

## AGE AND STYLE OF THRUSTING IN THE BERKSHIRE MASSIF, MASSACHUSETTS

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### 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 (Stop 2) are located in Mesoproterozoic units. They formed during the Mesoproterozoic Ottawan or Rigolet orogeny and they have no connection to the Ordovician Taconic orogeny. Many of the mapped Taconic thrusts within the massif closely follow the distribution of these sills, here informally called the felsic gneiss of Harmon Brook, yet the age of the sills is clearly incompatible with this fault interpretation. Independent evidence for faulting near the sills, such as mylonites and strain gradients, is lacking. Instead of being deformed into an imbricate stack, the Berkshire massif behaved as a rigid block during Paleozoic uplift. Where exposed along the western frontal thrust of the massif, the sills of felsic gneiss contain a moderate deformation fabric that may be related to Paleozoic thrusting (Stops 3 & 4).

The 430 to 435 Ma granite sills along the eastern margin of the massif (Stop 1), 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. Thus, the granite sills along the eastern margin of the massif do not constrain the basement-cover contact to be a Taconic thrust, as previously interpreted. A more viable interpretation is that the eastern basement-cover contact is 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.

The western contact between Mesoproterozoic rocks of the Berkshire massif and underlying Early Paleozoic rocks is clearly a thrust. Samples from well-exposed fault zones on the western margin of the massif are spectacular mylonites with a strong, recrystallized, planar foliation and a steep strain gradient. Sense-of-shear indicators are mostly consistent with westward thrusting, although textures suggest local reactivation into east-dipping normal faults. Electron microprobe dating of monazite, however, does not support a Taconic age for thrusting. Monazite from a highly deformed quartzite exposed in the hanging-wall of the Dry Hill fault (Stop 5) gives an age of  $392 \pm 14$  Ma (1s.e., n=16). Quartz-rich schist from a fault zone at Umpachene Falls contains monazite grains with complex age population that, when averaged, give a weighted age of  $422 \pm 8$  Ma. Monazite grains in graphitic schist from Benton Hill 200 m below a major thrust give a weighted average age of  $436 \pm 8$  Ma (n=21). Two localities from Yale Farm near the western frontal thrust of the Berkshire massif give weighted average monazite ages of  $401 \pm 9$  Ma (n=26) and  $400 \pm 10$  (n=40). These preliminary monazite ages from well-exposed fault zones suggest that motion on faults along the western margin of the massif occurred during the Silurian Salinic or Devonian Acadian

orogenies. So far, dating of monazite provides no evidence that faults were active during the Ordovician Taconic orogeny, but our ages may record reactivation of older faults. Interestingly, the monazite ages from fault zone rocks are in excellent agreement with hornblende and biotite  $^{40}\text{Ar}/^{39}\text{Ar}$  cooling ages from the western margin of the Berkshire massif reported by Sutter et al. (1985).

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  $^{206}\text{Pb}/^{238}\text{U}$  analyses from the cores is 1179  $\pm$  9 Ma, whereas nine spot analyses from the rims yield an age of 1004  $\pm$  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.

## 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 micro-continents, 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.

We also examined mylonites from the western frontal thrust of the Berkshire massif for kinematic indicators and evidence for the physical conditions during thrusting. We discovered that monazite is common in fault-zone rocks, and used the electron microprobe to obtain preliminary ages that help constrain the age of thrusting.

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

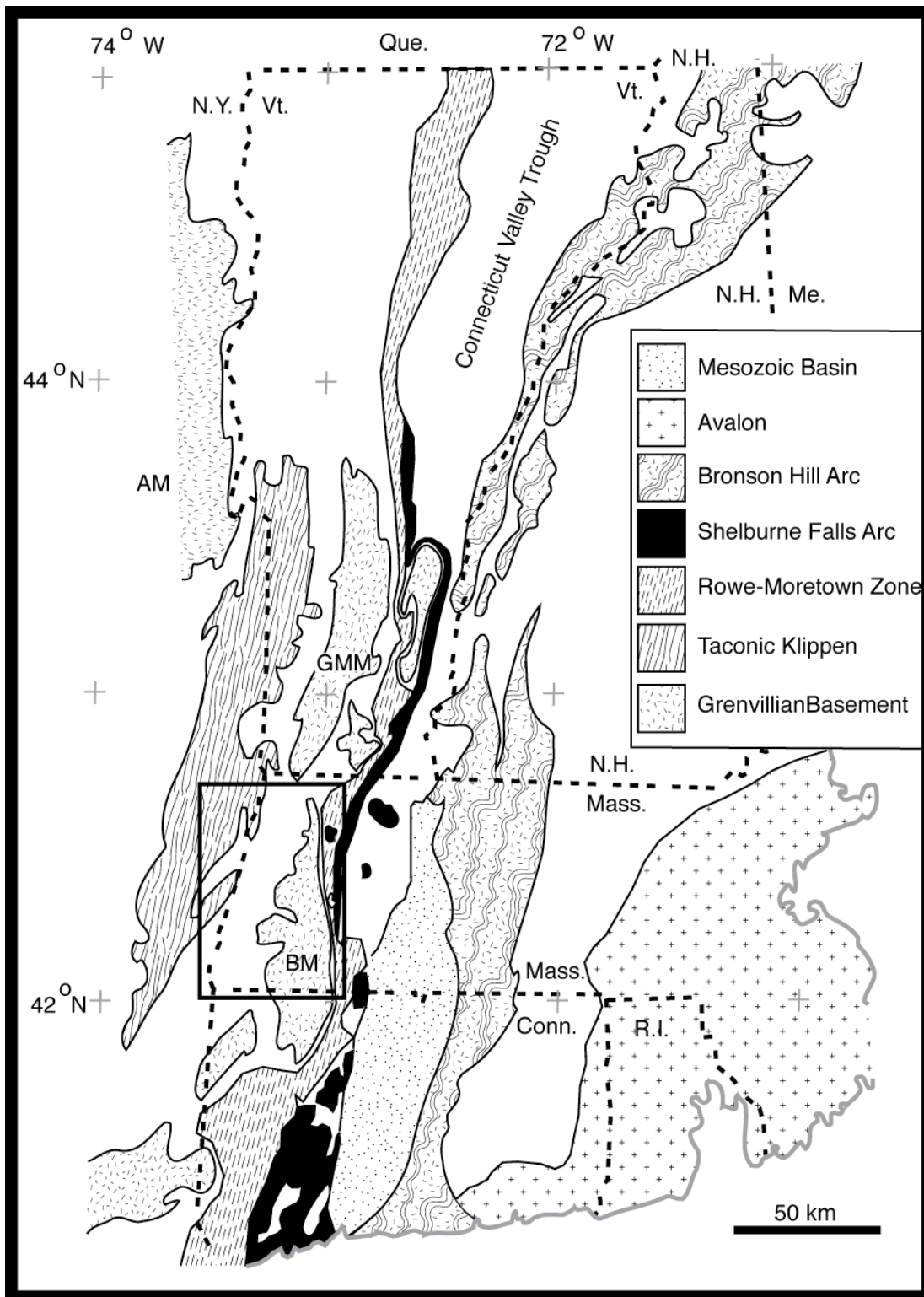


Fig. 1. Tectonic map of New England showing the location of the Adirondack Mountains (AM), Berkshire Massif (BM), and the Green Mountain Massif (GMM). Rectangle shows the location of area in figure 2.

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. Monazite ages from fault zone rocks suggest that displacement along the thrust occurred during the Silurian Salinic or Devonian Acadian orogenies.

### 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 Neoproterozoic 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 Walloomsac 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,

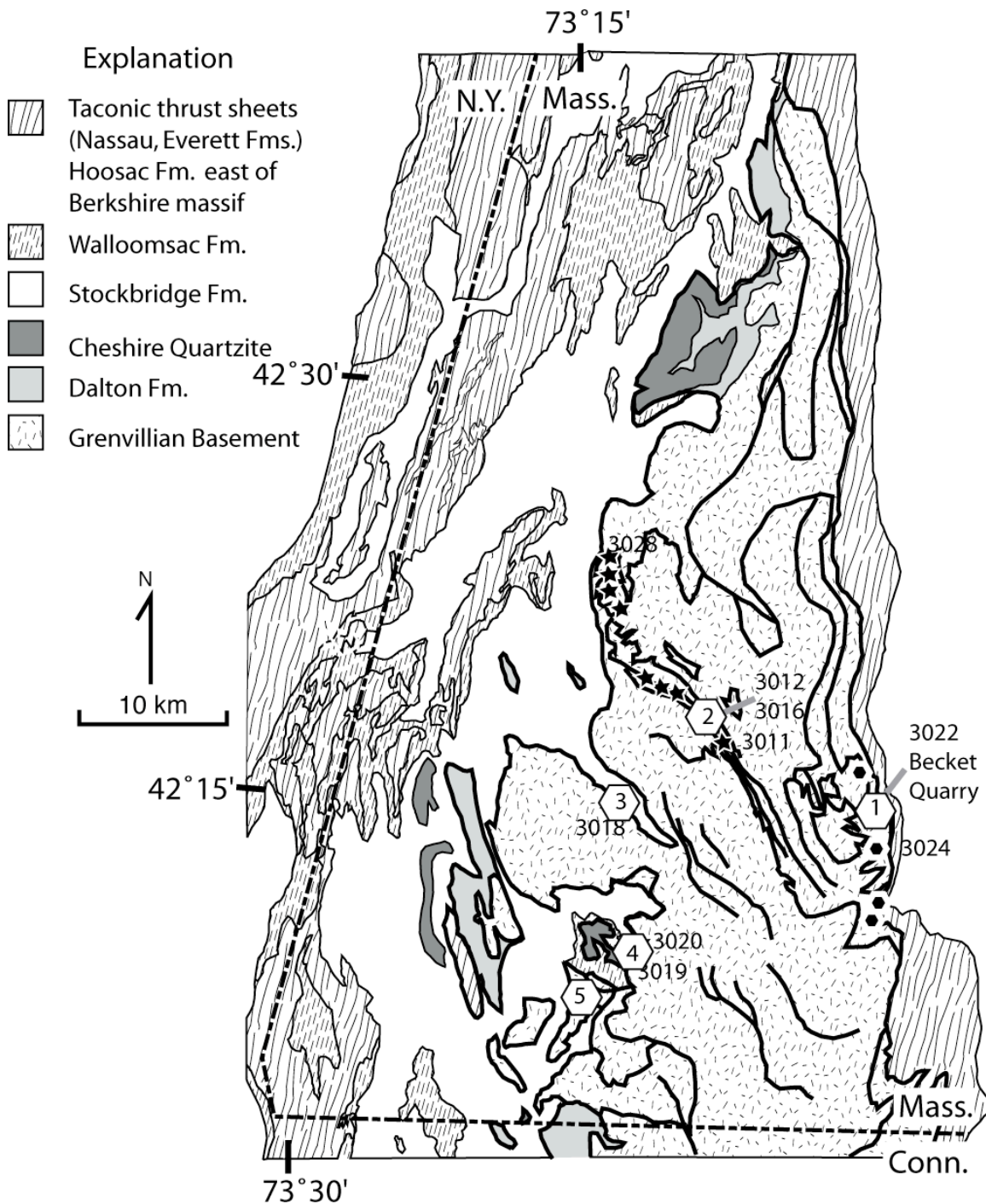


Fig. 2. Simplified geologic map of western Massachusetts showing sample locations of felsic gneiss of Harmon Brook (stars), granite of Becket Quarry (small hexagons), and field trip stops (large hexagons). Heavy black lines surrounding and within the Berkshire massif are mapped thrust faults (Zen and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

