Geology of the Shrewsbury Quadrangle, East-Central Massachusetts

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GEOLOGY OF THE SHREWSBURY QUADRANGLE, EAST-CENTRAL MASSACHUSETTS

a thesis
by
ROSS JOSEPH MARKWORT

submitted in partial fulfillment of the requirements
for the degree of
Master of Science

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GEOLOGY OF THE SHERBURY QUADRANGLE, EAST-CENTRAL MASSACHUSETTS
Ross J. Markwort
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ABSTRACT
The Shrewsbury quadrangle was geologically mapped at a scale of 1:24,000. The quadrangle spans the entire Nashoba terrane, a belt of amphibolite-grade rocks related to an early Paleozoic peri-Gondwanan arc.

Petrofabric studies of fault-rocks indicated that the final motion on several major shear zones – Ball Hill fault, Sulfur Hill shear zone, and Assabet River fault – was sinistral strike-slip with an oblique NW over SE thrust component.

Monazites from these shear zones were dated using an electron microprobe. Regional metamorphism (M1) took place around 420 Ma. A second regional metamorphism (M2) produced anatectic conditions around 394 Ma. A group of dates in the range 360-385 Ma indicates that the Nashoba terrane was also affected by Neoacadian metamorphism and/or deformation. Major shear zones were active throughout the Devonian and may have persisted into the Carboniferous.
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GEOLOGY OF THE SHREWSBURY QUADRANGLE, EAST-CENTRAL MASSACHUSETTS

EXTENDED ABSTRACT

The Nashoba terrane is a distinct, fault-bounded lithotectonic belt in eastern Massachusetts lying between the Merrimack terrane to the west and the composite Avalon terrane of southeastern New England to the east. It consists largely of northeast-striking, northwest-dipping Cambrian, Ordovician, and Silurian arc-related volcanic rocks and sediments metamorphosed to upper amphibolite facies conditions during the Silurian and Devonian. Major faults and ductile shear zones are present throughout the terrane and suggest that these rocks now form a tectonic assemblage rather than a coherent stratigraphic succession.

During 1:24,000 scale geologic mapping in the Shrewsbury quadrangle, the sense of motion was determined on three major mylonite zones from different structural levels: (1) the Ball Hill Fault, a roughly 25 km long mylonite zone that merges with the Clinton-Newbury fault zone near Lawrence, MA; (2) the Sulfur Hill shear zone, a relatively narrow mylonite zone tens of meters wide that coincides with a steep magnetic gradient; and (3) the Assabet River fault zone, which roughly bisects the entire terrane and structurally truncates many of the mapped units along its ~100 km trace. These faults generally strike NNE to NE and dip moderately to steeply NW with stretching lineations plunging NW to NE at moderate to shallow angles. Field and microstructural petrofabric shear indicators indicate sinistral strike-slip motion with a NW over SE oblique thrust
component. This sense of sinistral transpressive motion on major faults within the terrane is similar to that found for the terrane bounding fault zones (Goldstein, 1989; Goldstein, 1994; Kohut, 2001; Kohut and Hepburn, 2004) possibly indicating that they formed contemporaneously during the emplacement of the Nashoba terrane.

Oriented thin sections from rocks in or near these shear zones were analyzed with an electron microprobe to date monazite crystal domains. Three distinct age populations are interpreted to represent: (1) static sillimanite-muscovite zone metamorphism circa 423 Ma; (2) sillimanite-k-feldspar zone metamorphism and migmitization at 394 Ma; and, (3) Neoacadian non-coaxial deformation around 376 Ma. Additional crystal domain ages in the range 360-305 Ma are interpreted to represent retrograde metamorphism and sporadic fault activity during the earliest stages of exhumation.
PART ONE
Chapter 1. INTRODUCTION

The Appalachian orogen has traditionally been considered the cumulative result of three orogenic events distinct in both their spatial and temporal limits (Williams and Hatcher, 1983). All three events are evident in New England. The Taconic orogeny generated fold-thrust belts in eastern New York and western New England (Figure 1.1). This deformation resulted from Middle Ordovician accretion of peri-Laurentian volcanic arcs. The Devonian Acadian orogeny was responsible for widespread regional metamorphism throughout central and eastern New England. The driving force in this mid-Paleozoic orogeny has traditionally been considered to be the accretion of the Avalon terrane (Williams and Hatcher, 1983). The Alleghenian orogeny is most prevalent in southern New England where late Paleozoic regional metamorphism commonly overprints older Acadian features.

Acadian deformation in New England occurred largely during the Devonian but its driving mechanism is unclear. In Newfoundland, the docking of Avalon was responsible for the Acadian orogeny (Dunning and others, 1990); but, although an Avalonian terrane is present in southernmost New England, some evidence suggests that it was still outboard of the New England Laurentian margin during the Devonian (Wintsch and others, 1992; Wintsch and others, 1993).

The Nashoba terrane (Figure 1.2) – an enigmatic lithotectonic zone in southeastern New England – likely played some role in the Acadian orogeny given its present-day coordinates between the New England Avalon terrane to the east and Acadian-deformed rocks to the west. The Nashoba terrane is currently understood to be
Figure 1.1. Generalized lithotectonic map of New England. The Nashoba terrane of Massachusetts is correlative along strike with the Putnam terrane of Connecticut. The Cushing and Passagassawakeag terranes of Maine may also be correlative with the Nashoba terrane. Geology after Robinson and Kapo (2003).
comprised of early Paleozoic arc rocks metamorphosed and deformed during the Silurian (Hepburn and others, 1995).

Detailed geologic mapping, investigations of shear zones, and monazite dating of high grade fault-rocks was conducted in an area spanning across the entire Nashoba terrane with the aim of placing the terrane into the larger tectonic framework of the Acadian orogeny.

Brittle fractures were measured as part of a regional study aimed at a better understanding of the bedrock aquifers in the greater Boston area. Bedrock-aquifer well-water has become increasingly important in the I-495 corridor as rapid development and “suburbanization” place pressure on existing resources. Because this study is mostly unrelated to the Paleozoic accretionary history of the Nashoba terrane, it is discussed separately in PART TWO.

REGIONAL GEOLOGY

Introduction

Eastern Massachusetts is home to three distinct lithotectonic zones, referred to herein as “terranes”. Following the definition of Williams and Hatcher (1983), a terrane is an internally homogenous geologic province that contrasts sharply with surrounding areas. Usually terranes are separated by major faults. The terranes of eastern Massachusetts – Merrimack, Nashoba, and Avalon (Figure 1.2) – experienced different depositional, plutonic, and metamorphic histories prior to late Paleozoic time.
Figure 1.2. Generalized geologic map of the Nashoba terrane (after Zen and others, 1983). Basemap modified from Hepburn and others (1995).
Merrimack Terrane

The Merrimack terrane makes up the eastern portion of the Central Maine Belt (Figure 1.1) and is herein defined as the region west of the Ball Hill fault (Figure 1.2). It is comprised of largely Ordovician to Silurian metasedimentary rocks intruded by middle to late Paleozoic granites, diorites, and tonalities (Robinson and Goldsmith, 1991; Wones and Goldsmith, 1991; Bothner and others, 1993; Wintsch and others, 2007). Although the grade of metamorphism ranges to the upper amphibolite facies in central Massachusetts, it is lower greenschist facies in the areas that lie adjacent to the Nashoba terrane between the Wekepeke Fault and the Clinton-Newbury fault system. Formations of the Merrimack terrane in the study area include the Tower Hill and Vaughn Hills quartzites, the Worcester Phyllite, the Oakdale Formation, and the distinctively sulfidic and rusty-weathering Tadmuck Brook Schist.

Nashoba Terrane

The Nashoba terrane is defined as the region lying between the Ball Hill fault and the Bloody Bluff fault (Figure 1.3). It is comprised of Cambrian to Ordovician arc-related rocks that were metamorphosed to upper amphibolite facies conditions during the Silurian (Hepburn and others, 1995). It is divided into two main formations: the primarily metavolcanic Marlboro Formation in the east and the metasedimentary rocks of the Nashoba Formation in the west. Two other formations, the Shawsheen and Fish Brook gneisses, lie between the Nashoba and Marlboro formations but are cut out by faults northeast of the study area. The terrane is intruded by latest Ordovician to
Figure 1.3. Major structural features and terranes in the Shrewsbury area.

LEGEND
- Fault
- Fault, obscured
- Fault, adapted from other work or inferred.
early Devonian peraluminous granites and pegmatites (Zartman and Naylor, 1984; Hill and others, 1984; Wones and Goldsmith, 1991; Hepburn and others, 1995) as well as similarly aged calc-alkaline diorites (Zartman and Naylor, 1984; Hon and others, 1986; Hon and others, 1993; Hepburn and others, 1995; Acaster and Bickford, 1999). A Carboniferous I-type granite, the Indian Head Hill Granite, also intrudes the Nashoba terrane (Hepburn and others, 1995; Acaster and Bickford, 1999).

*Composite Avalon Terrane of Southeast New England*

The composite Avalon terrane of southeast New England, hereafter referred to as the Avalon terrane, is defined as the area southeast of the Bloody Bluff fault, including parts of southeastern Massachusetts, Rhode Island, and eastern Connecticut. The basement rock is comprised of metasedimentary and metavolcanic units that are intruded by late Proterozoic largely arc-related plutons of both mafic and felsic compositions. Cover sediments range in age from the early Paleozoic to the middle Mesozoic. The metamorphic grade of the terrane is predominantly greenschist facies or below although a few areas in southern New England reach the lower amphibolite facies (Goldsmith, 1991b). Avalon rocks exposed in and around the study area include the Westboro Formation and a foliated granite that may be correlative with either the Hope Valley Alaskite or Milford Granite of Zen and others (1983).
Rocky Pond Slice

The area in the northwest portion of the Shrewsbury quadrangle bounded by the Clinton fault and the Rattlesnake Hill fault (Figure 1.3) was referred to by Munn (1987) as the Western Nashoba Slice because the area was metamorphosed to the upper amphibolite facies, typical of rocks in the Nashoba terrane. Accordingly, Goldsmith (1991b) interpreted the area to be an upthrust block of the Nashoba Formation caught in the fault zone; however, stratigraphic correlations across the faults are tenuous, at best. To avoid the implications for its terrane affinity, the area will be referred to herein as the Rocky Pond slice.

PREVIOUS WORK – NASHOBA TERRANE

Regional

Emerson (1917) conducted some of the earliest work on the Nashoba terrane, mapping the metavolcanic Marlboro Formation. Hansen (1956) named the Nashoba Formation while mapping in Hudson and Maynard, Massachusetts. Skehan (1968), Skehan and Abu-Moustafa (1976), and Abu-Moustafa and Skehan (1976) reported on the structure and stratigraphy of the terrane while taking advantage of continuous exposure in the 12,000+ meters long Wachusett-Marlborough Tunnel between the towns of Clinton and Marlborough. Bell and Alvord (1976) divided the terrane into five formations and fifteen members based on surface mapping in the northeast portion of the terrane (in Middlesex County, Massachusetts). Zartman and Naylor (1984) dated many of the plutons in eastern Massachusetts, laying the groundwork for age estimates of deposition,
metamorphism, and deformation in the Nashoba terrane. Hill and others (1984) determined that many of the intermediate plutons are compositionally calc-alkaline, suggesting a continental arc environment for their origin. Munn (1987) and Bober, (1990) described the various metamorphic assemblages in the terrane and estimated the peak conditions for two separate metamorphic events. Hepburn and others (1995) and Acaster and Bickford (1999) dated igneous rocks using newer, more precise geochronological techniques. Zen and others (1983) produced the most recent statewide geologic map of Massachusetts and Goldsmith (1991a; 1991b) synthesized available data on the Nashoba terrane to summarize its stratigraphy as well as its structural and metamorphic history. Wones and Goldsmith (1991) summarized existing information on the igneous rocks of eastern Massachusetts and Zartman and Marvin (1991) summarized existing geochronologic data for the state. Goldstein (1989) conducted a structural study of the extensive Bloody Bluff fault system, determining its motion direction and shear-sense. Goldstein (1994) also studied portions of the western boundary of the Nashoba terrane while investigating the effects of possibly Alleghanian deformation in the rocks immediately west of the Nashoba terrane.

Shrewsbury Quadrangle

Abu-moustafa (1969) studied the geochemistry and metamorphism of the Nashoba Formation from exposures in the Wachusett-Marlborough Tunnel. Barosh (1978a) and Hepburn (1978) conducted reconnaissance geologic mapping in the quadrangle in preparation for the statewide geologic map of Massachusetts compiled by Zen and others.
(1983). Reconnaissance maps of the neighboring Clinton (to the north) and Marlborough (to the east) quadrangles have also been published as Open-File Reports (Peck, 1975; Hepburn and DiNitto, 1978; Barosh, 1978b). Grew (1970) mapped portions of the Clinton, Worcester North, Worcester South, and Shrewsbury quadrangles. Munn (1987) mapped the geology of the northern part of the Shrewsbury Quadrangle along with part of the Clinton Quadrangle at a scale of 1:24,000 for her study of the metamorphism along the western edge of the Nashoba Terrane. As part of the State Geologist's mapping initiative, the Marlborough Quadrangle was recently remapped at the quadrangle scale (Kopera and others, 2005) and mapping of the Grafton Quadrangle (to the south) is nearly complete (Walsh, personal communication, 2005). Bober (1990) conducted a more regional study of Nashoba terrane metamorphism but used some samples from the northern part of the Shrewsbury Quadrangle for his analyses. Jerden (1997) studied regionally the structural and metamorphic history of the Tadmuck Brook Schist.

DESCRIPTION OF STUDY AREA

All locations referred to in the text are in Massachusetts unless otherwise noted. All references to the study area refer to the Shrewsbury quadrangle unless otherwise qualified. The Shrewsbury quadrangle is 30-40 miles west of Boston (Fig. 1.2). The area includes parts of the towns of Shrewsbury, Northborough, Westborough, Berlin, and Boylston. The western quadrangle boundary nearly coincides with Lake Quinsigamond, which follows the trace of a fault (the Pine Hill Fault of Goldsmith, 1991b).
Wachusett Reservoir makes up a portion of the northern quadrangle boundary. Not far to the east and to the south of the quadrangle lie interstates I-495 and I-90 respectively.

Development in the area is divided between rural and suburban communities. Although much of the area is wooded or farmed, there is a significant amount of suburban development, particularly in the Shrewsbury area and along Route 9 in the southern portions of the quadrangle.

The terrain is characterized by gentle hills with a maximum relief in the study area of about 485 feet. The highest point is Mount Pisgah (715 ft) in Northborough with views of downtown Boston on a clear day. Several lakes and reservoirs and numerous small ponds dot the study area. Small creeks and streams are common and swampy wetlands are ubiquitous and extensive.

Surficially the study area is dominated by glacial features with drumlins and thick mantles of till deposits being much more common than bedrock. Glacial erratic boulders are not uncommon, some reaching the size of small homes. Areas of “float” are very common: “float” is characterized by numerous small erratic boulders, typically of the same lithology, that don’t appear to be too far out of place. Outcropping bedrock is not common in the study area. It is rare south of Route 9 and mostly absent in the central part of the study area between I-290 and Route 9. When bedrock is found exposed, it typically is present in small discontinuous outcrops. The regional grain of the rock is dominated by a pervasive northeast-striking, northwest-dipping metamorphic foliation and the most common rock types are gneiss and schist. In the northeast portion of the study area, topographic lineaments coincide with the regional grain of the rock.
METHODS OF INVESTIGATION

This investigation involved three main parts: (1) mapping the geology, structure, and general grade of metamorphism of the 7.5' quadrangle at a scale of 1:24,000. The area transects the entire Nashoba terrane and portions of its margins; (2) determining the motion direction and shear-sense of ductile faults and shear zones from mesoscopic and microscopic shape fabrics; and, (3) dating metamorphic and deformational events using electron probe microanalysis (EPMA). In support of this work a number of thin sections were examined petrographically to estimate the mineralogical composition of different rock units, to establish their typical metamorphic assemblages, and to determine the shear-sense of fault rocks. Brittle fractures and joints were also measured to help characterize bedrock aquifers for domestic water use. They are discussed in PART TWO.
Chapter 2. STRATIGRAPHY

The spatial extent and abbreviated descriptions of the following units mapped in the Shrewsbury quadrangle can be found on PLATE I. Modes for thin sections from stratified rocks can be found in Tables 2.1, 2.2, and 2.3. Many of the stratified rocks in the study area have been previously studied by other workers (Grew, 1970; Peck 1975; Skehan and Abu-Moustafa, 1976; Barosh, 1978a,b; Hepburn, 1978; Munn, 1987; Bober, 1990; Jerden, 1997) and their descriptions are presented where appropriate.

MERRIMACK TERRANE

Introduction

The Merrimack terrane is comprised predominantly of Silurian variably calcareous metasediments and turbidites (Bothner and others, 1993; Lyons and others, 1997). They experienced regional metamorphism and were subjected to several episodes of folding and faulting during the Devonian Acadian orogeny (Robinson and Goldsmith, 1991). The regional deformation was followed by post-metamorphic normal faulting along the Wekepeke Fault (Figs. 1.3) and other minor faults associated with it. These normal faults juxtapose greenschist-grade rocks of the eastern flank of the Merrimack terrane (between the Wekepeke and Clinton-Newbury faults) with amphibolite-grade rocks of the central and western Merrimack terrane (Robinson and Goldsmith, 1991). Accordingly, the rocks of the eastern Merrimack terrane exposed in the study area are generally phyllites and quartzites.
Worcester Formation – DSw

The Worcester Formation was originally mapped as the Worcester Phyllite by Emerson (1917) for exposures of a medium- to dark-gray phyllite in the Worcester area. The Worcester Formation also includes ~1 meter thick interbeds of meta-graywacke, marble, calc-silicate granofels, and quartzite as reported by Peck (1975), Hepburn (1978), and Robinson and Goldsmith (1991).

The Worcester formation was not observed in this study, but Hepburn (1978) mapped two small fingers of it in the northwest part of the study area. He observed the gray phyllite interbedded with 1m thick beds of calc-silicate granofels, quartz granofels, quartzite, and impure marble. The presence of garnet in the pelitic units was also observed.

Peck (1975) considered the Worcester Formation to lie conformably above the Oakdale Formation. Zen and others (1983) show the Wekepeke Fault truncating the Worcester Formation to the west.

Oakdale Formation – So

The Oakdale Formation was first mapped by Emerson (1917) near Oakdale in southern Massachusetts. In the study area, the best exposures are found on the southeast shores of the Wachusett Reservoir, particularly in the Andrews Harbor area in Boylston.

The Oakdale Formation weathers a dull brown, rusty color and is a well-foliated phyllite in the study area. Fresh, it exhibits a light- to medium-gray phyllitic sheen. Bed thickness is typically less than a few centimeters but may range up to a meter. Just north
of the study area along Route 70 are outcrops of medium- to dark-brown calcareous meta-siltstone more typical of the Oakdale Formation as described by Peck (1975) and Robinson and Goldsmith (1991). These rocks bear ankerite and actinolite and have internally-laminated beds that are typically 20-30 cm thick but range from only a few centimeters up to a meter or more.

The lower contact of the Oakdale Formation was not observed in the study area, but it has been reported to be conformable and gradational with the underlying Tower Hill Quartzite in the Clinton area (Peck, 1975). The upper contact with the Worcester Formation is not observed in the study area but is also reported to be conformable (Peck, 1975).

_Tower Hill Quartzite – St_

The Tower Hill Quartzite was originally mapped by Grew (1970) and named for quartzite exposures around Boylston forming ridges at the tops of Green Hill, Diamond Hill, and Tower Hill.

The Tower Hill Quartzite weathers buff to gray with beds typically tens of centimeters to several meters thick. The quartz grains are well-recrystallized giving this unit a massive texture. The color of a fresh exposure varies from a vitreous white to a very dark-gray color. The quartzite commonly contains thin millimeter- to centimeter-thick interbeds of medium- to dark-gray phyllite similar in appearance to the phyllite of the Oakdale Formation. Hepburn (1978) and later Zen and others (1983) also mapped a separate phyllite member where the amount of phyllite exceeds quartzite. This phyllite,
commonly rusty-weathering, had been mapped as part of the Boylston Formation previously (Grew, 1970).

The lower contact of the Tower Hill Quartzite with the Boylston Schist is the Clinton Fault. The upper contact is conformable and gradational with the overlying Oakdale Formation.

Vaughn Hills Quartzite – Svh

The Vaughn Hills Quartzite was first described by Hansen (1956) who reported that the Tadmuck Brook Schist (his mica-schist member of his Worcester Formation) graded into a quartzite in the Vaughn Hills near Bolton.

The Vaughn Hills Quartzite weathers light-tan to light-gray and has beds that range from about 5 centimeters to nearly 2 meters thick. The Vaughn Hills in many places has the appearance of sandstone-siltstone interbeds with fine millimeter- to centimeter-scale laminations caused by slight compositional variations and changes in grain size; in other places these compositional layers are thicker (1-3 centimeters) and slightly higher grade reflected by layers of phyllite and chlorite-biotite schist interbedded with quartzitic layers. Some samples also contained small flakes of muscovite. Thin beds of calcareous meta-siltstone were also observed that are texturally similar to the quartzite-phyllite interbeds but also bear an epidote mineral. Munn (1987) called these rocks the calcareous meta-siltstone member of the Vaughn Hills Quartzite and observed the presence of actinolite in addition to epidote. Where it is intruded by the Rocky Pond
Granite, Munn (1987) reported contact aureoles in the Vaughn Hills Quartzite reaching the sillimanite zone of metamorphism.

No thin sections were collected from the Vaughn Hills Quartzite for this study but Munn (1987) reported the following modes: for the phyllite and schist, 30-50% sericite or muscovite, 20-40% quartz, and 15-20% chlorite or biotite; for the quartzite she reported 46-57% quartz, 0-22% plagioclase, 0-20% muscovite or sericite, and 10-30% biotite or chlorite; for the calcareous meta-siltstone she observed 40-50% quartz, ~5% plagioclase, 25-30% chlorite or biotite, 0-11% actinolite, 10-20% of an epidote mineral, and 2-5% sericite.

In the northern part of the quadrangle, the upper contact of the Vaughn Hills with the Rocky Pond Granite is mapped as the Rattlesnake Hill Fault of Skehan (1968) and Castle and others (1976). Although not observed directly, the contact follows a very straight topographic depression and the Rocky Pond Granite near its trace is uncharacteristically foliated. In the central part of the quadrangle, just south of Rocky Pond near I-290 (PLATE I), the contact with the Rocky Pond Granite is no longer truncated by the fault and is irregular with the granite intruding the Vaughn Hills Quartzite in outcrops along the north side of I-290. 100 meters west (perpendicular to strike) of the southernmost exposures of Vaughn Hills on the south side of I-290, the metamorphic grade increases from the lower greenschist facies to the upper amphibolite facies of the Sewall Hill Formation. This suggests that the contact is once again faulted by the Rattlesnake Hill Fault. No exposures of Vaughn Hills Quartzite were observed along strike southwest of I-290. Exposures of the Tadmuck Brook Schist and the Sewall
Hill Formation observed in close proximity to each other southwest of I-290 near Route 9 (PLATE 1) suggest that the Vaughn Hills Quartzite is cut out by this fault somewhere between I-290 and Route 9. The eastern contact of the Vaughn Hills Quartzite with the Tadmuck Brook Schist was never directly observed but previous workers believed it could be conformable (Hansen, 1956; Peck, 1975; Bell and Alvord, 1976), although Munn (1987) considered the contact to be faulted. No evidence in the Shrewsbury quadrangle was observed that suggested the presence of a faulted contact. Thus, it is mapped as conformable.

_Tadmuck Brook Schist – Stmb_

The Tadmuck Brook Schist was named by Bell and Alvord (1976) for exposures along the Tadmuck Brook in Westford. It had previously been mapped as part of the Brimfield Schist of Emerson (1917) and part of Hansen’s (1956) Worcester Formation. In the study area, it is exposed along I-290, in outcrops on the flanks of Barnes Hill in Northborough, and near Route 9 southwest of Shrewsbury.

The Tadmuck Brook Schist is rusty-weathering and commonly exhibits conspicuous greenish-yellow streaks due to the weathering of fine-grained sulfides like pyrite and pyrrhotite. The unit changes metamorphic grade rapidly from the chlorite and biotite zones in the west to the sillimanite zone in the east. Accordingly its texture varies from phyllite to schist. Throughout the formation it is common to find large (~2-3 cm) porphyroblasts of biotite, andalusite, staurolite, garnet, or sillimanite, depending on metamorphic grade. Thinly-bedded (generally thinner than 10 cm) quartzites are found
throughout the formation but can be 2 or more meters thick toward the southeast. Lenticular bodies of medium-grained hornblende-plagioclase amphibolite are commonly found in the southeastern portion of the formation; they are typically lineated giving them a white-streaked appearance.

