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STRATIGRAPHY AND STRUCTURAL GEOLOGY IN THE ACADIAN GRANULITE FACIES[1]

by
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INTRODUCTION

The Merrimack belt in central Massachusetts (fig. 1) contains strongly deformed, metamorphosed sedimentary rocks. Similar rocks are preserved among the abundant plutons of New Hampshire and extend into central Maine where the metamorphic intensity is less and Silurian fossils are present. The stratigraphic interpretation presented on this trip depends on correlations extended from the more complete, better preserved and fossil-controlled stratigraphic sections of Maine. On this trip we will see rocks in the area between Brimfield and Sturbridge, Massachusetts and Union, Connecticut (fig. 2). This area includes the highest grade Acadian metamorphic rocks in the Appalachians, reaching into the granulite facies. Even though the rocks have been affected by partial melting and high-grade metamorphism, relict primary stratigraphic features can be discerned.

Because the stratigraphic interpretation is so vitally important, one objective of the trip is to show participants a variety of common and distinctive rock types in hopes that they may be familiar to workers from surrounding areas. The second objective is to demonstrate the critical relationships on the ground that have been used to reconstruct the sequence of structural, plutonic, and metamorphic events in this area, independent of regional stratigraphic considerations.

PREVIOUS WORK

Emerson (1917) made the distinction in central Massachusetts between Brimfield schist, dominated by sulfidic, graphitic schists, and Paxton quartz schist, a flaggy, biotitic quartz schist with calc-silicate lenses. In the late 1960's and early 80's, a U.S.G.S. detailed mapping program in the area around the Massachusetts-Connecticut state line produced 1:24,000 quadrangle maps for the Warren (Pomeroy, 1977), Wales (Seiders, 1976), Westford (Peper and Pease, 1975), and Eastford (Pease, 1972) quadrangles (fig 2). The increased detail of this work allowed stratigraphic subdivision into new units, as summarized by Peper and others (1976), and Peper and Pease, 1976). They assigned rocks of Emerson's Brimfield Schist and western parts of his Paxton quartz schist to the Hamilton Reservoir Formation, and eastern parts of the Paxton quartz schist were divided into the Bigelow Brook and Southbridge formations. All three west-dipping formations were interpreted to comprise a non-repeated, westward-facing stratigraphic sequence from the Southbridge up through the Bigelow Brook and Hamilton Reservoir.

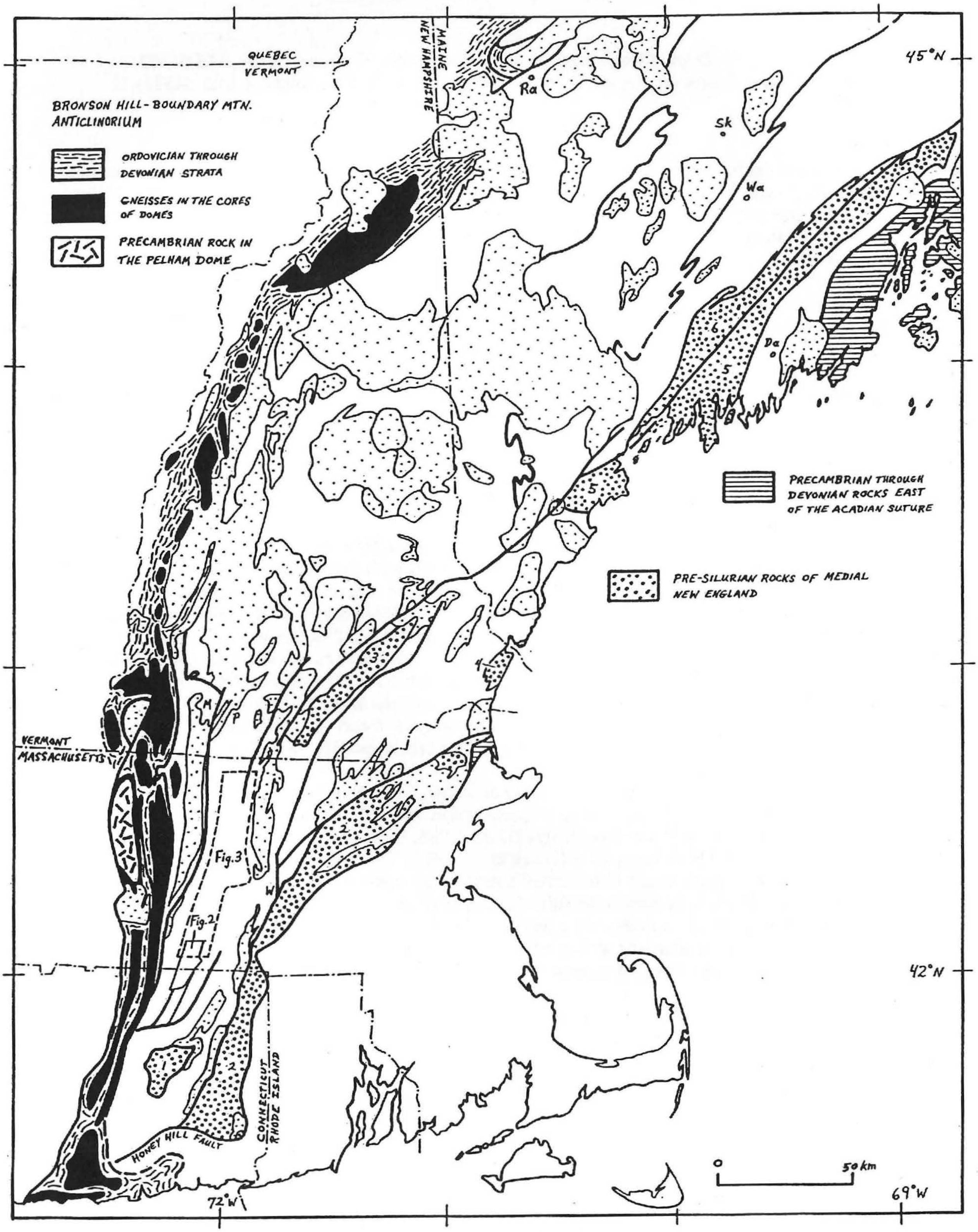
Peper and Pease (1976) recognized the overall similarity of the Hamilton Reservoir formations to rocks in the Peterborough quadrangle, southern New Hampshire as mapped by Greene (1970). Since that time, there has been a major revision of the stratigraphy in the Peterborough area (Duke, 1984; Duke et al., 1988), based on extensions from western Maine through central New Hampshire (Hatch et al., 1983). This suggested that the Hamilton Reservoir Formation, by chain reaction, might also warrant a new stratigraphic interpretation. My early suggestions (Berry, 1985; Robinson et al., 1989) have been more fully developed (Berry, 1989) and are presented on this trip. In remapping this area, the distribution of rocks as shown on the U.S.G.S. quadrangle maps has not changed significantly, except for the additional mapping of thin white schists units (fig. 20). Interpreted stratigraphic and structural relationships, however, have changed dramatically.

STRATIGRAPHY

Leadmine Pond gneiss

The Leadmine Pond gneiss is a new, informal name applied to a unit characterized by medium-gray to white plagioclase-quartz-biotite gneiss with subordinate interlayered biotite-richer gneiss and amphibolite. Local varieties may also include combinations of orthopyroxene, clinopyroxene, hornblende, garnet, K-feldspar, and magnetite. The gneisses occur in a variety of textural types from thinly layered to massive, with layered types more common. In addition, the Leadmine Pond includes subordinate thin units of schist, quartzite, granofels, sillimanite-bearing gneisses, and calc-silicate rocks, interpreted to be metamorphosed

[1] Reprinted with permission from: Robinson, P., and Brady, J. B. (editors), 1992, Guidebook for field trips in the Connecticut Valley region of Massachusetts and adjacent states, NEIGC 84th annual meeting, vol. 1, p. 95-119.


QUEBEC
VERMONT
MAINE
NEW HAMPSHIRE
45°N
BRONSON HILL - BOUNDARY MTN. ANTICLINORIUM
ORDOVICIAN THROUGH DEVONIAN STRATA
GNEISSES IN THE CORES OF DOMES
PRECAMBRIAN ROCK IN THE PELHAM DOME
Ra
Sk
Wa
Da
PRECAMBRIAN THROUGH DEVONIAN ROCKS EAST OF THE ACADIAN SUTURE
PRE-SILURIAN ROCKS OF MEDIAL NEW ENGLAND
VERMONT
MASSACHUSETTS
Fig.3
Fig.2
42°N
CONNECTICUT
RHODE ISLAND
HONEY HILL FAULT
72°W
0
50 km
69°W

sedimentary rocks. The Leadmine Pond gneiss is named for Leadmine Pond in Sturbridge, Massachusetts, where the largest section through the unit is exposed (fig. 2). It is also exposed in several thin, structurally isolated belts to the west.

Rocks assigned here to the Leadmine Pond gneiss were previously interpreted to be gneiss members interstratified with schists of the Hamilton Reservoir Formation (Seiders, 1976; Peper et al., 1975). A major difference between the two interpretations is that the Leadmine Pond gneiss is thought to be older (Precambrian?-Ordovician?) basement upon which the (Silurian?) Rangeley Formation was deposited, whereas the alternating schist and gneiss members of the Hamilton Reservoir Formation are thought to be interstratified parts of a single unit that becomes progressively younger toward the west. Geochemical studies of the gneisses are underway that might discriminate between these two interpretations, although the effects of granulite facies metamorphism and partial melting must be understood before the igneous characteristics of the gneisses can be isolated. Any geochronological studies intended to assign igneous crystallization ages are likewise expected to be significantly complicated by inherited and metamorphic components.

Rangeley Formation

The Rangeley Formation in the Brimfield-Sturbridge area is interpreted to rest unconformably on the Leadmine Pond gneiss. It is characterized by gray-, red-, brown-, or rusty-weathering schists interlayered with quartz-rich, feldspathic or calc-silicate granofels. The granofels layers are commonly 1/2 to 15 cm in thickness, but their abundance relative to schist is highly variable over short distances. In detail, the internal stratigraphy of the Rangeley is complex. Thin units of gray-weathering schist (Srg), sulfidic white schist (Srw), and calc-silicate granofels (Src) are mapped separately, some of which are shown in figure 2. In the western part of the field trip area, the upper part of the formation is exposed, including the upper contact against the Smalls Falls Formation. East of the westernmost exposure of Leadmine Pond gneiss, the Rangeley is exposed in a series of thrust slices that contain the base and lower parts of the formation. A sequence of thin units of white schist, calc-silicate granofels, and gray schist are present in several of the slices within 300 meters of the base of the unit, suggesting a persistent set of thin units may be present.

Smalls Falls and Madrid formations

The Smalls Falls and Madrid formations succeed the Rangeley conformably. These two units are only preserved in the north-central part of figure 2, and are cut out southward by a fault. For lithologic descriptions, see Stop 3.