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 to 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 to 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 Silurian Salinic and Devonian 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 et al, 1998, Tucker and others, 2001). Our results support the existence of a Silurian west-dipping subduction zone under Laurentia.

Although westward thrusting of the Berkshire massif was 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. Our monazite ages from fault zone rocks support Silurian to Devonian of the Berkshire massif. 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 & 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, Stop 1). 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 Algeria 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<sub>2</sub>, 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 B 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 multielement 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 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, 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).

## ZIRCON 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



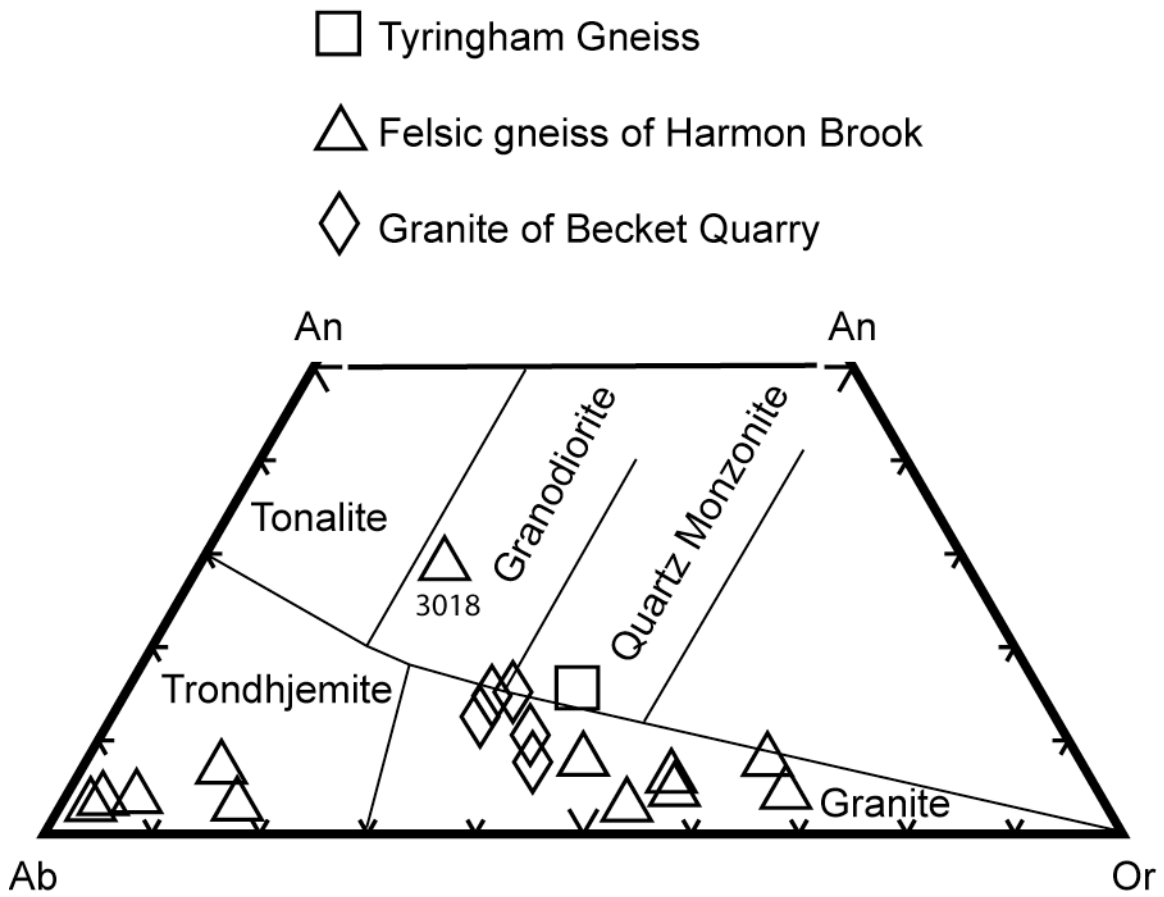


Fig. 3. Felsic igneous rock variation diagram showing normative components of albite (Ab), anorthite (An), and orthoclase (Or).

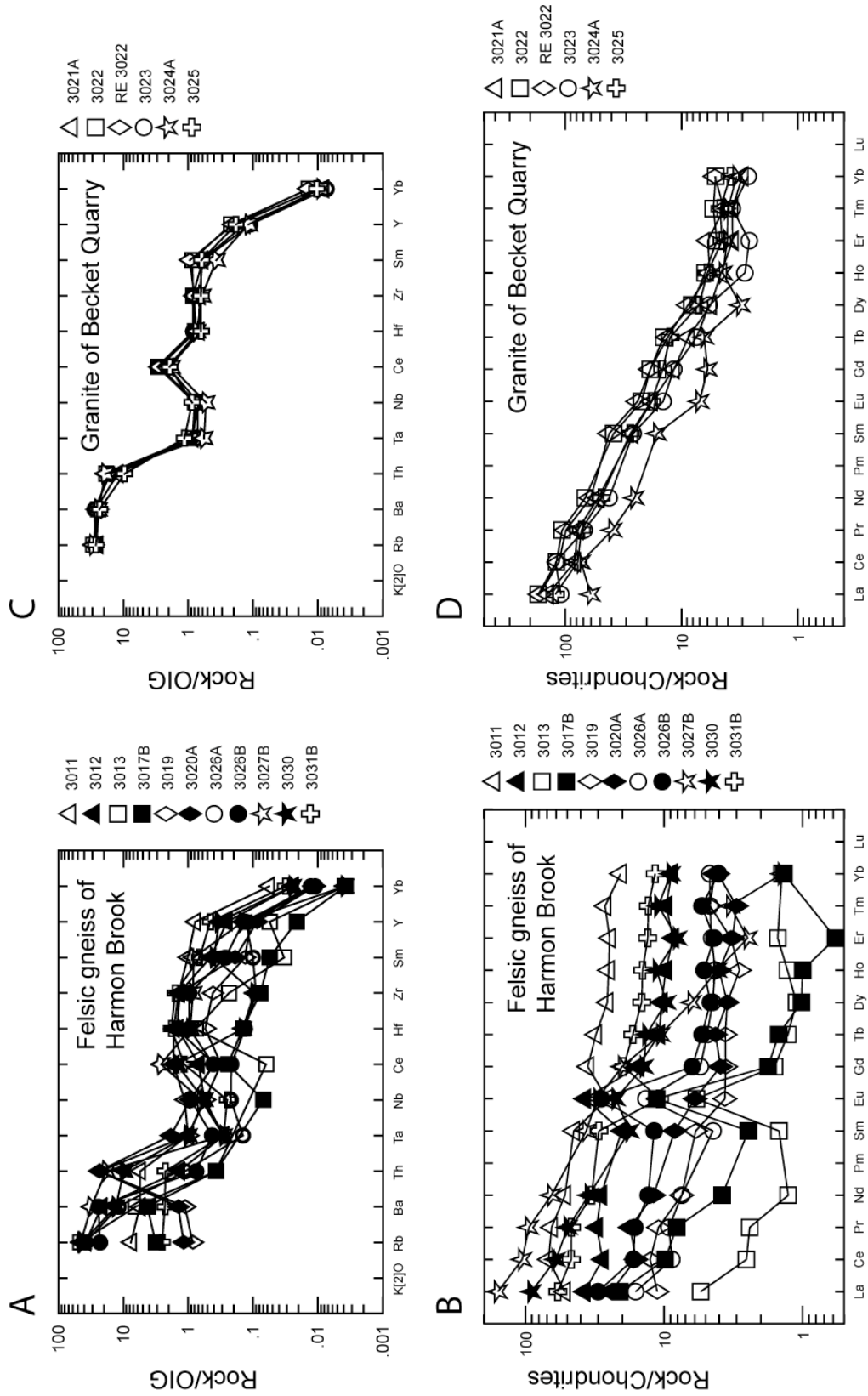


Fig. 4. (A) Ocean ridge granite (ORG)-normalized incompatible element diagram (Pearce and others, 1984) for felsic gneiss of Harmon Brook samples. (B) Chondrite-normalized rare-earth-element plot for felsic gneiss of Harmon Brook samples. (Nakamura and others, 1974). (C) Ocean ridge granite (ORG)-normalized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

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  $\mu\text{m}$  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  $^{16}\text{O}^-$  primary beam, projected onto the zircon grains at 10 kV. The count rates of ten isotopes of  $\text{Zr}^+$ ,  $\text{U}^+$ ,  $\text{Th}^+$ , and  $\text{Pb}^+$  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  $1\sigma$  external errors of  $^{206}\text{Pb}/^{238}\text{U}$  ratios reported in table 1 incorporate an error in calibrating the standard zircon between 0.5 and 1.1% (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  $2\sigma$  uncertainty level.  $^{207}\text{Pb}/^{206}\text{Pb}$  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  $^{206}\text{Pb}/^{238}\text{U}$  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, Stop 2). Ratcliffe and Zartman (1976) reported  $^{207}\text{Pb}/^{206}\text{Pb}$  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  $^{206}\text{Pb}/^{238}\text{U}$  ages (fig. 5B) shows two strong clusters of ages, and the weighted averages of these two groups are 1179  $\pm$  9 Ma (n=8, MSWD = 1.5) and 1004  $\pm$  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 amphibolite 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).