A representative sample of the Tadmuck Brook Schist (sample 2, Table 2.1) contained 37.3% sillimanite, 22% quartz, and 17.5% muscovite with the balance made up of mostly opaque minerals, biotite, chlorite, and minor amounts of plagioclase (An unknown). Another sample from the southwest portion of the study area was texturally similar but nearly all of the sillimanite and biotite had altered to muscovite and sericite. A sample from one of the amphibolites of the Tadmuck Brook Schist (sample 1, Table 2.1) contained 56% hornblende and 36% plagioclase with An₅₇. The balance of the sample was comprised of minor amounts of quartz, chlorite, and opaque minerals. Jerden (1997) conducted an in depth study of the Tadmuck Brook Schist in which he presented the modes for a number of thin sections from the area.

The western contact of the Tadmuck Brook Schist was not observed but appears to be conformable with the Vaughn Hills Quartzite in the study area. South of I-290 it is probable that the Vaughn Hills Quartzite is faulted out and that the Tadmuck Brook Schist is in fault contact there with the Sewall Hill Formation. The eastern contact with the Nashoba Formation has been called both a fault (Castle and others, 1976) and an unconformity (Bell and Alvord, 1976). In the study area, the Ball Hill fault forms the contact. Evidence of this fault contact is found throughout the study area.
Table 2.1. Modes of Merrimack terrane stratified rocks in the Shrewsbury quadrangle. Sample locations given in APPENDIX I.

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**Sample Description**

1 SUB Tadmock Brook Schist, hornblende-plagioclase amphibolite
2 TSC Tadmock Brook Schist, muscovite-quartz-sillimanite schist

**Discussion and Summary**

The sequence Tower Hill Quartzite-Oakdale Formation-Worcester Formation has been interpreted as a conformable, upward-younging sequence (Peck, 1975; Robinson and Goldsmith, 1991) that represents the base of Silurian and Devonian turbidite and fan deposits (Osberg, 1989; Robinson and Goldsmith, 1991). The relationship these rocks have with the Vaughn Hills Quartzite and Tadmock Brook Schist is unclear since they are
separated from them by faults and bodies of the Ayer Granite (Robinson and Goldsmith, 1991).

Additionally, although the Vaughn Hills Quartzite appears to be conformable with the Tadmuck Brook Schist in the study area, northeast of the study area the Vaughn Hills Quartzite is almost everywhere in fault contact with the Tadmuck Brook Schist. Zen and others (1983) included the Tadmuck Brook Schist with the Nashoba terrane, although Goldsmith (1991b) conceded that it might be easily assigned to the Merrimack terrane as done by Skehan and Abu-moustafa (1976). Because of its apparently conformable relationship with the Vaughn Hills Quartzite in the Shrewsbury quadrangle, the Tadmuck Brook Schist has been mapped herein as a part of the Merrimack terrane.

ROCKY POND SLICE

Introduction

Between Clinton and Worcester, the Clinton and Rattlesnake Hill faults bound a tectonic slice of rocks informally referred to herein as the Rocky Pond slice (Figure 1.3). The Rocky Pond slice contains rocks that could be correlative with either the Nashoba or Merrimack terranes and includes the Boylston Schist, the Sewall Hill Formation, the Rocky Pond Granite, and a few other minor intrusive rocks. The stratified rocks have been metamorphosed to the upper amphibolite facies and the slice is cut by numerous minor ductile shear zones and brittle faults.
Boylston Schist – Sho

The Boylston Schist was first mapped by Emerson (1917) and named for the weakly foliated rusty schist in and around Boylston. The best exposures in the study area are along Central Street just east of Boylston Center.

The Boylston Schist weathers a medium-brown that locally may also be rusty, purplish-gray, or yellowish-green. The rock lacks a strong foliation and is typically massive. Although named for its mica-rich parts, the Boylston Schist also contains massive quartzite and powdery, sulfide-rich calcareous layers. In the mica-rich layers, sillimanite is common and exhibits two generations of growth recognizable in hand sample. One generation consists of porphyroblasts up to several centimeters long and groundmass-sized euhedral crystals growing with the foliation. The second generation is comprised of fine fibrolite mats that grow across the foliation and earlier sillimanite.

Thin sections were not collected for this study, but for one sample of the “schist” lithology, Munn (1987) reported modes of 24% porphyroblasts (garnet, sillimanite, and biotite), 24% quartz, 25% muscovite, 11% biotite, and lesser amounts of plagioclase, fibrolite, groundmass sillimanite, sericite, and opaques.

Munn (1987) reported the eastern contact with the main body of the Rocky Pond Granite to be faulted; however, the Boylston Schist is intruded by smaller bodies of the same granite. The western contact with the Tower Hill Quartzite is the Clinton Fault. Munn (1987) observed sheared rocks near its trace.
Sewall Hill Formation – Ssh

The Sewall Hill Formation is named here for the thickly-banded biotite gneisses exposed at the top of Sewall Hill and along the road-cut on the access road leading up the hill to the back entrance of Shrewsbury High School. This rock has been referred to as the Science Park unit by Hepburn (1976) and later Goldsmith (1991b). It was mapped as part of the Nashoba Formation by Zen and others (1983) and later mapped separately as the Western Nashoba Formation by Munn (1987). It is renamed here to avoid the implications as to its terrane affinity.

This unit weathers medium- to dark-gray. It is a very thickly-banded gneiss with continuous alternating bands of quartzo-feldspathic and biotitic materials typically several centimeters thick. Along the road-cut leading to Shrewsbury High School these bands are commonly a meter thick or more. Munn (1987) called the gneisses with these thick alternating layers “ribbon rock”. Mylonite zones subparallel to the gneissic banding are common and range from several centimeters to several meters thick.

Munn (1987) reported modes for the gneiss as 45% quartz, 17% biotite, 14% plagioclase (An29), and 10% sericite, with lesser amounts of muscovite and chlorite comprising the rest of the rock. She also reported trace amounts of fibrolite.

The eastern contact with the Vaughn Hills Quartzite is covered, but inferred to be the Rattlesnake Hill Fault because of the rapid change in metamorphic grade. In the southwest portion of the study area, the Vaughn Hills Quartzite is probably faulted out putting the Sewall Hill Formation in fault contact with the Tadmuck Brook Schist. The
western contact with the Rocky Pond Granite seems to be an intrusive one, although it was not directly observed.

Discussion and Summary

Robinson and Goldsmith (1991) considered the Boylston Schist to be part of the base of the eastern Merrimack turbidite sequence and Goldsmith (1991b) interpreted the Science Park unit of Hepburn (1976) (the Sewall Hill Formation of this study) to be an upthrust block of the Nashoba Formation.

NASHOBA TERRANE

Introduction

The stratified rocks of the Nashoba terrane are predominantly gneisses, schists and amphibolites with subordinate granofels and calc-silicate rocks. These rocks are latest Cambrian to Ordovician in age and were metamorphosed under amphibolite-facies conditions during the Silurian and Devonian (Hepburn and others, 1995).

Nashoba Formation

The Nashoba Formation was named by Hansen (1956) for gneiss and schist exposed in the Nashoba Brook Valley of Maynard and Westford. Bell and Alvord (1976) divided the formation into ten members based on regional mapping in Middlesex County and Skehan and Abu-Moustafa (1976) mapped thirty members from continuous exposure in the Wachusett-Marlborough tunnel section. In the study area, the best exposures of the
Nashoba Formation are road-cuts along I-290 and ridge-top exposures between Mount Pisgah and Sulfur Hill in Northborough.

The Nashoba Formation in this area is mostly comprised of various feldspar-biotite-quartz gneisses with subordinate pelitic schist and amphibolite, and minor calc-silicate granofels. In the Shrewsbury quadrangle it has been further subdivided into six informal members based on lithology. The more numerous subdivisions of Bell and Alvord (1976) and Skehan and Abu-Moustafa (1976) could not be mapped in the Shrewsbury quadrangle. Areas mapped as undifferentiated Nashoba Formation either contained too few exposures or were lithologically too heterogeneous to fall within the definition of a given member.

**Nashoba Formation, undifferentiated – Snu.** This member contains the same lithologies as all the following members in varying amounts. These are quartzo-feldspathic gneiss, biotite gneiss, amphibolite, hornblende gneiss, calc-silicate granofels, migmatite, and sillimanitic or garnetiferous schist and gneiss. Generally areas mapped as Snu contain mostly quartzo-feldspathic gneiss and biotite gneiss interstratified with lesser amounts of the other lithologies, with migmatite, amphibolite, and sillimanitic schist or gneiss being more common than hornblende gneiss and calc-silicate granofels.

**Biotite gneiss and amphibolite – Snbga.** This member weathers medium-gray to black. It is a plagioclase-biotite-quartz gneiss that contains more biotite than typical Nashoba gneisses and grades into layers of massive fine- to medium-grained amphibolite gneiss.
that range from about a meter to ~50 meters thick. Sillimanite, garnet, and epidote are accessory minerals in the biotite gneiss. Garnet and epidote are accessory minerals in the amphibolite gneiss.

Two samples were taken of the biotite gneiss and amphibolite member – both were of the gneiss lithology, which makes up roughly 55-60% of the outcrop. Quartz content ranged from 29-40.6%, biotite from 3.5-24.8%, secondary muscovite from 0-35%, sillimanite from 1.5-16.8%, plagioclase of An$_{25-30}$ from 13-16.4%, and secondary chlorite from 0-11% (samples 3 and 4, Table 2.2). Both samples had minor amounts of garnet and opaques. The handsamples of the amphibolite lithology show that it is finer-grained and darker than the amphibolite of the Tadmuck Brook Schist. The amphibolite comprises approximately 35-40% of the outcrop of this member. Lesser amounts of sillimanitic schist and gneiss make up the rest of the outcrop. Migmatite occurs as lenses or pods in all lithologies of this member.

The western contact of the biotite gneiss and amphibolite member with the Tadmuck Brook Schist is the Ball Hill fault. The eastern contact with the sillimanite-biotite gneiss member appears to be gradational and conformable. The biotite gneiss and amphibolite member may be in part correlative with the Beaver Brook Member of Bell and Alvord (1976).

**Sillimanite-biotite gneiss – Sns-g.** This member weathers from medium-gray to black and is very similar to the biotite gneiss of the biotite gneiss and amphibolite member. What differentiates it is its relative abundance of both sillimanite and garnet together, each
Table 2.2. Modes of Nashoba terrane stratified rocks from the Shrewsbury quadrangle. Sample locations given in APPENDIX I.

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<th>Sillimanite</th>
<th>Garnet</th>
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Sample Description

3 305 Nashoba Formation, biotite gneiss and amphibolite member, plagioclase-sillimanite-biotite-quartz gneiss
4 303 Nashoba Formation, biotite gneiss and amphibolite member, plagioclase-quartz-muscovite gneiss
5 NSG Nashoba Formation, sillimanite gneiss member, garnet-plagioclase-quartz-biotite gneiss
6 806 Nashoba Formation, rusty schist member, microcline-plagioclase-quartz-sillimanite-biotite schist
7 907 Marlboro Formation, undifferentiated, biotite-hornblende-plagioclase gneiss
8 608 Marlboro Formation, undifferentiated, epidote-hornblende-quartz-plagioclase gneiss
9 911 Marlboro Formation, undifferentiated, epidote-quartz-biotite-plagioclase gneiss

commonly occurring with abundances greater than 10% of the mode. The sillimanite is commonly lineation-forming and the crystals may range from several millimeters to several centimeters long (Figure 2.1C). Garnet is abundant as porphyroblasts ranging
Figure 2.1. Nashoba Formation field images. (A) baseball-sized garnet porphyroblast in the rusty schist member; sample location for RVV-007. (B) migmatic sillimanite-biotite gneiss member of the Nashoba Formation; sample location for RVV-011. (C) long prismatic sillimanite crystals typical in Nashoba gneisses; chisel head for scale. (D) amphibolite dike with garnet coticule between sillimanitic quartz-feldspathic layers in the sillimanite-biotite gneiss member of the Nashoba Formation near the Sulfur Hill Shear Zone; boot toe for scale.

from 0.5-1.5 centimeters in diameter. Approximately 10-20% of the sillimanite-biotite gneiss member is comprised of zones of migmatite (Figure 2.1B), 0.2-1 meter thick lenses of fine- to medium-grained amphibolite, and/or 1-2 cm thick layers of garnet coticule (Figure 2.1D).

One representative thin section of the sillimanite-biotite gneiss (sample 5, Table 2.2) contained 33% biotite, 19.5% quartz, 15% sillimanite, 14% plagioclase (An$_{24}$), 12.5% garnet, 5% microcline, and 1% opaque minerals.
Two bodies of this member were mapped. The body to the northwest has a
gradational contact with the biotite gneiss and amphibolite member on both sides. The
southeastern body has a western contact that is gradational with the biotite gneiss and
amphibolite member, but the Sulfur Hill shear zone forms the eastern contact with the
quartzofeldspathic gneiss member. The southeastern body of the sillimanite-biotite
gneiss member may be correlative with the lower portion of the Long Pond Gneiss
Member of Bell and Alvord (1976).

Calc-silicate-bearing granofels – Sncs. This member weathers light- to medium-gray. It
is predominantly typical Nashoba biotite gneiss or quartzofeldspathic gneiss but also
contains lenses of massive granofels up to several meters thick. The granofels has a
sugary texture when fresh and contains minor calcite and diopside. Hepburn (1978) and
Barosh (1978a) also reported the presence of thin discontinuous marble beds.

In hand sample this rock resembles the sugary-textured biotite-quartz-feldspar
granofels of the Nashoba Formation, but also contains diopside and fine-grained calcite.
Munn reported finding calc-silicate gneiss along strike with this unit in Berlin, just north
of the study area. Her sample, dominated by calc-silicate minerals, had a mode of 31%
calcite, 23% diopside, 19% scapolite, 13% plagioclase, 8% biotite, and 3% quartz.

Both the upper and lower contacts of the calc-silicate-bearing granofels member
are probably conformable with the biotite gneiss and amphibolite member but are not
observed in the study area. The calc-silicate-bearing granofels member may correlate
with part of Bell and Alvord's (1976) Beaver Brook Member.
Quartzo-feldspathic gneiss and granofels – Snfg. This member forms ridges on the hills immediately east of Sulfur Hill and west of Cooledge Brook in Northborough. The rock weathers light- to medium-gray and is dominantly quartzo-feldspathic. Fresh surfaces vary with texture and composition along strike.

Just north of Maynard Street in Northborough, near a waterfall along Cooledge Brook the rock is a greenish to medium-gray, medium- to coarse-grained hornblende-bearing quartz-biotite-feldspar gneiss. Beds are several to ten centimeters thick. Along strike to the northeast, the rock becomes more thinly bedded (0.25-1 cm thick) and hornblende is no longer present 500 meters or farther north of Maynard Street. Texturally the rock grades to schist with slight increases in biotite, and just south of the Northborough-Berlin town line it is primarily quartz-feldspar granofels with minor biotite. The color of the rock becomes lighter gray or tan to the northeast.

Munn (1987) collected two samples from this member intermediate between the two extremes. She gives modes of 36-53% plagioclase (An$_{40}$), 12-20% quartz, 14-33% biotite, and 5-6% hornblende. Munn (1987) also reported plagioclase-hornblende amphibolites along strike of this member south of Maynard Street and north of I-290 in Northborough, indicating that this member’s gradational changes along strike continue a short distance to the southwest.

The western contact with the sillimanite-biotite gneiss member is the Sulfur Hill shear zone. The eastern contact with what was mapped as undifferentiated Nashoba was obscured. The unit itself may extend farther to the southeast, but there was no outcrop control to warrant mapping it as such. This member is rather extensively intruded by
small- to medium-sized bodies of medium- to coarse-grained two-mica, two-feldspar Andover Granite. These granite bodies are too small to map at 1:24,000 scale but together may cover as much as 30-40% of the area mapped as the quartzo-feldspathic member.

**Rusty schist – Snrs.** The rusty schist member was previously mapped by Hepburn (1978) for exposures of rusty-weathering schist along Route 20 south of Route 9 in Shrewsbury. These are the best exposures of the rusty schist member.

The rusty schist member weathers a conspicuous rusty reddish-brown to greenish-yellow color due to the presence of fine-grained sulfide minerals. Sillimanite porphyroblasts can be up to 2 centimeters long and garnet porphyroblasts can be 5 centimeters across (Figure 2.1A). This member also contains massive dark-gray quartzite beds with thicknesses ranging from 1-5 meters. Tabular bodies of pegmatite, fine- to medium-grained aplite, and medium-grained diorite intrude subparallel to the metamorphic foliation with typical thicknesses of 1-3 meters. The diorites are typically unfoliated or only weakly foliated, but some of the pegmatite exhibits a well-developed foliation. Additionally, this unit is extensively cut by minor shear zones and is in many places mylonitized, presumably related to deformation along the adjacent Assabet River Fault.

A representative sample (sample 6, Table 2.2) contained 22% biotite, 24% sillimanite, 11.5% quartz, 9% plagioclase of An28, 27% microcline, and 6.5% opaque minerals. Porphyroblasts of 0.5-1.5cm make up 30% of this sample and were one third
sillimanite and two thirds microcline. In outcrops and in hand samples, however, garnets (some reaching the size of baseballs, Figure 2.1A) are the most common porphyroblast in the rusty schist member.

The eastern contact with the Marlboro Formation is mapped as the Assabet River Fault. The associated granites and diorites are not found beyond the western contact with the undifferentiated Nashoba Formation suggesting that this contact is also a fault.

*Marlboro Formation – Omu*

The Marlboro Formation was named by Emerson (1917) for exposures of hornblende gneiss, biotite schist, and amphibolite in the vicinity of Marlborough. Although commonly described as consisting of massive amphibolites and hornblende gneisses (Bell and Alvord, 1976), where it is exposed in the Shrewsbury quadrangle the Marlboro Formation is typically biotite and hornblende-biotite schist with subordinate feldspathic gneiss and minor lenses of marble and diopside-calcite granofels. Exposures are rare and where found they generally weather medium-gray to black.

Several thin sections of different Marlboro gneisses were analyzed (samples 7, 8, and 9, Table 2.2). Their modes ranged from 6.3-18.3% quartz, 34-56% plagioclase (An_{26-33}), 0-31.3% biotite, 0-19.3% hornblende, 0-2.7% microcline, 4.3-13.7% epidote, and commonly contained accessory titanite and opaque minerals in amounts of 1-2%.

The undifferentiated Marlboro Formation is faulted on both sides in this area. It is truncated by the Assabet River fault to the northwest and by the Bloody Bluff fault system to the southeast.
Discussion and Summary

The Marlboro Formation and Nashoba Formation were interpreted to be a homoclinal sequence topping to the west by Bell and Alvord (1976) on the basis of relict sedimentary structures. These structures have not been observed by other workers. Goldsmith (1991a) proposed several correlation schemes in which parts of the Nashoba and Marlboro formations correlate with each other and with parts of the Fish Brook and Shawsheen gneisses (faulted out northeast of the study area, Figure 1.2) due to either imbricated strike-slip faulting along the Assabet River Fault or to large-wavelength folding. Castle (1964) interpreted the Fish Brook Gneiss as a core gneiss and possible basement to the terrane. Clearly our current understanding of the stratigraphy is hampered by the complex structure and high grade of metamorphism.

Protoliths. Abu-Moustafa and Skehan (1976) discerned two distinct sources of sediments – a deeply weathered terrane and fresh volcanic, plutonic, and volcanioclastic rocks, the average chemical composition of which is dacite. In general the Nashoba Formation is primarily metasedimentary and more aluminous than the primarily metavolcanic Marlboro Formation. Abu-Moustafà and Skehan (1976) showed that amphibolites typical of the Nashoba terrane have average compositions of basalt. Chemical analyses of the Marlboro Formation amphibolites have shown that they are mildly alkaline, high-alumina basalts, and have LREE patterns indicative of a subduction-related origin (DiNitto and others, 1984; Acaster and Bickford, 1999). The environment of deposition
of the sediments was interpreted to be a relatively shallow marine basin on the flank of a continental arc (Skehan and Abu-Moustafa, 1976; Goldsmith 1991a).

Age. If the Fish Brook Gneiss is basement to the terrane as Castle (1964) suggested, then its age of 499 Ma (Hepburn and others, 1995) limits the age of the presumably overlying formations from latest Cambrian to Silurian time, the younger limit imposed by the minimum age of the Sharpner’s Pond Diorite (430+/−5 Ma, Zartman and Naylor, 1984).

AVALON TERRANE

Westboro Formation – Zw

The Westboro Formation was first recognized by Emerson (1917) for exposures of quartzite in and around Westboro. Hepburn and DiNitto (1978) mapped exposures along I-495 in the southwest portion of the Marlborough quadrangle and felt that they are likely the best current exposures of the Westboro Formation in its type area.

Only a few outcrops of the Westboro Formation were observed within a limited area in the southeast portion of the Shrewsbury quadrangle near the Assabet River dam and along the shores of its reservoir. Near the inferred trace of the Bloody Bluff fault, they weather a dark gray and fresh surfaces have a medium- to dark-gray-green color. The rock has a strong foliation defined by thin layers of chlorite and epidote alternating
with much thicker layers of quartz. The rock appears to have been sheared and deformed.

The Westboro Formation in the Shrewsbury Quadrangle (sample 10, Table 2.3) contained 73.2% quartz, 10.7% chlorite, 8.3% epidote, 4.3% plagioclase (An$_{4-16}$), 2% opaque minerals, and 1.2% biotite.

The Westboro Formation is truncated to the north and west by the Bloody Bluff fault. Hepburn and DiNitto (1978) reported that it is intruded by the surrounding late
Proterozoic mafic-poor granite (either the Milford Granite or Hope Valley Alaskite of Zen and others, 1983). However, recent geochronological work on detrital zircons from the Westboro Formation indicates that the quartzite may actually be younger than the surrounding granite (Hepburn, unpublished data).

Goldsmith (1991c) discusses the stratigraphy of the New England Avalon terrane in considerable depth.
Chapter 3. IGNEOUS ROCKS

The spatial extent and abbreviated descriptions of the following igneous rocks in the Shrewsbury quadrangle can be found in PLATE I. Modes for thin sections from these rocks can be found in Table 3.1. Some of these rocks have been previously studied by other workers (Grew, 1970; Peck, 1975; Barosh, 1978a; Hepburn, 1978; Munn, 1987) and their descriptions are given where appropriate.

MERRIMACK TERRANE

The Merrimack terrane in the Shrewsbury quadrangle is intruded by the Straw Hollow Diorite. Additionally, the Tadmuck Brook Schist is intruded by a medium to coarse-grained peraluminous granite that was too small to map and remains unnamed.

Straw Hollow Diorite – DSshd

The Straw Hollow Diorite was named by Emerson (1917) with a type locality near Straw Hollow in Northborough near the intersection of I-290 and Church Street. It weathers dark-gray to black and fresh surfaces are black. The rock is very fine-grained and massive. Although the rock is typically unfoliated, two small bodies of the diorite intruding near the western contact of the Tadmuck Brook Schist are locally foliated in a zone approximately 10 meters wide (the west end of the road-cut on the south side of I-290 near interchange 24 and in the woods to the north, just south of Church Street).

A thin section from the type locality (sample 1, Table 3.1) indicates that the rock is comprised of 46% hornblende, 32% plagioclase, and 17% opaques with the rest
Table 3.1. Modes of igneous rocks from the Shrewsbury area. Sample locations given in Appendix I.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Field ID</th>
<th>Map Unit</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
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<tr>
<td></td>
<td></td>
<td></td>
<td>SHD</td>
<td>802(a)</td>
<td>UM*</td>
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<td></td>
<td></td>
<td></td>
<td>DShd</td>
<td>DSaqd</td>
<td>um</td>
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<tr>
<td>Groundmass grain size (mm)</td>
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<td>2.0-4.0</td>
<td>2.0-6.0</td>
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<td></td>
</tr>
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<tr>
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<td>An_{38}</td>
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</tr>
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</table>

Sample Description

1 SHD Straw Hollow Diorite, fine-grained plagioclase-hornblende diorite
2 802(a) Assabet Quartz Diorite, medium-grained plagioclase-hornblende diorite
3 UM Unnamed peridotite, medium-grained altered wehrlitic lherzolite

The modes for UM are given as relative proportions of olivine CPX, and OPX based on the relative proportions of the alteration products magnetite, serpentine, talc, and tremolite or actinolite.

of the rock made up of minor amounts of quartz and chlorite. The opaque minerals are of secondary origin and form a discontinuous film that grows across the earlier minerals.

The Straw Hollow Diorite intrudes the Tadmuck Brook Schist and possibly the Vaughn Hills Quartzite. It has previously been mapped to include other diorites such as
the Assabet Quartz Diorite, but is here limited to those small bodies of fine-grained and porphyritic diorite intruding the eastern portions of the Merrimack terrane in the vicinity of its type locality. The fine-grained or porphyritic Straw Hollow Diorite is texturally very different from the medium-grained Assabet Quartz Diorite. Additionally, the Assabet Quartz Diorite only intrudes the Nashoba terrane along the Assabet River fault and does not intrude the Tadmuck Brook Schist or Vaughn Hills Quartzite of the Merrimack terrane.

