$^{40}Ar/^{39}Ar$ hornblende ages from southwestern Maine: evidence for Late Paleozoic metamorphism

David P. West, Jr.
Daniel R. Lux
Department of Geological Sciences, University of Maine, Orono, Maine 04469

and

Arthur M. Hussey, II
Department of Geology, Bowdoin College, Brunswick, Maine 04011

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$^{40}Ar/^{39}Ar$ analyses of hornblendes from a 120 km long NE-trending transect within the high-grade rocks of the Casco Bay Group provide information regarding the timing of thermal events and subsequent cooling history of this region. In the north, plateau ages of 368-372 Ma record the time of cooling through argon closure temperatures (500°C) following Acadian metamorphism. In the central portion of the transect, hornblendes display younger ages (350-323 Ma) and release spectra which show evidence of a Late Paleozoic thermal overprint. To the south, significantly lower plateau ages are recorded (270-290 Ma). These lower ages date either the time of a Late Paleozoic thermal event or the time of cooling following a prolonged period of burial at deep crustal levels. The former interpretation is favored on the basis of the disturbed release spectra in the central portion of the transect and the fact that ages over the 60 km long southern portion of the transect are relatively constant at 280±10 Ma. If a Late Paleozoic thermal event occurred in this region it was evidently not accompanied by large amounts of deformation as structural evidence for such an event is lacking. The exact nature of the Late Paleozoic resetting of hornblendes in this portion of the Casco Bay Group is not clear; however, it may be related to the events which lead to granite emplacement 275 Ma ago in the Massabesic Gneiss Complex and the 272-282 Ma ages for monazites from the nearby Sebago Batholith.

Des analyses $^{40}Ar/^{39}Ar$, effectuées sur des hornblendes prélevées sur une traverse NE de 120 km de longueur au sein des roches métamorphiques de haut degré du Groupe de Casco Bay, ont fourni des données sur l'âge des épisodes thermiques et l'histoire du refroidissement qui leur succéda dans ce secteur. Au nord, des âges-plateaux de 368 à 372 Ma datent le refroidissement via les températures de fermeture de l'argon (500°C) suivant le métamorphisme acadien. Dans la portion centrale de la traverse, les hornblendes exhibent des âges plus jeunes (350 à 325 Ma) et des spectres de diffusion qui portent la trace d'une surimpression thermique tardi-paléozoïque. Vers le sud, on enregistre des âges-plateaux bien plus jeunes (270 à 290 Ma). Ces derniers datent soit un épisode thermique tardi-paléozoïque, soit un refroidissement après un enfouissement prolongé profondément dans la croûte. On favorise la première interprétation à cause des spectres de diffusion dérangés que montre la portion centrale de la traverse et parce que les âges obtenus au long des 60 km de la portion sud de la traverse sont relativement constants à 280±10 Ma. Si cette région a subi un épisode thermique tardi-paléozoïque, ce ne fut assurément pas de pair avec une déformation importante puisque la structure ne fournit aucun indice d'un tel événement. La nature exacte de la remise à zéro tardi-paléozoïque des hornblendes dans cette portion du Groupe de Casco Bay n'est pas apparente. On pourrait cependant la relier aux événements à l'origine de l'emplacement de granite dans le Complexe de Gneiss de Massabesic (il y a 275 Ma) ainsi qu'aux âges de 272-282 Ma des monazites du batholite avoisinant de Sebago.

[Traduit par le journal]

INTRODUCTION

In the New England Appalachians, episodes of Middle Ordovician (Taconic), Lower Devonian (Acadian), and Permian (Alleghanian) metamorphism have been documented. The spatial distribution of these events in New England is problematic and controversial. However, the extent of Late Paleozoic metamorphism in northern New England is especially difficult to establish due to the limited exposure of post-Middle Devonian sedimentary rocks. In this area, where the timing of metamorphism is poorly constrained, isotope geochronology can provide invaluable information, although uncertainties in interpretation do exist.

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Several earlier isotopic dating studies have identified a widespread area of anomalously low K-Ar biotite ages in northern New England (Faul *et al.*, 1963; Zartman *et al.*, 1970; Dallmeyer, 1979). Unfortunately the interpretation of these young ages is difficult because the effective closure temperature of Ar diffusion in biotite is relatively low (approximately 300°C; Harrison *et al.*, 1985). Therefore these young ages may be related to deep burial and slow cooling following the Acadian Orogeny rather than a distinct Late Paleozoic thermal event. Several recent studies in New England, employing thermally more resistant isotopic systems, have identified areas affected by episodes of Late Paleozoic metamorphism. In southeastern New England $^{40}Ar/^{39}Ar$ age spectra for hornblendes (Dallmeyer, 1982; Wintsch and Sutter, 1986), Rb-Sr mineral ages (O'Hara and Gromet, 1983), and U-Pb ages (Hermes and Zartman, 1985; Wintsch and Aleinikoff, 1987) are suggestive of extensive Late Paleozoic tectonism. To the north the discovery of Late Paleozoic metamorphism in western Maine (Lux and Guidotti, 1985) and granite of Permian age in the Massabesic Gneiss Complex of New Hampshire (Aleinikoff *et al.*, 1979) suggests this event may be of regional significance.

The purpose of this paper is to provide new $^{40}Ar/^{39}Ar$ age data for hornblendes from southwestern Maine. These data were collected in an attempt to determine the timing of metamorphism in this area as well as to determine any differences along strike. Hornblendes were collected along a NE-trending transect approximately 120 km long within high-grade rocks of the Casco Bay Group. $^{40}Ar/^{39}Ar$ hornblende ages given here are taken to represent the time of cooling below about 500°C (Harrison, 1981), i.e., cooling below middle amphibolite facies conditions. Thus the new data presented here may provide knowledge concerning the northerly extent of Late Paleozoic high-grade metamorphism.

REGIONAL GEOLOGY

The study area is located to the east of the Kearsarge-Central Maine Synclinorium (KCMS) of Lyons *et al.* (1982) and to the west of the Norumbega Fault Zone (Fig. 1). These rocks include the high-grade quartzofeldspathic gneisses and amphibolites of the Casco Bay Group. Detailed geologic descriptions of the Casco Bay Group and surrounding rocks are presented in Pankiwskyj (1978), Newberg (1981; 1985), Hussey (1985; in press), and Hussey *et al.* (1986).

The Casco Bay Group consists of metamorphosed Late Precambrian(?) to Early Ordovician(?) volcanic and volcaniclastic sedimentary rocks. Hussey (in press) subdivided the Casco Bay Group into two distinct lithotectonic packages separated by the NE-trending Flying Point Fault (FPF). The Falmouth-Brunswick (F-B) sequence lies to the west of the FPF and consists of the Nehumkeag Pond, Mount Ararat, Torrey Hill and Richmond Corner members of the Cushing Formation. The Saco-Harpswell (S-H) sequence lies to the east of the FPF and it includes the remaining members of the Cushing Formation (Peaks Island, Wilson Cove, Merepoint, Bethel Point, and Yarmouth Island), and the Sebascodegan, Cape Elizabeth, Spring Point, Diamond Island, Scarboro, Spurwink, Jewell and Macworth Formations of the Casco Bay Group.