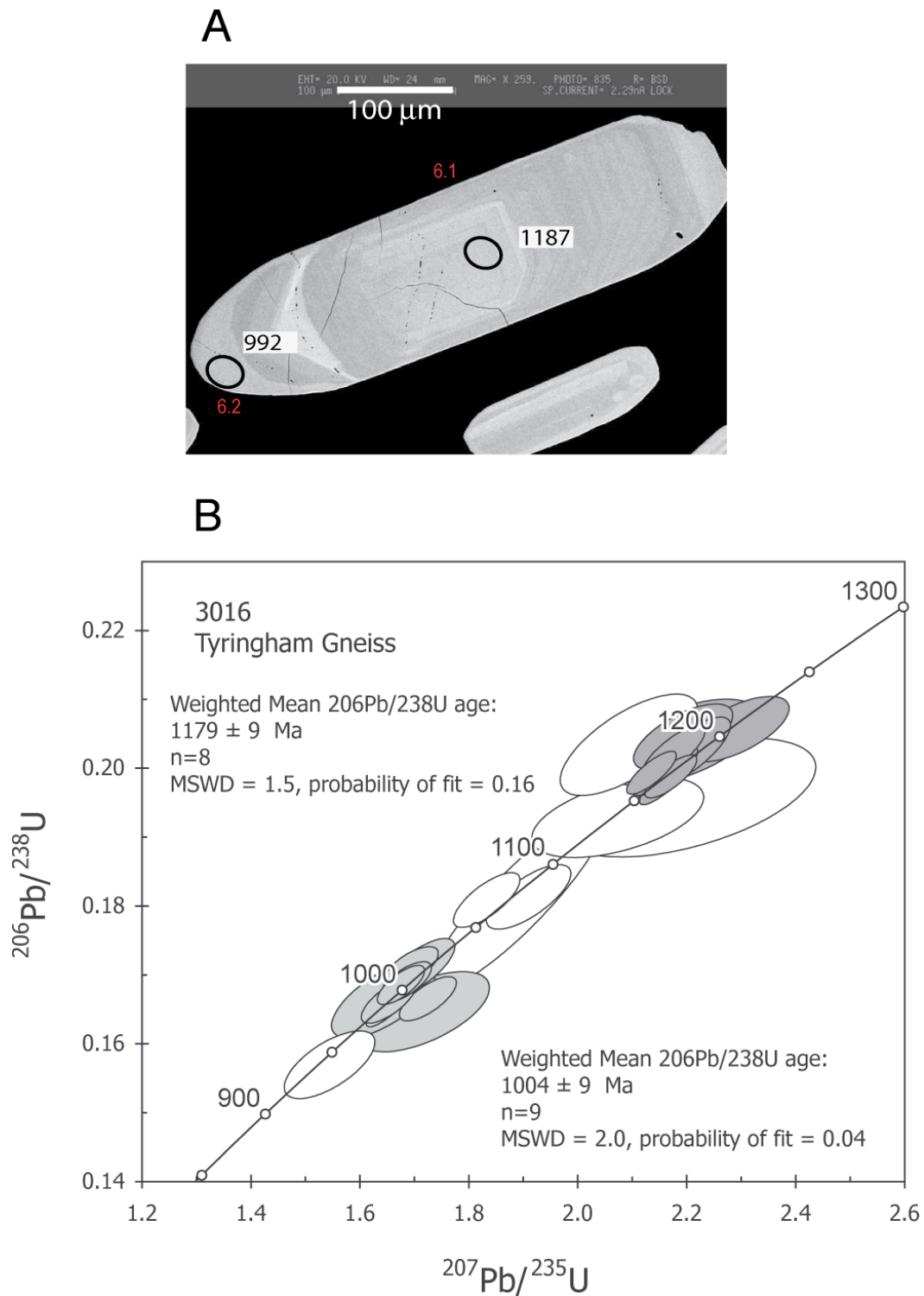


Fig. 5. (A) Back-scattered electron image of zircon grains from the Tyringham Gneiss (sample 3016) with spot analyses and  $^{206}\text{Pb}/^{238}\text{U}$  ages. (B) Concordia plot of error ellipses for all spot analyses. Dark shaded ellipses used for age determination of igneous cores, light shaded 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 (Stop 2) 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 (Stop 4) 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 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  $^{206}\text{Pb}/^{238}\text{U}$  rim ages is 997  $\pm$  5 Ma (MSWD = 1.8). The  $^{206}\text{Pb}/^{238}\text{U}$  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 (Stop 2). The concordia plot for this sample shows a number of rim ages at approximately 1000 Ma and a wide scattering of core ages from approximately 1070 to 1210 Ma (fig. 6C). The weighted average of eight  $^{206}\text{Pb}/^{238}\text{U}$  rim ages is 1004  $\pm$  19 Ma (MSWD = 5.3). Sample 3019, from the west margin of the massif (Stop 4), 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  $^{207}\text{Pb}/^{206}\text{Pb}$  ages is 1003  $\pm$  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, Stop 1) 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  $^{206}\text{Pb}/^{238}\text{U}$  age of 432  $\pm$  3 Ma (n=11, MSWD = 0.58). The older core  $^{207}\text{Pb}/^{206}\text{Pb}$  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  $^{206}\text{Pb}/^{238}\text{U}$  age of 434  $\pm$  5 Ma (n=8, MSWD = 1.4). The older core  $^{207}\text{Pb}/^{206}\text{Pb}$  ages for this sample range widely from approximately 790 to 1170 Ma.

We interpret the 432  $\pm$  3 Ma and 434  $\pm$  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  $\pm$  10 Ma and an upper age intercept of 1050  $\pm$  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.

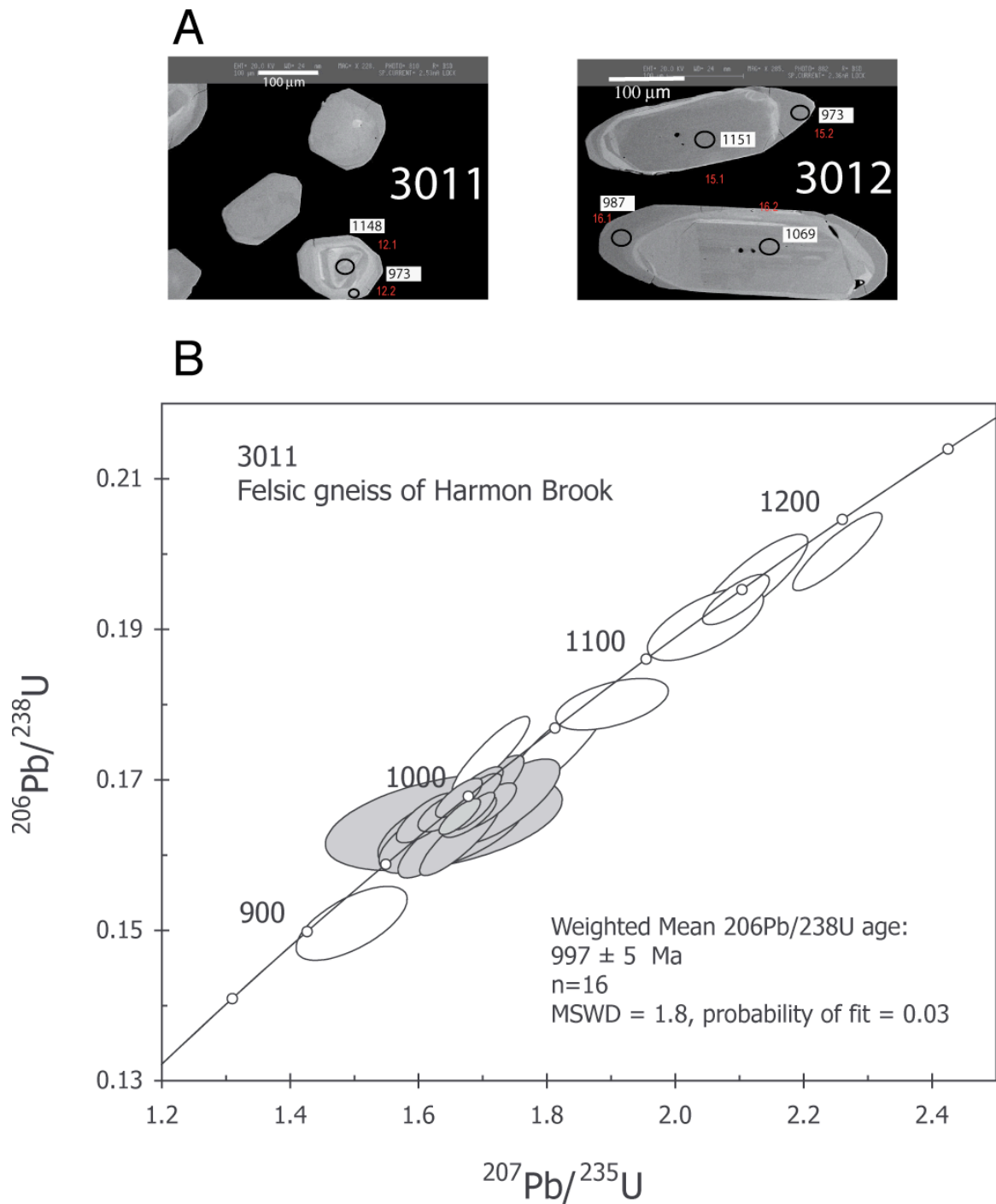


Fig. 6. (A) Back-scattered electron image of zircon grains from the felsic gneiss of Harmon Brook (samples 3011 and 3012) with spot analyses and  $^{206}\text{Pb}/^{238}\text{U}$  ages. (B) Concordia plot of error ellipses for all spot analyses from sample 3011.

