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Article abstract

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The high-grade terrane of this part of the Appalachian Orogen is composite. It is made up of crustal blocks that experienced discrete pulses of high-grade metamorphism beginning perhaps as long ago as the pre-Middle Ordovician and extending into the Permian. Ages of peak metamorphism support the hypothesis that the Central Maine and Merrimack teiranes had different tectono-metamorphic histories and are coincidentally juxtaposed at the same metamorphic grade.

The Campbell Hill-Nonesuch River-Norumbega fault zone has had an active and complex history, beginning approximately 360 Ma and lasting at least to 250 Ma. This boundary is a likely candidate for the western Alleghenian (Variscan) Front in New England. The final juxtaposition of the Central Maine and Merrimack terranes may have occurred during the Mesozoic along extensional, terrane-bounding faults, possibly the reactivated Acadian compressional and/or Alleghenian transpressional structures.

The timing of peak high-grade metamorphism in central-eastern New England

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L'application de la systématique U-Pb a permis la datation de la monazite et du sphène extraits de schistes métamorphisés au grade de la sillimanite, de gneiss et de granites à deux micas provenant de la Lanière de Central Maine et de la Fosse de Merrimack. Les âges ainsi obtenus imposent des contraintes précises sur l'époque du paroxysme métamorphique et du plutonisme en Nouvelle-Angleterre septentrionale. Dans la Lanière de Central Maine, le métamorphisme est d'âge acadien (éodévonien). Dans la Fosse de Merrimack, d'un côté à l'autre de la zone de failles de Campbell Hill-Nonesuch River-Norumbega, le métamorphisme date de l'Alléghanien(?) (Permien). Les âges des granites mettent en évidence un épisode distinct de magmatisme dévonien qui caractérise la Lanière de Central Maine.

Dans cette portion de l'Orogène appalachien, la lanière présentant un haut degré de métamorphisme est composite. Elle comprend des blocs crustaux ayant subi des épisodes distincts de métamorphisme de haut degré qui débutent possiblement à l'Ordovicien moyen pour s'étaler jusqu'au Permien. Les âges du paroxysme métamorphique confortent l'hypothèse voulant que les lanières de Central Maine et de Merrimack aient eu des histoires tectono-métamorphiques différentes et que leur juxtaposition à un même grade métamorphique ne soit que coïncidence.

L'histoire de la zone de failles de Campbell Hill-Nonesuch River-Norumbega est active, complexe et s'échelonne d'environ 360 Ma jusqu'à au moins 250 Ma. Cette frontière forme un candidat plausible pour le Front alléghanien (varisque) occidental en Nouvelle-angleterre. La juxtaposition finale des lanières de Central Maine et de Merrimack s'effectua peut-être au Mésozoïque le long de failles en extension bordant les lanières, possiblement par réactivation des accidents compressifs acadiens et/ou des structures transpressives alléghaniennes.

[Traduit par le journal]

INTRODUCTION

We present U–Pb ages for monazite and sphene from schists and granites in what are thought to be two juxtaposed geologic terranes, the Central Maine Terrane (Zen *et al.*, 1986) and the Merrimack Trough. The Merrimack Trough includes both the basement (Massabesic Gneiss Complex) and the cover sequence (Merrimack Group). The term Central Maine Terrane is used

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instead of Kearsarge-Central Maine Synclinorium, as defined by Lyons *et al.* (1982), to provide distinction between the Kearsarge-Central Maine Synclinorium proper, now recognized as only one of several synclinorial fold structures in the Central Maine Terrane, and the entire Siluro-Devonian basin itself.

Although the Central Maine Terrane and Merrimack Trough are thought to have had markedly different tectono-thermal histories (Lyons *et al.*, 1982; Gaudette *et al.*, 1984; Bothner *et al.*, 1984), they are juxtaposed at the same metamorphic grade. A knowledge of the time of peak high-grade metamorphism can test the composite terrane model put forth for this region. It is crucial to tectonic models to understand the precise timing of metamorphic events relative to regional deformation and the intrusion of syn- and post-tectonic plutons which may control or drive metamorphism. Constraints on the timing of metamorphism become even more critical when dealing with discrete terranes made up of somewhat lithologically similiar rocks at the same grade of metamorphism, as is the case for the Merrimack Trough and Central Maine Terrane. Fieldwork must be complemented by geochronology to establish the tectonic history.

REGIONAL GEOLOGY

Through the past decade, a progressively convincing data base has emerged suggesting that the coastal geology of the northern New England Appalachians is a composite of distinct lithotectonic terranes (Lyons *et al.*, 1982; Gaudette *et al.*, 1984; Bothner *et al.*, 1984; Zen *et al.*, 1986; Hussey, 1985; Osberg *et al.*, 1985). The major terranes in this region are shown in Figure 1. The Central Maine Terrane is bounded on the southeast by the Campbell Hill-Nonesuch River-Norumbega fault zone. Southeast of this terrane boundary lies the Coastal Lithotectonic Block of Maine, and the Merrimack Trough of southwestern Maine and southeastern New Hampshire. Along the New Hampshire coast

