Heat-Producing Elements and the Thermal and Baric Patterns of Metamorphic Belts

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The character of sedimentary basins, before they are deformed and metamorphosed, may strongly influence the thermal and baric patterns of metamorphic belts. Crustal thickening of anoxic sedimentary basins and subsequent thermal reequilibration may produce large areas of high-grade metamorphic rocks and granites because the concentrations of the heat-producing elements are high in such basins. In New England there is a spatial association among granites and high-grade metasedimentary rocks rich in U and Th that now form the Central Maine terrane. The high content of heat-producing elements in these rocks is attributed to fixing of U and Th in highly reduced sediments that were deposited in an anoxic basin that formed in the Silurian. When the basin was thickened during the Devonian Acadian orogeny, the thermal energy generated by the U- and Th-rich sediments produced the observed broad zone of high-grade rocks and anatectic granites. This hypothesis was tested with thermal calculations that reproduce most of the first-order thermal and baric patterns of the Acadian Appalachians, if pretectonic lateral variations in heat production are assumed.

ONE OF THE IMPORTANT PROBLEMS FACING GEOLOGISTS IS how granites and high-grade metamorphic rocks are related in the crust. Theoretical models of regional metamorphism show that it is difficult to generate high-grade metamorphic rocks and granites at relatively shallow crustal levels (*1*). Production of high-grade rocks at shallow depths requires either anomalously high values of heat production in the crust, anomalously low thermal conductivity, melting at deep crustal levels and upward advection of these melts in the crust, or the introduction of large amounts of heat from the mantle.

The introduction of significant amounts of thermal energy from the mantle is supported in some cases, for example, in high-grade metamorphic regions of the Pyrenées where the metamorphism has been attributed to a "deep" heat source such as that provided by basaltic underplating of the crust, asthenospheric upwelling, or intrusion of mantle-derived melts into the lower crust (*2, 3*). However, in other orogens the heat source for high-grade metamorphism is more enigmatic because there is no clear evidence for abnormally high mantle heat flow. In some of these metamorphic terranes, the high-grade metamorphism has been attributed to the intrusion of large amounts of granitic melts from deeper levels of the crust (*4*). However, even if the granites are produced by anatexis of the crust, the ultimate source of thermal energy that generated the melts remains to be identified (*5*).

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The identification of the source of thermal energy is important because it has implications for the fundamental processes that drive crustal metamorphism and deformation. If crustal heat sources alone can account for the observed metamorphism and melting, then there has been simply a redistribution of energy and mass within the crust. However, if either basaltic underplating or intrusion of mafic melts is invoked, then it implies the addition of heat and possibly mass to the crust and hence involves mantle processes as well as crustal processes.

The problem of how granites and high-grade metamorphism are produced is particularly relevant to the Acadian [400 to 380 million years ago (Ma)] metamorphic high located in New England. The Acadian thermal high, one of the most striking metamorphic features in New England, consists of thousands of square kilometers of sillimanite-zone (~600°C) metasedimentary rocks and associated synmetamorphic granitic plutons (Fig. 1A). The cause of this high-grade metamorphism and plutonism is a matter of debate, but the spatial association of granitic plutons and high-grade metamorphic rocks suggests that there is a cause-and-effect relation. Although thermal models show that it is difficult, if not impossible, to generate temperatures sufficiently high to partially melt the middle crust for normal values of mantle heat flux and crustal heat generation and reasonable amounts of crustal thickening (*4–6*), the granites in the Acadian metamorphic high nevertheless have been considered to be the product of melting of metasedimentary rocks during high-grade crustal metamorphism of the middle crust (*7*). On the other hand, the granites have also been considered to be the cause of the high-grade metamorphism because intrusion of large volumes of sheet-like granitic plutons into an orogen can produce vast areas of high-grade rocks by contact metamorphism (*4*). Two observations suggest, however, that the granitic melts did not provide the requisite thermal energy to produce the broad metamorphic high shown in Fig. 1A. First, the notable lack of contact aureoles around the Acadian plutons exposed in New Hampshire and Massachusetts suggests that the magmas forming the granites did not move very far upward after melting. Second, granites are lacking in adjacent terranes that were buried to similar depths during the Acadian; thus, simple tectonic burial, heating, and melting in a normal thermal regime cannot account for such lateral variation in plutonism. Any satisfactory model for Acadian metamorphism must account for the across-strike, lateral variations in the distribution of granites and high-grade rocks observed in New England.

In this paper, we suggest that the distribution of heat-producing elements in a pre-Acadian sedimentary basin controlled the thermal and baric pattern established in the Acadian orogeny. We present a general model in which fixing of U and Th in anoxic basins creates continental crust with relatively high concentrations of heat-producing elements. When these basins are thickened during orogeny, thermal reequilibration can produce vast areas of high-grade metamorphic rocks and granites at relatively shallow crustal depths. Supporting arguments for this hypothesis are based on geological and geophysical studies of the Acadian Appalachians and mathematical models of the thermal evolution of mountain belts.

High-Grade Rocks in the Acadian Appalachians

Most of the high-grade rocks and synmetamorphic granites in New England occur in the Central Maine terrane, hereafter referred to as the CMT. In the terranes immediately adjacent to the CMT, the metamorphic grade is generally lower and Acadian granitic rocks are less abundant.

The CMT extends as a linear belt from southern Connecticut north to Maine (Fig. 1A). It is bordered on the west by the Bronson Hill anticlinorium and on the east by the Merrimack trough (*8, 9*). The CMT is separated from rocks belonging to the Merrimack trough by faults; the two terranes were juxtaposed along these faults after Acadian deformation (*10*). The Bronson Hill and Central Maine terranes, however, were adjacent to one another during the Acadian orogeny and are stratigraphically related.

The Acadian tectonic history of the CMT and adjacent Bronson Hill anticlinorium can be divided into two phases. The first was a period of Silurian-Devonian clastic sedimentation in an eastward-thickening basin. During the Silurian the CMT was a deep-water anoxic basin filled with shale, quartzite, and calcareous rocks derived, in part, from the Bronson Hill anticlinorium, a topographic high situated to the west (*11–13*). Later, during the early Devonian, turbidites were deposited from a source area to the east into the basin (*14*), which was no longer anoxic. As a result of this sedimentation, the CMT now contains large volumes of Silurian graphitic and sulfidic shale (Rangeley Formation ~1500 m thick), quartzite (Perry Mountain Quartzite, ~500 m thick), and sulfidic calcsilicate rocks (Francestown and Madrid formations, ~300 and ~450 m thick), and Devonian graded-bedded schist (Littleton Formation, ~2000 m thick) (*12, 13, 15*).

