	62.2	96.7	373.4 ± 1.7
1050	28.50	0.10	2.58	80.8	79.4	97.3	373.0 ± 1.7
FUSION	29.77	0.50	7.16	96.4	100.	92.9	372.1 ± 1.9
PLATEAU AGE							372.9 ± 2.1
MH-42 Biotite (Maine) J = .010754							
465	18.30	0.32	42.25	15.74	0.850	31.8	109.9 ± 20.
600	19.33	0.02	4.43	124.82	7.57	93.2	319.5 ± 2.6
730	21.49	0.01	1.21	530.20	36.1	98.3	369.4 ± 2.4
890	22.03	0.01	0.94	447.95	60.2	98.7	379.1 ± 2.4
980	22.18	0.01	1.86	230.13	72.6	97.5	377.2 ± 2.5
1090	21.77	0.01	0.94	306.40	89.1	98.7	375.1 ± 2.5
1175	21.85	0.01	1.70	174.00	98.4	97.7	372.7 ± 2.5
FUSION	25.52	0.01	12.69	29.21	100.	85.3	379.5 ± 5.7
PLATEAU AGE							377.2 ± 2.1
MH-60 BIOTITE (Maine) J = 0.010694							
465	35.87	1.08	85.32	17.2	1.05	29.7	194.8 ± 14.
600	21.39	0.02	1.81	380.9	24.3	97.5	363.1 ± 2.4
730	21.57	0.02	0.89	293.6	42.2	98.7	370.2 ± 2.4
890	21.81	0.06	1.63	278.3	59.2	97.7	370.5 ± 2.4
980	21.72	0.13	1.15	253.4	74.6	98.4	371.4 ± 2.4
1090	21.61	0.14	1.13	336.2	95.1	98.4	369.8 ± 2.4
1175	23.14	0.44	6.34	72.4	99.6	91.9	369.7 ± 3.0
FUSION	80.79	0.71	208.3	7.1	100.	23.8	337.6 ± 24.
PLATEAU AGE							370.3 ± 2.1

Table 2
(continued)

Temp (°C)	$^{40}Ar/^{39}Ar$[1]	$^{37}Ar/^{39}Ar$[2]	$^{36}Ar/^{39}Ar$[1] ($\times10^{-3}$)	^{39}Ar ($\times10^{-14}$ mol)	% $^{39}Ar_K$ released	$^{40}Ar^*$[3] (%)	K/Ca	Age ± 1 s.d. (Ma)
MH-44 BIOTITE (Maine) J = .010514								
465	31.23	2.69	82.20	16.2	0.674	22.2		130.9 ± 12.
600	19.20	0.03	5.45	189.8	8.56	91.6		306.1 ± 2.1
730	21.97	0.01	1.44	494.6	29.1	98.0		368.3 ± 2.4
890	22.72	0.01	1.82	327.9	42.7	97.6		378.1 ± 2.5
980	22.73	0.01	1.23	497.7	63.4	98.4		381.0 ± 2.5
1090	22.28	0.01	1.00	628.9	89.5	98.6		375.1 ± 2.4
1175	22.72	0.03	2.30	202.3	97.9	97.0		375.9 ± 2.6
FUSION	26.55	0.05	16.00	49.6	100.	82.2		372.7 ± 3.6
MH-45 BIOTITE (Maine) J = .008687								
520	33.84	5.68	75.31	14.9	0.606	34.2		173.6 ± 42.
625	24.81	0.31	11.64	47.2	2.52	86.1		307.2 ± 3.6
750	26.70	0.05	3.01	439.5	20.3	96.6		364.9 ± 2.4
890	26.90	0.03	1.24	377.8	35.6	98.6		374.2 ± 2.4
990	27.31	0.07	1.74	261.5	46.2	98.1		377.5 ± 2.5
1090	26.82	0.07	1.05	589.1	70.1	98.8		373.8 ± 2.4
1175	26.62	0.09	0.68	558.6	92.7	99.2		372.6 ± 2.4
FUSION	27.39	0.24	2.81	179.5	100.	96.9		374.5 ± 2.5
PLATEAU AGE								373.6 ± 2.1
MH-103 BIOTITE (Maine) J = .008867								
520	32.24	1.23	66.87	15.14	0.651	38.7		190.7 ± 12.
625	24.62	0.03	8.70	70.86	3.70	89.5		322.1 ± 3.1
730	27.17	0.01	3.30	272.97	15.4	96.4		376.7 ± 2.5
890	26.70	0.01	1.50	384.70	32.0	98.3		377.5 ± 2.6
990	27.21	0.01	1.81	366.89	47.8	98.0		382.9 ± 2.5
1090	26.57	0.01	1.29	606.85	73.9	98.5		376.6 ± 2.5
1175	26.27	0.01	0.88	521.55	96.3	99.0		374.3 ± 2.4
FUSION	28.99	0.03	9.18	86.72	100.	90.6		377.8 ± 3.2
PLATEAU AGE								376.3 ± 2.1
MH-110 BIOTITE (Maine) J = .009125								
520	42.67	4.41	108.01	5.1	0.199	25.1		169.3 ± 30.
625	18.02	1.00	14.66	24.7	1.16	75.9		212.4 ± 2.4
710	25.31	0.15	5.80	137.0	6.47	93.2		351.7 ± 2.8
800	25.17	0.05	1.19	322.0	18.9	98.6		368.2 ± 2.4
875	25.36	0.09	1.15	323.0	31.4	98.6		370.9 ± 2.4
950	25.91	0.08	2.83	128.7	36.4	96.7		371.7 ± 2.5
1000	26.17	0.16	2.61	117.8	41.0	97.0		376.0 ± 2.6
1060	25.72	0.15	1.01	398.7	56.4	98.8		376.3 ± 2.4
1100	25.59	0.51	1.04	472.5	74.7	98.8		374.6 ± 2.5
FUSION	25.12	0.45	0.90	652.8	100.	98.9		368.7 ± 2.4
MH-8 Orthoclase (Albany) J = 0.006291								
500	207.6	1.12	213.1	0.3	0.019	69.1		1168 ± 50.4
530	32.96	0.05	18.88	1.8	0.138	82.3		286.4 ± 12.5
560	29.30	0.11	3.378	3.4	0.367	96.0		295.3 ± 3.8
590	30.80	0.11	2.830	5.9	0.759	96.9		311.3 ± 2.5
620	30.33	0.05	3.030	8.2	1.31	96.7		306.2 ± 2.8
650	27.03	0.01	1.344	10.4	2.00	98.2		279.1 ± 1.3
680	25.56	0.08	1.940	18.9	3.25	97.5		263.1 ± 1.3
710	24.41	0.12	2.143	21.0	4.45	97.2		251.2 ± 0.8
740	24.54	0.09	1.373	27.7	6.49	98.1		254.7 ± 0.6
770	25.74	0.08	1.210	28.7	8.40	98.4		266.9 ± 2.0
800	25.32	0.09	0.7708	36.3	10.8	98.9		264.2 ± 0.7
830	25.91	0.07	0.6781	34.8	13.1	99.0		270.2 ± 0.5
860	26.51	0.09	1.180	35.8	15.5	98.5		274.6 ± 0.4
900	28.90	0.09	1.123	53.0	19.0	98.7		297.9 ± 0.5
950	30.24	0.11	1.163	47.6	22.2	98.7		310.7 ± 0.8
1000	30.10	0.08	0.9305	60.2	26.2	99.0		310.0 ± 0.5
1040	31.03	0.07	1.007	59.3	30.1	98.9		318.6 ± 0.3
1080	31.64	0.06	1.117	55.6	33.8	98.8		324.1 ± 2.9
1120	32.06	0.06	0.7249	47.8	37.0	99.2		329.2 ± 1.8
1160	32.89	0.08	1.336	102.0	43.8	98.7		330.5 ± 0.7
1200	33.14	0.04	1.018	229.0	59.0	99.0		338.5 ± 0.5
1250	33.59	0.03	0.5547	495.0	91.9	99.4		344.1 ± 0.3
1300	34.27	0.06	0.8868	707.0	96.6	99.1		349.4 ± 0.6
1380	76.45	0.21	2.716	17.6	97.8	98.9		702.2 ± 0.9
1450	45.42	0.23	4.320	33.6	100.	97.1		442.1 ± 0.5

