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Monazite geochronology in central New England: evidence for a fundamental terrane boundary

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ABSTRACT Monazite crystallization ages have been measured *in situ* using SIMS and EMP analysis of samples from the Bronson Hill anticlinorium in central New England. In west-central New Hampshire, each major tectonic unit (nappe) displays a distinctive *P–T* path and metamorphic history that requires significant post-metamorphic faulting to place them in their current juxtaposition, and monazite ages were determined to constrain the timing of metamorphism and nappe assembly. Monazite ages from the low-pressure, high-temperature Fall Mountain nappe range from *c*. 455 to 355 Ma, and Y zoning indicates that these ages comprise three to four distinct age domains, similar to that found in the overlying Chesham Pond nappe. The underlying Skitchewaug nappe contains monazite ages that range from *c*. 417 to 307 Ma. $^{40}Ar/^{39}Ar$ ages indicate rapid cooling of the Chesham Pond and Fall Mountain nappes after 350 Ma, which is believed to represent the time of emplacement of the high-level Chesham Pond and Fall Mountain nappes onto rocks of the underlying Skitchewaug nappe. Garnet zone rocks from western New Hampshire contain monazite that display a range of ages (*c*. 430–340 Ma). Both the metamorphic style and monazite ages suggest that the low-grade belt in western New Hampshire is continuous with the Vermont sequence to the west. Rocks of the Big Staurolite nappe in western New Hampshire contain monazite that crystallized between *c*. 370 and 290 Ma and the same unit along strike in northern New Hampshire and central Connecticut records ages of *c*. 257–300 Ma. Conspicuously absent from this nappe are the older age populations that are found in both the overlying nappes and underlying garnet zone rocks. These monazite ages confirm that the metamorphism observed in the Big Staurolite nappe occurred significantly later than that in the units structurally above and below. These data support the hypothesis that the Big Staurolite nappe represents a major tectonic boundary, along which rocks of the New Hampshire metamorphic series were juxtaposed against rocks of the Vermont series during the Alleghanian.

Key words: geochronology; monazite; New England metamorphism; New England tectonics.

INTRODUCTION

Spear *et al.* (1990) demonstrated the explicit relationship between tectonic history and *P–T* path in rocks from the Fall Mountain nappe in west-central New Hampshire. In a subsequent contribution, Spear *et al.* (2002) documented that every tectonic domain along the Bronson Hill anticlinorium in western New Hampshire has a unique *P–T* path and that this unique metamorphic history could be used to define structural domains (i.e. nappes). It was argued that the thrust nappes as originally defined by Thompson *et al.* (1968) could be mapped not only on a stratigraphic basis but also on their metamorphic characteristics. Indeed, it was clear from this more recent study that the metamorphic history (*P–T–t* evolution) provides information about a rock's history through an orogenic cycle that is completely independent of any stratigraphic or structural models. Thus the *P–T–t* evolution of a domain can lead to interpretations of the structure and tectonic evolution that are *less* model dependent than stratigraphy-based structural interpretations.

Of particular significance in the study of Spear *et al.* (2002) was the recognition of a distinctive domain that had a metamorphic history unlike the units above or below it. Named the 'Big Staurolite' nappe (hereafter BSN) based on the nearly ubiquitous presence of large, centimetre-sized staurolite porphyroblasts, this domain extends nearly continuously some 250 km along the strike of the western margin of the Bronson Hill anticlinorium. Arguments based on microfabrics and petrogenesis (discussed below) demonstrated that this unit is bounded by thrust faults that were active following the peak of metamorphism. These inferences lead naturally to the question of when and how these units were juxtaposed, and what this might imply about the tectonic assembly of New England.

Our purpose here is to present new data on the crystallization ages of monazite from different structural levels of the Bronson Hill anticlinorium, with the goal of constraining the age of metamorphism of the different tectonic units. Monazite is particularly useful for this purpose, because it grows during prograde metamorphism, and may grow several times during a single metamorphic episode (e.g. Smith & Barreiro, 1990; Pyle & Spear, 2003; Wing *et al.*, 2003; Kohn & Malloy, 2004). Additionally, it is in some cases possible to assess the temperature of monazite crystallization by either monazite thermometry (e.g. Heinrich *et al.*, 1997; Pyle *et al.*, 2001; Seydoux-Guillaume *et al.*, 2002b) or by association with major phase reactions (e.g. Kohn & Malloy, 2004) and thus link the age directly to the metamorphic *P–T* path. The immediate goal of this study was to constrain the age of metamorphism of rocks in the BSN and those structurally above and below it, in order to constrain the timing of the assembly of the Bronson Hill zone in central New England. More generally, the results presented here explore the extent to which monazite geochronology can be used to delineate tectonic units that have undergone different metamorphic histories.

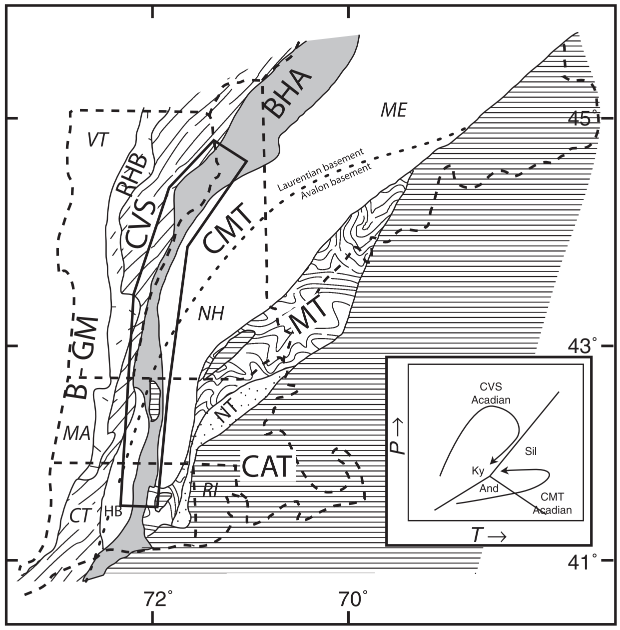


Fig. 1. Map of New England showing tectonic zones after Zartman (1988). B–GM, Berkshire–Green Mountains; RHB, Rowe–Hawley belt; CVS, Connecticut Valley synclinorium; BHA, Bronson Hill anticlinorium; CMT, Central Maine terrane; MT, Merrimack terrane; NT, Noshobu terrane; CAT, Composite Avalon terrane; HB, Hartford Basin. Dotted line shows inferred boundary between Laurentian and Avalon basement. Outlined area shows location of map of the Bronson Hill anticlinorium (Fig. 2). Inset shows schematic *P–T* paths for rocks of the CVS and CMT during the Acadian orogeny.

GEOLOGICAL AND METAMORPHIC SETTING

Regionally, central New England can be divided into a series of litho-tectonic terranes as shown in Fig. 1. Each terrane is characterized by a specific stratigraphy, and each also has a characteristic metamorphic style (Fig. 1, inset). The Connecticut Valley synclinorium (CVS) in eastern Vermont is characterized by relatively high-pressure (10 kbar), Barrovian-style metamorphism with clockwise *P–T* paths associated with domes cored by *c.* 1.1 Ga Proterozoic gneisses (Laurentian Basement). The Central Maine terrane in central New Hampshire is characterized by lower pressure Buchan-style metamorphism with dominantly counter-clockwise *P–T* paths. The intervening Bronson Hill anticlinorium (Figs 1, 2 & 3) is characterized by a series of thrust-and-fold nappes with disparate metamorphic histories punctuated by domes cored by Late Proterozoic and Ordovician gneisses.

