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A Thermal Model for Carboniferous Metamorphism near the Sebago Batholith in Western Maine

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ABSTRACT

In southwestern Maine, a Carboniferous-aged metamorphic event (M_C) produced widespread medium to upper amphibolite facies metamorphism. Although this region of high-grade metamorphism has a strong temporal and spatial correlation with the 330±5 Ma Sebago batholith, the effects of M_C extend some 30-50 km north of the batholith and the reason for that correlation is unclear.

In this paper we present geochronologic data which provide an estimate of the ambient temperature at the time of the intrusion of the Sebago batholith, outline the progression of cooling throughout the batholith from 245 Ma to 230 Ma, and delineate the northern limit of M_C. We also present a thermal model which suggests that M_C is a deep-level contact aureole of the batholith itself and that the pluton is likely to be a result of lower crustal melting in response to Acadian crustal thickening. We hypothesize that the Sebago batholith, or closely related granitic sheets, extend at least 30 to 50 km to the northeast and that the metamorphism to the north of the Sebago batholith was produced above the batholith while that to the south was produced below the batholith.

INTRODUCTION

In their classic paper on Paleozoic regional metamorphism in New England, Thompson and Norton (1968) said of the plutons: "Their distribution relative to the higher grade metamorphic zones shows a striking correlation ... A genetic relationship is thus highly likely, but it is by no means clear which is the primary and which is the secondary feature." They also noted that while contact aureoles are well-defined in northern Vermont and New Hampshire and in northeastern Maine, throughout most of the high-grade terrane distinct contact aureoles are lacking, and high-grade metamorphism can occur tens of kilometers away from the nearest igneous outcrop. This suggested to them that the granitoid plutons were as likely to have been a result of, as a heat source for, the regional metamorphism.

Since that time, more detailed petrologic studies have revealed a polymetamorphic history for this regional metamorphism, particularly in western Maine near the northern terminus of the New England metamorphic high. In this region at least three distinct Devonian metamorphisms (M_1, M_2, and M_3) have been described (Holdaway et al., 1982; Guidotti et al., 1983) which appear to correlate with periods of igneous activity (De Yoreo et al., 1989). Most recently, the existence of a Carboniferous-aged metamorphism (M_C), temporally and spatially connected with the Sebago batholith in western Maine, was documented by Lux and Guidotti (1985) and Aleinikoff et al. (1985). In addition, geochronologic studies have shown that at least some of the plutons in western Maine which are spatially correlative with regional metamorphic isograds were not melted in situ but emplaced from below (Lux et al., 1986). Combining these petrologic and geochronologic observations with geological (Moench and Zartman, 1976) and geophysical (Hodge et al., 1982; Nielson et al., 1976; and Carnese, 1983) evidence for the geometry of the plutons in the high-grade terrane, Lux et al. (1986) concluded that, at least in western Maine, the high-grade metamorphism results from contact effects near sill-like igneous intrusions at intermediate crustal levels. They also concluded that the plutons are likely to be a result of crustal thickening produced by the Acadian orogeny. The purpose of this paper is to present the results of a thermal model for Carboniferous-aged metamorphism in western Maine which addresses the question raised by Thompson and Norton (1968) by demonstrating that under conditions of normal, mantle heat-flow, the Sebago batholith itself was a viable heat source for the surrounding regional metamorphism provided its lateral dimensions are sufficiently large.

GEOLOGIC AND PETROLOGIC CONSTRAINTS

The Sebago batholith lies in the Kearsarge-central Maine synclinorium in southwestern Maine with its long axis perpendicular to the structural grain of the New England Appalachians (Fig. 1 and 2). The geology and petrology to the north of the batholith have been studied in detail (Guidotti, 1965; Moench and Zartman, 1976; Creasy, 1979; Holdaway et al., 1982; Guidotti et al., 1983). At least 13 km of Ordovician, Silurian, and Devonian metasedimentary rocks are exposed in the region (Moench and Zartman, 1976). These strata were deposited on a shelf/slope and were subsequently deformed into upright, northeast-trending, isoclinal folds during the Acadian event at about 400 Ma. The rocks were then metamorphosed during a series of static events (M_1?, M_2, M_3, and M_C).

The metamorphic grade of the rocks associated with M_C ranges from medium amphibolite facies to upper amphibolite facies. The K-feldspar + sillimanite isograd approximately parallels the northern boundary of the Sebago batholith at a distance of 10 to 25 km (Fig. 1). A transect from Puzzle Mountain southward to the northern contact of the Sebago batholith passes through lower sillimanite, upper sillimanite, and K-feldspar + sillimanite zones (Fig. 2). Textural evidence demonstrates that the reactions involved in M_C were prograde at pressures less than the alumino-silicate triple point pressure of Holdaway (1971). Muscovite-almandine-biotite-sillimanite geobarometry gives metamorphic pressures of 3.8 ± 0.25 kbar (Holdaway et al., 1988). This is consistent with a petrogenetic grid approach based on the melting relations for pelitic rocks of Thompson and Algor (1977). A petrogenetic grid for these rocks is shown in Figure 3 with $P_{H2O} = P_{Total}$, and the inferred temperatures of metamorphism for the various isograds are listed in Table 1. The heavy line in Figure 3 indicates the metamorphic field gradient (array of maximum temperatures) for the rocks of M_C. Metamorphic grade increases towards the batholith in a nearly isobaric fashion and temperatures of metamorphism range from about 580°C in the lower sillimanite zone at the top of Puzzle Mountain to about 635°C in the K-feldspar + sillimanite zone near the Sebago batholith. Some of the rocks in the upper sillimanite zone are migmatitic. In the K-feldspar +

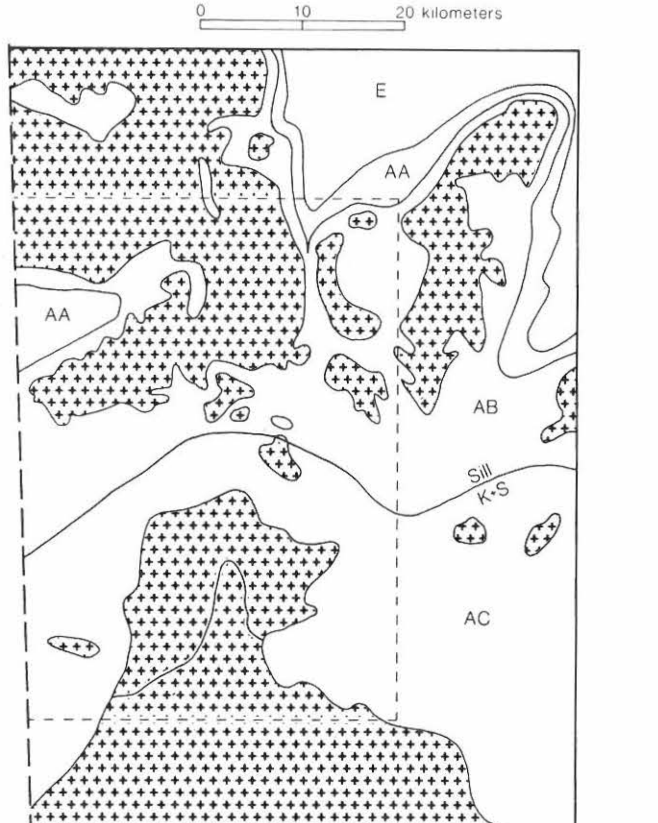

Figure 1. Metamorphic map after Guidotti et al., (1983) of southwestern Maine. Metamorphic facies designation. E -- epidote amphibolite characterized by Fe-garnet in pelites; AA -- lower amphibolite characterized by staurolite and kyanite or andalusite in pelites; AB -- medium amphibolite characterized by sillimanite + K-feldspar (K+S) in pelites. Igneous rocks are designated by pluses. The boxed-in area is shown in more detail in Figure 2. The axis of the Kearsarge-central Maine synclinorium is depicted by the dashed line on the index map.

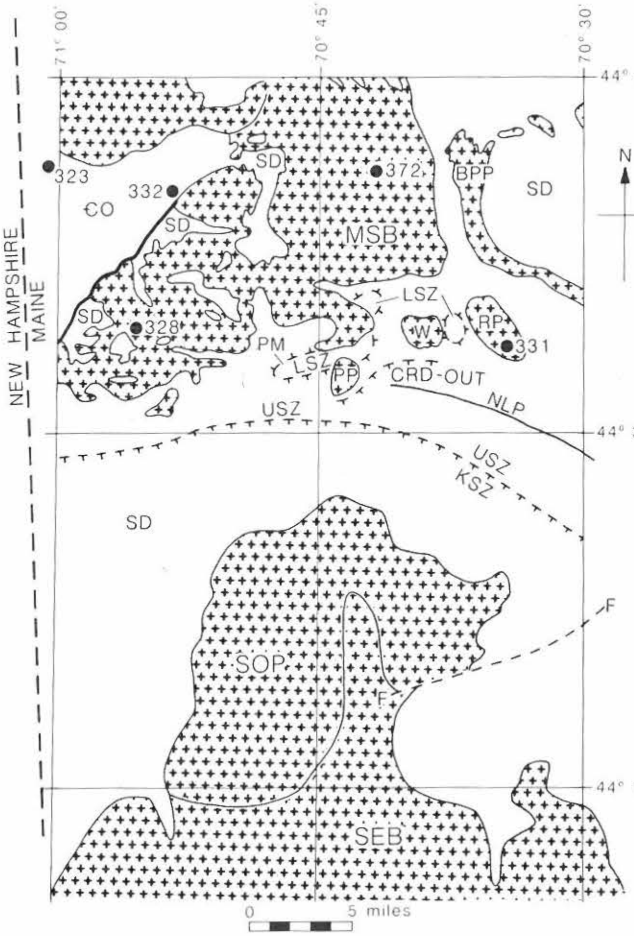

Figure 2. Metamorphic and plutonic map of region north of the Sebago batholith. (See Fig. 1 for index map). €O -- Cambro-Ordovician strata; SD -- Siluro-Devonian strata. Hachured line -- isograds; LSZ -- lower sillimanite, USZ -- upper sillimanite, and KSZ -- K-feldspar + sillimanite zones; CRD-out -- breakdown of cordierite. Heavy black line -- boundary of €O and SD strata. F -- fault. Pluses designate granitic bodies; MSB -- Mooselookmeguntic, BPP -- Bunder Pond, RP -- Rumford, W -- Whitecape, PP -- Plumbago, SOP -- Songo, and SEB -- Sebago intrusions. PM -- Puzzle Mountain. Solid circles with numbers give sample localities and hornblende ages of samples in Figure 4 and Table 2.

sillimanite zone, many of the pelitic rocks are migmatitic and up to 50% of the rocks are pegmatitic. This mixed zone is also intruded by many small plutons and dikes, and the distinction between granitic rocks with metamorphic inclusions and metamorphic rocks with granitic inclusions is often arbitrary.