TABLE 2
(continued)

Temp (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ ($x10^{-3}$)	^{39}Ar ($x10^{-14}$ mol)	% $^{39}Ar_K$ released	$^{40}Ar^*$ (%)	Age ± 1 s.d. (Ma)
MH-10 Orthoclase (Albany) J = 0.006490							
400	81.91	4.5	215.4	0.1	0.0058	21.7	206.3 ± 251
450	183.0	0.70	247.1	0.2	0.015	59.3	972.2 ± 120
490	281.4	0.73	86.32	0.5	0.037	90.6	1766 ± 51.5
530	265.7	0.09	42.78	1.0	0.087	95.1	1753 ± 19.6
560	109.0	0.18	42.40	1.3	0.149	88.2	876.9 ± 17.3
590	87.81	0.16	21.40	2.4	0.261	92.6	765.7 ± 12.8
620	63.90	0.04	13.78	3.8	0.440	93.4	591.6 ± 5.2
650	44.43	0.440	6.691	6.8	0.755	95.3	438.8 ± 3.1
680	33.04	0.08	6.410	9.9	1.22	94.0	331.8 ± 3.1
710	28.70	0.01	2.563	14.8	1.90	97.1	300.3 ± 1.9
730	26.14	0.01	2.583	17.4	2.71	96.8	274.6 ± 1.8
750	26.07	0.11	2.243	19.9	3.63	97.3	275.1 ± 2.4
780	26.42	0.04	1.644	33.2	5.17	97.0	280.3 ± 0.9
800	26.17	0.03	1.679	33.6	6.73	97.9	277.6 ± 1.1
820	26.37	0.03	0.9425	40.7	8.62	98.8	281.9 ± 1.0
840	26.85	0.03	1.402	40.5	10.5	98.3	285.3 ± 0.6
860	27.37	0.03	1.016	46.2	12.6	98.7	291.6 ± 0.7
880	27.86	0.03	1.233	48.1	14.9	98.5	295.9 ± 0.8
900	28.41	0.03	1.196	49.7	17.2	98.6	301.4 ± 0.6
930	29.19	0.03	0.9552	61.5	20.0	98.9	309.9 ± 0.6
960	30.08	0.03	0.7220	69.1	23.2	99.1	319.3 ± 0.5
990	31.22	0.02	0.8896	73.5	26.6	99.0	329.9 ± 0.7
1020	32.13	0.02	1.012	73.0	30.0	98.9	338.5 ± 0.8
1050	32.88	0.03	1.051	84.6	33.9	98.9	345.6 ± 0.3
1080	33.37	0.01	0.6735	73.6	37.4	99.3	351.4 ± 0.7
1110	33.62	0.01	1.135	60.8	40.2	98.9	352.5 ± 0.5
1140	33.53	0.01	1.169	89.5	44.3	98.8	351.5 ± 0.5
1170	33.68	0.01	1.180	95.5	48.8	98.8	352.9 ± 1.0
1200	33.75	0.01	1.768	114.0	54.0	98.3	351.9 ± 1.1
1230	34.48	0.02	1.549	96.9	58.5	98.6	359.6 ± 0.5
1300	34.76	0.01	0.5390	427.0	78.3	99.4	365.1 ± 0.6
1400	34.69	0.01	0.6865	400.0	96.9	99.3	364.0 ± 0.5
1450	35.69	0.02	3.478	67.3	100.	97.0	365.8 ± 0.9
MH-42 Microcline (Albany) J = 0.006200							
500	93.98	0.03	146.9	10.3	0.606	53.7	498.0 ± 7.8
550	18.02	0.06	5.526	14.0	1.4	90.6	176.7 ± 5.5
580	17.39	0.02	2.557	19.5	2.60	95.3	179.2 ± 4.9
610	18.55	0.11	2.715	20.0	3.79	95.4	190.7 ± 3.2
640	19.63	0.02	3.207	33.7	5.79	94.9	200.1 ± 2.2
670	20.84	0.01	1.138	41.8	8.27	98.2	218.5 ± 1.0
700	21.65	0.01	1.181	49.9	11.2	98.2	226.5 ± 1.7
730	22.50	0.01	0.9583	46.1	14.0	98.5	235.6 ± 1.4
760	23.28	0.02	1.045	54.4	17.2	98.5	243.1 ± 1.2
790	24.21	0.02	0.5500	37.9	19.5	99.1	253.7 ± 1.3
820	25.05	0.02	1.335	40.9	21.9	98.2	259.8 ± 1.1
860	25.79	0.02	1.040	48.9	24.8	98.6	267.9 ± 0.6
900	26.71	0.02	0.9694	54.0	28.0	98.8	277.1 ± 0.9
930	27.38	0.02	0.5260	49.4	30.9	99.3	284.9 ± 0.9
960	27.49	0.02	2.391	67.7	35.0	97.3	280.6 ± 0.7
1000	27.43	0.01	1.969	95.1	40.6	97.7	281.2 ± 0.7
1040	27.32	0.01	2.185	127.0	48.2	97.5	279.5 ± 0.6
1080	28.24	0.02	2.130	168.0	58.2	97.6	288.6 ± 0.5
1140	29.06	0.02	2.681	336.0	78.1	97.1	295.0 ± 0.4
1200	29.92	0.01	2.158	239.0	92.3	97.7	304.7 ± 0.6
1400	30.79	0.12	2.637	129.0	100.	97.4	311.8 ± 0.4

Notes:
1. Corrected for line blank.
2. Corrected for ^{37}Ar decay.
3. Includes line blank.