Paxton Formation

The field trip ends to the east in the Bigelow Brook member of the Paxton Formation. A lithologic distinction has been made farther to the south and east between the Bigelow Brook and Southbridge formations (Pease, 1972), but this distinction has not been mapped northward from the state line very far into Massachusetts. Therefore, much of central Massachusetts remains mapped as the Paxton Formation, a

Figure 1 (facing page). Regional geologic setting. Area of field trip, shown in more detail in fig. 2, is indicated on Massachusetts-Connecticut line. Field trip lies within an area of Silurian-Devonian strata (not patterned) that extends through Merrimack County, New Hampshire into central Maine. This area is bounded by older rocks to the west (Bronson Hill and Boundary Mountains anticlinoria) and by the Honey Hill and other faults of various age (heavy lines) to the east. Fine stipple: selected plutons. Localities: Ra=Rangeley, Sk=Skowhegan, Wa=Waterville, and Da=Damariscotta, Me.; P=Peterborough and M=Mt. Monadnock, N.H.; W=Worcester, Mass. Areas of pre-Silurian rocks in medial New England: 1=Willimantic dome, 2=Putnam-Nashoba zone, 3=Massabesic Gneiss, 4=Rye Fm., 5=Saco-Harpswell sequence of Cushing Fm., 6=Falmouth-Brunswick sequence of Cushing Fm. Original compilation from: Osberg et al. (1985), Osberg (1988), Moench and Pankiwskyj (1988), Hussey (1985; 1988), Berry and Osberg (1989), Billings (1956), Thompson et al. (1968), Lyons (1979), Bothner et al. (1984), Thompson (1985), Hall and Robinson (1982), Zen et al. (1983), Robinson et al. (1991), Peper and Pease (1976), Rodgers (1985), Wintsch (1985), Getty and Gromet (1992).

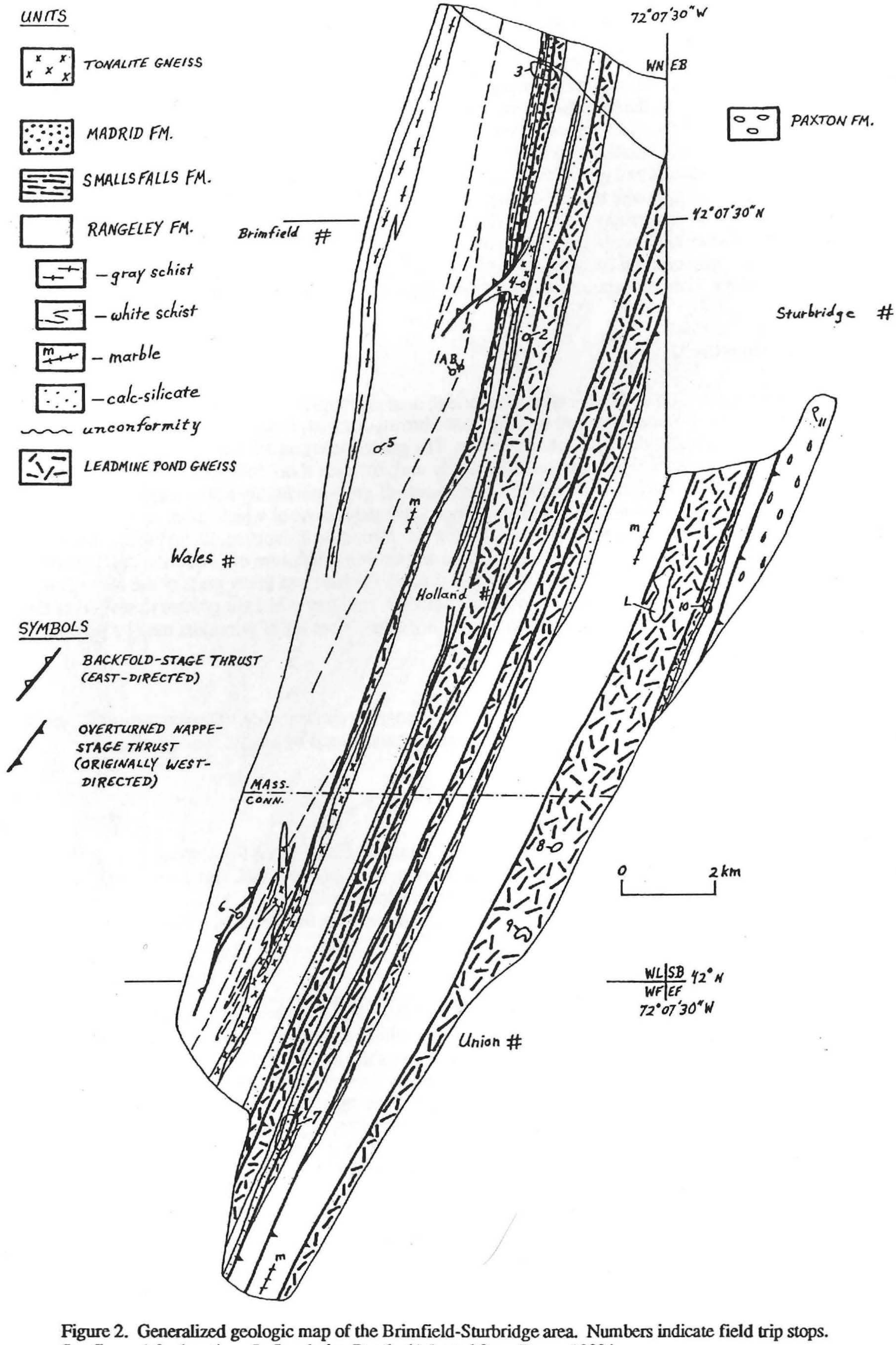


Figure 2. Generalized geologic map of the Brimfield-Sturbridge area. Numbers indicate field trip stops. See figure 1 for location. L=Leadmine Pond. (Adapted from Berry, 1989.)

heterogeneous unit that probably spans the entire Silurian Perod (Zen et al., 1983; Robinson and Goldsmith, 1991). The rock type characteristic of the Paxton Formation is gray-weathering, slabby, quartz-plagioclase-biotite granofels that is purplish-gray on a fresh surface (Stop 11). Thin layers and pods of green calc-silicate granofels are commonly present and locally abundant. Many lithologic units within the Paxton have been mapped, including rusty schist, rusty quartzite, and gray schist (figs. 2, 3), but shallow dips, poor outcrop, complicating late faults, and a probably complex internal stratigraphy have left stratigraphic relationships among many of these units unresolved.

Stratigraphic relationships between the Rangeley and Paxton formation are also uncertain. Where the Rangeley is predominantly schist and the Paxton is predominantly granofels, the distinction is fairly straightforward. But in places where the Rangeley is schist with interlayered granofels and the Paxton is granofels with interlayered schist, the distinctions are more subtle, suggesting that the two formations may at least partly interfinger. The Paxton has not been mapped since the Rangeley explosion of the past ten years, and the new stratigraphic perspective might help to solve some of these problems. Similar problems confronted workers in central Maine where the Huchins Corner (formerly Vassalboro) Formation was originally equated with the Madrid (formerly Fall Brook) Formation (Osberg, 1968), but now the Hutchins Corner is placed at the bottom of the section, and the Madrid is at the top (Osberg, 1988).

STRUCTURAL GEOLOGY

General features

The geometric pattern of units in figure 2 and the surrounding region appears to be fairly simple. All layering and foliation strike north-northeast and dip to the west at 35 to 60° for hundreds of square kilometers. Local repetition of strata (Stop 7), and low-angle truncation of units (fig. 2), however, indicate the presence of isoclinal folds and map-scale faults. The significance of isoclinal folding is difficult to assess because fold hinges are approximately horizontal, so that few fold noses are exposed on the ground. Furthermore, some areas of the map lack distinctive marker horizons that would clearly discriminate between structural repetition and stratigraphic complexity. Relative motion of the faults is likewise difficult to prove in all cases, because not all faults display fault-related fabrics, although some do. Differences in local interpretation have produced significantly different tectonic models for this region (Rodgers, 1981a; 1981b; Robinson and Tucker, 1981), hinging mainly on the inferred sense of motion on the major map-scale faults. Recent work indicates that not all faults are the same age, and that both west-directed and east-directed faults are present (fig. 2).

While not all features can be assigned to a definite place in the deformational sequence, cross-cutting relationships and timing with respect to metamorphism allow certain features to be assigned to either the nappe stage, backfold stage, or dome stage of Acadian deformation (Robinson and Hall, 1980).

Nappe stage

During the nappe stage of Acadian deformation, fold nappes and thrust nappes were transported westward over the Bronson Hill anticlinorium in Massachusetts and New Hampshire (Thompson et al., 1968; Robinson and Hall, 1980; Thompson, 1985; Robinson et al., 1991). Map-scale isoclinal folds and faults in the Brimfield area that pre-date the metamorphic peak are assigned to this stage. The nappe-stage folds are recognized by stratigraphic repetition and are truncated by nappe-stage faults (Stop 7). The nappe-stage faults (stops 3 and 7) are intruded, in turn, by tonalites that were recrystallized during the peak metamorphism (Stop 4). Therefore, the nappe-stage folds and faults pre-date the peak of metamorphism.

After the nappe-stage faults formed, the rocks were recrystallized at least during the peak metamorphism and perhaps during a pre-peak-metamorphic, andalusite-forming regional metamorphism and were affected by at least two phases of penetrative, ductile deformation. It is not surprising that even where the nappe-stage faults are exposed in outcrop no fault-related fabrics of this age have been recognized. The sense of displacement on the nappe-stage faults is based entirely on the inferred stratigraphic offset which depends on the stratigraphic interpretation. Each nappe-stage fault brings the Leadmine Pond gneiss to the east against the Rangeley, Smalls Falls, or Madrid to the west. This gives an east-side-up sense of offset (Stop 3), consistent with the west-directed thrust nappes of the Bronson Hill in New Hampshire and northern

Massachusetts. The fact that these faults now dip to the west is attributed to the later, backfold stage of deformation.

Backfold stage

The nappe-stage Brennan Hill and Chesham Pond thrusts in the western part of the Mondadnock quadrangle, New Hampshire, are west-directed, east-dipping thrust faults (Thompson, 1985). They can be traced southward along the east side of the Bronson Hill anticlinorium into southern Massachusetts where they are west-dipping, overturned to the east by a major backfold (Robinson et al., 1991; Robinson and Elbert, this vol., trip A-3). Westward dips continue uninterrupted from the east edge of the Bronson Hill anticlinorium to the Brimfield-Sturbridge area where the nappe-stage thrusts are apparently also overturned. The present, west-dipping orientation of the nappe-stage folds and thrusts in the Brimfield area is therefore attributed to eastward overturning during the backfold stage.

Minor structural features that are assigned to the backfold stage of Acadian deformation include mylonite zones from a centimeter to 100 meters in thickness (Stop 6), ductile shear zones, asymmetric boudinage and low-angle truncations of foliation, and a prominent west-plunging mineral lineation. These features are interpreted to have formed slightly after formation of the peak metamorphic minerals because peak metamorphic minerals are deformed, and yet the same minerals are recrystallized along shear planes and in the lineation direction. Where diagnostic, kinematic indicators consistently show west-side-up motion, although most rocks in the region contain a flattening fabric without obvious asymmetry. Apparent low-angle cross-bedding reported by previous workers (Peper et al., 1975) might be interpreted alternatively as asymmetric composite metamorphic foliation.

The backfold-stage deformational features are widespread and appear to be concentrated in certain lithologic types, particularly the tonalites and layered gneisses, rather than along mapped faults in the area of this field trip. Elsewhere, major faults both to the west (Peterson, this volume, trip A-1) and to the southeast (Peper et al., 1975) do contain associated minor features consistent with the east-directed backfold stage.

Dome stage

Late, asymmetric minor folds are common in central Massachusetts (Robinson, 1979). Their hinge lines trend north-south and plunge within 15° of horizontal. A common, north-south mineral lineation is assigned to the same deformational phase. This lineation has been mapped to the northwest where it is kinematically related to the Bronson Hill gneiss domes. The remarkable similarity in texture between the east-west lineation and the north-south lineation give a cloth-like fabric to some samples, and suggest that the backfold- and dome-stage lineations formed under similar, high-grade metamorphic conditions.