Earlier workers (e.g. Zartman and Naylor, 1984) suggested that the Straw Hollow and Assabet Quartz diorites may be time equivalent based on compositional and chemical similarities. However, given that the Sharpner’s Pond (430 +/- 5 Ma; Zartman and Naylor, 1984), Indian Head Hill (402 +/- 5 Ma; Hill and others, 1984), and Assabet Quartz (385 Ma; Acaster and Bickford, 1999) diorites were all once thought to be roughly time equivalent, it is felt prudent to assign an age of upper Silurian or younger with a likely Devonian age to the Straw Hollow Diorite.

Unnamed granite near Ball Hill

A small body of medium-grained granite was observed near Smith Road in Northborough (same location as RVV-012, APPENDIX 1). The granite weathers shades of gray and has fresh surfaces that are buff to white. The granite bears both garnet and muscovite, indicating that it is peraluminous and likely derived from the melting of sediments.

This unnamed granite is noted for two important reasons. First, it intrudes the Tadmuck Brook Schist. Second, it is mylonitized within the Ball Hill fault. A polished
thin section from the mylonitized portion of the granite (RVV-012) was used in the monazite dating portion of the study and is discussed in the MONAZITE DATING chapter.

ROCKY POND SLICE

The Rocky Pond slice is intruded by one large and several smaller bodies of the Rocky Pond Granite, two small bodies of gabbro and diorite, and several small unnamed granite bodies. These rocks are not found beyond the Clinton and Rattlesnake Hill faults that bound the slice.

Rocky Pond Granite –DSrpg

The Rocky Pond Granite was previously referred to as the Rattlesnake Hill Muscovite Granite by Skehan (1968) for exposures on Rattlesnake Hill in the Clinton quadrangle north of the study area. Munn (1987) referred to it as the Rocky Pond Granite for the abundant exposures along the shores of Rocky Pond and to avoid confusing it with an igneous rock named from another Rattlesnake Hill in southeastern Massachusetts.

The Rocky Pond Granite is medium- to very coarse-grained and weathers a medium-gray. Fresh surfaces have a very light- to medium-gray color. It is unfoliated except near faults and shear zones. Typical Rocky Pond Granite contains conspicuous aggregates of muscovite crystals that are commonly 3-4 centimeters across. Tourmaline crystals up to 5 centimeters long (Figure 3.1A-B) and garnets ranging from 1-4 mm
occur as accessory minerals. In addition, the Rocky Pond Granite commonly contains xenoliths of Vaughn Hills Quartzite. The abundance of muscovite and occurrence of garnet and tourmaline indicate that the Rocky Pond Granite is peraluminous and likely formed from the melting of sediments.

Thin sections of the Rocky Pond Granite were not collected, but Munn (1987) reported the rock being typically comprised of 30% microcline phenocrysts in a
groundmass of 26% quartz, 15% plagioclase (An26), 13% microcline, and 10% muscovite with garnet and chlorite present in trace amounts.

The Rocky Pond Granite has an intrusive contact with the Sewall Hill Formation. Its main body is in fault contact with the Boylston Schist and the Vaughn Hills Quartzite; however, smaller bodies intrude the Boylston Schist and for a short interval near I-290 it intrudes the Vaughn Hills Quartzite. Where it intrudes the Vaughn Hills Quartzite, the author has interpreted the granite as intruding the Rattlesnake Hill Fault as well, although it is also possible that the fault simply cuts through the granite there.

Zartman and Naylor (1984) attempted to date the Rocky Pond Granite (their ‘muscovite granite’ near West Berlin) using the Rb-Sr whole-rock method but were not able to obtain a suitable isochron. Its age is uncertain but is reasonably estimated as Silurian to Devonian.

*Diorite and Gabbro, unnamed – dg*

This unit was first recognized by Grew (1970) and later described by Munn (1987). Grew reported the rock to be a hornblende-biotite gabbro and diorite. A single outcrop of the rock near Boylston weathers dark gray to black and exhibits a strong foliation. The rock is a hornblende-biotite diorite to gabbro, but a significant amount of its amphibole has altered to biotite, giving the rock a weak schistosity.

Munn (1987) collected a sample from this outcrop and gave modes of 34% plagioclase (An49), 32% hornblende, 18% biotite, with minor amounts of muscovite,
epidote, titanite, and sausserite. She reported that some of the plagioclase occurred as phenocrysts, much of which had been sausseritized.

The unit is assumed to intrude the Boylston Schist although no contacts were observed.

*Other granites – g*

There are a number of other small bodies of fine- to medium-grained granitoids intruding the Rocky Pond slice and the Boylston Schist in particular. Compositionally these rocks vary from granite to granodiorite to quartz monzonite. Some of them are foliated; some are not.

Munn (1987) mapped a small granite body in the northern part of the Shrewsbury quadrangle near Scotland Swamp. She reported that it is in fault contact with both the Tower Hill Quartzite and the Rocky Pond Granite and suggested a possible correlation with the Ayer Granite. A comparison of thin sections with Ayer Granite from the Merrimack terrane showed that there were some similarities, but no unequivocal correlation could be made.

*Discussion and Summary*

The intrusive rocks of the Rocky Pond slice do not clearly correlate across the bounding faults. The Rocky Pond Granite is distinct from the Ayer and Andover granites, especially in its relative occurrence of tourmaline. The unnamed diorite and gabbro unit bears no resemblance to diorites in the adjacent Merrimack terrane or Nashoba terrane.
It also may be worth noting, if only as a notice for future workers, that Munn (1987) observed a lamprophyre dike intruding the Sewall Hill Formation in a road-cut at interchange 23 on I-290. She reported that it was post-metamorphic and likely Mesozoic in age.

NASHOBA TERRANE

There are two distinct groups of intrusive rocks in the Nashoba terrane in the study area: peraluminous S-type granites and calc-alkaline I-type diorites. None of the igneous rocks from the Nashoba terrane occur beyond the terrane-bounding faults.

Assabet Quartz Diorite – Dsaqd

Hanson (1956) named the Assabet Quartz Diorite for the diorite commonly found near the Assabet River in the Hudson area. In the Shrewsbury quadrangle quartz is only present in trace amounts if at all. The Assabet Quartz Diorite weathers dark-gray to black and fresh surfaces have a “salt and pepper” appearance due to its composition of primarily hornblende and plagioclase. The diorite is medium-grained and occasionally may exhibit a slight foliation.

A representative sample of the Assabet Quartz Diorite (sample 2, Table 3.1) indicates that the rock is comprised of 43.5% hornblende, 39% andesine (–An₃₈), 7.5% microcline, 6% titanite, and 3% opaque minerals.

There are no large bodies of Assabet Quartz Diorite in the quadrangle. Tabular dikes of diorite intruding the rusty schist member of the Nashoba Formation subparallel
to foliation are assigned to the Assabet Quartz Diorite. No Assabet Quartz Diorite was discovered intruding units outside of the rusty schist member. These bodies of medium-grained diorite have previously been included with the Straw Hollow Diorite by other authors (Zen and others, 1983) but are limited here to the medium-grained diorites cropping out in the vicinity of the Assabet River fault.

Acaster and Bickford (1999) dated a rock they called Straw Hollow Diorite and obtained an isotopic U-Pb zircon age of 385 +/- 10 Ma for it. Judging from their sample description and map location (the I-290/I-495 interchange), I believe the rock they dated comes from rocks that I have mapped as Assabet Quartz Diorite, but it is also possible that their sample came from rocks associated with the Indian Head Hill Diorite (Hepburn, personal communication, 2007).

Unnamed Peridotite – um

The unnamed peridotite weathers a charcoal gray to black and may have a chalky appearance due to the common alteration products talc and serpentine. It is medium-grained with pyroxenes ranging from 0.25-0.75 centimeters. Similarly sized olivine crystals and aggregations of serpentine are also visible in outcrop. The unit is distinguished by its massive nature, dark color, abundance of pyroxenes, occurrence of olivine, and the presence of the alteration products serpentine, magnetite, calcic amphibole, talc, and chlorite.

In thin section, clinopyroxene, orthopyroxene, and olivine are present as large (~2-6mm) fractured crystals. Their proportions relative to each other are 32% olivine,
39% clinopyroxene, and 29% orthopyroxene (sample 3, Table 3.1). The olivine’s composition was estimated to be approximately Fo⁷₀.⁷₅ on the basis of its observed birefringence of approximately 0.038; the orthopyroxene’s composition was estimated to be that of bronzite and hypersthene based on 1ˢᵗ order gray to yellow interference colors and biaxial negative interference figures (a few biaxial positive figures suggest that some of the bronzite may be very magnesium-rich). These crystals make up approximately 55% of the rock with the rest being comprised of alteration products including tremolite or actinolite, serpentine, talc, magnetite, and some chlorite. Plagioclase is not present in any of the samples except in trace amounts. Serpentine and magnetite are the most abundant alteration products and in many places appear to have replaced entire crystals of presumably olivine. Areas of the thin sections rich in tremolite or actinolite are assumed to have originally been clinopyroxene crystals. Given the relative abundance of alteration products the original rock was a peridotite, likely wehrlite or wehrlitic lherzolite.

Two small bodies of these rocks were mapped. Both were discovered near the Ball Hill fault – one just east of the fault in the undifferentiated Nashoba Formation and one just west of the fault within the the Tadmuck Brook Schist of the Merrimack terrane. The body in the Tadmuck Brook Schist is in fault contact with the surrounding rocks. This brittle fault was observed to strike ENE at 073° and dip steeply south at 83°. Field relationships with the rocks surrounding the other body are uncertain due to the small size of the body and the covered nature of its contacts.
Andover Granite – SOag

The Andover Granite was most thoroughly characterized by Castle (1964). It extensively intrudes the northeastern portion of the Nashoba terrane (Figure 1.2) and contains numerous phases – from foliated and gneissic phases to pegmatite and aplite dikes.

In the study area only one small body of the Andover Granite is mapped in the eastern part of the quadrangle near Route 20. It is a medium- to coarse-grained, two-feldspar, two-mica, strongly foliated granite. Small bodies of this same granite also extensively intrude the quartzo-feldspathic gneiss and granofels member of the Nashoba Formation; however, these bodies are generally too small to map. Aplite dikes and pegmatite are common throughout the Nashoba Formation and are assumed to be younger phases of the Andover Granite; these intrusions are particularly common within the rusty schist member of the Nashoba Formation.

Castle (1964) gave modes of the medium- to coarse-grained two-mica granite as 27-38% quartz, 26-46% plagioclase, 10-44% microcline, 0-11% muscovite, 0-11% biotite, and 0-0.6 % garnet. He gave modes for the pegmatite of 25-39% quartz, 32-49% plagioclase, 0-33% microcline, 0.2-17% muscovite, 0-4% biotite, and 0-3% garnet.

Andover Granite in the study area intrudes both the Nashoba Formation and the Marlboro Formation. Some of the pegmatite intruding the rusty schist member of the Nashoba Formation is protomylonitic. Several attempts have been made to determine the age of the Andover Granite. Handford (1965) gave a whole-rock Rb-Sr age of 450 +/- 23 Ma; Zartman and Naylor (1984) gave a whole-rock Rb-Sr age of 446 +/- 32 Ma for an
older, foliated phase and 408±22 Ma for a younger aplitic phase; Hepburn and others (1995) reported a U/Pb age of 412±2 Ma for a younger pegmatitic phase.

**Grafton Granite Gneiss – ZDgg**

Goldsmith (1991a) reported that Dixon informally named this granite gneiss during reconnaissance mapping in the Grafton quadrangle. In the study area, the best exposures of the Grafton Granite Gneiss are along a ridge beginning at Boston Hill in Westborough and trending southwest from there to the quadrangle boundary.

The Grafton Granite Gneiss is fine- to medium-grained and weathers various gray colors. Fresh surfaces are light-gray, tan, and sometimes a bit pink. The rock is strongly foliated, with the foliation defined by feldspar lenses and oriented biotite flakes. The typical composition of the Grafton is granodiorite. Goldsmith (1991a) described the unit as being fairly uniform in composition, but in the study area, it is commonly very heterogeneous with the amount of biotite and K-feldspar varying considerably within and between outcrops. Goldsmith (1991a) also reports “inclusions” or “schlieren” of amphibolite and biotite schists, presumably of the Marlboro Formation. Some workers have interpreted these lenses as indicating a conformable relationship between mafic and felsic volcanic protoliths to the Marlboro Formation (Acaster and Bickford, 1999). These lenses could also be xenoliths plucked from the Marlboro Formation. Hepburn (1978) suggested that the rock was plutonic. The spatial extent of the heterogeneities observed in this study was generally limited to several meters and they did not always conform to the foliation, suggestive of an intrusive or faulted, but not depositional relationship.
However, no contacts were observed so their nature remains uncertain. The age of the Grafton Granite Gneiss is unknown but if it is intrusive then it is presumably younger than the Marlboro Formation rocks surrounding it.

_Grafton Diorite – ZDgd_

A small body of diorite is present at the southern boundary of the study area. It was mapped in the Grafton quadrangle by Walsh (personal communication, 2005) for exposures in the vicinity of the office park southwest of Grafton State Hospital, which straddles the border between the Shrewsbury quadrangle (to the north) and the Grafton quadrangle (to the south).

Both weathered and fresh surfaces of the diorite are black. It is very fine-grained, cut by fractures filled with epidote or plagioclase, and may be weakly foliated. The rock is dominantly comprised of fine-grained hornblende, probably 40-60% of the mode, with subordinant plagioclase of uncertain anorthite content. The rock contains a small amount of biotite and clinopyroxene.

The contact of the diorite with the Grafton Granite Gneiss was not observed in the study area.

_AVALON TERRANE_

_Mafic-poor granite – Zmpg_

This medium-grained granite weathers a buff tan to light-gray color. Fresh surfaces of the rock are light-gray to white. The rock is typically poor to very poor in mafic minerals
which tend to be either biotite or magnetite and generally make up less than 5% of the mode. The rock exhibits everywhere a strong foliation defined by elongate quartz and feldspar, and oriented biotite flakes. In some areas, tiny amounts of chlorite or epidote give the rock a bit of a greenish color.

Wones and Goldsmith (1991) reported modes for the Milford Granite of 47% quartz, 24% oligoclase, 27% microcline, 2% biotite, 0.1% muscovite, 0.1% epidote, 0.1% garnet and trace amounts of chlorite, titanite, apatite, allanite, and zircon. They also reported modes for the Hope Valley Alaskite of 40% quartz, 29% albite, 30% perthite, 1.2% muscovite, and 0.3% magnetite with trace amounts of zircon.

The mafic-poor granite is fault-bounded to the northwest by the Bloody Bluff fault. Its southeastern extent lies beyond the boundaries of the quadrangle. It is unclear whether this granite should be assigned to the Hope Valley Alaskite or the Milford Granite since the two converge near the southeast corner of the Shrewsbury quadrangle in the maps of Zen and others (1983) and Goldsmith (1991c). These two units have overlapping lithological descriptions and indeed their appearance in the field is at times so similar that differentiating between them in the Shrewsbury area is difficult. In addition, the modes reported by Wones and Goldsmith (1991) for both granites satisfy the field description of the mafic-poor granite in the southeastern part of the study area. Because the mafic-poor granite likely belongs to either the Hope Valley Alaskite or Milford Granite, both of which have late Proterozoic ages, the mafic-poor granite is assigned a late Proterozoic age.
**Nourse Farm Granodiorite -- Znf**

The Nourse Farm Granodiorite is named here for pavement exposures *ca.* 100 meters behind the farm stand at Nourse Farm off of Nourse Road in Westborough. The same unit is found to the south in the Grafton quadrangle (Walsh, personal communication, 2005) and may also be found farther to the northeast in the Marlborough quadrangle (Kopera, personal communication, 2005).

The Nourse Farm Granodiorite weathers dark-gray to greenish-dark-gray. The rock is medium-grained and exhibits a strong foliation. It is distinguished by large (3-10 cm) pods of epidote as well as an abundance of matrix epidote.

No modes were collected for the Nourse Farm Granodiorite but it was found to be made of largely plagioclase (An$_{36}$), quartz, biotite, and epidote. Muscovite and chlorite make up roughly 15% of the rock and less than 5% of the rock is comprised of titanite and opaque minerals.

Only a few small outcrops of this unit were observed and the nature of its contact with the surrounding mafic-poor granite is unknown. Walsh (personal communication, 2005) indicated that in the Grafton quadrangle to the south, this unit intrudes late Proterozoic metavolcanic units (Zv of Zen and others, 1983). Thus, it must be late Proterozoic or younger in age.
Chapter 4. METAMORPHISM

The first systematic study of metamorphism within the Nashoba terrane was conducted by Abu-Moustafa and Skehan (1976). After determining modes for hundreds of thin sections from the Wachusett-Marlborough tunnel section and identifying the metamorphic mineral assemblages for the Nashoba Formation, they determined that the peak metamorphic conditions were in the sillimanite-almandine-orthoclase subfacies of the almandine-amphibolite facies, suggestive of temperatures ranging from 625-650°C and pressures of 5-6 kbar. Subsequent studies identified additional discrete metamorphic events and attempted to place temperature and pressure constraints on them using petrogenetic grids and various thermobarometric techniques (Munn, 1987; Bober, 1990; Jerden, 1997).

Work on metamorphism in this study was limited to recognizing mineral assemblages in hand sample and in thin sections. In most cases this corroborated the previous work. At least two amphibolite-facies events are currently recognized in the Rocky Pond slice and the Nashoba terrane, although events in the Nashoba terrane and Rocky Pond slice were not necessarily time equivalent. Most of the Merrimack terrane within the study area generally preserves a single greenschist-facies event; but, amphibolite-facies metamorphism is preserved in the Tadmuck Brook Schist along the Merrimack terrane's eastern margin. The Avalon terrane in the Shrewsbury quadrangle also experienced greenschist-facies metamorphism. It is not discussed in this text.
MERRIMACK TERRANE

In central Massachusetts, the Merrimack terrane is characterized by sillimanite zone amphibolite-facies metamorphism (Robinson and Goldsmith, 1991). East of the Wekepeke Fault (Figures 1.3), however, it has mineral assemblages generally associated with the greenschist facies (Robinson and Goldsmith, 1991).

Pelitic rocks in the northwest portion of the Shrewsbury quadrangle are characterized by the chlorite, biotite, and actinolite zones of the lower greenschist facies. Assemblages for the phyllite portion of the Tower Hill Quartzite were reported by Grew (1970) to be in the biotite zone of metamorphism (e.g. quartz-biotite-chlorite-muscovite). The same assemblage is found in the phyllites of the Oakdale and Worcester formations. Meta-siltstone of the Oakdale Formation commonly contains actinolite. Goldstein (1994) and Jerden (1997) both report a poorly preserved earlier metamorphism in pelitic rocks of the eastern Merrimack terrane with assemblages containing garnet, andalusite, and staurolite. Their evidence was primarily the local occurrence of relict cores of these minerals overgrown or pseudomorphed by chlorite or sericite.

The Vaughn Hills Quartzite is characterized by the chlorite and biotite zones with common assemblages of quartz-sericite-chlorite and quartz-muscovite-biotite-chlorite. Munn (1987) reported a limited zone of contact metamorphism in the Vaughn Hills Quartzite where it is intruded by the Rocky Pond Granite along I-290. The assemblages in this contact aureole range from quartz-biotite-andalusite to quartz-muscovite-biotite-sillimanite.
The Tadmuck Brook Schist has a somewhat more complicated metamorphic history than the adjacent formations of the Merrimack terrane. Although a brief summary will suffice here, the interested reader is referred to Jerden (1997) for detailed analysis.

The Tadmuck Brook Schist can be broadly divided into three members on the basis of metamorphic grade. Jerden (1997) referred to them as the northwest member, the central member, and the southeast member. Isograds in the Tadmuck Brook Schist typically parallel metamorphic foliation and compositional layering.

The earliest metamorphism is characterized by two assemblages observed in all members, but best preserved in the central member: andalusite-biotite and andalusite-staurolite-biotite (Munn, 1987; Jerden, 1997). Sillimanite-biotite and sillimanite-garnet-biotite assemblages overprint the andalusite-biotite assemblage in the southeast member within 300-500m of the Nashoba Formation (Munn, 1987; Jerden, 1997). Jerden (1997) also recognized a third amphibolite facies event with the assemblage staurolite-sillimanite-biotite. This assemblage overprints the other two and is only poorly preserved in the central and southeast member. Along the northwest member of the Tadmuck Brook Schist, the assemblages chlorite-sericite-quartz and chlorite-biotite-muscovite-quartz are pervasive. According to Jerden (1997), these assemblages overprint all earlier assemblages throughout the formation. Samples 1 and 2 of Table 4.1 have sillimanite-muscovite zone assemblages that are overprinted by chlorite zone metamorphism. In sample 1, biotite alters to chlorite and sillimanite goes to sericite; in sample 2, sillimanite goes to sericite.
Table 4.1. Metamorphic assemblages in the Shrewsbury quadrangle. Sample locations can be found in APPENDIX I.

A  Pelitic Assemblages

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C  Ultramafic Assemblages

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Table 4.1 (continued). Sample descriptions for metamorphic assemblages.

Sample Description
1 TSC Tadmuck Brook Schist, muscovite-quartz-sillimanite schist
2 705 Tadmuck Brook Schist, quartz-plagioclase-sillimanite-muscovite schist
3 305 Nashoba Formation, biotite gneiss and amphibolite member, sil-quartz-biotite-plag gneiss
4 303 Nashoba Formation, biotite gneiss and amphibolite member, mus-quartz-biotite-plag gneiss
5 NSG Nashoba Formation, sillimanite-biotite gneiss member, garnet-sil-qtz-biotite gneiss
6 806 Nashoba Formation, rusty schist member, microcline-sil-biotite-schist
7 806a Nashoba Formation, rusty schist member, garnet-sil-biotite-schist
8 709 Nashoba Formation, undifferentiated, sil-quartz-biotite-plag gneiss
9 308 Nashoba Formation, undifferentiated, ksp-sil-quartz-biotite-plag gneiss
10 SUB Tadmuck Brook Schist, plagioclase-hornblende amphibolite
11 306 Nashoba Formation, biotite gneiss and amphibolite member, biotite-plagioclase-hornblende amphibolite
12 608 Marlboro Formation, epidote-hornblende-plagioclase gneiss
13 906 Marlboro Formation, epidote-biotite-plagioclase gneiss
15 907 Marlboro Formation, epidote-hornblende-plagioclase gneiss
16 911 Marlboro Formation, epidote-biotite-plagioclase gneiss
17 902 Westboro Formation, quartzite
17 UM Unnamed peridotite
18 504 Unnamed peridotite
19 709 Unnamed peridotite
In summary, the Tadmuck Brook Schist was affected throughout by andalusite-staurolite zone metamorphism followed by sillimanite-muscovite zone metamorphism on the east. Sillimanite-staurolite zone metamorphism is poorly preserved overprinting these assemblages. Finally, chlorite zone metamorphism overprints all other assemblages and is pervasive in the northwest member.

ROCKY POND SLICE

The Rocky Pond slice was affected by at least two amphibolite-facies metamorphic events followed by greenschist-facies retrograde metamorphism.

The earliest metamorphism in the Rocky Pond slice is characterized by the sillimanite-muscovite zone. In the pelitic rocks of the Boylston Schist, this is reflected by the common assemblage quartz-biotite-muscovite-sillimanite-garnet. In the more quartzo-feldspathic gneisses of the Sewall Hill Formation, diagnostic minerals are absent in handsample; however, Munn (1987) reports “minute prisms” of sillimanite associated with muscovite in thin sections.

The Boylston Schist was also affected by later static sillimanite-muscovite zone metamorphism. It is recognized by conspicuous fibrolite growing randomly across the foliation in the more pelitic parts of the formation and is distinct from earlier prismatic sillimanite which grows with the foliation. Munn (1987) interpreted this sillimanite growth to reflect contact metamorphism caused by heat associated with the intrusion of the Rocky Pond Granite. It is unclear whether the Sewall Hill Formation was also
affected by the contact metamorphism because the Sewall Hill Formation’s quartzofeldspathic composition limits the occurrence of diagnostic sillimanite.

The third metamorphism in the Rocky Pond slice is chlorite-chloritoid zone retrograde metamorphism. Munn (1987) reported the presence of chlorite, chloritoid, and sericite with textures indicating that they were replacing earlier amphibolite-facies assemblages. She observed chlorite and sericite replacing garnet and sillimanite respectively. The effects of this event are discontinous across the Rocky Pond slice and generally localized in the vicinity of shear zones. The retrograde metamorphism was interpreted by Munn (1987) to be the result of fluids infiltrating along faults and shear zones.

To summarize, the Rocky Pond slice first experienced sillimanite-muscovite zone metamorphism. Parts of the Boylston Schist were later overprinted by sillimanite-muscovite zone contact metamorphism. Finally, chlorite-chloritoid zone assemblages overprinted earlier assemblages during retrograde metamorphism, which was enhanced near shear zones by fluid infiltration.

NASHOBA TERRANE

Metamorphic Events

The petrogenetic grid of Holland and Powell (1998) was used to estimate the pressure-temperature conditions of metamorphic events in the Nashoba terrane. Figure 4.1 shows the grid overlain with the estimated P-T conditions for the three metamorphic events in the Nashoba terrane.
Figure 4.1. Petrogenetic grid after Holland and Powell (1998). Shaded areas represent P-T estimates for different metamorphic events in the Nashoba Formation based on the observed mineral assemblages and on assemblages reported by Munn (1987) and Jerden (1997).