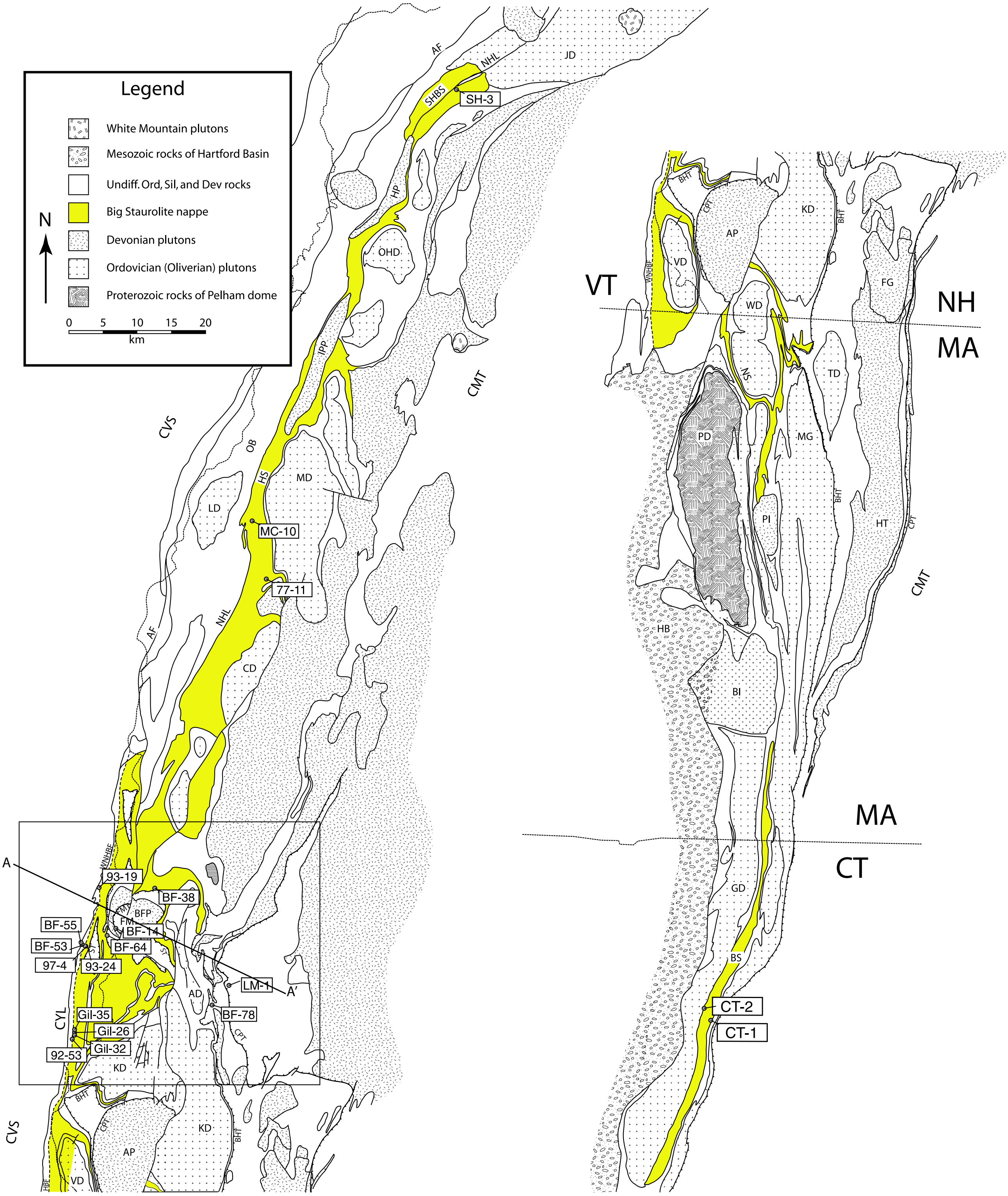
Spear *et al.* (2002) discussed the unique *P–T* history experienced by rocks of different structural settings along a transect across this region (Figs 2, 3 & 4). In the domes and adjacent cover of eastern Vermont, *P–T* paths are clockwise reaching peak pressures of ~10 kbar. The maximum pressure of metamorphism decreases eastwards towards the boundary between the Vermont and New Hampshire stratigraphic sequences, reaching a minimum value of ~4 kbar. Situated right along the border of the Vermont and New Hampshire stratigraphic sequences is a belt of chlorite-zone rocks that grade eastward over a short distance into garnet-zone pelites. The classic New Hampshire nappes of Thompson *et al.* (1968; and later Thompson, 1985) (e.g. Fall Mountain, Skitchewaug and Chesham Pond nappes) record a period of early contact metamorphism that is related to plutons of the *c.* 410–400 Ma New Hampshire magma series, followed by regional low-pressure, medium- to high-temperature metamor-

Fig. 2. Geological map of the Bronson Hill anticlinorium from northern New Hampshire to southern Connecticut (after Doll *et al.*, 1961; Thompson & Rosenfeld, 1979; Zen, 1983; Rodgers, 1985; Lyons *et al.*, 1997; Robinson, 2003). JD, Jefferson dome; SHBS, Salmon Hole Brook syncline; AF, Ammonoosuc Fault; NHL, Northey Hill Line; HP, Haverhill Pluton; IPP, Indian Pond Pluton; OHD, Owl's Head dome; HS, Hardscrabble syncline; LD, Lebanon dome; OB, Orfordville Belt; MD, Mascoma dome; CD, Croydon dome; BG, Bethlehem gneiss; KQM, Kinsman quartz monzonite; CYL, Chicken Yard line; FM, Fall Mountain; BFP, Bellows Falls Pluton; WNHBF, Western New Hampshire Boundary fault; AD, Alstead dome; CPT, Chesham Pond thrust; FMT, Fall Mountain thrust; ST, Skitchewaug Thrust; BHT, Brennan Hill Thrust; KD, Keene dome; AP, Ashuelot pluton; VD, Vernon dome; WD, Warwick dome; PD, Pelham dome; NS, Northfield syncline; MG, Monson gneiss; TD, Tully dome; BI, Belchertown intrusive complex; PI, Prescott intrusive complex; GD, Glastonbury dome; HT, Hardwick tonalite; FG, Fitzwilliam granite; HB, Hartford basin; BS, Bolton syncline; CVS, Connecticut Valley synclinorium, CMT, Central Maine terrane. The Big Staurolite nappe (BSN) is shown with dark ruling. Thrust faults are indicated by barbed lines. A–A′ shows line of cross section in Fig. 3. Sample locations are indicated by numbers.

phism (Spear *et al*., 2002). The peak metamorphic temperature increases upwards in each structurally higher nappe in an inverted metamorphic sequence. Only the highest nappe (the Chesham Pond) does not record an episode of isothermal loading.