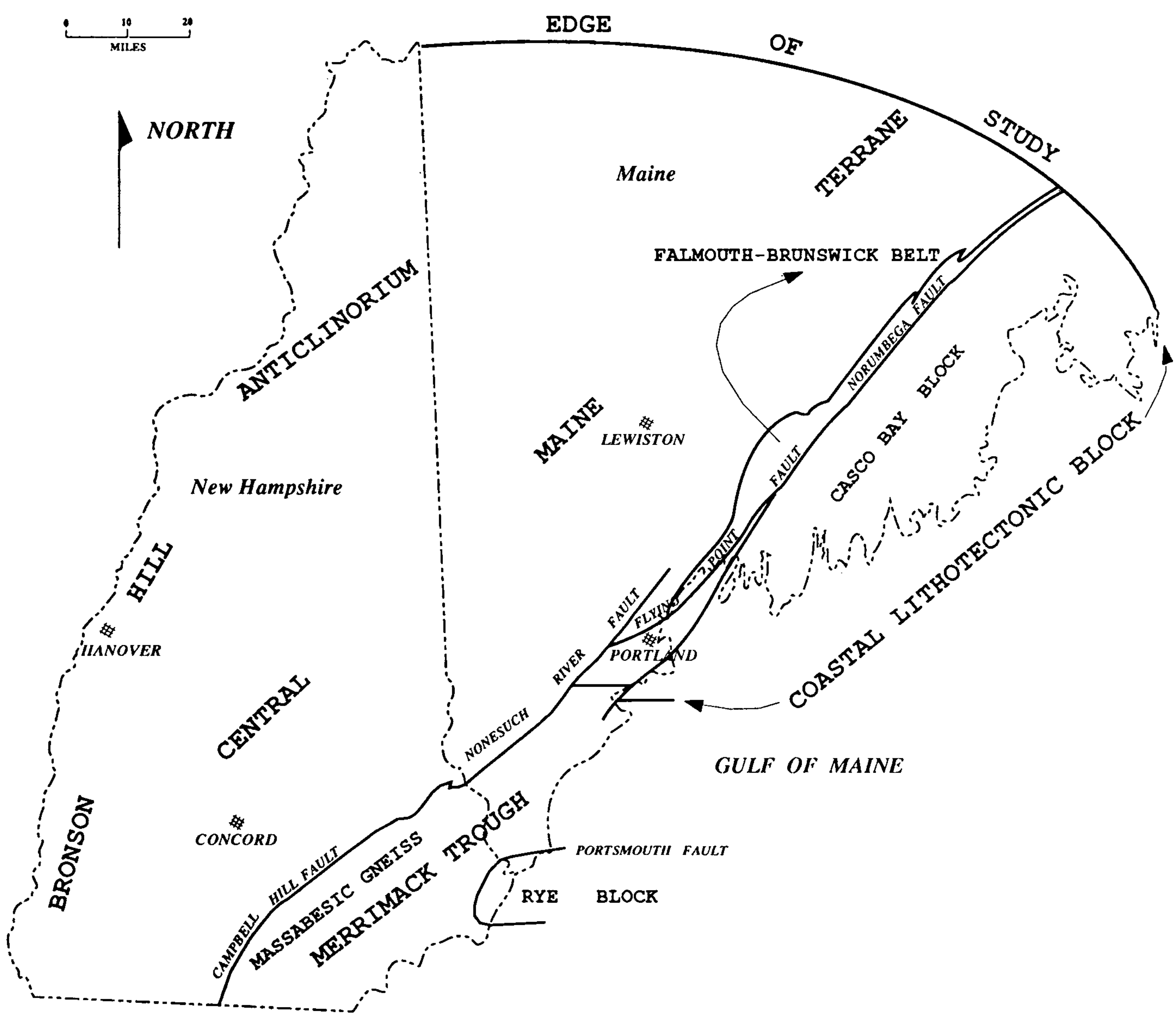

Fig. 1. Terranes of central and southeastern New Hampshire and southwestern Maine. Modified from Lyons *et al.* (1986), Osberg *et al.* (1985), and Hussey (1985).

and juxtaposed against the Merrimack Trough along the Portsmouth fault is the "Rye Block" (note: all the names that are in quotes are informally used here). Within the Coastal Lithotectonic Block are the Falmouth-Brunswick Belt (Hussey, 1985) and "Casco Bay Block" separated by the Flying Point fault. The Flying Point fault connects the Nonesuch River and Norumbega faults providing the link in a master fault system that extends from Massachusetts to New Brunswick (Fig. 1). The "Casco Bay Block" includes Hussey's (1985) Casco Bay Group, South Portland-Harpswell Belt, and East Harpswell-Merrymeeting Bay Belt. These terranes have intervening faults but have been grouped together here for simplicity. The Coastal Lithotectonic Block is separated from the Merrimack Trough by an east-west trending thrust fault in southwestern Maine (Hussey, 1985; Osberg *et al.*, 1985) (Fig. 1).

CENTRAL MAINE TERRANE

The Central Maine Terrane is composed of Late Ordovician to Early Devonian metasedimentary rocks (predominantly turbidites) that are multiply deformed and complexly metamorphosed. In New Hampshire, the metasedimentary rocks are Siluro-Devonian in age (Silurian Rangeley, Perry Mountain, Smalls Falls, and Madrid formations and Devonian Littleton Formation) (Lyons *et al.*, 1986). In Maine the deeper levels of the section, the Late Ordovician or Early Silurian Vassalboro Formation, are exposed (Osberg *et al.*, 1985). These metasedimentary rocks are part of a large basin, extending from New Brunswick to Connecticut, and their source in Late Ordovician through Silurian time was centered over the Bronson Hill Anticlinorium. In the Early Devonian, the source switched to the east-northeast (Hatch *et al.*, 1983; Hanson and Sauchuk, 1986; Hall *et al.*, 1976).

The metamorphic rocks are intruded by thin sheet-like (Hodge *et al.*, 1982; Nielson *et al.*, 1976) granitic rocks of the New Hampshire Plutonic Series (Lyons *et al.*, 1986). The New Hampshire Plutonic Series has three broad categories of granitoid rocks: (1) large, Early Devonian, syn-tectonic plutons (e.g., Bethlehem Gneiss, Kinsman Quartz Monzonite, Spaulding and Winnipesaukee Quartz Diorites, and Mooselookmeguntic Pluton); (2) smaller, Middle to Late Devonian, syn- and post–tectonic bodies of predominantly two-mica granite (e.g., Concord Granite); and (3) Carboniferous, predominantly post-tectonic, two-mica granites (e.g., Sebago Pluton and Effingham Pluton) (Fig. 2) (Lyons *et al.*, 1982; Lyons *et al.*, 1986; Osberg *et al.*, 1985).

The complex deformation of the Central Maine Terrane has historically been considered Acadian in age (Lyons *et al.*, 1982). Recent radiometric work by Hubacher and Lux (1987) has confirmed the Acadian age of deformation in Maine. At least four episodes of regional deformation have been recognized. In the Central Maine Terrane of New Hampshire a regional east and west verging nappe-stage folding event was followed by thrusting and then by three episodes of folding. Much of the section is inverted as a consequence, and most of the major fold structures face downward or are at least compound refolded structures (Eusden *et al.*, 1987; Robinson, 1987; Thompson *et al.*, 1987).

Though the style and sequence of Acadian regional deformation in Massachusetts and New Hampshire is essentially the same and attributed to regional strain, the deformation in parts of Maine is interpreted as magma-generated and different in style and sequence (Moench and Zartman, 1976). The change in structural style may be a reflection of a transition from higher (Maine) to lower (New Hampshire and Massachusetts) crustal levels in the Central Maine Terrane (Moench *et al.*, 1982). The nature of this strain response and the relationship between the folds generated by regional strain and those produced by forceful emplacement of plutons is unknown. The inferred change in crustal level from southwest to northeast in the Central Maine Terrane will significantly control the character and timing of regional metamorphism across the orogen.

MERRIMACK TROUGH

The Merrimack Trough is composed of multiply deformed and complexly metamorphosed turbidites (Kittery, Eliot and Berwick formations) that are of enigmatic age and stratigraphic sequence (Bothner *et al.*, 1984; W.A. Bothner and J.B. Lyons, personal communication, 1988). The section is intruded by post-tectonic Middle Ordovician diorites, the Exeter and Newburyport complexes, and by the Silurian Ayer granodiorite (Bothner *et al.*, 1984; Zartman and Naylor, 1984; Gaudette *et al.*, 1984). Bothner *et al.* (1984) have argued that the metasedimentary rocks of the Merrimack Trough pass gradationally into the Massabesic Gneiss Complex, which has been dated as Late Precambrian (Aleinikoff *et al.*, 1979). Therefore the best age assignment for Merrimack Trough sediments is at least pre-Middle Ordovician and probably Precambrian (Gaudette *et al.*, 1984; Bothner *et al.*, 1984). In addition to the Middle Ordovician Exeter and Newburyport diorites and the Silurian Ayer granodiorite, the metasedimentary rocks of the Merrimack Trough are intruded by post-tectonic, Devonian, Carboniferous, and Permian granitoid rocks, many of which are two-mica granites (Lyons *et al.*, 1986).

Three folding events have been recognized in the Merrimack Trough. Early recumbent nappe-stage folds were twice refolded (Hussey *et al.*, 1986). Because the Middle Ordovician Exeter diorite cuts these structures, the age of deformation is pre-Middle Ordovician or possibly Precambrian (Bothner *et al.*, 1984; Gaudette *et al.*, 1984). Bothner *et al.* (1988) have geophysical evidence to suggest the Merrimack Trough consists of anastamosing fault slivers which may have been operative in the Alleghenian.

Some of the units in the Merrimack Trough (the Berwick Formation in particular) are extremely similiar in lithology to Late Ordovician to Early Devonian formations in the Central Maine Terrane, particularly the Vassalboro Formation of Maine and the Paxton and Oakdale formations of Massachusetts. Furthermore, these units are juxtaposed just across the Nonesuch River fault zone. If these units do correlate, then there is a possibility of a Late Ordovician to Early Devonian depositional age for the Merrimack Trough sediments despite the available radiometric ages on cross-cutting plutons (Hussey, 1985; Hussey *et al.*, 1986; Barosh *et al.*, 1981). In that case, the need for a major terrane boundary between the Central Maine Terrane and Merrimack Trough becomes moot (Hussey, 1985; Hussey *et al.*, 1986).