Post-Acadian features

While rocks in the field trip area do not appear to carry penetrative post-Acadian deformational fabrics, significant high-temperature, ductile deformation of Late Paleozoic age occurred to the south in the Willimantic dome (Getty and Gromet, 1992), to the east in the Worcester area (Goldstein, this vol., trip B-2), to the northwest in the Pelham dome (Robinson and six others, this vol., trip B-3), and to the northeast (at least thermal effects) in the Massabesic gneiss (Eusden and Barreiro, 1988). The Oakham and Gardner anticlines are late foliation arches of unknown age (Robinson and Tucker, this vol., trip C-3), that have some structural similarity to the Willimantic dome. In some ways the most remarkable feature of the the Brimfield-Sturbridge area is that it was insulated from high-grade Late Paleozoic deformation (Gromet, 1989).

METAMORPHISM AND PLUTONISM

The entire field trip is in Zone VI, the highest-grade regional metamorphic zone in Massachusetts (Thomson et al., this vol., trip C-4). Only rocks at the easternmost stop (Stop 11) appear to be partially retrograded. U-Pb monazite analyses indicate that the age of peak metamorphism is Late Devonian (362-369 Ma), consistent with Acadian regional metamorphism and plutonism in central New Hampshire and central Maine (Thomson et al., this vol., trip C-4).

No crystallization ages have been determined for intrusive rocks within the region of figure 2. Samples collected by M.H. Pease from the Hedgehog Hill gneiss to the south in the Stafford Springs quadrangle, Connecticut (Pease, 1975), yielded zircons that were analyzed by R.E. Zartman in 1979. The Hedgehog Hill gneiss is an elongate body of foliated, metamorphosed tonalitic gneiss that extends northward from the Stafford Springs quadrangle into the southern part of figure 2 where it cuts a nappe-stage fault. Two zircon size-fractions were analyzed and both were discordant. Zartman (1988, written commun.) interpreted the discordia drawn through both analyses to give a meaningful upper intercept age of about 445 Ma, assuming the discordance was due to a post-crystallization Pb-loss event. Such an old crystallization age for a cross-cutting pluton suggests that the Hamilton Reservoir Formation should be revised from Silurian-Devonian (Peper et al., 1975) to pre-Late Ordovician (Pease and Barosh, 1981) or even pre-Ordovician (Barosh, 1982) in age. Alternatively, if the discordance of the Hedgehog Hill gneiss zircons is due to a mixture of older xenocrysts with newly-formed igneous zircon, the intrusive age would be *younger* than the Pb-Pb age, allowing a Silurian age for the country rocks. Further, detailed study of the zircon population is required before a crystallization age can be assigned to the Hedgehog Hill gneiss.

REGIONAL CORRELATION

Leadmine Pond gneiss

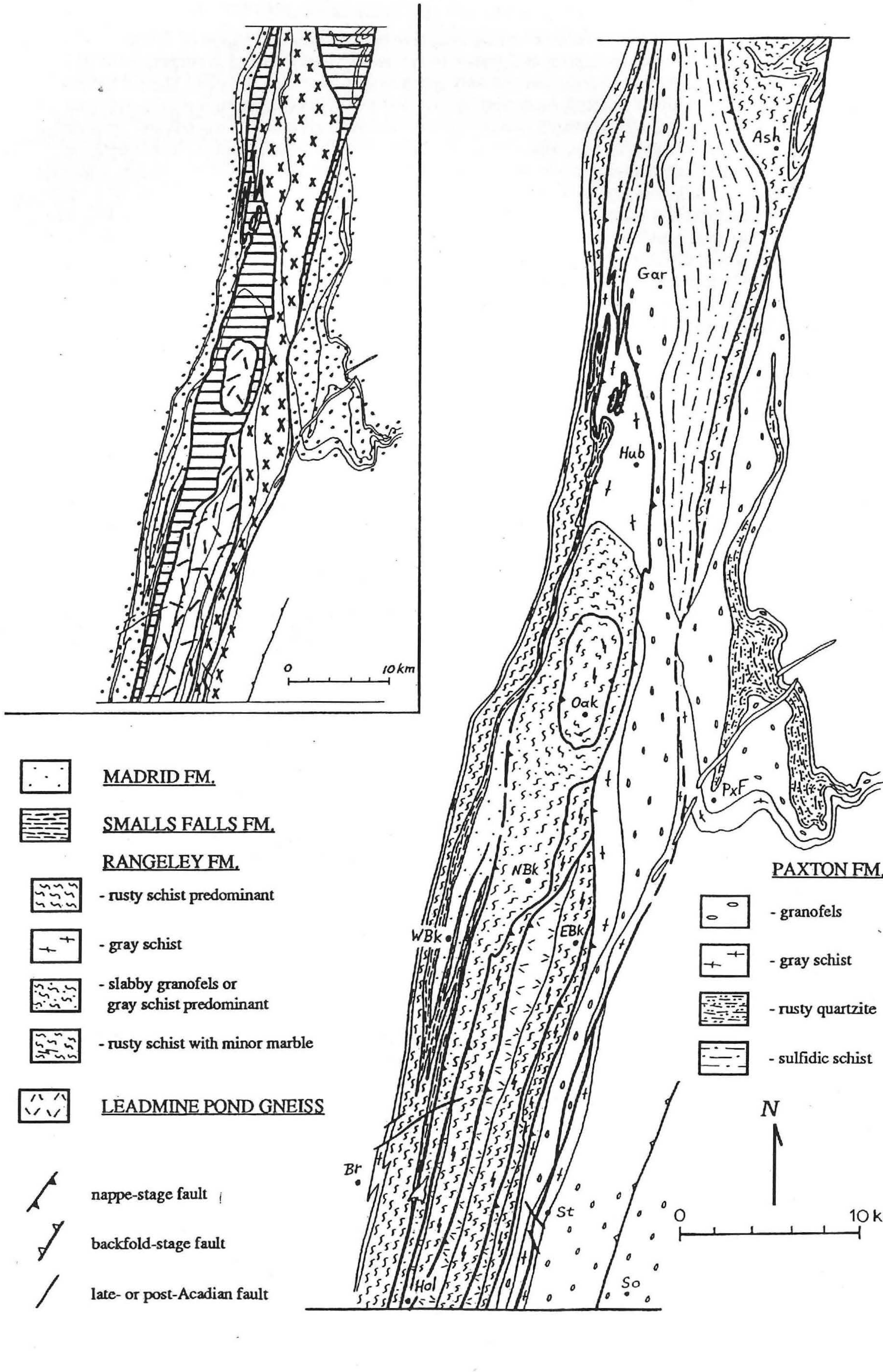
Part of the reason for considering the Leadmine Pond gneiss to be pre-Silurian basement is that the Silurian sections of New Hampshire and Maine do not contain within them similar sorts of thick, interstratified gneisses. On the other hand, pre-Silurian units in the surrounding region do contain rocks and sequences of rocks similar to those of the Leadmine Pond gneiss. Units that contain partly similar rocks include the Monson Gneiss and Ammonusuc Volcanics of the Bronson Hill anticlinorium in central Massachusetts; the Tatnic Hill Formation in eastern Connecticut and Nashoba Formation in eastern Massachusetts of the Putnam-Nashoba zone (see Goldsmith, 1991 for review); the Rye Formation in coastal New Hampshire; and part of the Cushing Formation in the Falmouth-Brunswick sequence, Maine (Hussey, 1985; 1988) (fig. 1). The broad similarities among these units suggests that a single continental basement, not to be confused with Cambrian-defined Avalon, extended beneath medial New England in Late Ordovician time (Osberg, 1978; Hall and Robinson, 1982; Berry and Osberg, 1989).

Silurian(?) strata in Massachusetts

In the interpretation presented here for the Brimfield-Sturbridge area (fig. 2), the major structural features are imbricated nappe-stage thrust faults overturned to the east. This interpretation is incompatible with that of Zen et al. (1983) who showed the anticline at Oakham (fig. 3) extending southward, implying that rocks east of Holland face east and rocks west of Holland face west. It is also incompatible with the model of Rodgers (1981) in which the rocks face predominantly west. A new suggestion is offered in figures 3 and 4 which attempts to meld the interpretation of the Brimfield-Sturbridge area with previous mapping in the Oakham area to the north. This proposal is a conceptual model that is meant to inspire further field investigations.

In constructing figures 3 and 4, several observations and bits of information from different sources have been incorporated. These include:

- The Smalls Falls Formation is bounded to the east by the Madrid Formation in the West Brookfield area, the Leadmine Pond gneiss in the Brimfield area, a gray schist unit in the Hubbardston area, and it ends northward at about the latitude of Gardner. Therefore, a fault is proposed that extends from the Brimfield area (Stop 3) northward across Massachusetts, approximately along the east side of the Smalls Falls.
- Field (1975) noted that the rocks east of the Smalls Falls at West Brookfield, mapped by him as Paxton Schist and shown here as Madrid Formation (fig. 3), have thinner layering and less calc-silicate rock than Paxton to the east. The fault proposed along the east side of the Madrid in the area north of W. Brookfield (fig. 3) is intended to separate these two rock types, although this subtle contact has not been mapped in the field.
- A unit of gray schist at Hubbardston is in contact to the south with a map unit dominated by slabby gray granulites with common calc-silicate granofels and interlayered rusty schist. This unit was


0 10km
Ash
Gar
Hub
Oak
PxF
NBk
WBk
EBk
Br
St
So
Hol
N
0 10 km
MADRID FM.
SMALLS FALLS FM.
RANGELEY FM.
- rusty schist predominant
- gray schist
- slabby granofels or gray schist predominant
- rusty schist with minor marble
LEADMINE POND GNEISS
nappe-stage fault
backfold-stage fault
late- or post-Acadian fault
PAXTON FM.
- granofels
- gray schist
- rusty quartzite
- sulfidic schist

mapped by Tucker (1977) north of the Oakham anticline as a member of the Paxton Schist, and is assigned here to the Rangeley (fig. 3). Similar rocks are present in the Brimfield-Sturbridge area in the belt that includes Stop 2 (fig. 2). A similar set of rock-types is also present in the Ashburnham area, mapped by Peterson (1984) as members of the Littleton and Paxton formations. This unit of the Rangeley includes thin layers of sulfidic white schist in the Brimfield (Berry, 1989), North Brookfield (Zen et al., 1983), and Ashburnham (Peterson, 1984) areas.

- The Rangeley rocks around Holland are dominated by rusty schists, but also include thin units of layered marble (fig. 2). Thin units of cocolitic limestone (graphitic diopside marble) were mapped by Emerson (1917) around East Brookfield. Rocks in the center of the Oakham anticline (fig. 3) are dominantly rusty schist. Although not exposed at the surface, limestone beds up to 15 feet thick are present in the rusty schist, reported by Fahlquist (1935) from the Quabbin aqueduct tunnel.
- A fault is postulated west of Gardner to account for apparent low-angle truncations of units along strike. In particular, the sulfidic schist west of Gardner ends just southwest of Gardner; the gray schist at Hubbardston ends toward the southeast; the belts of Leadmine Pond gneiss in the Holland area do not extend as far north as Oakham; and the gray schist west of Sturbridge extends north to the latitude of Oakham and seems to disappear. Robinson and Goldsmith (1991) offer an alternative interpretation that does not require a fault here.
- The Bigelow Brook member of the Paxton near Sturbridge is similar to the Paxton Formation near Gardner in that they both contain mappable units of massive, brown-weathering sulfidic schist associated with the characteristic purplish-gray Paxton granofels.

The interpretation of figures 3 and 4 accounts for these stratigraphic features mainly by "telescoping" along nappe-stage faults. Additional backfold-stage faults and younger faults may well complicate the picture.