Big Staurolite nappe

Originally described by Spear *et al*. (2002), the BSN is comprised predominantly of para-autochthonous Devonian Littleton Formation, typically associated



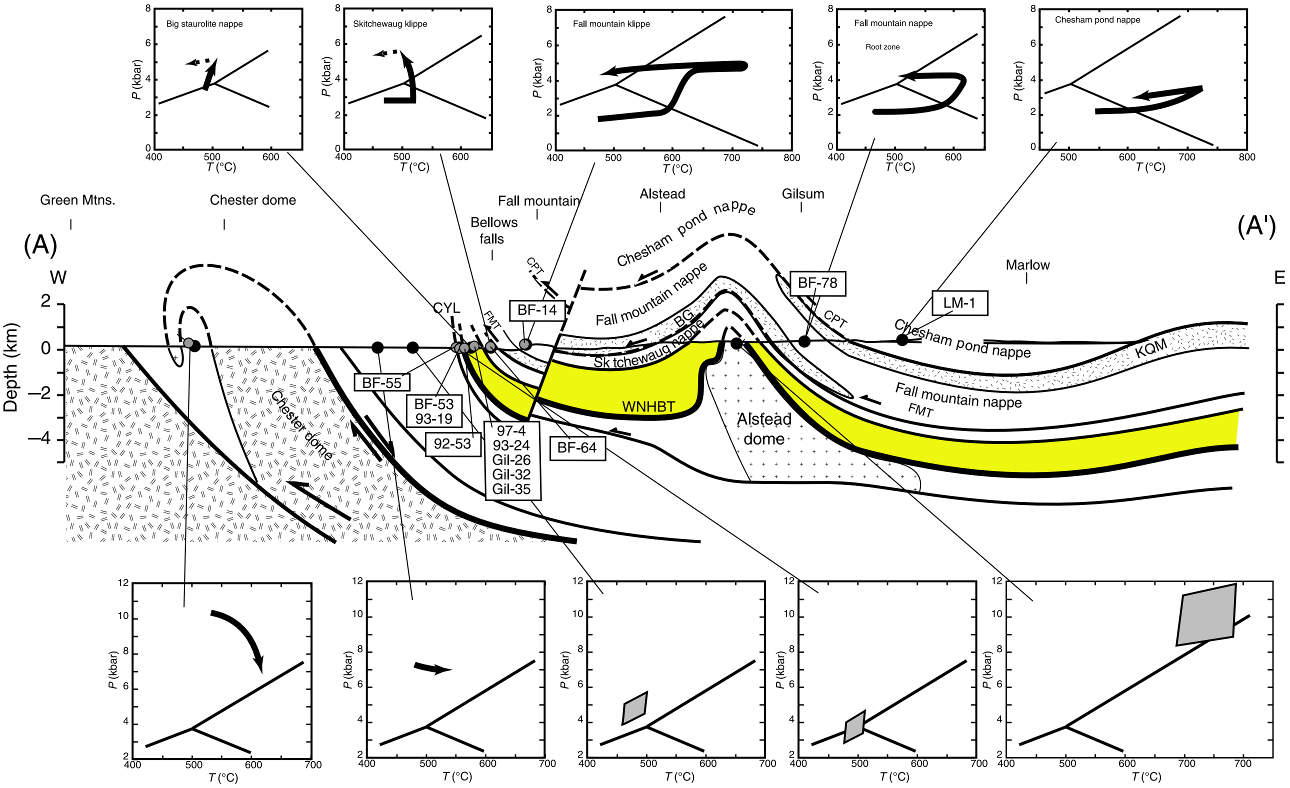


Fig. 3. Cross section along line A–A′ of Fig. 2 with *P–T* paths for different structural levels and sample numbers for geochronology. After Spear *et al*. (2002). Abbreviations as in Fig. 2. The BSN is shown with horizontal ruling.

with Silurian Fitch and Clough formations. The BSN extends from the northern Bronson Hill anticlinorium where it cores the Salmon Hole Brook syncline (e.g. Florence *et al*., 1993), through the Mascoma region where it comprises the Hardscrabble synclinorium (Kohn *et al*., 1992), through the Springfield–Bellows Falls region where it comprises the recumbent syncline beneath the Skitchewaug nappe (e.g. Thompson *et al*.,

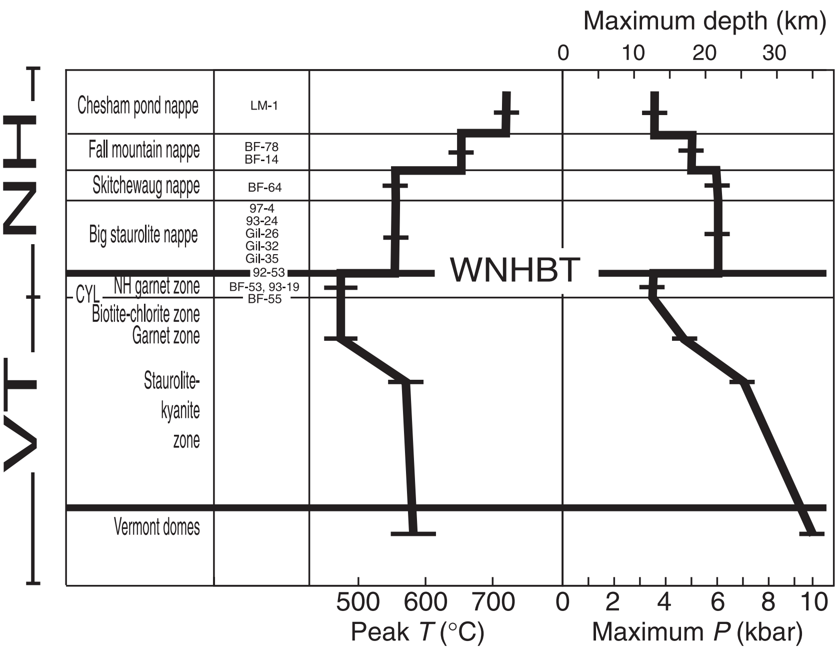


Fig. 4. Diagram summarizing the maximum temperature and pressures recorded in different structural levels across central New England along the line of cross section A–A′ (Figs 2 & 3). Sample numbers are indicated. WNHBT, Western New Hampshire Boundary thrust; CYL, Chicken Yard Line. From Spear *et al*. (2002).

1968), into north-central Massachusetts where it cores the Northfield syncline between the Warwick and Pelham domes (Fig. 2). It crops out again in south-central Massachusetts and into Connecticut where it cores the Bolton syncline (e.g. Busa & Gray, 2005). It is thus nearly continuous for nearly 250 km along the strike of the Bronson Hill anticlinorium. Although most researchers acknowledge the distinctive nature and petrological character of this structural domain, not all agree that it is a nappe everywhere along the Bronson Hill anticlinorium. In Massachusetts, Robinson (2003) recognized these rocks and suggested that they represent a *c*. 290 Ma shearing and metamorphic overprint of pre-existing sillimanite grade rocks. Nonetheless these rocks, even in Massachusetts, are in a distinctive tectonic domain that differs discontinuously from the bounding domains above and below.

The metamorphic history of the BSN is distinct from rocks structurally above or below it (Figs 3 & 4). First, along its entire strike in New Hampshire where the parageneses have been studied in detail, the *P–T* paths of rocks from the BSN display an episode of nearly isobaric loading, followed by heating (Fig. 3). Second, the early contact metamorphic episode experienced by the overlying Skitchewaug, Fall Mountain and Chesham Pond nappes is nowhere observed in rocks of the BSN. Third, rocks of the overlying Fall Mountain and Chesham Pond nappes experienced regional low-pressure, medium- to high-temperature metamorphism following the contact metamorphism, whereas the BSN experienced only Barrovian metamorphism. Fourth, although the peak metamorphic conditions of the BSN and overlying Skitchewaug nappes are similar, there is a clear metamorphic break between these units and structurally higher nappes (Fall Mountain and Chesham Pond) (Fig. 4). Indeed, both the BSN and parts of the Skitchewaug nappe contain large staurolite and the metamorphism was assumed to post-date nappe formation between the two structural levels because of this apparent continuity of grade. However, microstructural analysis has shown that porphyroblast growth in the overlying Skitchewaug nappe clearly post-dates the development of the dominant foliation, and that it is most likely related to the early contact metamorphism, whereas the large staurolite grains in the BSN clearly overgrow the dominant foliation, and they are related to isobaric loading. These observations led to the conclusion (Spear, 1992; Spear *et al*., 2002) that metamorphism in the BSN must have post-dated peak metamorphism in the overlying Skitchewaug and higher nappes, and required these units be juxtaposed by faulting. Mapping by Armstrong *et al*. (1997) has confirmed the existence of a thrust fault flooring the Skitchewaug nappe.