At the southern end of the Sebago batholith, fresh euhedral kyanite coexisting with biotite occurs, indicating that pressures of metamorphism were substantially higher than to the north (Thomson 1986; Thomson and Guidotti, this volume). Once again, the isograds are roughly parallel to the boundary of the batholith, but the mixed zone of pegmatitic and migmatitic bodies does not occur. The metamorphic grade again increases towards the batholith passing from garnet to staurolite to kyanite

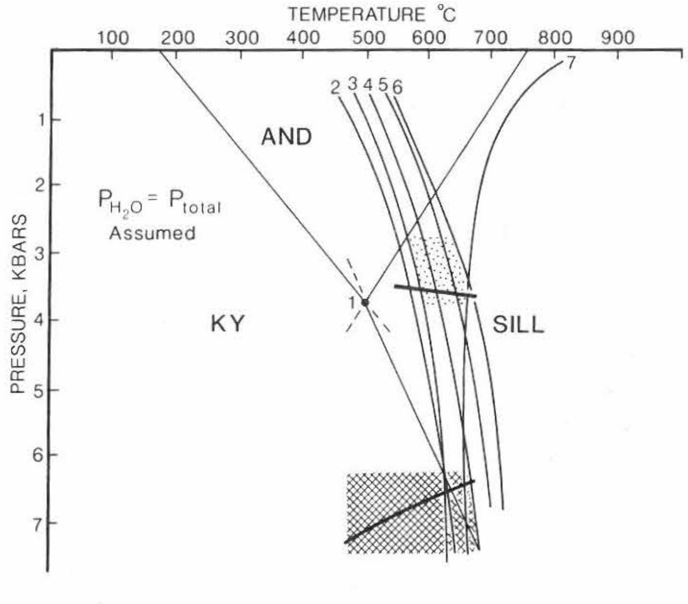

Figure 3. PT grid of equilibria relevant to the Sebago area with $P_{H_2O} = P_{Total}$ after Guidotti et al., (1986).

(1) Alumino-silicate triple point, Holdaway (1971).
(2) Paragonite breakdown, Chatterjee (1972).
(3) St + Chl = Al-Sil + Bio, Guidotti (1974).
(4) St = Al-Sil + Gn + Bio, Hoschek (1969).
(5) Ab + Mu + Al-Sil + Ksp, Chatterjee and Froese (1975).
(6) Muscovite breakdown, Chatterjee and Johannes (1974).
(7) Granite minimum melt curve, Tuttle and Bowen (1958).

Stippled area -- range of PT conditions to the north of the batholith (see text). Cross-hatched area -- range of PT conditions to the south of the batholith. Heavy lines -- metamorphic field gradients.

TABLE 1. INFERRED TEMPERATURES OF METAMORPHISM FOR THE SEBAGO AREA.

	North	South
KF/US	660	
US/LS	615	625-700
LS/ST	590	600-625
KY/ST		500-600
ST/G		450-480

KF – K-feldspar + sillimanite
US – upper sillimanite
LS – lower sillimanite
ST – staurolite
KY – kyanite
G – garnet

Estimates for the south based on Thomson (1986) and Thomson and Guidotti (this volume).

to lower sillimanite zone over a total distance of 10 km. Temperatures of metamorphism range from 450°C in the garnet zone to 700°C in the lower sillimanite zone based on a petrogenetic grid approach (Thomson, 1986; Thomson and Guidotti, this volume). This is consistent with garnet-biotite geothermometry which gives a temperature range of 475-625°C. Pressures of metamorphism are less certain. A petrogenetic grid approach with $P_{H2O} = P_{Total}$ yielded pressures in the range of 6.0 to 7.0 kbar (Thomson, 1986; Thomson and Guidotti, this volume). However, if $P_{H2O} < P_{Total}$ is considered, pressures could be as low as 5.0 kbar. Again, the metamorphic field gradient is nearly isobaric. The conditions of metamorphism at the southern end are also shown in Figure 3 for $P_{H2O} = P_{Total}$, and the inferred temperatures of metamorphism for the various isograds are listed in Table 1.

GEOCHRONOLOGY

The ages of several plutons in western Maine have been previously determined by isotopic age dating. The crystallization age of the Mooselookmeguntic pluton was found to be 371±6 Ma using the Rb/Sr whole rock isochron method (Moench and Zartman, 1976). (All ages discussed in this paper are calculated using the currently accepted decay constants (Steiger and Jager, 1977)). Lux et al. (in press) used Rb/Sr whole rock isochron methods to determine an age of 382 Ma for the Songo pluton. The Sebago pluton has also been dated by both U/Pb and Rb/Sr methods and was found to have a crystallization age of 325 Ma by Aleinikoff et al. (1985) and 332 Ma by Hayward and Gaudette (1987). Two U/Pb isotopic ages for monazites from the Sebago batholith have also been measured (Aleinikoff et al., 1985). Both fell on concordia curves and gave ages of 272 and 282 Ma. These were interpreted to be cooling ages dating the time at which the samples cooled below 600°C, the closure temperature for Pb in monazites.

Lux and Guidotti (1985) argued that the K-feldspar + sillimanite-grade metamorphism that surrounds the Sebago batholith developed during Carboniferous rather than Devonian time. In support of that argument they presented $^{40}Ar/^{39}Ar$ ages for hornblendes from the southern Mooselookmeguntic pluton and the Songo pluton, which were approximately equal to, or distinctly younger than, the age of the Sebago pluton. They suggested that these hornblendes were reset during a period of Carboniferous metamorphism and that, during that metamorphism, the samples had been raised above 500°C, the closure temperature for Ar in hornblende.

Twenty-one new $^{40}Ar/^{39}Ar$ ages are presented here (Tables 2 and 3). Five of these ages are for hornblendes from the Mooselookmeguntic pluton, a small, related, satellite pluton, and the adjacent Ammonoosuc formation (Fig. 2). The release spectra are shown in Figure 4. The sixteen remaining ages are for micas (eight biotite-muscovite pairs) from the Sebago pluton and the release spectra are given in Figure 5. Analytical methods are presented elsewhere (Lux et al., in press).

The new isotopic ages for hornblende provide further evidence for Carboniferous metamorphism. With one exception, the ages of the hornblendes range from 328-332 Ma. These are equal to the crystallization age of the Sebago pluton to within the limits of analytical uncertainty. However, the one exception is perhaps the most important data point. The sample locality of this hornblende is in the Mooselookmeguntic pluton and lies to the north of the other four sample localities. It has a plateau age

TABLE 2. INCREMENTAL RELEASE DATA FOR HORNBLENDE SAMPLES FROM THE MOOSELOOKMEGUNTIC AND RUMFORD PLUTONS AND FROM THE AMMONOOSUC FORMATION.

Temp °C	$\frac{^{40}Ar}{^{39}Ar}$	$\frac{^{37}Ar}{^{39}Ar}$	$\frac{^{36}Ar}{^{39}Ar}$	Moles ^{39}Ar	^{39}Ar %Total	%^{40}Ar Rad	K/Ca	Age(Ma)
		84-51-H			J = 0.004873			
765	380.8	1.873	0.5608	1.5	0.5	48.3	0.26	1295 ± 38
880	326.0	2.133	0.7296	2.2	0.7	29.2	0.23	778 ± 58
940	108.5	2.380	0.1726	3.9	1.3	46.4	0.21	448 ± 16
975	82.21	4.941	0.1445	4.1	1.4	44.6	0.01	321 ± 14
985	63.78	10.43	0.0897	5.4	1.8	59.9	0.05	309 ± 10
1005	50.35	13.58	0.0360	18.1	6.0	84.0	0.04	330 ± 6
1025	50.05	13.71	0.0353	26.8	8.9	84.5	0.04	329 ± 4
1040	48.41	14.38	0.0290	35.2	11.7	88.6	0.03	331 ± 4
1045	48.51	14.19	0.0283	30.5	10.1	88.7	0.03	334 ± 5
1060	47.75	14.32	0.0274	33.1	11.0	89.4	0.03	330 ± 4
1070	46.27	13.97	0.0219	38.2	12.7	92.1	0.04	331 ± 4
1080	46.18	13.73	0.0213	27.0	8.9	92.1	0.04	331 ± 4
1095	45.77	13.92	0.0212	22.8	7.5	92.5	0.04	329 ± 5
1110	46.20	14.96	0.0198	25.8	8.5	95.1	0.03	338 ± 4
Fuse	46.16	15.17	0.0192	27.3	9.1	95.2	0.03	337 ± 4
TOTAL				308.8	100.0			341 ± 3
PLATEAU AGE								331 ± 3