The earliest metamorphic event recorded in the Nashoba terrane (M1) is represented by the assemblages sillimanite-biotite and sillimanite-garnet-biotite in the Nashoba Formation (Table 4.1; Munn, 1987; Bober, 1990; Jerden, 1997). This event is poorly preserved owing to the near-complete textural equilibrium achieved by the second metamorphic event (M2) and is recognized by fine-grained sillimanite and fibrolite preserved in feldspar or garnet porphyroclasts. The conditions of this event in the Nashoba Formation can be constrained by the absence of staurolite, the presence of muscovite, and the stability field of sillimanite. These constraints suggest that M1
brought the terrane to temperatures over 600°C at a pressure between 3.2 and 4.8 kilobars. It is unclear whether any of the migmatite observed in the terrane was generated as a result of the M1 metamorphism.

The second metamorphic event affecting the Nashoba terrane (M2) is recognized by sillimanite-K-feldspar-biotite and sillimanite-K-feldspar-biotite-garnet assemblages in the Nashoba Formation (samples 5, 6, 7, and 9, Table 4.1; Abu-Moustafa and Skehan, 1976; Munn, 1987). These assemblages are associated with migmatite in the Nashoba Formation (Figure 2.1B) and may indicate P-T conditions along or above the wet granite solidus. The absence of muscovite and the presence of k-feldspar along with the stability of sillimanite and the presence of migmatite suggest temperatures greater than 650°C for M2 at pressures of 2.5-4.5 kilobars.

The third metamorphic event affecting the Nashoba terrane (M3) is represented by the assemblages chlorite-sericite-quartz and chlorite-biotite-muscovite-quartz. These assemblages overprinted earlier assemblages in the Nashoba Formation. In the Nashoba Formation, samples 4 and 9 (Table 4.1) have the assemblage sillimanite-K-feldspar-biotite, but sericite has replaced much of the sillimanite and some biotite is replaced by chlorite.

Geothermobarometry

Two prior studies made use of an electron microprobe and various geothermobarometers to calculate the P-T conditions in the Nashoba terrane (Munn, 1987; Bober, 1990). The highest results from the Ferry-Spear garnet-biotite thermometer yielded M1 and M2
temperatures from the Nashoba Formation as high as 615°C and 630°C (Munn, 1987) and 610°C and 640°C (Bober, 1990). However, the average temperatures that they reported for M1 and M2 were 591°C and 575°C (Munn, 1987), and 593°C and 592°C (Bober, 1990). The two studies reported Newton-Haselton garnet-plagioclase-sillimanite-quartz barometer pressures averaging 4.4 kbar and 4.6 kbar for M2, with no pressures determined for M1. The average temperatures were reported +/-50°C; the pressure calculations were reported +/-0.5 kbars.

SUMMARY OF METAMORPHISM

Sillimanite Textures

Munn (1987) and Jerden (1997) both reported two generations of sillimanite growth in the Nashoba Formation: large prismatic crystals, commonly fractured or boudinaged, and fibrolite, commonly growing across the foliation. Jerden (1997) interpreted the prismatic crystals as M2 sillimanite and Munn (1987) interpreted the fibrolite to be M2 sillimanite. Both had valid reasons: Munn interpreted fibrolite as overgrowing earlier foliation and therefore earlier metamorphism; however, Jerden's prismatic sillimanite approached textural equilibrium with biotite, garnet, and K-feldspar in all of his pelitic samples. As Jerden (1997) noted, fibrolitic sillimanite (interpreted as M1 sillimanite) is not nearly as common as prismatic sillimanite in the Nashoba Formation, indicative of nearly complete reequilibration during the M2 event. In the current study fibrolite and very fine sillimanite crystals were only rarely observed in thin section preserved as inclusions in
garnet or feldspar porphyroblasts, leading this author to conclude that the fibrolite preserves the earlier M1 event.

The Rocky Pond slice also preserves two generations of sillimanite growth in the Boylston Schist. Unlike Nashoba terrane fibrolite, the fibrolite in the Boylston Schist is fairly common and is easily recognizable in hand sample. It grows across the weak schistosity in randomly oriented mats and represents a static thermal event overprinting the dynamothermal sillimanite-muscovite zone metamorphism responsible for the prismatic sillimanite crystals.

Summary

The Merrimack terrane was affected by at least one chlorite zone metamorphism and possibly an earlier andalusite-staurolite zone metamorphism (Goldstein, 1994; Jerden, 1997). The Tadmuck Brook Schist experienced two amphibolite-grade events prior to the chlorite zone metamorphism experienced by the rest of the Merrimack terrane.

The Rocky Pond slice experienced two sillimanite-muscovite zone events: the first was dynamothermal; the second was static and may have only affected the Boylston Schist. Chlorite-chloritoid zone retrograde metamorphism overprinted earlier assemblages.

The Nashoba terrane was affected by two prograde amphibolite-grade events: the sillimanite-muscovite zone event (M1) followed by the sillimanite-K-feldspar zone event (M2). These events were followed by M3 retrograde metamorphism in the chlorite zone of the greenschist facies.
Chlorite zone metamorphic events throughout the Shrewsbury quadrangle all appear to be enhanced in the vicinity of faults and shear zones. It is possible that the chlorite zone events in the Merrimack terrane, Rocky Pond slice, and Nashoba terrane are in part correlative.
Chapter 5. STRUCTURE

FOLIATION AND FOLDS

$S_1$ – Foliation

The most dominant structural feature in the Nashoba terrane is its distinctive $S_1$ penetrative planar fabric defined by the gneissosity and schistosity of the stratified rocks of the terrane. $S_1$ typically strikes northeast and dips moderately to steeply to the northwest. It is commonly subparallel to compositional layering and at a scale of meters to tens or hundreds of meters, changes in lithology are also subparallel to $S_1$. Because of this, the $S_1$ surface is interpreted to be generally subparallel to relict bedding ($S_0$). Figure 5.1A shows the poles to all $S_1$ foliations measured in the Shrewsbury quadrangle.

$S_1$ is probably a transposition fabric in the Nashoba terrane, although no direct evidence of this was observed. Figure 5.1B shows the $S_1$ fabric in the process of being transposed into a new subparallel foliation during later ductile deformation in the Ball Hill fault.

The Merrimack terrane also has an $S_1$ fabric-forming foliation. In the Vaughn Hills Quartzite and Tadmuck Brook Schist this foliation is subparallel to fine compositional layering interpreted to be relict bedding ($S_0$). The foliation generally strikes NNE and dips moderately to steeply to the WNW. In the Vaughn Hills Quartzite this foliation is disturbed along I-290 where the Vaughn Hills Quartzite is intruded by the Rocky Pond Granite and the foliation deforms around the shape of the intrusion. $S_1$ is similarly NE-striking and NW-dipping in the Tower Hill Quartzite in the northwest part of the study area near the Wachusett Reservoir.
Figure 5.1. (A) Lower-hemisphere equal area projection of S1 foliation measurements (poles to planes) from across the Shrewsbury quadrangle; minor fold axes are represented by an 'X'. (B) PPL image of transposition fabric forming in the Ball Hill fault; isoclinal fold hinges and limbs are in various stages of detachment. The shear foliation formed from this transposition fabric is essentially subparallel to the S1 metamorphic foliation.
The Rocky Pond slice also has an S\(_1\) foliation. It is NE-striking and NW-dipping in the Sewall Hill Formation except where locally deformed by the intrusion of the Rocky Pond Granite. An overturned antiform mapped by Munn (1987) (shown on PLATE I) also disrupts the foliation in the Sewall Hill Formation. The Boylston Schist exhibits the S\(_1\) foliation as well; however, its orientation varies from the NE-striking, NW-dipping orientation common throughout the quadrangle to ESE-striking, NE-dipping and north-striking, west-dipping. These disruptions may be due to the intrusion of numerous small bodies of granite and diorite. Folding may also be responsible as suggested by Barosh (1978a).

\textit{D\(_2\) – Non-Coaxial Shear}

The S\(_1\) fabric was disrupted in numerous locations by D\(_2\), the result of non-coaxial shearing. Non-coaxial shearing created numerous ductile shear zones throughout the Nashoba terrane and will be discussed further below in the \textit{FAULTS} section. Figure 5.1B shows how these D\(_2\) structures can locally transpose the earlier S\(_1\) fabric. Although Jerden (1997) reports that some shear surfaces in the upper portions of the Nashoba Formation cut across the S\(_1\) foliation, they are essentially coplanar with S\(_1\) in the Nashoba terrane. Important shear zones discussed below in the \textit{FAULTS} section include the Ball Hill fault, Sulfur Hill shear zone, and Assabet River fault. These have mineral stretching lineations (Figure 5.2A) that indicate motion direction, and contain typical non-coaxial shear shape fabrics such as C-S fabrics, asymmetric extensional shear bands, S\(_6\) mineral
Figure 5.2. Structure images. (A) hornblende-plagioclase lineation (indicated by arrow) in Tadmuck Brook Schist amphibolite southwest of Shrewsbury. (B) chevron folds in the Sewall Hill Formation at interchange 23 on I-290 (C) folded Vaughn Hills Quartzite north of Wrack Meadow near contact with Rocky Pond Granite; fold axis plunges gently north. (D) folded migmatitic Nashoba gneiss; fold axis plunges very gently to the east. (E-F) domino structures of equivocal shear sense in the Sulfur Hill Shear Zone (E) and Assabet River Fault (F).
foliations, mantled and rotated porphyroclasts, and back-rotated structures such as mica-fish.

Non-coaxial shear zones in the Rocky Pond slice are also generally subparallel to $S_1$ and $S_0$; however, it is not uncommon to find them cutting $S_1$ at slightly oblique angles. Shear zones ranging in thickness from several centimeters to one meter wide are ubiquitous in the Sewall Hill Formation, not uncommon in the Boylston Schist, and scattered throughout the Rocky Pond Granite. Goldstein (1994) referred to these shear zones as the Wachusett Mylonite Zone.

Shear surfaces are less developed in the other units of the Merrimack terrane within the Shrewsbury quadrangle. They occur within the Tower Hill Quartzite near the Clinton Fault and within the Vaughn Hills Quartzite near the Rattlesnake Hill Fault.

**Folding**

Folding in the study area is complex and widespread. Minor folding, likely of several generations, is apparent from thin-section to outcrop-scale (e.g. Figures 5.1B, 5.2B-D). Detailed analysis of folding was not conducted in this study, but a few representative minor fold axes are plotted on Figure 5.1A.

**Nashoba terrane.** Skehan and Abu-Moustafa (1976) indicated that in the 12,806 meters of continuous exposure in the Wachusett-Marlboro tunnel section there was no evidence for large-scale repetition of lithologic units by folding. They did, however, observe
small-scale repetition of units due to folding with wavelengths of tens of meters. Many of these folds were interpreted as fault-associated drag folds.

Based partly on these observations of Skehan and Abu-Moustafa (1976) and partly on his own stratigraphic considerations, Goldsmith (1991a,b) felt that the apparent doubling in thickness of the Nashoba terrane to the northeast of the study area was more likely due to imbricated strike-slip faulting than to large-scale folding.

Medium-scale folds like the ones observed by Skehan and Abu-Moustafa (1976) in the tunnel section are extremely difficult to observe on the surface. The limited exposures at the surface, the typical steep dip of the foliation, and the heterogeneity of the stratigraphic units make folds with wavelengths of even several hundred meters potentially impossible to detect. Even so, alternating steep dips to the east and west for foliation measurements along the NNE trending spine of Mount Pisgah in Northborough may indicate the presence of small- or medium-scale folds thickening the biotite gneiss and amphibolite member of the Nashoba Formation there. Where small-scale folds were observed they were tight to open and generally rounded (e.g. Figure 5.2D).

**Rocky Pond slice.** Munn (1987) mapped a northeast-plunging antiform (PLATE I) in the current Sewall Hill Formation of the Rocky Pond slice (her Western Nashoba Formation of her Western Nashoba Slice). She determined that the fold closed to the northeast after measuring the foliation in the nose of the fold near interchange 23 on I-290. She indicated that the antiform was overturned to the southeast. Smaller-scale folds in the
Sewall Hill Formation can be both tight and open. They are commonly angular and sometimes have the appearance of chevron folds (Figure 5.2B).

**Merrimack terrane.** Small-scale folds are present throughout the Vaughn Hills Quartzite and are tight to open (Figure 5.2C). The Tadmuck Brook Schist has three main fold sets which Jerden (1997) discusses in depth. They include isoclinal folds that transposed the original bedding surface into the metamorphic foliation, asymmetric folds related to non-coaxial deformation in shear zones, and later folds that refold the first two sets.

**FAULTS**

*Introduction*

The Shrewsbury quadrangle is cut by numerous ductile faults and shear zones. These include the major terrane boundaries, conspicuous intra-terrane mylonite zones, and thin discontinuous mylonites. They will be discussed in geographic order from northwest to southeast.

The Clinton-Newbury fault system can be traced in Massachusetts from the Atlantic coast near Newburyport to the Oxford-Webster area near the Massachusetts-Connecticut border and beyond (Figure 1.2) (Castle and others, 1976). North of the Shrewsbury quadrangle in Clinton, the fault splits into two main splays: the Clinton fault and the Rattlesnake Hill fault (Fig. 5.3). These faults bound an enigmatic block of rocks informally designated herein as the Rocky Pond slice and rejoin to continue as one main splay southwest of Shrewsbury near Worcester (Fig 5.3). Castle and others (1976)
Figure 5.3. Major faults and shear zones of the Shrewsbury quadrangle and surrounding environs.
interpreted the Rattlesnake Hill fault to be the mid-Paleozoic expression of the Clinton-Newbury fault in the Clinton and Shrewsbury quadrangles. They considered the Clinton fault to be a later feature reflecting late Paleozoic repositioning of adjacent terranes.

Goldstein (1994) considered a number of minor shear zones within the current Rocky Pond slice to be part of a broad, several kilometers-wide ductile shear zone related to Alleghanian-aged deformation in Massachusetts. He collectively called these shear zones the Wachusett Mylonite Zone.

The Ball Hill fault forms a major terrane boundary separating the Tadmuck Brook Schist of the Merrimack terrane from the Nashoba Formation of the Nashoba terrane in the Shrewsbury quadrangle. Castle and others (1976) inferred a fault coinciding with this study’s Ball Hill fault. They traced it as far north as Lawrence, Massachusetts where they showed it merging with the Clinton-Newbury fault (Figure 1.2).

The Sulfur Hill shear zone is a newly recognized mylonite zone with similar strike, dip, ductility, and shear-sense to the Ball Hill fault. Its trace coincides with a steep magnetic gradient that continues tens of kilometers to the northeast. It does not appear to continue south of I-290.

The Assabet River fault separates the Nashoba Formation from the Marlboro Formation in the Shrewsbury quadrangle and can also be traced for tens of kilometers to the northeast (Castle and others, 1976; Goldsmith, 1991b).

The Bloody Bluff fault is not exposed in the Shrewsbury quadrangle but is inferred from the juxtaposition of contrasting Nashoba and Avalonian lithologies and contrasting metamorphic grade.
These faults and shear zones can be subdivided on the basis of their shear type and direction. Shear surfaces associated with the Ball Hill fault, the Sulfur Hill shear zone, and minor shear zones in the Rocky Pond slice have characteristics of general non-coaxial shear. General non-coaxial shear reflects a pure-shear component that causes shortening across the shear zone and extension parallel to it. Shear surfaces near the Assabet River fault on the other hand do not have structures indicative of general non-coaxial shear and reflect only simple shearing.

The motion direction also varies between different shear surfaces. Motion is assumed to be in the direction of mineral stretching lineations that lie within the shear plane. Figure 5.4 shows a stereoplot of all measured shear foliations and mineral stretching lineations in the Shrewsbury quadrangle. These measurements are also divided based on their proximity to major structural features in the area. Shear surfaces on and around the Ball Hill fault and Sulfur Hill shear zone indicate strike-slip motion oriented NNE-SSW. Southwest of Shrewsbury shear surfaces near the Ball Hill Fault indicate oblique motion in a NNW-SSE direction. Shear surfaces proximal to the Assabet River Fault also indicate oblique motion, but with an orientation varying from NNE-SSW to NNW-SSE. Shear zones in the Rocky Pond slice largely reflect dip-slip motion in a NNW-SSE direction. Minimal measurements were taken in the vicinity of the Rattlesnake Hill Fault and the Bloody Bluff Fault; their motion type and direction remains uncertain in the Shrewsbury quadrangle.

The shear sense was determined for a number of these faults by observing microstructural shape fabrics and shear indicators. In all cases thin sections were cut
Figure 5.4. Lower hemisphere equal-area stereoplot of all measured shear planes and mineral stretching lineations in the Shrewsbury quadrangle. Smaller stereoplots to the right show the same data grouped by proximity to a major structural feature. WMZ=Wachusett Mylonite Zone of Goldstein (1994).
perpendicular to the shear foliation and parallel to the mineral stretching lineation (inferred motion direction) to view the surface where diagnostic shear indicators are found. Figure 5.5 shows stereoplots of all shear foliations and stretching lineations grouped by structural feature and shown with a structural map of the Shrewsbury quadrangle. Locations and orientations of all mineral stretching lineations are indicated. Locations for samples discussed in the text are found in APPENDIX I.

*Clinton Fault*

**Location.** The Clinton Fault (Figure 5.3) is defined as the boundary separating the base of the Tower Hill Quartzite from the top of the Boylston Schist. The fault can be traced from near Clinton to the Worcester area for a total trace length of about 18 kilometers (Peck, 1975).

**Description.** The fault was not observed directly in this study, but has been seen by Skehan (1968), Peck (1975), and Munn (1987). Munn (1987) observed the presence of mylonitized rocks near its trace which suggested an average dip of 38°NW for the fault. From observations in the Wachusett-Marlborough tunnel section, Skehan (1968) measured the dips of this fault to range from 30° – 45° and interpreted the fault to be a northwest over southeast thrust fault. It is best defined in the Shrewsbury quadrangle by the sharp break in metamorphic grade from the chlorite zone in the Tower Hill Quartzite to the sillimanite-muscovite zone in the top of the Boylston Schist.
Figure 5.5. Location, trend, and plunge of mineral stretching lineations measured in the Shrewsbury quadrangle. Accompanying equal-area stereoplots show the orientation of the shear planes. WMZ=Wachusett Mylonite Zone; CF=Clinton Fault; RHF=Rattlesnake Hill Fault; BHF=Ball Hill Fault; SHSZ=Sulfur Hill Shear Zone; ARF=Assabet River Fault; BBF=Bloody bluff Fault.
Wachusett Mylonite Zone

Location. The Wachusett Mylonite Zone was named by Goldstein (1994) for numerous zones of mylonite in an area bounded by the Wachusett Reservoir on the west and the Rattlesnake Hill Fault on the east. His Wachusett Mylonite Zone contained rocks of both the current Rocky Pond slice and of the eastern Merrimack terrane.

Description. In the Shrewsbury quadrangle, the broad mylonite zone described by Goldstein (1994) was not apparent. However, mylonites ranging in thickness from several centimeters to several meters are common throughout the Rocky Pond slice. The best exposures are found in roadcuts at the interchange of I-290 and Route 140.

The fault rocks are dominantly quartzo-feldspathic protomylonites to ultramylonites that cut the Sewall Hill Formation and Rocky Pond Granite. Narrow, centimeter-scale shear zones in micaceous parts of the Boylston Schist were observed in the field but were not examined petrographically.

Sense-of-shear. Shear sense was determined from both outcrop-scale indicators and in thin section. In a large roadcut along the back entrance drive to Shrewsbury Regional High School in Shrewsbury, a roughly 35 cm wide mylonite zone was observed on a fresh surface subparallel to the roughly down-dip mineral lineation. Several σ porphyroclasts on this surface indicated NW side down normal motion on the fault (Figure 5.6A).
Figure 5.6. Shear-sense determinations for shear zones in the Rocky Pond slice (Wachusett Mylonite Zone of Goldstein, 1994). (A) Minor shear zone from Shrewsbury High School (Sample SHS) roadcut. Motion sense is normal, NW block down, determined from sigma-shaped porphyroclasts; (B) PPL image of sheared Rocky Pond Granite near I-290 and Route 140 (Sample 401); NW block down motion determined from asymmetrical extensional shear bands, sigma-shaped porphyroclasts, and verging folds.
Three oriented thin sections were cut from mylonites in the vicinity of the I-290/Route 140 interchange. Kinematic indicators were ambiguous or absent in two of the thin sections. In one, the mylonitic foliation was poorly developed – a conjugate set of asymmetric extensional shear bands was present but it could not be determined which bands were synthetic to the fault motion and which were antithetic to it. The other thin section was ultramylonite that was so finely laminated and attenuated that no asymmetrical structures could be identified to aid in shear-sense determination.

The third thin section was of ultramylonitized Rocky Pond Granite (5.6B). This thin section contained a well-developed asymmetric extensional shear band fabric that indicated NW side down motion. Numerous σ porphyroclasts and verging microfolded quartz ribbons also indicated NW side down motion. The shear bands indicate that the flow type was general non-coaxial shear.

Ductility. Fine-grained garnets observed growing along the S plane of a shear band (Figure 5.6B) suggest that some of the deformation occurred at temperatures at or above the garnet zone of metamorphism (~550° C, Holland and Powell, 1998). Ribbons of feldspar observed in the thin section confirm that some deformation occurred above the minimum temperature for feldspar plasticity; however, these ribbons were later boudinaged and in some places brecciated suggesting that extension in the shear plane – and presumably general non-coaxial shearing – continued as temperatures fell below the temperature required for feldspar plasticity, about 450° C (Scholz, 1988). Quartz ribbons are not significantly affected by brittle processes indicating that the lower-temperature
deformation proceeded above temperatures required for quartz plasticity, roughly 300° C (Scholz, 1988).

_Rattlesnake Hill Fault_

**Location.** The Rattlesnake Hill fault (Figure 5.3) was recognized by Skehan (1968) during his studies of exposures in the Wachusett-Marlborough Tunnel. It continues the trend of the Clinton-Newbury fault and exhibits the same steep dip, which is why Castle and others (1976) believed it to be the main trace of the Clinton-Newbury fault in the Clinton and Shrewsbury area.

The Rattlesnake Hill fault forms the western contact of the Tadmuck Brook Schist near its junction with the Clinton fault in the Clinton quadrangle (Goldsmith, 1991b). South of Clinton Goldsmith (1991b) shows the fault cutting west, exposing Vaughn Hills Quartzite and forming the Vaughn Hills Quartzite-Rocky Pond Granite contact (PLATE 1). Between Rocky Pond and I-290 the Rocky Pond Granite intrudes the Vaughn Hills Quartzite, indicating that either some of the Rocky Pond Granite intruded after the fault motion or that the fault cuts through the granite. Since no evidence was found to indicate that the fault cuts through the Rocky Pond Granite south of Rocky Pond (e.g. no sheared rocks along its trace were discovered), it is the author’s interpretation that the Rocky Pond Granite intrudes the Rattlesnake Hill fault in this area. South of I-290 the fault forms the contact between the Sewall Hill Formation and the Vaughn Hills Quartzite for several kilometers. Near Route 9 the Vaughn Hills Quartzite is cut out and the Rattlesnake Hill Fault forms the contact between the Sewall Hill Formation and the
Tadmuck Brook Schist. Southwest of the Shrewsbury quadrangle, Goldsmith (1991b) shows the fault being offset by the N-S striking Pine Hill Fault (Figure 5.3) of Grew (1970). At this juncture the fault is rejoined by the Clinton Fault.

Description. The fault itself is not exposed in this area. Its location is inferred near I-290 by a rapid change in metamorphic grade from the lower greenschist facies in the Vaughn Hills Quartzite to the upper amphibolite facies in the Sewall Hill Formation. The change occurs in less than 200 meters. To the south, the existence of the Rattlesnake Hill fault is inferred from the presence of sheared rocks near its trace as projected along strike from I-290. To the north, it is inferred to follow the straight contact between the Rocky Pond Granite and Vaughn Hills Quartzite, much of which lies along an equally straight topographic depression. The typically unfoliated Rocky Pond Granite was observed to be sheared near this boundary in this study and by previous workers (Skehan and Abu-Moustafà, 1976; Munn, 1987). In the area between Rocky Pond and I-290, the Rocky Pond Granite intrudes the Vaughn Hills Quartzite. In the same area, no sheared rocks were observed in the Rocky Pond Granite, suggesting that this part of the granite intruded across the fault zone after fault motion had ceased. Skehan (1968) interpreted this fault to have a motion sense of NW over SE thrust, but modern methods of shear-sense determination (e.g. Lister and Snoke, 1984; Hanmer and Passhier, 1991) had not yet been developed when he made his interpretations (Goldstein, 1989).
Ball Hill Fault

Location. The Ball Hill fault (Figure 5.3) is named herein for the excellent exposures of mylonite along Smith Road in the northwestern part of Northborough northeast of Ball Hill. It separates the lenticular amphibolite bodies at the base of the Tadmuck Brook Schist from the biotite gneisses at the top of the Nashoba Formation.