The relationship between the BSN and underlying units is also disparate, but entirely different in nature. Within the BSN, peak metamorphic conditions, porphyroblast size, and microstructural relations are similar going downwards and westerly towards the low-grade rocks along the Vermont–New Hampshire stratigraphic border. Then the metamorphic grade drops to garnet grade with a profound metamorphic break over a distance of a few tens of metres or less (Fig. 4). Significantly, as the base of the BSN is approached, the extent of chlorite-grade alteration increases to the point where, near the boundary with the garnet zone, most staurolite porphyroblasts are completely pseudomorphed by chlorite. Indeed, a greenschist facies zone of highly sheared rocks displaying west-vergent minor structures has been observed at the presumed location of the contact in several locations. Spear *et al*. (2002) interpreted this structure to be a late, west-vergent thrust fault that brought the rocks of the BSN in juxtaposition with the lower grade New Hampshire garnet-zone rocks and have named this structure the 'Western New Hampshire boundary thrust (WNHBT)'. The extent and timing of transport on this structure are unknown, but it was apparently active when rocks were at greenschist facies conditions, i.e. after the peak of metamorphism in the BSN.

In summary, the petrological and microstructural observations reported in Spear *et al*. (2002) suggested that the BSN is a distinct metamorphic unit bounded above and below by thrust faults. The upper thrust fault was active following the peak of metamorphism in the overlying Skitchewaug, Fall Mountain and Chesham Pond nappes (i.e. after these units had cooled somewhat), and the emplacement of these nappes was most likely responsible for the isobaric loading observed in the BSN *P–T* paths. The lower thrust was active in the greenschist facies, after the peak of metamorphism in the BSN.

Previous geochronology

A large number of geochronology studies have been performed in central New England (see Zartman, 1988; Robinson *et al*., 1998; Wintsch *et al*., 2003 and references therein for details), but few of these data constrain the timing of nappe emplacement (faulting), and especially the BSN. The New Hampshire magma series (e.g. Bethlehem gneiss and Kinsman quartz monzonite) has been dated at *c*. 413–405 Ma (Barreiro & Aleinikoff, 1985; Kohn *et al*., 1992), and field relations indicate that these plutons are responsible for the early contact metamorphism observed in the Skitchewaug, Fall Mountain and Chesham Pond nappes.

Pyle & Spear (2003) and Pyle *et al*. (2005b) reported four chemically distinct generations of monazite growth in rocks of the Chesham Pond nappe from central New Hampshire. The oldest age of *c*. 400 ± 10 Ma is interpreted as representing monazite growth in response to contact metamorphism associated with intrusion of the New Hampshire magma series, and is consistent with the age of the plutons. The second- and third-generation monazites (381 ± 8 and 372 ± 6 Ma, respectively) reflect monazite growth during regional low-pressure, high-temperature metamorphism and the fourth generation (352 ± 14 Ma) is interpreted as representing monazite growth during crystallization of the leucosomes that are abundant in these high-grade migmatites. The model proposed by Pyle *et al.* (2005b) involves lithospheric extension in the Early Devonian causing lower crustal melting that resulted in the New Hampshire series magmas. Propagation of the thermal anomaly caused by the upwelling of asthenosphere into the middle crust over 20–30 Myr produced the regional low-pressure, high-temperature metamorphism. Crystallization of the leucosomes was accomplished by cooling that resulted from emplacement of the migmatites onto cooler rocks, presumably by west-directed thrusting of the Chesham Pond nappe at *c.* 355–350 Ma. An additional inference from this study is that the high-precision TIMS monazite ages of Eusden & Barreiro (1988) in the high-grade terrane of central New Hampshire are most likely mixtures of these four age domains.

Rocks of the Fall Mountain nappe also show up to four generations of monazite growth (see below), and rocks of both the Fall Mountain and Skitchewaug nappes display episodes of early contact metamorphism. Presumably both units might be expected to contain monazite grown during contact metamorphism. Furthermore, the Fall Mountain nappe might contain monazite that grew during the regional low-pressure metamorphism as well as during leucosome crystallization. It is significant to note that rocks of the Fall Mountain nappe have *P–T* paths with an episode of loading (see Fig. 3), which is interpreted as resulting from emplacement of the overlying Chesham Pond nappe. If so, then the last generation of monazite growth in the Fall Mountain rocks should be younger than the last generation in the Chesham Pond rocks (i.e. younger than 352 ± 14 Ma). Similarly, rocks of the Skitchewaug nappe should contain a generation of monazite that grew in response to emplacement of the overlying nappes.

Finally, inasmuch as the petrological constraints indicate that the metamorphism in the BSN could not have occurred until after the overlying nappes were somewhat cool, and available evidence suggests this cooling began around 350 Ma, the major metamorphism of the BSN is constrained to have occurred later than *c.* 350 Ma.

METHODS

Several hundred samples from the study area have been examined over the past decade for monazite with distinctive growth textures. The samples chosen for detailed study are predominantly low-Ca pelites (i.e. no epidote, titanite, or allanite is present), and are either the same samples, or those collected very close to samples that have been used for detailed *P–T* path studies (e.g. Spear *et al.*, 1990, 2002; Kohn *et al.*, 1992; Florence *et al.*, 1993; Menard & Spear, 1994; Pyle & Spear, 1999, 2003; Pyle *et al.*, 2001).

Following the methods developed by Pyle & Spear (2003) a combination of methods have been employed to identify the distinct stages of monazite growth in each sample, and to constrain the conditions of this growth. These include petrographic analysis with special attention to the textural setting of monazite, backscatter and secondary electron imaging, X-ray compositional mapping, and quantitative chemical analysis.

SIMS analyses

Ion microprobe analyses of monazite were performed using the IMS 1270 ion microprobes at the Keck National Ion Microprobe facility at UCLA and the Northeast National Ion Microprobe Facility at Woods Hole Oceanographic Institute (WHOI) and the IMS 1280 at WHOI. Our initial efforts at UCLA followed the analytical procedures outlined by Harrison *et al.* (1995, 1997), using monazite standards '554' and 'UCLA 76'. A modification to the standardization procedure was introduced at the WHOI facility during the June 2002 session. Specifically, the standard curve was generated by changing the offset of the voltage window to simulate the effects of sample charging (i.e. using a voltage window of 50 V and offsets of −10, 0, +10, +20 and +30 V). During January 2007, monazite standard 'Moacyr' (obtained from J.-M. Montel) was used at WHOI with the standardization procedure outlined by Harrison *et al.* (1995, 1997). Although the published age of the standard is 474 ± 1 Ma (Seydoux-Guillaume *et al.*, 2002a), several researchers have found that both EMP and SIMS ages of some of this material is *c.* 506 Ma (M. Williams and J.-M. Montel, pers. comm.). Our EMP age on the standard used at WHOI is consistent with this older age and thus the 506 Ma age for the standard was used.

