[American Journal of Science, Vol. 308, June, 2008, P. 787–812, DOI 10.2475/06.2008.03]

AGE, ORIGIN, AND TECTONIC SIGNIFICANCE OF MESOPROTEROZOIC AND SILURIAN FELSIC SILLS IN THE BERKSHIRE MASSIF, MASSACHUSETTS

PAUL KARABINOS*, DAVID MORRIS*, MICHAEL HAMILTON**, and NICOLE RAYNER***

ABSTRACT. Discontinuous sills of felsic gneiss in the interior and western margin of the Berkshire massif and granite sills on the eastern margin of the massif were correlated by Ratcliffe (1984a, 1984b, 1985) and Ratcliffe and Hatch (1979), and interpreted by them as syntectonic anatectic melts that intruded Taconic thrusts. We dated three felsic gneiss sills and two granite sills in an attempt to constrain the age of Taconic thrusting, but discovered that the sills are not coeval. Rather, they were intruded during two widely separated episodes, one during the Mesoproterozoic at approximately 1000 Ma and the other during the Silurian at approximately 430 to 435 Ma.

The 1000 Ma sills of felsic gneiss in the interior of the massif are located in Mesoproterozoic units and many of the mapped Taconic thrusts within the massif closely follow the distribution of this unit, here informally called the felsic gneiss of Harmon Brook. These 1000 Ma sills formed during the Ottawan or Rigolet orogeny and they have no connection to the Taconic orogeny.

The 430 to 435 Ma granite sills along the eastern margin of the massif, informally called the granite of Becket Quarry, are found in both Mesoproterozoic basement and the Neoproterozoic Hoosac Formation. The sills are too young to have intruded during the Ordovician Taconic orogeny, but they may have formed during later faulting near the contact between Mesoproterozoic basement and Neoproterozoic cover rocks.

The Tyringham Gneiss is one of the most common Mesoproterozoic units in the Berkshire massif. Zircons from the Tyringham Gneiss contain cores with oscillatory zoning and thin unzoned rims. The weighted average of eight $^{206}Pb/^{238}U$ analyses from the cores is 1179 +/- 9 Ma, whereas nine spot analyses from the rims yield an age of 1004 +/- 9 Ma. We interpret these two ages to represent the crystallization of the Tyringham Gneiss protolith and a subsequent high grade metamorphism, coeval with the intrusion of the felsic gneiss of Harmon Brook.

The western contact between Mesoproterozoic rocks of the Berkshire massif and underlying Early Paleozoic rocks is clearly a thrust, but there is no independent evidence that movement occurred during the Taconic orogeny; displacement may also have occurred during the Silurian Salinic or the Devonian Acadian orogeny. Many contacts mapped as Taconic thrusts within the Berkshire massif follow the distribution of the 1000 Ma felsic gneiss of Harmon Brook. The age of the sills is clearly incompatible with this interpretation, and evidence for faulting along these mapped thrusts is lacking. Instead of being deformed into an imbricate stack, the massif behaved as a rigid block during Paleozoic uplift. Finally, the age of granite sills along the eastern margin of the massif does not constrain the basement-cover contact to be a Taconic thrust, as previously interpreted. The contact may be a Silurian fault, possibly related to extension and the opening of the Connecticut Valley trough as a back-arc basin. According to this model, the magma for the granite sills was generated above a west-dipping subduction zone under the Laurentian margin, which developed after the Taconic orogeny.

*Department of Geosciences, Williams College, Williamstown, Massachusetts 01267; Paul.M.Karabinos@williams.edu

**The Jack Satterly Geochronology Laboratory, Department of Geology, University of Toronto, Toronto, Ontario M5S 3B1, Canada

***Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario K1A 0E8, Canada

INTRODUCTION

The Late Precambrian break-up of the super-continent Rodinia created a succession of rift clastics and passive margin rocks in the Appalachians. These Neoproterozoic to Early Ordovician shelf, slope, and rise deposits of the Laurentian margin were later deformed during a succession of Paleozoic collisions of arcs and microcontinents, culminating in the Permian collision between Laurentia and Gondwana. In western New England, the Ordovician Taconic orogeny has long been considered responsible for most of the deformation preserved in rocks from the Laurentian margin (for example Rowley and Kidd, 1981; Stanley and Ratcliffe, 1985). Mesoproterozoic rocks in the Green Mountain and Berkshire massifs mark the eastern edge of exposed Laurentian basement and separate the Taconic thrust sheets from their eastern source area (fig. 1). According to prevailing interpretations (for example Stanley and Ratcliffe, 1985), there is a dramatic difference in the structural style of the two basement massifs. The contact between the Green Mountain massif and the adjacent cover rocks is an unconformity (Doll and others, 1961) with local faulting along the northwestern and southwestern parts of the massif (Karabinos, 1988). It behaved as a rigid tectonic unit during Paleozoic deformation, and the interior of the massif even preserves the east-west structural grain observed in Grenville rocks of the Adirondack mountains (Doll and others, 1961). In contrast, both the eastern and western boundaries of the Berkshire massif were interpreted as Taconic thrust faults, and numerous thrusts were mapped within the massif (Ratcliffe and Hatch, 1979; Zen and others, 1983). Ratcliffe and Harwood (1975) estimated 20 km of displacement along the western frontal thrust of the Berkshire massif and 40 km of internal shortening for a total displacement of 60 km. This large estimate for total displacement of the Berkshire massif was critical to Thomas' (2006) reconstruction of the New York promontory as a major irregularity along the Laurentian margin. The interpretation that the Berkshire massif was displaced a great distance from a major promontory suggested to us that it was a promising area for geochronological study to date the onset of Ordovician collision between Laurentia and the Taconic arc near the type locality of the Taconic orogeny. Understanding the timing and style of emplacement of the Berkshire massif is also critical to reconstructing the geometry and kinematics of faulting in the Taconic thrust belt.

Ratcliffe and Hatch (1979) and Ratcliffe (1984a, 1984b, 1985) described felsic sills in the Berkshire massif, which they interpreted as syn- to late-tectonic intrusives along Taconic thrusts. We dated five felsic sills in an attempt to constrain the age of Taconic thrusting, but discovered that the sills were intruded during two widely separated episodes, one during the Mesoproterozoic at approximately 1000 Ma and the other during the Silurian at approximately 430 to 435 Ma. The older group is found along the western margin of the massif and near many of the major mapped thrusts within the massif, whereas the younger group is concentrated along the eastern boundary of the massif. Here we describe the field setting, geochemistry, and geochronology of these two groups of felsic sills. Our new age data, together with our field observations, require a reinterpretation of some of the prevailing views of the Berkshire massif. (1) Many contacts previously interpreted as Taconic thrusts within the basement massif coincide with exposures of the 1 Ga felsic sills. We did not observe mylonites or strain gradients characteristic of thrust faults, and we suggest that the interior of the massif is not dissected by numerous thrusts. (2) The Silurian sills along the eastern contact of the Berkshire massif may have intruded an active fault, but if they did the fault must post-date the Taconic orogeny. (3) The evidence for a thrust contact along the western boundary of the Berkshire massif is compelling. However, the felsic sills do not independently support a Taconic age for faulting. Displacement along the thrust could

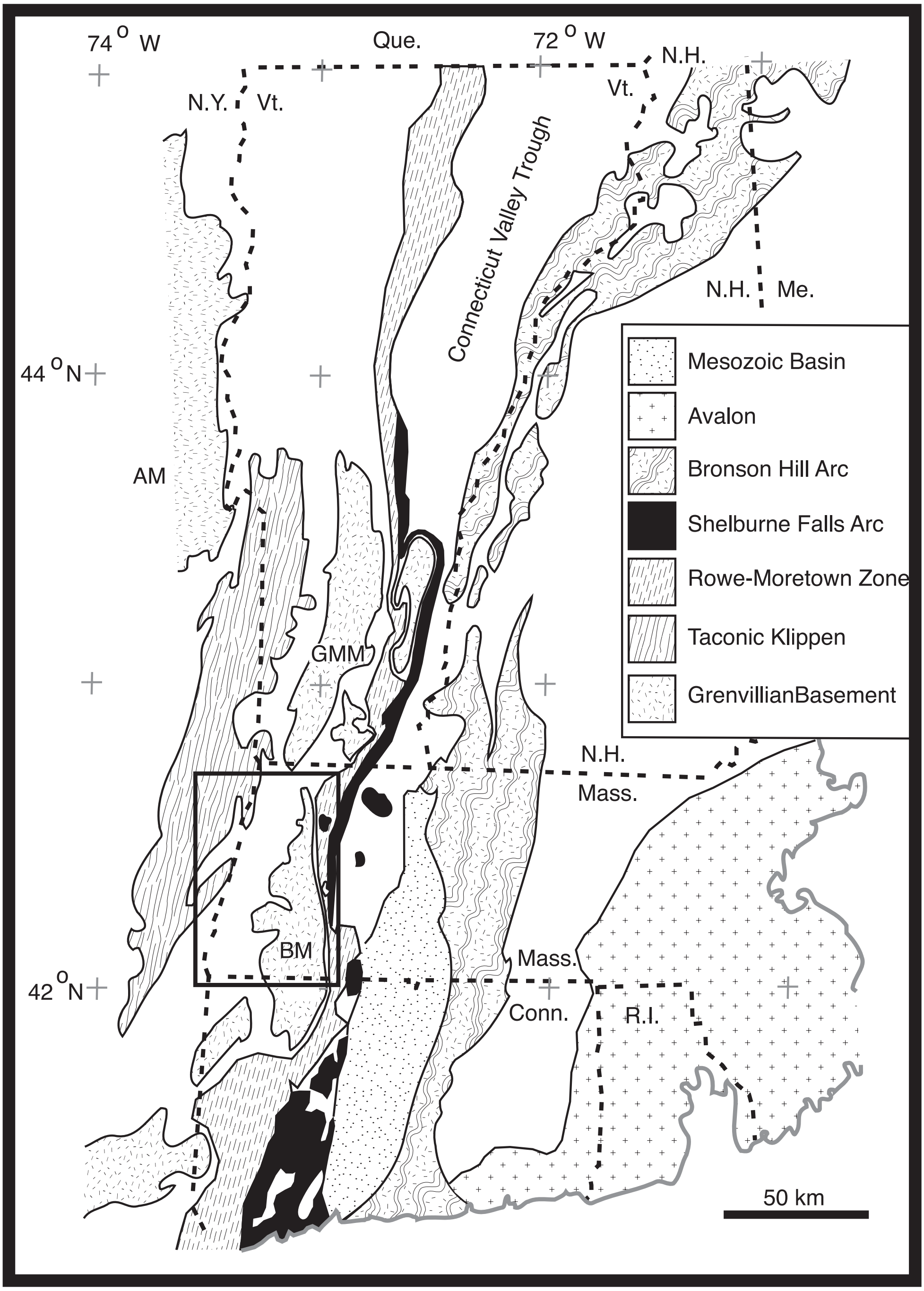


Fig. 1. Tectonic map of New England showing the location of the Adirondack Mountains (AM), Berkshire massif (BM), and the Green Mountain massif (GMM). Rectangle shows the location of area in figure 2.