TRIGA reactor (Maine and Reston samples): $(^{40}Ar/^{39}Ar)_K = 0.01$; $(^{36}Ar/^{37}Ar)_{Ca} = 2.64X10^{-4}$; $(^{39}Ar/^{37}Ar)_{Ca} = 6.73X10^{-4}$.

Ford reactor (Albany samples): $(^{40}Ar/^{39}Ar)_K = 3.82X10^{-2}$; $(^{36}Ar/^{37}Ar)_{Ca} = 2.86X10^{-4}$; $(^{39}Ar/^{37}Ar)_{Ca} = 7.51X10^{-4}$.

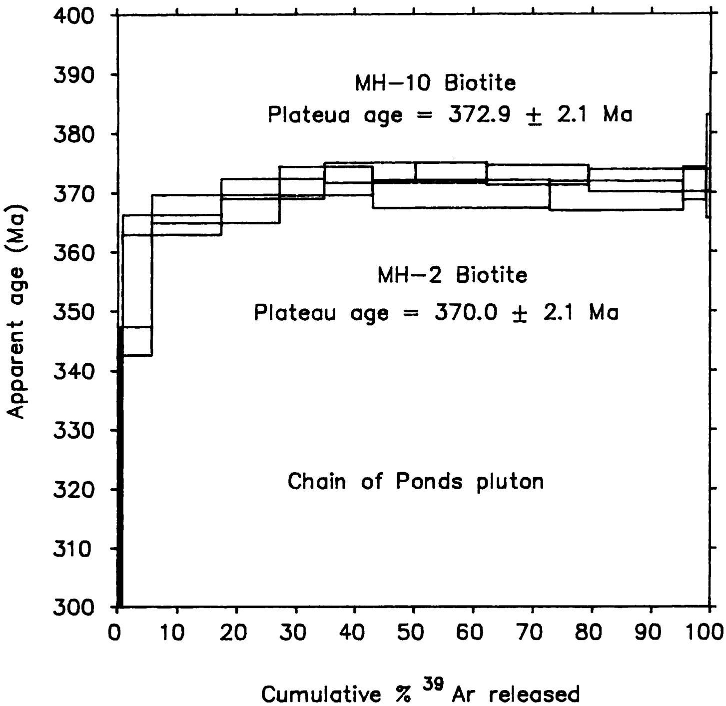

Fig. 5. Release spectra for youngest and oldest flat biotite samples from the Chain of Ponds pluton.

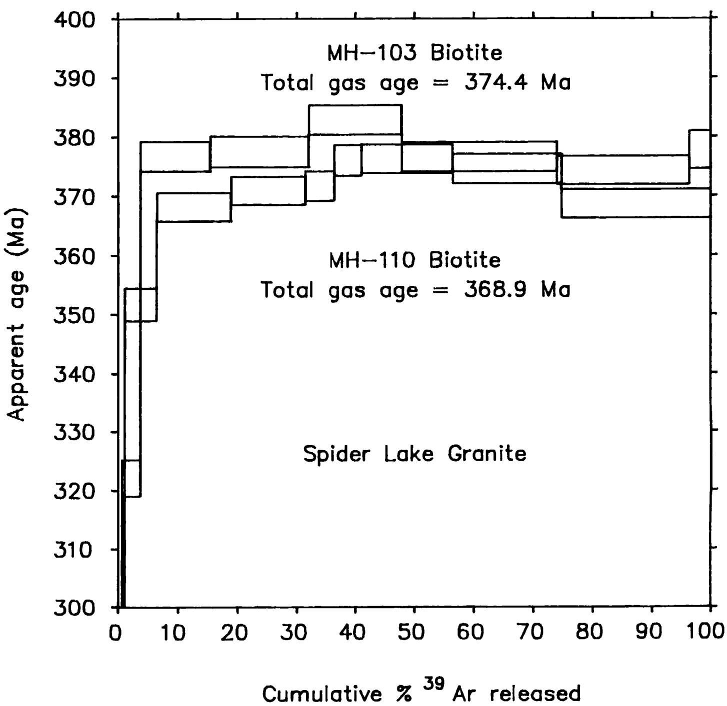

Fig. 6. Release spectra for Spider Lake Granite biotites. Note the hump-shaped pattern discussed in the text.

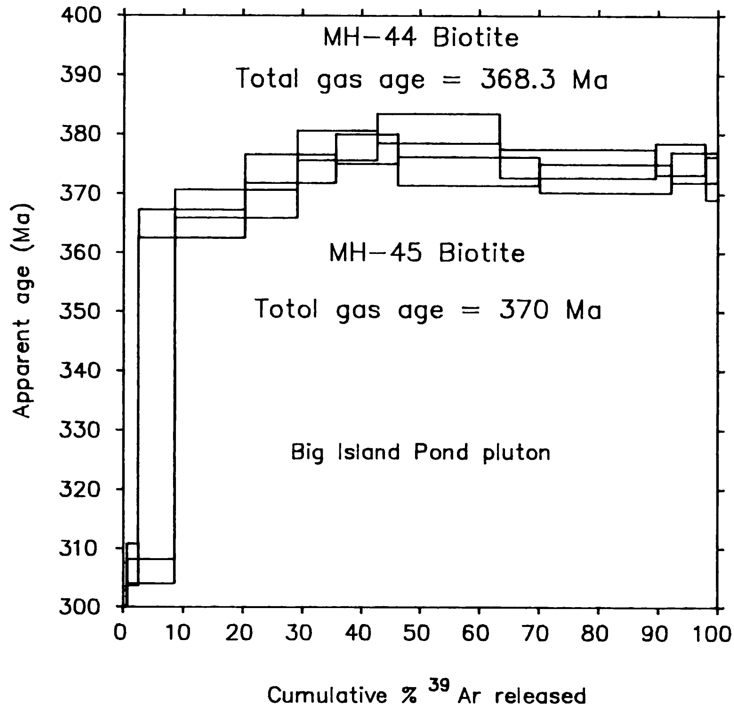

Fig. 7. Release spectra for Big Island Pond pluton biotites. Note the hump-shaped pattern discussed in the text.