Structurally the Hackmatack Pond Fault (Pankiwskyj, 1978) separates the F-B sequence from the KCMS. This fault is interpreted to be a west-dipping thrust fault on the basis of seismic reflection studies (Stewart *et al.*, 1986). The Flying Point Fault (Hussey, 1985) to the south and to the north the Beech Pond fault (Newburg, 1985) separate the F-B sequence on the west from the S-H sequence on the east. The Beech Pond Fault is also interpreted to be a major west-dipping thrust fault (Hussey, in press).

All of the data presented in this report are for samples from within the F-B sequence. Rocks of the F-B sequence consist of predominantly feldspathic metasedimentary rocks and felsic metavolcanic rocks with abundant interbeds of amphibolite, 2 cm to several meters thick (Hussey, 1985). Minor lithologies include pelitic schists, impure marble and thin coticule beds. The rocks of the F-B sequence have been metamorphosed to upper amphibolite facies and in places are extensively migmatized with mineral assemblages characteristic of sillimanite+K-feldspar grade metamorphism. The present prograde assemblage was interpreted to be the result of a low-pressure (Buchan-type) metamorphism during the Acadian Orogeny (Hussey, 1985).

PREVIOUS GEOCHRONOLOGY

The Casco Bay Group is currently regarded to be of Precambrian to Ordovician age (Osberg *et al.*, 1985). Isotopic ages bearing on the time of deposition or eruption of the Casco Bay Group are few and inconclusive. Rb/Sr whole rock ages for various portions of the Cushing Formation give ages of 481±40 Ma (Brookins and Hussey, 1978), 494±25 Ma (Gaudette *et al.*, 1983), and 495±23 Ma (Olszewski and Gaudette, 1988). All of these ages involve significant scatter which may be related to open system behavior during deformation and high-grade metamorphism or variations in $^{87}Sr/^{86}Sr$ at the time of formation. It is unclear whether these whole rock systems were isotopically homogenized during metamorphism and thus, the significance of these ages is unclear.

The study area straddles the northeastern termination of a belt of Permian K-Ar mica ages defined by Faul *et al.* (1963) and Zartman *et al.* (1970). A comprehensive study of $^{40}Ar/^{39}Ar$ biotite ages by Dallmeyer (1979), Dallmeyer and van Breemen (1981), and Dallmeyer *et al.* (1982) across the northern termination of this Permian mica belt revealed a range of ages which are progressively younger to the southwest. Dallmeyer (1979) also quoted three $^{40}Ar/^{39}Ar$ total gas ages (319, 333, and 341 Ma) for hornblendes collected within the F-B sequence and one hornblende plateau age of 352±5 Ma from the nearby Three Mile Pond Pluton. These ages also suggest younger ages to the southwest.

ANALYTICAL METHODS

The basic principles of $^{40}Ar/^{39}Ar$ dating methods have been described by Dalrymple and Lanphere (1971). Hornblendes (+80-100 mesh size) were separated from rocks of the F-B sequence using standard heavy liquid and magnetic techniques and an estimated purity of >99.9% was obtained. The mineral

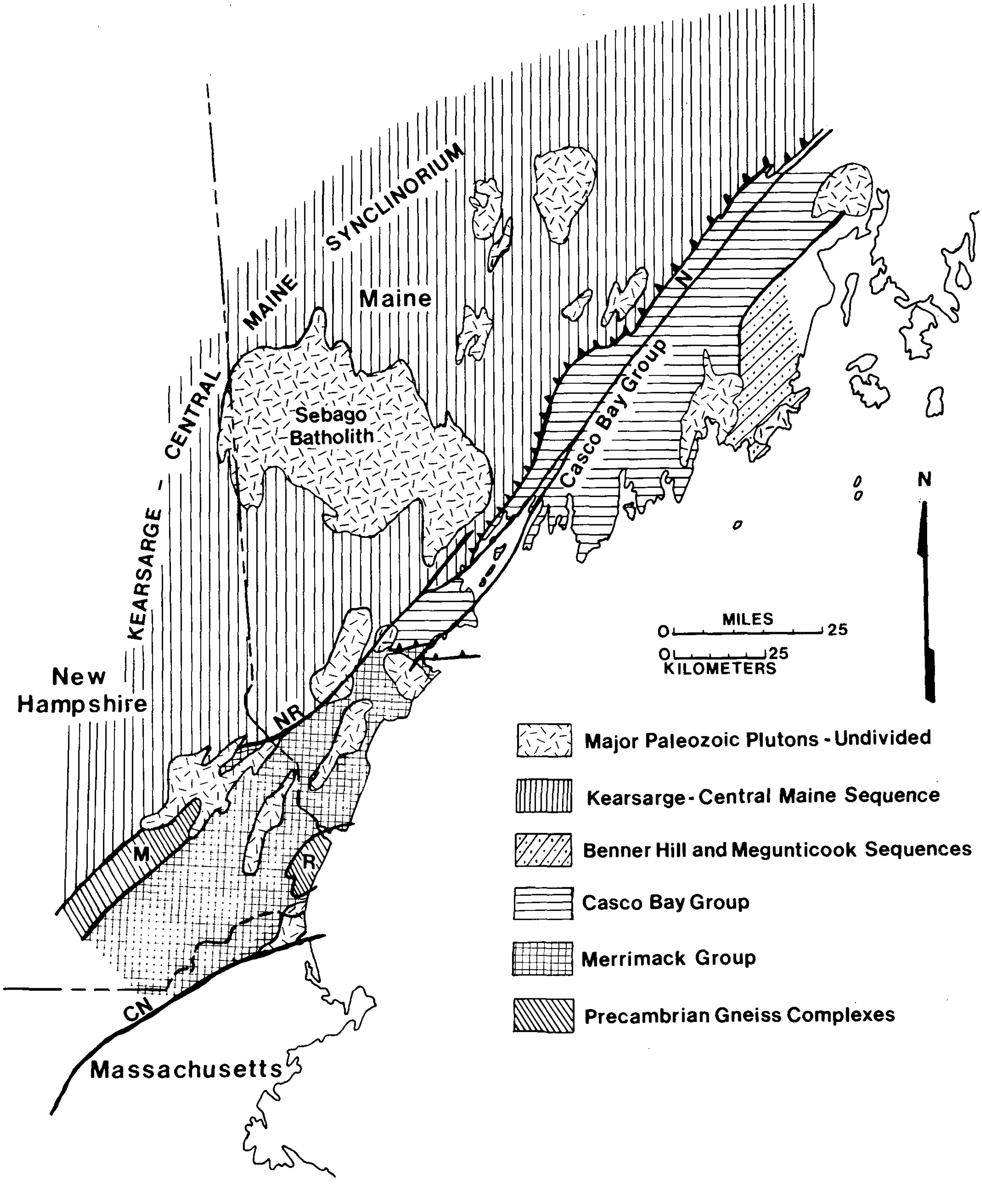

Fig. 1. Generalized geologic map of southwestern Maine and adjacent areas. N = Norumbega Fault; NR = Nonesuch River Fault; CN = Clinton-Newbury Fault; M = Massabesic Gneiss; R = Rye Formation (modified from Hussey, 1985, in press).

separates were wrapped in aluminum foil, sealed in silica glass vials and irradiated in the H5 facility of the Ford Nuclear Reactor at the University of Michigan. Two irradiation monitors were used: MMhb-1 (Alexander *et al.*, 1978) and a University of Maine interlaboratory standard, IEH, which has an age of 180.9 Ma relative to MMhb-1. Samples were incrementally heated at successively higher temperatures until fusion in a molybdenum crucible within an ultra-high vacuum Ar extraction system using radio frequency induction heating. A molecular sieve disiccant, CuCuO and Zr-Al getters were used to purify the gases extracted from the samples. The isotopic composition of Ar was measured with a Nuclide 6-60-SGA 1.25 mass spectrometer. All data are extrapolated to inlet time values and ^{37}Ar is corrected for decay during the time interval between irradiation and analysis. Corrections are made for all interfering isotopes produced during irradiations (Dalrymple *et al.*, 1981) using correction factors determined from irradiated K and Ca salts.