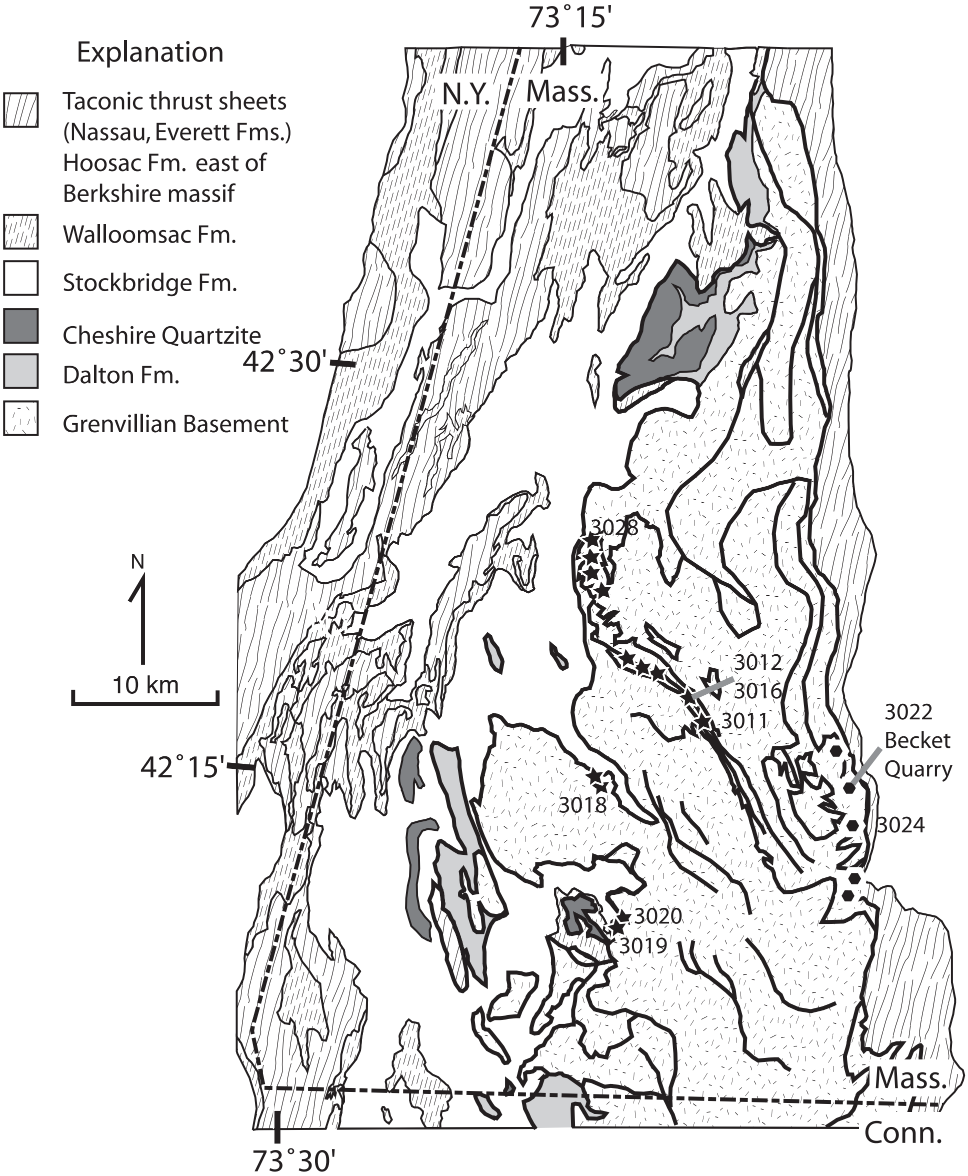


Fig. 2. Simplified geologic map of western Massachusetts showing sample locations of felsic gneiss of Harmon Brook (stars), and granite of Becket Quarry (hexagons). Heavy black lines surrounding and within the Berkshire massif are mapped thrust faults (Zen and others, 1983). Number refer to sample localities noted in text.

have occurred during the Taconic, Salinic, or Acadian orogeny, or a combination of these events.

Geologic Setting

The Mesoproterozoic rocks in the Berkshire massif (fig. 2) are diverse meta-sedimentary and meta-igneous gneisses that Ratcliffe and Zartman (1976) correlated with Grenvillian rocks in the Adirondack Mountains. However, zircon grains in orthogneisses contain multiple age domains, and require the spatial resolution of SHRIMP dating for precise age determinations, and reliable correlation of units. Here, we report the first crystallization ages for orthogneisses from the Berkshire massif. The ages of the Tyringham Gneiss and the felsic gneiss of Harmon Brook, support correlation of the Berkshire massif with Grenvillian rocks of Laurentia.

Ratcliffe (1984a, 1984b, 1985) mapped numerous thrusts within basement rocks of the Berkshire massif as summarized in Zen and others (1983). In terms of exposure area, the most extensive units are the Tyringham Gneiss, Washington Gneiss, and Biotite-quartz-plagioclase Gneiss of Ratcliffe (1984a, 1984b, 1985). These and other less common units are found throughout the massif; there are no important variations in the lithologic assemblage that correlate with the proposed thrust sheets within the massif. Indeed, many of the faults shown by Ratcliffe (1984a, 1984b, 1985) within the massif are located, at least in part, within individual basement units. Displacement on such faults, if they exist, cannot be great. Many, but not all, of the mapped thrusts within the massif coincide with exposures of felsic sills referred to as alaskite by Ratcliffe (1984a, 1984b, 1985), and by us, informally, as the felsic gneiss of Harmon Brook.

The Neoproterozoic Dalton Formation unconformably overlies the Mesoproterozoic basement rocks. This heterogeneous unit is composed of metamorphosed conglomerate, arkose, siltstone, and sandstone. It is characterized by large variations in thickness and relative abundance of these lithologies. Its variable distribution reflects deposition in actively forming rift basins during the Neoproteozoic breakup of Rodinia. Igneous rocks are not present in the Dalton Formation in Massachusetts, but correlative units in Vermont and Quebec contain dated volcanic layers that constrain rifting at approximately 554 Ma (Kumarapeli and others, 1989).

The gradual transition from the Dalton Formation into the very pure Cheshire Quartzite is the sedimentary response to the stabilization of the passive margin by Cambrian time. The stable passive margin also permitted deposition of the Early Cambrian to Early Ordovician Stockbridge Formation along the continental shelf. This unit is dominated by dolomitic and calcitic marble, and is part of the great carbonate bank that fringed the south-facing Laurentian margin during the early Paleozoic.

In less metamorphosed rocks of eastern New York and western Vermont, the Walloomsac Formation contains Ordovician graptolites, and it is interpreted as a syn-orogenic flysch that buried the carbonate bank before emplacement of the Taconic thrust sheets. In western Massachusetts, rocks mapped as the Walloomsac Formation do not contain fossils, and are compositionally similar to Neoproterozoic to Cambrian rocks in Taconic thrust sheets and in the Hoosac Formation on the east side of the Berkshire massif. The distinction between the Waloomsac Formation and older units in the Taconic thrust sheets is based entirely on the presence or absence of graphite, and the potential pitfalls of this criterion have been noted by Zen (1961, p. 310–312) for equivalent rocks in Vermont. Prindle and Knopf (1932) and Nemser and Karabinos (1998) suggested that the distribution of graphite may be structurally, rather than stratigraphically, controlled in western Massachusetts. If this suggestion is correct, then the Berkshire massif was locally thrust over rocks of the Taconic thrust sheets (see below).

West of the Berkshire massif, shelf rocks of the Stockbridge Formation are structurally overlain by Neoproterozoic to Cambrian pelitic schist, phyllite, and slate of the Taconic thrust sheets. Erosion has isolated the Taconic thrust sheets into klippen, and separated them from the correlative Hoosac Formation east of the Berkshire and Green Mountain massifs (fig. 1). The Hoosac Formation and similar rocks in the Taconic thrust sheets are metamorphosed shales and siltstones; they were deposited on the continental slope and rise of the Laurentian margin. The east-dipping boundary between the Neoproterozoic Hoosac Formation and Mesoproterozoic basement rocks along the eastern margin of the Berkshire massif was interpreted as a Taconic thrust by Ratcliffe and Harwood (1975) and Ratcliffe and Hatch (1979). Granite sills, which we informally call the granite of Becket Quarry, are locally found at the contact and close to it in either the basement rocks or the Hoosac Formation. Preliminary Rb/Sr analysis suggested that one of the granite sills *might* be Ordovician (463 +/- 62 Ma, Ratcliffe and Mose, 1978), and this age assignment, which was never verified, became critical evidence for Taconic thrusting in the Berkshire massif. This unverified age was also applied to the diverse assemblage of felsic gneisses in the massif (for example Ratcliffe, 1984a, 1984b, 1985), which we refer to here as the felsic gneiss of Harmon Brook.

Mesoproterozoic gneisses together with unconformably overlying Dalton Formation and Cheshire quartzite were thrust westward over the Stockbridge Formation (fig. 2). Evidence for the western frontal thrust of the massif is compelling, and includes unequivocal older-on-younger structural juxtaposition, dramatic strain gradients, and mylonites. Ratcliffe and Harwood (1975) described "fold-thrust blastomylonites" from the Berkshire massif; all of their convincing examples of fault-related fabric come from the western frontal thrust of the massif.

During the Ordovician Taconic orogeny (470 – 455 Ma), Laurentia collided with an island arc that formed above an east-dipping subduction zone. The characteristic deformation pattern was westward-directed thrusting of rocks of the continental margin, accretionary wedge, forearc basin, and arc complex (Rowley and Kidd, 1981; Stanley and Ratcliffe, 1985). Until recently the Bronson Hill arc in western New Hampshire and central Massachusetts and Connecticut (fig. 1) was commonly identified as the arc that collided with Laurentia. However, Tucker and Robinson (1990) pointed out that the 454 to 442 Ma age range of volcanic and plutonic rocks in the Bronson Hill arc in southern New Hampshire and Massachusetts is younger than the 470 to 460 Ma metamorphic cooling ages from rocks caught in the Taconic collision zone (for example Laird and others, 1984). Karabinos and others (1998) argued that the older Shelburne Falls arc (485–470 Ma) in eastern Vermont and western Massachusetts (fig. 1) collided with Laurentia during the Taconic orogeny, and that the Bronson Hill arc formed above a west-dipping subduction zone after a reversal in subduction polarity. Karabinos and others (1998) further suggested that this new west-dipping subduction zone accommodated plate convergence, thus bringing the Taconic orogeny to an end and setting the stage for the Salinic and Acadian orogenies. According to this model, the Laurentian margin was active throughout the Silurian and Devonian and the Connecticut Valley trough formed as an extensional back-arc basin above a west-dipping subduction zone (Karabinos and others, 1998; Karabinos, 1998).

The Silurian Salinic orogeny occurred during the accretion of Ganderia with Laurentia; its effects are better preserved in the Appalachians of maritime Canada and coastal Maine (van Staal and others, 2004) than in western New England. The Early Devonian Acadian orogeny resulted from the collision of Laurentia and Avalon (Robinson and others, 1998; Bradley and others, 2000; Tucker and others, 2001; van Staal and others, 2004). Studies using high-precision geochronology have demonstrated that the Acadian orogeny was time transgressive, and that it became younger to the northwest (Bradley and others, 2000). Bradley (1983) proposed that the collision occurred above two subduction zones, one dipping west beneath Laurentia and the other dipping east beneath Avalon, but other models invoke a single subduction zone under Avalon (for example Robinson and others, 1998; Tucker and others, 2001). Our results support the existence of a Silurian west-dipping subduction zone under Laurentia.

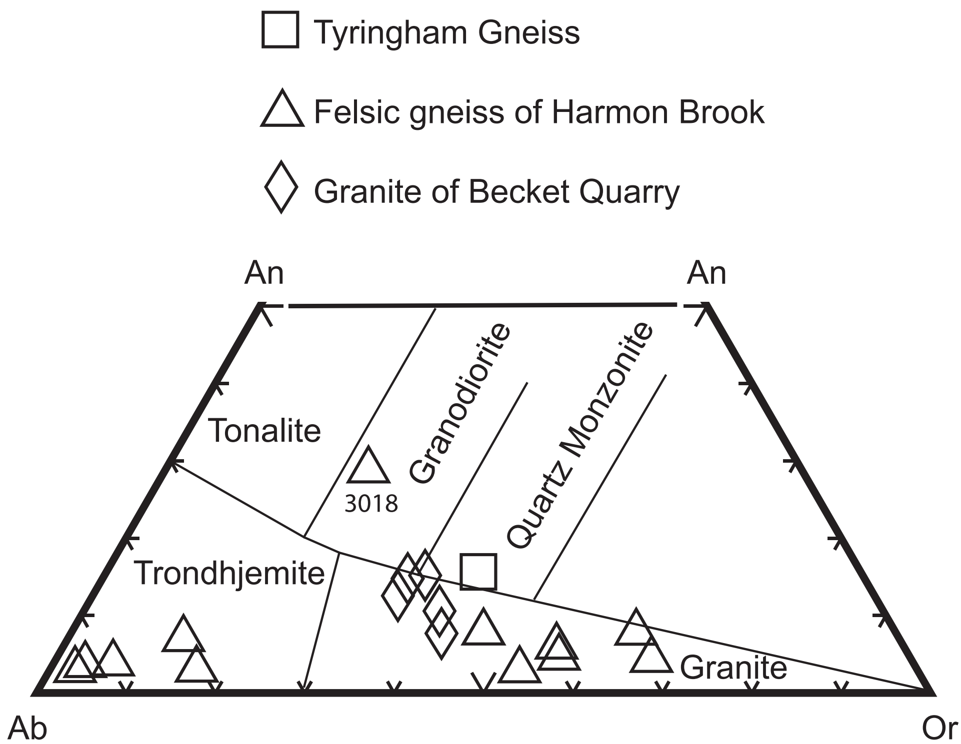


Fig. 3. Felsic igneous rock variation diagram showing normative components of albite (Ab), anorthite (An), and orthoclase (Or).

Although westward thrusting of the Berkshire massif is commonly assumed to have occurred during the Taconic orogeny (Ratcliffe and Hatch, 1979), it is important to bear in mind that it could have also occurred during the Salinic or Acadian orogenies, or some combination of them. A clear understanding of the timing and style of emplacement of the Berkshire massif is critical to unraveling the geometry and kinematics of the Taconic thrust sheets.