The results of SIMS analyses of monazite are presented in Table S1. The reported uncertainties in the ages are based on counting statistics on the standard and unknown monazites, and are generally in the order of 1–2% (1σ SE). However, it should be emphasized that the accuracy of an individual spot analysis may be significantly larger for several reasons. This larger uncertainty arises because many SIMS spots overlapped grain boundaries, cracks or inclusions within monazite grains. In addition, ages from multiple analyses of a single homogeneous monazite grain taken over several analytical sessions differed by much as ±5% depending on instrument parameters, vacuum quality and standardization curve. Furthermore, some SIMS spots commonly overlapped multiple age domains in some grains, as indicated by obvious growth zoning based on BSE and X-ray mapping. This results in spot analyses that are mixtures of two or more ages. Therefore, we assume that individual spot ages may be accurate to only ±5% or ±20 Ma at 400 Ma, and this must be kept in mind when interpreting the SIMS age data.

EMP analyses

Chemical ages of monazite in several samples were determined using the method of Montel *et al.* (1996) with numerous modifications (Pyle *et al.*, 2005a) and the results are reported in Table S2. Considerable effort was expended during the course of this study to improve the precision of individual analyses and to identify and correct for any systematic errors that could affect accuracy. Individual spot analyses performed with the JEOL 733 electron probe are precise to only around ±10% (i.e. ±40 Myr). Analyses with the CAMECA SX-100 are more precise by a factor of around 1.5 (i.e. ±26 Myr). Wherever possible, averages of multiple analyses of chemically similar domains were calculated, which yielded mean ages with precisions of ±2–8% (i.e. ±10–25 Myr; Table S2). The accuracy of chemical ages is more difficult to assess, but ages obtained on the same grain using both the EMP and SIMS differ by less than the relative error in either of the two methods, lending confidence to the accuracy of the chemical ages (see Pyle *et al.*, 2005a, for details).

RESULTS

Results of SIMS and EMP analyses are presented in Tables S1 and S2 and are plotted in Figs 5 and 6. All monazite grains were examined using backscattered electron (BSE) imaging and most were chemically mapped for Y, Th, Pb and U in order to identify growth zonations that might correlate with age zonation.

The zoning observed in monazite grains using either BSE or X-ray mapping is quite consistent within structural levels. Figures 7 and 8 illustrate the important differences between monazite of the BSN and overlying Fall Mountain nappe (for details of monazite zoning from the Chesham Pond nappe, see Pyle & Spear, 2003). Monazite from the BSN (Fig. 8) is unzoned in Y within the resolution of the X-ray mapping protocol (on the order of a few thousand ppm Y). Some, but not all monazite is zoned in Th. The typical pattern as shown in Fig. 8a, e is high Th in the core that decreases monotonically towards the rim. The cause of this systematic decrease is not known, but it is probably due to Rayleigh fractionation during a single episode of monazite growth as suggested for similarly zoned monazite grains by Kohn & Malloy (2004). Reversely zoned monazite with high Th rims occurs in only a few samples (e.g. Fig. 8e). One notable exception to the above is sample CT-2 from the Bolton Syncline in Connecticut. All five mapped grains in this rock have a sharply defined rim and a zoned core that is similar to grains described above; i.e. the core has a high U, Y and Th that decreases outward consistent

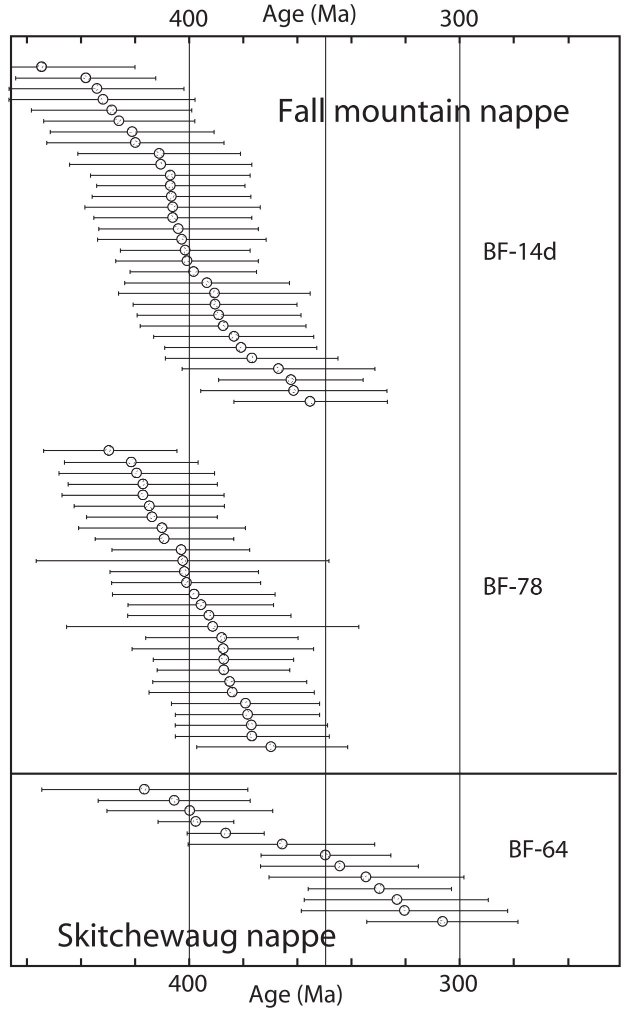


Fig. 5. Monazite chemical ages (EMP) of samples from the Fall Mountain and Skitchewaug nappe, samples BF-14d, BF-78 and BF-64. Individual spot analyses are shown with 2 sigma error bars determined from counting statistics. The apparent continuous range of ages is interpreted as three to four distinct age domains.

with Rayleigh fractionation. However, these grains all have irregular (0–5 μm) but sharply defined rims characterized by high Th, Y and U. These rims are conceivably related to the minor chlorite rimming of garnet in this sample. Monazite grains from lower grade rocks of this study are even less zoned than those of the BSN (see Appendix S1 for details).

In contrast, the zoning of monazite grains from the Fall Mountain nappe is similar to that reported by Pyle & Spear (2003) from the overlying Chesham Pond nappe. These Y zoning patterns imply several distinct growth episodes. At least three distinct growth zones can be seen in individual grains (e.g. Fig. 7c,d), but the samples have not been examined in sufficient detail to determine whether more zones exist.

Electron microprobe ages of monazite from two samples of the Fall Mountain nappe and one sample from the Skitchewaug nappe are shown in Fig. 5. Inasmuch as it is clear from the zoning maps that the grains from the Fall Mountain nappe have experienced multiple growth episodes, the nearly continuous array of ages shown in Fig. 5a results from statistical variations around several (three or possibly four) distinct age populations. For example, the data are consistent with the four age populations reported from the Chesham Pond nappe by Pyle *et al.* (2005b) of 400 ± 10, 381 ± 8, 372 ± 6 and 352 ± 14 Ma, respectively. However, we have not yet been able to correlate specific analysis spots with individual age domains *a priori*, so there is no justification for averaging the ages from either the Fall Mountain or Skitchewaug nappe EMP data. Rather, the range of ages is plotted on the summary diagram of Fig. 6. In any case it is clear that no ages from the Fall Mountain samples were recorded less than *c.* 350 Ma whereas the Skitchewaug nappe samples extend to a somewhat younger age of *c.* 307 Ma.

Figure 6 shows the SIMS ages from each tectonic unit plus EMP ages from the BSN and the ranges of EMP ages from the Fall Mountain and Skitchewaug nappe. The EMP ages from the Fall Mountain nappe are consistent with SIMS ages but, again, it is clear from the extent of zoning and the size of the different age domains in the Fall Mountain monazite grains that most, if not all, of these SIMS ages are mixtures of one or more age domains. Nevertheless, the ages are consistent with the observation of Pyle *et al.* (2005b) that no monazite crystallized in these high-level nappes after approximately 350 Ma. The SIMS ages from the New Hampshire garnet zone span a similar range as those of the Fall Mountain and Chesham Pond nappes. Similarly, the SIMS ages taken from the sheared rocks in the WNHBT span the same range, with the exception of two analyses of 294 ± 6 and 311 ± 14 Ma, and ages from the sheared sample collected at the CYL range from *c.* 386–324 Ma.

