Synchronous peak Barrovian metamorphism driven by syn-orogenic magmatism and fluid flow in southern Connecticut, USA

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ABSTRACT
 Recent work in Barrovian metamorphic terranes has found that rocks experience peak metamorphic temperatures across several grades at similar times. This result is inconsistent with most geodynamic models of crustal over-thickening and conductive heating, wherein rocks which reach different metamorphic grades generally reach peak temperatures at different times. Instead, the presence of additional sources of heat and/or focusing mechanisms for heat transport, such as magmatic intrusions and/or advection by metamorphic fluids, may have contributed to the contemporaneous development of several different metamorphic zones. Here, we test the hypothesis of temporally focussed heating for the Wepawaug Schist, a Barrovian terrane in Connecticut, USA, using Sm–Nd ages of prograde garnet growth and U–Pb zircon crystallization ages of associated igneous rocks. Peak temperature in the biotite–garnet zone was dated (via Sm–Nd on garnet) at 378.9 ± 1.6 Ma (2σ), whereas peak temperature in the highest grade staurolite–kyanite zone was dated (via Sm–Nd on garnet rims) at 379.9 ± 6.8 Ma (2σ). These garnet ages suggest that peak metamorphism was pene-contemporaneous (within error) across these metamorphic grades. Ion microprobe U–Pb ages for zircon from igneous rocks hosted by the metapelites also indicate a period of syn-metamorphic peak igneous activity at 380.6 ± 4.7 Ma (2σ), indistinguishable from the peak ages recorded by garnet. A 388.6 ± 2.1 Ma (2σ) garnet core age from the staurolite–kyanite zone indicates an earlier episode of growth (coincident with ages from texturally early zircon and a previously published monazite age) along the prograde regional metamorphic T–t path. The timing of peak metamorphism and igneous activity, as well as the occurrence of extensive syn-metamorphic quartz vein systems and pegmatites, best supports the hypothesis that advective heating driven by magmas and fluids focussed major mineral growth into two distinct episodes: the first at c. 389 Ma, and the second, corresponding to the regionally synchronous peak metamorphism, at c. 380 Ma.

Key words: Barrovian metamorphism; crustal over-thickening; garnet; Sm–Nd.

INTRODUCTION

The development of geodynamic models for regional metamorphism driven by crustal thickening has been an important focus of study since the widely cited work of England & Thompson (1984). One of the fundamental predictions of this work is that regional metamorphism driven by conductive relaxation of over-thickened crust should produce rocks of different metamorphic grades with different ages for the thermal maximum; for example, > 10 Myr difference in peak age between sillimanite- and garnet-grade rocks (cf. Thompson et al., 1997). In this scenario, the observed field gradient is not an isochron, and hence is not directly comparable with a steady-state geotherm (e.g. Jamieson et al., 1998). Other models have considered the effects of processes such as deep crustal anatexis and magmatic heating (Lux et al., 1986; De Yoreo et al., 1989), competing rates of accretion and erosion (Jamieson et al., 1998), transpressional tectonics (Thompson et al., 1997), deep crustal channel flow (Jamieson et al., 2004) and other 2D effects (e.g. Ruppel & Hodges, 1994). Notably, only models including spatially variable heat fluxes (or heat sources), which can create lateral thermal gradients and/or advective (rather than conductive) heat transport, are capable of producing a terrane where peak temperatures are reached at essentially the same time across all grades (e.g. Thompson & England, 1984; Lux et al., 1986).
1986; Jamieson et al., 2004). In addition, other studies have shown that metamorphism may be strongly influenced by brief pulses of fluid flow and associated heating which can focus mineral growth – both temporarily (e.g. Camacho et al., 2005; Ague & Baxter, 2007) and spatially (e.g. Chamberlain & Rumble, 1988). Despite this collective work, few direct regional geochronological constraints on peak and prograde metamorphic evolution (as opposed to cooling ages) are available to test these models. Here, we present such geochronological data to evaluate regional-scale thermal–temporal relationships which contribute to our understanding of the fundamental processes involved in Barrovian metamorphism.