DESCRIPTION OF ROCKS

Tyringham Gneiss

The Tyringham Gneiss is one of the most commonly exposed Mesoproterozoic units in the Berkshire massif (Zen and others, 1983). It is a light-gray quartz monzonite (fig. 3) composed of quartz, microcline, plagioclase, biotite, and amphibole; epidote and zircon are important accessory minerals. Large feldspar crystals form an augen texture surrounded by biotite-rich seams. According to Ratcliffe and Zartman (1976), the Tyringham Gneiss intruded adjacent basement units, including the Washington Gneiss and the Biotite-quartz-plagioclase Gneiss.

Felsic Gneiss of Harmon Brook

The felsic gneiss of Harmon Brook forms numerous isolated sills that were shown by Ratcliffe (1984a, 1984b, 1985) on the USGS 7.5' quadrangle maps of Pittsfield East, East Lee, and Monterey as Ordovician alaskite intrusives and labeled Oa and Oam (for magnetite-rich bodies). On the geologic map of Massachusetts, these rocks are labeled

Ogr (Zen and others, 1983). The sills are thin, elongate, and discontinuous bodies with sharp contacts. The mapped bodies vary from approximately 10 to 200 m in thickness and from 25 to 700 m in length. Actual exposures of the felsic gneiss of Harmon Brook are commonly much smaller. Figure 2 shows the location of the mapped sills in the Berkshire massif.

The felsic gneiss of Harmon Brook is white to light gray and contains quartz, plagioclase, microcline, biotite, and muscovite. Some of the sills contain too much biotite to meet the requirements of the definition for an alaskite (< 5% mafic minerals). Locally, the rocks contain a significant amount of disseminated magnetite and some sills have cm-thick magnetite layers. The sills vary in composition from granite to trondhjemite (fig. 3). The degree of fabric development is highly variable; some exposures are massive whereas others contain a very strong foliation defined by alternating quartz-feldspar-rich and mica-rich seams. Fabric in the sills is parallel to the gneissosity in the surrounding basement rocks. In thin section, even the massive samples show evidence for weak fabric development.

The felsic gneiss of Harmon Brook sills are found in the following basement units as defined by Ratcliffe and Zartman (1976): the Tyringham Gneiss, the Washington Gneiss, and the Biotite-quartz-plagioclase Gneiss. Where exposed, the contacts between the felsic gneiss of Harmon Brook sills and the surrounding basement gneisses are well defined and sharp. We did not observe strong deformation gradients near the contacts or other features that require the contacts to be faults, that is, fabrics observed in the sills and in basement gneisses near the contacts are not demonstrably different from those in the sills and basement rocks farther from the contacts. With one exception, the sills are surrounded by Mesoproterozoic gneisses. Furthermore, many sills are contained within a single unit, a feature which seems to us inconsistent with the interpretation that the sills were generated by and intruded active faults. One large exposure is located in the hanging wall of the western frontal thrust of the massif along Harmon Brook in the Monterey 7.5′ quadrangle (samples 3019 and 3020, see fig. 2). It is between the Biotite-quartz-plagioclase Gneiss and the Stockbridge Formation, part of the shelf sequence in the foot-wall. Another mapped exposure in the Pittsfield East 7.5′ quadrangle 100 m upslope from Mill Brook (sample 3028, see fig. 2) is located within the Washington Gneiss but only 50 m above the mapped contact with Dalton Formation. A sample from this latter exposure (3028) is certainly different from the other felsic layers and it should not be included in the felsic gneiss of Harmon Brook. Zircon grains separated from this sample are rounded, pitted, frosted, and diverse in color and shape, indicating a detrital origin for the population. This exposure is most likely a volcaniclastic layer, perhaps of the same age as the Washington Gneiss. The unusual characteristics of this exposure highlight the difficulties of correlating the isolated felsic sills and lens shaped bodies in the massif.

Granite of Becket Quarry

We informally call the sills found along the east margin of the Berkshire massif the granite of Becket Quarry after an excellent and accessible exposure at an abandoned quarry (fig. 2). These rocks do not appear on published 7.5’ quadrangle maps. Norton (1974) mapped the Becket 7.5’ quadrangle but did not show the distribution of the granite sills. There are no published maps available for the Otis and Tolland Center 7.5’ quadrangles, which also contain numerous exposures of these rocks. Large exposures of the granite of Becket Quarry appear on the geologic map of Massachusetts as Ogr (Zen and others, 1983), the same designation as the felsic gneiss of Harmon Brook sills already described, and their distribution is based on field work by Ratcliffe (personal communications, 2003). Ratcliffe and Hatch (1979) showed the distribution of the granite sills near the boundary of the Becket and Otis 7.5’ quadrangles and divided the rocks into two groups, the Algerie Road type and the

Cushman Brook type. As discussed below, the geochemical data suggest a common origin for both types. The rocks we studied are similar to, and may be correlative with, granite exposures in the South Sandisfield 7.5' quadrangle (Harwood, 1979) studied by Zartman and others (1986) and informally called the granite at Yale Farm by them.

The granite of Becket Quarry forms isolated sills that range in thickness from approximately 1 to 100 m. Several quarries provide excellent exposures of the granite and the contacts with surrounding units. The granite intruded the Washington Gneiss and the Biotite-quartz-plagioclase Gneiss of the basement complex and the Hoosac Formation in the cover sequence. The granite contains quartz, plagioclase, microcline, biotite, and muscovite. Contacts between the granite and host rocks, where exposed, are sharp. The granite is typically weakly foliated. In well-exposed quarries the fabric intensity increases with proximity to both upper and lower contacts and the foliation is approximately parallel to both the contact and the foliation in the surrounding rocks. Far from contacts, the granite commonly has a wispy or schlieren texture.

GEOCHEMISTRY

Tyringham Gneiss and Felsic Gneiss of Harmon Brook

Eleven samples of felsic gneiss of Harmon Brook are peraluminous and plot in the granite to trondhjemite field in a normative albite, anorthite, and orthoclase diagram (fig. 3). An unusual sample, 3018 (see fig. 2 for location), plots in the granodiorite field. It came from a small lens in Tyringham, Massachusetts, which is quite different in appearance from all of the other exposures of the felsic gneiss of Harmon Brook. This lens is a coarse-grained migmatitic rock that is either unrelated to the rest of the felsic gneiss of Harmon Brook occurrences or may have crystallized from a late residual melt. A sample of the Tyringham Gneiss plots as a quartz monzonite (fig. 3).

The felsic gneiss of Harmon Brook samples range from 70.7 to 77.6% SiO_2, when anomalous samples are excluded (3018, 3028). On multi-element discrimination diagrams normalized to ocean ridge granites (Pearce and others, 1984), trace element concentrations vary by an order of magnitude (fig. 4A). Figure 4B shows that rare earth element abundances in the felsic gneiss of Harmon Brook samples vary between 1 and 100 times chondritic abundances (Nakamura and others, 1974). Along with the significant variations in concentration of trace and rare earth elements, figures 4A and 4B also show that the samples do not have consistent trends in relative element concentrations. For example, some show positive Eu anomalies in figure 4B, whereas others show negative anomalies, suggesting a range of fractionation histories with respect to plagioclase. Incompatible element trends of most of the felsic gneiss of Harmon Brook samples in figure 4A, specifically the enrichment of Rb and Ba and depletion in Y and Yb are characteristic of rocks from volcanic arc settings (Pearce and others, 1984). However, some samples, including 3019 and 3020, do not show a typical volcanic arc trend. In summary, the felsic gneiss of Harmon Brook samples are chemically diverse; they range in composition from granite to trondhjemite and display complex and variable fractionation trends of trace and rare earth elements.

Granite of Becket Quarry

Five samples of the granite of Becket Quarry form a tight cluster in the granite field in figure 3. Four of the samples are from "Algerie Road type" outcrops of Ratcliffe and Hatch (1979) and one is from a "Cushman Brook type" outcrop. The multiele-ment discrimination plot normalized to ocean ridge granite (fig. 4C) shows that the five samples have nearly identical trace element concentrations. The enrichment in Rb, Ba, and Th, along with the depletion in Y and Yb are characteristics of volcanic arc granites. Chondrite normalized rare earth element abundances between the samples are not identical, but are quite similar. The granite samples have rare earth element

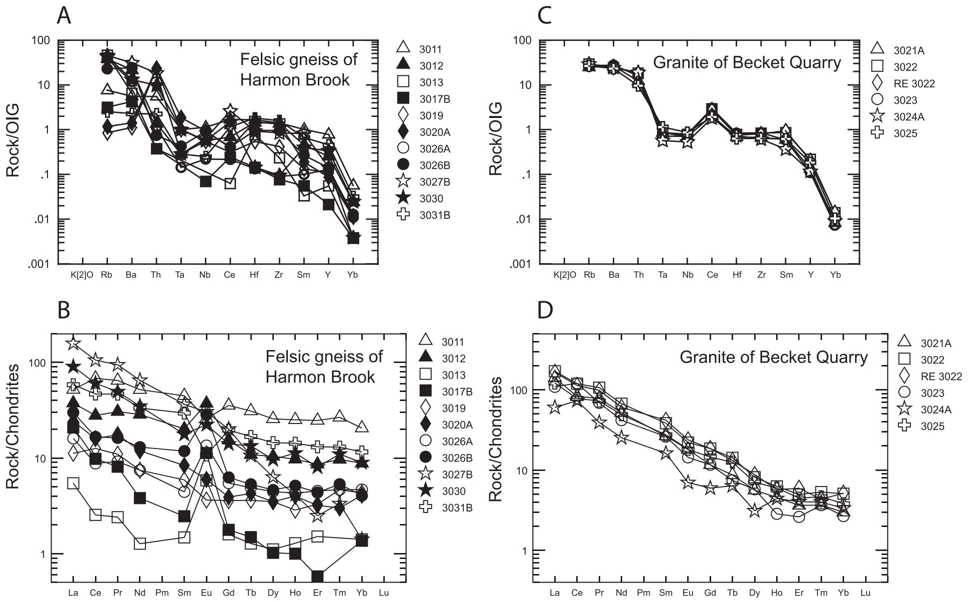


Fig. 4. (A) Ocean ridge granite (ORG)-normalized incompatible element diagram (Pearce and others, 1984) for felsic gneiss of Harmon Brook samples. (B) Chondrite-normalized rare-earth-element plot for felsic gneiss of Harmon Brook samples. (Nakamura and others, 1974). (C) Ocean ridge granite (ORG)-normalized incompatible element diagram (Pearce and others, 1984) for granite of Becket Quarry samples. (D) Chondrite-normalized rare-earth-element plot for granite of Becket Quarry samples. (Nakamura and others, 1974).

abundances between 1 and 175x chondritic abundances, are enriched in light rare earth elements (La_N/Yb_N ranges from 20.1 to 87.6), and there are no pronounced Eu anomalies (fig. 4D).

In tectonic discrimination diagrams (Yb vs. Ta, Y + Nb vs. Rb, and Ta + Yb vs. Rb) the granite of Becket Quarry samples are tightly clustered in the volcanic arc granite field (Morris, ms, 2003). The geochemical consistency of the granite of Becket Quarry samples is quite different from the widely scattered patterns observed in geochemical plots of the felsic gneiss of Harmon Brook samples. Based on geochemistry, there does not appear to be an important difference between the "Algerie Road type" and "Cushman Brook type" of granite (Ratcliffe and Hatch, 1979).

GEOCHRONOLOGY

Zircon grains from all of the samples studied are complex and commonly have core and rim textures that define separate age domains reflecting the multistage history of the rocks. The multiple age domains make it very difficult to define precisely the crystallization or metamorphic ages of the rocks using isotope dilution methods (for example Ratcliffe and Zartman, 1976; Zartman and others, 1986). To overcome this problem, we used the sensitive high-resolution ion microprobe (SHRIMP II) at the Geological Survey of Canada in Ottawa. Morris and Karabinos separated zircons at Williams College using conventional mineral separation methods. Hamilton and Rayner prepared mounts, imaged grains by cathodoluminescence (CL) and back-scattered electron (BSE), and analyzed carefully selected spots on individual grains using the SHRIMP II in Ottawa.

SHRIMP analytical procedures followed those described by Stern (1997), with standards and U-Pb calibration methods following Stern and Amelin (2003). Briefly, zircons were cast in 2.5 cm diameter epoxy mounts along with fragments of the GSC laboratory standard zircon 6266. The mid-sections of the zircons were exposed using 9, 6, and 1 μm diamond compound, and the internal features of the zircons (such as zoning, structures, alteration, *et cetera*) were characterized in either back-scattered electron (BSE) or cathodoluminescence (CL) mode utilizing a Cambridge Instruments scanning electron microscope. Mount surfaces were evaporatively coated with 10 nm of high purity Au.