Moles ^{39}Ar has been multiplied times 10^{14}

TABLE 2. (CONTINUED)

Temp °C	^{40}Ar/^{39}Ar	^{37}Ar/^{39}Ar	^{36}Ar/^{39}Ar	Moles ^{39}Ar	^{39}Ar %Total	%^{40}Ar Rad	K/Ca	Age(Ma)
			84-55-H		J = 0.004833			
880	223.3	1.3248	0.2559	6.6	0.6	56.5	0.39	937 ± 17
960	85.76	1.138	0.1080	10.7	0.9	54.2	0.43	418 ± 8
985	79.12	2.356	0.1247	7.6	0.6	47.3	0.21	337 ± 9
1005	74.77	4.682	0.1184	7.1	0.6	49.1	0.10	321 ± 8
1020	69.77	6.320	0.0911	8.6	0.7	57.9	0.08	344 ± 7
1025	57.79	6.656	0.0418	20.6	1.7	74.1	0.07	363 ± 5
1040	57.47	6.697	0.0359	19.9	1.7	76.6	0.07	373 ± 8
1050	52.61	6.462	0.0192	46.5	3.9	83.6	0.08	374 ± 5
1065	51.43	6.356	0.0152	78.8	6.6	85.3	0.08	374 ± 5
1075	50.32	6.268	0.0123	104.9	8.8	86.7	0.08	372 ± 4
1085	49.61	6.156	0.0120	208.0	17.5	87.6	0.08	371 ± 4
1110	48.81	6.080	0.0086	308.0	25.9	88.4	0.08	369 ± 4
Fuse	48.53	6.189	0.0070	359.7	30.3	89.4	0.08	370 ± 4
TOTAL				1187.20	100.0			373
PLATEAU AGE								372 ± 4
			82-30-H		J = 0.004800			
960	101.8	2.053	0.1759	20.0	3.8	49.1	0.24	388 ± 8
985	108.3	10.66	0.2224	4.8	0.9	40.0	0.05	343 ± 12
1000	105.0	12.01	0.2233	3.7	0.7	38.0	0.04	319 ± 17
1010	72.16	13.91	0.1077	8.2	1.6	57.3	0.04	330 ± 9
1025	53.48	14.37	0.0447	23.0	4.4	77.3	0.03	330 ± 5
1040	47.83	14.38	0.0258	61.5	11.8	86.2	0.03	329 ± 4
1050	49.93	14.47	0.0328	36.1	6.9	82.7	0.03	330 ± 5
1065	49.62	14.47	0.0306	56.7	10.9	83.9	0.03	332 ± 4
1075	56.11	14.23	0.0516	56.2	10.8	74.4	0.03	334 ± 5
1085	48.36	14.23	0.0263	78.1	15.0	86.1	0.03	332 ± 4
1100	49.50	14.08	0.0294	49.8	9.6	84.6	0.03	334 ± 4
1125	47.03	14.34	0.0214	51.6	9.9	88.8	0.03	333 ± 4
Fuse	45.32	14.14	0.0152	70.6	13.6	92.4	0.03	334 ± 4
TOTAL				520.2	100.0			334
PLATEAU AGE								332 ± 4
			82-33-H		J = 0.004915			
925	720.8	8.891	1.8140	0.6	0.2	25.7	0.06	1174 ± 73
970	419.3	8.762	0.9192	0.8	0.3	35.4	0.06	993 ± 55
990	208.5	11.22	0.5178	1.0	0.3	27.0	0.04	444 ± 37
1010	112.8	14.61	0.2511	1.7	0.6	35.2	0.03	325 ± 20
1025	105.3	13.97	0.2348	1.6	0.5	35.1	0.04	304 ± 2
1050	46.83	14.42	0.0237	26.2	8.9	87.3	0.03	334 ± 4
1075	43.89	13.55	0.0190	52.2	17.7	89.5	0.04	322 ± 4
1085	43.29	14.69	0.0165	57.4	19.5	91.3	0.03	324 ± 4
1100	43.96	13.48	0.0177	43.1	14.6	90.3	0.04	325 ± 4
1110	44.46	13.42	0.0184	36.9	12.5	90.0	0.04	327 ± 4
1135	43.73	13.18	0.0154	54.7	18.5	91.8	0.04	328 ± 4
Fuse	45.74	13.04	0.0209	18.6	6.3	88.6	0.04	311 ± 4
TOTAL				294.8	100.0			330
PLATEAU AGE								323 ± 3
			82-40-H		J = 0.006445			
765	1257	3.673	0.9154	0.6	0.1	78.5	0.13	3606 ± 52
800	214.0	1.190	0.1262	5.0	0.7	82.6	0.41	1373 ± 15
940	107.8	1.831	0.0654	7.7	1.1	82.1	0.27	816 ± 10
960	67.30	2.565	0.0670	5.5	0.8	70.6	0.19	484 ± 7
975	47.89	3.704	0.0520	5.7	0.8	67.9	0.13	347 ± 6
985	39.12	4.726	0.0288	9.7	1.4	78.3	0.10	329 ± 5
990	37.06	5.042	0.0210	12.1	1.7	83.2	0.10	332 ± 6
1000	34.73	5.464	0.0134	16.4	2.4	88.6	0.09	332 ± 5

Moles ^{39}Ar has been multiplied times 10^{14}

TABLE 2. (CONTINUED)

Temp °C	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	Moles ^{39}Ar	^{39}Ar %Total	%^{40}Ar Rad	K/Ca	Age(Ma)
		82-40-H			J = 0.006445			
1005	33.91	5.640	0.0105	19.8	2.9	90.8	0.09	332 ± 4
1010	32.82	5.851	0.0069	35.7	5.2	93.8	0.08	332 ± 4
1015	32.73	5.893	0.0065	54.3	7.8	94.1	0.08	332 ± 4
1025	32.81	5.885	0.0080	37.7	5.4	92.8	0.08	329 ± 4
1030	32.49	5.929	0.0073	44.7	6.4	93.4	0.08	328 ± 4
1040	32.62	5.943	0.0082	36.2	5.2	92.6	0.08	327 ± 4
1045	32.22	6.039	0.0063	36.2	5.2	94.2	0.08	328 ± 4
1050	31.95	6.073	0.0055	45.8	6.6	94.9	0.08	328 ± 4
1065	31.88	6.043	0.0053	36.9	5.3	95.1	0.08	328 ± 4
1070	31.82	6.119	0.0055	37.1	5.3	94.9	0.08	327 ± 4
1075	31.75	6.169	0.0056	36.3	5.2	94.8	0.08	326 ± 4
1080	32.16	6.202	0.0063	35.6	5.1	94.2	0.08	328 ± 4
1085	32.00	6.234	0.0055	26.7	3.8	94.9	0.08	328 ± 4
1090	31.95	6.130	0.0050	59.2	8.5	95.3	0.08	329 ± 4
1125	31.99	6.062	0.0038	58.2	8.4	96.5	0.08	333 ± 4
1135	33.74	5.791	0.0097	21.5	3.1	91.5	0.08	333 ± 4
Fuse	37.95	5.130	0.0257	9.2	1.3	80.0	0.10	327 ± 5
TOTAL				693.9	100.0			346
PLATEAU AGE								328 ± 2

Moles ^{39}Ar has been multiplied times 10^{14}

TABLE 3. INCREMENTAL RELEASE AND TOTAL FUSION DATA FOR BIOTITES (B) AND MUSCOVITES (M) FROM THE SEBAGO PLUTON.

Temp °C	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	Moles ^{39}Ar	^{39}Ar %Total	%^{40}Ar Rad	Age(Ma)
		SBG-3-B			J = 0.005758		
800	25.48	1.497	8.073	152.2	9.6	90.5	224.9 ± 2.4
880	25.31	0.1906	1.710	400.7	25.4	97.9	240.5 ± 2.3
960	25.62	0.4734	1.801	271.6	17.2	97.8	243.1 ± 2.4
1005	25.26	0.4863	0.5956	377.3	23.9	99.2	243.1 ± 2.3
1055	25.02	0.1265	0.1006	286.6	18.2	99.7	242.2 ± 2.3
Fuse	25.01	0.2253	0.0268	89.9	5.7	98.6	242.3 ± 2.6
TOTAL				1578.4	100.0		240.5 ± 2.3
PLATEAU AGE							242.2 ± 3.3
		SBG-4-B			J = 0.005753		
800	24.53	1.828	4.8306	173.3	9.7	94.0	224.8 ± 3.7
890	23.87	0.3454	0.8669	459.1	25.8	98.8	229.4 ± 2.4
960	23.85	0.6561	0.8844	236.5	13.3	98.7	229.2 ± 2.3
1005	23.56	0.3675	0.3440	392.1	22.0	99.4	228.0 ± 2.2
1055	23.58	0.4582	0.2304	367.5	20.6	99.5	228.5 ± 2.2
Fuse	24.07	1.102	1.007	151.1	8.5	98.6	230.9 ± 2.6
TOTAL				1779.6	100.0		228.6 ± 2.4
PLATEAU AGE							229.2 ± 3.3
		SBG-5-B			J = 0.00573		
825	25.29	0.3016	5.446	206.2	12.1	93.5	229.2 ± 2.3
915	24.21	0.09377	0.6039	410.4	24.0	99.1	232.4 ± 2.2
985	24.33	0.2254	1.275	275.5	16.1	98.3	231.7 ± 2.3
1030	24.11	0.1284	0.3107	397.0	23.2	99.5	232.3 ± 2.3
1080	24.16	0.2315	0.2732	325.8	19.1	99.5	232.8 ± 2.2
Fuse	24.72	0.2258	2.015	93.4	5.5	97.4	233.3 ± 2.7
TOTAL				1708.4	100.0		232.0 ± 2.3
PLATEAU AGE							232.5 ± 2.4