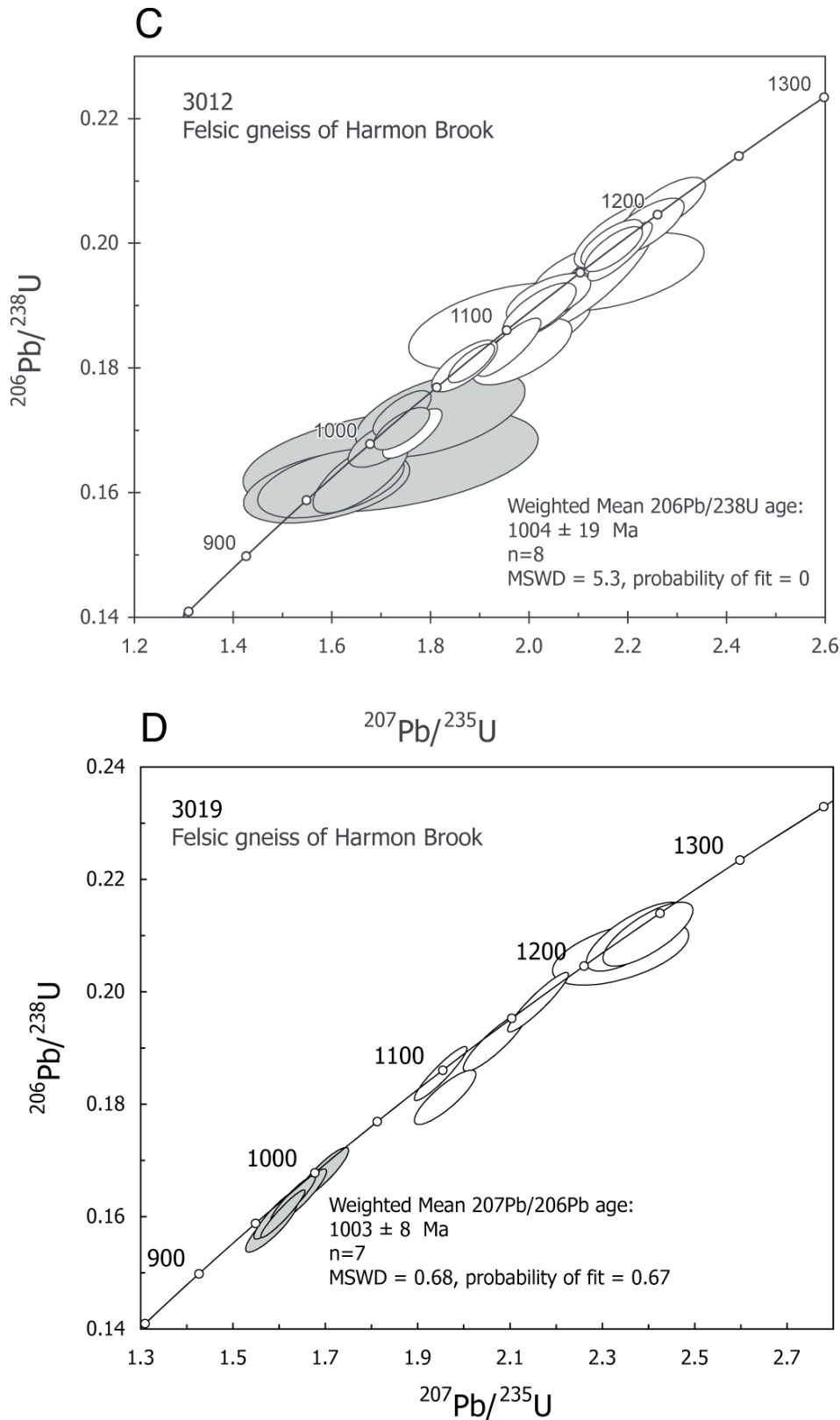
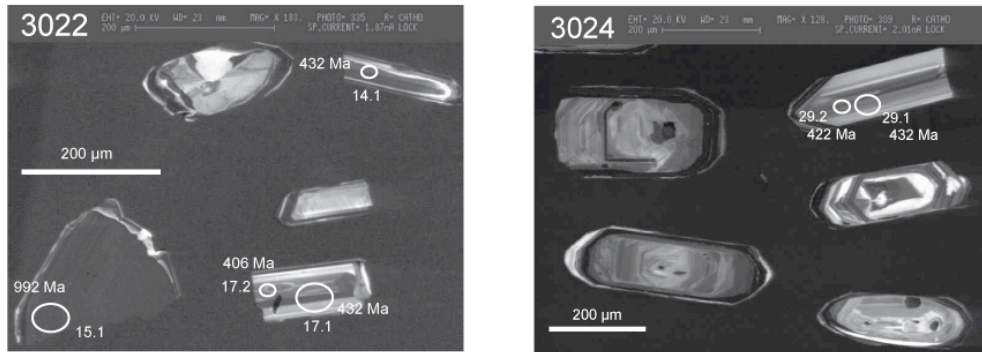


Fig. 6. (cont.) (C) Concordia plot of error ellipses for all spot analyses from sample 3012. (D) Concordia plot of error ellipses for all spot analyses from sample 3019. Shaded ellipses used for age determination of igneous rims in all samples.

A



B

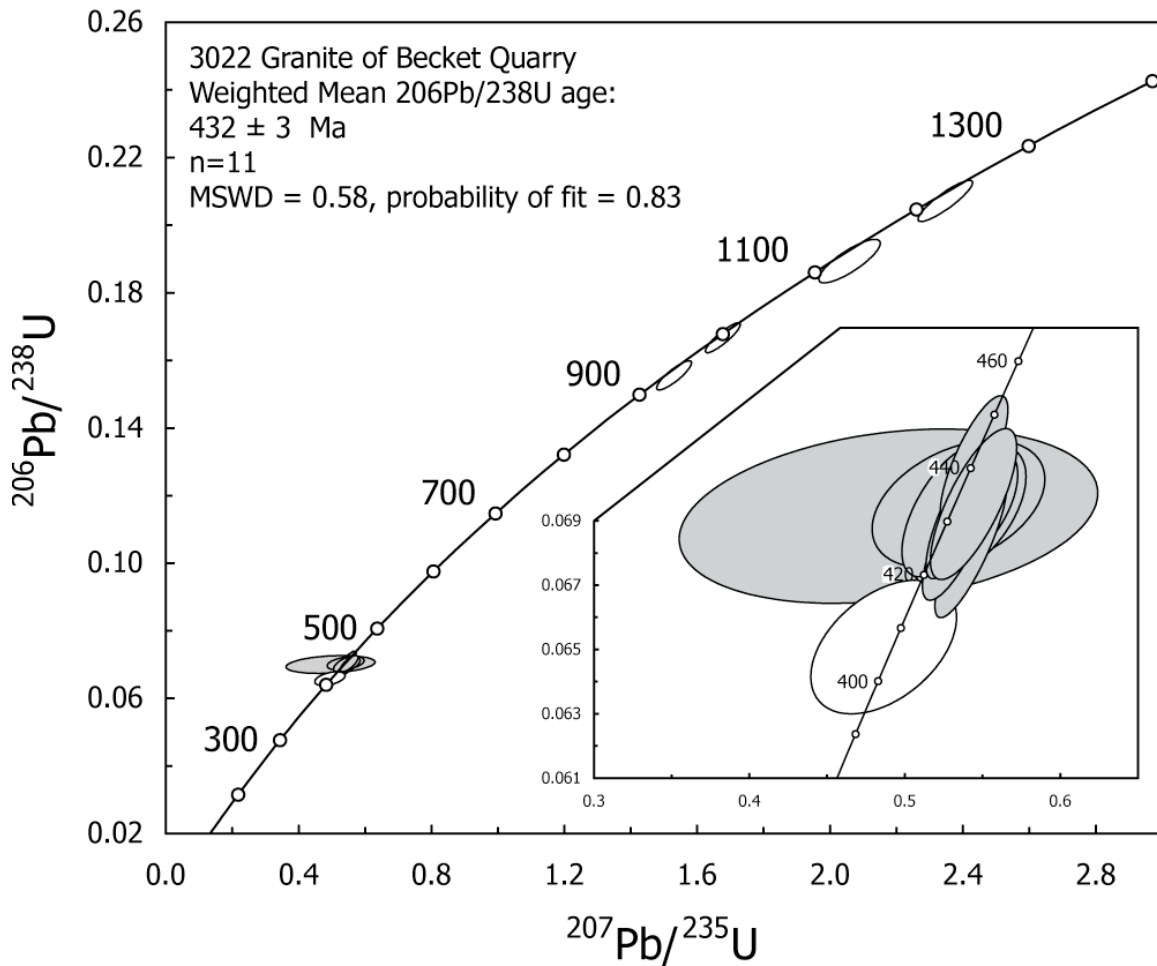


Fig. 7. (A) Cathodoluminescence image of zircon grains from the granite of Becket Quarry (samples 3022 and 3024) with spot analyses and  $^{206}\text{Pb}/^{238}\text{U}$  ages. (B) Concordia plot of error ellipses for all spot analyses from sample 3022.