The second phase was a period of crustal thickening and deformation during the Early Devonian. During this time, the basin in the CMT was deformed into a series of westward-directed nappes and later isoclinal folds (*8*). This deformation approximately doubled the crustal thickness in the CMT (*16, 17*).

Plutonic rocks. Abundant granitic melts intruded the CMT during and after the Acadian orogeny (*18*). As mentioned above, studies of the thermal history of the CMT have drawn conflicting conclusions with regard to the relation between granitism and metamorphism: whether intrusions caused the high-grade metamorphism or the metamorphism itself produced the granites by anatexis.

Petrologic, isotopic, and geochronologic studies have shown that most of the granites associated with the Acadian orogeny, collectively called the New Hampshire Plutonic Series, are roughly synchronous with metamorphism. The plutons can be divided into three groups by age. The earliest group contains syntectonic and synmetamorphic sheet-like bodies belonging to the Kinsman Quartz Monzonite, Bethlehem Gneiss, and Spaulding Series. These plutons

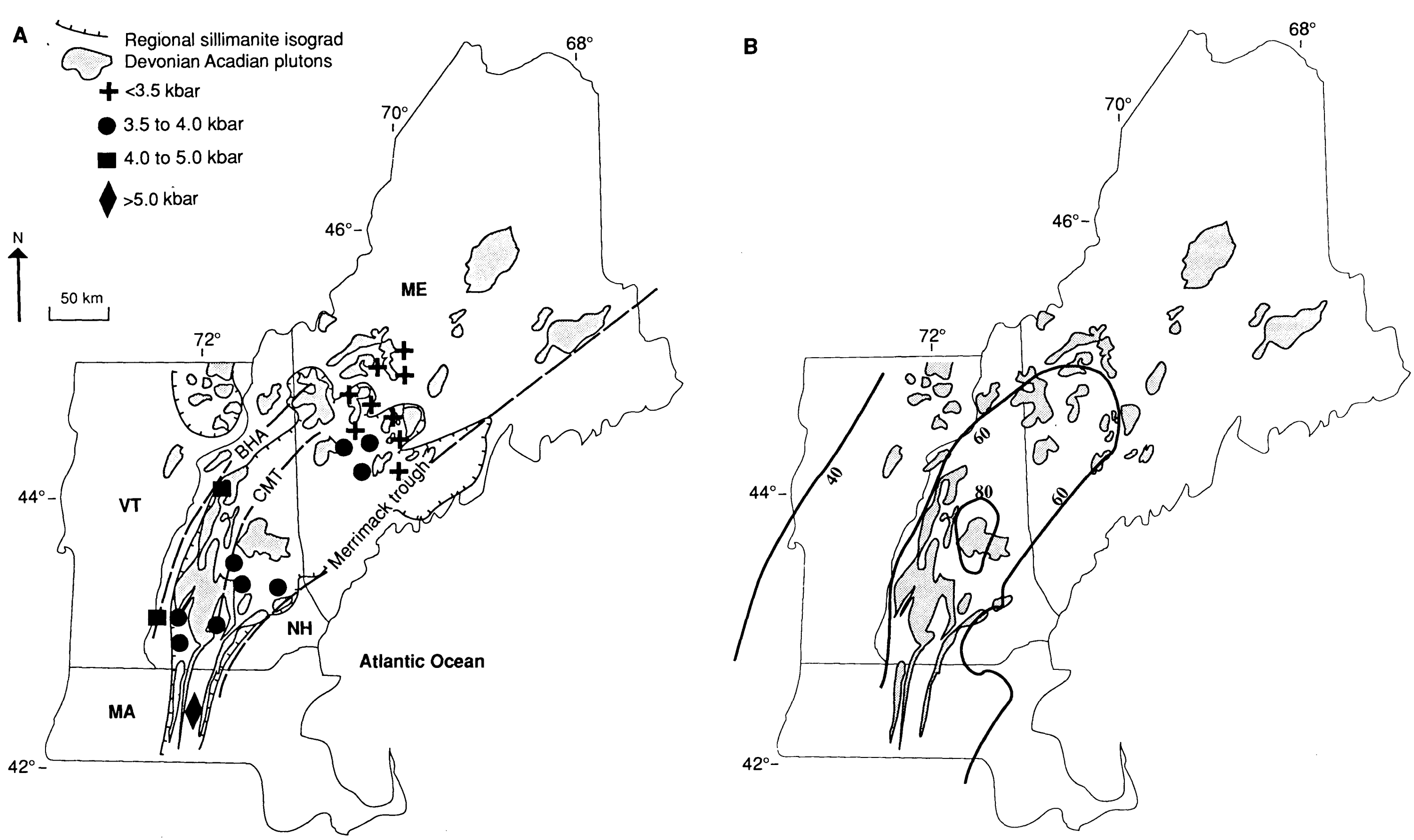

Fig. 1. (**A**) Metamorphic map of New England showing the sillimanite isograd, distribution of New Hampshire Plutonic Series granites, and pressure estimates. Sources for the data are given in the text. Axes of the Bronson Hill anticlinorium (BHA) and Central Maine terrane (CMT) are indicated by dashed lines. (**B**) Surface heat flow in New England. Data from (*31, 33–35*). Heavy black lines are contours of surface heat flow in milliwatts per meter squared. [Modified from (*17, 28*)]

range in age from approximately 410 Ma for the Kinsman to approximately 400 Ma for the Spaulding (*19, 20*). The middle generation of plutons consists of small bodies of two-mica granites, the Concord plutons. These granites are post-tectonic and yield Middle to Late Devonian ages (~380 Ma) (*8, 21*). They generally intruded the orogen after peak metamorphism. The youngest generation of the New Hampshire Series plutons yield Carboniferous ages (~320 Ma) (*15*). Volumetrically these are insignificant in most parts of the CMT, except in Maine where they apparently caused late thermal metamorphism (*22*).