Figure 3 (facing page). Geologic map of central Massachusetts. See figure 1 for location. Inset: distribution of lithotectonic belts. Towns: Ash=Ashburnham, Gar=Gardner, Hub=Hubbardston, Oak=Oakham, PxF=Paxton Falls, NBk=North Brookfield, WBk=West Brookfield, EBk=East Brookfield, Br=Brimfield, St=Sturbridge, Hol=Holland, So=Southbridge. Reinterpreted from Zen et al. (1983) based on Emerson (1917), Field (1975), Tucker (1977), Peterson (1984), Berry (1989), and Robinson and Goldsmith (1991).

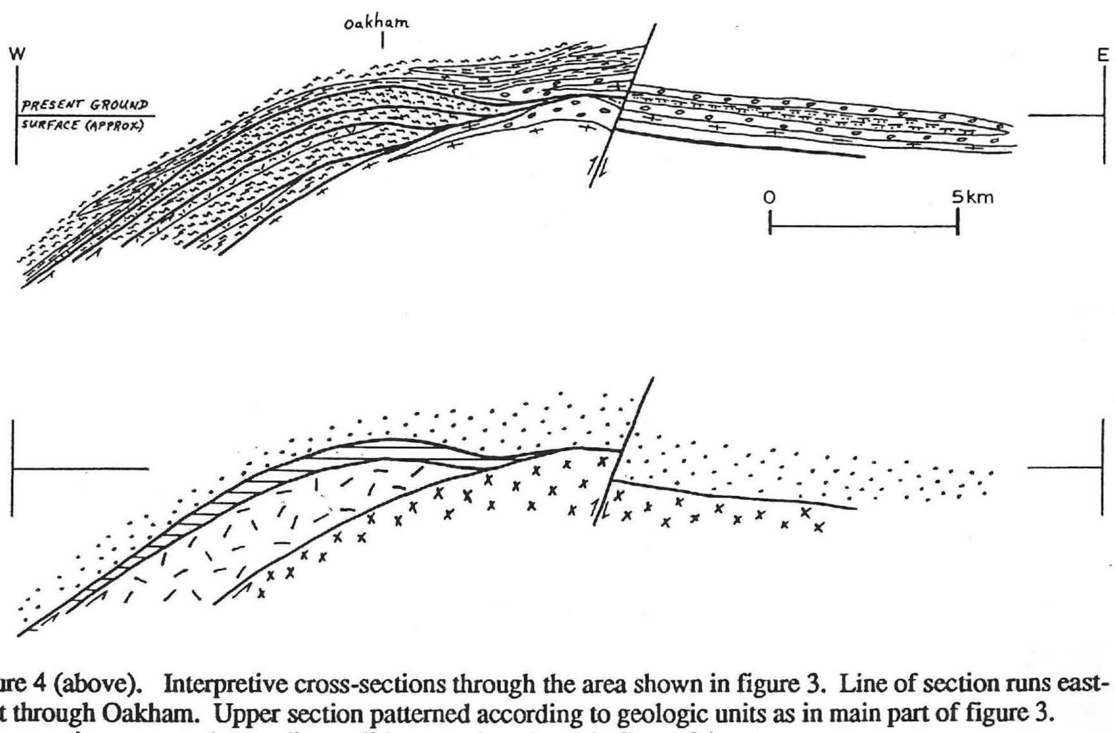


Figure 4 (above). Interpretive cross-sections through the area shown in figure 3. Line of section runs east-west through Oakham. Upper section patterned according to geologic units as in main part of figure 3. Lower section patterned according to lithotectonic units as in figure 3 inset.

Silurian strata in Maine

In a general way, the Brimfield - West Brookfield strata are similar to parts of the section near Rangeley, Maine (fig. 1), with passable Smalls Falls and Madrid correlatives. The parts of the Rangeley in the North Brookfield - Ashburnham and Holland - East Brookfield areas contain more calc-silicates and minor limestones, more like Silurian rocks in the Skowhegan and Waterville areas. To the east, the Southbridge Formation is a layered granofels unit free of schist, much like the Bucksport Formation in the Damariscotta area (fig. 1). It is suggested that the distribution of Silurian facies that has been described in Maine (Moench and Pankiwskyj, 1988; Osberg, 1988) from proximal in the west (Rangeley) to distal in the east (Damariscotta) is also present in the Merrimack belt of Massachusetts. But the geologic elements that cover 120 km across strike in Maine, can be found within 20 km across strike in Massachusetts (fig. 1). In this model, the Southbridge, Bigelow Brook, and Hamilton Reservoir formations might represent different Late Ordovician-Silurian facies that have been thrust together, rather than a continuously westward-younging stratigraphic section >21-km-thick (Peper and Pease, 1976).

ACKNOWLEDGMENTS

This field trip is based on the author's Ph.D. research at the University of Massachusetts (Berry, 1989) augmented by subsequent research. Guidance, discussions, assistance, and support from Peter Robinson during that time are gratefully acknowledged. Geologists familiar with Robinson's work will notice his influence in the content and style of this paper. Field work was supported by N.S.F. research grants EAR-81-1697, EAR-84-10370, and EAR-86-08762 (all to Peter Robinson).

ROAD LOG

Participants will leave at 8:00 Saturday morning from the parking lot north of the University of Massachusetts Football Stadium in Amherst according to meeting announcements. We can leave extra cars there, and travel together to the beginning of the trip in Brimfield, about an hour from Amherst.

Starting place: Public parking lot 150 feet northeast of traffic light at the intersection of Rt. 20 and Rt. 19, Brimfield, Massachusetts at 9:00.

Mileage

0.0 Turn left from SW corner of parking lot.
0.05 Bear right around obelisk, then turn left onto Route 20 East.
0.4 Turn right onto Holland Road.
0.5 Bear left at fork, toward Holland.
1.2 Turn left onto Five Bridge Road.
1.4 Pass flood-control gate.
1.8 Park to the right.

STOP 1. VARIETIES OF THE RANGELEY FORMATION. (Note: Stop locations are indicated in figure 2.) In the Brimfield area a Range of lithologic types is assigned to the Rangeley. We will see two types here at Stop 1, a third type at Stop 2, and other variants during the day, some of which have been mapped separately.

1A. Schist and granofels. Walk northwest from the road 300 feet along intended railroad bed to a cut on the right (northeast). The rock consists of rusty-weathering sillimanite-orthoclase-quartz-biotite-garnet-graphite-ilmenite-pyrhhotite ± cordierite schist interlayered with slabby, bluish-gray quartz-plagioclase-biotite ± garnet granofels in layers 5 to 15 cm thick. Schist is subordinate to granofels at this outcrop, but the proportion of schist to granofels is variable over very short distances and has not proven to be a useful criterion for mapping. The rock type here is common in the Rangeley Formation of the Brimfield area. This is probably what Emerson (1917) meant by Brimfield schist, since it is a "rusty, graphitic biotite schist" in Brimfield, but he did not give a specific type locality.

These rocks are lithologically similar and trace directly into rocks mapped as Rangeley in the eastern Monadnock (Thompson, 1985) and western Peterborough (Duke, 1984) quadrangles, New Hampshire (fig.

1). Compare this outcrop with Stop 6 of Thompson (1988) and with Stop 1 of Duke et al. (1988). It is by extension from those rocks in southern New Hampshire that the name Rangeley is used here.

Return to road. Turn left (east). Walk a short distance along Five Bridge Road. Turn left (north) onto old logging road. Walk north 600 feet along road to decrepit pavement outcrop.

1B. White schist. This rock is a very sulfidic, sillimanite-rich schist. It contains mostly white minerals, namely quartz, sillimanite, orthoclase, cordierite, and pale to white, Mg-rich biotite; therefore the informal name "white schist" was used by Field (1975) for this rock type. The black flakes in the rock are graphite, and rutile rather than ilmenite is the primary titanium-bearing oxide phase. White schist can be distinguished in the field from ordinary schists such as the one at Stop 1A by the presence of tiny brown rutile needles and pale biotite (muscovite not being stable in schists at this metamorphic grade), a lack of garnet, and a bright orange weathering color with red splotches. This rock represents a metamorphosed, carbonaceous black shale. Sulfur isotopes in white schists from the region preserve a primary, biogenic signature indicating that the high sulfur content is inherited from the sedimentary protolith (Tracy and Rye, 1981; Tracy and Robinson, 1988).

This locality was mapped in reconnaissance for the state map as the southern extent of the sulfidic schist and quartzite unit of the Paxton Formation (unit Spsq of Zen et al., 1983; Robinson and Goldsmith, 1991). Subsequent mapping has shown, however, that the white schist here does not trace into the Spsq unit to the north. Furthermore, the Spsq unit rests against granulites of the Paxton Formation to the east while the white schist here is enclosed by schist units on both sides, now assigned to the Rangeley. Therefore, despite its similar lithology, the white schist here is interpreted as a lens in the Rangeley, and not correlative with the white schist of unit Spsq. Lenses of black, carbonaceous pelite are similarly present within the Silurian Sangerville Formation of west-central Maine (Ludman, 1976). We will see the white schist of Spsq (Smalls Falls Formation) and its stratigraphic setting at Stop 3.

Return to cars. Continue east on Five Bridge Road.

2.0 Outcrop to the left consists of brown-weathering, slabby granofels and schist of the Rangeley.

2.7 Ledge in the woods west of road (to the left) is reddish-brown-weathering Rangeley schist with interlayered granofels. Layering is thin, 2-4 cm thick, with intervals up to 30-cm thick of layered granofels without schist.

3.1 Park to right before small stream gulley. Outcrops are in the woods west of the road at base of slope. (Private property.)

STOP 2. RANGELEY CALC-SILICATE GRANOFELS UNIT WITH PEBBLY LAYER. The outcrops here consist of light gray to greenish-gray, thinly layered granofels. The layers are generally 1/2 to 4 cm thick and laterally continuous. Most layers consist of medium-grained quartz-feldspar-biotite granofels with a salt-and-pepper look. Somewhat thicker light green to greenish-gray layers of calc-silicate granofels are spaced about 20 to 40 cm apart, interspersed with the gray granofels. These green and white speckled, medium- to coarse-grained calc-silicate layers contain quartz, plagioclase, diopside, and garnet. Rare seams of calcite within the calc-silicate layers weather brown. Thin quartz veins and white pegmatite stringers parallel to layering are common. One layer of quartz-rich granofels 10 cm in thickness contains round lumps of quartz less than 1 cm long that look like pebbles. Besides quartz, the layer contains 5 to15% biotite and a few percent of calcic plagioclase. The pebbly aspect is best evaluated on the outcrop, because microscopic textures are wholly metamorphic. Calcareous sandstones and feldspathic wackes are likely protoliths for these rocks. Similar rocks are present in the Sangerville Formation near Skowhegan, Maine (Pankiwskyj et al., 1976; Ludman, 1977), among other places.

We are in one of the calc-silicate units of the Hamilton Reservoir Formation (hugc) mapped in the Wales quadrangle by Seiders (1976). This unit was assigned to the granofels member of the Paxton Formation (Sp) on the Bedrock Geologic Map of Massachusetts (Zen et al., 1983), and tentatively assigned to the Southbridge Formation (mapped as SOs?) along strike to the south in Connecticut (Rodgers, 1985). The interpretation presented on this trip, based on local mapping, is that this calc-silicate unit is within the Rangeley. Whether the strata here interfinger to the east with the Paxton Formation depends on regional relationships, particularly around the Oakham anticline, that are still problematic (fig. 3). In the Southbridge Formation at Southbridge (Peper et al., 1975), renamed the Southbridge member of the Paxton Formation (Zen et al., 1983; Robinson and Goldsmith, 1991), the quartz-feldspar-biotite layers have a purple hue, the calc-silicate layers are commonly medium to dark green and smooth-looking, they are generally finer-grained than the rocks here at Stop 2, and not associated with schist. While the rocks here may correlate with some part of the Paxton Formation, the Southbridge member is probably not the right part. Compare the rocks here with those of the Paxton Formation at Stop 11.