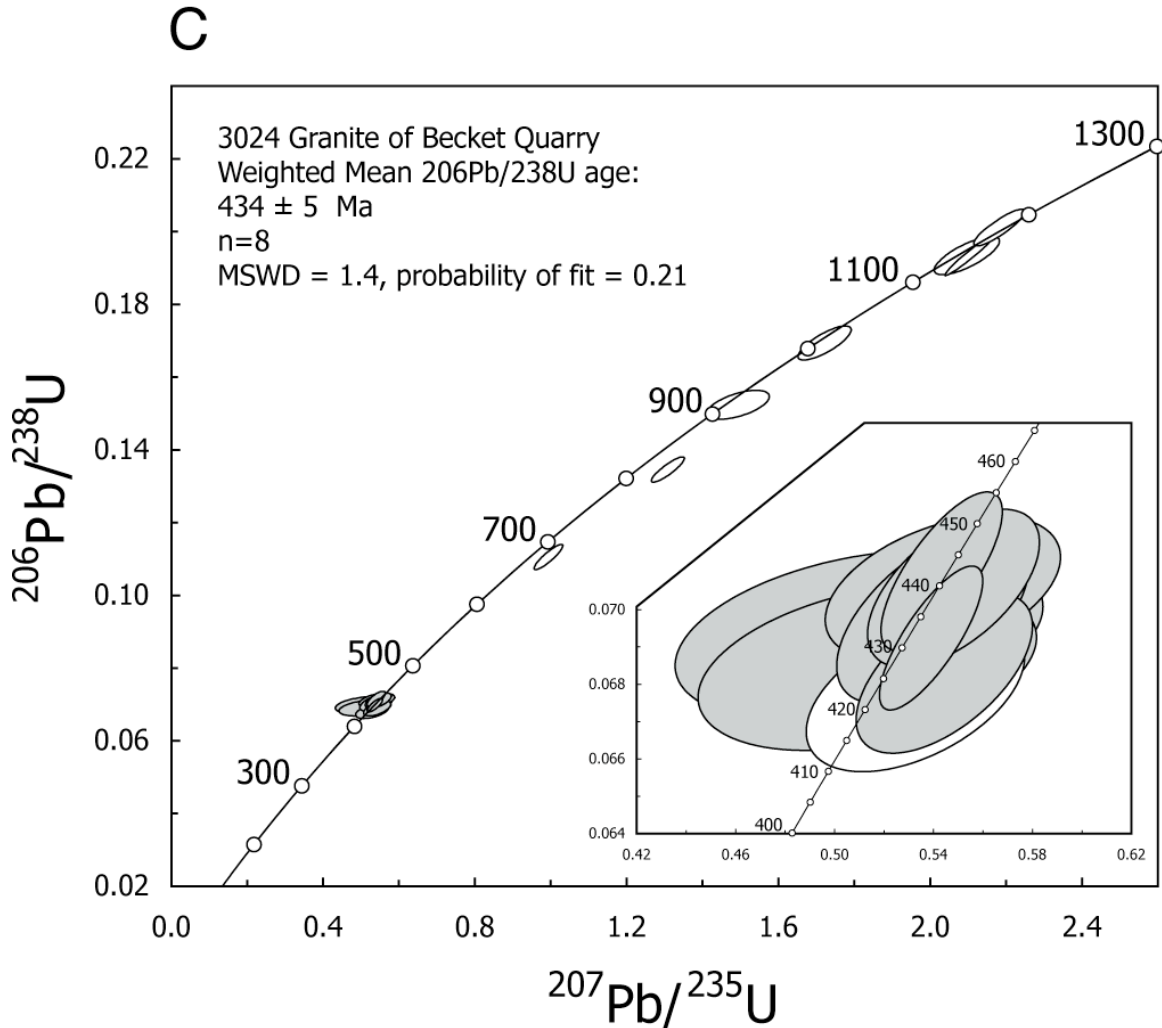


Fig. 7. (cont.) (C) Concordia plot of error ellipses for all spot analyses from sample 3024. Shaded ellipses used for age determination of igneous rims in both samples.

### FAULT ZONE FABRICS

Portions of the western frontal thrust of the Berkshire massif are spectacularly exposed, or at least the fault can be closely bracketed. Fault zone rocks are characterized by mylonitic to ultra-mylonitic fabric, with very planar foliation. Mineral segregation and grain size reduction are common, and the rocks typically contain a strong down-dip lineation consistent with an approximately east-west transport. Kinematic indicators include extensional shear bands, S-C fabric, and asymmetric porphyroclasts. In general the kinematic indicators are in accord with thrusting of the Berkshire massif over the shelf sequence rocks. Locally, however, an opposite sense of shear is suggested by some textures; perhaps late normal-sense reactivation occurred. Typically, the most highly strained rocks near fault zones are not very valuable for determining the sense of shear. We think that flattening was so intense in these rocks that asymmetric features are difficult to recover.

Microtextures in rocks collected from well-exposed segments of the western frontal thrust of the Berkshire massif indicate that mylonitization took place at metamorphic temperatures. All samples show evidence for grain size reduction by dynamic recrystallization through sub-grain rotation and grain boundary migration (Passchier and Trouw, 1996). Banded mylonites characteristically show marked differences in grain size and mineralogy in adjacent layers (Stop 3). Partially recrystallized feldspar crystals

form long, fine-grained continuous bands separated by quartz ribbons. Quartz grains are typically equant and meet at 120° triple junctions; undulose extinction, if present at all, is weak. Recrystallization in quartz appears to be by sub-grain rotation rather than grain size reducing processes such as grain-boundary migration. These observations suggest that quartz deformed by climb-accommodated dislocation creep at high temperatures (Hirth and Tullis, 1992; Passhler and Trouw, 1996). In contrast, feldspar grains retain strong internal deformation textures such as undulose extinction and highly irregular and sutured boundaries. Very small and unstrained feldspar grains are commonly present along the irregular boundary between two larger grains, indicating that recrystallization-accommodated dislocation creep was active. In some samples, feldspar grains with undulose extinction form sub-grains of similar size without a mantle of new very fine-grained crystals, suggesting that locally temperatures may have been high enough for climb-accommodated dislocation creep to have occurred in feldspar. Feldspar grains also contain myrmekitic textures, a characteristic of high temperature deformation. Collectively, these textures constrain the deformation in fault zone rocks to temperatures in excess of 500° C (Hirth and Tullis, 1992; Passhler and Trouw, 1996).

### MONAZITE GEOCHRONOLOGY

We used the electron microprobe at Rensselaer Polytechnic Institute to obtain U-Th-Pb ages from *in situ* grains of monazite from fault zone rocks. (Cocherie et al. 1998; Williams et al., 1999). These ages are preliminary and should be viewed as a reconnaissance effort to date faulting in the Berkshire massif; we hope to test these ages with an ion microprobe soon. Nonetheless, some interesting data are available (Fig. 8). For example, the electron microprobe dating of monazite does not support a Taconic age for thrusting. Monazite from a highly deformed quartzite exposed in the hanging-wall of the Dry Hill fault (Stop 5) gives an age of 392 +/- 14 Ma (1s.e., n=16). Quartz-rich schist from a fault zone at Umpachene Falls contains monazite grains with multiple age populations that peak at 530, 435, 380, and 290 Ma; a weighted average of all data gives an age of 422 +/- 8 Ma. Monazite grains in graphitic schist from Benton Hill 200 m below a major thrust give a weighted average age of 436 +/- 8 Ma (n=21). Two localities from Yale Farm just below the western frontal thrust of the Berkshire massif give weighted average monazite ages of 401 +/- 9 Ma (n=26) and 400 +/- 10 (n=40). These preliminary monazite ages from well-exposed fault zones suggest that motion on faults along the western margin of the massif occurred during the Devonian or Silurian. So far, dating of monazite provides no evidence that faults were active during the Ordovician Taconic orogeny. However, one sample, collected more than 0.5 km from any major mapped fault, does show two peaks in monazite ages at 470 and 520 Ma. This sample apparently preserves evidence for Early Ordovician metamorphism, but more data are needed to confirm this older age.

### 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 (Heumann and others, 2006, Hamilton and others, 2004), and thus supports correlation of rocks in the two regions. SHRIMP spot analyses from metamorphic 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)

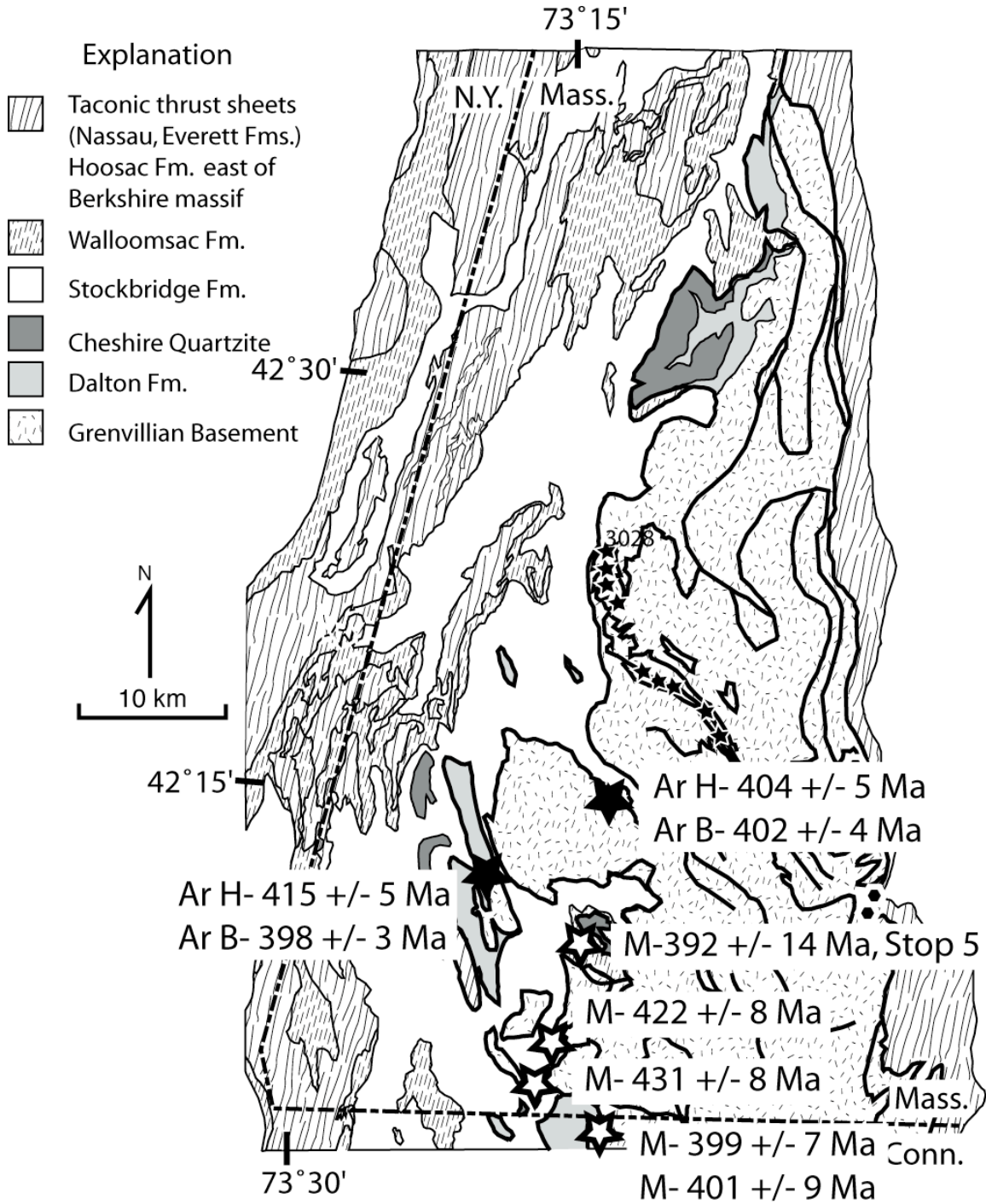


Figure 8. Map of the Berkshire massif showing new U-Th-Pb electron microprobe monazite ages (M-) and  $^{40}\text{Ar}/^{39}\text{Ar}$  plateau hornblende (Ar H-) and biotite (Ar B-) ages from Sutter et al. (1985).

partial melting of different source rocks, (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 Ottawa orogeny (Heumann and others, 2006). The younger metamorphism in the Berkshire massif may reflect the time transgressive nature of the Ottawa 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  $\pm$  8 Ma metamorphic rims on igneous zircons in Mesoproterozoic rocks of western Connecticut, and Gates and others (2004) dated 1007  $\pm$  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  $\pm$  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. Our preliminary electron microprobe monazite ages suggest that movement along the western frontal thrust occurred during the Silurian to Devonian.