Garnet has the potential to provide direct estimates of timing and P–T conditions during prograde mineral growth in slowly crystallizing metamorphic rocks (e.g. Christensen et al., 1989; Vance & O’Nions, 1992; Ducea et al., 2003). For any mineral to be an effective geochronometer of primary mineral growth, it must crystallize and remain below the closure temperature ($T_c$) of the relevant isotope system. For the Sm–Nd system in garnet, the relevant closure temperature for $>1$-mm-diameter garnet is surely above 650 °C (e.g. Baxter et al., 2002; Tirone et al., 2005). Although much excitement has surrounded developments in accessory mineral geochronology (e.g. monazite U–Pb methods; Williams et al., 1999; Catlos et al., 2002), ages of such minerals have sometimes proved difficult to interpret unambiguously within the context of a specific point in prograde P–T–t space, or to determine whether they have been recrystallized and reset by retrograde metamorphic fluids (although progress continues in these areas as well; e.g. Wing et al., 2003; Pyle et al., 2005; Mahan et al., 2006). Garnet is sufficiently resistant to diffusional resetting and recrystallization under Barrovian metamorphic conditions (e.g. Baxter et al., 2002; Tirone et al., 2005) and thus has the potential to provide the unambiguous prograde growth age information needed to test the predictions of different geodynamic models.

Several recent studies have considered the nature of heating in Barrovian terranes. Sm–Nd dating of garnet by Baxter et al. (2002) found that the ages of peak-T in the garnet and sillimanite zones of the Barrovian-type locality in Scotland were separated by only 2.8 ± 3.7 Myr (2σ). That study argued that igneous intrusions provided additional heat and a lateral thermal gradient, explaining the contemporaneous amphibolite facies peak metamorphism. Breeding et al. (2004) found that the age of large-scale metamorphic fluid flow coincided with peak-T, and fluids can potentially focus and transfer heat across terranes (Chamberlain & Rumble, 1989). Goscombe et al. (2003) also documented synchronous peak metamorphism and igneous activity in a Barrovian sequence in Namibia, and syn-metamorphic intrusions have been identified in many Barrovian zones (e.g. Brown & Walker, 1993; Abati et al., 1999; Calvert et al., 1999; Friedrich et al., 1999) and other regional metamorphic terranes (e.g. Lux et al., 1986; Sisson et al., 1989; Solar et al., 1998; Whitney et al., 2003). Our work tests the hypothesis that Barrovian-style regional metamorphism generally involves syn-metamorphic intrusion-related advective heating to drive and focus mineral growth.

**GEOLOGICAL SETTING**

The Wepawaug Schist of south-central Connecticut, part of the Orange-Milford Belt in the Connecticut Valley Synclinorium (CVS; Rodgers, 1985), is a Barrovian-style regional metamorphic terrane (see Fig. 1). To the west, the Wepawaug Schist is separated from the Devonian Straits Schist by the dextral East Derby Fault. Metamorphic grade in the Wepawaug Schist increases from chlorite zone (Chl; 420–430 °C) in the east to staurolite–kyanite zone (St–Ky; 600–610 °C) in the west (Ague, 2002), and clockwise P–T–t evolution has been documented (Ague, 1994). Scattered outcrops of leucocratic igneous rocks (mainly granitic or pegmatitic) are found across the Wepawaug Schist, and are generally more abundant in the biotite–garnet (Bt–Grt) and St–Ky zones. Some of these may represent metamorphosed tuffs or shallow intrusions, whereas others intruded during the metamorphism (Fritts, 1963; Ague, 1994). The Wepawaug Schist has been extensively studied, particularly with regard to metacarbonates (e.g. Hewitt, 1973; Ague, 2002, 2003), fluid flow (e.g. Tracy et al., 1983; van Haren et al., 1996; Ague, 2002, 2003) and P–T history (e.g. Ague, 1994). Few prograde metamorphic age data are available for the Wepawaug Schist. Within the Wepawaug Schist, Lanzirotti (1995) obtained ages of 390–370 Ma (U–Pb zircon) for pegmatites on the Wepawaug Schist side (St–Ky grade) of the East Derby Fault, although the same study determined an age of 454 ± 6 Ma (U–Pb titanite) from an ‘oligoclase-quartz intrusion’ in the St–Ky zone. U–Pb dating of monazite from St–Ky zone samples suggests both Ordovician (411 ± 18 Ma) and Devonian (388 ± 2 Ma) growth periods, although the latter age was interpreted as reflecting retrograde metamorphic fluid infiltration by these authors (Lanzirotti & Hanson, 1996). With the exception of these two ages (454 & 411 Ma), all other local geochronologies (including that reported in the present study) suggest younger ages of metamorphism. We interpret these Ordovician ages as resulting from inheritance (or alternatively, pre-garnet prograde metamorphic conditions) and do not discuss them further.