The analytical work presented here was collected over 2 sessions on 2 separate ion probe epoxy mounts with varying instrumental conditions. In all analytical sessions analyses were conducted using an $^{16}O^-$ primary beam, projected onto the zircon grains at 10 kV. The count rates of ten isotopes of Zr^+, U^+, Th^+, and Pb^+ in zircon were sequentially measured over 5 or 6 scans using a single electron multiplier. Off-line data processing was accomplished using customized in-house software. The 1σ external errors of $^{206}Pb/^{238}U$ ratios reported in table 1 incorporate an error in calibrating the standard zircon between 0.5 and 1.1 percent (see Stern and Amelin, 2003). No fractionation correction was applied to the Pb-isotope data; common Pb correction utilized the Pb composition of the surface blank (Stern, 1997). Isoplot v. 2.49 (Ludwig, 2001) was used to generate concordia plots and calculate weighted means. Error ellipses and weighted mean ages are reported at the 2σ uncertainty level. $^{207}Pb/^{206}Pb$ ages are reported for one Mesoproterozoic sample relatively rich in U (3019), and some of the xenocrystic core spot analyses. For Paleozoic samples and Mesoproterozoic samples with lower U concentrations $^{206}Pb/^{238}U$ ages are used because they are more reliable.

Tyringham Gneiss

To provide context for interpreting the felsic gneiss of Harmon Brook samples and a better understanding of the Grenvillian basement in the Berkshire massif, we collected a sample of the Tyringham Gneiss (3016, fig. 2). Ratcliffe and Zartman (1976) reported $^{207}Pb/^{206}Pb$ ages between 1040 to 1080 Ma for discordant multigrain zircon fractions from the Tyringham Gneiss, but the crystallization age of this unit remained uncertain. Zircon grains display smooth highly reflective surfaces without frosting or pitting; they are elongate and euhedral. These surface and morphology characteristics are typical of grains that crystallized from a melt. Closer examination by BSE (fig. 5A), however, reveals that many of the grains have cores with oscillatory zoning and unzoned rims or mantles. The concordia plots of $^{206}Pb/^{238}U$ ages (fig. 5B) shows two strong clusters of ages, and the weighted averages of these two groups are 1179 +/- 9 Ma (n=8, MSWD = 1.5) and 1004 +/- 9 Ma (n=9, MSWD = 2.0). The older ages consistently come from spots in the cores of grains and the younger ages consistently come from rims, although some grains do not have older cores.

The most straightforward way of interpreting the data is that the older core ages, approximately 1180 Ma, represent crystallization of the Tyringham Gneiss from a melt and the younger rims formed during metamorphism at approximately 1000 Ma. The geological significance of the intermediate ages is unclear, but they may be related to one or more of the other deformational episodes of the Grenville orogenic cycle, or reflect mixed ages from the two well-identified age domains. The crystallization age of 1180 Ma for the Tyringham Gneiss coincides with the Shawinigan orogeny in the Adirondack Mountains (Hamilton and others, 2004; Heumann and others, 2006). Granulite to amphiblolite grade metamorphism occurred in the Adirondacks during the Ottawan orogeny at 1050 to 1020 Ma (Heumann and others, 2006), somewhat earlier (approximately 20 m.y.) than the 1000 Ma metamorphic rims in the Tyringham Gneiss. The younger metamorphism in the Berkshire massif may reflect the time transgressive nature of the Ottawan orogeny or record the younger Rigolet orogeny proposed by Rivers (1997).

Table 1

SHRIMP U-Th-Pb data for zircons from the Berkshire Massif, Massachusetts

Spot name	U (ppm)	$\frac{Th}{U}$	$\frac{^{204}Pb}{^{206}Pb}$	$\frac{^{206*}Pb}{^{238}U}$	$\pm\frac{^{206}Pb}{^{238}U}$	$\frac{^{207*}Pb}{^{206*}Pb}$	$\pm\frac{^{207}Pb}{^{206}Pb}$	Apparent Ages (Ma)				
								$\frac{^{206}Pb}{^{238}U}$	$\pm\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{206}Pb}$	$\pm\frac{^{207}Pb}{^{206}Pb}$	Disc. (%)
3016 Tyringham Gneiss												
7521-16.2	402	0.22	0.000234	0.1572	0.0020	0.0713	0.0012	941	11	967	34	2.7
7521-15.1	300	0.27	0.000136	0.1648	0.0024	0.0756	0.0018	983	13	1085	48	9.3
7521-6.2	282	0.27	0.000065	0.1663	0.0013	0.0722	0.0006	992	7	991	18	-0.1
7521-10.2	384	0.23	0.000103	0.1666	0.0023	0.0716	0.0013	993	13	975	37	-1.8
7521-10.1	214	0.25	0.000044	0.1667	0.0013	0.0751	0.0007	994	7	1072	18	7.3
7521-16.1	1202	0.23	0.000057	0.1677	0.0021	0.0725	0.0005	999	11	999	15	-0.1
7521-7.1	288	0.25	0.000014	0.1687	0.0012	0.0722	0.0005	1005	6	990	15	-1.5
7521-11.1	319	0.27	0.000092	0.1691	0.0012	0.0723	0.0006	1007	7	994	17	-1.3
7521-2.1	314	0.29	0.000024	0.1712	0.0017	0.0725	0.0008	1019	9	1000	22	-1.9
7521-14.1	339	0.08	0.000104	0.1713	0.0012	0.0718	0.0007	1019	7	981	19	-3.8
7521-3.1	306	0.33	0.000027	0.1808	0.0053	0.0759	0.0012	1072	29	1092	31	1.9
7521-4.1	424	0.15	0.000041	0.1809	0.0016	0.0736	0.0007	1072	9	1029	19	-4.1
7521-7.2	159	0.38	0.000055	0.1814	0.0019	0.0765	0.0009	1075	10	1107	23	2.9
7521-12.1	64	0.24	0.000255	0.1929	0.0024	0.0781	0.0021	1137	13	1149	55	1.1
7521-1.2	31	0.25	0.000208	0.1957	0.0035	0.0816	0.0031	1152	19	1237	76	6.8
7521-9.1	444	0.54	0.000005	0.1987	0.0013	0.0793	0.0004	1169	7	1180	11	1.0
7521-9.2	416	0.54	0.000019	0.1993	0.0013	0.0778	0.0004	1172	7	1141	10	-2.6
7521-13.1	288	0.32	0.000078	0.1997	0.0015	0.0785	0.0006	1174	8	1159	16	-1.3
7521-4.2	1087	0.59	0.000034	0.2009	0.0025	0.0793	0.0005	1180	14	1179	12	-0.1
7521-8.1	186	0.53	0.000024	0.2022	0.0021	0.0790	0.0008	1187	11	1172	19	-1.3
7521-6.1	327	0.42	0.000059	0.2022	0.0016	0.0781	0.0005	1187	9	1150	14	-3.2
7521-1.3	291	0.24	0.000224	0.2034	0.0030	0.0748	0.0013	1193	16	1062	36	-12.4
7521-14.2	63	0.47	0.000135	0.2037	0.0026	0.0781	0.0017	1195	14	1151	44	-3.9
7521-1.1	164	0.39	0.000031	0.2045	0.0020	0.0779	0.0010	1200	10	1144	26	-4.8
7521-5.1	154	0.36	0.000010	0.2056	0.0019	0.0809	0.0011	1206	10	1220	27	1.2
3011 Felsic gneiss of Harmon Brook												
7519-5.2	316	0.22	0.000232	0.1521	0.0020	0.0714	0.0013	913	11	970	37	5.9
7519-12.2	577	0.26	0.000035	0.1630	0.0020	0.0730	0.0008	973	11	1013	21	3.9

Table 1

(continued)

Spot name	U (ppm)	$\frac{Th}{U}$	$\frac{^{204}Pb}{^{206}Pb}$	$\frac{^{206*}Pb}{^{238}U}$	$\pm\frac{^{206}Pb}{^{238}U}$	$\frac{^{207*}Pb}{^{206*}Pb}$	$\pm\frac{^{207}Pb}{^{206}Pb}$	**Apparent Ages (Ma)** $\frac{^{206}Pb}{^{238}U}$	$\pm\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{206}Pb}$	$\pm\frac{^{207}Pb}{^{206}Pb}$	Disc. (%)
3011 Felsic gneiss of Harmon Brook												
7519-18.1	541	0.53	0.000010	0.1634	0.0020	0.0740	0.0006	975	11	1041	16	6.3
7519-7.2	579	0.16	0.000080	0.1636	0.0020	0.0722	0.0012	977	11	992	35	1.5
7519-13.1	259	0.66	0.000273	0.1647	0.0023	0.0729	0.0017	983	13	1010	48	2.7
7519-17.1	115	0.80	0.000500	0.1655	0.0026	0.0719	0.0030	987	14	984	87	-0.3
7519-2.1	614	0.07	0.000071	0.1660	0.0013	0.0706	0.0006	990	7	946	17	-4.7
7519-5.1	2346	0.35	0.000036	0.1662	0.0010	0.0727	0.0004	991	5	1006	10	1.4
7519-10.1	473	0.59	0.000006	0.1663	0.0011	0.0734	0.0005	991	6	1024	14	3.2
7519-4.1	881	0.60	0.000038	0.1668	0.0011	0.0716	0.0006	995	6	974	17	-2.1
7519-3.1	1869	0.29	0.000023	0.1670	0.0010	0.0734	0.0003	995	6	1024	9	2.8
7519-6.1	408	0.44	0.000051	0.1676	0.0014	0.0729	0.0005	999	8	1011	14	1.3
7519-8.1	349	0.64	0.000017	0.1676	0.0013	0.0739	0.0005	999	7	1040	15	3.9
7519-11.2	333	0.33	0.000040	0.1682	0.0023	0.0748	0.0011	1002	13	1063	28	5.8
7519-1.1	919	0.60	0.000053	0.1687	0.0011	0.0716	0.0004	1005	6	975	12	-3.1
7519-15.1	669	0.69	0.000033	0.1692	0.0021	0.0729	0.0006	1008	12	1011	17	0.4
7519-9.1	496	0.64	0.000016	0.1692	0.0011	0.0726	0.0004	1008	6	1003	12	-0.5
7519-3.2	571	0.75	0.000010	0.1700	0.0012	0.0723	0.0005	1012	6	994	13	-1.8
7519-8.2	1187	0.10	0.000073	0.1743	0.0021	0.0714	0.0005	1036	12	968	14	-7.0
7519-16.1	1208	0.41	0.000047	0.1748	0.0028	0.0751	0.0007	1038	15	1071	19	3.1
7519-7.1	286	0.59	0.000068	0.1811	0.0014	0.0763	0.0013	1073	8	1103	33	2.7
7519-2.2	344	0.44	0.000051	0.1917	0.0020	0.0775	0.0011	1131	11	1135	27	0.4
7519-12.1	382	0.33	0.000040	0.1949	0.0014	0.0781	0.0005	1148	7	1148	13	0.0
7519-14.1	501	0.80	0.000103	0.1975	0.0025	0.0781	0.0007	1162	13	1149	17	-1.1
7519-11.1	405	0.74	0.000026	0.2012	0.0021	0.0813	0.0005	1182	11	1229	12	3.8
3012 Felsic gneiss of Harmon Brook												
7520-2.1	92	0.08	0.000295	0.1611	0.0024	0.0717	0.0028	963	13	976	81	1.3
7520-4.2	48	0.11	0.000085	0.1617	0.0023	0.0718	0.0024	966	13	980	70	1.4
7520-15.2	53	0.21	0.000010	0.1629	0.0025	0.0740	0.0012	973	14	1040	34	6.5
7520-16.1	29	0.16	0.000333	0.1654	0.0034	0.0755	0.0050	986	19	1083	137	8.9

Table 1

(continued)