$^{37}Ar/^{39}Ar$ has been multiplied times 10^2 $^{36}Ar/^{39}Ar$ has been multiplied times 10^3 Moles ^{39}Ar has been multiplied times 10^{14}

TABLE 3. (CONTINUED)

Temp °C	^{40}Ar/^{39}Ar	^{37}Ar/^{39}Ar	^{36}Ar/^{39}Ar	Moles ^{39}Ar	^{39}Ar %Total	%^{40}Ar Rad	Age(Ma)
		SBG-6-B			J = 0.005708		
800	24.66	0.4329	7.465	187.1	13.9	90.9	217.2 ± 2.2
880	24.53	0.1512	0.9743	316.9	23.5	98.7	233.4 ± 2.2
960	24.87	0.4543	2.003	221.2	16.4	97.5	233.8 ± 2.3
1000	24.44	0.2633	0.7141	334.5	24.8	99.0	233.4 ± 2.2
1050	24.29	0.1494	0.2879	238.3	17.7	99.5	233.1 ± 2.3
Fuse	23.68	0.8912	3.791	51.7	3.8	95.1	218.2 ± 15.9
TOTAL				1349.6	100.0		230.6 ± 2.8
PLATEAU AGE							233.4 ± 1.8
		SBG-7-B			J = 0.005729		
810	24.55	0.3997	8.354	133.8	6.4	89.8	214.6 ± 2.8
890	24.71	0.1058	1.264	641.4	30.8	98.3	235.1 ± 2.2
975	25.38	0.2552	1.649	311.0	14.9	97.9	240.1 ± 2.4
1025	24.99	0.1370	1.044	601.4	28.8	98.6	238.2 ± 2.3
Fuse	24.80	0.3103	0.5281	398.2	19.1	99.2	237.9 ± 2.3
TOTAL				2085.8	100.0		236.0 ± 2.3
PLATEAU AGE							238.8 ± 3.6
		SBG-8-B			J = 0.005718		
815	26.14	0.1954	7.119	103.7	6.3	91.8	231.9 ± 3.2
890	25.92	0.1764	2.008	488.7	29.5	97.6	243.7 ± 2.4
985	25.87	0.1694	1.197	343.8	20.7	98.5	245.3 ± 2.4
1025	25.73	0.04781	0.7406	364.4	22.0	99.0	245.3 ± 2.4
Fuse	25.63	0.06597	0.6286	358.8	21.6	99.1	244.7 ± 2.4
TOTAL				1659.3	100.0		243.9 ± 2.4
PLATEAU AGE							244.8 ± 2.8
		SBG-9-B			J = 0.005733		
800	26.29	0.5400	6.229	94.1	5.9	92.9	236.3 ± 7.5
890	25.71	0.1907	2.529	565.8	35.8	96.9	240.9 ± 4.6
980	25.72	0.3723	1.866	352.3	22.3	97.7	242.8 ± 6.3
1025	25.39	0.4298	0.4747	398.6	25.2	99.3	243.6 ± 10.5
Fuse	25.42	0.7184	1.718	171.7	10.8	97.9	240.5 ± 12.6
TOTAL				1582.4	100.0		241.7 ± 7.5
PLATEAU AGE							242.0 ± 4.1
		SBG-10-B			J = 0.005767		
800	26.61	0.3606	9.208	95.7	5.7	89.6	232.5 ± 6.1
890	25.00	0.08246	1.411	522.1	31.3	98.2	238.8 ± 3.4
990	25.11	0.07546	1.279	409.0	24.5	98.3	240.2 ± 4.9
1025	24.52	0.01216	0.6592	389.0	23.3	99.0	236.4 ± 3.0
Fuse	25.20	0.06797	0.8861	251.9	15.1	98.8	242.1 ± 2.9
TOTAL				1667.7	100.0		238.7 ± 3.7
PLATEAU AGE							238.5 ± 5.0
		SBG-3-M			J = 0.005753		
840	28.51	0.2755	10.99	76.0	3.5	88.5	244.4 ± 3.2
915	26.86	0.05356	4.678	479.2	21.9	94.7	246.4 ± 2.3
970	26.18	0.03200	2.487	482.9	22.1	97.0	246.1 ± 2.4
1017	25.99	0.03000	1.715	460.0	21.1	97.9	246.4 ± 2.3
1090	25.78	0.03151	0.9083	641.5	29.4	98.8	246.7 ± 2.4
Fuse	27.38	0.1309	5.437	44.1	2.0	94.0	249.0 ± 3.9
TOTAL				2183.7	100.0		246.4 ± 2.4
PLATEAU AGE							246.4 ± 1.8

^{37}Ar/^{39}Ar has been multiplied times 10^2 ^{36}Ar/^{39}Ar has been multiplied times 10^3 Moles ^{39}Ar has been multiplied times 10^{14}

TABLE 3. (CONTINUED)

Temp °C	^{40}Ar/^{39}Ar	^{37}Ar/^{39}Ar	^{36}Ar/^{39}Ar	Moles ^{39}Ar	^{39}Ar %Total	%^{40}Ar Rad	Age(Ma)
		SBG-4-M			J = 0.005753		
840	27.63	4.194	15.63	47.9	2.4	83.2	223.9 ± 13.1
915	25.54	1.120	3.235	135.0	6.7	96.1	238.3 ± 2.4
975	25.44	0.1598	2.052	579.3	28.9	97.5	240.6 ± 3.0
1015	25.22	0.3890	1.479	338.2	16.9	98.1	240.1 ± 2.5
1085	25.03	0.7289	0.06826	621.6	31.0	99.0	240.5 ± 3.0
Fuse	25.58	8.285	1.144	284.3	14.2	98.6	244.4 ± 2.8
TOTAL				2006.3	100.0		240.5 ± 3.1
PLATEAU AGE							240.4 ± 1.8
		SBG-5-M			J = 0.00571		
800	26.02	0.6518	12.72	17.1	0.7	85.4	215.5 ± 6.2
890	26.26	0.8031	6.364	79.4	3.3	92.7	234.8 ± 2.7
950	26.37	0.3024	4.703	350.9	14.5	94.6	240.2 ± 2.3
1000	25.40	0.07460	1.965	792.6	32.9	97.6	238.8 ± 2.3
1065	25.42	0.3050	1.829	460.8	19.1	97.7	239.3 ± 2.3
Fuse	25.42	3.368	1.005	710.9	29.5	98.7	241.5 ± 2.3
TOTAL				2411.5	100.0		239.6 ± 2.4
PLATEAU AGE							239.9 ± 3.6
		SBG-6-M			J = 0.005719		
840	29.75	0.2630	19.10	43.8	2.6	80.9	232.6 ± 6.2
905	26.60	0.01515	4.817	99.8	5.8	94.5	242.4 ± 2.5
970	26.43	0.06616	4.408	503.9	29.4	94.9	241.9 ± 2.3
1010	25.94	0.05964	2.700	324.9	19.0	96.8	242.0 ± 2.3
1070	25.64	0.006918	1.636	424.7	24.8	98.0	242.1 ± 2.4
Fuse	25.55	0.09338	0.9723	314.7	18.4	98.7	243.1 ± 2.4
TOTAL				1711.9	100.0		242.0 ± 2.5
PLATEAU AGE							242.3 ± 2.2
		SBG-7-M			J = 0.005729		
870	28.54	0.3791	12.59	61.6	3.2	86.8	239.5 ± 3.8
950	25.55	0.006895	1.985	840.7	43.3	97.6	240.8 ± 2.3
1000	25.46	0.7322	1.422	433.6	22.3	98.2	241.5 ± 2.3
1050	25.41	0.1553	1.339	368.8	19.0	98.3	241.3 ± 2.4
Fuse	25.33	2.547	0.4974	239.0	12.3	99.3	242.8 ± 2.7
TOTAL				1943.7	100.0		241.2 ± 2.4
PLATEAU AGE							241.2 ± 3.6
		SBG-8-M			J = 0.005705		
880	27.23	1.263	9.629	76.9	5.1	89.4	234.7 ± 3.2
930	26.32	0.5054	3.284	280.8	18.5	96.2	243.4 ± 2.4
990	25.81	0.29674	1.499	472.5	31.2	98.1	243.4 ± 2.4
1050	25.70	0.64622	1.407	342.8	22.6	98.2	242.8 ± 2.5
Fuse	25.74	7.388	0.4780	343.0	22.6	99.3	245.6 ± 2.4
TOTAL				1515.9	100.0		243.3 ± 2.4
PLATEAU AGE							243.2 ± 2.0
		SBG-9-M			J = 0.005762		
880	28.41	0.9474	12.83	101.7	8.8	86.5	239.0 ± 10.7
940	26.28	0.1752	3.784	519.9	45.1	95.6	243.9 ± 2.3
1000	25.72	0.1362	2.438	362.7	31.4	97.0	242.4 ± 2.5
Fuse	25.24	0.1670	0.2299	169.3	14.7	99.6	244.0 ± 2.7
TOTAL				1153.6	100.0		243.0 ± 3.2
PLATEAU AGE							243.4 ± 3.0

^{37}Ar/^{39}Ar has been multiplied times 10^2 ^{36}Ar/^{39}Ar has been multiplied times 10^3 Moles ^{39}Ar has been multiplied times 10^{14}

TABLE 3. (CONTINUED)