The fault can be traced as far south as Route 9 where sheared amphibolite of the lower Tadmuck Brook is exposed near a Subaru dealership. To the north, the fault can be traced at least 35 kilometers to Ayer where well data confirms its existence (Kopera, personal communication, 2006). Castle and others (1976) showed a fault occupying the same structural position running from Ayer to Lawrence where they showed it joining the Clinton-Newbury Fault. Their interpretation was based on the abrupt truncation of magnetic lineaments and stratigraphic units within the Nashoba Formation, and the sharp boundary near Lawrence between the Tadmuck Brook Schist and plutonic rocks to the southeast. Jerden (1997) in his analysis of the Tadmuck Brook Schist noted that the contact with the Nashoba Formation was generally cut by mylonites with subhorizontal mineral stretching lineations.

Description. The fault zone itself is roughly 10 to 20 meters wide and consists of many layers of mylonite and ultramylonite that vary in thickness from 2 to 20 centimeters. The shear plane strikes north and dips very steeply to the west or is vertical. South of I-290 the strike of the fault changes so that it dips to the northwest. The mineral stretching lineation plunges 10-30 degrees to the north and is defined by quartz and feldspar rods in
the fault zone. Hornblende crystals form a lineation in the amphibolite bodies closest to
the fault (Figure 5.2A).

**Sense-of-shear.** Large (2-5 cm) rotated $\sigma$ and $\delta$ porphyroclasts in mylonite outcrops
along Smith Road indicate sinistral shear and are shown in Figure 5.7A-B. Sinistrally
verging folds and stair-step structures are also present. The exposed surface of this
outcrop is perpendicular to the foliation and slightly oblique ($\sim 10^\circ$) to the mineral
stretching lineation.

A number of thin sections were also examined to determine shear sense. Figure 5.8 shows part of a polished thin section (sample RVV-012) from the outcrop shown in
Figure 5.7. The orientation of muscovite fish and $\sigma$ and $\delta$ porphyroclasts all indicate
sinistral shear. Verging folds and foliation fish provide further evidence of sinistral shear
in this thin section. Another thin section from this outcrop (sample 206) contains a large
$\delta$ porphyroclast that was rotated sinistrally (Figure 5.9A). Just above this porphyroclast
is a complex microfolded quartz ribbon with a sinistral vergence.

Moderately-developed asymmetric extensional shear bands in the eastern part of
the Tadmuck Brook Schist (sample TSC) also indicate sinistral shear (Figure 5.10A). These shear bands also indicate that the flow type was general non-coaxial shear. The
same thin section also contains a monomineralic quartz ribbon with a moderately
developed $S_b$ fabric (Figure 5.10B). In monomineralic aggregates, these fabrics are
produced during non-coaxial flow when competing strain and recovery mechanisms
reach a steady state. Thus, the tendency of elongate minerals to rotate towards the shear
Figure 5.7. Shear-sense determination for Ball Hill Fault. Field images from a mylonite outcrop along Smith Road in Northborough (sampling location for RVV-012). Nickel for scale. Foliation is vertical and mineral lineation plunges gently N to NNE. Mantled porphyroclasts, verging folds, and stair-stepping structures all indicate sinistral strike-slip motion.
looking down strike/dip: 184, 90; trend/plunge: 004,34

Figure 5.8. Shear-sense determination for Ball Hill Fault. PPL image of Ball Hill Fault mylonite (sample RVV-012). $\sigma$- and $\delta$-porphyroclasts, mica fish, foliation fish, and verging folds all indicate sinistral strike-slip motion. Width of image is approximately 2 cm.
Figure 5.9. Shear-sense determination for Ball Hill Fault (continued). PPL image of Ball Hill Fault mylonite; δ-porphyroclast and verging fold indicate sinistral strike-slip motion (A); XPL image of Tadmuck Brook Schist amphibolite; weakly developed asymmetric extensional shear bands and σ-porphyroclasts indicate NW-side up oblique sinistral transpression (B).
Figure 5.10. Shear-sense determination for Ball Hill Fault (continued). PPL image of Tadmuck Brook Schist showing asymmetric extensional shear bands (A); XPL image of Tadmuck Brook Schist; the CPO of quartz in a polymineralic quartz ribbon defines a strain-insensitive S\textsubscript{b} foliation; diagrammatic strain ellipsoid is shown (B). Shear-sense determined is sinistral transpression.
plane is balanced by the tendency of recovery processes to form grains with their long axes parallel to the maximum instantaneous stretching axis ($\sigma_3$). The result is a crystallographic preferred orientation (CPO) which lies between the maximum instantaneous stretching axis and the shear plane, from which the shear sense can be determined. Refer to Hanmer and Passchier (1991) for a detailed discussion of $S_0$ fabrics and other kinematic indicators. In Figure 5.10B, the $S_0$ fabric indicates sinistral shear.

An amphibolite from the base of the Tadmuck Brook Schist near Route 9 in Shrewsbury was also examined (sample 1, Table 2.1). Figure 5.9B shows large hornblende porphyroclasts form $\sigma$ porphyroclasts that also indicate sinistral shear. Finer-grained hornblende crystals and plagioclase crystals define weakly developed asymmetric extensional shear bands, also sinistral, which indicate a general non-coaxial flow type. Since the mineral stretching lineations rake to the NNE at this sample, located in the southern part of the quadrangle near Route 9, the shear sense for this segment of the fault is NW over SE sinistral oblique thrust.

Thus, the motion determined for the Ball Hill Fault is sinistral transpressive strike-slip in the northern part of the quadrangle and NW over SE sinistral oblique thrust in the southern part of the quadrangle.

**Ductility.** Textures in most thin sections indicate that feldspar was deforming plastically. Figure 5.8 and 5.9A both show ribbons of quartz and of feldspar. Also, small subgrains and recrystallized grains developed and grew along the edges of some of the larger feldspar porphyroclasts and formed asymmetric tails. In figure 5.9B, strain is
concentrated along the shear bands defined by fine-grained feldspar and hornblende – two typically competent minerals. The hornblende porphyroclasts also deform plastically, generating small sub-grains that recrystallize and form the asymmetric tails of the σ structures.

Thin section textures indicate that deformation along the Ball Hill Fault was dominantly ductile and in the zone of temperatures required for feldspar and hornblende plasticity (>450-500° C; Scholz, 1988).

*Sulfur Hill Shear Zone*

**Location.** The Sulfur Hill shear zone is named here for the exposures of mylonite at the base of Sulfur Hill a few kilometers east of Mount Pisgah in Northborough (Figure 5.3). It separates two members of the Nashoba Formation – the sillimanite-biotite gneiss to the west and the quartzofeldspathic gneiss and granofels to the east.

The shear zone can be traced north to the quadrangle boundary with the Clinton quadrangle and south nearly to I-290 for a trace length of at least 5 kilometers.

**Description.** The shear zone is at least 5 meters wide but may be up to tens of meters wide. It consists of layers 20 centimeters to 1 meter thick alternating between quartzofeldspathic mylonite and more competent fine-grained amphibolite with garnet coticule layers (Figure 2.2D). At the northwest edge of the shear zone the sillimanite-biotite gneiss has been sheared as well.
The shear plane strikes NNE and dips steeply to the WNW or is vertical and the mineral stretching lineation is defined by subhorizontal prismatic sillimanite crystals.

**Sense-of-shear.** In outcrop, amphibolite layers form domino structures (Figure 5.2E). The dominos' thicknesses range from 10 to 50 centimeters. They are ambiguous as kinematic indicators since they can be explained by several different shear regimes (Hanmer and Passchier, 1991).

In thin section, the sillimanite-biotite gneiss abutting the shear zone (samples NSG and RVV-011) has weakly- to moderately-developed asymmetric extensional shear bands (Figure 5.11) that indicate sinistral shear in a general non-coaxial flow. Thus, the motion determined for the Sulfur Hill shear zone is sinistral strike-slip.

**Ductility.** Sample RVV-011 (Figure 5.11B) has large feldspar porphyroclasts that have dynamically recrystallized to produce smaller grains around their edges. These small grains form tails and ribbons in some places. This indicates that deformation occurred in the zone of feldspar plasticity. In addition, sillimanite crystals form some fabric elements of the asymmetric extensional shear bands (such as the S planes) indicating that deformation proceeded after the thermal peak that produced the sillimanite assemblage. Ubiquitous boudinaged sillimanite crystals are farther evidence that the deformation post-dates the growth of sillimanite – it also corroborates the inferred general non-coaxial flow type as it demonstrates the presence of extension in the shear zone. The amphibolite

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Figure 5.11. Shear-sense determination for Sulfur Hill shear zone. PPL image of sillimanite-biotite gneiss near Sulfur Hill shear zone (A); PPL image of part of polished thin section (sample RVV-011). Width of image is roughly 2cm (B); weakly developed asymmetric extensional shear bands indicate general non-coaxial shearing with a sinistral strike-slip motion sense.
domino structures also attest to extension in the shear zone and indicate that the mineral hornblende was behaving in a brittle or semi-brittle manner.

Assabet River Fault

Location.

The Assabet River fault (Figure 5.3) is exposed across the Shrewsbury quadrangle along Route 20 with a trace length of 14 kilometers. Its total trace length in the Nashoba terrane may be as much as 85 kilometers (Goldsmith, 1991b). In the Shrewsbury quadrangle it is drawn as the boundary between the Nashoba and Marlboro Formations (PLATE I).

Description.

The fault is a zone several hundred meters wide that extends from the Nashoba Formation/Marlboro Formation boundary northwestward into the rusty schist member of the Nashoba Formation. The zone consists of numerous subparallel shear zones 1-10 meters wide that may be discontinuous along strike. The shear zones include protomylonitic pegmatite, ultramylonite, quartzo-feldspathic mylonite, sheared granites, and phyllonitized rusty schist. Most of these fault-rock types occur in alternating layers 20 centimeters to 2 meters thick, but some layers may reach thicknesses of 3, 4, or even 5 meters. The shear planes generally strike northeast and dip moderately to steeply northwest (Figure 5.4). The mineral stretching lineation plunges moderately to the north, although north of Northborough Center these lineations plunge nearly directly down-dip,
raking slightly towards the north (Figure 5.5). Stretching lineations are defined by rods of quartz and feldspar.

**Sense-of-shear.** In thin section the most useful rocks for determining shear sense were the sheared granites and quartzo-feldspathic mylonites. The protomylonitic pegmatite had not yet developed diagnostic shape fabrics and in the ultramylonite they were too highly attenuated.

In the mylonitized granite (sample 604), a strong C-S fabric is developed (Figure 5.12A). The biotite accumulated much of the strain in thin discontinuous C planes. The spacing of the C planes appears to be controlled by the size of the larger feldspar grains (2-5 mm). Elongate quartz crystals form an S₀ fabric that in part defines the S planes of the C-S fabric. Large σ porphyroclasts are also common. The mineral stretching lineation for this sample was nearly down-dip, raking slightly to the north. The shear-sense determined was NW over SE thrust with a small component of oblique sinistral shear.

The quartzo-feldspathic mylonite (sample 813) has a C-S fabric that is only weakly developed (Figure 5.12B). The relative paucity of mica (less than 5% of the mode) may have contributed to the poor development of C planes. Nevertheless, the C-S fabric is defined well enough to indicate sinistral shear-sense. The mylonite also contains numerous σ-shaped feldspar porphyroclasts and some δ-shaped garnet porphyroclasts, as well as mica and feldspar fish. These also indicate sinistral shear. The mineral stretching lineation for this sample plunges moderately to the NNE and the foliation strikes NE. Motion sense is sinistral strike-slip with an oblique NW over SE thrust component.
Figure 5.12. Shear-sense determination for Assabet River Fault. XPL image mylonitized granite showing σ porphyroclasts and well developed C-S fabric. NW side up thrust sense of motion (A); PPL image of quartzo-feldspathic mylonite showing weakly developed C-S fabric, d garnet porphyroclasts, f feldspar porphyroclasts, and feldspar and mica fish. NW side up oblique sinistral motion sense (B).
No indications of pure shear were detected in the Assabet River Fault so the flow type is inferred to be simple shear. The sense of motion was oblique sinistral NW over SE thrust with the sinistral component dominant in the southern part of the quadrangle and the thrust component dominant in the northern part. Both quartz and feldspar behaved plastically indicating conditions in the ductile zone of deformation (i.e. temperatures above \( \sim 450^\circ C \)).

**Bloody Bluff Fault**

**Location.** The Bloody Bluff fault is a young (probably Mesozoic) brittle fault that marks the easternmost limit of the Nashoba terrane in east central Massachusetts (Figure 5.3) (Skehan, 1968; Castle and others, 1976; Goldsmith 1991b). From southwest of Westborough to southern Connecticut, the terrane boundary is known as the Lake Char fault (Dixon and Lundgren, 1968), and in southernmost Connecticut where the fault strikes east-west it is called the Honey Hill fault (Dixon and Lundgren, 1968). In Massachusetts, the Bloody Bluff fault cuts zones of mylonites and cataclasites on the west edge of the Avalon terrane that can be more than 3 km wide. In Burlington, Lexington, and Concord these rocks are referred to as the Burlington Mylonite Zone (Castle and others, 1976). This zone of mylonitic rocks east of the terrane boundary thins to the southwest with its last expression exposed in Westborough. The Bloody Bluff fault is not exposed in the Shrewsbury quadrangle, although some Avalon rocks near near the trace of the fault have a weak shear foliation.
The location of the Bloody Bluff fault in the Shrewsbury quadrangle is inferred from contrasting lithologies on either side of it and from its mapped trace in the adjacent 7.5' geologic quadrangles. The outcrop control consists of an amphibolite-grade hornblende gneiss on the Nashoba terrane side (northwest) and weakly altered granite and weakly sheared Westboro Quartzite on the Avalon terrane side (southeast).

Description. Goldstein (1989) conducted a detailed study of the Bloody Bluff fault and its correlatives in Connecticut and indicated two sets of lineations for the Bloody Bluff fault and Burlington Mylonite Zone in Massachusetts: a northwest-plunging group was defined by chlorite streaks and was associated with Mesozoic brittle faulting; the second group was defined by quartz and feldspar rods plunging gently to the northeast or southwest and was inferred to reflect the motion direction of mid-Paleozoic ductile mylonites. One lineation in the Shrewsbury quadrangle was measured near the inferred trace of the Bloody Bluff fault in this study and it plunged roughly down-dip to the northwest at 64° (Figure 5.5). The lineation was defined by chlorite streaks and is inferred to belong to Goldstein’s younger group related to Mesozoic faulting.

Goldstein (1989), Kohut (1999), and Kohut and Hepburn (2004) all studied the mylonites adjacent to the Bloody Bluff fault in the Burlington Mylonite Zone and all reported that the majority of micro-structural shear indicators indicate sinistral strike-slip motion with a minor NW over SE thrust component.
Discussion and Summary of Faults

Observed fault motion throughout the Shrewsbury quadrangle was largely sinistral strike-slip, west side to the south, with varying amounts of an oblique NW over SE thrust component. Figure 5.13 summarizes the shear-sense determined for faults and shear zones in the Shrewsbury quadrangle. Note that the shear-sense for the Bloody Bluff fault was established by Goldstein (1989) and not observed in this study.

The mylonites from Goldstein’s (1994) Wachusett Mylonite Zone indicate NW down normal fault motion in a general non-coaxial flow regime. Its motion is unique among the mylonites studied.

The Ball Hill fault north of I-290 and the Sulfur Hill Shear zone both have largely sinistral strike-slip motions, also in a general non-coaxial flow regime; the Ball Hill Fault south of I-290 has a slightly different strike and lineation and has an oblique sinistral transpressive motion sense.

The Assabet River Fault departs from the general non-coaxial flow of the faults to the northwest and has features indicative of simple shear alone. North of I-290 its motion appears to be dominantly NW over SE east thrust with a minor sinistral component, while south of I-290 the motion is dominantly sinistral strike-slip with a minor NW over SE thrust.

Textures in thin section indicate that at least some deformation in all of these faults occurred in the ductile zone of deformation at temperatures above 450° C. In the Wachusett Mylonite Zone there is evidence that deformation also proceeded at the higher temperatures of at least the garnet zone (550° C) and at the lower temperatures of the
Figure 5.13. Observed shear sense for major faults and shear zones of the Shrewsbury quadrangle. CF=Clinton Fault; RHF=Rattlesnake Hill Fault; WMZ=Wachusett Mylonite Zone; BHF=Ball Hill Fault; SHSZ=Sulfur Hill shear zone; ARF=Assabet River Fault; BBF/BMZ=Bloody Bluff Fault/Burlington Mylonite Zone.
brittle-ductile transition zone (300-450° C). In the Ball Hill fault, Sulfur Hill shear zone, and Assabet River fault, all of the deformation took place in the ductile zone of deformation at temperatures above 450° C. Some of the deformation in the Sulfur Hill shear zone post-dated the thermal peak that produced the sillimanite mineral assemblages when temperatures were probably greater than ~600° C.

There is a variation in motion sense between the northern and southern portions of the quadrangle for both the Ball Hill and Assabet River faults. The changes in motion sense are mostly attributable to changes in the orientation of the mineral stretching lineations. These variations might be caused by later large scale folding or by the rotation of large rigid fault blocks. In addition, it is possible that the lineations for each fault are not all time-equivalent and represent fault motions that varied slightly throughout a long history of deformation. Future structural work should aim to measure a large number of stretching lineations from across the quadrangle (less than 30 were measured in this study). Such a study might farther elucidate the cause of variations in stretching lineations in the Shrewsbury area.
Chapter 6. MONAZITE DATING

BACKGROUND

Electron Probe Microanalysis

Electron probe microanalysis is a relatively new in situ dating method used to directly date monazite crystal domains related to metamorphic or deformational events. Since the method is non-destructive and uses standard polished thin sections, monazite grains can be studied petrographically before and after the analyses to identify textural clues linking the monazite grains to metamorphic or deformational events. The electron microprobe can measure the trace levels of U, Th, and Pb present in monazite on a spot as small as one micron across with enough precision to solve the age equation of Montel and others (1996):

\[
Pb = \frac{Th}{232} \times \left[ \exp\left(\lambda_{232}\tau\right) - 1 \right] \times 208 + \\
U/238.04 \times 0.9928 \times \left[ \exp\left(\lambda_{238}\tau\right) - 1 \right] \times 206 + \\
U/238.04 \times 0.0072 \times \left[ \exp\left(\lambda_{235}\tau\right) - 1 \right] \times 207
\]  

Equation (6-1)

Pb, U, and Th are concentrations in parts per million, \(\lambda\)s are radioactive decay constants, and \(\tau\) is the age. This equation for a chemical age depends on two important assumptions: that the only lead present is radiogenic in origin; and, that there is no subsequent diffusion or loss of lead.
**Monazite**

Monazite is a rare earth element phosphate mineral ([Ce, La, REE]PO₄) that occurs as an accessory mineral in felsic igneous rocks and medium- to high-grade metamorphic rocks. It commonly contains 15 weight percent or more of Th and up to 5 weight percent of U (Parrish, 1990). Parrish (1990) demonstrated that the mineral incorporates only negligible amounts of initial Pb (less than 1ppm) but typically accumulates radiogenic Pb in concentrations well above the detection limits of the electron microprobe after about 100 million years.

Metamorphic monazite crystals commonly begin to form in the middle amphibolite facies. Although monazite has long been considered to be a product of apatite breakdown, recent work suggests that monazite can also be formed during reactions among common silicates (Kohn and Malloy, 2004). Kohn and Malloy (2004) suggested that the major monazite-in isograd is closely tied to the staurolite-in isograd. The rocks of that study were buried to pressures in excess of 8 kilobars and the temperature of their “in” reaction was estimated at 600° C. The rocks of this study were only subjected to pressures of 3-6 kilobars (Munn, 1987; Bober, 1990), so if monazite-in is tied to the silicate reactions of staurolite-in, then its “in” temperature in this study area may have been as low as 500° C.

**Genesis of Chemical Zones in Monazite**

Monazite crystals commonly exhibit complex chemical zoning similar to that of zircon (Figure 6.1). These zones reflect differences in the amount of Y, U, and Th incorporated
into different parts of the crystal. Not surprisingly zones with contrasting concentrations of U and Th typically yield different dates when analyzed.

Understanding the origin of different domains in a crystal is extremely important when interpreting the geologic significance of these different ages (Williams and others,
1999; Crowley and Ghent, 1999). For the purpose of this study, five types of crystal domains were defined and identified from the nature of their chemical zones: overgrowth and recrystallized domains were the most common; other domains studied were primary metamorphic cores, igneous cores, and detrital grains.

**Overgrowth Domains.** Monazite is particularly resistant to lead diffusion with a closure temperature of at least 700° C (Cocherie and others, 1998) and possibly as high as 900° C (Braun and others, 1998). Rather than being reset during thermal events subsequent to its formation, monazite tends to form chemically distinct crystal overgrowths. When an overgrowth domain forms, the original grain boundary is preserved keeping the earlier chemical zoning pattern intact. The new overgrowth may grow evenly around the grain; or, if the crystal is subjected to non-coaxial deformation, an overgrowth may grow in the direction of maximum instantaneous stretching for the flow. The overgrowth does not form at the expense of the earlier crystal’s integrity (Figure 6.1); it incorporates new materials from the intergranular fluids.

The chemical constituents of monazite – LREEs and phosphate – can be limiting so that overgrowths may not be able to grow even though a rock may attain a high enough temperature. However, common silicates have been shown to contain enough of these elements to form monazite. Specifically, Kohn and Malloy (2004) found that feldspars and garnet contained high enough phosphate concentrations and micas contained enough LREEs to form monazite. The implication of their study is that
reactions among these common silicates may liberate enough LREEs and phosphate to produce monazite as a reaction byproduct.

The temperatures and pressures at which overgrowths of monazite can form are assumed to be at least as high as those required to form monazite in the first place, presumably at least 500-600° C at pressures of 3-8 kbar (Kohn and Malloy, 2004).

Recrystallized Domains. Although monazite is not reset by most thermal events, it is susceptible to dissolution by fluids even at the relatively low temperatures of the greenschist facies. The introduction of fluids can effectively mobilize some trace elements in the crystal structure. When this happens parts of a grain may “dissolve” and recrystallize in place – not really changing the structure of the grain, but chemically producing a new domain where U and Th concentrations reflect the homogenization of whatever prior zones were dissolved. Accumulated radiogenic Pb is expelled from a domain’s crystal lattice when it recrystallizes. These new domains remain within the original grain boundaries of the crystal and have very sharp boundaries with other domains – as fine as 2 microns or less (Montel and others, 1996). Because of their nature these new domains tend to truncate existing chemical zoning patterns (Figure 6.1) (analogous to an erosional surface truncating a set of crossbeds).

Recrystallized domains have been observed over a wide range of temperatures from ~400° C (Poitrasson and others, 1996) up to ~900° C (Braun and others, 1998). Fluids must be present for these reactions to take place (Braun and others, 1998; Cocherie and others, 1998; Crowley and Ghent, 1999).
Other domains. There are three other types of domains discussed in this text: metamorphic core, igneous core, and detrital domains.

Domains representing the primary metamorphic crystallization of monazite are typically the innermost core domains and do not truncate other domains. This study treats them essentially the same as overgrowths – they are interpreted to form above 500-600° C.

An igneous core domain is simply a core of a monazite crystal that is believed to have originally been an igneous monazite. These cores are typically euhedral and have better terminations than a metamorphic core. This is due to the fact that in felsic intrusions monazite forms relatively early. Igneous core domains form during the early cooling of an igneous body.

A detrital domain usually cores a grain with multiple overgrowths or is a small lone grain. Detrital domains are typically weathered or rounded from having been reworked as sediment and can come from the weathering of a metamorphic or an igneous rock. The age of a detrital domain is the age of an igneous or metamorphic event prior to or coeval with the deposition of the sedimentary rock in which it is found.
THIS STUDY

Samples Descriptions

Polished thin sections were cut from 3 samples: one sample each from the Sulfur Hill shear zone, the Ball Hill fault, and the Assabet River fault (Figure 6.2). All samples were cut parallel to the mineral stretching lineation and perpendicular to the shear plane.

Grains from an additional sample, RVV-004, appear in some figures. This sample comes from the Assabet River Fault several kilometers east of the Shrewsbury quadrangle near the intersection of I-290 and I-495. More detailed analysis and discussion of this sample can be found in Markwort and others (2007) and Stroud (in preparation). More detailed location descriptions for all samples can be found in APPENDIX I.