Sedimentologic evidence argues for the existence of two

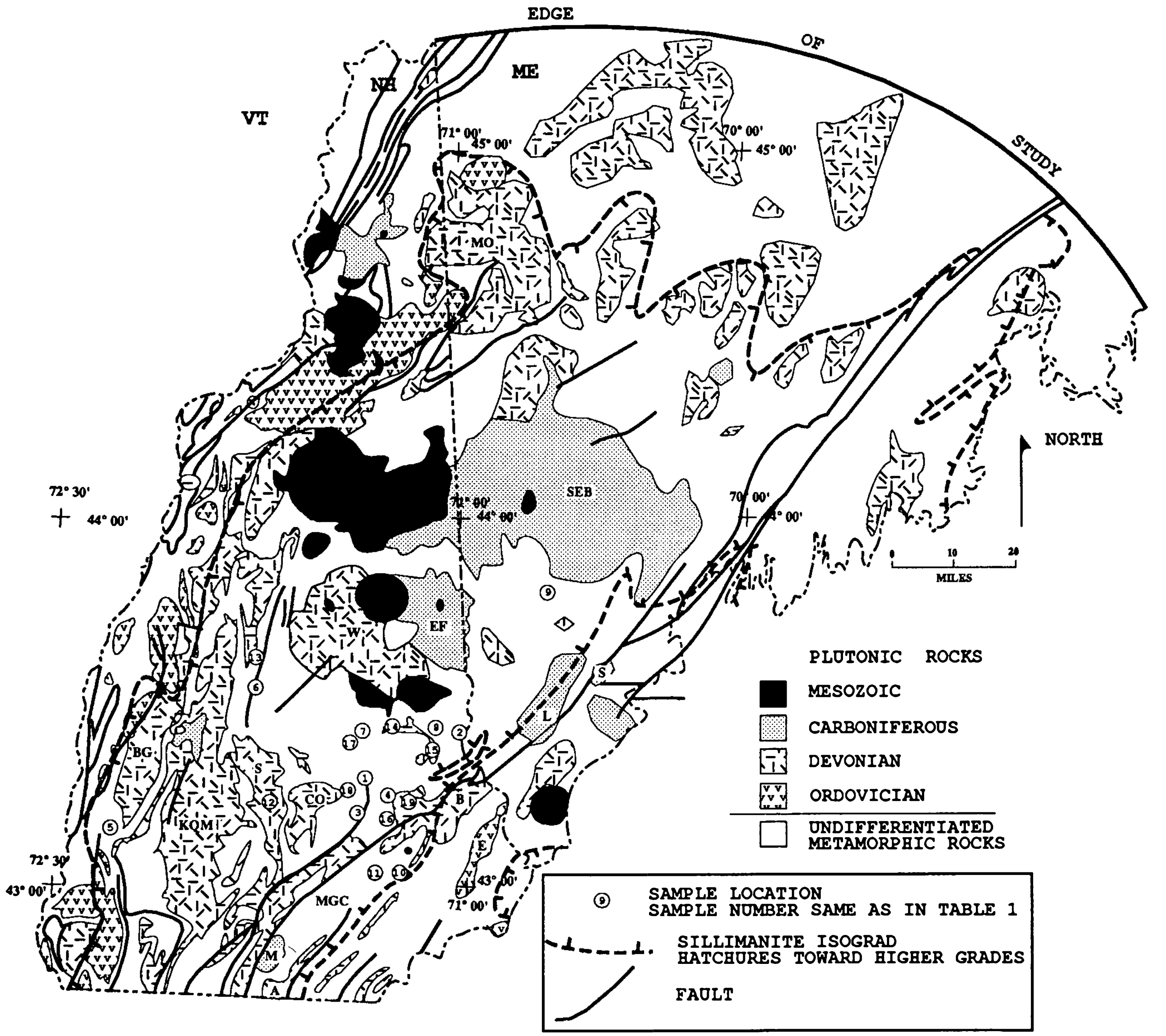

Fig. 2. Simplified geologic map of New Hampshire and southwestern Maine modified from Lyons *et al.* (1986) and Osberg *et al.* (1985). Pluton abbreviations: A - Ayer; B - Barrington; BG - Bethlehem Gneiss; CO - Concord; EF - Effingham; E - Exeter; KQM - Kinsman Quartz Monzonite; L - Lyman; M - Milford; MO - Mooselookmeguntic; SEB - Sebago; S - Saco; MGC - Massabesic Gneiss Complex.

distinct terranes. Paleocurrent indicators in the Kittery Formation of the Merrimack Trough show that the source of these sediments was from the east, the site of the present Atlantic ocean (Rickerich, 1983; Hussey *et al.*, 1986). This is opposite from the source direction of the Silurian Central Maine Terrane sequence which was centered roughly over the Bronson Hill Anticlinorium (Hatch *et al.*, 1983). Based on the available radiometric and sedimentologic data, we favor the two-terrane hypothesis.

Northwest of the Merrimack Group lies the Massabesic Gneiss Complex. It is bounded on the northwest by a thin belt of Berwick Formation and in turn by the Campbell Hill-Nonesuch River-Norumbega fault zone. The Massabesic gneiss is composed of migmatites interpreted to consist of ortho- and paragneisses. The ~650 Ma paragneiss is thought to be the high-grade equivalent of the Berwick Formation based on lithic similiarities and gradations between the two (Gaudette *et al.*, 1984; Bothner *et al.*, 1984; Olszewski and Gaudette, 1988; Aleinikoff *et al.*, 1979). Also present are 650 and 475 Ma orthogneisses thought to be of igneous, possibly metavolcanic origin, based on zircon morphology, contact relations with the paragneiss, and the presence of a wide variety of xenoliths (Bothner *et al.*, 1984; Aleinikoff *et al.*, 1979).

Of particular interest in our study is the Permian age (275 Ma), based on zircon U-Pb geochronology, of a granite at Milford, New Hampshire which cuts the Massabesic Gneiss Complex, and a discordant Permian (250 Ma) monazite age from Massabesic paragneiss adjacent to the granite at Milford as reported by Aleinikoff *et al.* (1979). These have been interpreted as vestiges of Alleghenian (Permian) orogenesis, similiar to that reported in Rhode Island but, at that time, not recognized in other parts of New England (Aleinikoff *et al.*, 1979). The possibility of more widespread Alleghenian/Permian deformation and metamorphism throughout much of New England has been recently promoted by Gromet (1988).

TIMING OF HIGH-GRADE METAMORPHISM

As shown on Figure 2 the upper amphibolite facies regional metamorphic terrane terminates to the northeast in Maine and extends southeast through New Hampshire into Massachusetts and Connecticut. The age of high-grade metamorphism has historically been considered Acadian (i.e., Devonian) (Billings, 1956; Thompson and Norton, 1968) and recent compilations continue to show the peak high-grade assemblages in this area as Acadian (Robinson, 1986). The sillimanite isograd, outlining the metamorphic plateau (shown on Figure 2), crosses many of the aforementioned tectonostratigraphic terrane boundaries with little or no offset (Hussey, 1985; Newberg, 1986 and references cited within). Many of the terranes are juxtaposed along these boundaries at identical sillimanite metamorphic grade (Bothner *et al.*, 1988 and 1984).

If the metamorphic plateau was formed during a single episode of regional metamorphism, the simplest conclusion is that the terranes were assembled in pre-Acadian time and subsequently experienced regional metamorphism during the Devonian. Later events caused only minor shuffling of the isograds and bedrock along the terrane boundaries.