It is interesting that a number of monazite samples from the Fall Mountain nappe, NH garnet zone, and WNHBT all record ages greater than *c.* 410 Ma, which is greater than the age of the New Hampshire magma series and the age of the contact metamorphism in the Chesham Pond, Fall Mountain and Skitchewaug nappes. The significance of these older ages is not known, and there does not appear to be any systematic relationship between the age and the textural setting of the monazite, or the location of the spot within the crystal. It is impossible to rule out an analytical

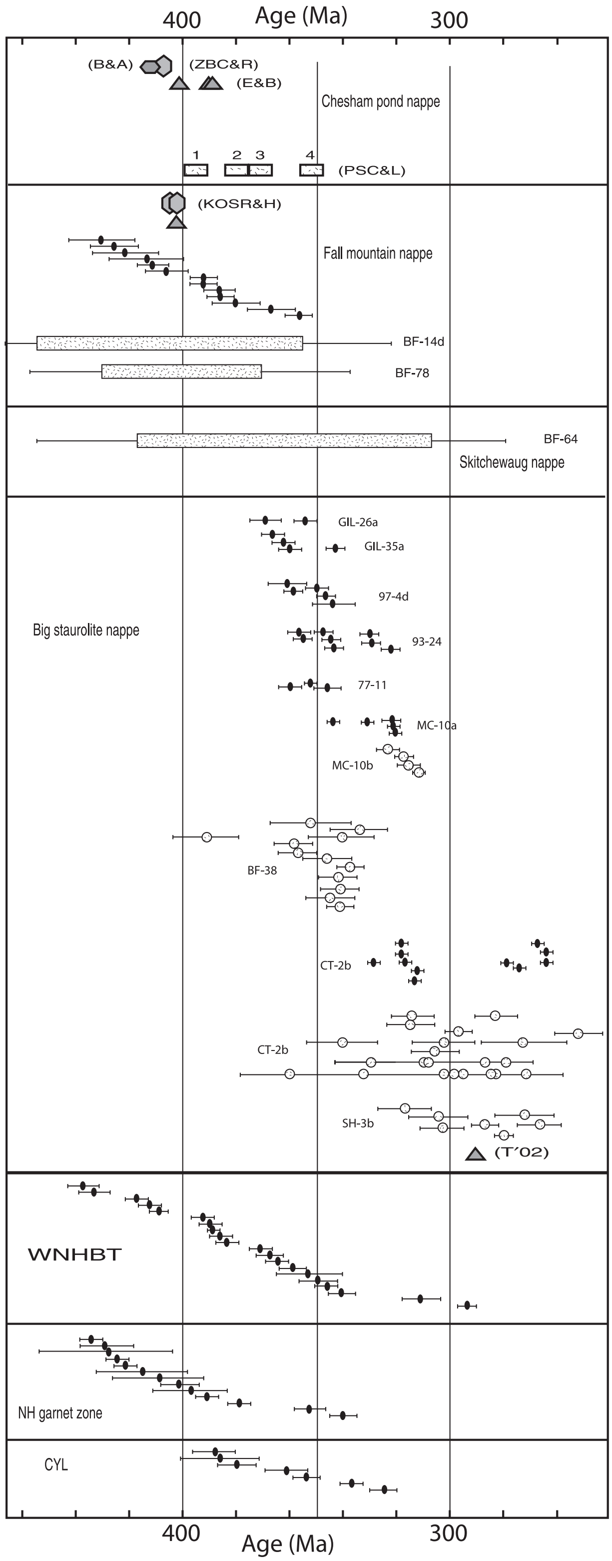


Fig. 6. Summary of monazite ages from west-central New Hampshire as a function of structural position with additional data from the literature. SIMS ages on monazite (this study) indicated by black dots. Chemical EMP ages of monazite indicated by stippled circles (BSN) and stippled rectangles (FMN and SKN; PSC&L: Pyle *et al.*, 2005b; numbers 1–4 are monazite domains). Error bars on spot analyses are 1σ SE (Table 2) about the mean for each grain. Triangles = multi-grain TIMS analyses of monazite (E&B: Eusden & Barreiro, 1988; T'02: R.D. Tucker cited in Robinson, 2003); zircon shapes = SHRIMP analyses of zircon (ZBC&R: Zeitler *et al.*, 1990; KOSR&H: Kohn *et al.*, 1992); garnet shapes = Sm/Nd and Rb/Sr on garnet (B&A: Barreiro & Aleinikoff, 1985).

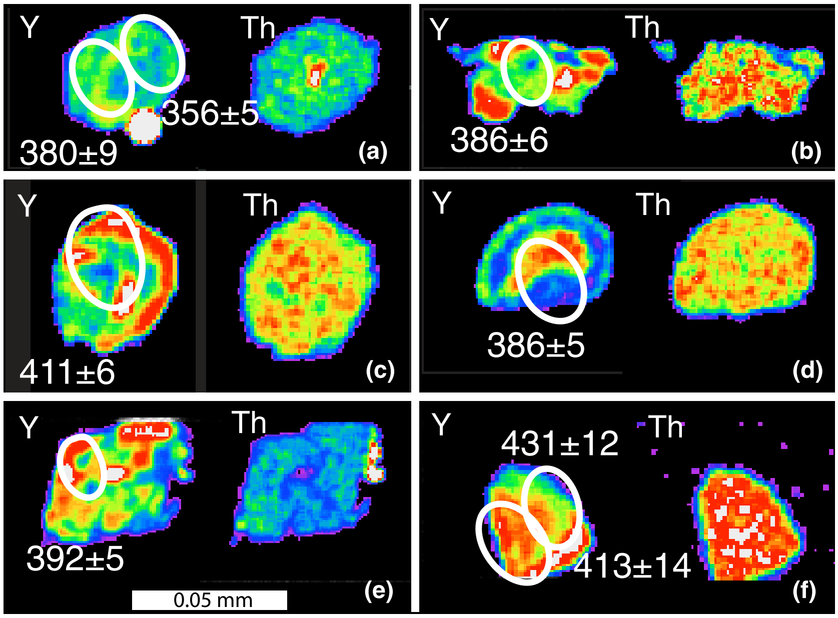


Fig. 7. X-ray maps of Y and Th for monazite from the Fall Mountain nappe. (a)–(d) Sample BF-78; (e, f) sample BF-14d. Numbers are SIMS ages measured at the indicated oval.

artefact producing a slightly older age, or the possibility that a Pb-rich inclusion was encountered during the analysis. It is also possible that the ages reflect monazite growth during diagenesis or low-grade burial metamorphism or mixed analyses with detrital