The effects of these plutons on the thermal budget of the orogen are largely unknown. Although contact metamorphism is not observed around the Acadian plutons in New Hampshire and Massachusetts, many of the plutons in Maine are surrounded by local contact aureoles. Indeed, in west-central Maine, the high-grade zone has been attributed to overlapping contact aureoles produced by multiple intrusions of sheet-like plutons (*4*). The recognition of contact aureoles does not by itself indicate that additional thermal energy has been added to the crust. When considering the thermal budget of the orogen, one must make a distinction between metamorphism by melts produced by anatexis during high-grade metamorphism in deeper parts of the crust and metamorphism by melts intruded from the mantle. In the former case neither additional thermal energy nor mass is added to the crust, but in the latter case both thermal energy and mass are contributed to the crust from the mantle [see (*5*)].

Information from petrologic and isotopic studies can be used to distinguish between these two end-member cases. Petrologic and geochemical studies of the New Hampshire Plutonic Series suggest that they were produced largely by anatexis of pelitic sedimentary rocks in the CMT or more deeply buried sedimentary rocks (*23, 24*). Limited isotopic studies support a crustal origin for the granites and show that some of the granites have initial $^{87}Sr/^{86}Sr$ ratios around 0.711, although early dikes found within the Kinsman Series plutons have initial $^{87}Sr/^{86}Sr$ ratios of 0.704, implying a mantle component (*19*). These dikes are, however, volumetrically insignificant.

Metamorphism. The most striking feature of the CMT is the vast area made up of high-grade metamorphic rocks. Sillimanite-zone rocks extend hundreds of kilometers along the strike of the CMT from the southernmost exposure of the CMT in Connecticut to Maine where the high-grade zone terminates in an area of abundant Acadian plutons (Fig. 1). High-grade rocks are also distributed across the strike of the CMT for a width of 100 km, from the east edge of the Bronson Hill anticlinorium to the west edge of the Merrimack trough (Fig. 1A).

There are both across-strike and along-strike variations in peak metamorphic conditions in the CMT. Pressure and temperature generally increase from north to south. Peak metamorphic conditions occurred at ~475° to ~600°C and 3 to 4 kbar in Maine (*25–27*), at ~550° to 650°C and 3.5 to 5.0 kbar in central New Hampshire (*16, 28*), and at somewhat higher temperatures (~700°C) and pressures (~6.5 kbar) farther south in Massachusetts (*17*). These measured pressures most likely reflect the pressure obtained at the maximum temperature of metamorphism, not necessarily the maximum depth of burial of any of the rocks (*28*).

Across the strike of the CMT, peak metamorphic temperatures vary, but pressures remain relatively constant (*28*). In New Hampshire, peak temperatures vary from ~550° to 650°C along the axis of the CMT to ~450° to 500°C at the east edge of the Bronson Hill anticlinorium. In contrast, pressures along this traverse are constant at 4.0 ± 1.5 kbar over a distance of greater than 100 km (Fig. 1A). A similar across-strike variation in temperature is also observed in Massachusetts (*17*). Here, peak temperatures vary from ~700°C along the axis of the CMT to ~550°C along the Bronson Hill anticlinorium, but pressures at peak metamorphism are relatively constant at 6.5 kbar (*17*).

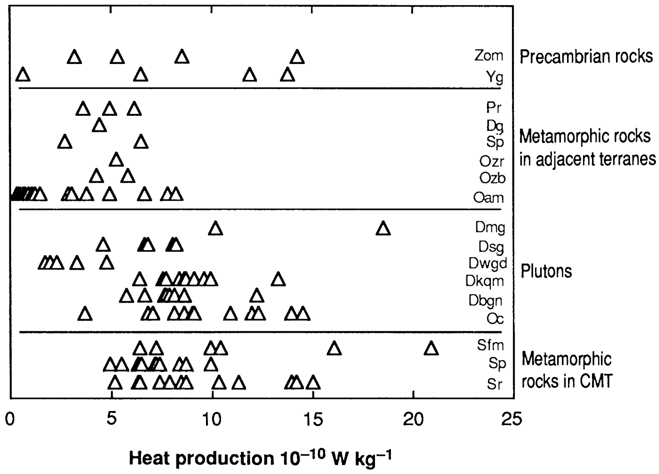

Fig. 2. Heat production versus rock type. Heat production in watts per kilogram is calculated from data on U, Th, and K concentrations (*50*). Sp, Perry Mountain; Sr, Rangeley, Sfm, Madrid and Francestown; Oam, Ammonoosuc volcanics; Ozb, Berwick; Ozr, Rye; Dg, Gile Mountain; and Pr, Rhode Island formations. Dwgd, Winnepesauke quartz diorite; Dsg, Spaulding plutons; Dmg, Concord plutons; Dbgn, Bethlehem gneiss; Dkqm, Kinsman quartz monzonite; Oc, Oliverian and Highlandcroft plutons; Yg, Grenville basement; and Zom, Massabesic gneiss. Sources for K, U; and Th concentration data are (*21, 29, 34, 51–55*).

The thermal and baric pattern in the CMT was largely established during the Acadian orogeny. Timing of high-grade metamorphism is best constrained by U-Pb ages of metamorphic monazites (*10, 29, 30*). The monazite ages vary from 402 to 380 Ma across a wide area of the CMT in New Hampshire (*10*). In Maine, the northern part of the metamorphic high, similar Acadian ages for metamorphism were determined from monazites, although there appear to be two distinct ages of metamorphism, one at ~400 Ma and the other at ~370 Ma (*29*). The timing of metamorphism is further complicated in northern Maine by a later thermal overprint during the Carboniferous associated with a period of plutonism (*22*). No similar Carboniferous overprint has been observed to the south in the CMT in New Hampshire.

Heat Flow and Heat-Producing Elements

Because the 360-million-year interval since the Acadian orogeny is much greater than the thermal time constant for the crust, any thermal perturbations arising from Acadian deformation have had ample time to decay to zero. If there have been no appreciable thermal perturbations since the Acadian, then the distribution of temperatures in the crust should be at steady state. Thus the present-day surface heat flux should reflect the sum of the heat flux into the crust from the mantle and the heat produced in the crust and can be used to constrain the Acadian thermal history (*6*).