However, within the Central Maine Terrane, recent work suggests that timing of peak high-grade metamorphism varied across the area. Lux and Guidotti (1985) show that some of the peak high-grade metamorphism in the Central Maine Terrane near the Sebago batholith is Hercynian (Alleghenian?) and not Acadian. Furthermore, new radiometric ages that can be interpreted as constraints on the timing of high-grade metamorphism show that rocks at the same metamorphic grade in different terranes were metamorphosed at different times. For example, West *et al.* (1988a, b) report Permian and Carboniferous metamorphic ages from the Cushing Formation and Olszewski and Gaudette (1988) and Gaudette *et al.* (1984) reported a Cambrian metamorphic event within the Merrimack Trough.

These data, all from the same metamorphic plateau, suggest that: (1) within a single terrane, the mapped regional isograds are composite, although they do not appear so; (2) the view that this high grade metamorphic plateau formed exclusively during the Acadian may not be correct; and (3) the ages of peak high-grade metamorphism may help constrain the tectono-thermal history of the terranes in this composite region.

U-Pb GEOCHRONOLOGY

To determine the timing of high-grade metamorphism, we have used the U–Pb system in monazite and sphene from sillimanite- or higher grade metasedimentary rocks. We have also dated monazite from peraluminous granites to assess the spatial and temporal relationships between metamorphism and plutonism. The advantage in dating high-grade metamorphism with monazite and sphene in this region is that there is an abundance of monazite-bearing, sillimanite-grade, pelitic schists with subsidiary sphene-bearing calc-silicate units. The lack and/or scarcity of hornblende-bearing mafic schists precludes the use of $^{40}Ar/^{39}Ar$ release spectra on hornblendes as an alternative mineral chronometer for dating high-grade metamorphism in much of the region studied. The U-Pb ages of monazites from high-grade schists can record the timing of their growth during sillimanite-grade or higher metamorphism rather than an inherited detrital age (Koppel and Grunenfelder, 1975; Koppel *et al.*, 1980; Oberli *et al.*, 1981; Black *et al.*, 1984; Parrish, 1987; and Parrish *et al.*, 1987). The closure temperature of monazite is not well known but is in the range of 675° to 725°C (Koppel and Grunenfelder, 1975; Copeland *et al.*, 1988).

One factor which may affect U–Pb ages in monazite is excess radiogenic ^{206}Pb inherited from excess ^{230}Th derived from the ^{238}U decay chain, which is incorporated into the monazite during crystallization (Scharer, 1984; Scharer *et al.*, 1986). However, unless the Th/U ratio in the source material (i.e., the whole rock or mineral precipitating fluid) was abnormally low (an order of magnitude below the terrestrial value of 4), the excess ^{206}Pb effect is small in monazites of this age with our calculated Th/U ratios. Whole-rock Th/U ratios determined using neutron activation analysis on the schists we dated range from 2.0 to 3.0, similiar to analyses reported by Lyons (1964) for the same formations. Therefore, we believe that the excess ^{206}Pb effect is insignificant among the schists. However, it is a concern for the granites which commonly have higher Th/U ratios and measured reverse discordance.

There has been less work on sphene from metasedimentary rocks, though studies of igneous or meta-igneous sphene are common (Tucker *et al.*, 1986; Mattinson, 1982). The closure temperature of the U-Pb system in sphene is estimated to be about 550±50°C, close to, but slightly higher than that of the $^{40}Ar/^{39}Ar$ system in hornblende (Mattinson, 1986).

Garnet-biotite geothermometry and phase relations for the samples we have dated show that the temperatures during metamorphism ranged from 500° to 700°C (Eusden, 1988). This temperature window also agrees with regional estimates of peak metamorphic conditions within the sillimanite plateau (Chamberlain and Lyons, 1983). The current best estimates for the closure temperatures of both monazite and sphene are similiar to the peak metamorphic temperatures in this region. We believe that the U–Pb ages of these minerals, which crystallize during metamorphism, closely record the timing of peak high-grade metamorphism (see also Overstreet, 1967). At the very least, the ages may represent cooling ages soon after peak metamorphism.

GEOCHRONOLOGY OF THE SCHISTS AND GNEISSES

The U-Pb ages of nine high-grade pelitic schists (sillimanite-grade or higher) from the Silurian Rangeley and Perry Mountain formations of the Central Maine Terrane are either concordant within analytical precision or exhibit slight normal discordance (Table 1, Fig. 3, and Appendix 1; sample locations shown on Figure 2). The ages range from $^{206}Pb/^{238}U$ = 365-398 Ma, $^{207}Pb/^{235}U$ = 367-398 Ma, and $^{207}Pb/^{206}Pb$ = 376-402 Ma.

Table 1. U-Pb data.

	Sample (4)	Concentrations U, ppm	Pb(rad),ppm	Atomic ratios (1) 206Pb/204Pb	206Pb*/238U	207Pb*/235U	207Pb*/206Pb*	208Pb*/206Pb*	Th/U (2)	Ages, (Ma) (3, 5) 206*/238	207*/235	207*/206*
	Schists											
1	Route 106	3029	403	14400	0.06098	0.4569	0.05435	1.47	04.6	382	382	385
2	Spaulding Turnpike	9107	960	36800	0.05964	0.4476	0.05444	0.99	03.1	373	376	389
3	Route 393	7346	1053	19100	0.06183	0.4648	0.05451	1.63	05.0	387	388	392
4	Catamount	4853	633	17500	0.05986	0.4493	0.05443	1.47	04.5	375	377	389
5	Gilsum	5153	978	17400	0.06366	0.4806	0.05475	2.39	07.4	398	399	402
6	Bristol	1501	520	11800	0.06273	0.4715	0.05452	5.32	16.5	392	392	392
7	Route 107	8237	1018	19300	0.06018	0.4507	0.05432	1.32	04.1	377	378	384
	Rte 107 2nd fraction	4146	2147	21800	0.06038	0.4527	0.05437	1.35	04.3	378	379	387
8	Rte 11	3516	1757	10200	0.05825	0.4348	0.05413	1.89	06.0	365	367	376
9	Limerick, Me	3642	1920	38100	0.06149	0.4604	0.05431	0.97	03.1	385	385	384
10	Berwick Fm	2398	922	4820	0.04485	0.3200	0.05174	2.59	08.3	283	282	274
	Berwick Fm 2nd fraction	2659	988	4776	0.04332	0.3086	0.05165	2.47	07.9	273	273	270
11	Massabesic paragneiss sphene	149	54	366	0.04248	0.3101	0.05294	0.12	00.4	268	274	326
	M P sphene 2nd fraction	133	45	422	0.03955	0.2930	0.05373	0.22	00.7	250	261	360
	Granites											
12	Spaulding quartz diorite	2713	986	31700	0.06349	0.4790	0.05472	5.55	17.2	397	397	401
13	Bristol pegmatite	4871	438	12500	0.06365	0.4787	0.05454	0.58	01.8	398	397	393
14	Hall's Sill	2307	986	7918	0.05943	0.4449	0.05429	7.24	22.3	372	374	383
	Hall's Sill 2nd fraction	1145	581	8540	0.05920	0.4412	0.05405	6.96	22.2	371	371	373
15	New Durham Pluton	4189	1379	11300	0.05913	0.4374	0.05365	5.37	16.7	370	368	356
	New Durham 2nd fraction	1940	1005	20600	0.06039	0.4509	0.05414	5.55	17.8	378	378	377
16	Pembroke Peg	2200	1126	9062	0.05966	0.4440	0.05398	3.13	10.0	374	373	374
	Pembroke Peg 2nd fraction	671	348	5724	0.06041	0.4504	0.05407	4.8	15.4	378	378	374
17	Belmont Sill	1519	739	17300	0.05672	0.4244	0.05427	4.66	14.7	356	359	382
18	Loudon Sill	1634	794	11800	0.05670	0.4198	0.0537	3.49	11.1	356	356	359
19	Barrington Pluton	7543	3656	150000	0.05653	0.4196	0.05383	0.04	00.1	354	356	364