Spot name	U (ppm)	$\frac{Th}{U}$	$\frac{^{204}Pb}{^{206}Pb}$	$\frac{^{206*}Pb}{^{238}U}$	$\pm\frac{^{206}Pb}{^{238}U}$	$\frac{^{207*}Pb}{^{206*}Pb}$	$\pm\frac{^{207}Pb}{^{206}Pb}$	Apparent Ages (Ma) $\frac{^{206}Pb}{^{238}U}$	Apparent Ages (Ma) $\pm\frac{^{206}Pb}{^{238}U}$	Apparent Ages (Ma) $\frac{^{207}Pb}{^{206}Pb}$	Apparent Ages (Ma) $\pm\frac{^{207}Pb}{^{206}Pb}$	Disc. (%)
3012 Felsic gneiss of Harmon Brook												
7520-8.1	152	0.43	0.000086	0.1681	0.0016	0.0737	0.0010	1002	9	1032	27	3.0
7520-10.1	170	0.36	0.000010	0.1696	0.0016	0.0755	0.0007	1010	9	1082	18	6.7
7520-11.1	238	0.15	0.000004	0.1704	0.0014	0.0742	0.0007	1014	8	1048	19	3.2
7520-17.1	108	0.27	0.000308	0.1727	0.0028	0.0766	0.0025	1027	15	1109	67	7.4
7520-7.1	225	0.34	0.000041	0.1728	0.0015	0.0732	0.0007	1028	8	1020	20	-0.7
7520-16.2	164	0.46	0.000043	0.1804	0.0017	0.0753	0.0007	1069	9	1075	20	0.6
7520-1.2	633	0.15	0.000029	0.1808	0.0013	0.0757	0.0005	1071	7	1086	13	1.3
7520-14.1	159	0.33	0.000190	0.1826	0.0022	0.0789	0.0012	1081	12	1171	32	7.6
7520-9.1	380	0.34	0.000060	0.1834	0.0019	0.0776	0.0006	1085	10	1136	15	4.5
7520-11.2	37	0.43	0.000438	0.1867	0.0028	0.0755	0.0026	1104	15	1082	70	-2.0
7520-1.1	474	0.43	0.000119	0.1892	0.0018	0.0776	0.0008	1117	10	1135	21	1.6
7520-9.2	194	0.32	0.000013	0.1901	0.0022	0.0779	0.0008	1122	12	1145	21	2.0
7520-3.1	832	0.24	0.000023	0.1912	0.0016	0.0775	0.0011	1128	9	1134	28	0.5
7520-4.1.1	170	0.32	0.000066	0.1947	0.0034	0.0797	0.0009	1147	18	1190	22	3.7
7520-15.1	51	0.59	0.000010	0.1954	0.0025	0.0811	0.0023	1151	14	1223	56	5.9
7520-14.2	361	0.26	0.000028	0.1987	0.0019	0.0799	0.0005	1168	10	1194	12	2.1
7520-12.1	268	0.37	0.000009	0.1990	0.0015	0.0792	0.0006	1170	8	1178	15	0.6
7520-5.1	197	0.20	0.000037	0.2000	0.0015	0.0787	0.0007	1176	8	1164	16	-1.0
7520-13.1	196	0.30	0.000012	0.2012	0.0021	0.0786	0.0009	1182	11	1162	22	-1.7
7520-2.2	284	0.41	0.000072	0.2026	0.0019	0.0801	0.0008	1189	10	1200	20	0.9
7520-6.1	163	0.35	0.000035	0.2059	0.0019	0.0803	0.0008	1207	10	1204	20	-0.3
3019 Felsic gneiss of Harmon Brook												
7689-50.1	833	0.28	0.000079	0.1605	0.0018	0.0721	0.0004	959	10	990	12	3.1
7689-101.1	783	0.28	0.000029	0.1631	0.0017	0.0724	0.0004	974	10	998	10	2.4
7689-4.1	916	0.22	0.000180	0.1582	0.0019	0.0725	0.0005	947	10	1000	14	5.3
7689-41.1	1012	0.20	0.000032	0.1613	0.0019	0.0725	0.0004	964	11	1001	11	3.7
7689-77.1	1175	0.19	0.000017	0.1606	0.0018	0.0725	0.0003	960	10	1001	8	4.1
7689-72.1	902	0.23	0.000042	0.1639	0.0019	0.0729	0.0004	978	11	1011	12	3.2

TABLE 1
(continued)

Spot name	U (ppm)	Th/U	$^{204}Pb/^{206}Pb$	$^{206*}Pb/^{238}U$	$\pm ^{206}Pb/^{238}U$	$^{207*}Pb/^{206*}Pb$	$\pm ^{207}Pb/^{206}Pb$	Apparent Ages (Ma)				
								$^{206}Pb/^{238}U$	$\pm ^{206}Pb/^{238}U$	$^{207}Pb/^{206}Pb$	$\pm ^{207}Pb/^{206}Pb$	Disc. (%)
3019 Felsic gneiss of Harmon Brook												
7689-99.1	921	0.23	0.000062	0.1677	0.0019	0.0732	0.0004	1000	10	1021	12	2.1
7689-48.1	937	0.15	0.000028	0.1855	0.0020	0.0762	0.0003	1097	11	1099	9	0.2
7689-13.1	827	0.24	0.000010	0.1813	0.0020	0.0783	0.0006	1074	11	1155	15	7.0
7689-60.1	1010	0.12	0.000075	0.1911	0.0021	0.0784	0.0005	1128	12	1158	12	2.6
7689-18.1	1708	0.28	0.000018	0.1982	0.0022	0.0790	0.0004	1166	12	1173	9	0.6
7689-81.1	201	0.48	0.000108	0.2099	0.0025	0.0820	0.0010	1228	13	1246	25	1.4
7689-75.1	119	0.45	0.000132	0.2070	0.0024	0.0820	0.0018	1213	13	1246	43	2.7
7689-10.1	165	0.56	0.000078	0.2103	0.0023	0.0828	0.0009	1230	12	1263	22	2.6
3022 Granite of Beckett Quarry												
7687-17.2	153	0.41	0.000154	0.0650	0.0009	0.0542	0.0019	406	5	378	82	-7.5
7687-44.1	388	0.05	0.000010	0.0682	0.0009	0.0576	0.0006	425	6	516	21	17.6
7687-89.2	633	0.12	0.000045	0.0687	0.0009	0.0565	0.0006	428	5	471	25	9.0
7687-38.1	163	0.07	0.000369	0.0691	0.0011	0.0513	0.0056	431	7	254	254	-69.5
7687-41.2	209	0.65	0.000084	0.0692	0.0009	0.0566	0.0013	432	5	477	53	9.5
7687-17.1	293	0.56	0.000010	0.0692	0.0009	0.0564	0.0012	432	6	466	49	7.4
7687-14.1	332	0.64	0.000010	0.0693	0.0009	0.0561	0.0006	432	5	455	23	5.1
7687-19.2	375	0.63	0.000125	0.0693	0.0008	0.0552	0.0010	432	5	422	42	-2.4
7687-41.1	255	0.69	0.000157	0.0693	0.0009	0.0560	0.0013	432	5	453	54	4.7
7687-19.1	324	0.64	0.000075	0.0695	0.0008	0.0557	0.0022	433	5	442	91	2.0
7687-73.1	283	0.00	0.000010	0.0695	0.0010	0.0568	0.0008	433	6	482	31	10.1
7687-89.1	469	0.11	0.000010	0.0709	0.0008	0.0557	0.0006	441	5	440	23	-0.2
7687-11.1	1552	0.16	0.000018	0.1551	0.0017	0.0712	0.0005	930	10	962	15	3.4
7687-15.1	574	0.27	0.000014	0.1663	0.0018	0.0729	0.0005	992	10	1011	13	1.8
7687-102.1	285	0.37	0.000007	0.1891	0.0026	0.0787	0.0008	1116	14	1165	21	4.2
7687-69.1	325	0.32	0.000010	0.2069	0.0025	0.0821	0.0006	1213	13	1247	13	2.8

TABLE 1
(continued)

Spot name	U (ppm)	Th/U	$^{204}Pb/^{206}Pb$	$^{206*}Pb/^{238}U$	$\pm ^{206}Pb/^{238}U$	$^{207*}Pb/^{206*}Pb$	$\pm ^{207}Pb/^{206}Pb$	Apparent Ages (Ma) $^{206}Pb/^{238}U$	$\pm ^{206}Pb/^{238}U$	$^{207}Pb/^{206}Pb$	$\pm ^{207}Pb/^{206}Pb$	Disc. (%)
3024 Granite of Beckett Quarry												
7688-29.2	194	0.27	0.000031	0.0677	0.0009	0.0571	0.0017	422	5	493	67	14.4
7688-70.2	290	0.33	0.000019	0.0683	0.0009	0.0578	0.0013	426	5	523	48	18.5
7688-29.3	170	0.29	0.000247	0.0685	0.0009	0.0544	0.0028	427	5	387	119	-10.3
7688-5.1	396	0.17	0.000010	0.0692	0.0008	0.0565	0.0006	432	5	470	22	8.2
7688-29.1	134	0.26	0.000340	0.0693	0.0009	0.0534	0.0030	432	6	345	132	-25.3
7688-65.2	243	0.23	0.000078	0.0698	0.0010	0.0561	0.0014	435	6	454	55	4.3
7688-70.1	401	0.38	0.000238	0.0706	0.0008	0.0559	0.0018	440	5	447	74	1.6
7688-65.1	397	0.36	0.000035	0.0706	0.0009	0.0563	0.0012	440	5	464	48	5.3
7688-5.2	597	0.21	0.000043	0.0710	0.0009	0.0555	0.0007	442	5	431	28	-2.8
7688-35.1	719	0.06	0.000015	0.1101	0.0014	0.0656	0.0005	674	8	793	15	15.0
7688-102.1	2339	0.19	0.000058	0.1343	0.0015	0.0707	0.0004	812	8	949	13	14.4
7688-83.1	525	0.17	0.000118	0.1521	0.0016	0.0713	0.0013	913	9	965	38	5.4
7688-100.1	236	0.30	0.000124	0.1692	0.0020	0.0738	0.0008	1008	11	1035	21	2.7
7688-41.1	187	0.43	0.000127	0.1932	0.0022	0.0787	0.0009	1139	12	1165	22	2.2
7688-82.1	1710	0.27	0.000003	0.1935	0.0023	0.0789	0.0002	1140	13	1170	6	2.5
7688-99.1	618	0.40	0.000036	0.2010	0.0021	0.0787	0.0005	1181	11	1165	12	-1.3

Spot name follows the convention x-y.z; where x = laboratory number, y = grain number and z = spot number.
Uncertainties reported at 1 s (absolute) and are calculated by numerical propagation of all known sources of error
*refers to radiogenic Pb (corrected for common Pb)
Discordance relative to origin = 100* (1-($^{206}Pb/^{238}U$ age)/($^{207}Pb/^{206}Pb$ age))
K100 = 17 μm diameter spot, 6 scans, 5 nA primary beam intensity, error in $^{206}Pb/^{238}U$ calibration 1.0%
Th/U calibration: F = 0.03900*UO + 0.85600

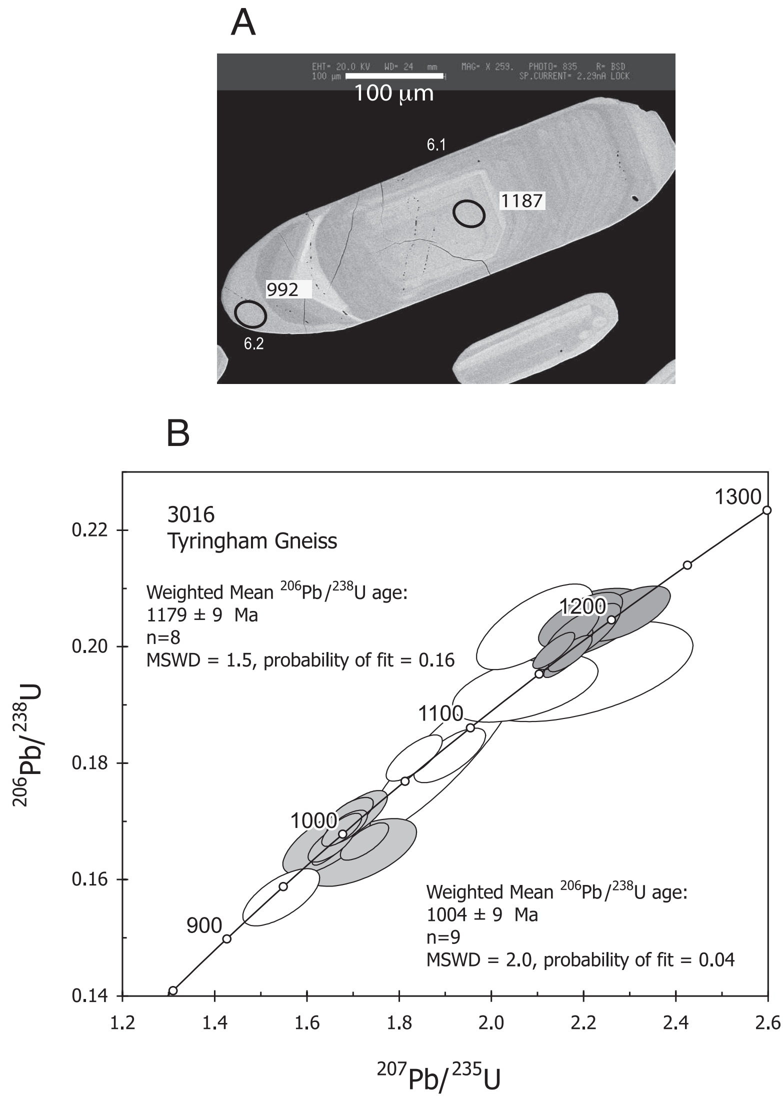
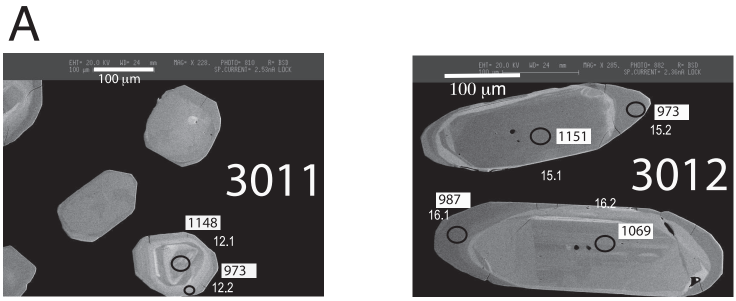


Fig. 5. (A) Back-scattered electron image of zircon grains from the Tyringham Gneiss (sample 3016) with spot analyses and $^{206}Pb/^{238}U$ ages. (B) Concordia plot of error ellipses for all spot analyses. Dark shaded ellipses used for age determination of igneous cores, light shaded ellipses used for age determination of metamorphic rims.