The present-day surface heat flux in New England varies from ~40 to ~90 mW m^{-2}. Because of the linear relation observed between surface heat flux and heat production of surface rocks, the surface heat flow in New England can be separated into two components: (i) a crustal contribution from the decay of radioactive elements concentrated at relatively shallow depths (less than 7 km) in the upper crust and (ii) a reduced heat flow contribution from the lower crust and mantle, which is relatively constant at ~30 mW m^{-2} throughout New England (*31–35*). If this is the case, then the lateral variations in surface heat flow observed in New England reflect lateral variations in the total amount of heat production in the crust.

Heat flow measurements in the CMT average around 65 mW m^{-2}; however, heat flow measurements in adjacent terranes are significantly lower, around 50 mW m^{-2} (Fig. 1B) (*31, 33–35*). The higher heat flow values have been attributed to higher than average heat production in Acadian plutons in the CMT (*31*). However, reexamination of the data suggests that the metasedimentary rocks in the CMT contain relatively high amounts of heat-producing elements as well.

We calculated heat production values for rocks in New England (Fig. 2). The data show that: (i) the metasedimentary rocks in the CMT in New Hampshire tend to have higher heat production than metasedimentary rocks from adjacent terranes; and (ii) in the CMT, the metasedimentary rocks have heat generation values equal to or greater than those from Acadian plutons.

These variations in heat production must be related to variations in the concentrations of heat-producing elements (U, Th, and K) in the rocks. Metasedimentary rocks in the CMT tend to be enriched in both U and Th compared with most rocks in other terranes (Fig. 3). This enrichment, if persistent throughout the upper 10 km of crust, is sufficiently large to account for between 75 and 100% of the observed variation in heat flow. Moreover, the K concentrations of rocks in the CMT and surrounding terranes are fairly uniform [generally 2 to 4 weight percent (*34*)]; therefore, variations in K concentrations can account for differences in surface heat flow of no more than 2 mW m^{-2}.

Most of the metasedimentary rocks in New England have typical Th/U ratios of around 3.0 to 4.0 (see Fig. 3). However, some of the rocks from the CMT are enriched in U such that they have low Th/U ratios (Fig. 3). These ratios are not surprising, because the rocks that show U enrichment belong to the Silurian Rangeley, Francestown, and Madrid formations, which are reduced graphitic and sulfidic schists and calcsilicate rocks and which must have had highly reduced protoliths.

We suggest that the high concentrations of U in the metasedimentary rocks in the CMT were derived from fixing of U dissolved from seawater in sulfidic and organic-rich sediments. Fixing of U in the Silurian anoxic basin is consistent with studies that show that organic-rich sediments in anoxic basins are a major sink for dissolved U in ocean waters, and many reduced sediments, such as organic-rich black shales, have high U concentrations compared to most sediments (*36, 37*).

Such an explanation, however, does not account for the high concentrations of Th in the metasedimentary rocks in the CMT relative to those in the rocks in adjacent terranes (Fig. 3). The concentration of Th in the rocks probably reflects its original concentration in the sediment source region, because most Th in marine sediments is contained in the detritus (*38*). It is possible that Th concentrations were high in the source region of the sediments deposited in the CMT; average Th concentrations in the adjoining Precambrian Grenvillian terrane (open triangle in Fig. 3) are high. The Ordovician plutons (Oo) in the Bronson Hill anticlinorium have high U and Th values as well (Fig. 2). The Th values of the rocks in the CMT might be high if these rocks provided the detritus for the sediments in the CMT. We therefore suggest that the high concentrations of both Th and U in the CMT are a result of the sedimentation history of the basin.

If our hypothesis is correct, the observed concentrations of U and Th in the metasedimentary rocks in the CMT should be roughly the same as those present before Acadian deformation. However, metamorphic, magmatic, or near surface fluid flow processes may also have been responsible for producing the high concentrations of U and Th observed today. Metamorphic fluid flow could have remobilized U and Th by way of dehydration reactions or fluid infiltration. Jaupart *et al.* (*33*) and Newton (*39*) have suggested that metamorphic fluids deplete the lower crust in U and Th and concentrate these elements in the upper crust. Isotopic and petrologic studies of metamorphic rocks in New Hampshire show that metamorphic fluid flow was highly concentrated into narrow zones about 10 km^2 in area (*40, 41*); however, the U- and Th-rich metasedimentary rocks are distributed over much larger areas that show little evidence for infiltration of fluids. Therefore we doubt that metamorphic fluid infiltration significantly affected the distribution of heat-producing elements. In addition, because there is no change in the concentration of U and Th across the sillimanite-muscovite isograd, where substantial dehydration has occurred (*29*), remobilization of heat-producing elements by dehydration reactions can also be ruled out.

Uranium and Th could have been redistributed in near surface rocks by circulation of ground water. Studies of U, Th, and K concentrations in wells and outcrops in the CMT show that Th can be depleted in near surface rocks relative to levels in more deeply buried rocks, although the concentrations of U and K are unchanged (*34*). However, if this depletion of Th is significant, it implies that the observed Th concentrations are, if anything, underestimates of the Acadian values.

Emplacement and extraction of melts may also affect the distribution of heat-producing elements in the crust. We envision three mechanisms by which this might occur: (i) emplacement into the CMT of U- and Th-rich melts from sources outside the CMT could have added these elements to the metasedimentary rocks by large-scale exchange; (ii) removal of melts that were depleted in U and Th could have enriched the restitic metasedimentary rocks in heat-producing elements; or (iii) melting of CMT rocks to produce magmas with high concentrations of U and Th and removal of such melts from the CMT could deplete the remaining restite in heat-producing elements.

Table 1. Concentrations of U and Th (parts per million) resulting from batch partial melting for different bulk distribution coefficients. Concentrations of U and Th before melting are assumed to be the average values observed in metasedimentary rocks outside the CMT. Initial concentrations of U and Th are 2.2 ppm and 7.1 ppm, respectively. Average concentrations of U and Th in CMT are 7.7 and 10.9 ppm, respectively.