Temp °C	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	Moles ^{39}Ar	^{39}Ar %Total	%^{40}Ar Rad	Age(Ma)
		SBG-10-M			J = 0.005759		
880	28.21	0.3592	10.56	83.7	4.5	88.8	243.1 ± 2.8
950	26.66	0.09105	5.233	251.1	13.5	94.1	243.3 ± 2.4
990	25.77	0.01400	2.600	690.0	37.0	96.9	242.3 ± 2.3
1060	25.55	0.03828	1.394	373.1	20.0	98.2	243.5 ± 2.4
Fuse	25.49	0.03960	1.106	465.4	25.0	98.6	243.8 ± 2.4
TOTAL				1863.3	100.0		243.1 ± 2.4
PLATEAU AGE							243.2 ± 2.4

$^{37}Ar/^{39}Ar$ has been multiplied times 10^2 **$^{36}Ar/^{39}Ar$ has been multiplied times 10^3** **Moles ^{39}Ar has been multiplied times 10^{14}**

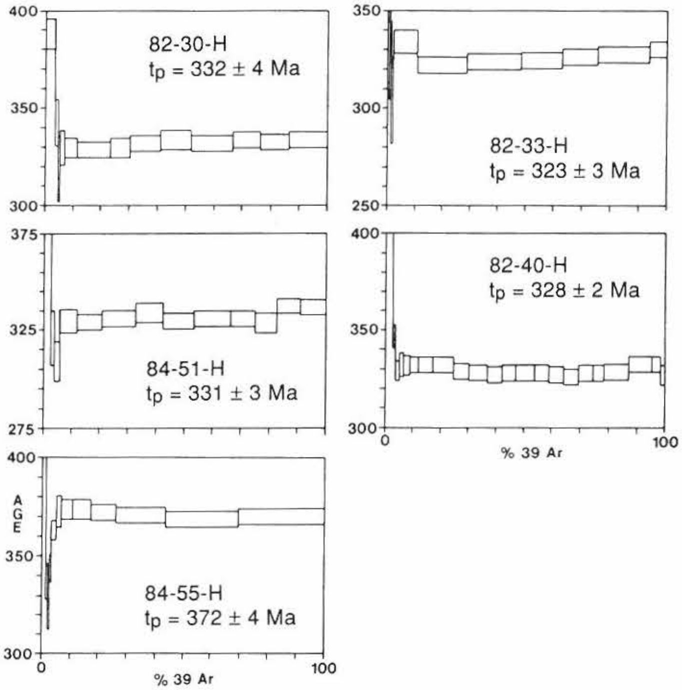

Figure 4. Age spectra of hornblende from samples of the Mooselookmeguntic pluton, a small satellite pluton, and the Ammonoosuc Formation. Note that the vertical scales are variable and that small increments with anomalously old ages have been omitted. The horizontal scales are identical. Individual box heights represent 2 sigma analytical uncertainties.

of 372 Ma which is identical to the crystallization age of the Mooselookmeguntic pluton. This demonstrates that ambient temperature was below the closure temperature for Ar in hornblende, 500°C, and that the pluton cooled rapidly below that temperature following emplacement. It also delineates the northern limit of the Carboniferous metamorphic event. Apparently, temperatures in excess of 500°C were experienced only up to 30-50 km north of the present-day surface outcrop of the Sebago batholith.

Mica ages from throughout the Mooselookmeguntic pluton are all younger than 305 Ma (Lux, 1986), implying that ambient temperature in the region before 305 Ma was above 350°C. Thus, ambient temperature at the time of emplacement of the Sebago batholith is constrained to be between approximately 350°C and 500°C.

The new $^{40}Ar/^{39}Ar$ ages for muscovites and biotites from the Sebago batholith range in age from 246 to 240 Ma, and 245 to 229 Ma respectively. These ages are interpreted to date the time that the micas last cooled through their closure temperatures, 280°C for biotite (Harrison et al., 1985) and 350°C for muscovite (Cliff, 1985), in response to regional uplift and erosion. There is a general trend towards younger ages to the southwest indicating that either: (1) the region uplifted more rapidly in the northeast, or (2) the region was buried more deeply to the southwest. The second explanation requires differential uplift across the region, with the present erosion surface exposing deeper levels of the crust towards the southwest. This is consistent with the geometry of the region (De Yoreo et al., 1989; Lux et al., 1986; Hon and Schulman, 1983) as is discussed below.

The average discordance between the muscovite and biotite ages is 5 Ma implying that, on average, the region cooled at a rate of 15°C/MY between approximately 245 Ma and 230 Ma. Previous mica age discordance determinations on nearby, shallower plutons indicate average cooling rates for the region of 1-3°C/MY from 370 Ma to 270 Ma and 6-9°C/MY from 270 Ma to 250 Ma (De Yoreo et al., 1989). These cooling rates will be used to constrain the erosion rates used in our thermal model.

GEOMETRY OF THE PLUTONS

In the first regional gravity survey of Maine, Kane and Bromery (1968) noted that the plutons in the high-grade metamorphic terrane had very little gravity signature and, hence, were likely to be relatively thin bodies. Later gravity studies by Hodge et al. (1982) in Maine and by Neilson et al. (1976) in New Hampshire comfirmed this observation. They concluded that the thickness of these plutons ranged from 0.5 km to 2 km. Hodge et al. (1982) estimated the thickness of the Sebago batholith to

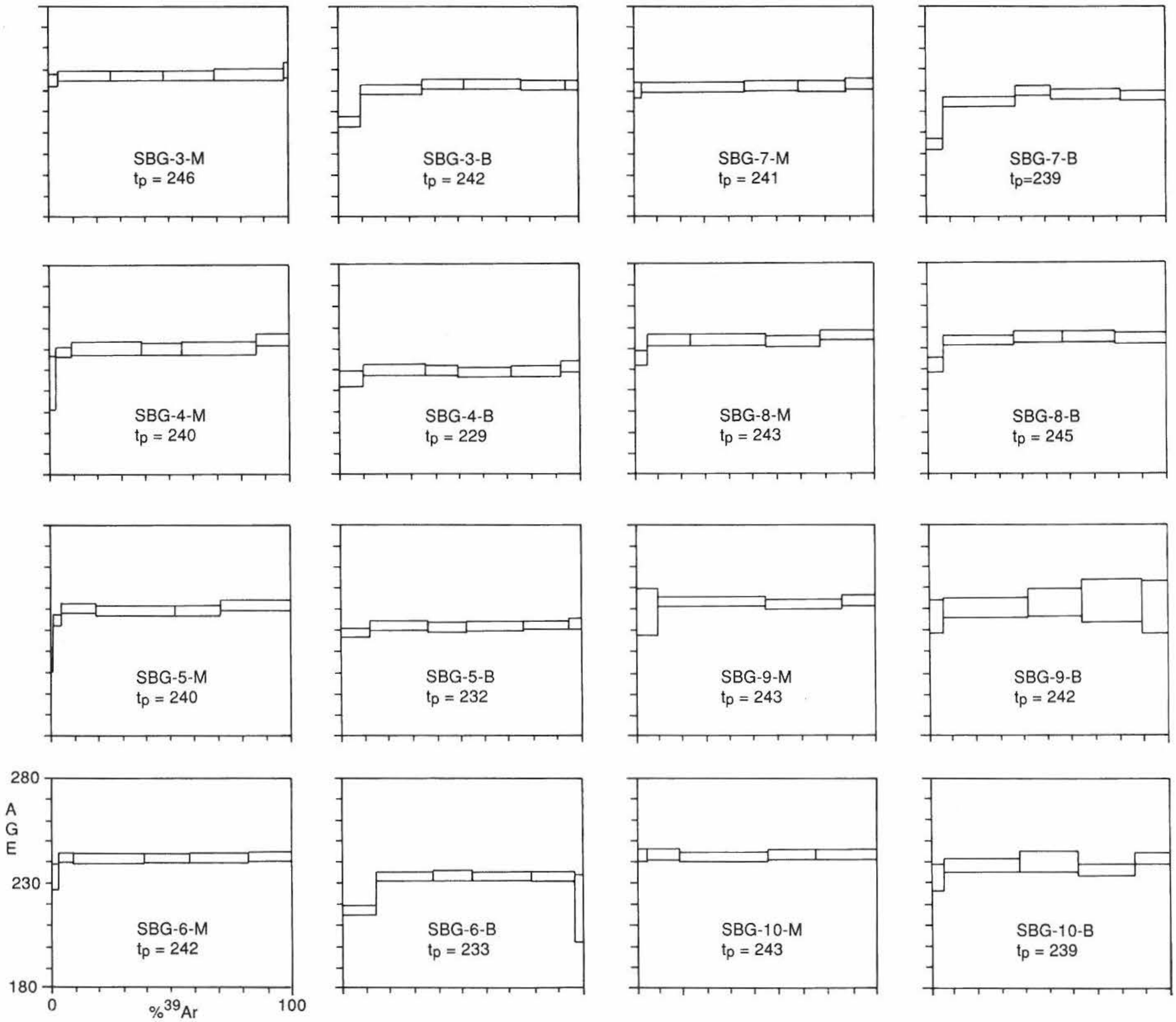

Figure 5. Age spectra of biotite (B) and muscovite (M) from samples of the Sebago pluton. The vertical and horizontal scales are identical and are as shown in the lower left. Individual box heights represent 2 sigma uncertainties.

be approximately 1 km. Detailed gravity surveys across a number of the plutons in western Maine (Carnese, 1983) showed them to be thin tabular masses that homotropically dip to the northeast at about 3 degrees. Many extend far beyond their surface contacts. For example, although the Mooselookmeguntic and Redington plutons are separated on the surface by 10-15 km, gravity measurements suggest that the Mooselookmeguntic pluton is approximately 2 km thick and actually extends underneath the Redington pluton, staying within a kilometer of the surface in the intervening region. In addition, peak pressures of metamorphism from northeastern Maine to central Massachusetts along the Kearsarge-central Maine synclinorium imply a gentle northeastward plunge of approximately 3 degrees (De Yoreo et al., 1989). It is reasonable to assume that the Sebago batholith also dips to the northeast at about 3 degrees and extends beyond its surface contact. Given the present southwest-northeast surface exposure of 45 km for the Sebago batholith, this dip results in an estimated thickness of about 2 km. In its present day configuration the batholith should be very thin near its southwest contact and thicken to nearly 2 km at the northeast contact and beyond (see Fig. 6). The average thickness below the exposed surface is then about 1 km, in agreement with the estimate of Hodge et al. (1982). With this geometry, the metamorphic terrane to the north of the Sebago batholith lies above its upper surface while that to the south once lay below its lower surface (Fig. 6).