Felsic Gneiss of Harmon Brook

Zircon grains from three samples of the felsic gneiss of Harmon Brook were analyzed using the SHRIMP II. Two of the samples, 3011 and 3012 are from the interior of the massif, within a kilometer of each other, and along strike in the same elongate, discontinuous belt of felsic sills within the Tyringham Gneiss (fig. 2). The third sample, 3019, is from Harmon Brook on the west side of the massif, below the Biotite-quartz-plagioclase Gneiss and above the Stockbridge Formation (fig. 2). Zircon grains from all felsic gneiss of Harmon Brook samples are commonly elongate and



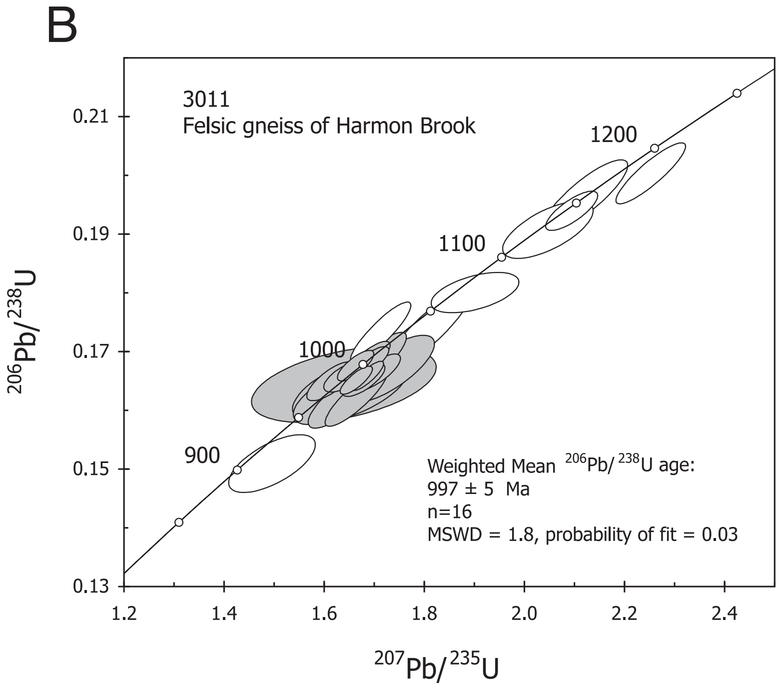


Fig. 6. (A) Back-scattered electron image of zircon grains from the felsic gneiss of Harmon Brook (samples 3011 and 3012) with spot analyses and $^{206}Pb/^{238}U$ ages. (B) Concordia plot of error ellipses for all spot analyses from sample 3011. (C) Concordia plot of error ellipses for all spot analyses from sample 3012. (D) Concordia plot of error ellipses for all spot analyses from sample 3019. Shaded ellipses used for age determination of igneous rims in all samples.

euhedral, and in CL and BSE images many of the grains show cores with oscillatory zoning, locally truncated at the rims; the rims also display oscillatory zoning (fig. 6A).

The concordia plot for sample 3011 shows a single maximum and a wide scatter of other ages (fig. 6B). The weighted average of sixteen $^{206}Pb/^{238}U$ rim ages is 997 +/- 5 Ma (MSWD = 1.8). The $^{206}Pb/^{238}U$ ages from cores range from approximately 1050 to 1200 Ma without a clear maximum. Sample 3012 is from the same large outcrop as the dated Tyringham Gneiss sample. The concordia plot for this sample shows a number of rim ages at approximately 1000 Ma and a wide scattering of core ages from approxi-

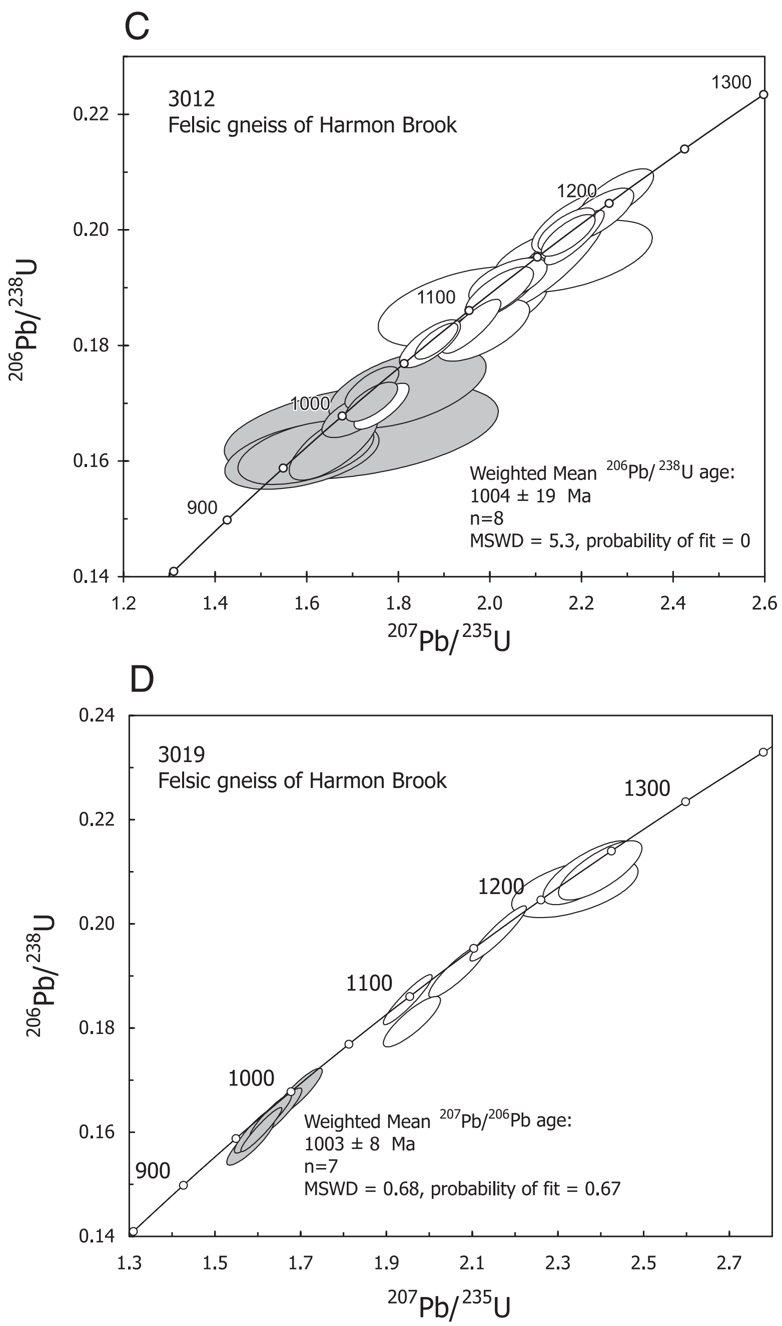


Fig. 6 (continued)

mately 1070 to 1210 Ma (fig. 6C). The weighted average of eight ^{206}Pb/^{238}U rim ages is 1004 +/- 19 Ma (MSWD = 5.3). Sample 3019, from the west margin of the massif, also shows a tight cluster of ages at approximately 1000 Ma and a wide scatter of ages from 1100 to 1220 Ma (fig. 6D). The weighted average of seven ^{207}Pb/^{206}Pb ages is 1003 +/-

8 Ma (MSWD = 0.68). Although the weighted average age of sample 3012 shows a wide scatter (MSWD = 5.3), it is in excellent agreement with the other two samples, which display only limited scatter.

The wide range of core ages from all three felsic gneiss of Harmon Brook samples suggests that the zircon cores are xenocrystic, that is they are relicts of incompletely dissolved zircon grains from the rocks that were partially melted to produce the magma. The rim ages from all three samples are identical, within analytical uncertainty, and approximately 1000 Ma. We interpret this as the crystallization age of the felsic gneiss of Harmon Brook and suggest that partial melting of basement rocks occurred during the high-temperature metamorphism that produced metamorphic rims on zircon grains in the Tyringham Gneiss.

Granite of Becket Quarry

Two samples of the granite of Becket Quarry were analyzed with the SHRIMP II. One sample, 3022, is from the Becket Quarry (fig. 2) and is a weakly foliated, >50 m thick sill within basement gneisses. The other sample, 3024, is a more strongly foliated, 2 m thick sill within the Hoosac Formation (fig. 2). Zircon grains from both samples are elongate and euhedral. Many grains show oscillatory zoning with no cores whereas others contain cores with oscillatory zoning and rims that also show oscillatory zoning (fig. 7A).

The concordia plot for sample 3022 (fig. 7B) shows a strong cluster of young ages that give a weighted average $^{206}Pb/^{238}U$ age of 432 +/- 3 Ma (n=11, MSWD = 0.58). The older core $^{207}Pb/^{206}Pb$ ages range from approximately 960 to 1250 Ma. The concordia plot for sample 3024 (fig. 7C) also shows a strong cluster of young ages that give a weighted average $^{206}Pb/^{238}U$ age of 434 +/- 5 Ma (n=8, MSWD = 1.4). The older core $^{207}Pb/^{206}Pb$ ages for this sample range widely from approximately 790 to 1170 Ma.

We interpret the 432 +/- 3 Ma and 434 +/- 5 Ma ages as the time of crystallization of the granite of Becket Quarry. The older cores are xenocrystic and their ages indicate that Mesoproterozoic basement rocks contaminated the granitic magma.

Zartman and others (1986) studied granitic exposures in the southern part of the Berkshire massif in Massachusetts and Connecticut and analyzed numerous highly discordant multigrain zircon fractions from eight samples. One of their samples, which they informally called the granite at Yale Farm, gave a lower age intercept of 430 +/- 10 Ma and an upper age intercept of 1050 +/- 40 Ma, based on three highly discordant fractions. It is possible that the granite at Yale Farm is the same age and had a similar origin as the granite of Becket Quarry, and we plan to investigate this possibility. If these two rocks are related it would be important because the granite at Yale Farm is near the western margin of the Berkshire massif in Norfolk, Connecticut, in the South Sandisfield 7.5′ quadrangle (Harwood, 1979), whereas the granite of Becket Quarry sills are concentrated on the east side of the Berkshire massif.