Monazite from schistose material (384–379 Ma) and a pegmatite (384–381 Ma) from the Straits Schist have been dated (Lanzirotti & Hanson, 1995), but their direct relevance to the fault-bounded Wepawaug Schist is uncertain. Additionally, monazite inclusions in garnet, staurolite and kyanite from similar rocks just to the north in Massachusetts all date within
372 ± 10 Ma (2σ; Cheney et al., 2006). Some of the apparent difficulty in constraining prograde and peak metamorphic ages may rest with uncertainties in the relative timing of accessory mineral growth and/or resetting, as well as the potential for contamination of desired phases by inheritance. U–Pb and Ar–Ar dating of amphibole and muscovite yielded ages of 220–374 Ma in the general south-central Connecticut region, although not including the Wepawaug Schist, and suggest a slow, prolonged cooling path and/or later reheating during the Alleghanian Orogeny (e.g. Moecher et al., 1997; Wintsch et al., 2003).

Samples

Three garnet-bearing schists representing different grades across the Wepawaug Schist (Fig. 1) were chosen for Sm–Nd geochronology; sample locations are given in Table 1. Sample WW2A is located in the Bt–Grt zone (500–525 °C, 0.7–0.8 GPa; Ague, 1994, 2002). It is a homogeneous, fine-grained mica schist composed mostly of quartz, plagioclase, muscovite, biotite and chlorite (mostly retrograde), plus small (~1–2 mm) garnet (see Fig. 2a). Inclusions in garnet consist of abundant quartz in the core with a few ilmenite and rutile grains. Tiny zircon and monazite both occur as inclusions. Garnet is variably retrograded to sericite and chlorite in patches along cracks, near the rim and in pressure shadows. These small garnets were sampled in bulk with no separation of core from rim.

Samples JAW113D and JAW56 were collected from a railway cutting through the St–Ky zone (0.8–1 GPa, 600–610 °C; Ague, 2002). Both sites contain abundant quartz veins. JAW113D was located ~5 cm from the nearest veins. It contains quartz, plagioclase, muscovite, biotite and ~5- to 10-mm-diameter garnet; accessory Fe–Ti oxides and graphite are found throughout. Staurolite and kyanite are rare in the dated hand sample, but increase in abundance toward the veins. Slight retrogression is evidenced by sericite and chlorite growth on index minerals. JAW56 was located a few centimetres from an intrusive pegmatitic dyke and associated quartz vein system. The mineralogy is similar to that of the JAW113D locality, except staurolite and kyanite are absent and graphite is considerably more abundant. In both samples, garnet inclusions resemble those of sample WW2A except that graphite is highly concentrated in the rims (outer ~2 mm) and rare in the cores (see Fig. 2b and Wilbur & Ague, 2006); JAW113D rims also contain rutile.

Garnet cores in many St–Ky zone Wepawaug Schist samples, including those studied here, show distinctive star-shaped growth textures in the core, indicative of a burst of core growth under thermodynamically overstepped conditions (see discussion and photos in Wilbur & Ague, 2006). Because of this graphite contrast, and the sufficient thickness of the rims, it was relatively straightforward to physically separate ‘core’ from ‘rim’

Table 1. Sample locations.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Latitude (°N)</th>
<th>Longitude (°E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Garnet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WW2A</td>
<td>41.39332</td>
<td>72.98638</td>
</tr>
<tr>
<td>JAW113D</td>
<td>41.26932</td>
<td>73.08272</td>
</tr>
<tr>
<td>JAW56</td>
<td>41.25832</td>
<td>73.07051</td>
</tr>
<tr>
<td>Zircon</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JAW119A</td>
<td>41.39102</td>
<td>72.96859</td>
</tr>
<tr>
<td>JAW199A</td>
<td>41.30269</td>
<td>73.08272</td>
</tr>
<tr>
<td>JAW200A</td>
<td>41.28649</td>
<td>73.07051</td>
</tr>
<tr>
<td>JAW202A</td>
<td>41.28478</td>
<td>73.07472</td>
</tr>
<tr>
<td>JAW203A</td>
<td>41.28333</td>
<td>73.08677</td>
</tr>
</tbody>
</table>
material by hand picking for independent dating. In addition, the presence of rutile in the rims of JAW113D garnet provided an opportunity to further constrain peak temperatures during that later phase of garnet growth. Some garnet from the garnet-grade WW2A sample also shows indications of the star-shaped growth pattern.