Notes:

1 * = radiogenic Pb corrected for common Pb with isotopic composition 204:206:207:208:=1:18.38:15.68:38.42 (samples 1-4, 7, 9-11) or with Pb isotopic composition deduced from leached feldspars (samples 5, 6, and 8)
2 Th/U calculated assuming concordancy of the Th/Pb system with the 206Pb*/238U ages
3 Ages calculated using 235U=9.8485E-10 y-1 and 238U=1.55125E-10 y-1
4 Sample numbers are the same as those shown on Figure 2. Locations on Figure 2.
5 Maximum uncertainties: 206/238 = .2%; 207/235 = .5%; 207/206 = .5%

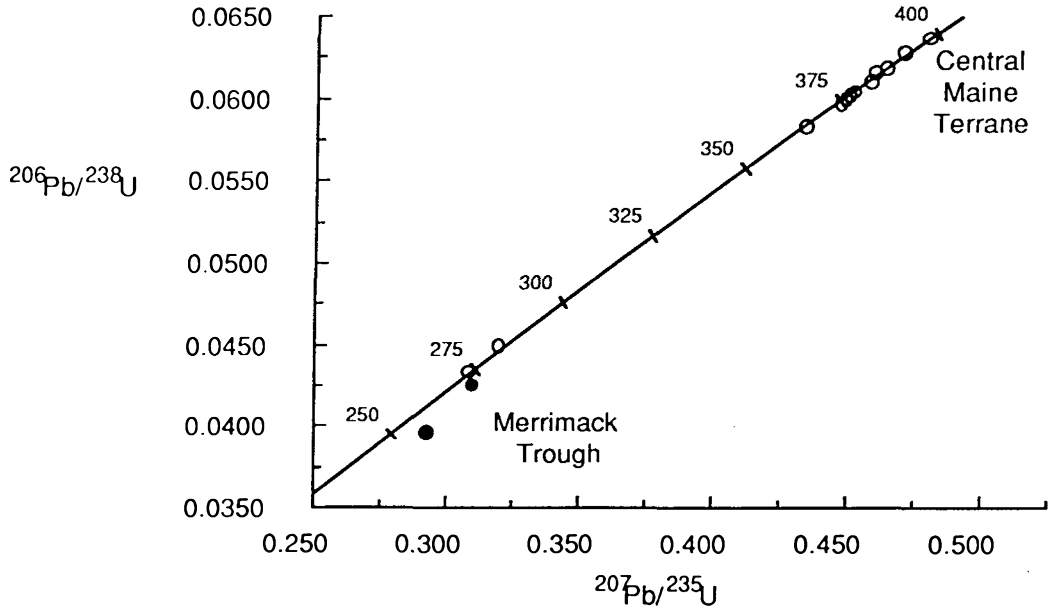

Fig. 3. Concordia plot showing monazite ages from schists in the Central Maine Terrane and monazite and sphene ages from schists in the Merrimack Trough. Open circles - monazite. Filled circles - sphene. Errors smaller than size of circles.

As both excess ^{206}Pb and non-modern Pb-loss decrease the $^{207}Pb/^{206}Pb$ age, we consider the $^{207}Pb/^{206}Pb$ ages as minimum ages. Therefore, the minimum range of metamorphic ages is 376-402. These ages are Acadian (Early to Middle Devonian) and agree well with constraints placed on the timing of regional deformation and metamorphism as inferred by the ages of syntectonic and crosscutting and post-tectonic New Hampshire Series granites (Lyons *et al.*, 1982).

Two fractions of monazite from the sillimanite-grade Berwick Formation have ages of $^{206}Pb/^{238}U$ = 273 and 293 Ma, $^{207}Pb/^{235}U$ = 273 and 282 Ma, and $^{207}Pb/^{206}Pb$ = 270 and 274 Ma (Table 1, Fig. 3, and Appendix 1; locations shown on Figure 2). Because these samples are reversely discordant, probably due to excess ^{230}Th rather than U-loss common in high-U minerals, the $^{207}Pb/^{235}U$ age should be considered a minimum age. Two fractions of sphene from the Massabesic gneiss are discordant but have Permian $^{206}Pb/^{238}U$ ages of 270 and 252 Ma and $^{207}Pb/^{235}U$ ages of 276 and 263 Ma.

In contrast to the Central Maine Terrane data, U-Pb ages from the Massabesic Gneiss Complex and Merrimack Trough imply that peak high-grade metamorphism was Permian. The two sphenes that were dated can be interpreted as having been disturbed during a Permian event which resulted in recrystallization of new sphene partially or completely resetting older sphene. It is possible that an early, pre-Middle Ordovician metamorphism preceded the Permian metamorphism. Olszewski and Gaudette (1988) suggested that a Cambrian metamorphic-plutonic event is a characteristic of the Merrimack Trough, and Fagan (1986) reported petrographic evidence from the Merrimack Trough suggesting two episodes of metamorphism.

GEOCHRONOLOGY OF THE GRANITES

We have dated eight granites, seven of which are entirely within the Central Maine Terrane. The eighth is the Barrington granite which is thought to stitch the Campbell Hill-Nonesuch River-Norumbega fault zone. The granite data show a greater incidence of reverse discordance, possibly due to excess ^{206}Pb. Calculated Th/U ratios of monazite from granite (see Table 1) are higher than in the schists and gneisses, implying a greater chance for initial ^{230}Th disequilibrium. The following discussion will use only the $^{207}Pb/^{206}Pb$ ages for normally discordant samples and $^{207}Pb/^{235}U$ ages for reversely discordant samples. The problems with inherited Pb (Sawka and Harrison, 1986; Copeland *et al.*, 1988), excess ^{206}Pb from ^{230}Th, and the marked discordancy of the granite samples inhibit us from presenting anything more than generalizations concerning the significance of the granite ages (Table 1). Despite the possible complications with the monazite U-Pb systematics, the granite ages range from 393-356 Ma. These ages contribute to the already voluminous data base showing a distinct pulse of Devonian magmatism in the Central Maine Terrane (Table 2).

The Barrington Pluton, also called the Center Strafford Pluton (Lyons, personal communication, 1988), stitching the Campbell Hill-Nonesuch River-Norumbega fault zone, has also been affected by motion in zones parallel to and along the boundary, as evidenced by well developed mylonitic S-C fabrics (Eusden, 1988). The pluton must have experienced only minor offset as it shows insignificant map scale displacement. The monazite $^{207}Pb/^{206}Pb$ age of the Barrington is 364 Ma. The Lyman (322 Ma) and Saco (307 Ma) granites of southwestern Maine are

Table 2. Timing of plutonism in the Central Maine Terrane as compared to the Merimack Trough/Messabesic Gneiss based on available radiometric ages.