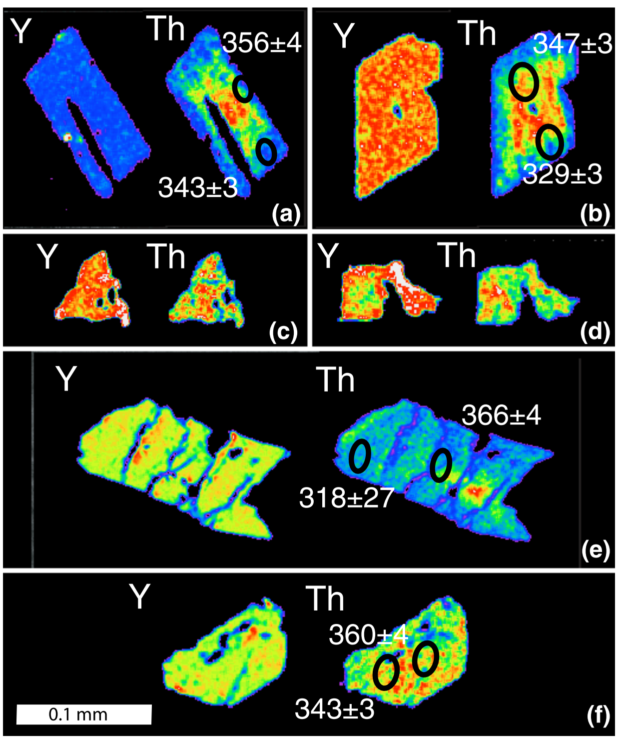


Fig. 8. X-ray maps of Y and Th for monazite from the BSN. (a, b) Sample 93-24; (c, d) sample MC-10a (see Fig. 9 for additional images); (e, f) sample Gil 35a. Spots are locations of SIMS ages indicated by numbers.

cores and further studies are required to resolve this question.

Big Staurolite nappe of New Hampshire

Six samples from the BSN were analysed by SIMS and four by EMP (Fig. 6). The data shown are individual spot analyses for the SIMS analyses and the weighted averages for individual grains with associated standard errors of the mean for the EMP data. Averaging the EMP analyses is justified, because the BSE images and X-ray maps indicate only one period of growth for these monazite except those in sample CT-2. Of note, the SIMS ages for sample CT-2 are apparently bimodal (Fig. 6) but these ages do not simply correlate with the zoning. The 20 μm SIMS beam is much larger than the scale of zoning and the ages reflect two distinct populations and not a mixing of ages. Although not germane here, the two grains with significantly younger ages are elongate whereas the other three grains with older ages are all equant in shape. SIMS ages for all samples, except the elongate grains from CT-2, range from 369 $\pm$ 12 to 312 $\pm$ 6 Ma.

The monazite ages of samples from the BSN reveal a pattern of metamorphism that is distinctly different in time from that of either the overlying or underlying units that is well outside analytical uncertainty. First, there are no monazite ages in the BSN that are older than *c.* 370 Ma, when compared with both higher and lower structural levels that display ages above *c.* 400 Ma. Second, the BSN contains monazite that crystallized later than any of the monazite in the higher or lower structural levels. With the exception of a few analyses from the Skitchewaug nappe and two analyses from the WNHBT, monazite in units other than the BSN is older than *c.* 350 Ma.

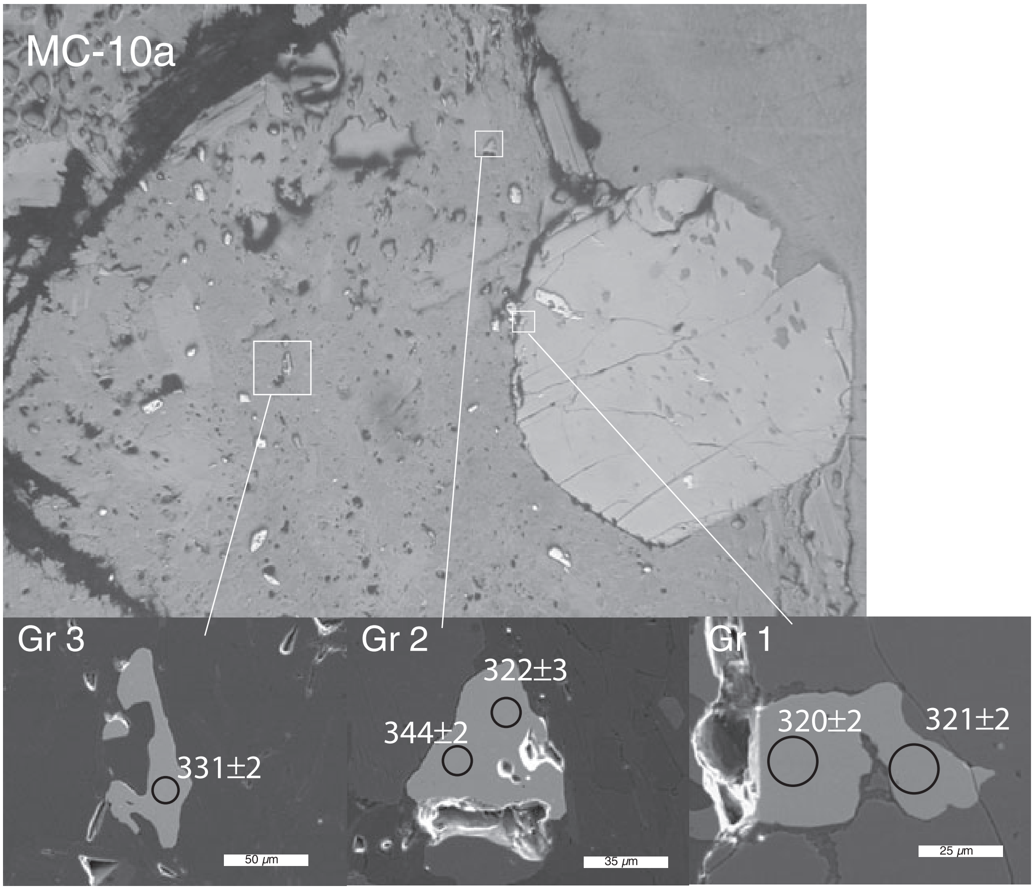


Fig. 9. Reflected light and SE images of monazite from staurolite zone samples MC-10a (BSN, Mascoma, NH quadrangle). Spots show location of ion probe analyses and Th/Pb ages.

The significance of these ages can be seen in Fig. 9, which are images from a part of sample MC-10a. Matrix monazite grains record ages that range from *c*. 344–322 Ma, but a grain contained within a garnet crystal records ages of 320 ± 4 and 321 ± 4 Ma. This result requires that at least part of the garnet grew later than *c*. 320 Ma. Similarly, in sample 93-24 a monazite inclusion inside garnet records an age of 330 ± 6 Ma and one inside staurolite records an age of 329 ± 6 Ma, requiring staurolite growth after *c*. 329 Ma. It is also revealing that the two samples collected within the same stratigraphic and structural unit along strike to the north (SH-3b) and south (CT-2b) also contain monazite grains that crystallized in the Permian (*c*. 302–257 Ma and *c*. 278–261 Ma, respectively). Even though the zoning in CT-2 indicates multiple growth events, and the ages seem bimodal, all ages in this sample are less than 328 ± 6 Ma. Taken together, these data suggest that the main metamorphism of the BSN occurred after *c*. 330–320 Ma, significantly later than the metamorphism in either the overlying or underlying structural units. That is, the peak of metamorphism in the BSN could not have occurred before the Pennsylvanian and could have occurred as late as the Permian.