Emplacement of the Berkshire massif after the Taconic orogeny would also have dramatically altered the original geometry of the Taconic thrust belt by creating an arch in the thrust system. 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.

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 syntectonic 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.

*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  $^{206}\text{Pb}/^{238}\text{U}$  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  $^{40}\text{Ar}/^{39}\text{Ar}$  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  $^{207}\text{Pb}/^{206}\text{Pb}$  ages ranging from 790 to approximately 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.

#### ACKNOWLEDGEMENTS

This work was supported by NSF grant EAR-0125476.

#### ROAD LOG

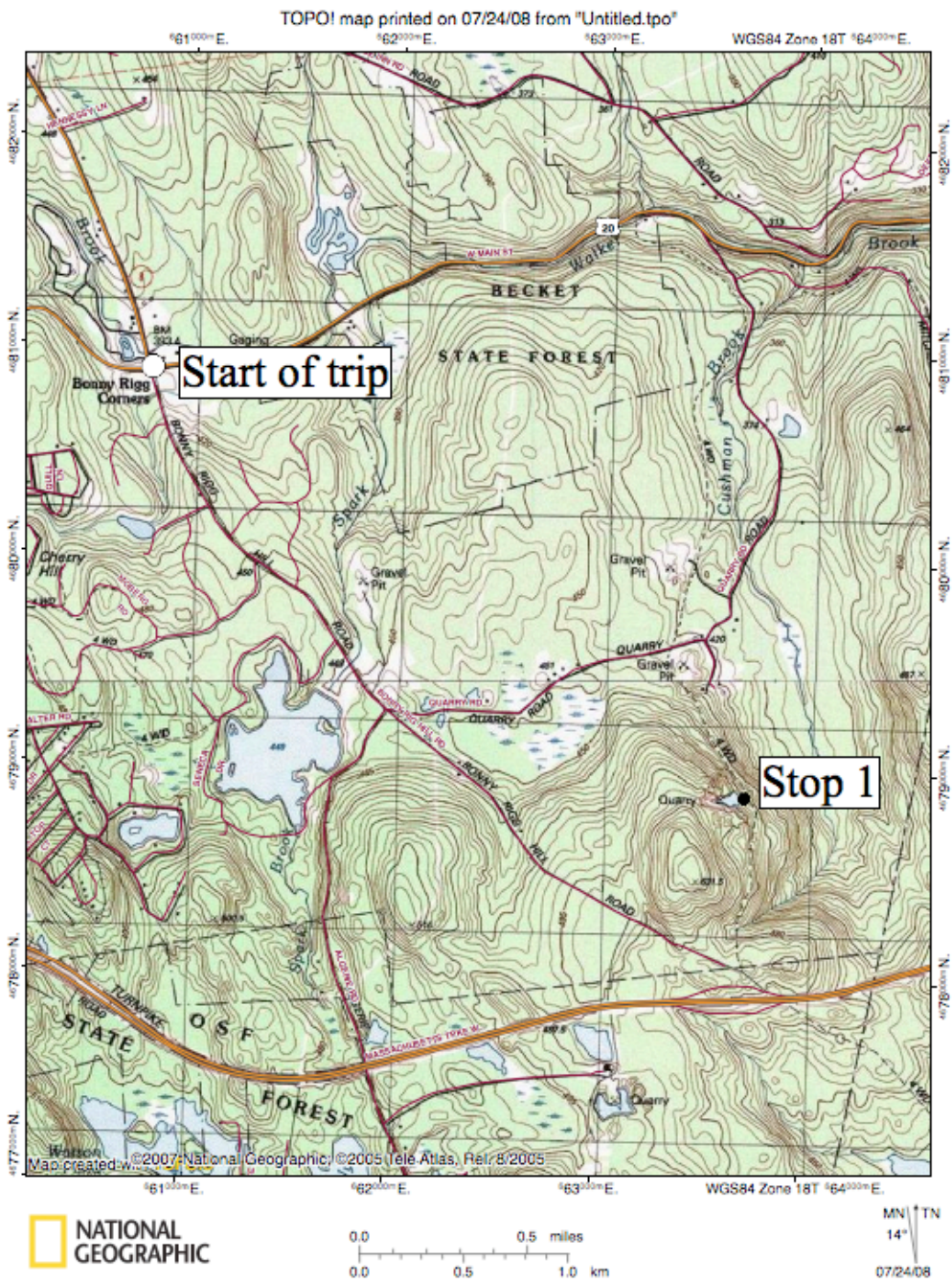
0.0 Assemble at 8:00 am at the eastern intersection of Route 8 and Route 20 where Route 8 heads north, also known as Bonny Rigg Corners. The assembly point is in the East Lee 7.5 x 15' quadrangle. (Note that there is a western intersection of these roads where Route 8 heads south; you do not want to start there.)

Drive south on Bonny Rigg Hill Road.

C2-22 KARABINOS, MORRIS, GORDON, HAMILTON, RAYNER, and PYLE

- 1.3 Turn right, east, on Quarry Road.
- 2.3 Park in Becket Quarry lot on right side of road.

Walk south on wide hiking trail about 900 m. Turn right near an old truck and follow path about 25 m to main quarry pit which is now filled with water and suitable for swimming.



**STOP 1. Becket Quarry, SILURIAN SILL, GRANITE OF BECKET QUARRY, IN MESOPROTEROZOIC BASEMENT.**

Otis 7.5 x 15' quadrangle, UTM coordinates: 18T 663661 m E and 4678644 m N.

This excellent and accessible exposure of the granite is the source for our informal name for this unit, the granite of Becket Quarry. The quarry extracted medium-grained, weakly-foliated, microcline-plagioclase-quartz-biotite-muscovite granite. Locally, there are 30 to 50 cm long biotite-rich streaks approximately 1 cm thick that have a quartz-feldspar-rich halo around them. On the north side of the quarry at water level are several meter-scale xenoliths of Biotite-quartz-plagioclase Gneiss, one of the units in the Mesoproterozoic basement. It is a bit hard to see and it may be necessary to swim out there to convince yourself that the biotite gneiss forms xenoliths rather than the lower contact of the sill. The upper contact between the granite and gneiss is visible on the north side of the quarry if you position yourself on the southeast side on one of the accessible talus cones. The dark gray biotite gneiss is clearly visible in the cliffs above the granite. An inaccessible, light gray, 1 to 2 m thick pegmatite with an irregular, wavy bottom intruded the gneiss. Pegmatites are common in rocks that were intruded by the granite.

Eleven spot analyses on zircon rims and grains without cores from this quarry (sample 3022, Fig. 7) give a weighted average  $^{206}\text{Pb}/^{238}\text{U}$  age of 432 +/- 3 Ma. The older zircon core  $^{207}\text{Pb}/^{206}\text{Pb}$  ages range from 962 +/- 15 to 1247 +/- 13 Ma. Again, we believe these ages suggest that the parent rock of the granite was a Mesoproterozoic paragneiss from the Berkshire massif.

Return to car. Return to Bonny Rigg Hill Road on Quarry road.

- 3.3 Turn right, northwest, onto Bonny Rigg Hill Road.
- 4.4 Turn left, west, onto Route 20/Route 8.
- 9.6 Intersection with Route 8 South, continue west on Route 20.
- 12.1 Entering Lee.
- 12.5 Turn right, north, onto Becket Road (also called Tyne Road), and drive uphill.
- 13.4 Park on right near sign for Appalachian National Scenic Trail.

Walk southeast on trail about 250 m. After a very small drainage crossing the trail turns right and starts going downhill. Leave the trail where it turns downhill and continue southeast at a constant elevation. Look for traces of an old dirt road, which contours and follow it. As you continue southeast, the slope to your left, northeast, becomes gradually steeper. About 300 m beyond the Appalachian trail, turn left and walk up the slope about 50 m to abundant outcrops.