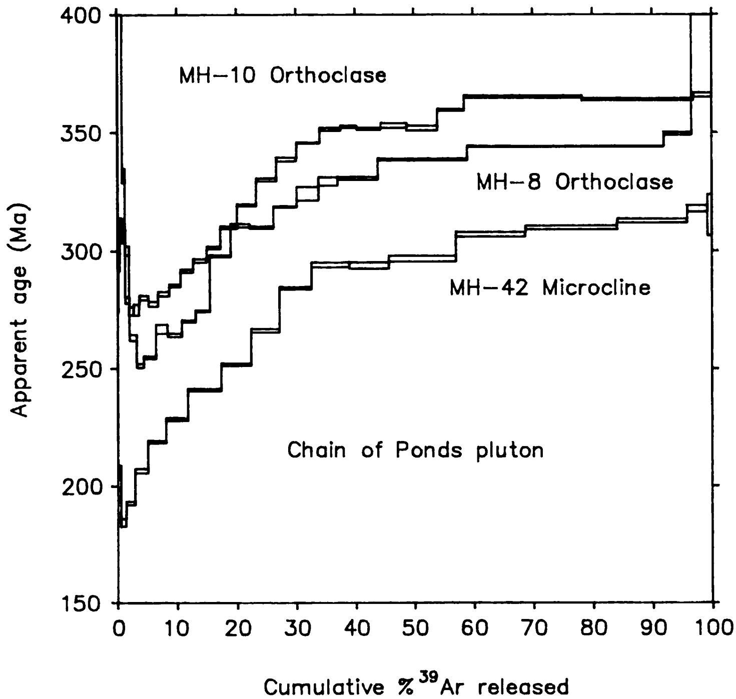

Fig. 8. Release spectra for Chain of Ponds pluton K-feldspars.

Typically, biotites from granitic rocks are about An_{56} and have a closure temperature of 345°C for a cooling rate of 100°C/Ma, a frequency factor of 0.077 cm^2/sec, and a diffusion radius of 150 μm (Harrison, Duncan, and McDougell, 1985). The biotites from the granodiorites in this study have a similar composition, and therefore this closure temperature was used.

Reported diffusion parameters for K-feldspar are highly variable and result in a large range of closure temperatures. Because of the complexity of K-feldspar with respect to structural state and degree of perthite development, it is inappropriate to assign a closure temperature to K-feldspar without specific knowledge of the diffusion characteristics of the K-feldspar in question.

Using the fractional loss data of ^{39}Ar during the extraction experiments, diffusion coefficients for orthoclase were calculated using a spherical geometry model due to the non-perthitic nature of the samples. The orthoclase samples produce linear arrays on an Arrhenius plot for argon extracted between the temperature 400° to 860°C (fig. 9). For sample MH-8, the first two data points fall below the regression line and most likely are the result of underestimating the analytical uncertainty assigned to these very small gas aliquots (less than 0.2 percent of the total gas released). The slope of the data begins to decrease at temperatures above 860°C and suggests a change in the diffusion mechanism at elevated temperature in the vacuum system. The perthitic microcline D/a^2 values were calculated using a plane sheet geometry from equations given by Harrison and McDougall (1981). This sample also shows a "knee" in the Arrhenius relation (fig. 9) but at a significantly lower temperature (750°C). Harrison, Morgan, and Blackwell (1986) attributed this knee to homogenization of perthite lamellae during argon extraction. This could be the explanation for the perthitic microcline sample, but the orthoclase samples do not exhibit optically visible exsolution features. A non-homogeneous feature of the orthoclase samples is the occurrence of myrmekite which may contribute to the observed break in slope on the Arrhenius plot.

From the slopes and intercepts given by the Arrhenius relations, E and D_0/a^2 can be obtained, and the closure temperature for each sample can be calculated using equations given by Dodson (1973). The microcline has a closure temperature of 185°C whereas the two orthoclase samples have closure temperatures of 245° and 315°C (table 3).

Thermal model results.—We infer that the approximately circular outcrop pattern of the CPP (fig. 1) reflects a cylindrical body of identical cross section to that exposed from closure about the exposed pluton of poorly constrained regional gravity contours and the observation of steeply dipping discordant contacts. We chose to describe this geometry as a simple prismatic intrusion which conductively cools in a uniform half-space of identical thermal properties to the pluton.

The thermal model assumes that the pluton is a rectangular parallel-piped below a horizontal surface maintained at constant temperature by use of an image source. The expression for the temperature T(X, Y, Z, t) in the vicinity of this prism is

$$\begin{aligned} T(X, Y, Z, t) = T_0 + 1/8(T_1 - T_0)\{&\mathrm{erf}[(X + d)/2(\kappa t)^{1/2}] \\ &- \mathrm{erf}[(X - d)/2(\kappa t)^{1/2}\} \\ &\cdot \{\mathrm{erf}[(Y + l)/2(\kappa t)^{1/2} - \mathrm{erf}[(Y - l)/2(\kappa t)^{1/2}]\} \\ &\cdot \{\mathrm{erf}[(Z - h_1)/2(\kappa t)^{1/2}] - \mathrm{erf}[(Z - h_2)/2(\kappa t)^{1/2}] \\ &+ \mathrm{erf}[(Z + h_1)/2(\kappa t)^{1/2}] - \mathrm{erf}[(Z + h_2)/2(\kappa t)^{1/2}]\} \end{aligned}$$

where X, Y, and Z are space variables, and t is time since intrusion (Carslaw and Jaeger, 1959). The top of the prism is at depth $Z = h_1$, the bottom is at $Z = h_2$, and the lateral dimensions of the mass are 2d and 2l.