Melting (%)	$D = 0.1$		$D = 10$		$D = 100$		$D = \infty$	
	U	Th	U	Th	U	Th	U	Th
10	1.2	3.9	2.4	7.7	2.4	7.7	2.4	7.7
30	0.59	1.9	3.0	9.7	3.1	10	3.1	10
50	0.40	1.3	4.0	13	4.4	14	4.4	14
70	0.30	1.0	5.9	19	7.2	23	7.3	24
90	0.24	0.77	12	39	20	65	22	71

Table 2. Values of parameters used in thermal calculations.

Parameter	Description	Value
K	Thermal conductivity	2.25 W m^{-1} K^{-1}
κ	Thermal diffusivity	10^{-6} m^2 s^{-1}
C_p	Specific heat	1.2×10^{-3} J kg^{-1} K^{-1}
Q_0	Basal heat flux	30 mW m^{-2}
d	Length scale for heat production	10 km
ρ	Density of crust	2.7×10^3 kg m^{-3}
s_0	Initial crustal thickness	30 km
L	Depth of solution region	150 km
x_{max}	Width of solution region	75 km
f	Crustal thickening factor	1.5, 1.75, 2

Because some of the metasedimentary rocks have higher concentrations of U and Th than the plutons (Fig. 2), we dismiss the possibility that the concentrations are the result of large-scale exchange; moreover, bulk redistribution of U and Th from the plutons to the metasedimentary rocks would require fluid migration over thousands of square kilometers, for which there is no evidence (*40, 41*).

Evaluation of the other two mechanisms requires knowledge of the bulk distribution coefficients for partitioning of U and Th between restite and melt. It is a commonly held assumption that U and Th are partitioned into the melt during anatexis. However, whether these elements are concentrated in the melt or restite is strongly dependent upon the solubility of U- and Th-rich minor phases, such as monazite and zircon. The solubility of minerals such as monazite in melt may be low (*42, 43*); if so, U and Th may be partitioned into the restite during anatexis. (In other words, the distribution coefficients for U and Th partitioning are much greater than 1.) To test whether this is a viable mechanism for altering the U and Th concentrations in sediments deposited in the Silurian basin that became the CMT, we calculated the concentrations of U and Th in the metasedimentary rocks as a function of their degree of partial melting. To maximize the effect of this mechanism, we assumed that all U and Th were concentrated in the insoluble phase monazite before melting and that batch melting occurred. Table 1 shows that even for large bulk distribution coefficients ($D > 10$), more than 70% melting is required if the concentrations of both U and Th in the CMT rocks were to attain their present values by partial melting of rocks having initial concentrations of these elements similar to those in terranes surrounding the CMT. Although there has been some anatexis in the CMT (*44*), 70% partial melting is unreasonably large. Such a high degree of partial melting would require that vast areas of the CMT be composed of highly restitic material. In addition, there is no evidence for the presence of the large volume of magma depleted in U and Th that would be a consequence of this mechanism.

The third mechanism for altering U and Th concentrations is that, because of the melting of U- and Th-rich phases, the melts were enriched, rather than depleted, in U and Th relative to the rocks undergoing anatexis (that is, distribution coefficients less than or equal to 1). However, this mechanism implies that the premelting concentrations of U and Th were larger than present-day values and thus lends support to the hypothesis that the thermal evolution of the CMT was strongly influenced by the concentrations of heat-producing elements.

Tests of Model: Thermal Calculations

By examining solutions to the heat flow equation, taking into account the burial and erosional history of the CMT, and using reasonable assumptions of deformation, erosion, and thermal parameters, we can test whether the high U and Th contents of the metasedimentary rocks in the CMT provided the additional thermal energy needed for granite genesis and high-grade metamorphism. In particular, the thermal history calculations must: (i) reproduce the magnitude of the peak metamorphic temperatures observed across the orogen; (ii) show why granites are largely restricted to the CMT; and (iii) account for the differences in peak temperatures between the CMT and Bronson Hill anticlinorium.

We solve the heat flow equation for advection and diffusion of heat in a two-dimensional region:

$$\frac{\partial T}{\partial t} + v_z \frac{\partial T}{\partial z} = \kappa \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{H(x,z)}{\rho C_p}$$

where T is temperature, x and z are horizontal and vertical coordinates, respectively, and t is time. The parameters that control the temperature distribution in space and time are the rate of erosion v_z, thermal diffusivity κ, heat production H, density ρ, and specific heat C_p.

With the exception of the heat production H, we used values of the thermal parameters [κ, ρ, C_p, Q_0 (basal heat flux), and k (thermal conductivity)] similar to those used by Chamberlain and England (*6*) in an earlier investigation of the thermal evolution of the Acadian orogeny [see Table 2; (*45*)]. Heat production was assumed to vary exponentially with depth, with a vertical length scale d, that is, $H(x,z) = H(x,0)e^{-z/d}$. The horizontal variation of heat production was chosen with the data of Fig. 2 in mind. Median heat production for exposed metamorphic rocks outside the CMT is about 5×10^{-10} W kg^{-1} (1.4×10^{-6} W m^{-3}). Within the CMT, there is a wide range of heat production values, but the median is about 1.3×10^{-9} W kg^{-1} (3.5×10^{-6} W m^{-3}). We allowed the surface heat production to vary sinusoidally between these limits:

$$H(x,z) = [2.45 \times 10^{-6} + 1.05 \times 10^{-6} \cos (\pi x / x_{max})] e^{-z/d}$$

where x_{max} is the horizontal distance between the locations of minimum and maximum surface heat production. This heat production distribution, with the values of basal heat flux and heat production length scale given in Table 2, results in steady-state heat flow values of 65 mW m^{-2} at $x = 0$ (high heat production side of the solution region) and 44 mW m^{-2} at $x = x_{max}$ (low heat production side), which are consistent with present-day observations in the CMT and Bronson Hill anticlinorium, respectively (see Fig. 1B).

Comparison of the calculated pressures and temperatures with measured pressures and temperatures in the CMT shows that several of the observed thermal and baric features can be reproduced (Table 3). Most importantly, the calculation reproduces the magnitude of the thermal and baric variations observed in New England, where peak temperatures vary across the strike of the CMT, but pressures are relatively constant (Table 3 and section on metamorphism). In the calculations the difference in peak temperatures between regions of high and low heat production is similar to that observed, between 80° and 120°C, but pressures at peak temperatures vary across the same region by no more than a few tenths of a kilobar (*46*).