Five felsic igneous rocks from all grades across the Wepawaug Schist were selected for U–Pb zircon geochronology (Fig. 1, Table 1). Full descriptions of these and other igneous rocks may be found in Ague (1994). Sample JAW198A is a fine-grained sample representative of ~1- to ~10-m-thick bodies of ‘Woodbridge Granite’ (metamorphosed dykes and/or tuffaceous layers; cf. Fritts, 1963) in the chlorite zone. JAW199A is a coarser grained sample of Woodbridge Granite from a decimetre- to metre-thick layer parallel to schistosity at the type locality of the Wepawaug Schist in the Bt–Grt zone. JAW200A, JAW202A and JAW203A are from ~1- to ~10-m-thick pegmatitic intrusions (some mapped as Woodbridge Granite, others as ‘Devonian pegmatite’; Fritts, 1963) from the St–Ky zone. JAW202A contains xenoliths of wallrock schist with truncated metamorphic quartz veins, indicating intrusion was not pre-metamorphic.

ANALYTICAL METHODS

Garnet separates were prepared by crushing and sieving to between 150 and 180 µm, followed by magnetic separation and hand picking. Samples JAW113D and JAW56 had sharply zoned graphite distributions within individual garnet, allowing further hand-picking separation into core (light pink and graphite-poor) and rim (dark and graphite-rich) cuts. Garnet separates were cleansed of inclusions or alteration products (e.g. chlorite) with a partial dissolution protocol using HF and HClO₄ as described by Baxter et al. (2002). This approach, similar to other published methods (e.g. Amato et al., 1999; Anczkiewicz & Thirlwall, 2003), is necessary to remove rare earth element-rich inclusions (notably monazite) and other silicates which could otherwise compromise Sm–Nd age precision and/or accuracy.

Cleansed pure garnet separates and associated whole-rock powders were dissolved in HF followed by 50% nitric acid to eliminate secondary fluorides. REE were separated either on first-stage RE-Spec micro-columns at Boston University (BU) or on first-stage cation exchange resin columns at the University of California, Berkeley (UCB); Sm and Nd were separated on second-stage 2-methyl-lactic acid columns at UCB or at BU (sample WW2A-2 only).

Most isotopic measurements were performed on the Triton TIMS at UCB. Early garnet–whole-rock pairs were analysed as Nd metal, whereas later samples were analysed as NdO⁺ to achieve improved ionization of small samples. Samples run as Nd metal were loaded conventionally in nitric acid onto double Re filaments and were normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.636151$. Samples run as NdO⁺ were loaded onto single Re filaments with a TaO slurry and were normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$ (the normalization protocol at UCB changed between the two sets of analyses). No other corrections were applied to the reported data (Table 2). All isochron age pairs were from samples run and normalized in the same manner. One garnet–whole-rock pair (WW2A-2) was prepared and analyzed in the Triton TIMS Facility at BU. These were run within the same barrel as NdO⁺ on single Re filaments, loaded with a TaO slurry and were normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$ (Baxter et al., 2007).

ID-TIMS analyses of cleansed garnet and whole rock, listed in Table 2, were used to create two-point garnet–whole-rock isochrons. We did not seek to

![Fig. 2. Thin section photographs (PPL) of representative garnet.](image-url)
To measure garnet Nd isotope ratios so far for this sample, the peak temperatures determined by conventional thermobarometry (500–525 °C, 0.7–0.8 GPa; Ague, 1994, 2002) certainly indicate the temperature of garnet growth. For the JAW113D garnet rims (outer ∼2 mm), the question is whether the rims actually grew during peak St–Ky-grade conditions or much earlier. To corroborate growth temperatures of St–Ky zone garnet rims, the Zr-in-rutile thermometer was used in rocks with the full buffering assemblage of rutile + zircon + quartz (Watson et al., 2006). Zr determinations in rutile inclusions were made using the JEOL JXA-8600 electron microprobe at Yale University. Analyses employed zircon and rutile standards, wavelength-dispersive spectrometers, PET crystals for Zr, off-peak background corrections and a beam current of 100 nA. To account for any count rate drift during acquisition, Zr counts were accumulated in two cycles consisting of a 60 s on-peak measurement and two 30 s backgrounds (one each on the low and high sides of the peak). Zr determinations represent the aggregated results from two spectrometers; so, the total count times were 240 s on peak and 120 s for each background. The electron beam was defocussed (5 μm) to prevent damage to the rutile crystals. Results are for multiple analysis spots on multiple crystals.

**RESULTS**

Two garnet–whole-rock isochrons from WW2A (Bt–Grt zone) yielded ages of 378.9 ± 1.2 (2σ) and 379.2 ± 6.7 Ma (2σ). JAW113D (St–Ky zone) garnet cores yielded 378.5 ± 14.9 Ma (2σ), whereas the rims are 379.9 ± 6.8 Ma (2σ). Results for JAW56 (St–Ky zone) are 388.6 ± 2.1 (2σ; core) and 384.0 ± 31.2 Ma (2σ; rim). Poorer precision on two of these ages (JAW113D core and JAW56 rim) is because of relatively low garnet Sm–Nd ratios and poor internal run precision; these ages will not be considered further.