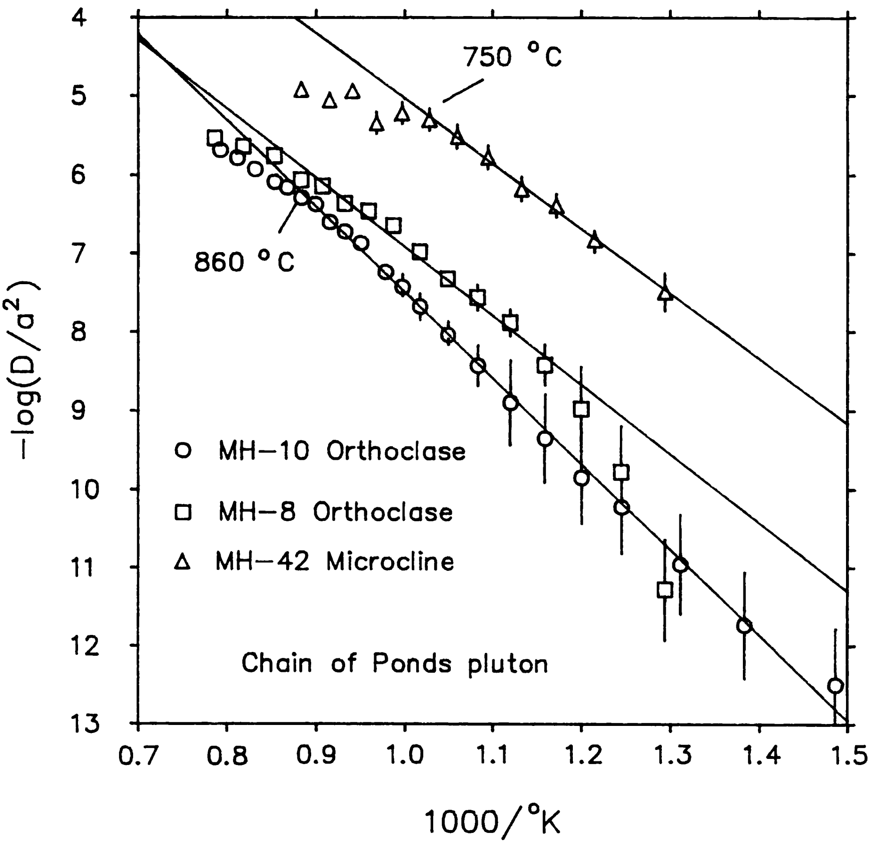

Fig. 9. Arrhenius plot for K-feldspars from the Chain of Ponds pluton. D/a^2 for orthoclases calculated using a spherical geometry model and the microcline using a plane sheet geometry model.

TABLE 3

Calculated parameters for Arrhenius plot using a spherical geometry model for the orthoclase samples and a plane sheet geometry model for the microcline. T_c is the closure temperature calculated for the core of the crystal based on equations given in Dodson (1973). Calculated errors given by York (1969) regression method.

Temperature °C	10^3/°K ± 0.01	− log D/a^2
MH-8 Orthoclase		
500	1.294	11.281 ± .56
530	1.245	9.777 ± .49
560	1.200	8.980 ± .45
590	1.159	8.420 ± .17
620	1.120	7.887 ± .08
650	1.083	7.565 ± .08
680	1.049	7.328 ± .04
710	1.017	6.981 ± .04
740	.987	6.645 ± .03
770	.959	6.463 ± .03
800	.932	6.364 ± .03
830	.907	6.144 ± .03
860	.883	6.066 ± .03
900	.853	5.764
950	.818	5.640
1000	.786	5.535
E = 40.15 ± 2.56 kcal/mol D_0/a^2 = 73.5 ± 21.9/sec		τ = 2.13 x 10^{14} sec T_c = 242 ± 15°C
MH-10 Orthoclase		
400	1.486	12.49 ± .62
450	1.383	11.74 ± .59
490	1.311	10.96 ± .55
530	1.245	10.22 ± .51
560	1.200	9.850 ± .49
590	1.159	9.353 ± .47
620	1.120	8.903 ± .45
650	1.083	8.436 ± .17
680	1.049	8.047 ± .08
710	1.017	7.681 ± .07
730	.997	7.434 ± .07
750	.978	7.245 ± .04
780	.950	6.873 ± .03
800	.932	6.721 ± .03
820	.915	6.604 ± .03
840	.899	6.378 ± .03
860	.883	6.291 ± .03
880	.867	6.163
900	.853	6.097
930	.831	5.932
960	.811	5.793
990	.792	5.693
E = 49.93 ± 0.73 D_0/a^2 = 2634 ± 119/sec		τ = 1.99 x 10^{14} sec T_c = 317 ± 5°C
MH-42 Microcline		
500	1.294	7.494 ± .15
550	1.215	6.827 ± .07
580	1.172	6.388 ± .06
610	1.133	6.178 ± .06
640	1.095	5.777 ± .03
670	1.060	5.517 ± .03
700	1.028	5.303 ± .03
730	.997	5.220
760	.968	5.348
790	.941	4.938
820	.915	5.057
E = 37.70 ± 1.25 kcal/mol D_0/a^2 = 1603 ± 137/sec		τ = 2.27 x 10^{14} sec T_c = 185 ± 6°C

The thermal diffusivity κ is the same everywhere in the half-space. The prism is emplaced at a uniform initial temperature T_1, while all surrounding space is at the same initial temperature T_0. The Y direction is parallel to the strike direction of the prism, and the planes $X = 0$ and $Y = 0$ are planes of symmetry.

An assessment of the sensitivity of these calculations to perturbations in input parameters (thermal diffusivity, prism size, depth of emplacement, initial temperatures, et cetera) is summarized in figure 10A,B and table 4A,B and suggests that relatively large variations do not greatly affect calculated thermal histories within the prism and emphasizes that these plutons cooled rapidly (within 3 Ma) to ambient temperatures.

The lateral dimensions of the model for the CPP were estimated from the outcrop areas shown on published geologic maps. Briefly, an average radius of 8 km was determined from the roughly circular outcrop pattern (fig. 1), and so a surface area of about 200 km^2 was calculated. Because an "equivalent" square would be approx 14 by 14 km, d and l values for the prismatic model of the CPP were both taken to be 7 km.

A thickness of 8 km was chosen for the model. Although this value is somewhat arbitrary, gravity interpretations (Hodge and others, 1982) are consistent with 8 to 10+ km thick Devonian plutons in low grade metamorphic rocks in eastern Maine. Interpretation of gravity anomalies elsewhere in Maine and in nearby parts of New Hampshire indicate that many Devonian intrusives in low and high grade units in the northern Appalachians have thicknesses in the range 1 to 3 km (Hodge and others 1982; Kane and Bromery, 1968; Neilson and others 1976). We can not be more exact about the thicknesses assumed for modeling, but as seen in figure 10A, this is not a critical parameter in the resulting thermal histories.