The calculations also show that temperatures should have been high enough in the CMT to produce abundant anatectic melts at depths around 10 km (Table 3). Even in the calculations with the least amount of thickening ($f = 1.5$), rocks that would currently be 10 km below the surface experienced peak temperatures that exceeded the granite solidus. Thus the calculations imply that granitic melts could have been generated in situ in rocks now exposed in Massachusetts, and in rocks ~10 km below the present-day surface in the CMT in New Hampshire and Maine. In contrast to the CMT, in crust that contains normal concentrations of heat-producing elements (for example, the Bronson Hill anticlinorium), the calculations suggest that melting should have occurred only at the deepest levels of the crust and that abundant melts and high-grade metamorphism should be absent. Thus, the abundance of granites in the CMT and the relative scarcity of granites in the Bronson Hill anticlinorium can be ascribed to variations in abundance of heat-producing elements. It is unlikely that the distribution of granites was controlled by variations in thickening because the two terranes had similar burial histories (*28*).

The magnitudes of peak temperatures and pressures at peak temperature in the calculation with $f = 2$ match very well with the observed temperatures and pressures in parts of the orogen that experienced the largest amount of thickening (central Massachusetts). The agreement suggests that under conditions of normal mantle heat flow but augmented crustal heat production, near granulite-grade conditions can be produced by thermal relaxation in tectonically thickened crust. However, rocks in the CMT in New Hampshire and Maine generally show peak metamorphic temperatures that are 30° to 100°C higher than those given in Table 3 for currently exposed rocks. Although this discrepancy may be within the limits of accuracy of many geothermometers, additional heat sources may be necessary to account for the highest grades of metamorphism in these less deeply buried and exhumed areas of the CMT. One possibility is the advection of heat upward in the crust by the introduction of granitic melts generated at greater depths. Strong evidence for extensive contact metamorphic effects are observed in the CMT in Maine (*4*). In New Hampshire, however, the role of contact metamorphism by intrusion of granites is less certain. The lack of strong contact aureoles around many New Hampshire plutons may indicate that the plutons were intruded into metasedimentary rocks that were already close to granite melting temperatures. However, some plutons evidently did provide additional thermal energy; the earliest plutons belonging to the Kinsman and Bethlehem series show local contact aureoles a few meters in width (*13, 16*). In addition, the local thermal anomalies reflecting temperatures in excess of 600°C in central New Hampshire could be a result of upward migration of both hot hydrothermal fluids and melts (*41*).

Can the observed variations in peak temperatures be explained by horizontal variations in other variables, such as erosion? Day (*47*), using solutions to the one-dimensional heat flow equation, showed that the geometry of isobaric and isothermal surfaces in an orogen is strongly dependent on the erosional and thermal history. We have extended this study, using more general two-dimensional calculations, to investigate how erosional and thermal histories influence the metamorphic field gradients in an orogen. The key observation in the CMT is that peak metamorphic temperatures decrease but pressures remain relatively constant from the axis of the CMT to the axis of the Bronson Hill anticlinorium (*16, 17, 28*). Our calculations (*48*) suggest that this distribution can be produced in orogens by variation of thermal parameters across strike, but not by variation of erosional parameters [see also (*28*)].

Implications for the Thermal Evolution of Orogenic Belts

We have presented a working model in which the production of high-grade metamorphic and granitic rocks in New England is related to high concentrations of heat-producing elements in metasedimentary rock and plutons. We suggest that the observed high concentrations of U and Th in the metasediments in the CMT are approximately the same as the concentrations in these units before Acadian deformation. In our model the high concentrations of U result from fixing of U in the anoxic sediments within this basin, and the high Th concentrations reflect weathering of a source with relatively high Th concentrations. During Acadian deformation, the crust, which included the metasedimentary rocks containing the anomalous concentrations of heat-producing elements, was thickened. After thickening, the thermal energy provided by the heat-producing elements was sufficient to cause upper amphibolite zone metamorphism at middle crustal depths and the generation of granitic melts deeper in the crust. Upward and lateral advection of these melts from the deeper parts of the crust to shallower levels in the orogen redistributed thermal energy for the Buchan-type, low-pressure and high-temperature metamorphism observed in central and northern New Hampshire and Maine. In the adjacent terranes, such as the Bronson Hill anticlinorium, which contain more normal concentrations of heat-producing elements, the metamorphism followed the more normal Barrovian style.

If this model is correct, it would imply that the metamorphic history of a terrane may be strongly influenced by its early sedimentary history [see also (*49*)]. Many anoxic basins next to continental margins contain sediments with high amounts of heat-producing elements. If these basins are thickened during orogenesis then they may become the sites for later high-grade metamorphism and anatexis.

This is an attractive model to explain the generation of granites

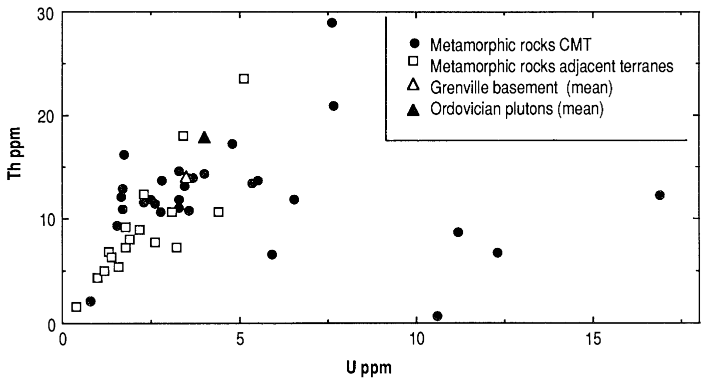

Fig. 3. Uranium versus Th concentrations for metasedimentary rocks in the Central Maine terrane and metasedimentary rocks and metavolcanic rocks in terranes adjacent to the Central Maine terrane. Also shown are the mean U and Th concentrations for the Ordovician plutons and Grenville basement.