Individual ages and uncertainties (two sigma) were calculated using the decay constants recommended by Steiger and Jager (1977) and the equations given by Dalrymple *et al.* (1981). Criteria for the determination of plateaus are from Fleck *et al.* (1977), and the critical value test (Dalrymple and Lanphere, 1969, p. 120) was used to test for concordancy between increments. The total gas ages represent a weighted average based on the amount of ^{39}Ar in each increment. A plateau age is the mean of the ages deemed to be concordant. Uncertainties associated with plateau ages are two standard deviations plus an uncertainty in the J-value (estimated at 0.25%). Analysis of the MMhb-1 monitor indicates that apparent K/Ca ratios may be calculated through the relationship 0.518 (±0.005) x $(^{39}Ar/^{37}Ar)_{corrected}$.

RESULTS

The results of $^{40}Ar/^{39}Ar$ incremental release spectrum dating of 10 hornblendes from the F-B sequence are presented in Table 1. Sample locations and plateau ages are shown in Figure 2. Age spectrum diagrams are shown in Figure 3. Exact sample locations are also contained in Table 1. Samples were analyzed in 12-16 increments to produce high resolution age spectra. The plateau ages are interpreted as the best estimate of the time of cooling through the closure temperature for hornblende. In slowly cooled metamorphic terrains this temperature is about 480 to 500°C (Harrison, 1981). The results are discussed in terms of sample locations, progressing from north to south.

Samples Pal-2 and Pal-4 are from the extreme northern end of the transect. Both samples display slightly discordant ages during the first 20% of the gas released. Sample Pal-2 contains older apparent ages in the initial increments while Pal-4 has slightly younger ages in the low temperature steps. Both samples display nearly concordant ages over the remaining 80% of the gas released and apparent K/Ca ratios remain nearly constant. Pal-2 has a plateau age of 371.9±3.9 Ma and Pal-2 a plateau age of 367.6±3.9 Ma.

Samples Gar-10, Gar-12, and Gar-13 were collected from the central portion of the F-B sequence. All three samples from this region are characterized by low apparent ages in the initial low temperature increments. Sample Gar-10 contains anomalously low apparent ages in the initial four increments. These ages show a systematic increase from 299.9 to 342.9 Ma which coincides with a systematic decrease in apparent K/Ca ratios. Diffusive loss of ^{40}Ar from a less retentive phase during a later thermal event is suggested. The next five increments contain 53% of the total gas released and define a plateau age of 349.0±4.9 Ma. The remaining five increments have slightly older apparent ages and lower K/Ca ratios than the plateau increments, suggesting degassing of a lower K, more retentive phase. Samples Gar-12 and Gar-13 also have anomalously low ages in the initial low temperature steps and thus show evidence of episodic ^{40}Ar loss. The minimum ages recorded for these samples in the low temperature increments are 243.7±4.5 and 273.5±20 Ma. Sample Gar-12 has a total gas age of 335.7 Ma. A plateau age was not determined for this sample as ages show a gradual increase from 335.7 to 352.8 Ma over the last 80% of the sample. This may reflect ^{40}Ar concentration gradients or compositional differences as apparent K/Ca ratios do vary slightly over this range. Sample Gar-13 has a plateau age of 323.4±4.3 Ma and apparent K/Ca ratios are essentially constant. The first two increments have large analytical uncertainties associated with the calculated ages due primarily to their relatively small size.

The five hornblende samples from the southern portion of the transect yield drastically lower plateau ages (270-290 Ma). Gar-8 displays a nearly concordant age spectrum with a plateau age of 282.0±2.5 Ma. The three low temperature increments record anomalously young ages but they only comprise about 2.5% of the total gas released. Hornblende from sample Bdm-15 has a slightly discordant age spectrum with slightly younger apparent ages recorded in the first 10% of the gas released. This probably reflects degassing of relatively unretentive sites within the hornblende as K/Ca ratios are substantially higher in these initial increments. Samples Yar-17, Fre-19, and Ba-30 record nearly concordant release spectra with plateau ages of 289.8, 280.7, and 269.7 Ma, respectively. In each of the samples, only older apparent ages in the initial 2-3% and final 5% of the gas released disturb otherwise concordant spectra. These slightly "saddle-shaped" spectra are indicative of small amounts of excess ^{40}Ar (Lanphere and Dalrymple, 1976). Apparent K/Ca ratios are nearly constant in each of these samples.

INTERPRETATION OF RESULTS

In the northern portion of the F-B sequence, samples Pal-2 and Pal-4 record plateau ages of 372 and 368 Ma, respectively. These plateau ages are interpreted to represent the time of cooling through argon retention temperatures (500°C) following Acadian high-grade metamorphism. To the southwest, in the central part of the transect, systematically lower plateau ages (323-349 Ma) are recorded. This supports the findings of Dallmeyer (1979) and Dallmeyer and van Breemen (1981) that northeast-southwest cooling of the country rocks occurred following Acadian metamorphism. Though Dallmeyer and van Breemen (1981) documented a diachronous slow cooling in central Maine, this feature was never explained. DeYoreo *et al.* (in press) reported $^{40}Ar/^{39}Ar$ release spectra for micas across the northern terminus

Table 1. $^{40}Ar/^{39}Ar$ analytical data and exact locations for hornblende samples. Moles of ^{39}Ar are x 10^{-14}. Apparent ages are in 10^6 years.