Lovering (1935, 1936, 1955) summarizes data and calculations that suggest crustal rocks and magmas are likely characterized by thermal diffusivities in the range 0.005 to 0.02 cm^2/sec. Also, Jaeger (1965) strongly implies that a diffusivity of 0.01 cm^2/sec can be used for reliable analytical modeling of heat conduction in the vicinity of intrusions in crustal rocks, thus 0.01 cm^2/sec was assumed.

An initial intrusion temperature of 800°C was assumed. Estimates for temperatures of granodiorite melts range from 800° to 1000°C depending on H_2O content, crystal content, and depth of emplacement (Wyllie, 1971, 1977; Harrison and Clarke, 1979; Wyllie, 1984). As the results in table 4B indicate, the choice of intrusion temperature has little effect on the calculated cooling history within the pluton.

Biederman (ms) estimated the depth of emplacement for the present exposure of the CPP to be 7.6 to 9.3 km, based on the sillimanite–andalusite–staurolite mineral assemblage observed in the contact aureole and assuming that $P_{H_2O} = P_{total}$. If P_{H_2O} did not equal P_{total}, the stability field of staurolite may be expanded to the Al-silicate triple

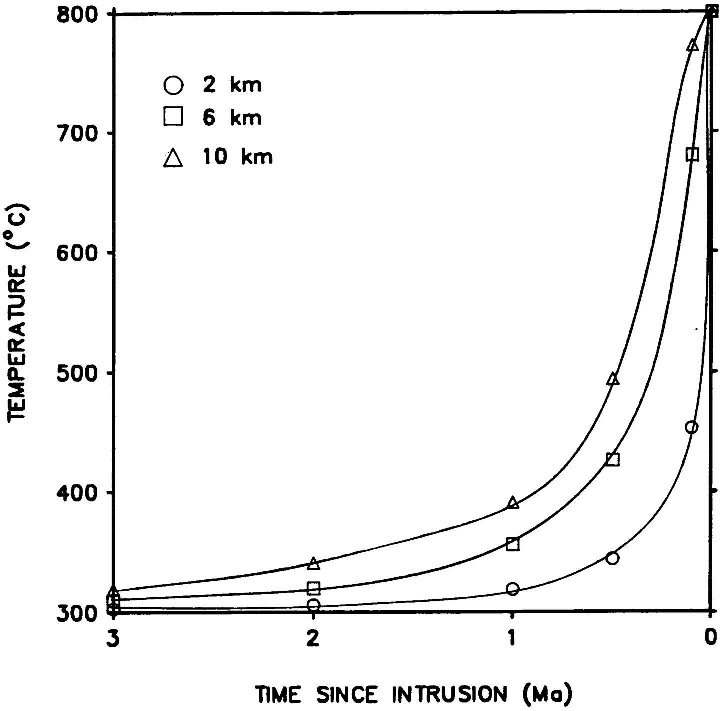

Fig. 10(A) Temperature distribution in the center of a mass for varying thicknesses. $T_1 = 800°C$, $T_0 = 300°C$, $d = \ell = 7$ km, $X = Y = 0$, $\kappa = 0.01$ cm^2/sec, $h_1 = 9$ km.

point, and an emplacement depth of 12 km could be inferred. As shown in table 4A, the depth of emplacement has little effect on calculated thermal models if the same T_0 is assumed. As will be discussed, a T_0 of 325°C is used for calculations—thus if a gradient of 30°C/km and surface temperature of 10°C is assumed, a depth of emplacement of ~10 km is calculated and therefore used in the model.

Finally, the point of calculation for the model was chosen to be $X = Y = 0$ and $Z = 10.5$ (0.5 km in from the top of the pluton). Large roof pendants (fig. 1) in the CPP suggest that it has not been eroded deeply and justify scrutiny of this "close in" point.

The results of this model are shown in figure 11 for the first 3 Ma following intrusion. This model predicts very rapid cooling during the first 1 Ma, and overall the prism would cool from 800° to 330°C in 3 Ma. The temperature distribution outside the prism can also be calculated. For a point $Y = 0$, $Z + 10.5$, and $X = 7.5$ (0.5 km from the pluton contact is where Biederman, (ms), documented the observed mineral assemblage). The results in figure 11 indicate heating of the country

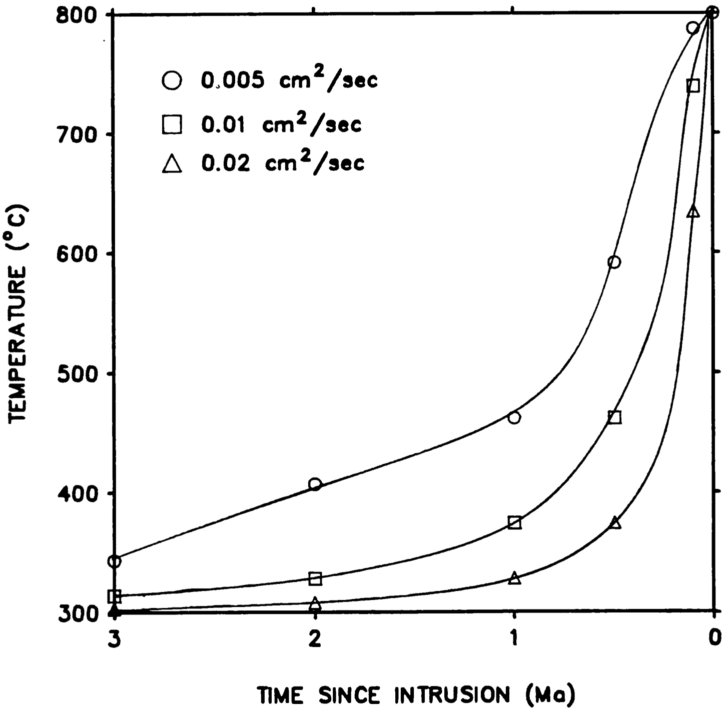

Fig. 2 (continued) (B) Temperature distribution in the center of a mass for varying diffusivities. $T_1 = 800°C$, $T_0 = 300°C$, d = ℓ = 7 km, X = Y = 0 h_1 = 9 km, h_2 = 17 km.

rock to 460°C within 0.1 Ma following intrusion, and by 3 Ma the thermal distrubance from the pluton has nearly dissipated.