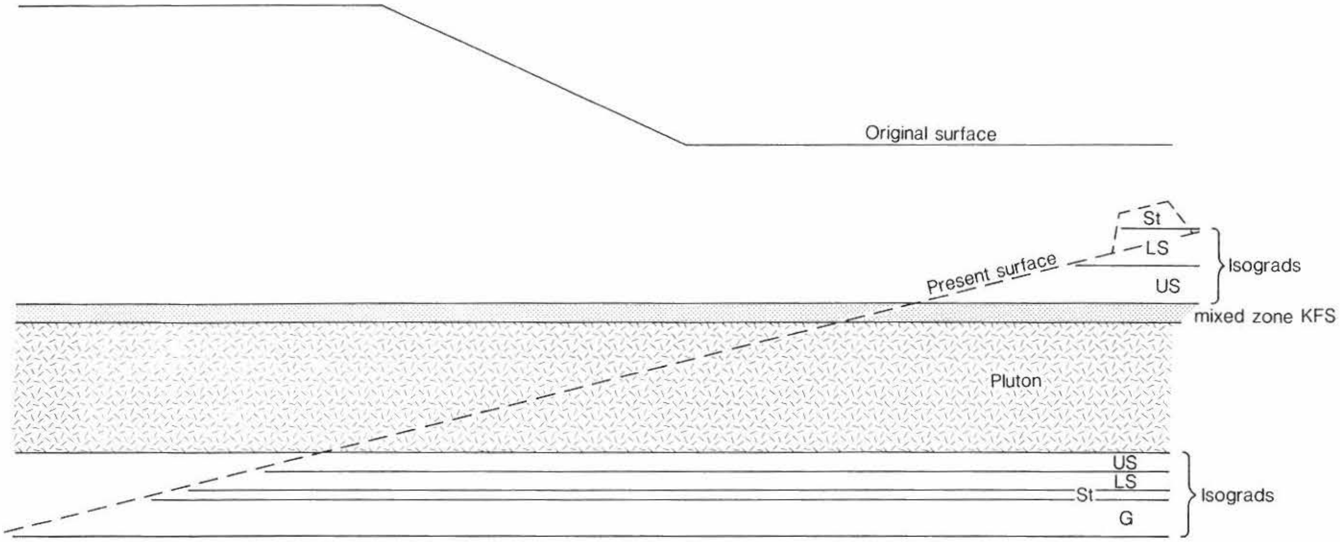

Figure 6. Schematic diagram showing proposed geometry for the Sebago batholith and surrounding metamorphic terrane. Original surface allows for increasing topographic relief to the southwest. Metamorphic zones: G -- garnet, St -- staurolite, LS -- lower sillimanite, US -- upper sillimanite, KFS -- K-feldspar + sillimanite.

Conservative estimates of 3.8 and 5.5 kbar for the northern and southern ends of the Sebago batholith respectively imply a change in depth of burial of about 6 km from north to south. However, the assumption that the pluton dips at 3 degrees can account for only half of this change. Errors in the pressure estimates or an increase in topographic relief to the southwest as shown in Figure 6 are possible sources of this discrepancy.

THERMAL MODEL

The central question of this paper is: was the Sebago batholith capable of transferring the amount of heat necessary to produce the surrounding regional, high-grade metamorphism, or were other sources such as hot, hydrous fluids or high, transient, mantle flux required? In order to address this question it is necessary to solve the heat diffusion equation (Carslaw and Jaeger, 1959) which for one dimension is given by:

$$(1)\quad \partial^2 T(x,t)/\partial x^2 - (1/K)\partial T(x,t)/\partial t = (u/K)\partial T(x,t)/\partial x - A(x)/\Lambda$$

where $T(x, t)$ is the temperature at position x and time t, K is the thermal diffusivity, u is the erosion rate, Λ is the thermal conductivity, and $A(x)$ is the distribution of heat production in the crust due to radiogenic heating.

We seek a solution of Equation 1 for the solidification and cooling of a liquid in a semi-infinite solid with an arbitrary initial temperature distribution, $T(x,0)$. In general, this is an intractable problem and we are forced to make a number of assumptions. However, the geometry of the problem at hand leads to enormous simplification and enables us to generate a solution that is accurate to a good approximation. The least lateral dimension of the batholith is greater than 40 km, the surface area is greater than 2.5×10^3 km^2, and the thickness is only 2 km. Furthermore, the petrologic studies discussed previously indicate that the upper surface of the batholith at the time of emplacement was at approximately 14 km depth. Thus, three simplifications can be made. First, since the ratio of heat that flows perpendicular to the sheet to that which flows parallel to the sheet is on the order of the square of the width divided by the square of the thickness, the problem is essentially one dimensional. Second, in the time it takes for the sheet to solidify, the heat diffuses roughly one pluton thickness away from the boundary of the pluton, allowing us to ignore the boundary at the earth's surface. We assume that the magmatic sheet is in an infinite medium up until the time of solidification, t_s. Third, since the pluton is thin, little error is made in assuming that the temperature of the country rock affected during solidification is initially independent of position, i.e. $T(x, t \le t_s) = T_o$

This problem has been studied in detail by numerous authors (Jaeger, 1964; Carslaw and Jaeger, 1959; Irvine, 1970). For the situation depicted in Figure 7, the solution for $t \le t_o$ is given by

$$(2)\quad T(x,t) = T_o + (T_m - T_o)(\mathrm{erfc}(x/(4Kt)^{0.5}))/(1 + \mathrm{erf}\lambda)\quad t \le t_s,\ x \ge x_m$$
$$x_m = -(4Kt)^{0.5}\lambda$$
$$t_s = d^2/(16K\lambda^2)$$

where T_o is the temperature of the country rock, T_m is the temperature of the magma, x_m is the position of the solidification surface, d is the thickness of the pluton, and λ is given by

$$(3)\quad L\pi/c(T_m - T_o) = e^{-\lambda^{2}}/\lambda(1 + \mathrm{erf}\lambda)$$

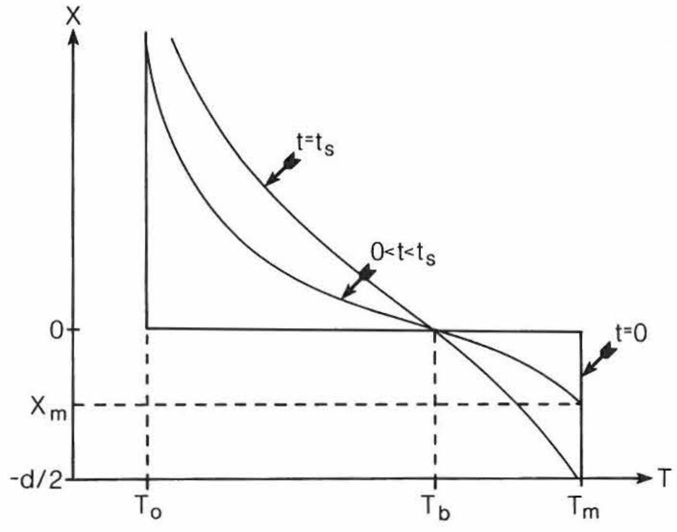

Figure 7. Temperature distributions near a solidifying igneous slab of thickness d with an initial temperature, T_m, in an infinite solid with initial temperature, T_o. $t = 0$: $T = T_o$ for $x > 0$, $x < -d$ and $T = T_m$ for $-d < x < 0$. $0 < t < t_s$: $T = T_m$ for $-d + x_m < x < x_m$. $t = t_s$: the solidification boundary, x_m, is at $x = -d/2$. $T = T_b$ at the pluton country-rock boundary for $0 < t \leq t_s$.

Here L and c are the latent heat and the specific heat of the magma respectively. Equation 2 assumes that the thermal properties of the magma and the country rock are identical. The pluton solidifies symmetrically from top and bottom.

For $t > t_s$ the solution is obtained numerically by applying a Crank-Nicholson implicit finite difference technique (Crank, 1981) to Equation 1, with $T'(x,t_s) = T(x,0) + T(x,t_s) - T_o$ as the initial temperature distribution.

The values of a number of parameters need to be specified. The thickness of the sheet, d, is taken to be 2 km. The thermal diffusivity, thermal conductivity, and the specific heat are given values for "average" crustal rocks with $K = 32$ km^2/MY, $\Lambda = 2.5$ W/mK, and $c = 1.1$ J/gK. (For a discussion of the values of these parameters see England and Thompson, 1984). Based on the latent heats of oxides in the CRC Handbook of Chemistry and Physics (Weast and Astle, 1982), a value of 320 J/g is a reasonable average for L.

Varying K, Λ , c, and L over the range of relevant values has little effect on the result provided T_o and T_m are not changed. In contrast, variations in T_m and T_o can have significant effects. Fortunately, studies on plutons of similar composition and depth of emplacement provide reasonable limits on T_m. Typical emplacement temperatures for S-type granites are in the range of 750-850°C (Clemens et al., 1986; Clemens and Wall, 1981; Wyborn et al., 1981; Clemens, 1984). A value of 800°C is taken for T_m.