TEMP °C	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	MOLES ^{39}Ar	% ^{39}Ar	% ^{40}Ar	K/Ca	APPARENT AGE
			PAL-2		J = 0.005643			
			Location: 44°24'57"N, 69°66'58"W					
925	201.1	5.833	0.5054	7.2	1.3	26.0	0.084	467.5 ± 12.6
940	175.6	6.764	0.4553	9.3	1.7	23.7	0.072	381.9 ± 10.6
960	170.0	7.716	0.4462	9.6	1.7	22.8	0.063	358.3 ± 10.6
975	156.0	8.273	0.4047	9.9	1.8	23.7	0.059	344.4 ± 10.2
985	89.87	8.315	0.1706	13.7	2.4	44.6	0.059	370.1 ± 9.9
995	86.74	8.399	0.1627	16.3	2.9	45.3	0.058	363.5 ± 5.4
1005	96.63	8.433	0.1986	17.2	3.1	39.9	0.058	357.5 ± 9.4
1015	80.62	8.289	0.1382	19.3	3.4	50.1	0.059	372.7 ± 9.2
1025	71.95	8.373	0.1127	22.4	4.0	54.6	0.058	363.3 ± 4.5
1035	71.48	8.434	0.1072	22.2	4.0	56.6	0.058	373.0 ± 5.0
1045	72.37	8.357	0.1109	19.6	3.5	55.6	0.058	371.3 ± 4.3
1055	59.65	8.247	0.0678	32.6	5.8	67.5	0.059	371.3 ± 4.0
1095	56.95	8.233	0.0591	47.4	8.5	70.4	0.059	370.2 ± 3.6
1110	46.54	8.154	0.0230	118.9	21.3	86.7	0.060	372.3 ± 3.7
1125	48.00	8.102	0.0279	86.5	15.5	84.1	0.060	372.3 ± 3.5
FUSE	47.08	7.993	0.0245	106.4	19.1	85.9	0.061	372.9 ± 3.5
TOTAL				558.7	100.0			371.7 ± 4.8
PLATEAU AGE								371.9 ± 3.9
			PAL-4		J = 0.005790			
			Location: 44°22'34"N, 69°26'47"W					
880	57.29	0.736	0.0638	9.1	1.8	67.1	0.665	362.9 ± 6.4
940	51.88	1.273	0.0520	10.2	2.0	70.5	0.385	346.8 ± 5.9
975	53.14	2.038	0.0560	8.2	1.6	69.1	0.240	348.3 ± 7.0
990	50.64	3.968	0.0453	10.4	2.0	74.2	0.123	355.9 ± 5.7
1005	46.47	6.332	0.0256	28.9	5.7	84.7	0.077	372.1 ± 4.4
1015	41.15	6.061	0.0092	85.7	16.8	94.5	0.080	368.0 ± 3.4
1025	40.66	5.091	0.0081	104.8	20.5	95.1	0.096	365.6 ± 3.4
1030	40.86	5.761	0.0085	56.3	11.0	94.9	0.085	366.8 ± 3.4
1040	41.25	5.590	0.0093	37.8	7.4	94.4	0.087	368.1 ± 3.6
1065	40.33	5.533	0.0063	52.4	10.3	96.4	0.088	367.6 ± 3.4
1100	41.28	5.457	0.0092	35.9	7.0	94.4	0.089	368.4 ± 4.2
FUSE	40.19	5.472	0.0055	71.1	13.9	97.0	0.089	368.5 ± 3.4
TOTAL				510.8	100.0			366.6 ± 3.7
PLATEAU AGE								367.6 ± 3.9

Table 1. $^{40}Ar/^{39}Ar$ analytical data and exact locations for hornblende samples. Moles of ^{39}Ar are x 10^{-14}. Apparent ages are in 10^6 years.

TEMP °C	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	MOLES ^{39}Ar	% ^{39}Ar	% ^{40}Ar	K/Ca	APPARENT AGE
			GAR-8		J = .005677			
			Location: 44°05'57"N, 69°52'22"W					
925	700.8	7.293	2.3170	7.2	0.9	2.4	0.067	164.1 ± 60.5
960	401.9	8.201	1.2871	4.1	0.5	5.5	0.059	215.3 ± 33.3
975	130.7	10.250	0.3596	9.3	1.2	19.3	0.047	243.3 ± 17.3
985	46.11	10.100	0.0599	51.3	6.4	63.3	0.048	278.7 ± 3.0
1000	36.48	9.339	0.0259	152.1	19.1	81.0	0.052	281.5 ± 2.7
1020	37.40	9.050	0.0289	134.4	16.9	79.0	0.054	281.5 ± 2.9
1030	40.06	8.882	0.0376	77.9	9.8	74.0	0.055	282.3 ± 2.8
1040	49.39	8.702	0.0690	41.5	5.2	60.1	0.056	282.6 ± 4.4
1050	52.75	8.751	0.0795	34.9	4.4	56.7	0.056	284.7 ± 4.1
1065	45.25	8.715	0.0555	46.4	5.8	65.3	0.056	281.3 ± 2.8
1085	36.79	8.376	0.0255	113.4	14.2	81.3	0.058	284.5 ± 2.7
1125	39.59	8.200	0.0338	75.2	9.4	76.4	0.059	287.5 ± 3.3
FUSE	60.84	8.240	0.1070	49.6	6.2	49.1	0.059	284.1 ± 3.2
TOTAL				797.1	100.0			280.9 ± 3.9
PLATEAU AGE								282.0 ± 2.5

TEMP °C	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	MOLES ^{39}Ar	% ^{39}Ar	% ^{40}Ar	K/Ca	APPARENT AGE
			GAR-10		J = 0.002948			
			Location: 44°12'40"N, 69°48'49"W					
850	149.4	0.713	0.2983	5.0	1.1	41.0	0.687	299.9 ± 6.5
890	79.63	1.061	0.0614	12.6	2.3	77.3	0.462	300.9 ± 3.2
935	71.81	3.504	0.0298	22.3	4.2	88.1	0.139	309.2 ± 3.1
975	74.35	7.951	0.0148	68.4	12.8	94.9	0.061	342.9 ± 3.2
990	74.91	7.586	0.0133	81.2	15.2	95.5	0.064	347.2 ± 3.3
1010	75.28	7.214	0.0122	79.1	14.8	95.9	0.068	350.0 ± 3.4
1030	75.71	6.890	0.0133	55.9	10.4	95.5	0.071	350.2 ± 3.3
1050	76.25	6.711	0.0151	41.8	7.8	94.8	0.073	350.2 ± 3.4
1075	76.81	6.958	0.0193	27.8	5.2	93.2	0.070	347.2 ± 3.3
1100	76.14	7.588	0.0131	44.8	8.4	95.7	0.064	352.8 ± 3.4
1115	76.95	7.531	0.0132	36.9	6.9	95.7	0.065	356.2 ± 3.5
1135	78.88	7.320	0.0163	27.7	5.2	94.6	0.067	360.5 ± 3.4
1150	86.69	7.444	0.0437	16.4	3.1	85.7	0.065	359.3 ± 3.7
FUSE	85.52	7.457	0.0404	14.9	2.8	86.7	0.065	358.5 ± 3.8
TOTAL				535.9	100.0			346.9 ± 3.4
PLATEAU AGE								349.0 ± 4.9

Table 1. $^{40}Ar/^{39}Ar$ analytical data and exact locations for hornblende samples. Moles of ^{39}Ar are x 10^{-14}. Apparent ages are in 10^6 years.