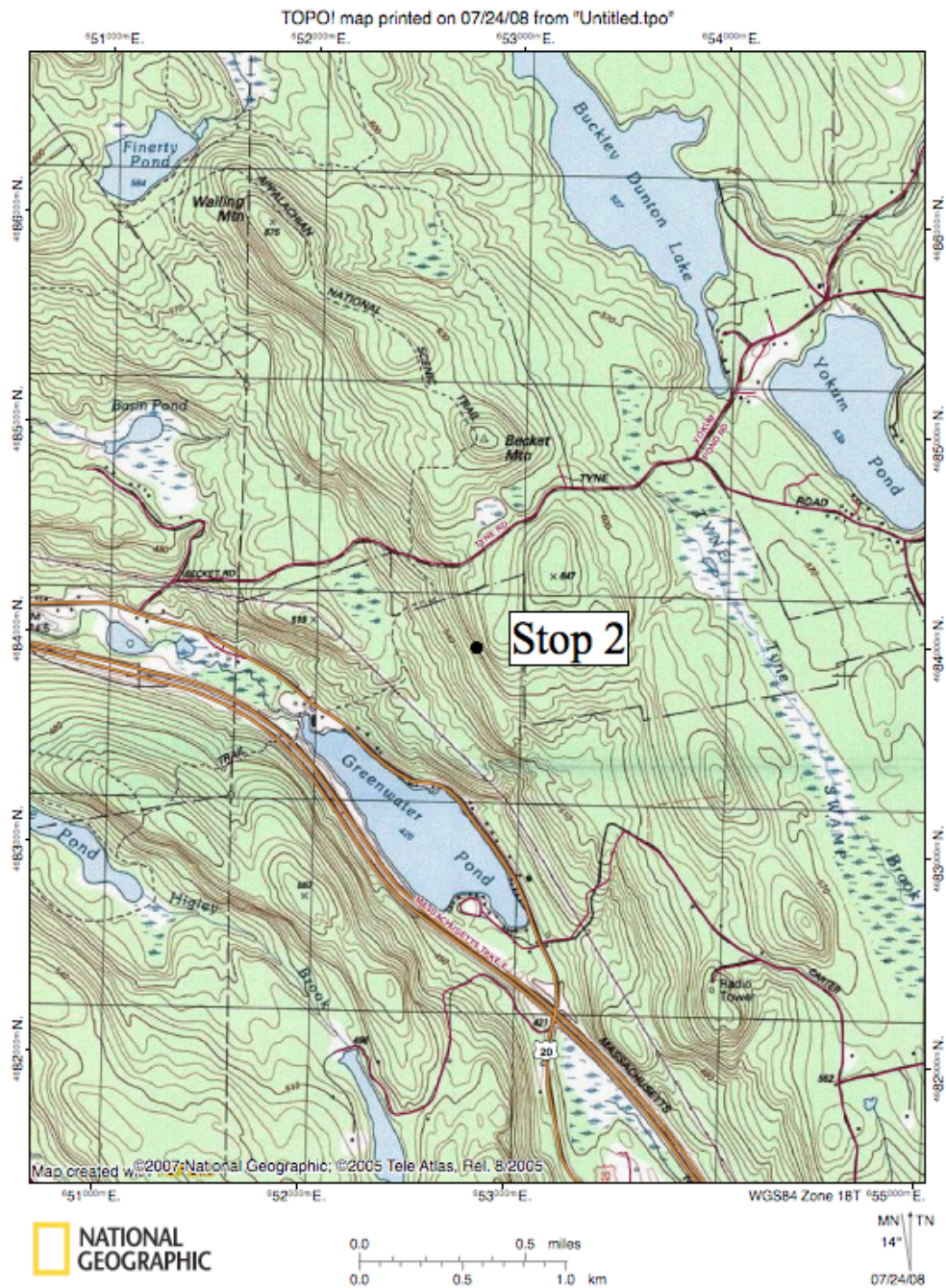
**STOP 2. FELSIC GNEISS OF HARMON BROOK, A MESOPROTEROZOIC SILL IN THE TYRINGHAM GNEISS.**

East Lee 7.5 x 15' quadrangle, UTM coordinates: 18T 652692 m E and 4683799 m N.

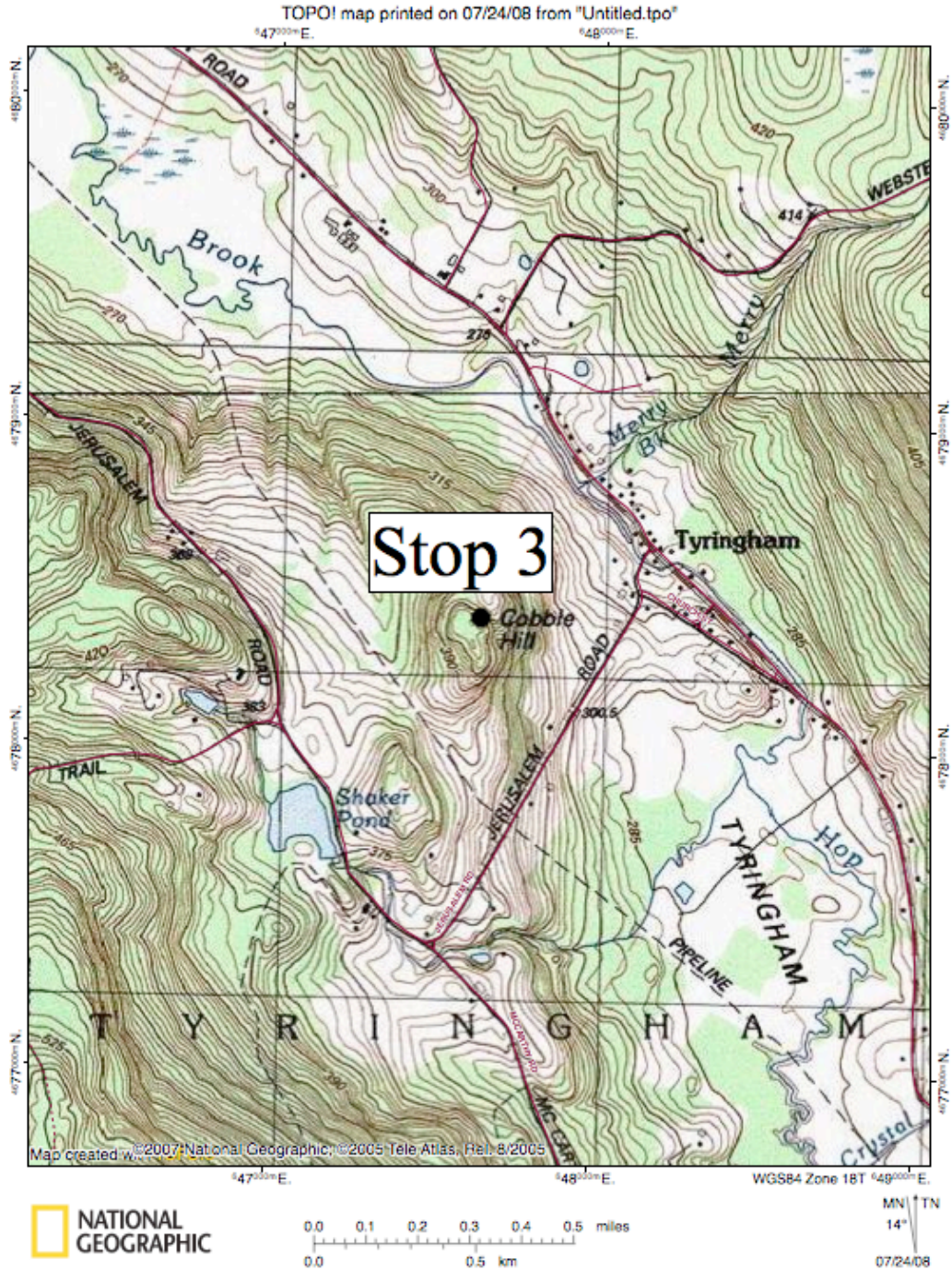
The upper contact of the sill with the Tyringham Gneiss is exposed sporadically over 400 m along strike on this slope. The sill is a medium-grained granite composed of microcline, plagioclase, quartz, biotite, muscovite, and epidote. There is too much biotite in the rock here for it to be accurately called an alaskite, the designation used in the maps by Ratcliffe (1984a, 1984b, 1985). Foliation in the granite is approximately parallel to the foliation in the Tyringham Gneiss and to the contact. The Tyringham Gneiss is a coarse-grained, strongly-foliated augen gneiss with a granite composition and mineralogy similar to the sill. The Tyringham Gneiss contains numerous pegmatite veins near the contact with the sill. The deformation fabric in the Tyringham Gneiss close to the contact is similar to the fabric in the gneiss hundreds of meters away from the contact upslope; there is no clear evidence for fault-related deformation in either the gneiss or the sill. Ratcliffe (1985) mapped a Taconic-age thrust through here that carried

Tyringham Gneiss over itself and he interpreted the alaskite sill as an Ordovician syntectonic intrusive in the fault. He suggested that frictional heating along the fault or widespread metasomatism produced the sills during the Taconic orogeny.

Our geochronological data are inconsistent with Ratcliffe's (1985) interpretation. The crystallization age of the sill here is  $1004 \pm 19$  Ma (sample 3012, Fig. 6). Another sill, 2 km to the southeast, gave a crystallization age of  $997 \pm 10$  Ma (sample 3011, Fig. 6). Both samples contain abundant xenocrystic zircon cores that range widely from 1050 to 1210 Ma. The Tyringham Gneiss







crystallized at  $1179 \pm 9$  Ma and many of the zircon grains have metamorphic rims that grew at  $1004 \pm 9$  Ma (sample 3016, Fig. 5). We suggest that the contact between the sill and the Tyringham Gneiss is intrusive and that the felsic gneiss was generated by anatectic melting of Mesoproterozoic paragneisses during high-grade metamorphism at approximately 1 Ga. If a fault does cut through the Tyringham Gneiss, there is no evidence for it being a Taconic thrust.

Walk back to car. Turn around and head back downhill to Route 20.

- 14.3 Turn right, west, on Route 20.
- 18.2 Turn left, south, on Route 102.
- 18.3 Bear left, south, on Tyringham Road.
- 22.5 Turn right, southwest, onto Jerusalem Road.
- 22.6 Bear right.
- 22.9 Turn right into parking lot for Tyringham Cobble.

The trail from parking lot through the Trustees of the Reservation property is a loop that intersects the Appalachian Trail. Walk across the field, go through stile, and turn left. The loop trail follows the Appalachian Trail briefly, but then diverges uphill to the northeast. Walk up to the very top of Cobble Hill.

**STOP 3. THRUST OF MESOPROTEROZOIC BASEMENT OVER PALEOZOIC SHELF SEQUENCE, FELSIC GNEISS OF HARMON BROOK.**

Otis 7.5 x 15' quadrangle, UTM coordinates: 18T 647625 m E and 4678156 m N.

At the top of the Cobble is Mesoproterozoic gneiss mapped by Ratcliffe (1984a) as Biotite-quartz-plagioclase Gneiss that contains a fabric typical of the Grenvillian basement. The basement gneisses belong to the Beartown Mountain "slice" of Ratcliffe (1984a). (See Ratcliffe and Hatch (1979, their stop 4) for their interpretation of this location.) Down slope to the east, just off the trail, are mylonitic rocks. The gneisses contain a strongly foliated felsic sill and a mafic layer. Below the cliffs, the trail goes through a covered interval in the woods and there are good exposures of marble beyond the woods in the pasture. The contact between the gneisses and the marble is a thrust and it is reasonable to assume that the mylonitic fabric is related to deformation concentrated near the fault. Mylonitic fabric, such as observed here, is not present near the Tyringham Gneiss-felsic sill contact at Stop 2.