### Table 2. TIMS data for garnet (Grt) and whole-rock (WR) samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mass (mg)</th>
<th>Nd</th>
<th>Sm</th>
<th>147Sm/144Nd</th>
<th>143Nd/144Nd</th>
<th>Age ± 2σ (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW2A Grt</td>
<td>7.86</td>
<td>0.135</td>
<td>0.955</td>
<td>4.278</td>
<td>0.521548 (176)</td>
<td>379.2 ± 6.7</td>
</tr>
<tr>
<td>WW2A WR</td>
<td>n.a.</td>
<td>35.64</td>
<td>7.342</td>
<td>0.1246</td>
<td>0.511235 (004)</td>
<td></td>
</tr>
<tr>
<td>JAW113D Grt core</td>
<td>12.26</td>
<td>0.297</td>
<td>0.691</td>
<td>1.408</td>
<td>0.514399 (126)</td>
<td>378.5 ± 14.9</td>
</tr>
<tr>
<td>JAW113D Grt rim</td>
<td>51.11</td>
<td>0.383</td>
<td>0.330</td>
<td>0.5211</td>
<td>0.512206 (015)</td>
<td>379.9 ± 6.8</td>
</tr>
<tr>
<td>JAW113D WR</td>
<td>n.a.</td>
<td>38.42</td>
<td>7.482</td>
<td>0.1171</td>
<td>0.511201 (003)</td>
<td></td>
</tr>
<tr>
<td>As NdO⁺ ion⁺</td>
<td></td>
<td>90.90</td>
<td>0.099</td>
<td>0.429</td>
<td>2.621</td>
<td>0.518430 (020)</td>
</tr>
<tr>
<td>JAW56 Grt core</td>
<td>28.89</td>
<td>1.224</td>
<td>0.601</td>
<td>0.2969</td>
<td>0.512512 (018)</td>
<td>384.0 ± 31.2</td>
</tr>
<tr>
<td>JAW56 WR</td>
<td>n.a.</td>
<td>43.30</td>
<td>8.520</td>
<td>0.1310</td>
<td>0.512095 (007)</td>
<td></td>
</tr>
<tr>
<td>WW2A-2 Grt</td>
<td>27.29</td>
<td>0.149</td>
<td>0.895</td>
<td>3.645</td>
<td>0.520748 (035)</td>
<td>378.9 ± 1.6</td>
</tr>
<tr>
<td>WW2A-2 WR</td>
<td>n.a.</td>
<td>37.09</td>
<td>7.55</td>
<td>0.1235</td>
<td>0.512010 (007)</td>
<td></td>
</tr>
</tbody>
</table>

*a Analysed weight of garnet sample.

*b Values in parentheses indicate 2σ SE in the last three digits. At UCB, external reproducibility of 143Nd/144Nd (Ames metal) run as a metal is ±0.000010 (2σ SD), and ±0.000024 (2σ SD) for NdO⁺ runs. At BU, within barrel external reproducibility of 143Nd/144Nd (Ames metal) on 4 ng loads run as NdO⁺ is ±0.000087 (2σ RSD; n = 20). Sm–Nd uncertainty is ±0.1%. In determining isochron age uncertainty, the external reproducibility reported here was used unless the internal analytical precision (in table) was worse, in which case it was used instead. Isochron age pairs do not mix Nd metal and NdO⁺ data.

*c All Nd metal data reported normalized to 146Nd/144Nd = 0.7219.

d All NdO⁺ data reported normalized to 146Nd/144Nd = 0.7219.
The mean Zr contents of rutile included in garnet rims and in kyanite for sample JAW113D are 155 ± 33 (2σ, n = 10 spots) and 171 ± 21 p.p.m. (2σ, n = 10) respectively. Mean Nb and Fe contents are <1 wt%. Correlations between Zr, Nb and Fe were not observed. These measurements yield a mean temperature of 592 ± 16 °C (2σ) based on the average of all individual spot analyses (Zr p.p.m.) and propagating the 2σ uncertainty of that mean through the temperature calculation. This estimate is