Ball Hill Fault. Sample RVV-012 was collected from an outcrop along the west side of Smith Road several hundred meters north of its intersection with Green Street and Ball Street in Northborough, MA (NAD27 UTM Coordinates: 0279922 m Easting, 4692889 m Northing). The outcrop is made up of alternating layers of mylonite and ultramylonite with thicknesses ranging between 2 and 20 cm thick (Figure 5.7) and is mapped as the Ball Hill fault — the contact between the Nashoba Formation and the Tadmuck Brook Schist. Four monazites from this sample were mapped and dated. Fault motion for the Ball Hill fault was determined to be sinistral strike-slip in a NNE-SSW direction in the vicinity of Sample RVV-012. In the southwest portion of the Shrewsbury quadrangle the
Figure 6.2. Monazite dating sample locations. Detailed location descriptions given in APPENDIX I. For abbreviations, see Figure 5.13.
motion had an additional component of oblique NW over SE thrust. Active deformation along the Ball Hill fault took place at temperatures above 450° C.

Sulfur Hill Shear Zone. Sample RVV-011 was collected from an outcrop along the west side of South Street in Berlin, MA (NAD27 UTM Coordinates: 0282496 m Easting, 4694428 m Northing). The outcrop is migmatitic garnet-sillimanite-biotite gneiss mapped as Snsg. A thin section from the same outcrop (sample 5, Table 2.1) had a mode of 33% biotite, 19.5% quartz, 15% sillimanite, 14% plagioclase (An24), 12.5% garnet, 5% microcline, and 1% opaque minerals. The outcrop forms the western margin of the Sulfur Hill shear zone. The motion in the shear zone was determined to be sinistral strike-slip oriented in a NNE-SSW direction with an additional component of extension parallel to the shear direction. The Sulfur Hill shear zone was active at temperatures above 450° C and at least some of the deformation took place after the thermal peak that produced abundant sillimanite.

Assabet River Fault. Sample RVV-007 was collected from an outcrop along the west side of RT-20 south of RT-9 and just north of Cherry Street in Shrewsbury, MA (NAD27 UTM Coordinates: 0277845m Easting, 4682346m Northing) (Figure 6.2). The rock is typical Nashoba Formation rusty schist (Snrs) with abundant garnet, sillimanite, and K-feldspar porphyroblasts. A sample from the same outcrop (sample 6, Table 2.1) had a mode of 22% biotite, 19% microcline porphyroblasts, 14% sillimanite, 11.5% quartz, 10% sillimanite porphyroblasts, 9% plagioclase of An28, 8% microcline, and 6.5%
opaque minerals. RVV-007 contained a ~3cm garnet porphyroblast that comprised roughly 65% of the sample’s mode. The trace of the Assabet River fault was drawn approximately 100 meters southeast of the outcrop, which had been subjected to significant shearing. Motion on this fault was determined to be oblique sinistral thrust with the NW side moving up. The motion was in a roughly N-S direction. The Assabet River fault was active at temperatures in the ductile zone of deformation above 450° C.

*Dates and Textures of Analyzed Grains*

Element maps of each polished thin section (using elements such as Ce, Ca, P, and Mg) were completed to identify monazite grains. These grains were subsequently probed to create grain element maps for Y, U, Th, and Ca. False-color images of these maps were generated in Adobe Photoshop using the same color table and histogram stretch for every grain. These images were studied to identify and classify crystal domains. By using the same color table and histogram, it was also possible to compare the Y, U, and Th levels of different monazite grains, allowing populations of chemically similar domains to be identified.

Zones were identified as either metamorphic core, overgrowth, recrystallized, detrital, or igneous core domains based on the criteria discussed above (Montel and others, 1996; Crowley and Ghent, 1999; Kohn and Malloy, 2004).

The monazite grains’ petrographic textures were also observed with the help of backscattered electron and optical images. A grain’s location in a thin section and the
minerals around it are of paramount importance when interpreting the significance of ages assigned to that grain (Williams and others, 1999; Shaw and others, 2001).

Following the method set forth in Williams and others (2006), 5-15 spots in each homogenous chemical domain were analyzed for U, Th, and Pb in order to solve equation 6-1. These analyses were then averaged to determine a date for that particular chemical domain. All spots analyzed for a domain were used in the calculation of the date and error unless otherwise noted. The short-term random error for a date is typically reduced to less than 1% (2σ of ~10 m.y. or less) with 5 or more analyses (Williams and others, 2006). Short-term random error is attributed to counting uncertainty of detectors, and minute variations in operating and environmental conditions. All dates are reported in millions of years at the 95% confidence level with 2σ errors that represent the short-term random error (see APPENDIX II for calculations). Short- and long-term systematic error are not figured into the reported dates and are caused by uncertainties in background levels of trace elements and the uncertainties for values of decay constants. To mitigate these systematic uncertainties a consistency standard was run before each analytical session. Data from the consistency standard runs is reported in APPENDIX III.

Chemical dates from all grains can be found in Table 6.1. These dates do not necessarily have geological significance until they are interpreted (in the next section). When interpreted, if a date or the weighted mean of a group of dates is construed to have geological significance, then an age will be reported.
<table>
<thead>
<tr>
<th>Sample #</th>
<th>Grain #</th>
<th>Domain Name</th>
<th>Longest Dimension (in μm)</th>
<th>Number of Chemical Zones</th>
<th>Textural Position</th>
<th>Date (Ma)</th>
<th>Error (2σ)</th>
<th>Number of Analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>RVV-007</td>
<td>7m1</td>
<td>core</td>
<td>15</td>
<td>2</td>
<td>included in edge of sil porphyroblast</td>
<td>431</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>RVV-007</td>
<td>7m3</td>
<td>core</td>
<td>50</td>
<td>2</td>
<td>in sil-bit matrix</td>
<td>376</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>RVV-007</td>
<td>7m3</td>
<td>rim</td>
<td>30</td>
<td>1</td>
<td>included in edge of gt porphyroblast</td>
<td>452</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>RVV-007</td>
<td>7m4</td>
<td>–</td>
<td>30</td>
<td>1</td>
<td>in sil-bit matrix</td>
<td>390</td>
<td>8</td>
<td>13</td>
</tr>
<tr>
<td>RVV-007</td>
<td>7m5</td>
<td>–</td>
<td>40</td>
<td>1</td>
<td>in sil-bit matrix</td>
<td>335</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>RVV-007</td>
<td>7m6</td>
<td>left</td>
<td>55</td>
<td>1</td>
<td>in sil-bit matrix</td>
<td>392</td>
<td>16</td>
<td>3</td>
</tr>
</tbody>
</table>

| RVV-011  | 11m1    | low-Y core  | 100                       | 3                       | in sil-bit matrix asym. shear band | 345       | 6          | 7                 |
| RVV-011  | 11m1    | high-Y rim  | 40                        | 3                       | between recrystallized grains in qtz stringer | 376       | 8          | 7                 |
| RVV-011  | 11m2    | low-Y core  | 90                        | 6                       | between fsp and bt in matrix | 410       | 4          | 8                 |
| RVV-011  | 11m3    | low-Y mantle| 155                       | 5                       | between recrystallized qtz grains and touching bt near edge of fsp porphyroblast | 369       | 4          | 8                 |
| RVV-011  | 11m5    | mantle      | 100                       | 4                       | between qtz, sil, and bt in matrix | 396       | 6          | 6                 |
| RVV-011  | 11m6    | low-Y core  | 100                       | 4                       | between qtz, sil, and bt in matrix | 396       | 6          | 6                 |
| RVV-011  | 11m7    | core        | 90                        | 3                       | between qtz, sil, and bt in matrix | 384       | 10         | 8                 |

Table 6.1. Monazite dates. Each date is identified by the sample number, grain number, and domain name. The type of domain is discussed in the text.

* The 2σ error presented is the standard deviation of the mean (SDOM); see APPENDIX II for calculations and discussion.
Ball Hill Fault—RVV-012. Four monazites were analyzed from sample RVV-012—12m1, 12m2, 12m3, and 12m4. To aid the reader in following the descriptions of individual monazite grains and their crystal domains, refer to the following figures.

Figure 6.3 shows the location of these grains on a PPL image of the polished probe section. Figure 6.4 shows the textural context of each grain in a backscattered electron image with a 1.5 mm wide field of view; this figure also includes insets with the yttrium element maps for each grain. Finally, Figure 6.5 shows the location of the individual spot analyses for each domain on backscattered electron images of each monazite grain.

**Grain 12m1** is located in the middle of a small fractured feldspar grain. A large fracture transecting the feldspar contacts but does not cut the monazite (Figure 6.4). The monazite has a euhedral core with a date of 438+/-4 Ma and two asymmetrical rimming overgrowth domains with dates of 392+/-4 Ma and 397+/-4 Ma (Figure 6.5A).

**Grain 12m2** is located at the edge of a feldspar porphyroclast within a 200 micron thick mantle of matrix material mingled with material derived from the feldspar. The edge of the feldspar is jagged with quartz and mica embayments. The monazite crystal itself is largely destroyed except for a small remaining core. The tiny core was dated at 422+/-6 Ma. Just left of the core, another small domain was dated as 422+/-8 Ma. Ten to twenty microns to the right of the core, another small remaining part of the monazite crystal was analyzed 5 times. Two of those analyses yielded a date of 383+/-8 Ma while the other three analyses yielded a date of 426+/-4 Ma (Figure 6.5B).

**Grain 12m3** is located in the middle of a fractured feldspar grain. The monazite is small and rounded and surrounded by thin fractures that cut across the feldspar to small
Figure 6.3. PPL image of sampe RVV-012. Locations of analyzed monazite grains are indicated. Field of view is approximately 3.5 cm.
Figure 6.4. False color backscattered electron images of monazite grains from sample RVV-012. Inset for each grain shows yttrium element map. Y maps are adjusted to the same color levels; levels for the BSE images may vary slightly.
Figure 6.5. BSE images showing the location of electron microprobe spot analyses for grains from sample RVV-012. Refer to text for descriptions of monazites and characterizations of the crystal domains. A=12m1; B=12m2; C=12m4; D=12m3.
biotite inclusions, sericite patches, and to the surrounding matrix. The monazite is very weakly zoned in Y. The left side of the grain was dated at 419+/-6 Ma and the middle of the grain was dated at 417+/-8 Ma (Figure 6.5D).

**Grain 12m4** is located in the middle of a large fractured feldspar grain. It is in contact with the fracture network as are a nearby grain of biotite and a patch of sericite (light green and light blue in Figure 6.4) – possible sources of LREEs and phosphorous. The monazite has two Y domains – a core and a large mantling overgrowth. The Th zoning is more complex, though. The mantling overgrowth seen in Y is divided into a thick low-Th inner mantle and a thin high-Th outer rim. The core and inner mantle overgrowth domain yielded dates of 431+/-2 Ma and 431+/-<1 Ma respectively. The outer rimming overgrowth domain yielded a date of 427+/-10 Ma.

**Sulfur Hill Shear Zone—RVV-011.** Six monazites were analyzed from sample RVV-011 – 11m1, 11m2, 11m3, 11m5, 11m6, and 11m7. To aid the reader in following the descriptions of individual monazite grains and their crystal domains in RVV-011, refer to the following figures. Figure 6.6 shows the location of these grains on a PPL image of the polished probe section. Figure 6.7 shows the textural context of each grain in a backscattered electron image with a 1.5 mm wide field of view; this figure also includes insets with the yttrium element maps for each grain. Finally, Figure 6.8 shows the location of the individual spot analyses for each analyzed domain on backscattered electron images of each monazite.
Figure 6.6. PPL image of sample RVV-011. Locations of analyzed grains are indicated. Width of image is approximately 3.5 cm.
Figure 6.7. False color backscattered electron images of monazite grains from sample RVV-011. Inset for each grain shows yttrium element map. Y maps are adjusted to the same color levels; levels for the BSE images may vary slightly.
Figure 6.8. BSE images showing the location of electron microprobe spot analyses for grains from sample RVV-011. Refer to text for descriptions of monazites and their crystal domains. A=11m5; B=11m3; C=11m7; D=11m1; E=11m2; F=11m6.
Grain 11m1 is located in the matrix in a band of biotite, sillimanite, and quartz. The monazite is in direct contact with biotite, sillimanite, and quartz grains (Figure 6.7). It is weakly zoned in Y with a high-Y recrystallized rim domain. The core was dated at 345 +/- 6 Ma and the recrystallized rim was dated at 343 +/- 10 Ma.

Grain 11m2 is located in a large ribbon of quartz that entrains some biotite. The monazite is small and rounded and located along a quartz-quartz grain boundary about halfway between two nearby biotite crystals. It is zoned in Y with the core yielding a date of 376 +/- 8 Ma and a recrystallized rim domain yielding a date of 354 +/- 4 Ma (Figure 6.8).

Grain 11m3 is located in the middle of a small fractured feldspar crystal (Figure 6.7). The monazite is in contact with biotite crystals that have impinged along the fractures to the middle of the feldspar crystal. The monazite is concentrically zoned in Y with a low-Y core, a higher-Y overgrowth mantle, a low-Y overgrowth mantle, and a recrystallized high-Y rim that truncates the low-Y mantle. The core and inner mantle were not analyzed but the low-Y mantle was dated at 410 +/- 4 Ma and the recrystallized rim was dated at 376 +/- 12 Ma.

Grain 11m5 is located between large grains of quartz and feldspar and a smaller biotite. The feldspar it touches is part of a very large feldspar aggregate. The monazite is large and irregularly shaped and has many different chemical zones (Figure 6.7). The innermost zone is low in Y and was dated at 382 +/- 4 Ma. An overgrowth mantle that is somewhat higher in Y was dated at 374 +/- 6 Ma. Most of the right side of the grain has been recrystallized in stages. The first recrystallization truncated much of the core and
mantle and was dated at 369+/-4 Ma. The second recrystallization mostly affected the first recrystallization and was dated at 363+/-2 Ma.

**Grain 11m6** is located in the matrix between a mass of sillimanite crystals, quartz, and biotite. The monazite is zoned in Y and has a core, a low-Y overgrowth mantle, and a high-Y recrystallized rim (Figure 6.7). The core yielded a date of 411+/-6 Ma; the overgrowth mantle, a date of 396+/-6 Ma; and, the recrystallized rim, a date of 384+/-10 Ma (Figure 6.8).

**Grain 11m7** is located in the matrix between several grains of biotite and some quartz. The monazite is actually an aggregate of three small monazite crystals that all share a low-Y core zone rimmed by a high-Y recrystallized zone (Figure 6.7). The core was dated at 372+/-6 Ma and the recrystallized rim was dated at 363+/-10 Ma.

**Assabet River Fault—RVV-007.** Five monazites were analyzed from sample RVV-007 – 7m1, 7m3, 7m4, 7m5, and 7m6. More detailed analysis and discussion of RVV-007 can be found in Stroud (in preparation, 2007). Optical images, 1.5mm field of view backscattered electron images, and backscattered electron spot images are not available for RVV-007. See Stroud (in preparation) for more detailed analysis.

**Grain 7m1** is located inside of and near the edge of a large sillimanite porphyroblast. The monazite is small and rounded and is zoned in Y with a low-Y core and a higher-Y rim. The core yielded a date of 431+/-8 Ma and the rim was too small to analyze.
Grain 7m3 is located in the sillimanite-quartz-biotite matrix. The monazite is zoned in Y with a low-Y core and a higher-Y recrystallized rim. Both rim and core are truncated themselves by the growth of other minerals. The core was dated at 378+/-2 Ma and the recrystallized rim was dated at 371+/-4 Ma.

Grain 7m4 is located within and near the edge of a very large garnet porphyroblast. The monazite is small and rounded with a slightly irregular shape. The crystal is not chemically zoned and yielded a date of 452+/-10 Ma.

Grain 7m5 is located in the sillimanite-quartz-biotite matrix. The monazite is small and irregularly shaped. The crystal is very weakly zoned in Y with the higher Y towards the edges of the crystal. A single date of 390+/-6 Ma was obtained for the crystal.

Grain 7m6 is also located in the sillimanite-quartz-biotite matrix. This monazite is also small but shaped as a rounded polygon. It is not zoned but a low-Y linear feature transects the crystal dividing it into two parts. The left side of the crystal was dated at 392+/-16 Ma and the right side was dated at 335+/-10 Ma.

Assabet River Fault—RVV-004. A number of monazite crystals were also analyzed from sample RVV-004, which comes from the Assabet River fault in the vicinity of the I-290/I-495 interchange (Figure 6.2). Detailed analysis and discussion of this sample and monazites from it can be found in Stroud (in preparation). In the discussion of ages below, monazite grains from RVV-004 are mentioned or shown in figures where they are used as part of an age population in this study.
**Interpretation of Dates and Textures**

After all of the grains were analyzed and their various crystal domains were dated, Gaussian probability distributions were plotted for each dated domain. Each curve’s peak is at the mean age for that domain, the width of the curve reflects the $2\sigma$ confidence interval for short-term random error, and the area beneath the curve is 1.

A single curve summarizing all of the data was then constructed by summing each individual probability distribution curve (Figure 6.9). This curve has peaks where there are multiple dates that overlap within error and troughs where no dates were recorded. The height of these peaks and troughs are of arbitrary scale, but do represent the relative frequency of the reported dates.

From this curve populations of similar dates were identified and the individual crystal domains they represented were subsequently studied together. These populations included the date ranges (in Ma) 435-400, 400-385, 385-360, and 360-305. In some cases these populations could be farther classified or subdivided on the basis of core-rim relationships, grain texture, or chemical zoning. In other cases, populations of similar dates shared little else in common. In addition, two domains with unique ages were studied alone: 7m4 and 12m1core.

For every distinct population of dates that could be interpreted to represent a single event, a weighted mean age was calculated (see APPENDIX II for calculations). That age is interpreted to represent a particular geological event. The ages of these events and their significance as well as the evidence leading to those interpretations are detailed below.
Figure 6.9. Summary of all monazite dates from samples RVV-012, RVV-011, RVV-007, and RVV-004. Curve represents the sum of every monazite domain's age probability distribution; horizontal scale is arbitrary but represents the relative abundance or lack of dates of a given age. Gray bars show ages of some previously dated igneous rocks for frame of reference. Age ranges discussed in text are indicated.
Detrital Age – 452 Ma. Grain 7m4 is a small rounded grain preserved within the edge of a large garnet porphyroblast in a sheared pelitic schist of the Nashoba Formation near the Assabet River Fault. Its date of 452 +/− 10 Ma limits the last stages of garnet growth to having occurred after this time, but it is likely that all of the metamorphism took place well after the formation of the monazite. This monazite is interpreted to be a detrital grain incorporated into the garnet.

The intrusions of the Andover Granite and the Sharpner’s Pond Diorite cap the deposition of the stratified rocks of the Nashoba terrane. Zartman and Naylor (1984) reported a U-Pb age of 430 +/- 5 Ma for the Sharpner’s Pond Diorite, establishing the age of the sediments it intruded as early Silurian or older. The age of the Andover Granite is less well constrained: Zartman and Naylor (1984) reported a Rb-Sr whole-rock age of 446 +/- 32 Ma; and, Hill and others (1984) suggested an age of ~455 Ma based on their own data combined with that of Zartman and Naylor (1984). Grain 7m4 certainly predates the Sharpner’s Pond Diorite, but given the uncertainty in the age of the Andover Granite, it could be interpreted as either a metamorphic crystal postdating the intrusion of the Andover Granite or a late detrital grain.

Hepburn and others (1995) established the age of metamorphism in the Nashoba terrane as Silurian with their 425 Ma U-Pb monazite age from the Fish Brook Gneiss. If 7m4 is metamorphic it would represent an earlier as yet unrecognized metamorphic event.

Wintsch and others (2007) used U-Pb SHRIMP analysis to date detrital zircons from the Tatnic Hill Formation of the Putnam terrane in Connecticut, which is in part
correlative with the Nashoba Formation in Massachusetts (Dixon and Lundgren, 1968; Goldsmith, 1991a). They found that detrital zircon core ages were dominantly Ordovician ranging from 491-444 Ma (they also reported a few detrital core ages from the Neoproterozoic and Mesoproterozoic). The 452 Ma date of 7m4 falls within that range.

The following lines of evidence lead to the conclusion that monazite 7m4 is a detrital grain: (1) its small, rounded morphology is a common characteristic of detrital grains; (2) its date lies within the range of known detrital ages in a correlative terrane; and, (3) its textural position within the garnet porphyroclast indicates that it predates at least some of the metamorphism that presumably began circa 425 Ma.

Igneous Crystallization Age – 438 Ma. Grain 12m1 is a large monazite (~150 microns) inclusion within a small feldspar porphyroclast in the mylonitized granite of the Ball Hill fault (Figure 6.4). The core of the monazite is euhedral and yielded a date of 438 +/-4 Ma (Figure 6.5A). This is interpreted to be the igneous crystallization age of the mylonitized granite.

The texture and composition of the rock indicates that before it was mylonitized it was a medium- to coarse-grained peraluminous granite. Such granite could conceivably be related to the Andover Granite or Rocky Pond Granite, but further geochemical studies are required to determine whether there is such a relationship.

The monazite core includes a low-Y domain in its upper left (Figure 6.4) that may represent a relict detrital core from some earlier event. This domain (Figure 6.5A) may have acted as a nucleus for the 438 Ma euhedral core to overgrow, but was not analyzed.
The granite that forms some of the mylonite in the Ball Hill fault also intrudes the Tadmuck Brook Schist. The 438 Ma age of the granite provides a minimum age for the Tadmuck Brook Schist and a maximum age for deformation. The 438 Ma core presumably predates the crystallization of the feldspar porphyroclast surrounding it. Therefore, it is likely that the euhedral monazite core crystallized in a felsic melt sometime prior to the crystallization of the feldspar crystal. It follows that the igneous crystallization age of the mylonitized granite is 438 +/- 4 Ma.

This granite was emplaced in a limited zone along the contact between the Tadmuck Brook Schist and the Nashoba Formation and it was observed to intrude the Tadmuck Brook Schist (Figure 6.10). This relationship constrains the age of the Tadmuck Brook Schist to early Silurian or older. The age of this granite also provides a
maximum age of deformation along the Ball Hill fault. Mylonitization of this granite did not proceed until after it was emplaced.

The igneous protolith age of the mylonite in the Ball Hill fault is 438+/-4 Ma. This provides a minimum age for the deposition of the Tadmuck Brook Schist and a maximum age for deformation along the Ball Hill fault.

M1 Metamorphism – 423 Ma. Ten grains contribute to the 435-400 Ma date range, including four from sample RVV-004 (sheared rock of the Assabet River Fault, discussed in Stroud, in preparation). The other six grains are 12m2, 12m3, 12m4, 11m3, 11m6, and 7m1. The grains in RVV-012 have dates ranging from 431-417 Ma; the grains from RVV-011 have a mantle and core dated 411-410 Ma, and the grain in RVV-007 has a single date of 431 Ma. The dates from the RVV-004 grains range from 423-407 Ma.

These grains make up the largest peak of ages in the age summary diagram (Figure 6.9). No chemical or textural similarities could be found to either systematically link these grains together or to farther subdivide them. In fact, chemical or textural similarities between dated domains do not correspond to similar dates. Figure 6.11 shows the date probability distribution curve for each analyzed domain in this date range with accompanying Y element maps. The large dark curve is the total summed probability curve for this date range. A weighted mean age calculated from all ten grains yields 423+/-2 Ma. I interpret this weighted mean age to be a true mean age in the sense that it probably represents the average age of a 30 million year period of regional metamorphism.
Fig 6.11. M1 metamorphism. Domain dates in the interval 435-400 are cores and mantles and have no systematic similarities in their chemical zoning. The 423 Ma weighted mean age may simply be the average age of a protracted 30 m.y. period of metmorphism.
Grains 12m2, 12m3, and 12m4 initially seem out of place in this date range. Given the monazites’ locations within feldspar grains of a mylonitized granite, one might conclude that their dates (ranging from 431-417 Ma) might also reflect the igneous crystallization of this rock like the core of 12m1 (438 Ma) (note the bulge in the summary curve, Figure 6.9, created by the cluster of ~430 Ma dates). However, the analyses comprising the 438 Ma age of 12m1 and the dates of 12m4, 12m3, and 12m2 pass a statistical $\chi^2$-test at the 0.1% confidence level so there is no statistical basis for assuming that they are not two distinct ages. Given the textural locations of 12m2, 12m3, and 12m4 – in a reaction halo, near the edge of a feldspar porphyroclast, and adjacent to mica inclusions in a porphyroclast (Figure 6.4) – a simple explanation for their genesis is as a byproduct of early metamorphic feldspar and mica recrystallization. This process purges impurities such as phosphate and LREEs from the crystal lattice making them available for monazite growth (Kohn and Malloy, 2004).

Some of the younger dates from 11m3, 11m6, and three of the RVV-004 grains may reflect a thermal pulse corresponding to the intrusion of the younger pegmatitic phase of the Andover Granite. This granite has been assigned ages from 415-408 Ma (Zartman and Naylor, 1984; Hill and others, 1984; Hepburn and others, 1995; Acaster and Bickford, 1999). This range falls in the younger half of the dates from the 435-400 Ma date range, indicating that the intrusion of pegmatite and aplite of the Andover suite is not the impetus for this 30 million year period of monazite growth. It is likely that this protracted period of monazite growth corresponds to early regional metamorphism (M1).
and that its effects included the generation and rise of younger Andover suite rocks from anatexis of sediments at deeper levels than presently exposed.