TEMP °C	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	MOLES ^{39}Ar	$\%^{39}Ar$	$\%^{40}Ar$	K/Ca	APPARENT AGE
			GAR-12		J = 0.00553			
			Location: 44°12'27"N, 69°47'17"W					
750	71.24	1.729	0.1273	28.7	1.8	47.3	0.283	308.8 ± 8.5
825	43.48	1.458	0.0570	31.6	2.0	61.5	0.336	249.0 ± 6.7
875	38.47	3.918	0.0429	32.6	2.1	67.8	0.125	243.7 ± 4.5
935	39.25	5.896	0.0210	70.4	4.5	85.3	0.083	307.7 ± 4.0
975	38.90	5.585	0.0106	137.1	8.7	93.0	0.087	330.3 ± 3.3
990	39.14	5.439	0.0094	135.6	8.6	94.0	0.090	335.2 ± 3.6
1010	39.02	5.358	0.0081	164.8	10.5	94.9	0.091	337.2 ± 3.5
1030	39.33	5.204	0.0074	141.2	9.0	95.4	0.094	341.5 ± 3.7
1050	39.31	4.938	0.0075	147.7	9.4	95.3	0.099	340.9 ± 3.5
1075	39.38	4.962	0.0087	103.9	6.6	94.4	0.098	338.5 ± 3.5
1100	39.38	5.200	0.0065	141.1	9.0	96.1	0.094	344.1 ± 3.4
1115	39.98	5.237	0.0074	145.5	9.3	95.5	0.093	346.9 ± 3.6
1135	40.01	5.223	0.0063	195.7	12.4	96.3	0.093	349.9 ± 3.5
1150	42.44	5.358	0.0138	48.3	3.1	91.3	0.091	351.7 ± 4.5
FUSE	43.08	5.487	0.0155	49.1	3.1	90.3	0.089	352.8 ± 4.5
TOTAL				1573.3	100.0			335.7 ± 3.8
NO PLATEAU								
			GAR-13		J = 0.005416			
			Location: 44°07'58"N, 69°45'58"W					
750	337.26	7.978	1.0057	2.3	0.6	12.1	0.061	361.2 ± 80.9
825	152.29	9.426	0.4035	2.4	0.6	22.2	0.052	305.1 ± 50.3
875	75.57	14.624	0.1585	3.5	0.9	39.5	0.033	273.5 ± 20.0
935	44.46	16.611	0.0369	21.8	5.7	78.4	0.029	315.6 ± 3.9
975	40.78	16.704	0.0206	45.5	12.0	88.3	0.029	325.1 ± 3.2
990	40.46	16.610	0.0181	37.5	9.9	90.0	0.029	328.7 ± 3.3
1010	39.99	16.618	0.0175	32.0	8.4	90.3	0.029	325.9 ± 3.6
1030	39.76	16.661	0.0174	24.7	6.5	90.4	0.029	324.5 ± 3.7
1050	38.56	16.655	0.0132	30.4	8.0	93.3	0.029	324.9 ± 3.7
1075	37.82	16.635	0.0118	37.7	9.9	94.3	0.029	322.2 ± 3.2
1100	43.68	16.617	0.0304	37.4	9.8	82.4	0.029	325.0 ± 3.4
1115	37.96	16.616	0.0120	45.2	11.9	94.1	0.029	322.7 ± 3.2
1135	37.56	16.540	0.0108	28.2	7.4	95.0	0.029	322.5 ± 3.6
1150	38.01	16.346	0.0123	17.1	4.5	93.8	0.030	322.2 ± 4.9
FUSE	39.96	15.753	0.0166	14.5	3.8	90.8	0.031	327.4 ± 4.5
TOTAL				380.1	100.0			323.7 ± 4.5
PLATEAU AGE								323.4 ± 4.3

Table 1. $^{40}Ar/^{39}Ar$ analytical data and exact locations for hornblende samples. Moles of ^{39}Ar are x 10^{-14}. Apparent ages are in 10^6 years.

TEMP °C	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	MOLES ^{39}Ar	$\%^{39}Ar$	$\%^{40}Ar$	K/Ca	APPARENT AGE
			BDM-15		J = 0.005854			
			Location: 44°02'27"N, 69°54'01"W					
750	185.8	3.479	0.4276	3.1	0.4	32.1	0.140	541.7 ± 64.5
865	41.58	0.793	0.0497	13.9	1.6	64.8	0.617	264.3 ± 6.1
925	32.44	1.512	0.0244	14.2	1.6	78.0	0.324	249.5 ± 4.2
975	33.89	3.551	0.0258	11.3	1.3	78.2	0.138	260.9 ± 4.2
1015	35.79	4.965	0.0312	8.6	1.0	75.2	0.098	264.8 ± 5.6
1050	33.17	7.443	0.0212	16.0	1.8	82.7	0.065	270.0 ± 4.8
1090	32.50	8.174	0.0178	20.6	2.3	85.6	0.060	273.6 ± 4.3
1115	31.16	8.287	0.0110	45.6	5.2	91.5	0.059	280.2 ± 3.1
1130	30.44	8.099	0.0083	98.1	11.1	93.9	0.060	280.6 ± 3.5
1140	30.04	7.768	0.0069	216.0	24.5	95.0	0.063	280.3 ± 3.0
1155	30.18	7.430	0.0064	165.2	18.8	95.5	0.066	282.8 ± 3.3
1175	30.28	7.139	0.0064	138.0	15.7	95.4	0.068	283.3 ± 3.0
FUSE	29.81	7.287	0.0050	129.4	14.7	96.8	0.067	283.0 ± 3.0
TOTAL				880.0	100.0			281.1 ± 3.5
PLATEAU AGE								281.7 ± 4.3
			YAR-17		J = 0.003025			
			Location: 43°45'47"N, 70°10'35"W					
750	379.0	2.332	0.6326	3.1	0.6	50.7	0.210	828.3 ± 25.2
825	207.4	3.008	0.3532	3.5	0.7	49.8	0.163	491.2 ± 12.9
875	123.9	5.128	0.2040	3.2	0.6	51.6	0.095	320.2 ± 8.8
935	79.51	9.664	0.0779	8.8	1.8	72.0	0.050	290.0 ± 3.9
975	63.87	9.585	0.0244	33.4	6.8	89.9	0.051	290.7 ± 2.9
990	61.06	8.742	0.0159	58.1	11.8	93.4	0.056	288.9 ± 2.8
1010	59.73	8.200	0.0101	98.5	20.1	96.0	0.059	290.4 ± 2.8
1030	60.26	8.026	0.0124	71.7	14.6	94.9	0.061	289.6 ± 2.8
1050	60.79	7.842	0.0141	51.3	10.4	94.1	0.062	289.6 ± 3.0
1075	61.88	7.973	0.0194	30.5	6.2	91.7	0.061	287.5 ± 2.9
1100	62.26	8.555	0.0215	23.5	4.8	90.8	0.057	286.6 ± 3.2
1115	61.27	8.643	0.0172	30.8	6.3	92.8	0.056	288.0 ± 2.9
1135	61.67	8.533	0.0172	27.5	5.6	92.8	0.057	289.8 ± 2.9
1150	64.08	8.371	0.0253	20.7	4.2	89.3	0.058	289.8 ± 3.1
FUSE	63.16	8.226	0.0196	26.5	5.4	91.8	0.059	293.3 ± 3.0
TOTAL				491.0	100.0			294.6 ± 3.2
PLATEAU AGE								289.8 ± 2.7

Table 1. $^{40}Ar/^{39}Ar$ analytical data and exact locations for hornblende samples. Moles of ^{39}Ar are x 10^{-14}. Apparent ages are in 10^6 years.