TECTONIC IMPLICATIONS

Grenville Geology

Correlation of rocks in the Berkshire massif with Mesoproterozoic rocks in the Adirondack Mountains, has been based on lithologic similarities, rather than reliable geochronological data. Our new SHRIMP ages for the Tyringham Gneiss (approximately 1180 Ma) and the felsic gneiss of Harmon Brook (approximately 1000 Ma), are the first crystallization age for orthogneisses from the Berkshire massif. The age of the Tyringham Gneiss coincides with the Shawinigan orogeny in the Adirondack Mountains (Hamilton and others, 2004; Heumann and others, 2006), and thus supports correlation of rocks in the two regions. SHRIMP spot analyses from metamorphic

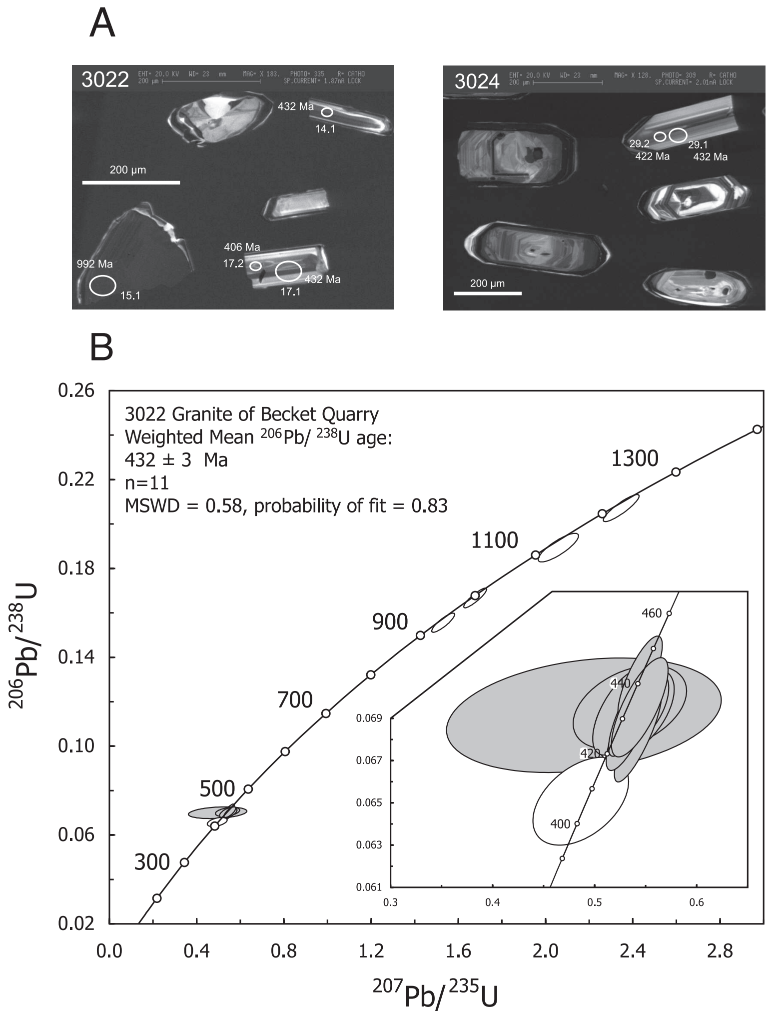


Fig. 7. (A) Cathodoluminescence image of zircon grains from the granite of Becket Quarry (samples 3022 and 3024) with spot analyses and $^{206}Pb/^{238}U$ ages. (B) Concordia plot of error ellipses for all spot analyses from sample 3022. (C) Concordia plot of error ellipses for all spot analyses from sample 3024. Shaded ellipses used for age determination of igneous rims in both samples.

zircon rims in the Tyringham Gneiss (fig. 5B) indicate that a major thermal pulse occurred at approximately 1000 Ma, contemporaneous with intrusion of the felsic gneiss of Harmon Brook.

Zircon rims, which we interpret as igneous overgrowths, from all three samples of the felsic gneiss of Harmon Brook give identical Mesoproterozoic ages of approximately 1000 Ma. The wide range in age of the xenocrystic cores of zircon grains from these samples, from approximately 1050 to 1220 Ma, suggests that the magma for the sills was generated by partial melting of paragneisses in the Grenvillian basement rocks of the massif. The sills range widely in composition from granite to trondhjemite (fig. 3), and there is considerable variation in the concentration of trace and rare earth elements (fig. 4). The variability in composition of the sills probably reflects some combination of the following four factors: (1) partial melting of different source rocks,

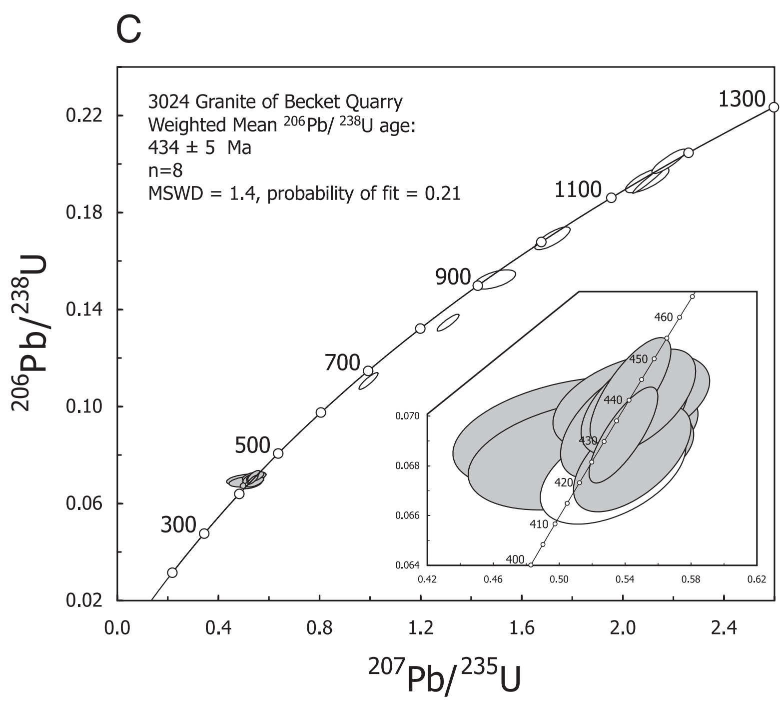


Fig. 7 (continued)

(2) different degrees of partial melting of source rocks, (3) fractionation of magma during transport, and (4) contamination of magma by wall rocks during transport. The lens shaped bodies are parallel to the gneissic foliation in the host rocks. There is no clear evidence for faulting near the elongate bodies and we interpret them as sills that intruded parallel to Mesoproterozoic deformation fabrics. The important implication, developed further below, is that much of the deformation fabric in the basement rocks records Grenville events rather than Taconic thrusting.

It is worth noting that the 1000 Ma thermal event recorded in the Berkshire massif is significantly younger than high-grade metamorphism in the Adirondack Mountains, which occurred at 1050 to 1020 Ma, during the Ottawan orogeny (Heumann and others, 2006). The younger metamorphism in the Berkshire massif may reflect the time transgressive nature of the Ottawan orogeny or record the younger Rigolet orogeny proposed by Rivers (1997). Coeval metamorphism occurred in other external basement massifs in southwestern New England. Walsh and others (2004) documented 993 +/- 8 Ma metamorphic rims on igneous zircons in Mesoproterozoic rocks of western Connecticut, and Gates and others (2004) dated 1007 +/- 4 Ma metamorphic rims on detrital zircons from a semi-pelitic gneiss from the Hudson Highland in New York. The relatively young (1000 Ma) metamorphism preserved in some of the external basement massifs raises the intriguing possibility that the massifs record an outboard event not preserved in the Adirondacks.

Appalachian Geology

Age of emplacement of the Berkshire massif.—Ratcliffe and Hatch (1979) and Ratcliffe (1984a, 1984b, 1985) correlated the felsic gneiss of Harmon Brook with the granite of Becket Quarry, and interpreted them both as syntectonic intrusives along Taconic thrust faults. This interpretation held that the sills were either the result of anatexis driven by shear heating along faults or metasomatism caused by fault zone migration of fluids. The Taconic age assignment of faulting in the massif assumed that its emplacement was approximately coeval with transport of Taconic thrust sheets to the west. It was supported by one preliminary Rb-Sr date (463 +/- 62 Ma) from a sill of the granite of Becket Quarry (Ratcliffe and Mose, 1978), which permitted, but did not require, an Ordovician age. The correlation of the felsic gneiss of Harmon Brook and the granite of Becket Quarry, as well as their Taconic age assignment, is inconsistent with our new age data.

The felsic gneiss of Harmon Brook (approximately 1000 Ma) is too old, and the granite of Becket Quarry (approximately 430–435 Ma) is too young to have intruded active Taconic faults, and they do not constrain the age of emplacement of the Berkshire massif. Although there is unequivocal evidence for a thrust along the western boundary of the massif (fig. 2), the timing of movement along this fault is not well constrained. Displacement could have occurred during the Taconic, Salinic, or Acadian orogenies, or some combination of them. Clearly, we should renew our efforts to constrain independently the age of faulting of the Berkshire massif, and to treat the Taconic age assignment of thrusting as a testable hypothesis rather than an established fact. For example, the Long Range massif in Newfoundland occupies a structural position similar to the Berkshire and Green Mountain massifs, and it was faulted onto the shelf sequence rocks during the Acadian orogeny (Cawood and Williams, 1988).

Internal thrusting in the Berkshire massif.—Another long-standing interpretation of the Berkshire massif is that the basement gneisses were shortened and stacked into about a dozen thrust sheets during the Taconic orogeny (for example Ratcliffe and Hatch, 1979). This structural interpretation relied, to a large extent, on the assumption that the felsic sills were sytectonic intrusives, and the preliminary Ordovician age assignment of a sill of the granite of Becket Quarry (Ratcliffe and Mose, 1978). Many of the mapped thrusts within the massif follow the distribution of the felsic gneiss of Harmon Brook sills and are located, at least in part, within a single basement unit (Ratcliffe, 1984a, 1984b, 1985). We did not observe structural evidence for faulting near the sills that we studied, and interpret them as intrusive lenses parallel to Grenville deformation fabrics. However, even if such faults are present and related to the sills, they must be Mesoproterozoic faults and have relatively small displacement. As noted above, we interpret the gneissic fabric in the interior of the massif as a record of Grenville deformation rather than Paleozoic thrusting. An important observation is that the most extensive units, the Tyringham Gneiss, Washington Gneiss, and Biotite-quartz-plagioclase Gneiss, along with other less common units, are found throughout the massif. There are no important variations in the lithologic assemblage that correlate with the mapped thrust sheets. Our interpretation is that the massif was emplaced during the early Paleozoic as a rigid block. The rheological behavior of the quartz-feldspar-rich gneisses of the Berkshire massif must have been very different than the slate, phyllite, and schist dominated rocks of the Taconic thrust sheets, so a lack of internal, imbricate thrusting in the massif is not surprising. There may be some Taconic thrusts with limited displacement within the Mesoproterozoic gneisses, but it appears that that massif behaved as a coherent basement uplift, similar to the Green mountain massif in Vermont, and the classic Laramide uplifts (for example Bump, 2003).

This interpretation has important implications for understanding tectonic inheritance along the Laurentian margin (Thomas, 2006). Ratcliffe and Harwood (1975) estimated total displacement of the Berkshire massif to be 60 km, a figure that included a minimum of 20 km of displacement along the western boundary of the massif and 40 km of internal shortening. If the Berkshire massif behaved as a rigid block, total displacement only needs to be 20 km, as constrained by movement along the frontal thrust. This lower displacement constraint suggests that the New York Promontory of Thomas (2006) was a less prominent irregularity in the Laurentian margin.

Emplacement of the Berkshire massif as a rigid block after the Taconic orogeny would also have dramatically altered the original geometry of the Taconic thrust belt. Such overprinting would have obscured the connection between Taconic thrust sheets and possible 'root zones' to the east. The structural uplift of the massif in the middle of the thrust belt may also have set into motion the erosion that eventually isolated western portions of the thrust system into klippen.

Eastern margin of the Berkshire massif.—Ratcliffe and Hatch (1979) interpreted the eastern margin of the Berkshire massif to be a Taconic thrust that carried Neoproterozoic Hoosac Formation over older Mesoproterozoic basement gneisses. Two samples of the granite of Becket Quarry from the eastern margin of the Berkshire massif give 432 +/- 3 Ma and 434 +/- 5 Ma weighted average ^{206}Pb/^{238}U ages; clearly too young to be syntectonic intrusives along postulated Taconic thrust faults.

The contact between the Hoosac Formation and basement units along the eastern margin of the Berkshire massif is structurally complex and is consistent with a fault interpretation (for example Norton, 1974, 1975). The sense of displacement along the contact, however, has not been established by reliable kinematic criteria. In light of the approximately 430 to 435 Ma age of the granite sills, and the fact that younger rocks are juxtaposed over older rocks, it seems worth considering the possibility that the contact reflects Silurian extension. Karabinos and others (1998) suggested that the Connecticut Valley trough formed as a Silurian back-arc rift basin above a west-dipping subduction zone. A back-arc basin model in which deposition was synchronous with rifting (Karabinos, 1998) can explain many of the stratigraphic and structural problems in the Connecticut Valley trough. This model is also consistent with the back-arc basin geochemistry of the Silurian Standing Pond Volcanics in Vermont (Karabinos and others, 1998), and with work by Castonguay and others (1997) who presented ^{40}Ar/^{39}Ar muscovite ages of 421 +/- 2 to 425 +/- 2 Ma from Quebec and suggested that they record Silurian extension.