The concentric shape of the 410+/4 Ma mantle on grain 11m3 (Figure 6.11) suggests that during this stage of the grain’s growth, there was little or no deviatoric stress. This in turn suggests that M1 was at least in part a static thermal event. This corroborates the earlier observation that M1 sillimanite occurs as random fabric fibrolite inclusions in other minerals.

M1 metamorphism took place during the interval 435-400 Ma with an average age of 423 Ma. It is important to understand that dated monazite domains represent P-T-t points along a path and not necessarily peak metamorphic conditions (Williams and others, 1999). One might interpret the 30 million year span of monazite growth as a prograde P-T-t path leading to the sillimanite-muscovite zone; along the path monazite forms as a byproduct in various silicate reactions that constantly change as metamorphic grade increases (Kohn and Malloy, 2004). Dates from this study and existing isotopic ages in the range 400-430 Ma (Hepburn and others, 1995; Acaster and Bickford, 1999; Wintsch and others, 2007) demonstrate that this event was widespread temporally and regionally, affecting the western and eastern parts of the Nashoba Formation, the Fish Brook Gneiss, and the Marlboro Formation. M1 was at least in part a static thermal event and there is no evidence to suggest fault activity during this interval in the Shrewsbury area. It is possible that a more detailed geochronological study might be able to resolve this 30 million year period into two or more pulses; however, the current data have a roughly normal distribution and do not support such a conclusion.
Second Metamorphism (M2) – 394 Ma. There are only four grains in the 400-385 Ma date range. Grains 11m6 and 12m1 have overgrowth rim domains low in Y with dates ranging from 392-397 Ma. Grains 7m5 and 7m6 are small irregularly-shaped grains with similarly low Y dated at 390+/-6 Ma and 393+/-16 Ma respectively. These four domains form a distinct age range and are chemically similar. The weighted mean age of these dates is 394+/-2 Ma and is interpreted to be the age of the second metamorphism (M2) in the Nashoba terrane that was responsible for widespread migmatization, especially in the northwest portions of the Nashoba Formation. Figure 6.12 summarizes the dates for this population and includes Y element maps for the 4 grains.

Hepburn and others (1995) reported an isotopic U-Pb monazite age of 395+/-2 Ma for a migmatitic leucosome in a stratigraphic position similar to that of RVV-011 in the northwest portion of the Nashoba Formation near Boxborough. They suggested that it could represent an Early Devonian melting event possibly caused by additional heat input from nearby intrusions. This challenged a long-standing assumption that the peraluminous Andover Granite was derived from melted Nashoba Formation sediments (e.g. Hall and Robinson, 1982).

In this study all three samples contain monazite cores or overgrowth rim domains growing at ~395 Ma, suggesting that the sample of Hepburn and others (1995), located more than 30 kilometers away from RVV-011, was not a restricted melting event, but a regional metamorphic event, M2. In fact sample RVV-011 was collected from an outcrop containing significant migmatite.
Fig 6.12. Age of M2 metamorphism. Four overgrowth and core domains with similar Y levels yield a weighted mean age of 394 Ma, interpreted to be the age of the M2 metamorphism that brought much of the Nashoba terrane to the second sillimanite zone generating anatectic conditions. The subtle double-peak in the data is interpreted to be an artifact of too few samples given that all of the domains are chemically very similar.
Abu-Moustafa and Skehan (1976) first described peak pelitic assemblages in the Nashoba terrane of sillimanite-k-feldspar. The predicted pressure-temperature conditions for this assemblage coincide with the wet solidus for melting granite (Holland and Powell, 1998). Samples RVV-007 and RVV-011 both have the metamorphic assemblage sillimanite-k-feldspar (samples 5 and 6, Table 2.1; samples 5 and 6 Table 4.1).

The ~395 Ma age is linked to more than M2 metamorphism. The overgrowth rim domain of 12m1 has an asymmetric shape indicative of possible sinistral non-coaxial shear (Figure 6.13). The rim has preferentially grown from the upper left and lower right portions of the core – the same directions as maximum instantaneous stretching in a sinistral non-coaxial flow (Hammer and Passshier, 1991). A thick fracture transecting the feldspar and terminating against 12m1 was likely a pathway providing materials necessary for monazite growth (Figure 6.13). This evidence is hampered by the feldspar grain enclosing the monazite: the bulk flow in the matrix immediately outside of a porphyroclast may not necessarily have an expression inside that porphyroclast – and if it does that expression may be partitioned such that it does not reflect the bulk flow in the matrix. However, the simplest explanation and the interpretation of this author is that the overgrowth did respond to the bulk flow of the mylonite during its crystallization – in this case, sinistral non-coaxial flow.

The age of M2 metamorphism in the Nashoba terrane is 394+/-2 Ma. This is also the age of migmatite associated with the M2 assemblage of sillimanite-k-feldspar-biotite-(garnet). Sinistral non-coaxial shear prevailed along the Ball Hill Fault at this time.
Figure 6.13. Monazite 12m1 from mylonite of the Ball Hill Fault. (A) a backscattered electron image of the feldspar porphyroclast enclosing 12m1; note the single large fracture that intercepts the monazite at the right middle of its long dimension; also notice the hint of a δ-shaped winged appendage curving up and away from the lower left of the porphyroclast. (B) a Y element map of 12m1 clearly showing the early Silurian core and the Devonian rim; the sketch diagram of the grain shows the sinistral shear-sense responsible for the asymmetry of the overgrowth rim. Both images are looking down at the X-Z plane of the finite strain ellipsoid; north is to the right.
376 Ma – Major Deformation. The 385-360 Ma date range has been undocumented in the Nashoba terrane until now. Chemical similarities that corresponded to core-rim relationships allowed this range to be split into two groups. Grains 7m3, 11m2, 11m5, and 11m7 all have similar low-Y cores with dates from 382-372 Ma. The weighted mean age of these cores is 378+/-2 Ma. Grains 7m3, 11m3, 11m5, 11m6, and 11m7 all have similar high-Y rim or mantle domains dated from 384-363 Ma. Most of these rims or mantles truncate earlier domains (all but 7m3, Figure 6.14) and are interpreted to be recrystallized domains. Their weighted mean age is 372+/-2 Ma. The 363 Ma date from 11m5 (Figure 6.8A) was not included in the calculation for the weighted mean since its lower age and low error were deemed to disproportionately bias the weighted mean. An additional grain, 12m2, had an analyzed domain for which three of five spot analyses yielded a date of 383 Ma with the other two indicating a date of 426 Ma (Figure 6.5B). This domain is too small to compare with the domains of the 378 Ma group but is considered with them on the basis of age. Data from this date range is summarized in Figure 6.14.

Grain 12m2 is located in a thin zone around a feldspar porphyroclast where smaller grains are recrystallizing in order to minimize strain. The monazite appears to have been involved in grain-size reduction processes and feldspar sub-grain formation and much of the crystal has been altered to something else (Figure 6.4). In one of three dated domains, three of five spots give a date of 383+/-7 Ma – much younger than the other two which have a date of 426+/-6 Ma, similar to the other two domains in this grain. These three spots are interpreted to represent monazite at an intermediate phase of
Fig. 6.14. Neo-Acadian ages. Monazite domains with dates in the interval 385-360 can be divided into two groups on the basis of Y levels and domain type. Low-Y core domains yield an age of 378 Ma and high-Y, mostly recrystallized rims have an age of 372 Ma.
the recrystallization process. Since the last motion on the Ball Hill fault was non-coaxial sinistral shear and the 383 Ma date seems to have caught a monazite partway through the recrystallization process, the Ball Hill fault is interpreted to have undergone sinistral non-coaxial shearing during the middle Devonian. This is the youngest date obtained from the Ball Hill fault; it indicates that at this time ductile processes still prevailed in the fault zone, indicative of temperatures greater than 450° C.

Grain 11m5 is the most complexly zoned crystal observed in this study (Figure 6.7). Its metamorphic core domain is 382±4 Ma and it has three recrystallized domains truncating the core and each other, dated at 374 Ma, 369 Ma, and 363 Ma. This grain’s location is similar to 12m2’s – near the margin of a large feldspar aggregate. The feldspar is forming subgrains and smaller recrystallized grains – especially near its margins – presumably to reduce the strain associated with shearing. All domains in this grain are interpreted to have formed successively as the feldspar porphyroclast formed subgrains and recrystallized near its margins in response to shearing. Feldspar was deforming via ductile processes so temperatures in the Sulfur Hill shear zone at this time must have been higher than 450° C.

Grain 11m3 has a thin recrystallized rim dated at 376±12 Ma. The rim truncates the earlier concentric mantle that was interpreted to represent somewhat static conditions during M1 metamorphism. The rim is not evenly distributed or concentric like the earlier mantle suggesting that it represents dynamic conditions during this time that may have included non-coaxial shearing.
The bimodal date population for the range 385-360 Ma is interpreted to represent major deformation and fault activity in the Nashoba terrane around 378 Ma followed by the infiltration of fluids into and along shear zones around 372 Ma as shearing continued. The weighted mean age of all domains in this range is 376+/-2 Ma and is chosen as the age of major deformation and ductile faulting in the Nashoba terrane. This deformation may be related to the Neoacadian orogeny (Van Staal and Whalen, 2006).

**Younger Events – 360-305 Ma.** Grains 11m1, 11m2, 7m6, and a grain from RVV-004 all have domains yielding dates in the interval 360-305 Ma. Most of these domains truncate other chemical domains, indicating that they probably formed via recrystallization during fluid-mineral interactions. This indicates both the presence of fluids and the possibility of temperatures as low as 400° C (Poitrasson and others, 1996). Because the dates are scattered over 50 million years throughout the late Devonian and Carboniferous, they are interpreted to represent discrete hydrothermal events of lower metamorphic grade restricted to limited areas in the vicinity of faults, shear zones, and other conduits for fluid infiltration.

One grain, 11m1, has a 343 Ma recrystallized rim and a slightly older 345 Ma core. The morphology of the grain strongly suggests that it pseudomorphed a sillimanite crystal – the monazite, along with quartz and biotite grains, inherited one of the basal partings commonly found in sillimanite (Figure 6.7). 11m1 indicates that sillimanite was no longer stable by 345 Ma. This is in agreement with ⁴⁰Ar/³⁹Ar isotopic hornblende
ages in the Nashoba terrane of 354-325 Ma suggestive of temperatures below ~500° C by this time (Hepburn and others, 1987).

Other recrystallized rims throughout this interval may indicate infusions of fluids, subsequent reactivation of fault zones, and retrograde metamorphism but farther study is required to give these dates geological significance. 345 Ma is taken to be the minimum age of sillimanite stability in the Nashoba terrane, indicating temperatures less than 550° C by this time.

Summary of Monazite Ages

34 crystal domains were dated. They come from 15 separate monazite grains and from three different samples (Table 6.1). Monazite grains from an additional sample, RVV-004, were also dated and used (Stroud, in preparation 2007). Five distinct populations of dates were identified and along with three unique dates they yielded five geologically significant ages.

452 Ma is a new Nashoba Formation detrital monazite age that correlates well with a range of detrital zircon ages reported for the Nashoba-correlative Tatnic Hill Formation in Connecticut (Wintsch and others, 2007). 438 Ma is the age of a mylonitized granite that was observed to intrude the Tadmuck Brook Schist. It provides a younger constraint on the age of the Tadmuck Brook Schist and a maximum age of Ball Hill fault deformation.
Figure 6.15. Summary of all monazite dates from samples RVV-012, RVV-011, RVV-007, and RVV-004. Large solid curve represents the sum of every monazite domain's age probability distribution; small solid curves represent weighted mean ages of different monazite groups; dashed curves are age probability distributions for each analyzed monazite domain. Each age group is labelled according to its interpretation discussed in the text.
423 Ma is the weighted mean age of M1 metamorphism when P-T conditions of the sillimanite-muscovite zone prevailed in the Nashoba terrane. This may have been in part or wholly a static thermal event.

394 Ma is the age of M2 metamorphism when rocks of the Nashoba terrane were brought to the sillimanite-k-feldspar zone producing anatectic conditions. The formation of migmatite was widespread at this time and sinistral deformation along the Ball Hill fault occurred.

376 Ma is the age of major fluid infiltration and ductile faulting in the Nashoba terrane. The Ball Hill fault, Sulfur Hill shear zone, and Assabet River fault were all active at this time.

Sporadic monazite growth during the interval 360-305 Ma, indicates that the main phase of ductile deformation along the faults was over, but that they still acted as fluid pathways. M3 retrograde metamorphism may have taken place during this interval. By 345 Ma the terrane had cooled below the stability limit of sillimanite.
Chapter 7. CONCLUSIONS

AGES OF STRATIFIED ROCKS

Tadmuck Brook Schist

Some early workers considered the Tadmuck Brook Schist to lie unconformably on the Nashoba Formation (Skehan and Abu-Moustafa, 1976; Bell and Alvord, 1976) due to an abrupt change in lithology and a slight angular discordance of structural data (Hepburn, 1978; Goldsmith, 1991b). Although the Tadmuck Brook Schist is in contact with the Ordovician or Silurian Andover Granite, Castle and others (1976) believed it “[seemed] impossibly fortuitous that it could be an intrusive contact,” citing the straight-line trace of the contact as evidence. Instead they suggested a steeply dipping fault contact which was observed in this study and is referred to herein as the Ball Hill fault.

A small body of an unnamed granite was observed to intrude the Tadmuck Brook Schist near its boundary with the Nashoba Formation (Figure 6.10). The granite’s monazite age of 438 Ma constrains the Tadmuck Brook Schist’s depositional age to Silurian or older.

Nashoba Formation

The depositional age of stratified rocks in the Nashoba Formation has been previously estimated by Hepburn and others (1995) to range from latest Cambrian to earliest Silurian constrained by the 499 Ma age of the Fish Brook Gneiss, presumably basement to the terrane (Castle, 1964), and the 430 Ma age of the intruding Sharpner’s Pond Diorite. The maximum age of deposition is constrained by the age of the youngest detrital grains. The
452 Ma detrital age of grain 7m4 limits the deposition of the Nashoba Formation to Ordovician or Silurian time. Taking the results of Wintsch and others (2007), whose metamorphic and detrital zircon dates from the correlative Tatnic Hill Formation in Connecticut are in agreement with dates from this study, the depositional age of the Nashoba Formation may be farther restricted to early Silurian.

**Marlboro Formation**

Attempts to directly date the Marlboro Formation have met with limited success. DiNitto and others (1984) failed to produce a satisfactory isochron using samarium and neodymium isotopes; however, they were able to calculate a neodymium model age by assuming a typical depleted mantle source. Their calculations put the age of the volcanic protoliths of the Marlboro Formation between 550 Ma and 450 Ma. Acaster and Bickford (1999) conservatively estimated the volcanic crystallization age of the Sandy Pond member of the Marlboro Formation to be between 473 Ma and 445 Ma from isotopic U-Pb studies of nearly concordant zircons. Given the 499 Ma age Fish Brook Gneiss (Hepburn and others, 1995) which has been interpreted to be basement to the terrane (Castle, 1964), the volcanic crystallization age of the Marlboro Formation can reasonably be estimated to be Ordovician.

**ORIGIN OF THE ROCKY POND SLICE**

The Rocky Pond slice is bound by the Clinton and Rattlesnake Hill faults between Clinton and Worcester (Figure 1.2). It contains rocks that could be correlative with either
the Nashoba or Merrimack terranes and includes the Boylston Schist, the Sewall Hill Formation, the Rocky Pond Granite, and other minor intrusive rocks. The stratified rocks have been metamorphosed to the upper amphibolite facies and the slice is cut by numerous minor ductile shear zones and brittle faults. It has previously been mapped as a part of the Nashoba terrane by Zen and others (1983) and Goldsmith (1991b) on the basis of its amphibolite facies metamorphism.

**Stratigraphic Correlations**

Munn (1987) suggested that her Western Nashoba Formation (the Sewall Hill Formation of this study) might be a higher-grade equivalent of the Vaughn Hills Quartzite citing their similarities in composition and layering. This is a reasonable correlation given her modes and the visible similarities of the rock (compare layering in Figure 5.2C and Figure 5.6A). A correlation with the Nashoba Formation is difficult. The Sewall Hill and Nashoba Formations are similar in metamorphic grade, but the Nashoba Formation does not exhibit the uniquely thick and continuous banding of the Sewall Hill Formation gneisses. In addition, the Nashoba Formation contains significant amounts of pelitic schist, amphibolite, and migmatite – all of which are found in the Sewall Hill Formation in only small amounts, estimated at less than 20% of the total formation (Munn, 1987).

The Boylston Schist has been suggested to be correlative with the Tadmuck Brook Schist (Robinson and Goldsmith, 1991). Both units are dominantly sillimanite-bearing mica schists that are typically sulfidic and rusty-weathering. They also both occupy similar structural positions adjacent to the Nashoba terrane. Northeast of the
Rocky Pond slice, the Tadmuck Brook Schist lies just northwest of the Nashoba Formation while southwest of the Rocky Pond slice in the Worcester area the Boylston Formation occupies that position. There are differences, though: the Tadmuck Brook Schist lacks the calc-silicate granofels present in the Boylston Schist and contains a distinctive amphibolite at its base that is absent in the Boylston Schist. The Tadmuck Brook Schist is also very strongly foliated whereas the Boylston Schist is not. If these two units are correlative, these differences might be explained as lateral facies changes.

*Magnetic Correlations*

Figure 7.1 shows a magnetic anomaly map of the region surrounding the Shrewsbury quadrangle. Magnetic data has been used for the construction of past regional geologic and structural maps (Alvord and others, 1976; Bell and Alvord, 1976; Castle and others, 1976). Castle and others (1976) demonstrated that when a magnetic lineament coincides with an observed geological boundary, that boundary can be further extended on the basis of the magnetic data. Figure 7.1 uses the magnetic dataset of Zietz and others (1980) (recently digitized by the USGS, 2002) to illustrate the magnetic contrast between the Nashoba terrane and Rocky Pond slice. It is clear that the Nashoba Formation is highly magnetic and that rocks to the west of it are not – in particular the low magnetic intensity gneisses of the Sewall Hill Formation contrast markedly with the highly magnetic gneisses of the Nashoba Formation, making some of the highest magnetic relief in Massachusetts. This makes a correlation between the Sewall Hill Formation and Nashoba Formation untenable.
Figure 7.1. Magnetic intensity map of the Shrewsbury area. Brown and white colors represent high magnetic intensity while green, tan, and blue colors represent low magnetic intensity. Shrewsbury quadrangle indicated by black box; fainter lines are contacts. Image and color table was generated in ArcGIS 9.1 using the dataset of Zietz and others (1980).
Kinematic Models

Two structural models and correlation schemes are presented that can potentially explain the contrast in metamorphic grade between the Rocky Pond slice and the lense of Merrimack terrane rocks that lie to its east. These models depend heavily on the motion senses of the Rattlesnake Hill and Clinton faults, which have not yet been satisfactorily determined using modern shear-sense techniques (e.g. Hanmer and Passhier, 1991).

Lateral displacement. If primarily lateral motions took place on the Rattlesnake Hill Fault then its displacement is probably at least as much as its trace length, 17 kilometers. In this model (Figure 7.2A), Rocky Pond slice rocks that lie northwest of the Rattlesnake Hill fault would originally be the upper part of the Nashoba terrane and its boundary with the Merrimack terrane (Ayer Granite, Vaughn Hills Quartzite, Tadmuck Brook Schist, Nashoba Formation). The rocks would be faulted out of the sequence and transported laterally southwest to their present position as the Rocky Pond slice. In this model the Rocky Pond Granite would correlate with the Ayer Granite, the Boylston Formation would correlate with the Tadmuck Brook Schist, the Nashoba Formation would correlate with the Sewall Hill Formation, the Tower Hill Quartzite would correlate with the Vaughn Hills Quartzite, and the Clinton Fault would have to be a dominantly strike-slip fault.

Some minor stratigraphic problems arise: the differences between the Sewall Hill Formation and Nashoba Formations were discussed above; in addition, the Vaughn Hills
Figure 7.2. Fault models for the origin of the Rocky Pond Slice. Numbers in the figure refer to: 
1, the Rocky Pond Slice; 2, Vaughn Hills Quartzite and Tadmuck Brook Schist; 3, Tadmuck Brook Schist only. (A) A strike-slip origin; the diagram on the left shows the future trace of the
Rattlesnake Hill Fault cutting across a bulge in the Nashoba terrane; the second diagram shows
this detached slice moved into its present position. (B) A dip-slip origin; the Rattlesnake Hill
Fault is a major thrust placing Merrimack rocks on top of Nashoba; the Clinton Fault is a later
normal fault that juxtaposes low-grade rocks with the higher grade Rocky Pond Slice; strike-slip
motion along the Ball Hill Fault is responsible for Vaughn Hills Quartzite and Tadmuck Brook
Schist between the Nashoba terrane and the Rocky Pond Slice.
Quartzite typically has well-defined beds whereas the Tower Hill Quartzite has a massive texture.

The biggest problem with this model is where the slice actually came from. If the motion was sinistral, as motion was observed to be on the Ball Hill Fault and Sulfur Hill shear zone, then the sequence of rocks now comprising the Rocky Pond slice must have been cut out of the sequence somewhere to the northeast. However, that part of the Nashoba terrane is actually much thicker (Goldsmith, 1991a) and has more of the stratigraphic package, not less (Castle and others, 1976) (Figure 1.2). Nevertheless, it is possible that the missing section is located somewhere northeast of Lawrence, where the Tadmuck Brook Schist and Nashoba Formation are cut out or obscured entirely by faults and granite. If that is the case, then the displacement along the Rattlesnake Hill/Clinton-Newbury Fault is on the order of several tens of kilometers.

An alternative scenario would have the Rocky Pond slice arrive at its present position from the southwest via dextral fault motion. This alternative explanation would be favored by the fact that the Nashoba terrane thins drastically southwest of Shrewsbury towards the Massachusetts-Connecticut border; however, there is currently no evidence for large-scale dextral motion in the Nashoba terrane or along its boundaries.

Dip-slip displacement. Another possibility is that the Rattlesnake Hill Fault is a major thrust fault as Skehan (1968) considered it to be from direct observations in the Wachusett-Marlborough tunnel. In this model (Figure 7.2B), the Merrimack terrane rocks west of the fault move up significantly, juxtaposing higher grade Merrimack rocks
from deeper levels with the lower grade Vaughn Hills Quartzite. The Clinton Fault then is a later normal fault that down-drops the lower grade Merrimack rocks to the west of the Rocky Pond slice.

Goldstein (1994) demonstrated that the main strand of the Clinton-Newbury Fault had a final ductile motion sense of NW side down normal motion, which was confirmed by Jerden (1997). This apparently contradicts Skehan’s (1968) earlier observations of thrust motion. However, Goldstein (1994) and Jerden (1997) both indicated that only the final ductile motion was NW down and did not preclude earlier, now obscured senses of motion. If one considers the Clinton-Newbury Fault to have consisted of an early NW side up thrust motion followed by NW side down normal motion as suggested by Goldsmith (1991b), then Skehan’s (1968) observations can be resolved. Elsewhere along the fault system, the two different motions occurred along the same fault surface (the Clinton-Newbury fault), with the late normal motion obscuring earlier evidence of thrust motion. In the vicinity of the Rocky Pond slice, however, the motion was accommodated by two faults – the Rattlesnake Hill fault reflects the early thrust motion; the Clinton fault, later normal motion (Figure 7.2B). This model satisfies the axiom that high-grade rocks are found in the hangingwalls of thrust faults and that low-grade rocks are found in the hangingwalls of normal faults.

Indirect evidence from Goldstein (1994) and this study lend some credence to this model. That is, Goldstein’s (1994) Wachusett Mylonite Zone was observed to have NW side down normal motion (Figure 5.6). This zone is proximal to the Clinton fault and it is possible that normal motion was partitioned between the Clinton fault and the shear
zones of the Wachusett Mylonite Zone. This fits the model where the early thrust motion sense of the Rattlesnake Hill Fault is preserved. Later normal motion is partitioned between minor shear zones within the Rocky Pond slice and the Clinton fault.

**Discussion**

Both models are severely hampered by the fact that the motion sense of the Clinton and Rattlesnake Hill faults is in question. Fortunately, it is a question likely resolvable by future work. Given the possible stratigraphic correlations, the magnetic intensity map, and the motion sense of the Wachusett Mylonite Zone, the dip-slip model for the Rocky Pond slice seems most attractive at the current time.

Given the change in metamorphic grade across the Rattlesnake Hill and Clinton faults, the peak temperature contrast between the Rocky Pond slice and the eastern Merrimack terrane must have been at least 100-200° C (>600° C in the Rocky Pond slice compared with 400-500° C in the eastern Merrimack terrane). Depending on the geothermal gradient during the deformation, this temperature contrast might have translated into a vertical displacement of 5-10 km, close to a third of an average crustal thickness. It is conceivable that some of the late normal motion in the Wachusett Mylonite Zone and along the Clinton-Newbury fault (Goldstein, 1994) is related to orogenic collapse and that the Rocky Pond slice is in part a small metamorphic core complex.
METAMORPHISM AND DEFORMATION

*Merrimack Terrane*

The eastern Merrimack terrane was affected by at least one chlorite zone metamorphism and an earlier andalusite-staurolite zone metamorphism (Goldstein, 1994; Jerden, 1997). The age of the chlorite zone event is interpreted to be Carboniferous or younger since it affected blocks of the Pennsylvanian Harvard Conglomerate in the eastern portion of the Merrimack terrane (Goldstein, 1994). The age of the andalusite-staurolite zone is not known but is reasonably considered here to be early Devonian or late Silurian based on the 414+/−3 Ma age of the Canterbury Gneiss (Wintsch and others, 2007) that cross-cuts deformed and metamorphosed rocks of the Merrimack terrane.