TEMP °C	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	MOLES ^{39}Ar	% ^{39}Ar	% ^{40}Ar	K/Ca	APPARENT AGE
			FRE-19		J = 0.005957			
			Location: 43°51'52"N, 70°01'15"W					
750	286.3	4.555	0.7165	3.2	0.5	26.1	0.017	667.2 ± 30.4
875	68.63	9.032	0.1488	2.3	0.4	36.9	0.054	255.0 ± 3.8
935	33.44	10.986	0.0199	19.1	2.9	84.8	0.044	283.7 ± 3.1
975	30.92	10.635	0.0127	49.9	7.7	90.4	0.046	279.9 ± 4.0
990	31.02	10.621	0.0128	44.2	6.8	90.3	0.046	280.4 ± 5.8
1010	30.70	10.558	0.0114	54.6	8.4	91.6	0.046	281.4 ± 3.3
1030	30.57	10.503	0.0115	63.2	9.8	91.4	0.046	279.7 ± 3.0
1050	30.27	10.446	0.0098	82.0	12.7	92.9	0.047	281.5 ± 4.1
1075	30.15	10.397	0.0097	99.4	15.4	93.0	0.047	280.6 ± 2.8
1100	30.06	10.310	0.0090	106.2	16.4	93.6	0.047	281.5 ± 2.8
1120	30.38	10.197	0.0094	71.1	11.0	93.3	0.048	283.4 ± 2.7
1140	31.20	10.293	0.0111	35.8	5.5	91.9	0.047	286.5 ± 3.6
FUSE	35.69	10.332	0.0227	15.8	2.4	83.3	0.047	296.4 ± 7.3
TOTAL				646.7	100.0			283.7 ± 3.8
PLATEAU AGE								280.7 ± 3.0
			BA-30		J = 0.005823			
			Location: 43°54'57"N, 69°58'25"W					
800	103.2	3.121	0.1623	8.9	1.5	53.7	0.157	506.0 ± 9.2
875	48.41	4.794	0.0607	13.1	2.3	63.7	0.102	298.8 ± 5.3
935	36.19	8.901	0.0307	22.7	3.9	76.8	0.055	272.3 ± 3.0
975	31.10	9.792	0.0149	57.0	9.9	88.3	0.050	269.3 ± 4.4
990	30.25	9.741	0.0116	67.1	11.7	91.1	0.050	270.5 ± 2.6
1015	29.87	9.677	0.0105	73.6	12.8	92.1	0.050	269.9 ± 3.5
1030	29.75	9.628	0.0107	65.7	11.4	91.8	0.051	268.1 ± 3.0
1050	29.49	9.547	0.0091	72.3	12.6	93.4	0.051	270.2 ± 2.6
1075	29.34	9.432	0.0085	68.6	12.0	93.9	0.052	270.2 ± 2.6
1110	29.14	9.627	0.0081	56.3	9.8	94.4	0.051	269.7 ± 3.2
1135	29.57	9.788	0.0085	38.0	6.6	94.1	0.050	272.7 ± 5.1
FUSE	30.64	9.820	0.0111	30.9	5.4	91.8	0.050	275.5 ± 5.3
TOTAL				574.2	100.0			274.6 ± 3.5
PLATEAU AGE								269.7 ± 2.9

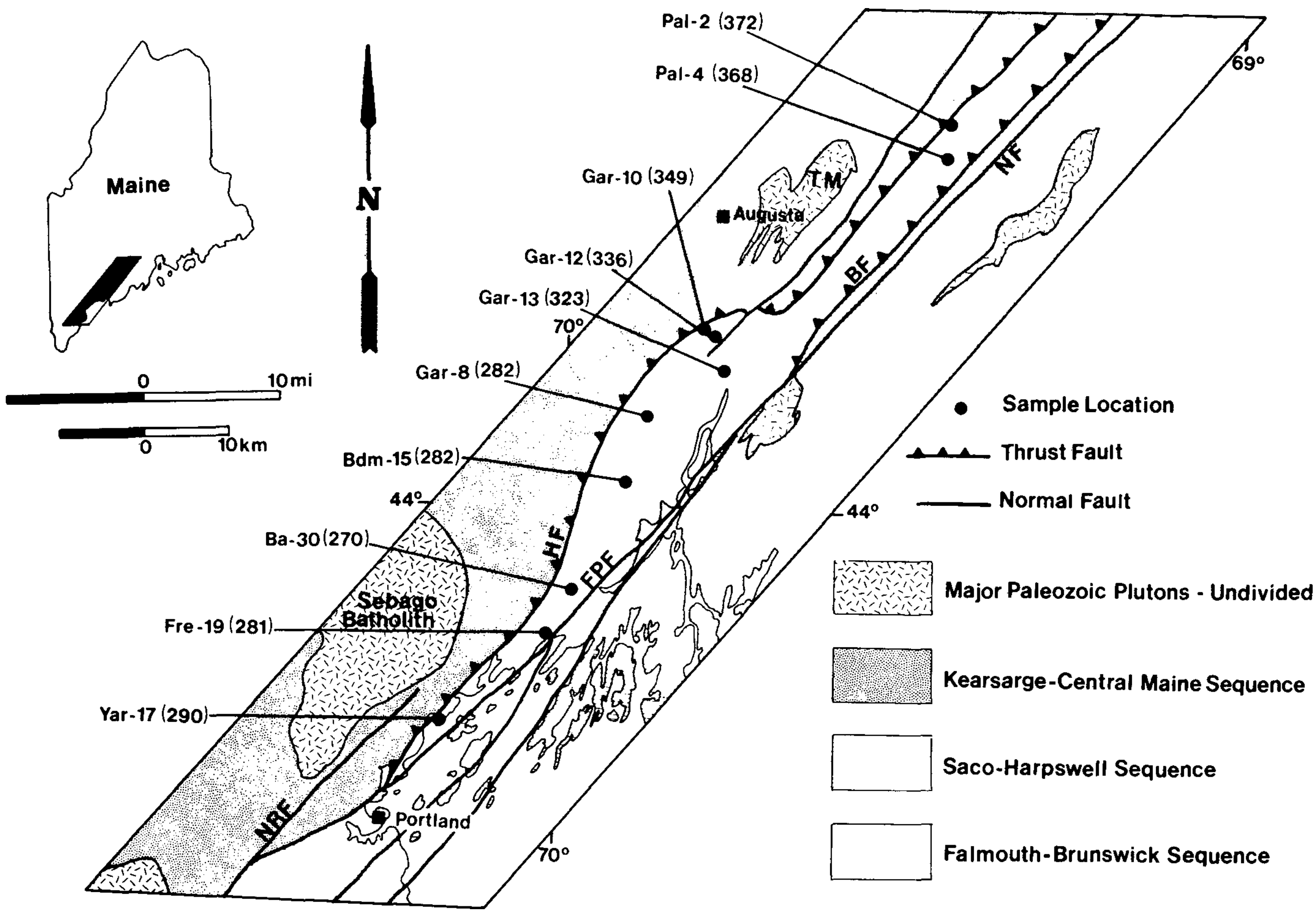

Fig. 2. Generalized geologic map of southwestern Maine showing the distribution of sample locations. Ages shown in parenthesis are plateau ages except for Gar-12 which is a total gas age. NF = Norumbega Fault; BF = Beech Pond Fault; HF = Hackmatack Pond Fault; FPF = Flying Point Fault; NRF = Nonesuch River Fault; TM = Three Mile Pond Pluton (modified from Osberg *et al.*, 1985; Hussey, in press).

of the anomalously low mica-age belt of New England in western Maine. They also observed a pattern of progressively younger ages towards the southwest for both muscovites and biotites. Using petrologic data which indicate that the present erosion surface in New England was progressively more deeply buried to the southwest, they interpreted the pattern of mineral ages to be the result of the progressive unroofing of the orogen and cooling as minerals uplifted through isotherms corresponding to their closure temperatures. As deeper crustal levels are encountered to the southwest, younger $^{40}Ar/^{39}Ar$ mineral ages must be encountered. We invoke a similar interpretation of slow cooling of the F-B sequence in response to differential unroofing following Acadian metamorphism. An alternative interpretation will be discussed below.