The initial temperature distribution in the country rock, $T(x,0)$, is the most uncertain parameter. It is a function not only of the thermal properties of the rocks, but of the mantle heat flux, Q_m, the distribution of radiogenic heat producing elements in the crust, $A(x)$, and the burial and erosion history of the region.

For the thermal diffusivity and the thermal conductivity we again choose values of 32 km^2/MY and 2.5 W/mK. The mantle heat flux is assumed to be that of present day New England for which $Q_m = 35$ mW/m^2 (Birch et al., 1968; Jaupart et al., 1981).

The burial history is one of sedimentation from about 440 to 400 Ma followed by rapid Acadian thickening at about 400 Ma. Some 10-15 km of deep-water sediments were deposited prior to the Acadian orogeny (Moench and Zartman, 1976). The pressures of metamorphism in the region indicate initial depths of burial of the present erosion surface of between 10 to 15 km (Holdaway et al., 1987) and the thickness of the present day synclinorium is 10-12 km (Stewart et al., 1985). Thus the sedimentary pile was roughly doubled in thickness by Acadian folding and thrusting. For our model we take the sedimentation rate to be 0.3 km/MY for 42 million years (442-400 Ma). The sediments are homogeneously thickened by a factor of two instantaneously at 42 million years (400 Ma).

In order to avoid overestimating T_o and hence the thermal effect of the Sebago batholith, these sediments were modeled as being deposited on an old craton. In the model, they are deposited onto a basement whose volumetric heat production is similar to that of the Precambrian basement of the Adirondacks for which the total contribution to the surface heat flow from crustal radiogenic sources is 10 mW/m^2 (Birch et al., 1968). If this is distributed uniformly over 30 km, then $A(x) = A_o = 0.33$ uW/m^3.

The heat production in the sediments is then constrained by the present day distribution of crustal heat production for New England for which, on average, $A_o = 4.2$ uW/m^3 distributed uniformly over 7 km (Birch et al., 1968). In the model presented here, $A_o = 2.25$ W/m^3 for the sediments. After thickening and erosion, the average present day *contribution* to surface heat flow from crustal sources is properly obtained. The present day *distribution* of crustal heat production is thought to be a result of upward enrichment of radiogenic elements by the metamorphism and plutonism following the Acadian deformation.

As discussed above, the cooling rate, up until 325 Ma, at the depths of interest, was about 1-2°C/MY. Since the ambient temperature was between 300 and 500°C, the average gradient was 20-35°C/km. Geothermal gradients are likely to be steepest near the surface, so we take, as a starting point, an average gradient to the depth of interest of 20°C/km, giving a first guess at the erosion rate of 0.05 km/MY. The cooling rates predicted by the model with this erosion rate were found to be consistent with those determined through isotopic age dating and lead to muscovite and biotite ages of 260 Ma and 240 Ma respectively.

Note that no care has been taken to ensure that the original crustal thickness is obtained after erosion. Some 25 km of material are deposited onto 30 km of crust but not all of it is removed. This is done with the belief that 5-10 km of lower crustal material are melted and transported upward as granitic magmas in response to the crustal thickening (De Yoreo et al., 1989; England and Thompson, 1986). Also note that the initial deposition of the sediments onto stable, continental crust contradicts the principle of isostasy. It is more likely that the basement for these sediments was a subsiding basin. However, the region today is underlain by normal, continental, sialic basement (Stewart et al., 1986; Stewart et al., 1985; Taylor and Toksoz, 1982) so it is clear that in some way this material was thickened and emplaced onto normal, continental crust. A number of different models have been tried, and in each case it is this deformational event which controls the subsequent thermal evolution. As long as the thickness of the pile and the distribution of the volumetric heat production is unchanged, the thermal histories are nearly identical within 10 million years after thickening. In short, the deformational event erases any memory of the period of sedimentation.

Equation 1 was solved numerically for the above parameters using a Crank-Nicholson implicit, finite difference method with grid spacing of 1 km and 1 MY. The effect of the intrusion of the Sebago batholith was then calculated as described above. The geotherms for 400 Ma, 395 Ma, 370 Ma, and 325 Ma as well as the pressure-temperature-time (P-T-t) paths for crustal horizons initially buried to 10, 20, 30, 40, and 50 km are shown in Figure 8. At 325 Ma, the ambient temperature at 14 km is about 370°C, and the cooling rates at shallower levels during the cooling phase are nearly 1°C/MY at the depths of interest. Thus the geochronologic constraints are satisfied.

In the absence of igneous intrusions, the resultant metamorphic grade for the crustal horizon passing through 14 km at 325 Ma is greenschist facies. Figure 9 shows the predicted effect of the intrusion of a 2 km thick magmatic sheet. The pluses and diamonds give the geotherms at 400 Ma and 325 Ma respectively and the triangles give the array of maximum temperatures (or metamorphic field gradient) obtained following the emplacement and cooling of the magma, which takes 40,000 years to solidify. The cross-hatched band shows the observed metamorphic field gradient from the 500°C paleoisotherm to the K-feldspar + sillimanite isograd, assuming a dip of about 3 degrees and the temperatures listed in Table 1. The agreement is excellent. The K-feldspar + sillimanite zone, which roughly coincides with the mixed zone and is highly migmatized, is predicted to have temperatures in excess of 660°C. According to the melting relations for pelitic rocks of Thompson and Algor (1977), abundant migmatization in this zone would have been likely.

It is conceivable that similar arrays of maximum temperatures at the depth range of interest could be obtained with some scheme of burial, erosion, thermal parameters, and crustal heat production. However, it would result in melting the entire crust below about 15 km, which has clearly not happened. In addition, the direction of the P-T-t paths would be counter-clockwise as in Figure 8. They would cross the andalusite-sillimanite reaction curve in a retrograde fashion. As noted previously, this is contradictory to observation; this reaction curve was crossed in a prograde direction. As can be seen in Figure 10, the P-T-t paths caused by an igneous intrusion will cross all reaction curves in a prograde fashion and do so nearly isobarically as is observed both to the north and to the south of the Sebago batholith.

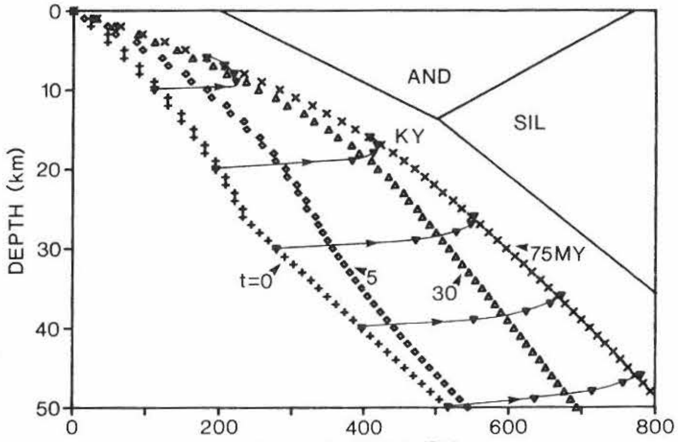

Figure 8. Thermal history for southwestern Maine based on burial and erosion history and thermal properties described in text. Pluses -- t = 0 (400 Ma); diamonds -- t = 5 MY (395 Ma); open triangles -- t = 30 MY (370 Ma); and crosses -- 75 MY (325 Ma). Closed triangles with solid lines -- P-T-t paths for horizons buried to 10, 29, 39, 40, and 50 km at t = 0; each triangle represents 20 MY. AND, SIL and KY -- andalusite, sillimanite, and kyanite. Alumino-silicate triple point after Holdaway (1971).

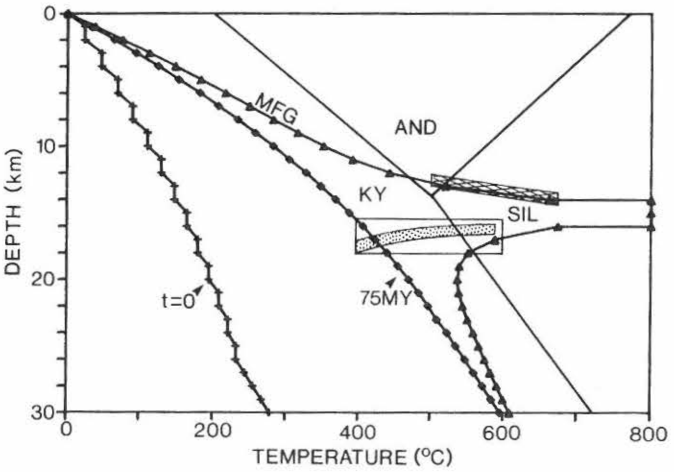

Figure 9. Effect of a 2 km thick igneous intrusion emplaced below 14 km on the temperature profile at 75 MY (325 Ma) of Figure 8. Pluses -- t = 0 (400 Ma); diamonds -- 75 MY (325 Ma); triangles -- array of maximum temperatures or metamorphic field gradient (MFG) experienced during solidification and cooling of the pluton. Cross-hatched band -- observed conditions of metamorphism south of the Sebago batholith assuming $P_{H2O} < P_{Total}$. Stippled band -- approximate MFG south of the Sebago batholith (see text). AND, SIL, and KY -- andalusite, sillimanite and kyanite. Alumino-silicate triple point after Holdaway. (1971).