Return to cars. Continue north on Five Bridge Road.

3.7 Stop sign. Proceed straight across Rt. 20, onto Little Alum Pond Road.
4.7 Little Alum Pond visible to left.
4.8 Outcrop on left before driveway, of light gray, interlayered quartz-feldspar-biotite granofels and calc-silicate granofels, similar to the rocks at Stop 2.
5.0 Outcrops of brown-weathering quartz-feldspar-sillimanite-garnet Rangeley "hardschist" to the left (west).
5.4 Ridge of light gray granulites and pegmatite along right side of road.
5.9 Turn left at sawmill onto dirt road.
6.3 Pull into field to right and park. (Private property.)

STOP 3. PRE-SILURIAN GNEISSES THRUST AGAINST RANGELEY, SMALLS FALLS, AND MADRID(?) FORMATIONS. The three important things to see at this stop are: 1. Pre-Silurian gneisses (locality A); 2. Silurian strata (localities B, C, and D); and 3. The absence of a prominent mylonite zone at the contact between them (in contrast with the mylonite we will see at Stop 6).

Walk across field and into woods, following logging road to the west then north. Locality A is where road again turns west (left) at stone wall, close to Massachusetts Turnpike fence.

3A. Layered mafic and felsic gneisses of the Leadmine Pond gneiss. Among the rocks interlayered here are black hornblende amphibolite; brown-weathering, equigranular plagioclase-quartz-hornblende ± biotite ± orthopyroxene gneiss; light gray plagioclase-quartz-biotite ± orthoclase ± garnet gneiss; and white plagioclase-orthoclase-quartz-biotite-garnet pegmatite. In the hazardous turnpike cut 200 feet north of here, a hornblende-orthopyroxene-olivine-spinel ultramafic pod is enclosed among the layered amphibolites. From their compositions, igneous protoliths are inferred for all these gneisses. Whether they were originally volcanic or intrusive is less certain, but the nature of the layering here suggests a volcanic origin.

Follow road up hill. We are intentionally walking past several outcrops that we will see on the way back. Walk to the crest of the hill and continue west, staying close to the fence. Outcrop B is just across stream gulley near a jog in the fence.

3B. Brown-weathering schist and granulite of the Rangeley. The rock here is similar to that at Stop 1A, except that there is a greater proportion of schist here, with the granofels layers spaced 20 to 50 cm apart. The schist, as almost every schist in the region, is full of very thin quartz-feldspar pods and stringers concordant with foliation. This outcrop clearly shows the difference between these metamorphic features and the slabby, bluish-gray granofels layers that represent relict beds. At the top of the outcrop is a late-stage, asymmetric minor fold in a granofels layer that appears to be right-handed in plan view, but is actually plunging gently to the south, with east-side-up rotation sense. Shallow-plunging minor folds of this age are scattered through the region.

Walk back toward the east, then south along the ridge crest.

3C. White schist and quartzite of the Small Falls Formation. This unit includes very sulfidic, graphitic, sillimanite-orthoclase-quartz-biotite-cordierite white schist interlayered with yellow-weathering, white quartzite. The schist weathers deeply to a rusty, crusty, pitted surface. The quartzite is very clean, commonly with small amounts of sillimanite, graphite, and feldspar. Due to the resistant quartzites, this unit commonly forms topographic ridges, as it does here.

To the north, this unit is mapped more or less continuously to Templeton, Massachusetts as the sulfidic schist and quartzite member of the Paxton Formation (Spsq of Zen et al., 1983). Its correlation with the Smalls Falls Formation of western Maine, first suggested by Field (1975), is based primarily on the extreme sulfide content, and the consequently distinctive mineralogy of the schists (Robinson et al., 1982b). In a great wave of correlation through the 1980's, most schists of high sulfide content through central New Hampshire (Hatch et al., 1983, e.g.), Massachusetts (Robinson, 1981), and into Connecticut (Berry, 1985) were swept into the Smalls Falls. Unfortunately, lithologically similar sulfidic schists also occur in lenses and thin layers at other stratigraphic horizons (fig. 2), and so some of the rocks that recently have been called Smalls Falls probably belong to lower parts of the section (Berry, 1989). I now believe that most (but not all) of the thin white schist units previously assigned to the Smalls Falls in this area (Berry, 1985; Robinson et al., 1989) represent deeper stratigraphic levels. The unit Spsq at this locality is still correlated with the Smalls Falls, however, because: 1) in addition to the distinctive sulfidic white schist it contains interlayered white quartzites, as does the lower member of the Smalls Falls in western Maine (Moench and Pankiwskyj, 1988); 2) it is fairly thick by Massachusetts standards (60-80 meters) and laterally persistent; and 3) it is between rocks similar to the Rangeley (Stop 3B) and Madrid (Stop 3D) formations. The rock at Stop 1B does not pass these criteria.

Walk carefully down the steep, rubbly slope toward the east. Locality 3D consists of several small outcrops beginning partway down the hill where the slope is less steep and continuing intermittently down the hill.

3D. Light gray, thinly layered feldspathic granofels of the Madrid(?) Formation. The principal rock type here is a light-gray-weathering, fine- to medium-grained, quartz-calcic plagioclase-biotite-garnet ± graphite granofels in layers 1/2 to 3 cm thick. Partings between layers are richer in biotite, causing the rock to split readily into tabular slabs. The fresh rock is dark bluish-gray and vitreous. Thin layers of fine-grained, green, diopside calc-silicate granofels are present, but not abundant. Within about 10 meters of the Smalls Falls contact (not exposed) the rocks are slightly rusty-weathering and contain thin interlayers of feldspathic sillimanite-biotite-garnet schist. Thin interlayers of sillimanite-biotite-garnet schist are also present near the bottom of the hill in the outcrop closest to the Leadmine Pond gneiss where we began our traverse (Stop 3A). Fissile sillimanite-garnet-biotite schist is rare in this unit.

Correlation with the Madrid Formation of Maine was suggested by Field (1975) from lithologic similarity and the stratigraphic sequence. In western Maine, layering is thin near the lower contact of the Madrid Formation at the type locality (Osberg et al., 1968), whereas the upper part of the type locality and the "eastern facies" are thick-bedded (Moench and Pankiwskyj, 1988; Bradley and Hanson, 1989). Relationships of the thin-bedded rock here to the rest of the Paxton Formation to the east are uncertain (fig. 3).

If correlations with the Rangeley, Smalls Falls, and Madrid are correct at this stop, then there are two major implications: 1. There is a fault between the pre-Silurian Leadmine Pond gneiss (locality A) and the Silurian Madrid Formation at the adjacent outcrop to the west (locality D); and 2. The Siluran sequence we have just walked across from localities B, C, and D is younging to the east. Since all units dip uniformly to the west, the sequence is overturned to the east, or stratigraphically upside-down (fig. 5).

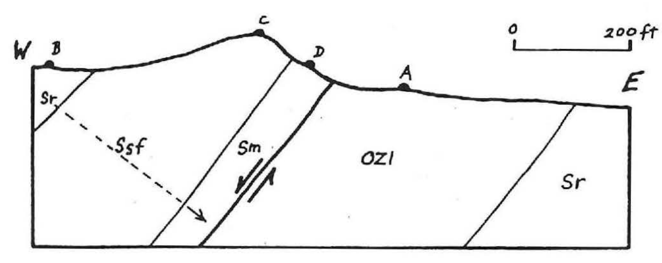


Figure 5. Geologic cross-section at Stop 3. Localities A-D are indicated. Units: OZl= Leadmine Pond gneiss, Sr=Rangeley Fm., Ssf=Smalls Falls Fm., Sm=Madrid Fm. Dashed arrow shows younging direction inferred from stratigraphy.

Return to cars. Turn around and drive out the way we came.

6.7 Turn right onto paved road.

8.6 The rocks we are driving over here (and have been since the last stop) are Rangeley schist and calc-slicate granofels. Hillside outcrops behind the houses to the left (east) of us consist of plagioclase gneiss and amphibolite of the Leadmine Pond gneiss. Therefore, there is a fault between us and the gneisses behind the houses. This is a nappe-stage thrust fault like the one we crossed at Stop 3 that brings older gneisses on the east up against Silurian rocks on the west.

8.9 Stop sign. Turn right on Rt. 20W.

9.1 Turn right onto old segment of Rt. 20.

9.2 Park cars.

STOP 4. TONALITE GNEISS. We are in a tonalitic pluton that cuts across mapped contacts, including the fault we saw at Stop 3. The rock is a massive, medium-gray plagioclase-quartz-biotite-hornblende gneiss with accessory apatite, magnetite, and sphene. Metamorphic pyroxene is locally abundant. Commonly, hornblende and magnetite grains form small clusters, elongate in the foliation. In addition to the common sort of white, medium-grained quartz-feldspar-biotite ± garnet dikes, the tonalite here is intruded by pegmatite dikes with red plagioclase. All the dikes were deformed together with the tonalite and display compatible foliations, lineations, folds, and boudinage.

One of the major mapping problems in this high-grade area is to distinguish metamorphosed Acadian intrusive rocks from stratified gneisses of the Leadmine Pond gneiss. For this particular body, the mapped cross-cutting contacts demonstrate that it is intrusive. The intrusive rocks are generally massive, uniform tonalites in contrast to the Leadmine Pond gneiss that is generally well layered, with a variety of mafic and felsic rock types and minor intercalated schist, quartzite, and calc-silicate rock. Ubiquitous apatite seems to be a common characteristic of the Acadian intrusive rocks.

The map pattern indicates that the tonalite is younger than the nappe-stage fault we crossed at Stop 3. The tonalite itself is internally deformed and was affected by the peak, granulite-facies metamorphism. Therefore, the nappe-stage fault at Stop 3 is older than the peak metamorphism.

Return to cars.

9.3 Stop sign. Turn right onto Rt. 20 W.
9.7 Roadcut on right at crest of hill contains the western contact of the tonalite body, with rusty schist and granulite to the west. Originally this was an intrusive contact, but due to subsequent deformation and high-grade metamorphism the foliation in the tonalite, the intrusive contact, and the foliation and layering in the schist are all parallel.
9.9 Roadcuts on curve, of strongly foliated, mylonitic gneiss with presumed tonalitic precursor.
10.0 Small roadcut to right (north) of interlayered fissile sulfidic schist and dark blue-gray quartz-plagioclase-biotite-garnet granofels.
10.2 Outcrops on right (north) of sulfidic schists and interlayered rusty-weathering quartzite. A thin, separately-mapped layer of white schist runs through here (fig. 2).
11.0 Roadcuts on both sides. If you look quickly, you might see very sulfidic, fissile, sillimanite-biotite-graphite schist, followed at the highest part of the outcrop by sulfidic calc-silicate granofels in blocky, thin layers and large (1 x 8 meter) pods, followed to the west by massive, light gray schist with big garnets. This gray schist can be traced northward for over 70 km into a pluton just short of the New Hampshire line (fig. 3; Zen et al., 1983). Small amounts of sulfidic white schist and black calc-silicate rocks are present intermittently along the contact.
11.4 Dangerous curve.
11.5 Turn left onto Holland Road.
11.6 Bear left toward Holland (as before).
13.3 Rattlesnake Mtn. visible ahead.
13.4 Holland town line.
13.6 Turn right onto North Wales Rd.
14.0 Park on right, safely past curve. Outcrops are to west of road. (Private property.)