DISCUSSION

The new geochronology results from the present study (Fig. 6) are incorporated with existing $^{40}Ar/^{39}Ar$ data as temperature–time histories in Fig. 10. Several important points emerge from these data. It appears that the metamorphism in the high-level nappes of New Hampshire (Chesham Pond, Fall Mountain and Skitchewaug) began in as contact aureoles around the *c*. 410–400 Ma plutons of the New Hampshire magma series. Older monazite from these units (up to *c*. 440 Ma) could reflect monazite growth during burial and diagenesis, but it cannot also be ruled out that some of these older ages are analytical artefacts. Most importantly, the metamorphism in these nappes apparently ceased at around 350 Ma. This result is also corroborated by the $^{40}Ar/^{39}Ar$ cooling ages (Fig. 10), which show rapid cooling of the Chesham Pond and Fall Mountain nappes commencing at this time. Coupled with the observation that this was also the time of leucosome crystallization in these units, we conclude that the most reasonable interpretation is one in which these high-level nappes were cooled as a result of emplacement during west-directed thrusting from an

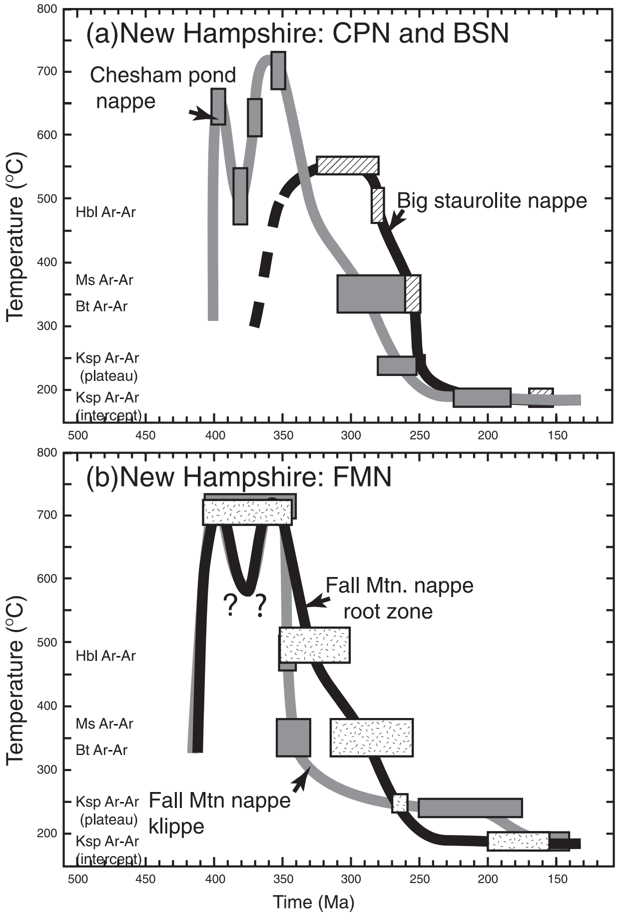


Fig. 10. *T–t* plots for the different structural levels. Boxes show ages of monazite with inferred metamorphic temperatures. Other boxes show $^{40}Ar/^{39}Ar$ ages with assumed closure temperature.

original location some distance to the east of their present outcrop position.

The observation that the metamorphism in the BSN is considerably younger than that in the overlying nappes is more surprising. Considering their present outcrop positions (Skitchewaug, Fall Mountain and Chesham Pond nappes structurally above the BSN) it is impossible to imagine a scenario whereby the BSN could have escaped the regional low-pressure, high-temperature metamorphism that these nappes underwent. Therefore we must conclude that placement of the nappe assembly (Skitchewaug, Fall Mountain and Chesham Pond) onto the BSN must have occurred after these higher units were cool. Based on monazite ages in rocks of the BSN, this must have occurred sometime after *c*. 330 Ma. We propose that the fault responsible for this emplacement is the Skitchewaug Mountain thrust at the base of the Skitchewaug nappe. There is also apparent along-strike variation in the emplacement of this nappe assembly because monazite from BSN rocks in northern New Hampshire and in Connecticut is younger than that in the region of west-central New Hampshire. The simplest scenario to achieve this type of age variation is with a wedge-shaped indentation that first collides in the central part of the collision zone. $^{40}Ar/^{39}Ar$ data support a Late Pennsylvanian to Permian metamorphism in the BSN inasmuch as cooling ages do not lock in until the Late Permian.

Equally curious is the range of ages found in rocks of the low-grade belt along the Vermont–New Hampshire border. These ages overlap those of the high-level nappes of New Hampshire, but the character of the metamorphism is Barrovian, rather than Buchan. Indeed, the ages and style of metamorphism suggest that this belt is, in fact, the easternmost extension of the Vermont metamorphic zones, a result consistent with recent geochronology on monazite from the CVS and vicinity (Cheney *et al*., 2006, unpublished data). The very lowest grade rocks along the CYL simply require post-metamorphic folding of the garnet isograd to achieve the present-day isograd configuration. The eastern boundary of this low-grade belt is the WNHBT, which must have been active after metamorphism was complete in the BSN because of the disparate metamorphic histories across the boundary. It had been hoped that monazite found within highly sheared and retrogressed rocks of the WNHBT would have recrystallized during shearing and alteration and therefore record the time of movement along this shear zone. However, this does not appear to have been the case as the monazite ages from the WNHBT span the same range as those of their precursors in the New Hampshire garnet zone. Nevertheless, the cooling histories in Fig. 10 require that this fault was not active until the Late Permian during the Alleghanian.

CONCLUSIONS AND SPECULATIONS

Ages reported in the present study are consistent with ages presented in the literature (e.g. Zartman *et al*., 1970; Harrison *et al*., 1989; Gromet & Robinson, 1990; Getty & Gromet, 1992; Coleman *et al*., 1997; Robinson *et al*., 1998; Wintsch *et al*., 1998, 2001, 2003; Moecher, 1999; Boyd *et al*., 2001; Robinson, 2003) and extend the range of Alleghanian metamorphism northward to at least the vicinity of the Salmon Hole Brook syncline. It was pointed out earlier that rocks of the BSN typically occur in synclines formed between adjacent domes of the Bronson Hill anticlinorium (e.g. the Salmon Hole Brook syncline in northern New Hampshire, the Northfield syncline in Massachusetts and the Bolton syncline in Connecticut). It is suggested that the folding of these rocks into synclines by dome formation took place subsequent to the peak metamorphism. If true, this requires that the dome stage occurred during the Permian (i.e. Alleghanian). This suggestion is consistent with the conclusions of Kohn & Spear (1999) who found a metamorphic break between the domes cored by the Oliverian magma series along the Bronson Hill anticlinorium and the overlying sillimanite-grade rocks. They suggested that the juxtaposition occurred late in the tectonic history when the regional thermal conditions were that of the greenschist facies (see also Spear *et al.*, 2002). The similarity of grade of the shear zones in the domes and that of the Western New Hampshire Boundary Thrust leads us to suggest that these features are coeval. That is, dome formation occurred along Late Pennsylvanian to Permian shear zones, presumably associated with ramp anticlines formed during the last stage of deformation along the Bronson Hill anticlinorium.

The results of the present study support the hypothesis that the rocks described as the BSN experienced metamorphism considerably later than the rocks above or below it. We do not believe that this represents remetamorphsim of previously metamorphosed material. Rather, the weight of the metamorphic, microstructural and geochronological data indicates that this zone experienced metamorphism only in the Alleghanian. We propose that the cause of this metamorphism is the westward thrusting of the high-grade nappes and that the BSN is essentially a regional shear zone that accommodated considerable shortening during the final Alleghanian assembly of central New England. Finally we note that virtually every element of this hypothesis is testable with additional petrologically focused age determinations.

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SUPPLEMENTARY MATERIAL

The following supplementary material is available for this article online from http://www.blackwell-synergy.com:

Appendix S1. BSE and secondary electron images of monazite showing position of analyses and ages.

Table S1. Isotope ages by SIMS of monazite from central New England, USA.

Table S2. Electron microprobe ages of monazite from central New England, USA.

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