Age (Ma.)		Central Maine Terrane: Large Syn-tectonic Plutons		Central Maine Terrane	Merimack Trough/Massabesic Gneiss Complex: All Post-tectonic (?) except gneisses of Massabesic Complex		Age (Ma.)
			POST-TECTONIC		Milford (275, 10B)		
	PERMIAN					PERMIAN	
···286···	···········					···············	286···
300							300
				Saco (307, 1A,*)	Saco (307, 1A,*)		
310							310
320	CARBONIFEROUS			Lyman (322, 1A,*)	Lyman (322, 1A,*)	CARBONIFEROUS	320
				Sebago (325, 2B,3A); Effingham (325, 3A)			
330							330
340				Center Strafford (???,0C)	Biddeford (341, 1A)		340
350							350
				Barrington (356,0C*); Sunapee (354, 4B, 5A); Loudon Sill (356,0C)	Barrington (356,0C*)		
···360···	···············			Phillips (360,18,E); Belmont Sill (359,0C)		···············	360····
				Concord (365, 6B); Newfoundland Lake (365, 7B);Hooksett (365, 7B)			
370		Mooselookmeguntic (371,16A)	SYN-TECTONIC	Hall's Sill (371,0C)			370
				New Durham (375,0C); Pembroke Peg (375,0C)			
380	DEVONIAN			Fitzwilliam (383,5A); Umbagog (382, 7B); 3 Mile Pd. (381,15A); Songo (380, 17B)		DEVONIAN	380
				Hallowell (387, 15A)			
390		Kearsarge (393,8A); Spaulding (393, 0C)		Bristol Peg (393, 0C); Togus (394, 15A)			390
		Mt. Clough (399, 7B)					
400							400
					Webhannet (403,1A)		
···408···	···········	Cardigan (402-413,8A, 9D)				···············	408···
420							420
	SILURIAN	(Older Highlandcroft and Oliverian				SILURIAN	
430		Granites Not Shown)					430
					Ayer (433, 11B)		
···438···	···········					···············	438···
					Newburyport (450, 11B)		450
							460
						ORDOVICIAN	
							470
					Exeter (473, 12A); Massabesic Orthogneiss (475, 10B)		
					Appledore Island Diorite (479,12A)		480
							490
						···············	505···
							520
							530
						CAMBRIAN	
							540
							550
						···············	570···
							580
						PRECAMBRIAN	
							590
					Massabesic Gneiss (600-640, 12B,10B,14A)		600

All ages are listed in parentheses following the name of the pluton.
Ages are followed by a number and letter that refer to the source and method used.
An * means that this pluton seals the terrane boundary and has experienced no or only minor offset

SOURCES

0 This Study
1 Gaudette, Kovach, and Hussey, 1982
2 Aleinikoff, Moench, and Lyons, 1984
3 Hayward and Gaudette, 1984
4 Harrison et al., 1987
5 Hayward, 1983
6 Aleinikoff unpublished
7 Aleinikoff in Moench, 1986
8 Lyons and Livingston, 1977
9 Barreiro and Aleinikoff, 1985
10 Aleinikoff, Zartman, and Lyons, 1979
11 Zartman and Naylor, 1984
12 Olszewski and Gaudette, 1988
13 Besancon, Gaudette, and Naylor, 1977
14 *Kelly, Olszewski, and Gaudette, 1980*
15 Dallmeyer and VanBreeman, 1981
16 Moench and Zartman, 1976
17 Lux and Aleinikoff, 1985
18 Lux and Guidotti, 1985

The granites listed below have the following sample numbers
Hall's Sill = sample14
Belmont Sill = sample 17
New Durham = sample 15
Loudon Sill = sample 18
Pembroke Peg = sample 16

METHOD
A Rb/Sr
B U/Pb zircon
C U/Pb monazite
D Nd/Sm
E Ar/Ar

also in this family of plutons that stitch the fault and show minor offset (Gaudette *et al.*, 1982; Hussey, 1985). The Barrington is then the oldest of the stitching granites and as such places a minimum limit on the time of initial terrane accretion along the Campbell Hill-Nonesuch River-Norumbega fault zone.

DISCUSSION

Implications for the Central Maine Terrane

Most of the monazite samples from sillimanite-grade schists of the Central Maine Terrane (except samples 5, 6, and 9) were collected in regions where we have done or are currently doing detailed structural work and petrography. In thin section, monazites from the Central Maine Terrane occur within the pelitic matrix and as inclusions in biotite porphyroblasts. In all samples monazite occurs as inclusions with pleochroic haloes in biotite that define the S_1 and S_2 foliations. These fabrics formed during F_1 (nappe-stage) and F_2 folding during the early stages of Acadian orogenesis. This textural evidence suggests that monazite growth and high-grade metamorphism occurred early in the Acadian event. The syn-tectonic nature of metamorphism is also well documented in the field; migmatitic layering, equivalent to S_1, is commonly folded by F_2 folds (Eusden, 1988).

Due to the uncertainties in the monazite ages we cannot confidently relate them to discrete folding events in the Central Maine Terrane. However, the data suggest that high-grade metamorphism and deformation occurred simultaneously and that the main pulse of the Acadian event was over by approximately 380 Ma. Similarly, Naylor (1971) has argued that the Acadian was an abrupt and brief event. This is consistent with the timing of the Acadian orogeny as inferred from other isotopic ages of crosscutting plutons in New Hampshire and Maine (Lyons *et al.*, 1986; Osberg *et al.*, 1985). The magmatic pulse of the New Hampshire Plutonic Series overlapped and extended beyond the deformation and metamorphism, lasting from roughly 410 Ma to 355 Ma. Table 2 shows this distinct pulse of Devonian magmatism, after which there is a gap until about 325 Ma when the Sebago, Effingham and Lyman plutons intruded. Emplacement of these plutons caused an episode of Carboniferous contact-regional, high-grade metamorphism overprinting the Acadian metamorphism (Lux and Guidotti, 1985).

Implications for the Merrimack Trough

In the Massabesic gneiss of southern New Hampshire, Aleinikoff *et al.* (1979) reported a discordant $^{207}Pb/^{206}Pb$ monazite age of 289 Ma, suggesting either the possibility of local resetting due to the intrusion of the 275 Ma granite at Milford, or regional Permian metamorphism. Our monazite and sphene ages from the Berwick Formation and Massabesic gneiss suggest Permian regional high-grade metamorphism in this terrane. The 473 Ma Exeter pluton cut and imparted a narrow contact aureole to low–grade rocks. The low-grade metasedimentary rocks are thought to be part of the regional metamorphism reaching sillimanite-grade within the Massabesic. Therefore, based on the age of the Exeter pluton, the Merrimack Trough experienced an earlier, pre-Middle Ordovician(?) metamorphism (Bothner *et al.*, 1984). Disequilibrium petrographic textures observed by Fagan (1986) in high-grade rocks of the Merrimack Trough support polymetamorphism but do not provide age discrimination.

The possibility of a distinct Permian event restricted to the Merrimack Trough would appear to constrain the westward limit of the Alleghenian or Variscan Front in northern New England. This Late Carboniferous to Early Permian orogenic event is well established in the central and southern Appalachians and has been documented in southeastern New England (Zartman *et al.*, 1988). However, until now, little evidence pointed to its existence in the classic Acadian and Taconian terranes of northern New England. Gromet (1988) has suggested that the Late Paleozoic tectonism documented in southeastern New England may have occurred farther north. Gromet also suggested that a major Alleghenian imprint on the Masssabesic Gneiss Complex should be considered. Based on the contrasting monazite ages across the Campbell Hill-Nonesuch River fault zone, this boundary is the most likely candidate for the Variscan or Alleghenian Front.

Timing of High-Grade Metamorphism and Terrane Accretion

Within the high-grade terrane shown on Figures 2 and 4, different age estimates of peak high-grade metamorphism have been proposed. They are summarized on Table 3 and Figure 4. There is a rather confusing picture of the timing of peak high-grade regional metamorphism from an area where, historically, all was thought to be Acadian. The ages of metamorphism for the proposed terranes and even within a single terrane, for example the Central Maine Terrane, range considerably.