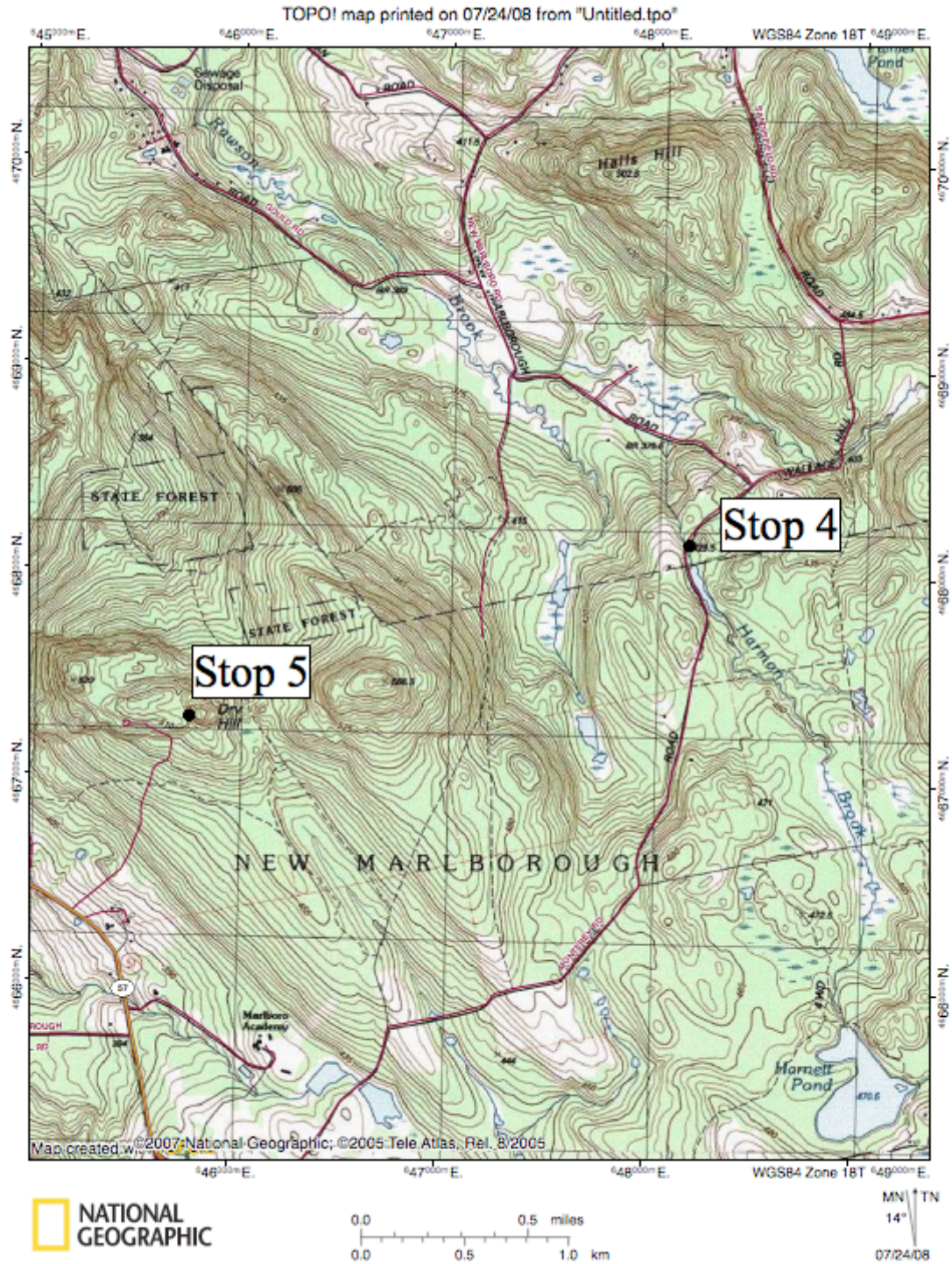
The felsic sill from this outcrop has the composition of a granodiorite. It was not dated but it is similar enough in appearance and geochemistry to the three Mesoproterozoic sills that have been dated that we believe that it too is Mesoproterozoic. Thus, the presence of the felsic sill does not provide independent evidence for Taconic movement on the thrust. Sutter et al. (1985) reported  $^{40}\text{Ar}/^{39}\text{Ar}$  plateau ages of  $404.0 \pm 4.5$  Ma (hornblende) and  $402.1 \pm 4.4$  Ma (biotite) from this locality, which they interpreted as cooling ages from the Taconic orogeny. An alternative interpretation, which is in accord with our monazite ages from fault zone rocks, is that the  $^{40}\text{Ar}/^{39}\text{Ar}$  record recrystallization of hornblende and biotite during thrusting. If correct, this interpretation requires at least some of the thrusting of the Berkshire massif to have occurred during the Acadian orogeny.

Hike back to car. Drive down Jerusalem Road back to Tyringham Village.

- 23.1 Turn right, southeast, onto Main Road.
- 24.5 Turn right, southwest, onto Monterey Road.
- 28.4 Monterey Village, turn left, east onto Route 23.
- 28.5 Turn right, southeast, onto Sandisfield Road.
- 29.9 Turn right, south, onto Wallace Hall Road.
- 30.4 This is the location for 3019, one of the dated Mesoproterozoic felsic gneiss samples.

30.7 Intersection, go straight.

30.9 Pull over to right.



Follow path that starts on the east side of Harmon Brook and the north side of the road and walk north-northwest down slope.

**STOP 4. CONTACT BETWEEN MESOPROTEROZOIC FELSIC GNEISS AND ORDOVICIAN STOCKBRIDGE FORMATION, FRONTAL THRUST OF BERKSHIRE MASSIF.**

Otis 7.5 x 15' quadrangle, UTM coordinates: 18T 648147 m E and 4667943 m N.

There is very good outcrop of weakly foliated felsic gneiss in Harmon Brook all the way down to an elevation of 405 m. This is the best exposure of the felsic gneiss we know of, and the our informal name for this unit comes from this location. Even the lowest outcrops of felsic gneiss, near the contact with the Stockbridge Formation, are only weakly foliated. There is a 50 m covered interval and the next outcrops downstream are marble of the Stockbridge Formation. At the same elevation as the first marble outcrop, much, or all, of the stream, depending on water flow, disappears into a sinkhole. Bedding in the marble is almost vertical and the water probably flows straight down parallel to a particularly soluble bed. Continue downstream about 50 m to a cliff or waterfall, depending on the time of year, where a large fold in bedding is visible. This may be a fault-bend-fold over a ramp in a structurally lower thrust within the Stockbridge Formation.

The felsic gneiss outcrops here (sample 3020) and in the brook at mile 30.4 (sample 3019) are both trondhjemitic in composition. We dated zircons from sample 3019, and they show a tight cluster of ages at ca. 1000 Ma and a wide scatter of ages from 1100 to 1220 Ma (Fig. 10). The weighted average of seven  $^{207}\text{Pb}/^{206}\text{Pb}$  ages is 1003 +/- 8 Ma. We interpret this as the crystallization age of the felsic gneiss.

The felsic gneiss exposure here and to the east along Wallace Hall Road were mapped by Ratcliffe (1984a) above the Beartown Mountain thrust that carried Middle Proterozoic basement over the Cambrian and Ordovician Stockbridge and Walloomsac Formations. The upper contact of the felsic gneiss is with Biotite-quartz-plagioclase paragneiss and Leucocratic biotite Gneiss and granulite of the Mesoproterozoic basement. Ratcliffe (1984a) interpreted the felsic gneiss as a syntectonic intrusive into the thrust fault and used the preliminary Rb-Sr Ordovician age from a sill of the granite of Becket Quarry (Ratcliffe and Mose, 1978) to argue that the frontal thrust of the Berkshire massif must be a Taconic fault.

The frontal thrust of the Berkshire massif certainly could have a component Taconic displacement, but the Mesoproterozoic age of the felsic gneiss means that the sill cannot be used as evidence for this interpretation. We should try to confirm the Taconic age assignment independently, rather than accepting it as proven. As discussed at our next stop, there appears to be movement on the frontal thrust of the Berkshire massif during the Silurian and Devonian, suggesting that mid-crustal shortening occurred during the Salinic and Acadian orogenies.

Return to cars and continue south on what is now called Monterey Road.

32.9 Turn right onto Harmon Road.

33.1 Park in Trustees of the Reservation lot for Dry Hill. Hike northwest on the dirt road and through the pass east of Dry Hill. Turn left on the trail that goes around the north side of Dry Hill and follow to the steep cliff on the west side of the hill.

**STOP 5. DRY HILL THRUST, MYLONITIC CHESHIRE QUARTZITE.**

Otis 7.5 x 15' quadrangle, UTM coordinates: 18T 645797 m E and 4667287 m N.

The cliff is made up of Cheshire Quartzite, which was thrust over graphitic schist. At the base of the cliff, the quartzite forms thin layers separated by micaceous parting planes. Layering becomes gradually thicker towards the top of the cliff. The strong lineation on parting planes trends 80° and plunges 10°. Graphitic schist is exposed some distance to the west. Ratcliffe (1984a) mapped it as Walloomsac Formation. We think it is a Neoproterozoic graphitic schist belonging to the Taconic thrust sheet.

An electron microprobe U-Th-Pb monazite age from the Cheshire Quartzite here is 397 +/- 14 Ma. If this age can be verified by ion microprobe dating, it means that the basement rocks of the Berkshire massif were not thrust over the shelf sequence rocks during the Taconic orogeny. If this is indeed the case,

there is no need, from a structural geometry standpoint, for schist exposed below basement rocks to be part of the shelf sequence.

#### END OF TRIP

Retrace the trip through Monterey and Tyringham to Lee. An entrance to the Massachusetts turnpike is located near the intersection of Route 102 and Route 20 that we passed at mile 18.3

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