Fig. 3. Combined back-scattered electron (BSE) and cathodoluminescence (CL) images of representative zircon illustrating the texturally 'old' group, the concordant cores from JAW-198A, and the texturally 'young' group. All weighted concordia ages for analysis spots shown with 2σ errors. Imaging was carried out on the JEOL JXA-8600 electron microprobe at Yale University. All scale bars are 20 μm except JAW198A Row 8 Grain 9, which is 50 μm.
indistinguishable from both the mean temperature recorded by rutile inclusions in kyanite from an adjacent sample (598 ± 10 °C, 2σ), and the peak St–Ky zone estimate for the Wepawaug Schist of 609 ± 18 °C (Ague, 2002). Thus, we conclude that the JAW113D garnet rims grew during the peak St–Ky-grade conditions. The pink garnet cores from JAW56 are chemically distinct, and contain ilmenite instead of rutile inclusions, preventing direct temperature measurement. However, ilmenite generally indicates lower pressure growth than rutile. This observation suggests growth prior to peak pressures, presumably at lower garnet-grade conditions, which is consistent with the older Sm–Nd age. If it is assumed that garnet growth in JAW56 began at the same conditions as WW2A – a reasonable assumption given the uniformity of protolith bulk compositions (Ague, 1994) – a temperature of 500–525 °C can be assigned for the growth of JAW56 cores. It is also possible that garnet core growth in JAW56 occurred at higher temperatures if the garnet isograd conditions were overstepped.

Texturally old zircon is found in all samples and yield ages between c. 420 Ma and 1.0–1.3 Ga, most likely indicating inheritance. Zircon cores from JAW198A characterized by euhedral growth zoning define an independent weighted mean concordia age of 391.4 ± 4 Ma (2σ, MSWD = 0.38, n = 9, calculated using ISOPLOT v3.41b; Ludwig, 2003) and probably record the crystallization age of the Woodbridge Granite. Ubiquitous texturally young zircon is found in JAW198A, 199A, 202A and 203A, and yield a mean weighted concordia age of 380.6 ± 4.7 Ma (2σ, MSWD 0.98, n = 6).

FIG. 4. Concordia plot of concordant analysis spots from cores of zircons showing euhedral growth zoning, sample JAW198A. The c. 391 Ma age is interpreted as being the igneous emplacement age for this rock.

FIG. 5. Concordia plot of all ‘old’ (core) zircon analyses.

FIG. 6. Concordia plot of texturally young analysis spots on zircon.

DISCUSSION

The peak-\(T\) garnet ages obtained in this study are statistically indistinguishable (considering propagation of 2σ age uncertainties), with a separation of 1.0 ± 7.0 Myr (2σ) between the Bt–Grt zone (500–525 °C; 378.9 ± 1.6 Ma) and the St–Ky zone (≈600 °C; 379.9 ± 6.8 Ma). The core age from the St–Ky zone sample JAW56 is significantly older [388.6 ± 2.1 Ma, separated from the rim age by 8.9 ± 7.1 Myr (2σ)], suggesting prolonged (>10 Myr) prograde regional metamorphism. Because garnet rim growth ages in the St–Ky zone represent the time of peak temperatures (based on temperatures measured in rutile rim inclusions), these data suggest that peak temperatures were probably attained contemporaneously across grade. Whereas our geochronological uncertainties cannot rule out the possibility of a greater
separation in peak ages (i.e. up to 8.0 Myr separation at 2σ), this possibility is (statistically) unlikely (see Fig. 7).

This probable peak age concurrence suggests that the Wepawaug Schist is another Barrovian terrane which is not well explained solely by standard conductive crustal over-thickening models (i.e. different grades peaked at different times) as discussed in the Introduction. It is not the magnitude of peak temperatures that is at issue; rather, it is the contemporaneity of those peak conditions across grades that is not reproduced by most 1D and 2D thermal conductive heating models. Extremely rapid (<10 Myr) overall prograde metamorphism, which would compress peak metamorphic ages enough to explain our data, is precluded here by the evidence for early prograde garnet growth, and the likelihood of slow cooling (e.g. Moecher et al., 1997; Oliver et al., 2000). Modelling by England & Thompson (1984) showed that unusually low crustal conductivity could help compress timescales across grade, but given the quartz-rich nature of much of the Wepawaug Schist, crustal conductivities lower than ~2.0 W m⁻¹ K⁻¹ are unlikely (Clauser & Huenges, 1995). Thompson et al. (1997) found that transpressional convergent zones with low pure/simple shear ratios (i.e. low degrees of obliquity) experienced slower exhumation and longer periods of metamorphic heating, approaching a limit of nearly total simple shear where high temperatures normally associated with the addition of mantle heat may be reached. Jamieson et al. (1998) showed that accretion of radiogenic material may also contribute patterns of additional heat that produce Barrovian P–T conditions. However, neither of these models explains the fundamental result of this study – the synchronicity of peak temperatures across grade.

