TRANSECT ACROSS THE NORTH-CENTRAL GREEN MOUNTAINS FROM THE CARBONATE SHELF TO ULTRAMAFIC SLIVERS IN THE TACONIAN SUBDUCTION ZONE

by

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INTRODUCTION

The main objective of this field trip is to compare the intensity of deformation and metamorphism within each fault-bounded lithotectonic package at the latitude of cross section D-D' of the new Vermont bedrock map (Ratcliffe et al., in press), just north of Middlebury. The cross-section, originally constructed by Stanley et al. (1987b,c,d), was further developed by Gale and Thompson and spans the orogen from the shores of Lake Champlain to the Silurian unconformity. Laird and Honsberger will present data on pressure, temperature, and timing of metamorphism, some Taconian and some Acadian, which complement the structural interpretations. The trip starts in fossiliferous, barely metamorphosed autochthonous Ordovician rocks below the Champlain thrust and ends at intensely deformed late Proterozoic to Cambrian schists, ultramafics and mafic rocks with chemically zoned amphiboles in Stockbridge. (We will not go all the way east to the Silurian unconformity.) Among the stops in between we will see a textbook example of an open, upright fold in the Cheshire Quartzite, a sheared unconformity (late Proterozoic boulder conglomerate on the Grenvillian Lincoln massif), the mylonitic root zone for thrusts west of the Green Mountains, multiply deformed rocks in the allochthonous rocks at Appalachian Gap, and evidence for increasingly pervasive Acadian deformation toward the east.

GEOLOGIC SETTING

Vermont is positioned between the New York promontory and the Quebec re-entrant along the northeast-trending Appalachian Mountain system, east of the Adirondack Highlands of New York (fig. 1). The rocks record a sequence of rift clastic and volcanic rocks deposited on Grenville basement, development of a continental platform which marks the ancient margin of eastern North America in the Cambrian and Ordovician, Ordovician accreted rocks, and Silurian-Devonian rocks of the Connecticut Valley trough. A variety of metasedimentary, metavolcanic and serpentinized ultramafic rocks are associated with the collapse and destruction of the continental margin during the Ordovician Taconian Orogeny. Deformation associated with the Devonian Acadian Orogeny and with eventual Mesozoic rifting to form the current Atlantic Ocean add complexity to the geologic history. Taconian thrust faults associated with an island arc-continent collision were re-activated during the Acadian Orogeny when the Iapetus Ocean closed and the eastern portion of New England collided with Laurentia. No evidence for the

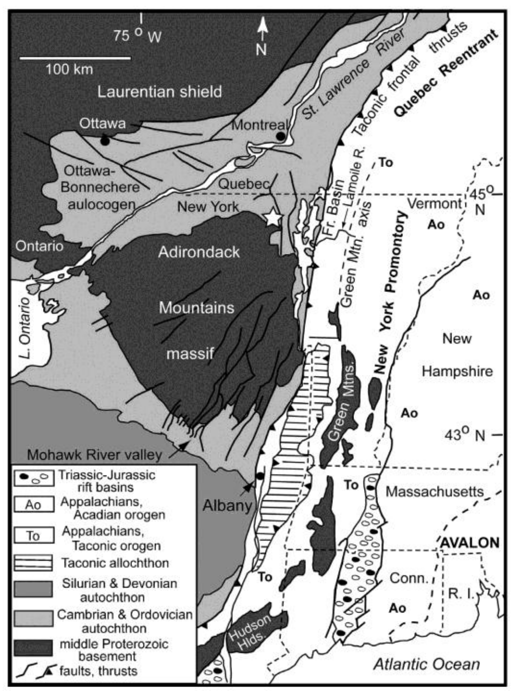

Figure 1. General geologic setting of Vermont (from Landing et al., 2009).

Alleghanian Orogeny, during which Africa docked, has been recognized in northern Vermont. The resulting supercontinent of Pangaea began to break up around 200 million years ago; Mesozoic dikes and high angle faults in western Vermont record that event.