STOP 5 (OPTIONAL). MEDIUM- TO COARSE-GRAINED PELITIC SCHIST OF THE RANGELEY. This is a brief stop to look at a pretty rock. We are somewhere in the midst of the Rangeley Formation, to the south and slightly west of Stop 1A. A few thin layers of dark bluish-gray granofels are present, but most of the rock consists of massive, medium- to coarse-grained sillimanite-biotite-garnet-cordierite-quartz-feldspar schist with quartz-feldspar veins and stringers concordant with the foliation. The lower part of the outcrop to the right (north) of the stream weathers brown, while most of the upper parts of the outcrop weather gray. Similar gray schists nearby have been mapped separately, although this particular one has not.

Return to cars. Continue south on North Wales Rd.

14.2 Continue straight. Now on Wales Rd.
14.5 Cross Wales town line. Road improves.
14.9 Cross Tenneco gas pipeline. Thick gravel deposit here continues northward through Brimfield center and beyond.

15.2 Stop sign. Turn left onto Rt. 19S.
15.9 Wales Market on right. Stay on Rt. 19S through Wales.
16.6 Turn left just before Lake George, onto Union Rd.
17.3 Bear left at fork.
18.4 Ridge of Rangeley red-weathering feldspathic schist on left.
18.6 Dangerous intersection. Turn right toward Stafford.
18.8 Rounded blocks of massive tonalite gneiss on slope to right.
19.2 Cross state line into Stafford, Connecticut.
19.8-20.0 Ledges to the right (west) of slabby Rangeley schist with calc-silicate granofels pods.
20.1 Outcrop in cellar hole next to boarded-up red building contains a layer of hornblende ± clinopyroxene amphibolite. A sample from here was studied by Schumacher (1986, her sample 76), that has the whole-rock chemistry of basalt. Rocks such as this with of a composition appropriate for metamorphosed volcanics are very rare in the Rangeley Formation of the Brimfield area. Scattered amphibolites are present in this belt of schist along strike to the north in central Massachusetts (Field, 1975; Tucker, 1977). Whether these rocks are metamorphosed intrusive or volcanic rocks is not known.
20.2 Slabby schist on left.
20.3 Turn left onto Burley Hill Rd. (Dead End).
20.4 Park valuable cars here. Rental cars and university vehicles may continue into the woods. Turn right onto woods road before farmhouse and proceed with care. The outcrop is within walking distance if time allows or if road conditions demand.
20.7 Park cars.

STOP 6. MYLONITE. The rock is a fine-grained, dark-gray to black mylonite with ribbons of quartz and feldspar, and porphyroclasts of plagioclase, biotite, hornblende, and sphene. The groundmass contains these minerals plus magnetite and apatite. Because of its mineralogy, the mylonite here is thought to have had a precursor of tonalite gneiss like the one we saw at Stop 4. The mylonite also contains embedded trains of quartz-feldspar rock, some of which have red plagioclase, believed to be dismembered equivalents of the dikes we saw in the tonalite gneiss at Stop 4. Rocks elsewhere in this mylonite zone are interpreted to be deformed schists of the Rangeley sort.

The mylonitic lineation plunges toward the west, approximately down the dip of the foliation. The lineation is best seen on flatter parts of the outcrop to the right. Work around the outcrop, circling toward the left, to an east-west striking vertical face that is approximately parallel to the lineation. There, asymmetric fabrics and rotated porphyroclasts consistently indicate a west-over-east shear sense. Although rotated porphyroclasts (delta grains) are by far the most common, there are also some rotated grains which have recrystallized asymmetric tails superimposed on them (complex delta-sigma grains of Passchier and Simpson, 1986). Farther around the outcrop, on the overhanging surface, dismembered bits of a red-plagioclase pegmatite outline a ghostly west-side-up asymmetric fold. This fold is tentatively thought to be younger than the mylonite formation.

Mylonite at this outcrop was shown on the map by Seiders (1976) who interpreted a west-side-up reverse fault through here. Finkelstein (1987) looked at some of the microstructures in this mylonite zone, which corroborate a west-side-up shear sense on the down-dip lineation. Berry (1989) mapped this zone of mylonitic rocks for 2 1/2 km along strike, with a maximum width of about 100 meters.

The relationships deduced here indicate that the age of mylonite formation post-dates the peak of metamorphism and tonalite emplacement. These mylonites and related kinematic indicators are therefore not related to the fault we saw at Stop 3, because that fault is older than the cross-cutting tonalite and the peak metamorphism (Stop 4). The early faults have been assigned to the west-directed nappe-stage of Acadian deformation (Robinson et al., 1991). The east-west trending, down-dip lineation and associated folding and mylonitic deformation, such as we see here, are found throughout central Massachusetts and have been assigned to the east-directed backfold stage of Acadian deformation (Robinson, 1979).

Return to cars. Turn around and drive back the way we came.
21.0 Turn left onto dirt road.
21.1 Turn right (north) onto New City Rd.
22.7 Enter Massachusetts.

22.8 Stop sign. Please be careful. The crossing road does not have a stop sign! Turn right.
23.5 Entering Union, Connecticut.
23.7 Massive tonalite gneiss outcrops in yard to the left (east).
24.7 Slabby, red-weathering Rangeley schist to the left.
25.6 Continue straight
26.1 Turn right at triangular intersection onto Staffordville Rd.
26.5 Rusty road cut on right contains felsic gneiss of the Leadmine Pond gneiss. Parts of this outcrop have high proportions of orthoclase (~50%) and garnet (~25%) in addition to quartz, plagioclase, sillimanite, and biotite. It may represent either an unusual, perhaps altered protolith or else some type of restite. Adjacent outcrops to both sides include more normal kinds of mafic and felsic Leadmine Pond gneisses.
26.6 Bear left.
27.6 Turn left onto Webster Rd.
27.9 Pavement ends.
28.2 Roadcut to the left and stream exposures to the right of Leadmine Pond gneiss. Some sillimanite-bearing gneisses and dark-gray, garnetiferous calc-silicate pods are present here.
28.3 Park on right. We will be partly on private property and partly in the Nipmuck State Forest.

STOP 7. SYNCLINE OF WEBSTER ROAD. This stop will entail a traverse through several units (fig. 6A). We will again cross an early, nappe-stage, pre-peak-metamorphic fault that brings the Leadmine Pond gneiss to the east against parts of the Rangeley Formation to the west. The main features to see at this stop are: 1. Thin units of garnet quartzite and amphibolite in the Leadmine Pond gneiss (localities B and C); 2. A sequence of brown-weathering schist, calc-silicate granofels and well-layered gray schist in the Rangeley (localities D, F, and G); and 3. Repetition of the calc-silicate unit about the gray schist, suggesting an isoclinal syncline that pre-dates the fault (locality H).

Leave road on obscure trail 30 feet east of telephone pole 1899. Follow trail to the south. Cross footbridge and walk up gentle incline to pavement outcrops in the trail (about 5 mins. from road).

7A. Felsic gneiss of the Leadmine Pond gneiss. The two outcrops in the trail show a type of strongly foliated, yet poorly layered felsic gneiss that is common in the Leadmine Pond. It is a light gray to white, medium-grained quartz-plagioclase-biotite gneiss with small, pinhead garnets. Thin, biotite-rich folia give the rock a striped appearance, but the folia do not form continuous layers. In some places, layers with slightly different shades of light gray can be distinguished. The rocks here are similar to parts of the Monson Gneiss of the Bronson Hill zone. Coarser-grained gneisses and pegmatites off the trail to the west (optional) contain coarse-grained orthopyroxene.

Continue south on trail to a fork. Take the trail less traveled by, and follow it down the slope to the right (southwest). Outcrops of interest are 10 meters off the trail to the left (south), just before the trail bottoms out in a swampy gulley.

7B. Garnet quartzite of the Leadmine Pond gneiss. The rock is a yellow- to red-weathering, watery-gray, garnet quartzite interlayered with milky-gray feldspathic, sulfidic garnet quartzite. The layers are 5 to 15 cm thick, and are believed to represent beds. The conspicuous 1-3 mm garnets make up commonly 10% and up to 50% of the rock. The protolith is uncertain, but might be a metamorphosed cherty sediment. The presence of interlayered sediments suggests that the Leadmine Pond gneiss is a stratified unit, and that the gneisses may have been volcanic rather than intrusive rocks.

Continue on trail across the gulley (40 feet?) then walk north (to the right) about 150 feet to hillside outcrops west of the gulley.

7C. Amphibolite of the Leadmine Pond gneiss. The outcrops along this small ridge are dominated by mafic gneisses including amphibolite and hornblende-biotite-plagioclase-quartz gneiss, with lesser amounts of quartz-feldspar-biotite gneiss.

Return to trail. Follow trail as it heads west over the small ridge, then turns south. We have left the Leadmine Pond gneiss behind us, and are walking approximately on the trace of the fault that separates it from Rangeley rocks on the cliff to the west. Continue walking south along the trail