DISCUSSION

The mean plateau age for hornblendes from the CPP, BIPP, and SLG are 373.3 ± 2.0, 367.7 ± 1.3, and 367.6 ± 1.3 Ma respectively. The plateau ages are well defined, and the hornblende release spectra suggest the samples have been undisturbed since initial cooling following intrusion.

Hornblendes from the CPP have higher apparent ages than hornblendes from the BIPP or the SLG. Because some of the hornblendes were irradiated with similar geometry, the error in the J-factor can be ignored when comparing relative differences in age. Thus the 6 Ma age difference in the hornblendes is significant and suggests that the CPP is older than the SLG and BIPP. The hornblende age of the CPP is interpreted to represent not only the time the CPP was at 550°C but also

TABLE 4

Temperature distribution

A. In the center of a mass for varying depths of emplacement. $d = l = 7$ km, $X = Y = 0$, $T_0 = 300°C$, $T_1 = 800°C$, $k = 0.01\ cm^2/sec$, $h_2 = h_1 + 10$ km. Time is time since intrusion

Time (Ma)	7 km	9 km Temperature °C	12 km
0.01	800	800	800
0.1	772	772	772
0.5	494	494	494
1.0	390	391	391
3.0	316	319	320

B. At the top of a mass for varying intrusion temperatures. $d = l = 7$ km, $X = Y = 0$, $T_0 = 310°C$ $k = 0.01\ cm^2/sec$, $h_1 = 10$ km, $h_2 = 18$ km. Time is time since intrusion

Time (Ma)	800°C	900°C Temperature °C	1000°C
1.0	373	386	399
2.0	332	336	341
3.0	316	318	320

the time of emplacement. The following criteria support this interpretation:

1. Hornblende and biotite ages are nearly concordant, suggesting the CPP cooled quickly between 550° and 350°C. This suggests even more rapid cooling from intrusion temperatures to 550°C.

2. The metamorphic assemblage in the contact aureole indicates a depth of emplacement for the CPP between 7 to 12 km; this relatively shallow emplacement would contribute to quick cooling.

3. The thermal model predicts that after intrusion at 800°C, the CPP would have cooled to 550°C in less than 1 Ma.

The hornblende ages of the SLG and BIPP are also interpreted to be intrusion ages at ~368 Ma and suggest these plutons are the same age.

The best estimated biotite age of 371.1 ± 2.7 Ma for the CPP is interpreted to be the time when this pluton cooled below 350°C. The biotites from the SLG and BIPP have somewhat complex age spectra with total gas ages that average 370.3 ± 3.4 Ma. The concordant biotite and hornblende ages are consistent with rapid cooling of these plutons.

The plateau and terminal ages of the K-feldspars are interpreted to be the time when the core of the crystals cooled through their respective closure temperatures. There is a good correlation between age and closure temperature as MH-10 has an age of 365 Ma and a closure temperature of 315°C. The plateau age for MH-8 is 345 Ma and corresponds to a temperature of ~240°C while MH-42 is the youngest at ~312 Ma and has a closure temperature of 185°C. The argon loss

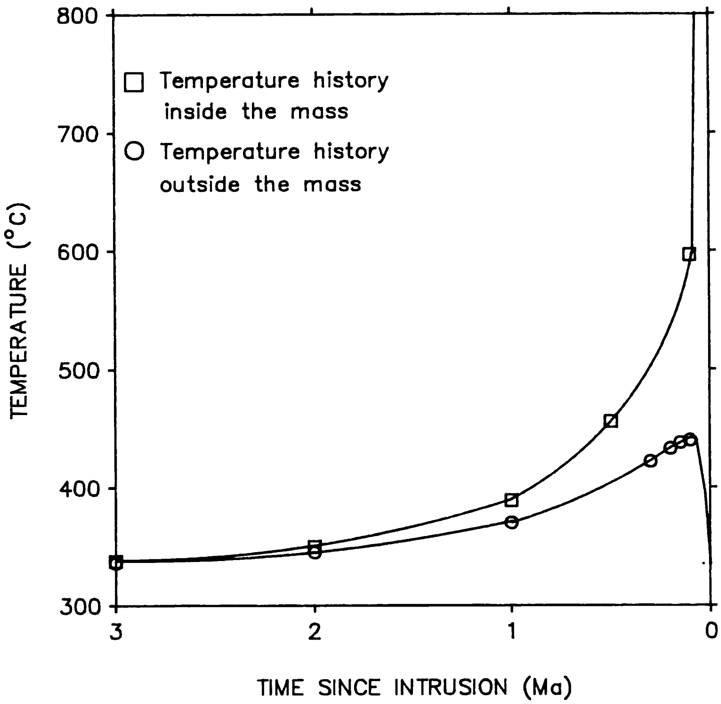

Fig. 11. Temperature history as modeled for the Chain of Ponds pluton. T_1 = 800°C, T_0 = 325°C, d = ℓ = 7 km, h_1 = 10 km, h_2 = 18 km, κ = 0.01 cm^2/sec. Inside the mass X = Y = 0, Z = 10.5 km; outside the mass X = 0, Y = 7.5 km, Z = 10.5 km.

during a Jurassic thermal event has undoubtably lowered the plateau ages (especially for MH-42). For less than 30 percent outgassing, the plateau ages (especially for spherical geometries) would not be dramatically affected. The time-temperature history revealed by the K-feldspar terminal ages remains essentially the same, but slightly faster post-crystallization cooling rates could be inferred.

A cooling curve is shown in figure 12 for the CPP. Hornblende and biotite age data show that the pluton cooled from 550° to 350°C very rapidly (~100°C/Ma), with the cooling rate decreasing exponentially to the microcline terminal age. Cooling curves of this nature have been determined for the Separation Point Batholith in New Zealand and Quottoon pluton in British Columbia, and the initial part of the cooling curve is attributed to conductive cooling to ambient conditions (Harrison and McDougall, 1980a; Harrison and Clarke, 1979).