Lux and Guidotti (1985) reported ^{40}Ar-^{39}Ar hornblende ages of 305 to 310 Ma from rocks in the central-western Maine part of the Central Maine Terrane and suggested that much, if not all, of the high-grade metamorphism there was Hercynian (325 Ma) and not Acadian in age. Gromet (1988) suspected that widespread Alleghenian (or Hercynian) metamorphism occurred throughout the metamorphic belt of New England as far west as the Bronson Hill Anticlinorium based on preliminary Rb-Sr dating and observations in southeastern Massachusetts and Rhode Island. Dallmeyer reported ^{40}Ar-^{39}Ar hornblende ages of 350 to 330 Ma from south-central Maine and concluded that the age of peak high-grade metamorphism is Acadian, or approximately 380 Ma (Dallmeyer, 1979; Dallmeyer and van Breemen, 1981). Our monazite ages indicate that the age of high-grade metamorphism was Acadian in central New Hampshire.

In the Coastal Lithotectonic Block, results of several geochronologic studies bracket the timing of peak high-grade metamorphism. West *et al.* (1988a, b) reported ^{40}Ar-^{39}Ar hornblende ages from the Falmouth-Brunswick Belt, part of the Casco Bay Group (Fig. 1). The northeastern part of the belt has ages of 367 to 377 Ma, whereas the southwestern part has ages of 280 to 290 Ma. This belt includes the Cushing Formation, a basement complex often equated with the Massabesic gneiss (Hussey, 1985). Southeast of the Flying Point fault in the Saco-Harpswell

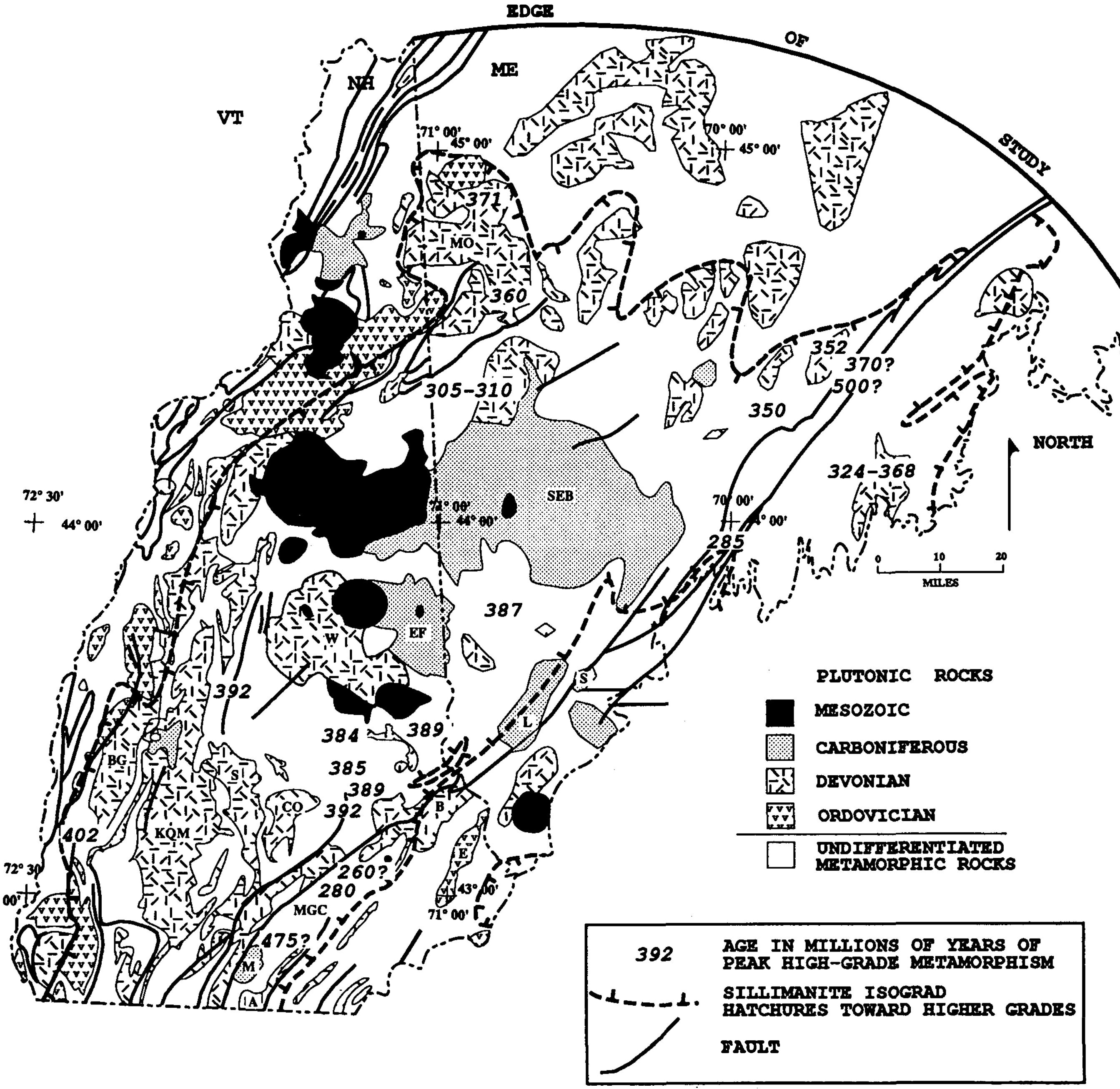

Fig. 4. Simplified geologic map of New Hampshire and southwestern Maine. Plateau of high-grade metamorphism enscribed by the sillimanite isograd. Available radiometric ages of peak high-grade metamorphism are plotted. Ages of metamorphism show considerable spread within the high-grade plateau. Even within discrete terranes the age of peak high-grade metamorphism varies. Abbreviations same as in Figure 2.

area, or part of what is termed here the "Casco Bay Block", ^{40}Ar-^{39}Ar hornblende ages range from 324 to 368 Ma (West *et al.*, 1988). Olszewski and Gaudette (1988) reported a Rb-Sr whole rock age of 495 Ma from the Cushing Formation and suggested that a unique period of intrusion and metamorphism from 540 to 470 Ma is characteristic of the rocks southeast of the Campbell Hill-Nonesuch River-Norumbega fault zone. Brookins and Hussey (1978) reported Rb-Sr whole rock ages of 481 Ma for the Cushing and 539 to 485 Ma for the rocks of the "Casco Bay Block." Our monazite and sphene ages suggest Permian high-grade metamorphism in the Merrimack Trough. The ages of high-grade metamorphism span the Cambrian through Permian and it is interesting that Permian metamorphism appears in both the Cushing and Massabesic gneiss complexes, suggestive of significant regional metamorphism in the basement rocks at this time.

The overall history of the high-grade zone must be complex. The available radiometric ages constrain several aspects concerning the existence and tectono-metamorphic histories of the proposed terranes. First, monazite ages from schists are markedly different across the Campbell Hill-Nonesuch River-Norumbega fault zone; Acadian in the Central Maine Terrane and

Table 3. Timing of peak high-grade metamorphism in New Hampshire and Maine based on available radiometric ages.