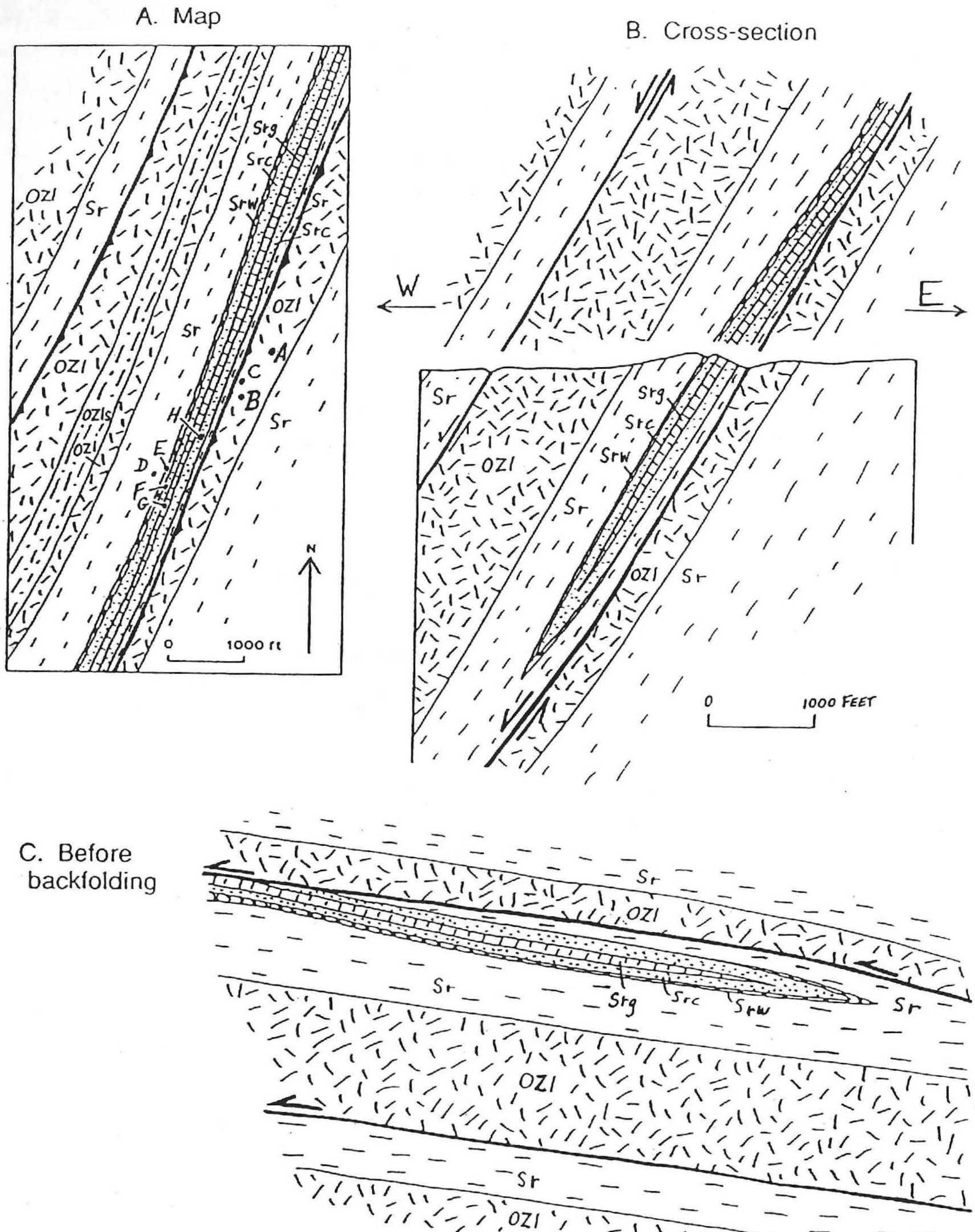


Figure 6. Geologic relationships at Stop 7. A. Geologic map. Localities A through H are indicated. Repetition of units about "Srg" indicates an isoclinal syncline. B. Cross-section showing present geometry, with isoclinal fold truncated by nappe-stage thrust fault. C. Inferred geometry at the time of thrusting, with Leadmine Pond gneiss (OZl) thrust westward over younger, previously folded rocks. Leadmine Pond gneiss units: OZl=undifferentiated gneiss, OZls=schist unit. Rangeley Fm. units: Sr=undifferentiated schist, Srw=white schist, Src=calc-silicate unit, Srg=gray schist.

in the shadow of the cliff for about 10 minutes. Then head west into area of abundant outcrop at the south end of the ridge. Please stay with the group. The intended outcrops will be difficult to find on your own. We will work through the outcrops from west to east in what is believed to be ascending stratigraphic order.

7D. Rangeley schist and granulite. The red- to brown-weathering, feldspathic sillimanite-biotite-garnet schist here is similar to rocks in other strike belts to the west (such as at stops 3B and 5), and is likewise assigned to the Rangeley.

Go east across logging road to small, barely-exposed outcrop under laurel bush.

7E. Rangeley white schist. A small excavation project by Peter Robinson and me uncovered this occurrence of sulfidic white schist sandwiched between Rangeley schists to the west and a slabby calc-silicate granofels unit to the east. Although the contacts are not exposed, they are closely constrained by outcrop to within 10 meters, so the unit is certainly less than 20 meters thick, and probably less than 5.

Continue east a few feet to the next outcrop.

7F. Calc-silicate granofels unit. The rocks consist of medium- to coarse-grained, quartz-plagioclase-biotite granofels interlayered with green-speckled diopside-quartz-feldspar-biotite±garnet calc-silicate granofels. The green calc-silicate layers have pinch-and-swell structure, and isolated boudins are locally present. Small pegmatite pods are common. Sillimanite-bearing schist is virtually absent from this unit.

Follow abundant low outcrops of the calc-silicate unit to the southeast, diagonally across strike to a large outcrop sticking out of the south end of the hill.

7G. Gray schist unit. This unit contains coarse-grained, gray-weathering, pelitic schist interlayered with quartz-rich granofels. The schist, dominated by quartz, sillimanite, and biotite, contains abundant garnets ranging from 3 to 30 mm across. In some places the schist and light gray quartz-rich granofels alternate in beds 5 cm thick.

Walk down hill to the east to join the trail. Follow trail to the left (north). Partway back along the trail, go west to the base of the cliff.

7H. Calc-silicate granofels unit. We are again in the calc-silicate granofels unit, but now east of the gray schist. At locality 7F, this calc-silicate granofels unit was to the west of the gray schist. Both contacts of the gray schist unit, though not easily accessible, are exposed in the cliff above us. Repetition of the calc-silicate unit about the gray schist suggests that we have crossed the axial surface of an isoclinal fold (fig. 6B). The axial surface of this fold must trace on the ground through the gray schist unit. Whether this fold is a syncline or an anticline depends on the stratigraphic facing direction. If the sequence youngs toward the gray schist unit, as currently believed, this fold is an overturned syncline.

Along strike to the north of Stop 7, the calc-silicate granulite and gray schist units are gradually cut out by the fault to their east (fig. 2). Therefore, the syncline here is older than the fault. Both the syncline and the fault are believed to be nappe-stage features that were originally west-directed, and have been overturned by backfolding into their present orientation (fig. 6C).

Return to cars. Continue east on Webster Rd.

28.8 Series of low, flat outcrops to the right are made of brown- to rusty-weathering schist and granofels of the Rangeley Formation. In some places here and elsewhere on Bald Hill, the layering is a little thinner than average, about 1 to 3 cm thick. So far, rocks with this bedding style have not been mapped separately in this area.
29.0 Pavement begins.
29.3 Stop sign. Turn right and go about 30 feet to second stop sign.
29.31 Turn left onto Rt. 190E.
29.7 Continue straight toward I-84E.
29.8 Turn left onto I-84E.

31.1 Roadcuts on both sides, of rusty-weathering, crumbly, graphitic schist and interlayered quartzites of the Leadmine Pond gneiss. The road exploits this unit for the next 1.8 miles.
32.1 The western contact of the rusty schist unit is exposed partway up the roadcut to the left (west), where light gray quartz-plagioclase gneisses with minor amphibolite layers rest above the rusty schist. Layering dips away from us (toward the west) at about 50 degrees.
32.6 In the large roadcut to the left the gneiss unit contains a prominent, 3-foot-thick black amphibolite layer, about 10 feet above the schist contact. The amphibolite layer is parallel to the schist-gneiss lithologic contact, indicating that the schist, gneiss, and amphibolite are concordant.
32.9 Road curves to the right. Dip-slope outcrops to the right contain rusty quartzite layers in schist.
33.5 Take Exit 74 toward Rt. 171, Union, Connecticut.
33.7 Stop sign. Turn left, crossing over interstate.
33.8 Turn left.
33.9 Go straight.
34.0 Turn left onto Moore Rd.
34.1 Park at end of road, by barrier. Walk into abandoned rest area.

STOP 8 (OPTIONAL). LEADMINE POND GNEISS. This is a brief stop to see two of the rock types in the Leadmine Pond gneiss in the same strike belt as the type area at Leadmine Pond, Sturbridge (fig. 2).

8A. Layered mafic and felsic gneiss. Under the old Ashford Motel billboard is a good exposure of thinly layered amphibolite and plagioclase gneiss.

Walk to the southwest about 500 feet to hillside outcrop near bottom of east-facing slope.

8B. Rusty schist and quartzite of the Leadmine Pond gneiss. The schist is a rusty-weathering, feldspathic sillimanite-biotite-graphite schist that weathers rustier and is less aluminous than most Rangeley varieties, although similar schists can be found in the Rangeley. The main reasons that this schist is assigned to the Leadmine Pond gneiss are a) because brittle white quartzite beds are interlayered with the schist, and b) this rusty schist unit is flanked to both sides by plagioclase gneiss and amphibolite.

Return to cars. Turn around.
34.2 Stop sign. Turn right.
34.4 Stay straight.
34.5 Turn right.
34.6 Stop sign. Turn right toward Union, Connecticut.
35.9 Turn right onto Cemetery Rd.
36.3 Park on right. (Private property.)

Stop 9. Leadmine Pond gneiss. The objective of this stop is to see some of the rock types found together in the Leadmine Pond gneiss here, and compare them with rocks in the Leadmine Pond gneiss south of Webster Road (Stop 7). We have moved a short distance across strike to the east from Stop 8, still in the same belt of Leadmine Pond gneiss (fig. 2).

Walk up hill to west.

9A. Felsic gneiss. Take a passing look at small outcrops near the top of the slope to see that they are foliated plagioclase-quartz-biotite gneisses.

Walk 500 feet north across fairly level ground to small, rocky knob.

9B. Rusty-weathering feldspar-graphite schist. This poorly exposed unit contains deeply rusty-weathering, crumbly, graphitic rocks. In some places it has sillimanite-rich folia, with pale biotite or sparse garnet, but in most places garnet and biotite are rare, sillimanite is sparse, and the predominant minerals are quartz, feldspar, and graphite. It is coarse-grained, with K-feldspar megacrysts. Graphite is ubiquitous, occurring in masses up to 5 mm across.

Walk 300 feet southwest to long, low outcrops sticking out of the south side of the slope.

9C. Mafic gneiss unit. This unit contains layered medium- to dark-gray gneisses. The most distinctive type is a foliated, streaky hornblende-biotite-clinopyroxene-plagioclase gneiss with small clumps of hornblende (± pyroxene) grains. Thinly layered biotite-plagioclase ± hornblende ± clinopyroxene schist is also common. A subordinate amount of leucocratic plagioclase gneiss is present in this unit as well. This unit is similar to the one we saw at Stop 7C.

Walk 100 feet southwest to hillside outcrop and rubble.

9D. Garnet quartzite. Yellow- to red-weathering, layered quartzite peppered with garnets. Some layers contain thin boititic laminae. Small amounts of graphite are present. This unit is believed to be the same one we saw at Stop 7B.

The units here in the Leadmine belt are similar to the units south of Webster Road (Stop 7). A unit-for-unit correlation seems warranted for the following sequence: 1. Layered, predominantly felsic gneisses (stops 7A, 8A); 2. Garnet quartzite (stops 7B, 9D); and 3. Mafic gneiss and amphibolite (stops 7C, 9C). Other units of the Leadmine Pond gneiss are present in the Leadmine belt (such as stops 8B, 9A, and 9B), but are presumably cut out by faulting near Webster Rd. Although the younging sense of this sequence is not known, it faces in opposite directions in the two belts.

The similarity of Leadmine Pond gneiss units in two different strike belts is compelling evidence that there is a coherent lithostratigraphy in the Leadmine Pond gneiss, and that the same units are structurally repeated on the ground. This is believed to represent the pre-Silurian (Precambrian ?) basement of the Merrimack belt at this latitude (Berry, 1988). Similar sequences of thin units are present in parts of the Putnam Group (Connecticut), Nashoba Formation (Massachusetts), and the Falmouth-Brunswick sequence of the Cushing Formation (Maine) (fig. 1).

Walk east and return to cars. Turn around and retrace route to the east on Cemetery Rd.

36.7 Stop sign. Turn left.
38.0 Turn left toward I-84.
38.1 Turn right onto I-84E.
38.4 Large roadcut along southbound exit ramp (to left) contains various rocks of the Leadmine Pond gneiss.
38.6 Enter Massachusetts.
39.1-39.6 Large roadcuts of rusty-weathering schist and slabby, light purplish and greenish granofels of the Paxton Formation.
41.4 Outcrop to the right at north end of weigh station is purple Paxton granofels with white, popcorn pegmatites.
41.9 Take Exit 1, Mashapaug Rd., Southbridge.
42.0 Stop sign at end of exit ramp. Turn right.
42.3 Pass under I-84E.
42.7 Pass under I-84W.
43.1 Pull off to right, near dirt road. Walk up dirt road to outcrop in back of dumping area.