Release spectra of all samples from the central portion of the transect are characterized by younger apparent ages in the low temperature gas fractions. Theoretical studies (Turner, 1968) have predicted and field studies (Harrison and McDougall, 1980) have shown that release spectra characterized by low apparent ages in the initial low temperature increments are a result of partial diffusive loss of radiogenic ^{40}Ar ($^{40}Ar^*$) due to a thermal event following initial cooling through argon retention temperatures. A similar interpretation is favored for the central F-B samples. Additionally, Turner's (1968) model demonstrated that if potassium sites near grain boundaries lost all accumulated $^{40}Ar^*$ at the time of the thermal event, the $^{40}Ar^*$ that now resides in those sites would be only that which accumulated since the event. Theoretically, the first infinitesimal fraction of gas extracted from the sample should therefore date the time of the thermal event.

Based upon this theoretical framework, the age data from the central portion of the transect suggest that the area cooled below about 500°C following Acadian high-grade metamorphism about 325-350 Ma ago and this was followed by a subsequent thermal event which caused partial $^{40}Ar^*$ loss. The low temperature ages for these samples indicates that episodic loss occurred between 244-300 Ma ago.

It should be noted that if $^{40}Ar^*$ loss during the thermal event was substantial even the high-temperature gas fractions could record ages less than the time of initial argon closure. Turner *et al.* (1966) showed that the predicted maximum ages for an age spectrum will be lower than the original cooling age if $^{40}Ar^*$ losses

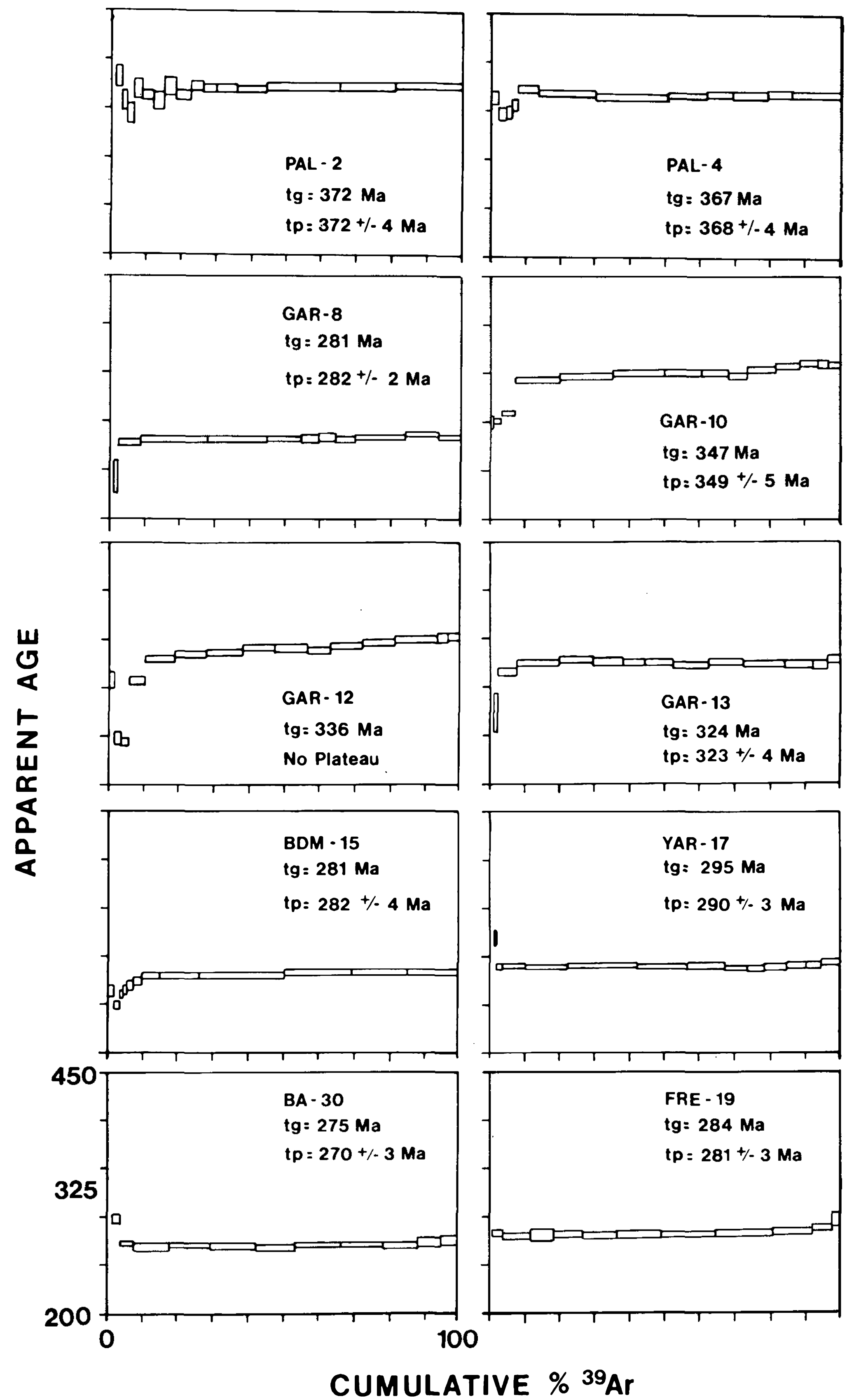

Fig. 3. Incremental release age spectrum diagrams for hornblende samples. The vertical and horizontal scales are the same on each age specturm. Some small low-temperature increments are omitted. Complete results are presented in Table 1.

exceed about 10%. In this alternative interpretation, the age spectra of the central F-B samples may entirely reflect the effects of a superimposed thermal event. That is, $^{40}Ar^*$ loss may have occurred in all portions of the crystal, from rim to core. In such a case even the high temperature increments would have ages lower than the initial time of closure to $^{40}Ar^*$ loss. Indeed two of the samples (Gar-10 and Gar-12) from this region have diffusion gradients up to apparent ages (359 and 353 Ma, respectively) not much less than the plateau ages of the northern F-B samples (368-372 Ma). Therefore it can be argued that the lower plateau ages recorded in the central F-B sequence reflect partial $^{40}Ar^*$ loss in response to a thermal event rather than slower cooling following Acadian metamorphism. However, based upon the independent evidence cited above and because Gar-13 has a well defined plateau age (323 Ma) substantially younger than the northern samples, we favor the model of slow cooling of the F-B sequence in response to differential unroofing following Acadian metamorphism. However the possibility that at least some of the lower plateau ages were the result of thermally induced $^{40}Ar^*$ loss can not be discounted.