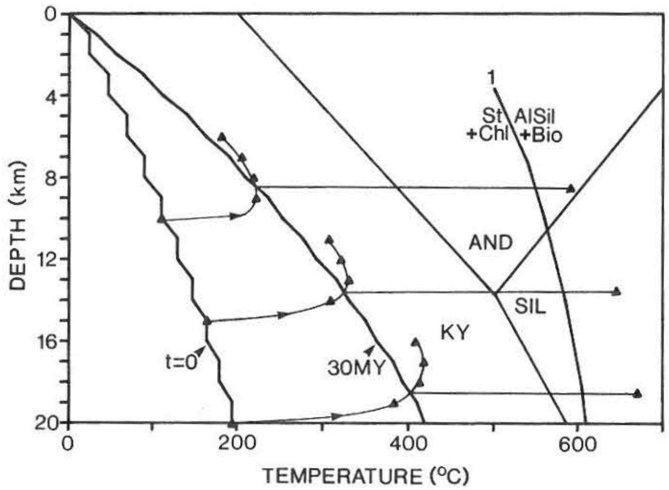

Figure 10. Effect of igneous intrusions at 30 MY on the P-T-t paths in Figure 8 for horizons buried to 10, 15 and 20 km at t = 0. Each horizon is placed in contact with the upper boundary of a 2 km thick magmatic sheet at 30 MY. (1) St = Chl + Al-Sil + Bio from Guidotti (1974).

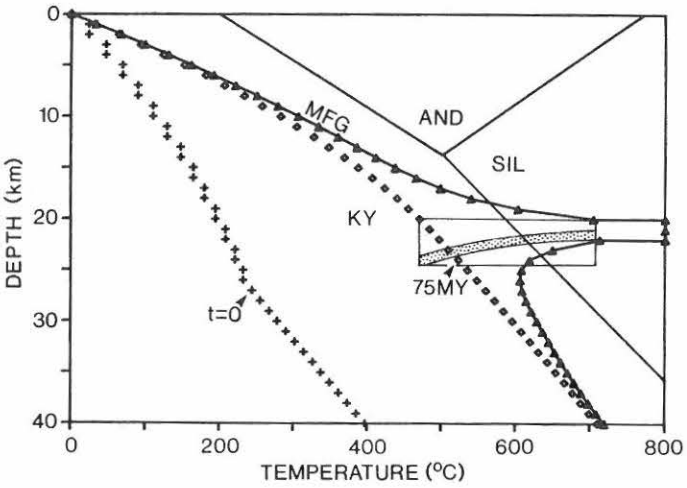

Figure 11. Effect of 2 km thick igneous intrusion emplaced below 20 km on the temperature profile at 75 MY (325 Ma) of Figure 8. Pluses -- t = 0 (400 Ma); diamonds -- t = 75 MY (325 Ma); triangles -- array of maximum temperatures or metamorphic field gradient (MFG) experienced during solidification and cooling of the pluton. Large open box -- observed conditions of metamorphism south of the Sebago batholith assuming $P_{H2O} = P_{Total}$. Stippled band -- approximate MFG south of the Sebago batholith (see text). AND, SIL, KY -- andalusite, sillimanite, kyanite. Alumino-sillicate triple point after Holdaway (1971).

Application of the model to the southern end of the batholith is more difficult for two reasons: (1) The pressure is very uncertain. (2) The study area is in a cove of the Sebago batholith where both the perimeter of the batholith and the isograds run parallel to to the dip direction. If a 3 degree dip is maintained, then the pressures of metamorphism would have been about 5.5 kbar, indicating $P_{H2O} < P_{Total}$. If we assume $P_{H2O} = P_{Total}$, then pressures were about 6.5 kbar, indicating a sharp increase in topographic relief from north to south at the time of emplacement. A traverse perpendicular to the isograds is perpendicular to the dip direction; thus pressure would have been nearly constant and it is then necessary to take into account the effect of being near the edge of the magmatic sheet. Unfortunately, the relationship of the isograds to the boundary of the igneous body is complicated by their location in the cove. With these complications in mind, the results of a straightforward application of the model to the southern end are presented in Figures 9 and 11 for the two pressure ranges discussed above. The large open box shows the range of conditions and the stippled band approximates the inferred metamorhpic field gradient (Thomson, 1986; Thomson and Guidotti, this volume). The sharp decrease in temperature with increasing depth below the pluton indicates that: (1) the Sebago batholith was the heat source for the metamorphism; (2) edge effects become important in this area.

Although the thermal effect of the pluton is large, it falls off rapidly with distance. Temperatures in excess of 500°C are experienced only out to approximately 1.5 km above the upper surface. For a dip of 2-3 degrees this is equivalent to a distance along the erosion surface of 30-50 km, in good agreement with the geochronologic data discussed above. These results demonstrate that, with only normal mantle heat flow and a lower limit of crustal radiogenic heat production, the Sebago batholith itself is the likely heat source for the surrounding regional metamorphism provided it extends to the northeast 30 to 50 km beyond its surface contact.

An upper-limit calculation was also performed. The volumetric heat production of the sediments was held at 2.25 uW/m^3 while that of the basement was increased to the value of present-day New England. The results are nearly identical. Ambient temperature at 14 km increases to 440°C at 325 Ma. Maximum temperatures within 2 km of the pluton increase by 30-45°C, and the slope of the predicted metamorphic field gradient is unchanged.

The effect of varying the melt temperature, T_m, was also examined. Variations in T_m of ± 50°C result in changes in the maximum temperatures near the pluton of <30°C.

DISCUSSION

The model presented here should be considered a lower estimate of the effects of the Sebago batholith for a number of reasons, aside from the modest values chosen for the thermal parameters. We have assumed that the magma was emplaced in a single episode, that the magma has a melting point rather than a melting range, and that the thermal diffusivity of the melt equals that of the solid. If the magma was injected in pulses on a 0.01 - 1.0 MY time scale, if the magma solidified over a range in temperature, or if the decreased thermal diffusivity of the melt was considered, the solidification and cooling time would have been prolonged and the thermal effects would have been more extensive.

The results of the model require the batholith to extend 30-50 km beyond its northern contact. The zone of pegmatites which wraps around the northeastern side of the batholith (Fig. 2) may provide evidence for this northeastern extension. We propose that these pegmatites are apophyses of the Sebago batholith, extending upward from the underlying sheet. The most northern of these pegmatites, the Whitecap Mountain pegmatite, (Fig. 2), is about 35 km north of the batholith, and there is evidence that it is Carboniferous in age rather than Devonian (Guidotti et al., 1986). If this northerly extension does not exist, the model may still apply if the Sebago batholith is only one of a number of related and possibly interconnected sill-like granite bodies intruded into the region at about 325 Ma ago.

Even if the above arguments are correct, the problem of a primary heat source still remains. However, as is shown in Figure 8, even with the lower-limit calculation, temperatures in excess of 800°C are experienced at the bottom of the crust by 325 Ma. In the upper limit, temperatures above 800°C are experienced everywhere below 40 km depth by 325 Ma. Thus it is likely that granitoid magmas would have been generated in response to Acadian thickening. Chamberlain and England (1985) reached a similar conclusion in examining the thermal evolution of the Kearsarge-central Maine synclinorium in New Hampshire.

As discussed above, Aleinikoff et al. (1985), obtained U-Pb ages on both zircons and monazites from the Sebago batholith. They found that the U-Pb age of the monazite was 50 million years younger than that of the zircon and suggested that the Sebago batholith, intruded at 325 Ma, did not cool below 600°C until 275 Ma. Furthermore, they suggest that cooling to 600°C was due to uplift and that, therefore, ambient temperature was 600°C. If the depth of emplacement of the Sebago batholith was 14 km, this would lead to an average gradient of over 40°C/km and pervasive melting of the crust below 15 km depth. In addition, for any reasonable radioactive productivity for the crust, the mantle heat flux would have had to have been 2-3 times that of present-day New England.

Aleinikoff et al. (1985) also suggest that the 10 million year difference in monazite ages between the two samples studied had two possible causes: (1) Because it was near the edge of the pluton, the sample near the northeast margin of the batholith cooled more rapidly than the sample near the center of the batholith. (2) The northeast portion of the batholith was uplifted more rapidly, causing a regional cooling gradient. The first explanation is unlikely to be correct because the batholith is so thin (≤2 km) that both samples would have cooled primarily from top and bottom and not from the edges. (Both sample localities are far more than 2 km from the edge.) Furthermore, for a reasonable ambient temperature (≤400°C), the time required to cool below 600°C is on the order of 10,000-100,000 years and not 10 million years. The second explanation is also unlikely because, once again, it required an ambient temperature of >600°C at 14 km. One can only conclude that either: (1) The closure temperature for Pb loss in monazite is hundreds of degrees lower than assumed. (2) The actual monazite ages are tens of millions of years older than the calculated ages. (3) The monazite ages represent a reheating event for the Sebago batholith. While there is no petrologic evidence for the latter, it should be noted that several $^{40}Ar/^{39}Ar$ release spectra for hornblendes from the region have diffusion gradients whose minimum ages are in the range of 270-290 Ma (Lux and Guidotti, 1985; Lux, unpub. data). These could also be interpreted as a result of a Permian heating event. However, these diffusion gradients are only observed in a few samples from the region. This suggests that if they are due to reheating, they may well be the result of local heat sources.

CONCLUSION

We have presented geochronologic data which provide an estimate of the ambient temperature at the time of the intrusion of the Sebago batholith, give a picture of the progression of cooling throughout the Sebago from 245 Ma to 230 Ma, and delineate the northern limit of the Carboniferous regional metamorphic event (M_C) in western Maine.

We have also presented a thermal model for the sheet-like Sebago batholith which suggests that M_C is a deep-level contact aureole of the batholith itself and that the pluton is likely to be a result of lower crustal melting in response to Acadian thickening. We hypothesize that the Sebago batholith, or closely related granitic sheets, extend at least 30 to 50 km to the northeast and that the metamorphism to the north of the Sebago batholith was produced above the batholith while that to the south was produced below the batholith.

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