Table 3. Results of thermal calculations with horizontal sinusoidal variation in heat production. Results of three calculations are shown, each with different amounts of crustal thickening *f*, corresponding to estimated thickening in central Massachusetts, southern New Hampshire, and central New Hampshire. Peak temperatures (T_{max}) and pressures at peak temperatures (P_{Tmax}) are given for rocks along the axis of the CMT (hot) and in the Bronson Hill anticlinorium (cold). Calculated values of T_{max} and P_{Tmax} are given for rocks located at the maxima (hot) and minima (cold) of crustal heat production; values are shown for rocks exposed at the surface and at 10 km depth at the end of the calculation (present day). Also indicated is the difference in temperature (ΔT) between the maximum and minimum peak temperatures of surface rocks. Pressures are calculated for a crustal density of 2.7×10^3 kg m^{-3}. Observed pressures and temperatures are from (*16, 17, 28*).

Location	Observed				f	Calculated, surface rocks				ΔT	Calculated, rocks at 10 km depth			
	Hot (CMT)		Cold (BHA)			Hot		Cold			Hot		Cold	
	T_{max}	P_{Tmax}	T_{max}	P_{Tmax}		T_{max}	P_{Tmax}	T_{max}	P_{Tmax}		T_{max}	P_{Tmax}	T_{max}	P_{Tmax}
Central MA	650 to 700	6.7 to 7.0	550	6.7 to 7.0	2.0	670	7.4	550	7.2	120	800	9.5	700	9.3
South NH	550 to 600	4.0 to 5.0	450 to 500	5.0	1.67	500	5.1	400	5.1	100	710	8.5	620	8.4
Central NH	550 to 600	3.5 to 4.0	450 to 500	4.0	1.5	400	4.0	320	4.0	80	580	6.5	490	6.4

and high-grade metamorphic rocks in orogenic belts for several reasons. It is an explanation that follows naturally from the consequences of the accumulation of sediments in anoxic basins off convergent continental margins, of which there are numerous present-day examples. It is also testable in that the additional thermal energy needed to produce melts can be estimated and compared with measured concentrations of heat-producing elements in orogenic regions and in modern-day analogues to pre-orogenic sedimentary basins.