The Tadmuck Brook Schist also underwent an additional amphibolite-grade event. The southeast portion of the formation, within several hundred meters of the Nashoba Formation, has been metamorphosed to the sillimanite-muscovite zone. Jerden (1997) interpreted this metamorphism to be contact-type resulting from the structural juxtaposition of the Tadmuck Brook Schist with hot rocks of the Nashoba Formation. An asymmetric monazite rim (Figure 6.13) indicates that non-coaxial sinistral deformation occurred along the Ball Hill fault by the early Devonian (~394 Ma). This is interpreted as the faulting which ultimately brought the Tadmuck Brook Schist into contact with the Nashoba Formation and caused the contact metamorphism. The direction of that motion is sinistral strike-slip with a small oblique NW side up thrust component.

The Clinton-Newbury fault was demonstrated to have a final ductile motion sense of NW side down normal motion (Goldstein, 1994). Goldstein (1994) interpreted this
motion to have taken place sometime during the Carboniferous or Permian. He also suspected that there may have been an earlier sinistral oblique thrust motion during the Carboniferous on the basis of rotated foliation patterns in a portion of the eastern Merrimack terrane. Additional earlier motion on the Clinton-Newbury fault is not precluded, but currently there is no evidence for it.

Rocky Pond Slice
The Rocky Pond slice experienced one amphibolite-grade metamorphic event that was followed by contact metamorphism and later retrograde metamorphism. The timing of the prograde metamorphic event is uncertain: if the rocks are truly correlative with the Merrimack terrane then this event was probably early Devonian or late Silurian and contemporaneous with high-grade Acadian metamorphism and deformation in Merrimack terrane rocks of central Massachusetts. Some of the later retrograde metamorphism might be time-equivalent to retrograde metamorphism in the Nashoba terrane and Merrimack terrane and is probably Carboniferous or younger in age.

The Wachusett Mylonite Zone has a NW side down normal motion sense. Textures from the single thin section presented (Figure 5.6B) indicate that the fault was active at temperatures in the zone of feldspar plasticity (>~450° C) and remained active as temperatures fell into the brittle-ductile transition zone (~300-450° C). The cooling history of the Rocky Pond slice is not known, but if the Rocky Pond slice and the Nashoba terrane both experienced chlorite zone retrograde metamorphism in the Carboniferous, then it is reasonable to conclude that the two were in thermal equilibrium
by then. If that is the case, then the Wachusett Mylonite Zone probably remained active into the middle Carboniferous at least (when the Nashoba terrane was cooling through 400-500° C, Hepburn and others, 1987). Goldstein (1994) interpreted the Wachusett Mylonite Zone to have been active around the same time as the Clinton-Newbury Fault – the late Carboniferous or early Permian

*Nashoba Terrane*

The Nashoba terrane experienced two amphibolite-grade metamorphic events. The earliest metamorphism (M1) may have lasted 30 million years and has an average age of 423 Ma. A concentric monazite overgrowth (11m3, Figure 6.7) suggests that this may have been a static thermal event. Heat generated by a subduction zone and the associated I-type intrusions (such as the 430 Ma Sharpner’s Pond Diorite) may have been the impetus for M1 conditions. Later metamorphism (M2) produced anatectic conditions around 394 Ma and metamorphic conditions may have persisted into the middle Devonian (*circa* 376 Ma). Retrograde metamorphism (M3) in the chlorite zone overprinted earlier assemblages during the Carboniferous or later. M3 may reflect a number of discrete events caused by fluid infiltration in shear zones and is possibly correlative with more widespread chlorite zone metamorphism in the adjacent Rocky Pond slice and Merrimack terrane. Fluid infiltration in shear zones is evidenced by recrystallized monazite rims in the range 372-305 Ma. By 345 Ma, the terrane had cooled below the stability of sillimanite (~550°C) and had probably done so earlier (e.g. hornblende cooling ages of 354-325 Ma, Hepburn and others, 1987).
The earliest evidence of major faulting adjacent to the Nashoba terrane is the Burlington Mylonite Zone of the Bloody Bluff fault system. Goldstein (1989) and Goldsmith (1991b) both indicate that major deformation along this mylonite zone likely occurred during the interval from the early Silurian to the late Devonian, when the Peabody Granite intruded mylonites of the Burlington Mylonite Zone and was itself undeformed (Zartman, 1977). The motion sense determined by Goldstein (1989) and Kohut (1999) is sinistral strike-slip with a component of NW over SE thrust.

An asymmetric monazite rim from the Ball Hill fault suggests that sinistral non-coaxial shearing with a minor thrust component had begun by the early Devonian (~394 Ma). The fault’s ductility indicates that it was not active during Carboniferous cooling and exhumation; the youngest monazite date from this fault was 383 Ma for a domain that was associated with non-coaxial shearing.

Two bodies of hydrothermally altered ultramafic rocks were observed near the trace of the Ball Hill fault terrane boundary. They are separated across strike by roughly 2 kilometers and both bodies lie within several hundred meters of the fault trace in the base of the Tadmuck Brook Schist and at the top of the Nashoba Formation. While there is no firm evidence to suggest that these are alpine peridotites and not cumulates, it seems more than a coincidence that these rocks are found very close to a terrane boundary far from large bodies of gabbro or basalt.

The Assabet River fault and the Sulfur Hill shear zone both have significant populations of middle Devonian monazite dates. Like the Ball Hill fault, these faults do not appear to have been active below the brittle-ductile transition for feldspar. They too
are interpreted then to have been active mostly during the Devonian and possibly the early Carboniferous. Evidence from the Sulfur Hill shear zone suggests that it was not active during the early Devonian. A reasonable estimate for the maximum age of deformation along these faults is middle Devonian.

Recrystallized monazite rims spanning the Carboniferous indicate that shear zones experienced intermittent periods of fluid infiltration that may have been accompanied by fault reactivation, retrograde metamorphism, or both. The youngest igneous rock in the Nashoba terrane, the Indian Head Hill Granite, is also Carboniferous (349 Ma, Hepburn and others, 1995).

TECTONIC SYNTHESIS

The Nashoba terrane is interpreted to be comprised of volcanic rocks and sediments derived from an early Paleozoic arc. Neo- and meso-Proterozoic detrital zircons from the Tatnic Hill Formation in Connecticut suggest that this arc may have been built on Gander-type crust (Wintsch and others, 2007). Figure 7.3 summarizes existing geochronological data for the Nashoba terrane.

Subduction below the Nashoba terrane generated I-type plutons and brought enough heat to shallower depths to cause M1 metamorphism in the Nashoba terrane. By 394 Ma, more heat brought into the crust by continued subduction and more calc-alkalic
### Figure 7.3. Age correlation chart for the Nashoba terrane. Shown are monazite dates from this study, ages of calc-alkalic plutons, other isotopic ages, inferred ages of faulting, and inferred ages of metamorphism (see references in text). WMZ = Wachusett Mylonite Zone; BHF = Ball Hill Fault; SHSZ = Sulfur Hill Shear Zone; ARF = Assabet River Fault; BBF/BMZ = Bloody Bluff Fault/Burlington Mylonite Zone.
intrusions such as the Indian Head Hill Diorite (402 Ma, Hill and others, 1984) caused M2 generating anatectic conditions in parts of the Nashoba terrane. The Ball Hill fault was active at this time possibly signifying the initiation of a short-lived subduction zone below the Merrimack terrane.

The final calc-alkaline intrusions (e.g. the ~385 Ma Assabet Quartz Diorite, Acaster and Bickford, 1999) and subsequent cessation of calc-alkaline magmatism probably marks the end of subduction beneath the Nashoba terrane and the amalgamation of the Nashoba terrane with the Avalon terrane. The last evidenced motion on the Ball Hill fault around ~383 Ma suggests the amalgamation of the Nashoba terrane and Merrimack terrane at this time, thrusting the Tadmuck Brook Schist onto the hotter rocks of the Nashoba Formation. Major D2-style ductile deformation took place \textit{circa} 376 Ma and was widespread throughout the Nashoba terrane during this time. Retrograde metamorphism took place after this time, with its effects strongest in areas adjacent to shear zones. Motion along the Sulfur Hill shear zone and Assabet River Faults may have structurally thickened the Nashoba terrane to the northeast.

PROPOSED MODEL

Introduction

Evidence from the Shrewsbury quadrangle reveals a long and complex Paleozoic history for east-central Massachusetts. This history is divided here into four stages that can be distinguished on the basis of metamorphic and deformational style. These stages are also tentatively correlated with northern Appalachian orogenic events proposed by Van Staal.
and Whalen (2006), especially the Acadian and Neoacadian orogenies. These correlations are mostly conjectural although the data is in agreement with them. Figure 7.4 diagrammatically shows how Paleozoic events in the Nashoba terrane might be explained by accretionary tectonics.

**Stage One – Salinic(?) Orogeny**

Early Paleozoic arc volcanism (the Marlboro Formation) and early Silurian sedimentation (the Nashoba Formation) created the Nashoba terrane, a magmatic arc terrane built on or adjacent to Ganderian crust (Wintsch and others, 2007). The rocks presently exposed record a long, nearly 30 million year period of Abukuma-type metamorphism during the middle Silurian and early Devonian (M1). Conditions peaked in the sillimanite-muscovite zone.

The northern Appalachian Salinic orogeny of Van Staal and Whalen (2006) was caused by the accretion of Ganderia to Laurentia. During the final stages of the collision, Avalonia began to converge with Ganderia; subduction was initiated and the Nashoba arc was formed along or near Ganderia’s trailing edge. Although a Salinic orogeny is not widely recognized in central New England, this does not preclude the Nashoba arc from forming along the eastern edge of Ganderia.

**Stage Two – Acadian Orogeny**

Early Devonian sinistral non-coaxial shearing along the Ball Hill fault and the occurrence of ultramafic rocks along its trace suggests the initiation of a short-lived subduction zone
Figure 7.4. Accretionary model for the Nashoba terrane. La=Laurentia, Ga=Gander, Av=Avalon, Mg=Meguma; SF=Shelburne Falls Arc, BH=Bronson Hill Arc, M=Merrimack terrane, N=Nashoba terrane. (A) At the end of the Salinic orogeny, subduction below the Nashoba arc causes calc-alkaline magmatism (e.g. Sharpner's Pond Diorite) and Abukuma-type metamorphism; back-arc spreading behind the Bronson Hill arc accommodates the deposition of the Merrimack terrane. (B) As Avalon docks with the Nashoba arc, a short-lived subduction zone forms below the sediments of the Merrimack terrane; Watts and others (2001) indicated that Silurian-Devonian intrusive rocks of the Merrimack terrane are chemically distinct from similarly aged rocks in the Nashoba terrane. (C) Avalon and Nashoba amalgamate with the assembled North American continent (Laurentia and Gander) causing major ductile faulting in the Nashoba terrane; subduction and calc-alkaline magmatism in the Nashoba terrane cease.
beneath the Merrimack terrane. The initiation of subduction beneath the Merrimack terrane may coincide with the cessation of subduction beneath the Nashoba terrane, signaling the accretion of the Avalon terrane. Loading caused by the Tadmuck Brook Schist and Merrimack terrane sediments over the Nashoba terrane generated anatectic metamorphic conditions in the Nashoba Formation (M2).

Stage Three – “Neoacadian Orogeny”

The last calc-alkaline diorites (Figure 7.2) coincide with major ductile faulting in the Devonian and the final amalgamation of the Avalon, Nashoba, and Merrimack terranes probably takes place. Sinistral and sinistral-oblique thrust deformation along the Assabet River fault and Sulfur Hill shear zone may structurally thicken parts of the Nashoba terrane.

Although the accretion of the Meguma terrane is responsible for the “Neoacadian orogeny” in the northern Appalachians (Van Staal and Whalen 2006), in Massachusetts the presence of a relatively undeformed Avalon terrane between the Meguma terrane and Nashoba terrane makes this possibility less likely there. Post-amalgamation motion among the Merrimack, Nashoba, and Avalon terranes may in part be responsible for deformation in Massachusetts at this time.

Stage Four – Early Alleghanian Orogeny

Major ductile faulting in the Nashoba terrane ended before it cooled through the argon blocking temperatures of hornblende and biotite during the Carboniferous. Late normal
motion along the Clinton-Newbury fault, Wachusett Mylonite Zone, and probably the Clinton fault was probably related to orogenic collapse. This collapse exhumed the Rocky Pond slice, a small metamorphic core complex. Chlorite zone retrograde metamorphism (M3) occurred throughout the Carboniferous and some of it may reflect the earliest effects of the Alleghanian orogeny.

The Alleghanian orogeny is the result of the final interaction between Gondwana and composite Laurentia. Its effects are limited in the Shrewsbury quadrangle, though Goldstein (1994) believes that normal fault motion during the Carboniferous or Permian contributed to the formation of Alleghanian cleavages within a limited group of rocks in the Merrimack terrane.
PART TWO
Chapter 8. FRACTURE STUDY

INTRODUCTION

Understanding the presence and distribution of fractures in bedrock has become increasingly important in the past two decades in New England. Their orientation and spacing is a prime factor affecting the yields of water wells drilled into bedrock (Mabee and others, 1994).

An increasing number of citizens are drilling their personal water-supply wells into bedrock in northeastern states like New Hampshire and Massachusetts. Some communities in these states have explored the possibility of using high-yield bedrock wells for local town water supplies (Moore and others, 2002; Lyford and others, 2003). The availability of local and regional data on the orientation and distribution of fractures can help contractors eliminate some unfavorable well sites without the need for detailed field investigations. The data is also useful for the remediation of groundwater contamination as it allows investigators to more quickly understand the fate and transport of contaminants in the aquifer.

METHODS

At each large outcrop 30 to 100 fractures were measured. Information gathered for each feature included the fracture type, strike, dip, aperture, spacing, trace length, yield, and mineralization. In all, 20 outcrops were visited for a total of roughly 1,106 fracture measurements. These measurements were limited to some extent by areas where large or closely spaced exposures were present.
A unique record in a relational database was created for every measured fracture surface. A single record contains the outcrop number, rock type, data type (e.g. fracture, fault, foliation, etc.), data sub-type (e.g. sheeting joint, common joint, etc.), strike, dip, zone width, spacing to next feature, trace length, and type of termination. These records were subsequently queried to create separate files for different fracture types (e.g. for sheeting joints, partings parallel to foliation, macro joints, common joints, etc.). These files were then used to generate stereoplots showing the orientation of fractures with common characteristics. These plots are included on Plate II. Finally, separate files were created for steeply dipping fractures from each outcrop station. Rose diagrams were generated from these files using the program Daisy v4.65 (written by Francesco Salvini, 2007) and plotted along with structural data and the geology on the USGS 7.5' topographic sheet for the Shrewsbury quadrangle.

RESULTS

The results of the fracture investigation are shown graphically in PLATE II. The Microsoft Access database containing all the data is on the accompanying CD.

Major Fracture Sets

Steeply dipping fractures – dips > 60°.

635 of the measured fractures had dips greater than 60°. These fractures may contribute to the recharging of bedrock aquifers. In the Shrewsbury quadrangle steeply dipping fractures are dominantly controlled by partings parallel to the S₁ foliation. The average
strike of this fracture set is 037° and roughly one third of all steeply dipping fractures measured fell into this set (+/-13°). The next most common set is oriented 146°+/-12° and contains 22% of the data. The third major fracture set strikes 115°+/-9° and contains 19% of the data. Two other sets – 091°+/-12° and 177°+/-10° – contain 17% and 10% of the data respectively.

**Sheeting joints – dips << 60°.**

113 sheeting joints were measured. Sheeting joints are gently dipping fractures that seem to form in response to unroofing and local topography. Not all fractures dipping less than 60° were classified as sheeting joints. In the Shrewsbury quadrangle their gently dipping surfaces also appear to be influenced by the metamorphic foliation. Although they are fairly uniformly distributed on the stereoplot (PLATE II) the poles to these joints are slightly skewed towards the northwest and southeast indicating that there are more sheeting joints with northeasterly strikes. This may also reflect the fact that in much of the quadrangle, topographical lineaments tend to parallel the metamorphic foliation. The preferred orientation of the topography might also influence the orientation of sheeting joints.

**Distribution of Fractures**

There does not seem to be any lithologic control on the distribution of different steeply dipping fracture sets. The dominant northeast-striking set is present at nearly all stations, as are most of the other fracture sets. Fracture sets that are absent at a single station are
present in nearby stations. The relative proportion of certain fracture sets measured at a given station varies considerably; however, it is probable that much of this is due to bias in the measurements caused by direction of measurement, orientation of the outcrop, or a limited number of measurements (usually at least 30, but sometimes less). The distribution of steeply dipping fractures does not appear to be affected by mapped ductile faults and shear zones.
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PART THREE
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<th>Sample</th>
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<th>Lithology</th>
<th>Town</th>
<th>Street Location</th>
<th>UTM Zone 19</th>
<th>Foliation Strike Dip Trend Plunge</th>
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<td>303</td>
<td>Snbga</td>
<td>gneiss</td>
<td>Northborough</td>
<td>N side of Green Street, 175 m E of Howard Brook, turn into residential development.</td>
<td>0280696</td>
<td>4691323</td>
<td>Go all the way to the back of the neighborhood up the hill</td>
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<td>Park on Smith Road, 500 m N of Green Street. Take the path to Mt. Pisgah (take the right fork to the south peak).</td>
<td>207 85</td>
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<td>Outcrop is along path that leads SE from south peak down the hill</td>
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<td>0282329</td>
<td>4690999</td>
<td>207 62</td>
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<td>DSrpg</td>
<td>granite</td>
<td>Shrewsbury</td>
<td>W side of Rt. 140, 730 meters S of I-290 and 135 meters N of Hill Street</td>
<td>0276017 238</td>
<td>4688140</td>
<td>53 326 50 Shear zone is on the side of the outcrop opposite of the road</td>
</tr>
<tr>
<td>504</td>
<td>um</td>
<td>peridotite</td>
<td>Northborough</td>
<td>S side of eastbound I-290 on onramp to Church Street approximately 120 m W of Church Street</td>
<td></td>
<td></td>
<td>Outcrops are behind third house on the right in the neighborhood</td>
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<td>Snrs</td>
<td>granite</td>
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<td>4685415</td>
<td>225 52</td>
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<tr>
<td>705</td>
<td>Stmb</td>
<td>schist</td>
<td>Shrewsbury</td>
<td>On Maple Avenue, 900m N of Rt. 9, take the second street on the right E 250m to the last house on the left</td>
<td>0274751</td>
<td>4684376</td>
<td>Outcrop is between the overpasses above Whitney Street and the Wachusett Aqueduct Homeowner reports &quot;underground river&quot; at this location; high-yield fracture zone?</td>
</tr>
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<td>um</td>
<td>peridotite</td>
<td>Shrewsbury</td>
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<td>0274705</td>
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<td>44 013 26</td>
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<tr>
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<td>quartzite</td>
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<td>Take Jasper Street about 100 m S of Nourse Street to the Nourse Farm stand.</td>
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<td>055</td>
<td>84 013 26</td>
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<td>gneiss</td>
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<td>204</td>
<td>72 40</td>
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<td>schist</td>
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<td>From Nourse Street take Glenn Street N to a &quot;T&quot; intersection (350 m). Go RT 215 m. On corner.</td>
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<td>270</td>
<td>38 300 25</td>
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<td>NSG</td>
<td>Snsn</td>
<td>gneiss</td>
<td>Berlin</td>
<td>W side of South Street, about 150 m N of North Brook</td>
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<td>208</td>
<td>50 224 14</td>
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<tr>
<td>SHD</td>
<td>DSshd</td>
<td>diorite</td>
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<td>S side of Ball Street 135 m NE of Church Street</td>
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<td>40 42</td>
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<td>Ssh</td>
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<td>N side of Route 9, 375 m W of Maple Avenue at Subaru dealership; outcrop is 30 m NNE of front lot</td>
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<td>TSC</td>
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<td>On Smith Road, 700 m N of intersection with Green Street; take a long driveway W 275 m (the turn is the 2nd after the drive for 31 Smith Road)</td>
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<td>UM</td>
<td>um</td>
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<td>245 5</td>
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<td>004 34</td>
<td>The people that live at this outcrop are very friendly (Mike &amp; Julia)</td>
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APPENDIX II.

STATISTICAL METHODS

Calculation of Error for Monazite Dates

For every dated monazite domain, 5-15 spots were generally analyzed. The number of spots is reported in Table 6.1 in the last column (the heading is ‘n’). The U, Pb, and Th concentrations measured for each spot were run through the age equation 6-1 producing a single analysis. The reported date for a domain was calculated by finding the arithmetic mean of all the analyses, that is:

\[
\text{DATE} = \left[ \sum_{i=1}^{n} (a_i) \right] / n
\]  
(A2-1)

where ‘a’ is an analysis and ‘n’ is the total number of analyses.

The method of Williams and others (2006) was followed to report the error at the 95% confidence level. They use the Standard Deviation of the Mean (SDOM) method which is sometimes referred to as the Standard Error. This method assumes that repeated statistical samples (the 5-15 spot analyses) are collected from a homogenous, normally distributed population. In long-term studies of their consistency standard GSC-8153, they found that the mean and uncertainty during an analytical session typically stabilized after more than 5 analyses were included in their calculations. The SDOM essentially improves the uncertainty by taking into account the size of the sample.
The SDOM is calculated by taking the traditional standard deviation:

\[ \sigma = \left[ \frac{1}{n} \sum_{i=1}^{n} (a_i - \text{DATE})^2 \right]^{\frac{1}{2}} \]  

(A2-2)

and dividing it by the square root of the number of analyses contributing to the mean:

\[ \text{SDOM} = \frac{\sigma}{(n)^{\frac{1}{2}}} \]  

(A2-3)

Williams and others (2006) found that using the SDOM produced nearly identical results to propagating counting uncertainties through the age equation (Equation 6-1).

Calculation of Weighted Mean Ages

For groups of dates that were deemed to represent a single geologic event a weighted mean age with error was calculated. A weighted mean is similar to a simple arithmetic mean, except that each date contributing to the mean is given a weight. In this study dates were weighted according to their SDOM. In this way, more robust dates with small error values contributed more to the weighted mean than dates with large errors. The calculation for the weighted mean age using the SDOM for weights was adapted from Montel and others (1996):

\[ \text{AGE} = \left[ \sum_{i=1}^{n} \left( \frac{\text{DATE}_i}{\text{SDOM}^2_{\text{DATE}_i}} \right) \right] / \left[ \sum_{i=1}^{n} \left( \frac{1}{\text{SDOM}^2_{\text{DATE}_i}} \right) \right] \]  

(A2-4)
Note that in equation A2-4, ‘n’ represents the number of dates included in the weighted mean. A standard deviation of this weighted mean age can be calculated by using a similar equation also adapted from Montel and others (1996):

\[
\sigma_{\text{AGE}} = \left[ \frac{1}{\left( \sum_{i=1}^{n} \left( \frac{1}{\text{SDOM}^2_{\text{DATE}}_i} \right) \right)^{\frac{1}{2}}} \right] 
\]

(A2-5)

APPENDIX III.
CONSISTENCY STANDARD

Before each analytical session during monazite dating, a consistency standard was run. Figure A3.1 shows the results of consistency standard runs at the University of Massachusetts-Amherst Electron Microprobe Facility during a two-month period in 2005 (Williams and others, 2006). Also shown are the consistency standard runs conducted before and after the analytical sessions for samples from this study. The consistency standard runs associated with this study’s samples fall within the 2\(\sigma\) range for the 2-month mean published in Williams and others (2006) even though they were conducted over a year later. This demonstrates the consistency of the facility and the reproducibility of this study’s results.
Figure A3.1. Analytical runs of consistency standard GSC-8153. Runs during April and May of 2005 were reported by Williams and others (2006); runs during June, July, and August 2006 were completed during analysis of this study’s samples. Date of sessions for samples from this study are indicated by arrows. The black line at 498 Ma is the mean date reported by Williams and others (2006) for all sessions during April and May of 2005; the gray bars represent the 2-sigma standard deviation for those runs, +/-8 Ma; the white rectangle between the gray bars represents the weighted mean age with error, +/-3 Ma (for explanation of weighted mean ages, refer to Appendix II). Black error bars on analyses represent short-term random error, and is about 1% for most analyses. All runs were completed at the University of Massachusetts-Amherst Electron Microprobe Facility.
APPENDIX IV.

MONAZITE DATA: SAMPLES RVV-011 & RVV-012 (AGES IN MA)

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- Average
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- Standard deviation of the mean

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Average: 2866, Standard deviation: 1318

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192
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