		Central Maine Terrane		Merrimack Trough/Massabesic Gneiss	Falmouth-Brunswick Belt	Cape Elizabeth Block	
Age (Ma.)		New Hampshire	Maine				Age (Ma.)
250				250 Monazite, 4			250
260				261-274? Sphene, 0			260
270				273 Monazite, 0			270
280	PERMIAN			282 Monazite, 0			280
---286---	-----------				280-290 Hornblende, in southwest, 5		---286---
300							300
			305-310 Hornblende, 2				
310							310
320	CARBONIFEROUS						320
330							330
340						324-369, Hornblende, 5	340
350			350 Hornblende, 3				350
---360---	-----------						---360----
					367-377 Hornblende, in northeast, 5		
370							370
		376 Monazite, 0					
380	DEVONIAN						380
			384 Monazite, 0				
390		383-402 Monazite, 0					390
400							400
---408---	-----------	409 Zircon rim, 1					---408---
420	SILURIAN						420
430							430
---438---	-----------						---438---
450							450
460	ORDOVICIAN						460
470				Pre-Ordovician or Older, Rb/Sr wr, 7 zircon, 4			470
480							480
490							490
					495 Rb/Sr, 7		
---505---	------------					481-539 Casco Bay Group, Rb/Sr, 6	---505---
520							520
530	CAMBRIAN						530
540							540

Sources of isotopic ages
0 This study
1 Barreiro et al., 1988
2 Lux and Guidotti, 1985
3 Dallmeyer and VanBreeman, 1981
4 Aleinikoff et al., 1979
5 West et al., 1988b
6 Brookins and Hussey, 1978
7 Olszewski and Gaudette, 1988

Permian in the Merrimack Trough. Second, the Central Maine Terrane experienced a distinct pulse of Devonian magmatism that the Merrimack Trough did not. Finally, the Barrington (364 Ma), Lyman (322 Ma) and Saco (307 Ma) plutons that stitch the terrane-bounding Campbell Hill-Nonesuch River-Norumbega fault zone have undergone at least minor deformation but show no major offset. However, the radiometric ages suggest that significant motion must have occurred along the fault to juxtapose the cooled Acadian high-grade rocks against the Permian high-grade rocks.

From our results and compilation we suggest the following tectono-metamorphic history for the Central Maine Terrane. Acadian plutonism, metamorphism and deformation occurred immediately after deposition of the Siluro-Devonian sediments (see also Naylor, 1971). High-grade metamorphism and early deformation was completed by about 380 Ma; plutonism ended at about 355 Ma and then was renewed in the Carboniferous (~325 Ma) causing contact-regional metamorphism in Maine. The late stages of deformation in the Central Maine Terrane may have extended into the Carboniferous (Alleghenian).

The Merrimack Trough experienced pre-Middle Ordovician high-grade metamorphism and deformation prior to accretion with the Central Maine Terrane. There appears to be no record of the Acadian orogeny in the Merrimack Trough. Initial accretion of the Merrimack Trough and Central Maine Terrane occurred just before the intrusion of the Barrington Pluton (~365 Ma) because (1) this pluton stitches the fault, and (2) if accretion occurred any earlier the Merrimack Trough would have experienced some of the characteristic Devonian magmatism of the Central Maine Terrane. Furthermore, Acadian F_2 axial traces are clearly truncated by the Campbell Hill-Nonesuch River-Norumbega fault zone (Eusden *et al.*, 1987), suggesting that accretion was post-F_2 folding.

Following accretion, the Campbell Hill-Nonesuch River-Norumbega fault zone remained active through at least the late Carboniferous as constrained by the age of the Saco pluton (307 Ma) which stitches but is also cut by the fault. The Merrimack Trough then experienced Permian magmatism locally, as well as high-grade metamorphism. The rocks in the Central Maine Terrane were not affected by this younger metamorphism. Permian K-Ar muscovite ages (Zartman *et al.*, 1970) suggest that the Central Maine Terrane was several hundred degrees cooler than the Merrimack Trough in the Permian. Sufficient movement must have occurred along the fault to juxtapose the cooled Acadian and presumably hot Permian high-grade terranes. This is a quandry because the movement had to be sufficient vertically to cause the juxtaposition but little horizontally so as not to significantly offset the Barrington, Lyman and Saco plutons.

It seems likely that the postulated Permian metamorphic overprint in the Merrimack Trough and Cushing Formation is a result of Late Paleozoic Alleghenian or Variscan sliver tectonism as suggested by Bothner *et al.* (1988). However, the final juxtaposition of basement complexes and cover sequences must have been later, Late Permian or Early Triassic. At this time, the tectonic regime in New England became extensional. If the basement-bounding faults moved substantially in the Mesozoic, they were probably extensional rather then compressional or transpressional. The faults could have been thrusts or strike-slip faults in the Acadian through Alleghenian, later switching sense of motion. An analogous scenario involving multiple motions along similiar terrane-bounding faults has been documented by Goldstein (1988) in southeastern New England. The basement complexes (Massabesic gneiss and Cushing Formation, and perhaps the Rye and Passagassawakeag gneisses) may have evolved structurally like the basement exposed in Cordillerian metamorphic core complexes. Historically, extensional tectonics in New England generally have not been regarded as a viable alternative when explaining the deformation and metamorphism seen in the Paleozoic and Precambrian rocks. Nevertheless, this alternative is worth considering, and requires detailed structural analysis along the terrane boundaries and geochronologic studies within the proposed terranes.

CONCLUSIONS

Ages of peak metamorphism from the Central Maine Terrane and Merrimack Trough are Devonian and Permian, respectively. The ages support the hypothesis that these are separate terranes with distinct tectono-metamorphic histories coincidentally juxtaposed at the same metamorphic grade.

The high-grade terrane of this part of the Appalachians is composite. It is made up of crustal blocks that experienced discrete pulses of high-grade metamorphism beginning as long ago as the pre-Middle Ordovician and extending into the Permian.

The Campbell Hill-Nonesuch River-Norumbega fault zone has had an active and complex history, from the late Devonian to the Mesozoic. This boundary is a likely candidate for the Alleghenian (Variscan) Front in New England.

Mesozoic extension was the last type of motion along the terrane boundary between the Central Maine Terrane and Merrimack Trough. The fault may be a reactivated Acadian/Alleghenian compressional /transpressional structure.

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APPENDIX 1: ANALYTICAL PROCEDURES

Monazite and sphenes were separated from the rocks using a Wifley table, heavy liquids, magnetic techniques and hand picking. On the average, 10 lbs of schist and 100 lbs of granite were crushed to acquire a suitable amount of monazite. Ten pounds of calc-silicate rock were crushed to acquire a suitable amount of sphene. Monazite and sphene were leached in 6 N HCl and HNO_3 acid to dissolve sulfides. The monazite was hand-picked and panned in acetone to 99% purity. During this step all monazite with inclusions, most commonly opaques (sulfides?) and less commonly those with 'dirty', possibly inherited detrital, cores, were removed. The resulting separates consisted of translucent, round, yellow monazites with vitreous to waxy luster, ranging in size from 5 to 100 microns in diameter. Positive identification and purity of the separates were spot checked by immersion oil techniques and X-ray diffraction.

After an acid wash in 7N HNO_3, monazite was dissolved overnight, at least once and in some cases twice, in Teflon (Krogh, 1973) bombs at 205-210°C in 6.2 N HCl. Monazite was spiked with ^{205}Pb-^{235}U before dissolution or aliquoted and then spiked with ^{208}Pb-^{235}U. Pb and U were eluted using 0.150 ml exchange columns and HCl chemistry after Krogh (1973). The Pb blank in this procedure is 60-200 pg. Isotope ratios were measured on a MAT 261 multicollector mass spectrometer at the University of California, Santa Barbara. Pb was loaded on a single rhenium filament with H_3PO_4-Si gel; U was loaded with HNO_3-graphite. Mass fractionation was monitored using NBS 981 and U500 standards, and amounted to 0.12% correction per mass unit. The error analysis used here follows Mattinson (1987), and depends on uncertainties in measured ratios, mass fractionation, identity of common Pb, and the precision of the $^{204}Pb/^{206}Pb$ measurement. These uncertainties are much larger than any effect of initial unsupported ^{230}Th in the samples, which are in this case insignificant for the normal whole rock Th/U values. Decay constants are from Steiger and Jager (1977).