REFERENCES AND NOTES

1. P. C. England and A. B. Thompson, *J. Petrol.* **25**, 894 (1984).
2. S. M. Wickham and E. R. Oxburgh, *Nature* **318**, 330 (1985).
3. S. M. Wickham and H. P. Taylor, *Contrib. Mineral. Petrol.* **95**, 255 (1987).
4. D. R. Lux, J. J. DeYoreo, C. V. Guidotti, E. R. Decker, *Nature* **323**, 794 (1986).
5. E. Zen, *Trans. R. Soc. Edinburgh* **19**, 223 (1988).
6. C. P. Chamberlain and P. C. England, *J. Geol.* **93**, 593 (1985).
7. J. B. Thompson, Jr., P. Robinson, T. N. Clifford, N. J. Trask, Jr., in *Studies of Appalachian Geology: Northern and Maritime*, E. Zen, W. S. White, J. B. Hadley, J. B. Thompson, Jr., Eds. (Wiley-Interscience, New York, 1968), pp. 203–218.
8. J. B. Lyons, E. L. Boudette, J. N. Aleinikoff, *Geol. Soc. Canada Spec Pap.* **24**, 43 (1982).
9. E. Zen, D. Stewart, L. R. Fyffe, *Geol. Soc. Am. Abstr. Prog.* **18**, 800 (1986).
10. J. D. Eusden and B. Barreiro, *Marit Sediments Atl. Geol.* **24**, 241 (1988).
11. G. M. Boone, E. L. Boudette, R. H. Moench, in *Guidebook for Field Trips in the Rangeley Lakes—Dead River Basin Region Western Maine*, New England Intercollegiate Geology Conference, 62nd Annual Meeting, Rangeley, Maine (Syracuse, NY, 1970), pp. 1–24.
12. N. L. Hatch, R. H. Moench, J. B. Lyons, *Am. J. Sci.* **283**, 739 (1983).
13. C. P. Chamberlain, thesis, Harvard University (1985).
14. B. A. Hall, S. G. Pollock, K. M. Dolan, *Geol. Soc. Am. Mem.* **148**, 57 (1976).
15. J. B. Lyons, W. A. Bothner, R. H. Moench, J. B. Thompson, Jr., *Bedrock Geologic Map of New Hampshire* (Open-File Report, State Geologist Office, Manchester, NH, 1986).
16. C. P. Chamberlain and J. B. Lyons, *Am. Mineral.* **68**, 530 (1983).
17. R. J. Tracy and P. Robinson, in *The Caledonides in the USA*, D. R. Wones, Eds. (IGCP Project 27, Blacksburg, VA, 1980), pp. 189–195.
18. D. L. Nielson, R. G. Clark, J. B. Lyons, E. J. Englund, D. J. Borns, *Geol. Soc Am. Mem.* **146**, 301 (1976).
19. J. B. Lyons and D. E. Livingston, *Geol. Soc. Am. Bull* **88**, 1808 (1977).
20. B. Barreiro and J. Aleinikoff, *Eos* **69**, 464 (1985).
21. T. M. Harrison, J. N. Aleinikoff, W. Compston, *Geochim. Cosmochim Acta* **51**, 2549 (1987).
22. D. R. Lux and C. V. Guidotti, *Geology* **13**, 696 (1985).
23. E. F. Duke and C. P. Chamberlain, *Geol. Soc. Am. Abstr. Prog.* **13**, 130 (1981).
24. R. G. Clark and J. B. Lyons, *J. Petrol.* **27**, 1365 (1986).
25. M. J. Holdaway, C. V. Guidotti, J. M. Novak, W. E. Henry, *Geol Soc. Am. Bull* **93**, 572 (1982).
26. M. J. Holdaway, B. L. Dutrow, R. W. Hinton, *Am. Mineral.* **73**, 20 (1988).
27. R. P. Dickerson and M. J. Holdaway, *Am. J. Sci.* **289**, 945 (1989).
28. H. W. Day and C. P. Chamberlain, in *Evolution of Metamorphic Belts*, J. S. Daly, R. A. Cliff, B. W. D. Yardley, Eds. (Blackwell, Oxford, 1989), pp. 215–222.
29. H. A. Smith, thesis, Dartmouth College (1989).
30. ——— and B. Barreiro, *Contrib. Mineral. Petrol.*, in press.
31. F. Birch, R. F. Roy, E. R. Decker, in *Studies in Appalachian Geology: Northern and Maritime*, E.-A. Zen, W. S. White, J. B. Hadley, J. B. Thompson, Jr., Eds. (Wiley-Interscience, New York, 1968), pp. 203–218.
32. R. F. Roy, D. B. Blackwell, F. Birch, in *ibid.*, pp. 1–12.
33. C. Jaupart, J. G. Sclater, G. Simmons, *Earth Planet Sci. Lett.* **52**, 328 (1981).
34. C. Jaupart, J. R. Mann, G. Simmons, *ibid.* **59**, 267 (1982).
35. E. R. Decker, *Geophys Res Letts.* **14**, 256 (1987).
36. S. Bloch, *Geochim. Cosmochim. Acta* **44**, 373 (1980).
37. H. H. Veeh, *Earth Planet Sci. Lett* **3**, 145 (1967).
38. C. Lalou, in *Uranium Series Disequilibrium*, M. Ivanovich and R. S. Harmon, Eds. (Oxford Univ. Press, Oxford, 1982), pp. 431–766.
39. R. C. Newton, *Geophys. Res Lett* **14**, 287 (1987).
40. C. P. Chamberlain and D. Rumble, *J. Petrol.* **29**, 1215 (1988).
41. ———, in *Evolution of Metamorphic Belts*, J. S. Daly, R. A. Cliff, B. W. D. Yardley, Eds. (Blackwell, Oxford, 1989), pp. 203–213.
42. R. P. Rapp and E. B. Watson, *Contrib. Mineral. Petrol.* **94**, 304 (1986).
43. R. P. Rapp, F. J. Ryerson, C. F. Miller, *Geophys. Res. Lett.* **14**, 307 (1987).
44. R. J. Tracy, *Am J. Sci.* **278**, 150 (1978).
45. Boundary conditions must be specified at the top, base, and sides of the solution space. We chose $T = 0$ at $z = 0$ and a constant heat flux, Q_0, at the base $z = L$ [see (*1*) for comparison]. No horizontal heat flow through the sides of the solution space was allowed ($\partial T/\partial x = 0$). The initial temperature distribution is that which is in steady state with basal heat flux, zero surface temperature, and the above heat production distribution. At time $t = 0$, the crust was instantaneously and homogeneously thickened by a factor f. [Whether the crust is thickened homogeneously or by large overthrust sheets is unimportant because the results of calculations are insensitive to the mode of thickening, as discussed in (*6*)]. Several experiments were carried out, for values of f between 1.5 and 2 (Tables 2 and 3), which reflect the variable amounts of Acadian thickening inferred along strike in the CMT [see section on metamorphism and (*16, 17, 47*)]. The erosional history is that used by Chamberlain and England [(*6*), curve 2], and when $f = 2$, consists of a 30-million-year interval of no erosion, 15 km of erosion over the next 95 million years, and 15 km of erosion in the next 155 million years. Erosion rates for experiments with $f < 2$ were decreased proportionately so that erosion returned the crust to its pre-orogenic thickness over the same 150-million-year erosion interval. The heat flow equation was solved numerically with an implicit alternating direction finite difference scheme [W. H. Press, B. P. Flannery, S. A. Teukolsky, W. T. Vetterling, *Numerical Recipes* (Cambridge Univ. Press, New York, 1986)].
46. In general, the magnitudes of the metamorphic temperature and pressure differences across the model CMT are most sensitive to horizontal variations in heat production and are much less sensitive to the way in which heat production varies vertically or to the way in which crustal thickening is effected. For example, consider a calculation in which the crustal thickness is doubled by emplacement of a thrust sheet of thickness 30 km on top of the pre-existing crust. Heat production in the lower plate varies as described in the section on thermal models, but the upper plate is assumed to have a normal heat production distribution of $1.4 \times 10^{-6} \exp(-z/d)$ W kg^{-1}. (This calculation could represent a CMT tectonically buried by thrusting of crustal material with normal concentrations of U and Th.) The calculated metamorphic temperature and pressure of rocks now exposed on the surface are 643°C and 6.6 kbar, respectively, on the hot side, and 550°C and 6.6 kbar on the cold side, a difference of 97°C in temperature and no difference in pressure (compare with results for $f = 2$ in Table 3). Rocks now at 10 km depth were calculated to have experienced metamorphic maximum conditions of 824°C, 8.8 kbar (hot side) and 715°C, 8.8 kbar (cold side). Obviously, there are many plausible distributions of heat production and deformation that could produce the distribution of metamorphic conditions observed in the CMT; common to them all, however, must be a significant horizontal variation in heat production but little or no variation in erosional parameters.
47. H. W. Day, *J. Geol.* **95**, 807 (1987).
48. L. J. Sonder and C. P. Chamberlain, in preparation.
49. A. E. Patino Douce, E. D. Humphreys, A. D. Johnston, *Earth Planet. Sci. Lett.* **97**, 290 (1990).
50. Mean and standard deviation for heat production for all rock units with more than one datum are: Sp (in CMT), 7.28 ± 1.46; Sr, 9.59 ± 3.35; Sfm, 11.8 ± 5.59; Oam, 2.44 ± 2.61; Ozb, 5.04 ± 1.05; Sp (in adjacent terranes), 4.58 ± 2.68; Pr, 4.90 ± 1.29; Dwgd, 2.80 ± 1.05; Dsg, 6.84 ± 1.44; Dmg, 14.34 ± 5.89; Dbgn, 8.06 ± 1.91; Dkqm, 8.89 ± 1.75; Oc, 9.65 ± 3.06; Yg, 8.20 ± 5.91; Zom, 7.82 ± 4.84. Units are 10^{-10} W kg^{-1}; key to rock units given in caption to Fig. 2.
51. J. B. Lyons, *U.S Geol. Surv. Bull* **1144F**, 1 (1964); W. A. Bothner, *U S. Geol Surv. Open File Rep. 78-482* (1978); J. D. Eusden, thesis, Dartmouth College (1988); M. Hingston, thesis, Dartmouth College (1990); B. Barreiro, unpublished data; R. Moench, unpublished data.

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