STOP 10 (OPTIONAL). EASTERN CONTACT OF LEADMINE POND GNEISS. We have seen two places where the western contact of the Leadmine Pond gneiss is faulted against the Rangeley Formation (stops 3 and 7), based on truncation of units and inferred stratigraphic offset. In contrast, the eastern contact of the Leadmine Pond gneiss is interpreted to be an unconformity based on the persistence of thin units in the basal parts of the Rangeley in the Brimfield-Sturbridge area (Berry, 1989). A thinly layered calc-silicate granulite unit that occurs at several places along the eastern contact of the Leadmine Pond gneiss is interpreted to be at the base of the Rangeley Formation. It is assigned to the base of the Rangeley rather than the top of the Leadmine Pond gneiss because similar rocks are also found higher in the Rangeley. The objective of this stop is to see this basal calc-silicate unit of the Rangeley.

10A. Base of the Rangeley. The rocks from west to east in the outcrop include: interlayered plagioclase gneisses, granitic gneisses, hornblende-biotite gneisses and amphibolites of the Leadmine Pond Gness; thinly interlayered light gray quartz-feldspar-biotite granofels and medium- to light-green diopside calc-silicate granofels of the basal Rangeley; and rusty-weathering, migmatitic sillimanite-garnet-biotite schist with interlayered pegmatites of the Rangeley.

Unfortunately, there is no evidence at this outcrop that would indicate the presence of an unconformity. It is by mapping along this contact and by considering the regional stratigraphic relationships that an unconformity is proposed. The rocks here, as elsewhere, have been strongly deformed and metamorphosed. West-side-up asymmetric fabrics of the backfold stage are well developed, especially in the migmatitic schist.

Return to road. Drive or walk ahead to:
43.3 Roadside outcrop on banking to the right.

10B. Rangeley schist and granofels. This outcrop of rusty-weathering sillimanite-garnet-biotite schist with interlayered feldspathic granofels is representative of a thin belt of rocks lying east of the Leadmine Pond gneiss and west of the Paxton Formation (Stop 11). From lithologic similarity with rocks to the west, and from their apparently similar stratigraphic position above the Leadmine Pond gneiss, the rocks here are assigned to the Rangeley.

Turn around and retrace route to the north.
43.9 Pass under I-84W.
44.0 Abandoned "Sturbridge Isle" service area on right. An exposure at the south end of the parking lot contains light gray, coarse-grained sillimanite-biotite-garnet-cordierite schist interlayered with quartz-feldspar-biotite-garnet granofels (Stop 6 of Thomson et al., this volume). Similar rocks on strike to the southwest were mapped as a member of the Bigelow Brook Formation (Peper et al., 1975). In the Westford quadrangle, Connecticut, the Kinney Pond fault separates the Bigelow Brook from the Hamilton Reservoir Formation to the west (Peper and Pease, 1975). It is not known whether the Kinney Pond fault extends northward into Massachusetts. If so, it would lie between stop 10 and here, approximately under the westbound lane of I-84. This gray schist and granulite unit was assigned to the Littleton Formation by Zen et al. (1983).
44.3 Outcrop of Paxton granulite and pegmatite lurking in the shadows to the right.
44.4 Pass under I-84E.
44.7 Turn left onto I-84E.
46.1 Take Exit 2, to 131 Sturbridge, Southbridge.
46.3 Stop sign. Turn left.
46.5 Stop sign. Turn left.
46.7 Park near telephone pole with "Shattuck Rd" sign.

Stop 11. Layered granofels of the Paxton Formation. The main objective at this stop is to see an example of layered granofels characteristic of the Paxton Formation for comparison with the granofels at stops 2 and 7F. The quartz-plagioclase-biotite±garnet granulites have a distict purplish hue caused by the fine-grained reddish biotite. These purplish-gray granulites are interlayered with smooth-looking, fine-grained, green, diopside calc-silicate granulites. Conformable white pegmatite layers are common. Dome-stage minor folds deform the layering and pegmatites together, with hinges plunging about 10° toward the south and axial surfaces dipping shallowly to the west. A large pegmatite body at the southwest end of the outcrop contains enclaves of sillimanite-biotite schist with a west-plunging, backfold-stage lineation. Muscovite is present in this and other pegmatite bodies in the outcrop. The muscovite is thought to be of retrograde origin because it appears to surround sillimanite in some places, but the petrology of these rocks has not been studied.

The rocks here have been assigned to the Bigelow Brook member of the Paxton Formation (Zen et al., 1983, Robinson and Goldsmith, 1991). Sulfidic schist, which is common in the Bigelow Brook, is exposed at the northeast end of the outcrop and along the southbound entrance ramp. We are approximately on strike with the type locality of the Paxton Formation at Paxton Falls, Massachusetts to the north. Although the purple and green granofels that we see here is similar to the rock at Paxton Falls, the sulfidic schist here is not present at the type locality, suggesting intervening structural and stratigraphic complications (fig. 3).

End of trip.

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9C. Mafic gneiss unit. This unit contains layered medium- to dark-gray gneisses. The most distinctive type is a foliated, streaky hornblende-biotite-clinopyroxene-plagioclase gneiss with small clumps of hornblende (± pyroxene) grains. Thinly layered biotite-plagioclase ± hornblende ± clinopyroxene schist is also common. A subordinate amount of leucocratic plagioclase gneiss is present in this unit as well. This unit is similar to the one we saw at Stop 7C.

Walk 100 feet southwest to hillside outcrop and rubble.

9D. Garnet quartzite. Yellow- to red-weathering, layered quartzite peppered with garnets. Some layers contain thin boititic laminae. Small amounts of graphite are present. This unit is believed to be the same one we saw at Stop 7B.

The units here in the Leadmine belt are similar to the units south of Webster Road (Stop 7). A unit-for-unit correlation seems warranted for the following sequence: 1. Layered, predominantly felsic gneisses (stops 7A, 8A); 2. Garnet quartzite (stops 7B, 9D); and 3. Mafic gneiss and amphibolite (stops 7C, 9C). Other units of the Leadmine Pond gneiss are present in the Leadmine belt (such as stops 8B, 9A, and 9B), but are presumably cut out by faulting near Webster Rd. Although the younging sense of this sequence is not known, it faces in opposite directions in the two belts.

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Walk east and return to cars. Turn around and retrace route to the east on Cemetery Rd.

36.7 Stop sign. Turn left.
38.0 Turn left toward I-84.
38.1 Turn right onto I-84E.
38.4 Large roadcut along southbound exit ramp (to left) contains various rocks of the Leadmine Pond gneiss.
38.6 Enter Massachusetts.
39.1-39.6 Large roadcuts of rusty-weathering schist and slabby, light purplish and greenish granofels of the Paxton Formation.
41.4 Outcrop to the right at north end of weigh station is purple Paxton granofels with white, popcorn pegmatites.
41.9 Take Exit 1, Mashapaug Rd., Southbridge.
42.0 Stop sign at end of exit ramp. Turn right.
42.3 Pass under I-84E.
42.7 Pass under I-84W.
43.1 Pull off to right, near dirt road. Walk up dirt road to outcrop in back of dumping area.

STOP 10 (OPTIONAL). EASTERN CONTACT OF LEADMINE POND GNEISS. We have seen two places where the western contact of the Leadmine Pond gneiss is faulted against the Rangeley Formation (stops 3 and 7), based on truncation of units and inferred stratigraphic offset. In contrast, the eastern contact of the Leadmine Pond gneiss is interpreted to be an unconformity based on the persistence of thin units in the basal parts of the Rangeley in the Brimfield-Sturbridge area (Berry, 1989). A thinly layered calc-silicate granulite unit that occurs at several places along the eastern contact of the Leadmine Pond gneiss is interpreted to be at the base of the Rangeley Formation. It is assigned to the base of the Rangeley rather than the top of the Leadmine Pond gneiss because similar rocks are also found higher in the Rangeley. The objective of this stop is to see this basal calc-silicate unit of the Rangeley.

10A. Base of the Rangeley. The rocks from west to east in the outcrop include: interlayered plagioclase gneisses, granitic gneisses, hornblende-biotite gneisses and amphibolites of the Leadmine Pond Gness; thinly interlayered light gray quartz-feldspar-biotite granofels and medium- to light-green diopside calc-silicate granofels of the basal Rangeley; and rusty-weathering, migmatitic sillimanite-garnet-biotite schist with interlayered pegmatites of the Rangeley.

Unfortunately, there is no evidence at this outcrop that would indicate the presence of an unconformity. It is by mapping along this contact and by considering the regional stratigraphic relationships that an unconformity is proposed. The rocks here, as elsewhere, have been strongly deformed and metamorphosed. West-side-up asymmetric fabrics of the backfold stage are well developed, especially in the migmatitic schist.

Return to road. Drive or walk ahead to:
43.3 Roadside outcrop on banking to the right.

10B. Rangeley schist and granofels. This outcrop of rusty-weathering sillimanite-garnet-biotite schist with interlayered feldspathic granofels is representative of a thin belt of rocks lying east of the Leadmine Pond gneiss and west of the Paxton Formation (Stop 11). From lithologic similarity with rocks to the west, and from their apparently similar stratigraphic position above the Leadmine Pond gneiss, the rocks here are assigned to the Rangeley.

Turn around and retrace route to the north.
43.9 Pass under I-84W.
44.0 Abandoned "Sturbridge Isle" service area on right. An exposure at the south end of the parking lot contains light gray, coarse-grained sillimanite-biotite-garnet-cordierite schist interlayered with quartz-feldspar-biotite-garnet granofels (Stop 6 of Thomson et al., this volume). Similar rocks on strike to the southwest were mapped as a member of the Bigelow Brook Formation (Peper et al., 1975). In the Westford quadrangle, Connecticut, the Kinney Pond fault separates the Bigelow Brook from the Hamilton Reservoir Formation to the west (Peper and Pease, 1975). It is not known whether the Kinney Pond fault extends northward into Massachusetts. If so, it would lie between stop 10 and here, approximately under the westbound lane of I-84. This gray schist and granulite unit was assigned to the Littleton Formation by Zen et al. (1983).
44.3 Outcrop of Paxton granulite and pegmatite lurking in the shadows to the right.
44.4 Pass under I-84E.
44.7 Turn left onto I-84E.
46.1 Take Exit 2, to 131 Sturbridge, Southbridge.
46.3 Stop sign. Turn left.
46.5 Stop sign. Turn left.
46.7 Park near telephone pole with "Shattuck Rd" sign.

Stop 11. Layered granofels of the Paxton Formation. The main objective at this stop is to see an example of layered granofels characteristic of the Paxton Formation for comparison with the granofels at stops 2 and 7F. The quartz-plagioclase-biotite±garnet granulites have a distict purplish hue caused by the fine-grained reddish biotite. These purplish-gray granulites are interlayered with smooth-looking, fine-grained, green, diopside calc-silicate granulites. Conformable white pegmatite layers are common. Dome-stage minor folds deform the layering and pegmatites together, with hinges plunging about 10° toward the south and axial surfaces dipping shallowly to the west. A large pegmatite body at the southwest end of the outcrop contains enclaves of sillimanite-biotite schist with a west-plunging, backfold-stage lineation. Muscovite is present in this and other pegmatite bodies in the outcrop. The muscovite is thought to be of retrograde origin because it appears to surround sillimanite in some places, but the petrology of these rocks has not been studied.

The rocks here have been assigned to the Bigelow Brook member of the Paxton Formation (Zen et al., 1983, Robinson and Goldsmith, 1991). Sulfidic schist, which is common in the Bigelow Brook, is exposed at the northeast end of the outcrop and along the southbound entrance ramp. We are approximately on strike with the type locality of the Paxton Formation at Paxton Falls, Massachusetts to the north. Although the purple and green granofels that we see here is similar to the rock at Paxton Falls, the sulfidic schist here is not present at the type locality, suggesting intervening structural and stratigraphic complications (fig. 3).

End of trip.

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