All five samples of the granite of Becket Quarry display a limited geochemical variation (fig. 4), consistent with formation in an arc environment. Zircon grains commonly have xenocrystic cores with ^{207}Pb/^{206}Pb ages ranging from approximately 790 to 1250 Ma (fig. 7). These observations suggest that the granite formed from a mantle-derived magma, and that they were contaminated by Grenvillian basement during intrusion. The early Silurian west-dipping subduction zone under the Laurentian margin, which formed after a reversal in subduction polarity following the Taconic orogeny (Karabinos and others, 1998), is a potential source for this magma. This plate tectonic geometry is also compatible with the Connecticut Valley trough having formed as a back-arc basin following the Late Ordovician (Bronson Hill arc) to Early Silurian generation of arc magmas.

ACKNOWLEDGMENTS

This work was supported by NSF grant EAR-0125476. We thank R.A. Wobus for many useful discussions and Art Goldstein and Tracy Rushmer for visiting the outcrops and sharing their ideas. We thank Rebecca Flowers, Michael Williams, and an anonymous reviewer for constructive and helpful reviews.

REFERENCES

Bradley, D. C., 1983, Tectonics of the Acadian Orogeny in New England and adjacent Canada: The Journal of Geology, v. 91, p. 381–400.

Bradley, D. C., Tucker, R. D., Lux, D. R., Harris, A. G., and McGregor, D. C., 2000, Migration of the Acadian

Orogen and foreland basin across the Northern Appalachians of Maine and adjacent areas: United States Geological Survey Professional Paper 1624, 55 p.

Bump, A. P., 2003, Reactivation, trishear modeling, and folded basement in Laramide uplifts: Implications for the origins of intra-continental faults: GSA Today, v. 13, p. 4–10, doi:10.1130/1052-5173(2003)013<0004:RTMAFB>2.0.CO;2.

Castonguay, S., Tremblay, A., Ruffet, G., Féraud, G., Pinet, N., and Sosson, M., 1997, Ordovician and Silurian metamorphic cooling ages along the Laurentian margin of the Quebec Appalachians: Bridging the gap between New England and Newfoundland: Geology, v. 25, p. 583–586, doi:10.1130/0091-7613(1997)025<0583:OASMCA>2.3.CO;2.

Cawood, P. A., and Williams, H., 1988, Acadian basement thrusting, crustal delamination, and structural styles in and around the Humber Arm allochthon, western Newfoundland: Geology, v. 16, p. 370–373, doi:10.1130/0091-7613(1988)016<0370:ABTCDA>2.3.CO;2.

Doll, C. G., Cady, W. M., Thompson, J. B., Jr., and Billings, M. P., 1961, Centennial geologic map of Vermont: Vermont Geological Survey, scale 1:250,000.

Gates, A. E., Valentino, D. W., Chiarenzelli, J. R., Solar, G. S., and Hamilton, M. A., 2004, Exhumed Himalayan-type syntaxis in the Grenville orogen, northeastern Laurentia: Journal of Geodynamics, v. 37, p. 337–359, doi:10.1016/j.jog.2004.02.011.

Hamilton, M. A., McLelland, J., and Selleck, B., 2004, SHRIMP U-Pb zircon geochronology of the anorthosite-mangerite-charnockite-granite suite, Adirondack Mountains, New York: Ages of emplacement and metamorphism, *in* Tollo, R. P., Corriveau, L., McLelland, J., and Bartholomew, M. J., editors, Proterozoic Tectonic Evolution of the Grenville orogen in North America: Boulder, Colorado, Geological Society of America Memoir 197, p. 337–355.

Harwood, D. S., 1979, Geologic map of the South Sandisfield Quadrangle, Massachusetts and Connecticut: United States Geological Survey Quadrangle Map GQ 1519, scale 1:24,000.

Heumann, M. J., Bickford, M. E., Hill, B. M., McLelland, J. M., Selleck, B. W., and Jercinovic, M. J., 2006, Timing of anatexis in metapelites from the Adirondack lowlands and southern highlands: A manifestation of the Shawinigan orogeny and subsequent anorthosite-mangerite-charnockite-granite magmatism: Geological Society of America Bulletin, v. 118, p. 1283–1298, doi:10.1130/B25927.1.

Karabinos, P., 1988, Tectonic significance of basement-cover relationships in the Green Mountain massif, Vermont: The Journal of Geology, v. 96, p. 445–454.

——— 1998, Tectonic and stratigraphic development of the Connecticut Valley Trough in the New England Appalachians: Geological Society of America Abstracts with Programs, v. 30, p. 191.

Karabinos, P., Samson, S. D., Hepburn, J. C., and Stoll, H. M., 1998, Taconian Orogeny in the New England Appalachians: Collision between Laurentia and the Shelburne Falls Arc: Geology, v. 26, p. 215–218, doi:10.1130/0091-7613(1998)026<0215:TOITNE>2.3.CO;2.

Kumarapeli, P. S., Dunning, G. R., Pintson, H., and Shaver, J., 1989, Geochemistry and U-Pb zircon age of comenditic metafelsites of the Tibbit Hill Formation, Quebec Appalachians: Canadian Journal of Earth Sciences, v. 26, p. 1374–1383.

Laird, J., Lanphere, M. A., and Albee, A. L., 1984, Distribution of Ordovician and Devonian metamorphism in mafic and pelitic schists from northern Vermont: American Journal of Science, v. 284, p. 376–413.

Ludwig, K. R., 2001, User's manual for Isoplot/Ex rev. 2.49: a Geochronological Toolkit for Microsoft Excel, Special Publication, 1a: Berkeley, California, Berkeley Geochronology Center, 55 p.

Morris, D. J., ms, 2003, Geochemistry and geochronology of middle Proterozoic and Silurian igneous rocks in the Berkshire massif: Williamstown, Massachusetts, Williams College, Bachelor's thesis, 138 p.

Nakamura, N., 1974, Determination of REE, Ba, Fe, Mg, Na and K in carbonaceous and ordinary chondrites: Geochimica et Cosmochimica Acta, v. 38, p. 757–775, doi:10.1016/0016-7037(74)90149-5.

Nemser, E. S., and Karabinos, P., 1998, Thrust geometry and fault-controlled fluid flow on Mount Greylock, Massachusetts: Geological Society of America, Abstracts with Programs, v. 30, p. 63.

Norton, S. A., 1974, Preliminary geologic map of the Becket Quadrangle, Berkshire, Hampshire, and Hampden counties, Massachusetts: United States Geological Survey Open File Report 74-92, 17 p. 1 pl., scale 1:24000.

——— 1975, Chronology of Paleozoic tectonic and thermal metamorphic events in Ordovician, Cambrian, and Precambrian rocks at the north end of the Berkshire Massif, Massachusetts: United States Geological Survey Professional Paper 888, p. 21–31.

Pearce, J. A., Harris, N. B. W., and Tindle, A. G., 1984, Trace Element Discrimination Diagrams for the Tectonic Interpretation of Granitic Rocks: Journal of Petrology, v. 25, p. 956–983, doi:10.1093/petrology/25.4.956.

Prindle, L. M., and Knopf, E. B., 1932, Geology of the Taconic Quadrangle: American Journal of Science, v. 24, p. 257–302.

Ratcliffe, N. M., 1984a, Bedrock geologic map of the Monterey Quadrangle, Berkshire County, Massachusetts: United States Geological Survey Quadrangle Map GQ 1572, scale 1:24,000.

——— 1984b, Bedrock geologic map of the Pittsfield East Quadrangle, Berkshire County, Massachusetts: United States Geological Survey Quadrangle Map GQ 1574, scale 1:24,000.

——— 1985, Bedrock geologic map of the East Lee Quadrangle, Berkshire County, Massachusetts: United States Geological Survey Quadrangle Map GQ 1573, scale 1:24,000.

Ratcliffe, N. M., and Harwood, D. S., 1975, Blastomylonites associated with recumbent folds and overthrusts at the western edge of the Berkshire Massif, Connecticut and Massachusetts; a preliminary report: United States Geological Survey Professional Paper 888, p. 1–19.

Ratcliffe, N. M., and Hatch, N. L., Jr., 1979, A traverse across the Taconide Zone in the area of the Berkshire Massif, western Massachusetts, *in* Skehan, J. W., and Osberg, P. H., editors, The Caledonides in the United States; Geological Excursions in the Northeast Appalachians: Weston, Massachusetts, Boston College, Department of Geology and Geophysics, Weston Observatory, NEIGS, Project 27, p. 175–224.

Ratcliffe, N. M., and Mose, D. G., 1978, Probable Taconic age of the Middlefield thrust zone, eastern margin of the Berkshire Massif, Massachusetts; on the basis of Rb/ Sr geochronology of intrusive granitic rock: Geological Society of America Abstracts with Programs, v. 10, p. 81.

Ratcliffe, N. M., and Zartman, R. E., 1976, Stratigraphy, isotopic ages, and deformational history of basement and cover rocks of the Berkshire Massif, southwestern Massachusetts: Geological Society of America Memoir 148, p. 373–412.

Rivers, T., 1997, Lithotectonic elements of the Grenville Province: review and tectonic implications: Precambrian Research, v. 86, p. 117–154, doi:10.1016/S0301-9268(97)00038-7.

Robinson, P., Tucker, R. D., Bradley, D., Berry, H. N. I., and Osberg, P. H., 1998, Paleozoic orogens in New England, USA: GFF, Quarterly Journal of the Geological Society of Sweden, v. 120, p. 119–148.

Rowley, D. B., and Kidd, W. S. F., 1981, Stratigraphic relationships and detrital composition of the Medial Ordovician flysch of western New England: Implications for the tectonic evolution of the Taconic orogeny: Journal of Geology, v. 89, p. 199–218.

Stanley, R. S., and Ratcliffe, N. M., 1985, Tectonic synthesis of the Taconian orogeny in western New England: Geological Society of America Bulletin, v. 96, p. 1227–1250, doi:10.1130/0016-7606(1985)96<1227:TSOTTO>2.0.CO;2.

Stern, R. A., 1997, The GSC Sensitive High Resolution Ion Microprobe (SHRIMP): analytical techniques of zircon U-Th-Pb age determinations and performance evaluation, *in* Radiogenic Age and Isotopic Studies: Geological Survey of Canada, Current Research 1997-F, Report 10, p. 1–31.

Stern, R. A., and Amelin, Y., 2003, Assessment of errors in SIMS zircon U-Pb geochronology using a natural zircon standard and NIST SRM 610 glass: Chemical Geology, v. 197, p. 111–142, doi:10.1016/S0009-2541(02)00320-0.

Thomas, W. A., 2006, Tectonic inheritance at a continental margin: GSA Today, v. 16, p. 4–11, doi:10.1130/1052-5173(2006)016[4:TIAACM]2.0.CO;2.

Tucker, R. D., and Robinson, P., 1990, Age and setting of the Bronson Hill magmatic arc: A re-evaluation based on U-Pb zircon ages in southern New England: Geological Society of America Bulletin, v. 102, p. 1404–1419, doi:10.1130/0016-7606(1990)102<1404:AASOTB>2.3.CO;2.

Tucker, R. D., Osberg, P. H., and Berry, H. N. I., IV, 2001, The Geology of a Part of Acadia and the Nature of the Acadian Orogeny Across Central and Eastern Maine: American Journal of Science, v. 301, p. 205–260.

van Staal, C. R., McNicoll, V., Valverde-Vaquero, P., Barr, S. M., Fyffe, L. R., and Reusch, D. N., 2004, Ganderia, Avalonia, and the Salinic and Acadian orogenies: Geological Society of America Abstracts with Program, v. 36, no. 2, p. 128.

Walsh, G. J., Aleinikoff, J. N., and Fanning, C. M., 2004, U-Pb geochronology and evolution of Mesoproterozoic basement rocks, western Connecticut, *in* Tollo, R. P., Corriveau, L., McLelland, J., and Bartholomew, M. J., editors, Proterozoic tectonic evolution of the Grenville orogen in North America: Boulder, Colorado, Geological Society of America Memoir 197, p. 729–753.

Zartman, R. E., Kwak, L. M., and Christian, R. P., 1986, Uranium-lead systematics of a mixed zircon population; the granite at Yale Farm, Berkshire Massif, Connecticut, *in* Peterman, Z. E., and Schnabel, D. C., editors, Shorter contributions to isotope research: United States Geological Survey Bulletin 1622, p. 81–98.

Zen, E. A., 1961, Stratigraphy and Structure at the North End of the Taconic Range in West-Central Vermont: Geological Society of America Bulletin, v. 72, p. 293–338, doi:10.1130/0016-7606(1961)72[293:SASATN]2.0.CO;2.

Zen, E. A., Goldsmith, R., Ratcliffe, N. M., Robinson, P., Stanley, R. S., Hatch, N. L., Jr., Shride, A. F., Weed, A., and Wones, D. R., 1983, Bedrock geologic map of Massachusetts: United States Geological Survey, scale 1:250,000.