To explain our geochronological data, it is suggested that contemporaneous igneous heating and/or advective heat transport by fluids drove regional-scale peak Barrovian metamorphism. The texturally young group of igneous zircon dates provide a well-defined age of 380.6 ± 4.7 Ma that is indistinguishable from the age of peak metamorphic garnet growth. Furthermore, the Wepawaug Schist contains extensive quartz-rich vein systems, and veins become more abundant as grade increases, reaching 25–30 vol% in the St–Ky zone (Ague, 1994). The flux of fluid needed to precipitate these veins was large and would have been sufficient to transport considerable heat (Chamberlain & Rumble, 1989; Ague, 1994). Oxygen isotope data from vein quartz indicate that some veins were derived from underlying dehydrating schists, whereas others were probably derived from or equilibrated with magmatic rocks (e.g. Palin, 1992; van Haren et al., 1996; Ague, 2002, 2003), again supporting a magmatic origin for some of the heat bearing fluids. The exact nature of these magmatic rocks is difficult to determine, as the oxygen isotopic measurements support both felsic and mafic origins. Only felsic intrusives are found in outcrop, but mafic intrusives could exist below the present level of exposure.

Finally, the observed P–T array (Ague, 2002) in the Wepawaug Schist is consistent with efficient vertical and lateral heating beside the deep, hot core of an advectively perturbed geotherm. The peak pressures and temperatures recorded across the Wepawaug Schist represent a modified geotherm with a predominantly lateral component in their peak spatial distribution, with the lowest grade samples (Chl zone) furthest from the hotter core. Intrusions and fluids in the Wepawaug Schist provided a strong component of contemporaneous advective heat transfer that distributed heat laterally, creating synchronous peak metamorphism across grade. Pooled together, the two WW2A garnet ages, the JAW113D garnet rim age, and the texturally young zircon ages suggest a region-wide peak metamorphic heating event at 380 Ma.

The older garnet core age of 388.6 ± 2.1 Ma also seems to be accompanied by a cluster of igneous ages at about the same time (i.e. the texturally old zircon population at 391.4 ± 4.0 Ma) as well as the 388 ± 2 Ma monazite age of Lanzirotti & Hanson...
The distinctive star-shaped textures of the JAW56 garnet cores indicate a burst of growth at large thermodynamic overstepping (Wilbur & Ague, 2006). The emplacement of a magmatic body and/or the fluxing of heat-bearing fluids could rapidly elevate the temperature to create this overstepped growth. Although a greater number of sufficiently precise geochronological constraints would be desirable to test this hypothesis, this cluster of ages at c. 389 Ma (see Fig. 7) does suggest an earlier pulse of magmatic activity, associated fluid flow and heating and consequent metamorphic mineral growth during prograde regional metamorphism at c. 389 Ma. This is before the regionally synchronous peak metamorphism at c. 380 Ma described above (i.e. the age cluster including the two WW2A garnet ages, the JAW113D garnet rim and the young zircon population; see Fig. 7). Evidence for episodic or pulsed metamorphism has been reported elsewhere (e.g. Camacho et al., 2005; Ague & Baxter, 2007) and may have played a role in the Wepawaug Schist as well. While our data do not directly constrain the durations of the two proposed growth pulses at 389 and 380 Ma, previous work on garnet growth rates in pelitic schists (e.g. Vance & O’Nions, 1992; and see review in Baxter, 2003) suggests that garnet smaller than 1 cm in diameter typically grow over less than a few million years. This observation, in concert with the two zircon age populations, strengthens the hypothesis that the two pulses are temporally discontinuous, and separated by a few million years during which no garnet growth occurred and zircon growth was diminished. Direct dating of other prograde phases, such as staurolite or kyanite – which thus far has proved difficult to impossible (Lanzirotti & Hanson, 1995) – would help test whether there was indeed a lull in overall metamorphism between these two pulses (i.e. limited growth of all metamorphic minerals during this time) or instead a time during which thermodynamic conditions specifically favourable for garnet and zircon growth did not exist.