Based on both the model prediction of cooling to ambient within ~3 Ma and the biotite closure by ~2 Ma following intrusion, the ambient temperature prior to intrusion of the CPP was ~350°C. Also, MH-10

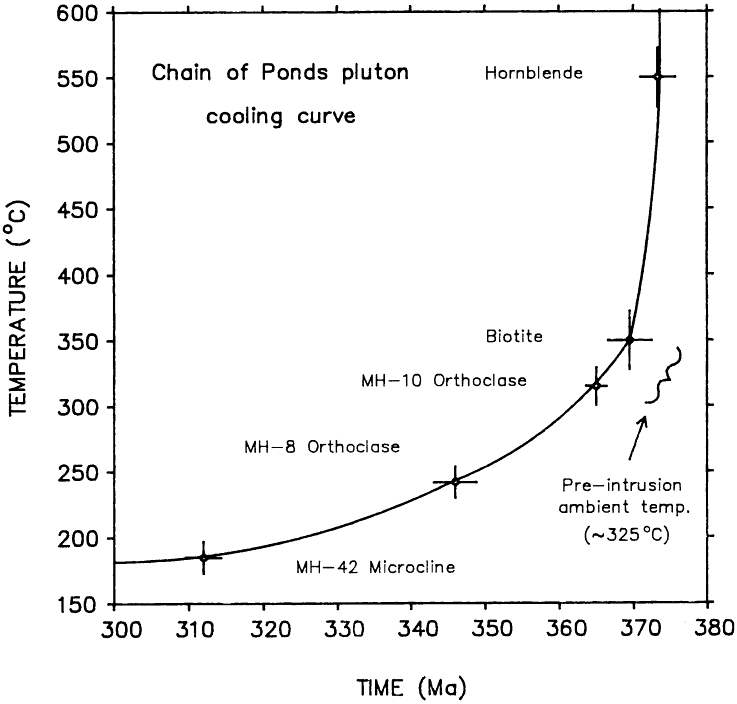

Fig. 12. Cooling curve for the Chain of Ponds pluton as defined by mineral ages and assigned closure temperatures. The decrease in cooling rate between 370 to 365 Ma is an indication of the ambient temperature before intrusion (~325°C).

orthoclase indicates cooling to 315°C by 365 Ma (8 Ma following intrusion), therefore constraining the ambient temperature to between 315° and 350°C; thus the choice of 325°C as the ambient temperature used in the thermal model.

The cooling rate from 365 to 315 Ma is on the average of 2 to 3°C/Ma. For a geothermal gradient of 30°C/km an uplift rate of 0.07 to 0.1 mm/yr is calculated. These rates are sufficiently slow not to cause advection of isotherms, thus the calculated cooling rate is valid (Harrison and Clarke, 1979). These cooling and uplift rates are consistent with predicted rates from discordant biotite and muscovite ages from plutons and metamorphic rocks in western Maine and New Hampshire.

Thermal modeling predicts the maximum temperature at 0.5 km outside the pluton is ~460°C at 0.1 Ma following intrusion. The metamorphic mineral assemblage indicates that this temperature would be 500° to 600°C, and therefore the model does not accommodate the observed contact aureole. Jaeger (1957) calculated the thermal distribution outside a mass with an added component of latent heat of crystallization. These results suggest that the contact temperature would be underestimated by ~100°C if one did account for latent heat. Thus, the apparent underestimate of the temperature in the contact aureole could be accounted for by the effects of latent heat.

An additional 100°C to the intrusion temperature would add 50°C to the contact temperature which would also account for the contact aureole assemblage. Using 900°C as an intrusion temperature does not conflict with the data from granodiorite melts and would not significantly alter the cooling history within the pluton.

Subsequent (since 315 Ma) cooling and heating of the area can be assessed to some extent from the age gradients in the K-feldspar release spectra. The linear gradient (Harrison and McDougall, 1982) in MH-10 orthoclase could readily by explained by slow cooling of the terrane. However, MH-8 and especially MH-42 age spectra seem to record an episodic loss event. Extrapolation of the age gradient in MH-42 to zero percent ^{39}Ar released indicates a thermal pulse at ~170 Ma. The timing of loss in MH-8 is more difficult to assess because of excess ^{40}Ar in the first few increments of its release spectrum but does not preclude an outgassing event at 170 Ma. MH-10 either has very minor $^{40}Ar^{*}$ loss (obscured by excess ^{40}Ar) due to this thermal pulse or because of its greater closure temperature relative to MH-8 and MH-42 did not record this low temperature event.

Heizler and Harrison (1986, 1987) have documented a thermal event that has variably outgassed K-feldspars in the northeastern United States during the Jurassic. Also, rocks of the White Mountain Magma Series were intruded in pulses between ~200 to 100 Ma (Foland and Faul, 1977), and it is possible that the thermal disturbance at ~170 Ma recorded in the K-feldspar is related to White Mountain Magma Series activity.

CONCLUSIONS

Based on hornblende, biotite, and K-feldspar $^{40}Ar/^{39}Ar$ ages, a cooling history for the Chain of Ponds pluton has been delineated. The mean hornblende age of 373.3 ± 2.0 Ma from the CPP is interpreted not only to be the time at which this pluton cooled below 550°C but as the intrusion age. A best estimate biotite age of 371.1 ± 2.7 Ma is assigned to the CPP and corresponds to an argon closure temperature of 350°C. Three K-feldspars from the CPP have significantly different ages but are readily interpretable in the context of their closure temperatures. This underscores the need to determine closure temperatures of K-feldspars if one is to assign a meaningful geologic interpretation to its apparent age.

A cooling curve for the CPP shows rapid cooling from intrusion to 300° to 350°C. This cooling history is consistent with a calculated thermal model that predicts rapid cooling (within 3 Ma) from intrusion to ambient conditions based on conductive heat transfer into surrounding country rock. The decrease in cooling rate (365–370 Ma, fig. 12) corresponding to a temperature of ~325°C can be used as a good estimation of ambient temperature as the thermal perturbation due to an intrusion is relatively short lived. Estimates of the depth of emplacement based on mineral assemblages in the contact auerole and the assessment of ambient temperature suggest that the average upper crustal geothermal gradient was about 30°C/km. An apparent underestimate by the thermal model of temperatures reached in the contact aureole could be accounted for by addition of latent heat of crystallization or an increased intrusion temperature.

The Big Island Pond pluton and Spider Lake Granite have mean hornblende ages of 367.7 ± 1.3 and 367.6 ± 1.3 Ma. These ages are also interpreted to be intrusion ages. This indicates that these plutons are the same age and ~6 Ma younger than the CPP. Biotites from these plutons have a mean total gas age of 370.3 ± 3.4 Ma.

Cooling of the area below 200°C by 315 Ma probably was the result of slow uplift (~0.1 mm/yr) and erosion. An average cooling rate of 2° to 3°C/Ma during this time is estimated from the K-feldspar ages and closure temperatures. The K-feldspar release spectra (especially MH-8 and MH-42) indicate a relatively low temperature thermal disturbance which peaked at ~170 Ma.

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