Hornblendes collected in the southwestern part of the transect have significantly lower plateau ages (270-290 Ma). These ages are also taken to represent the time of cooling below about 500°C following the last significant metamorphic event. These Late Paleozoic hornblende cooling ages in the southern part of the F-B sequence could date either (1) the time of cooling following a distinct Late Paleozoic thermal event or (2) Late Paleozoic cooling due to a prolonged period of burial at deep crustal levels following the Acadian Orogeny. The former interpretation is favored for the following reasons. Along the northern 40 km of the transect, hornblende ages range between 372 and 323 Ma and show a systematic relationship in that they become progressively lower towards the southwest. There is, however, a distinct break of 40 Ma in the age progression between the last of these, Gar-13, and Gar-8 to the south. Over the next 60 km of the transect, all of the hornblende ages are much younger and only range between 270 and 290 Ma but no systematic variation with position exists as would be expected if slow cooling and differential erosion was operative. Furthermore, the range of ages in the southern portion of the transect is overlapped by the range of minimum ages from apparent diffusion gradients preserved in hornblendes at the transition between the two parts of the transect. We interpret these data to indicate that the southern portion of the F-B sequence was affected by a Late Paleozoic (about 280 Ma) metamorphic event. The boundary of the area affected is marked by the transition zone for hornblende ages. In this region the thermal event was only sufficiently strong enough to partially reset hornblende Ar systems resulting in the diffusion gradients that are preserved.

In summary, hornblendes analyzed from the F-B sequence record the effects of both Acadian and Late Paleozoic thermal events. To the north, only the effects of the Acadian event are preserved (368-372 Ma). In the southern F-B sequence, only the effects of the Late Paleozoic thermal event are recorded (270-290 Ma). The central F-B samples, however, preserve evidence of both events, with plateau ages (323-349 Ma) recording the time of cooling following the Acadian event and the low temperature increments (244-300 Ma) showing evidence of diffusive loss of $^{40}Ar^*$ in response to the Late Paleozoic heating.

Hornblende plateau ages for samples from the east, in the adjacent S-H sequence, display older plateau ages (325-368 Ma) and suggest a substantial difference in thermal history for the S-H sequence in southwestern Maine (West *et al.*, 1988; West and Lux, 1988). The variations in plateau ages (270-290) in the southern part of the F-B sequence may be a reflection of compositional differences between hornblendes in this region. It has been suggested that differences in Fe/(Fe+Mg+Mn) in hornblendes may correspond to differences in closure temperature for diffusion of ^{40}Ar (O'Nions *et al.*, 1969; Onstott and Peacock, 1987). However, Harrison (1981) concluded that Fe:Mg ratios in hornblendes have no apparent effect on the closure temperature.

SIGNIFICANCE AND DISCUSSION

On the basis of the data available to Dallmeyer (1979) and Dallmeyer and van Breemen (1981), they concluded that there was no evidence for a distinct widespread Late Paleozoic metamorphism in south-central Maine. However their conclusions were based primarily on $^{40}Ar/^{39}Ar$ analyses for biotite from north of the area where Late Paleozoic hornblende ages have been found. Recently, increasing amounts of evidence have become available in the southern portion of Maine to suggest that significant Late Paleozoic heating of the rocks may have occurred (Lux and Guidotti, 1985; Aleinikoff *et al.*, 1985).

The suggestion of Late Paleozoic metamorphism affecting the rocks of the southern part of the F-B sequence has significant regional implications. As discussed earlier, the rocks of the F-B sequence are a part of a southwesterly dipping thrust sheet and therefore may be representative of rocks which underlie the Kearsarge-Central Maine Synclinorium (KCMS) in southern Maine. Recent studies in western Maine (Lux and Guidotti, 1985) and from the nearby Sebago Batholith (Aleinikoff *et al.*, 1985) have provided evidence of Late Paleozoic metamorphism which affected the rocks of the KCMS. Lux and Guidotti (1985) have documented significant Carboniferous metamorphism associated with the emplacement of the Sebago Batholith (325 Ma). Hornblendes from the Songo pluton, just north of the Sebago, have plateau ages around 308 Ma with release spectra which imply that ^{40}Ar loss occurred slightly after this time. Aleinikoff *et al.* (1985) reported U-Pb ages of 272 and 282 Ma for monazites from the Sebago Batholith. These ages apparently correspond to very high temperatures, perhaps on the order of 600°C (Gebauer and Grunenfelder, 1979), and were attributed to slow cooling of the Sebago Batholith by Aleinikoff *et al.* (1985). However, a thermal model for the cooling of the Sebago Batholith was presented by DeYoreo *et al.* (in press) which demonstrated that this was untenable. They suggested two alternative explanations, either that the area experienced a later thermal event (about 280 Ma ago) or that monazites have much lower closure temperatures which is considered unlikely.

Another area in northern New England apparently affected by a Late Paleozoic thermal disturbance is the Massabesic Gneiss Complex of southeastern New Hampshire described by Aleinikoff *et al.* (1979) and Bothner *et al.* (1984). It is interesting to note that the F-B sequence has lithologic similarities to portions of the Massabesic Gneiss and has been tentatively correlated with these rocks (Hussey, 1985). Gromet (in press) suggested that the rocks of the Massabesic Gneiss Complex may represent a type of "Alleghanian infra-structure." The F-B sequence may be a northeastward extension of this structure.

It should be noted that no structural evidence for Late Paleozoic tectonism in the F-B sequence has been described. The suggestion of Late Paleozoic metamorphism in this region is based solely on isotopic data. If a distinct Late Paleozoic thermal event occurred in this region it was evidently not accompanied by large amounts of deformation. However no detailed petrologic studies have been done in this area which could potentially reveal such features.

Recognition of the effects of Late Paleozoic tectonism in areas previously linked to the classical Taconian and Acadian orogenic events remains an elusive task in the northern Appalachians. Recent discoveries have indicated the effects of Late Paleozoic metamorphism may involve an area much greater than previously recognized. The use of relatively thermal resistant isotopic systems, such as $^{40}Ar/^{39}Ar$ dating of hornblendes, can help further delineate the relative importance of Acadian versus Late Paleozoic thermal events in the northern Appalachians.

CONCLUSIONS

(1) Hornblende from the northern portion of our transect along the F-B sequence record plateau ages of 368-372 Ma. This is interpreted to represent the time of cooling through the closure temperature for Ar loss in hornblendes (about 500°C) following Acadian high-grade metamorphism.

(2) In the central portion of the transect, hornblendes display lower plateau ages (350-323 Ma) and release spectra have apparent diffusion gradients which are interpreted to be the result of a Late Paleozoic thermal overprint.

(3) In the northern and central portions of the transect, systematically lower plateau ages (323-372) are recorded to the southwest. This supports the findings of Dallmeyer (1979) and Dallmeyer and van Breemen (1981) who suggested a diachronous NE-SW cooling following Acadian metamorphism. We suggest that this is the result of differential erosion, where areas to the northeast that were less deeply buried during the Acadian Orogeny were first uplifted through isotherms corresponding to the closure temperature for Ar loss in hornblendes.

(4) Hornblendes from the southern F-B sequence have significantly lower plateau ages (270-290 Ma). These lower ages could date either cooling of the region through the closure temperature for Ar loss in hornblende in response to erosion of the Acadian orogen or more likely the cooling of the terrain following a Late Paleozoic thermal event.

(5) If a Late Paleozoic thermal event occurred in this region it was evidently not accompanied by large amounts of deformation as structural evidence for an event is lacking.

(6) The Late Paleozoic thermal disturbance of hornblende ages in the F-B sequence may be related to the same regional event which resulted in the emplacement of 275 Ma granite into the Massabesic Gneiss Complex of New Hampshire (Aleinikoff *et al.*, 1979) and the event which resulted in 272-282 Ma U-Pb ages for monazites from the nearby Sebago Batholith (Aleinikoff *et al.*, 1985).

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