If the evidence for a temporal link between magmatism, fluid flow and region-wide peak metamorphism is clear in the Wepawaug Schist, the origins of the magmatic system itself are less so. Presumably, the heat required to cause the felsic magmatism was related to the regional conductive metamorphism, enhanced perhaps by some of the processes described by Jamieson & Beaumont (1989) or Thompson et al. (1997) to achieve melting temperatures. To explain our geochronology, a mechanism is required to temporally focus regional heating beyond that produced by most conductive models. The presence of a magmatic engine, driving advective transfer of heat via fluid flow, accomplishes this. Few thermo-tectonic models of regional orogenic systems have included advective heating because of magmas and/or fluids. Those that have (e.g. Lux et al., 1986; Chamberlain & Rumble, 1988, 1989) show the potential for magmas and associated fluids to focus and efficiently transport heat. Based on the growing body of evidence for regionally synchronous peak metamorphism and igneous activity in several orogens (e.g. Baxter et al., 2002; Goscombe et al., 2003; Ague & Baxter, 2007; this study), we suggest that future thermo-tectonic models seek to include and evaluate the role of advective heat transport (in addition to tectonically driven region-wide thermal conduction) to test the hypothesis we have outlined here and to reproduce the synchronous peak ages.

**CONCLUSIONS**

From the combined geochronology now available (Table 3), we suggest the following orogenic timeline for southern Connecticut (Figs 7 & 8). An early episode of prograde metamorphism and igneous activity at c. 389 Ma is recorded by the 391.4 ± 4.0 Ma texturally old zircon cores in sample JAW189A (Chl zone Woodbridge granite), the 388 ± 2 Ma metamorphic monazite age of Lanzirotti & Hanson (1996) and the 388.6 ± 2.1 Ma garnet cores in St–Ky zone sample JAW56. After this first episode of mineral growth, it is possible that only muted net reaction occurred in the Wepawaug Schist as ambient conditions, controlled by tectonically paced conductive heating (e.g. England & Thompson, 1984), remained at or returned to somewhat lower temperatures, and/or other kinetic factors (such as lack of catalysing fluid) slowed mineral growth (Baxter, 2003). As the orogenic event progressed, a second episode of magmatic intrusion and

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**Table 3. Chronology of the Wepawaug Schist.**

<table>
<thead>
<tr>
<th>Age (Ma ± 2σ)</th>
<th>Mineral and method</th>
<th>Rock type and location</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>410–1300</td>
<td>U–Pb zircon ('old' analyses)</td>
<td>Igneous rocks, Wepawaug</td>
<td>This paper</td>
</tr>
<tr>
<td>411 ± 18</td>
<td>U–Pb monazite</td>
<td>St–Ky zone schist, Wepawaug</td>
<td>Lanzirotti &amp; Hanson (1996)</td>
</tr>
<tr>
<td>391.4 ± 4.0</td>
<td>U–Pb zircon cores, JAW198A</td>
<td>Chl-grade Woodbridge Granite, Wepawaug</td>
<td>This paper</td>
</tr>
<tr>
<td>388 ± 2</td>
<td>U–Pb monazite</td>
<td>St–Ky zone schist, Wepawaug</td>
<td>Lanzirotti &amp; Hanson (1996)</td>
</tr>
<tr>
<td>388.6 ± 2.1</td>
<td>Sm–Nd garnet cores, JAW56</td>
<td>St–Ky zone schist, Wepawaug</td>
<td>This paper</td>
</tr>
<tr>
<td>380.6 ± 4.7</td>
<td>U–Pb zircon ('young' analyses)</td>
<td>Igneous rocks, Wepawaug</td>
<td>This paper</td>
</tr>
<tr>
<td>379.9 ± 6.8</td>
<td>Sm–Nd garnet rim, JAW113D</td>
<td>St–Ky zone schist, Wepawaug</td>
<td>This paper</td>
</tr>
<tr>
<td>379.2 ± 6.7</td>
<td>Sm–Nd garnet, WW2A</td>
<td>Br–Grt zone schist, Wepawaug</td>
<td>This paper</td>
</tr>
<tr>
<td>378.9 ± 1.6</td>
<td>Sm–Nd garnet, WW2A-2</td>
<td>Br–Grt zone schist, Wepawaug</td>
<td>This paper</td>
</tr>
<tr>
<td>273–374</td>
<td>Ar–Ar amphibole, muscovite</td>
<td>Schist, CVS, southern Connecticut</td>
<td>Moecher et al. (1997)</td>
</tr>
</tbody>
</table>
related fluid flow peaked at 380.6 ± 4.7 Ma (from widespread ‘young’ zircon ages). In concert with a large flux of fluid derived from regional metamorphic devolatilization, magmatism advectively transported heat into the Wepawaug Schist and produced peak-olatilization, magmatism advectively transported heat of fluid derived from regional metamorphic devolatilization, magmatism advectively transported heat, and advective heat transfer may be a fundamental component of the development of Barrovian sequences worldwide.

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REFERENCES


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**SUPPLEMENTARY MATERIAL**

The following material is available online at http://www.blackwell-synergy.com:

**Table S1.** U–Pb zircon age analyses.

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