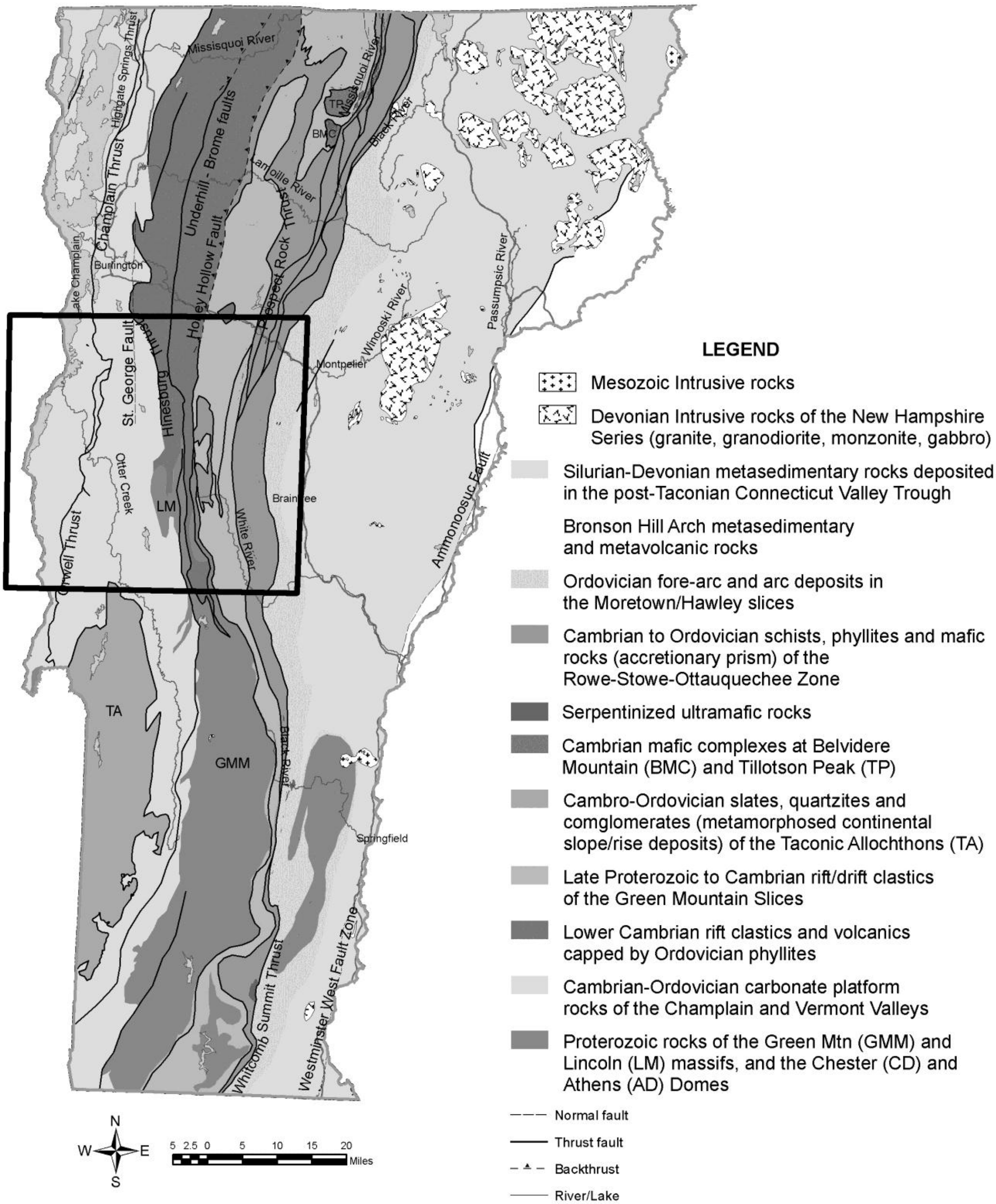

Figure 2. General geology of Vermont. Box indicates the field trip area.

LITHOTECTONIC PACKAGES

Pre-Silurian lithotectonic packages (fig.3) at the latitude of the field trip (about 44° north) are described below, from west to east. The reader is referred to previous NEIGC field trips for comparisons of the conditions and mechanisms of faults that separate the packages (Stanley et al., 1999 and Stanley et al., 1987a) and for a more detailed look at the hinterland (Stanley et al. 1987b, c and d), although the structural relationships and definitions of thrust slices there have been somewhat modified (especially east of the Underhill slice).

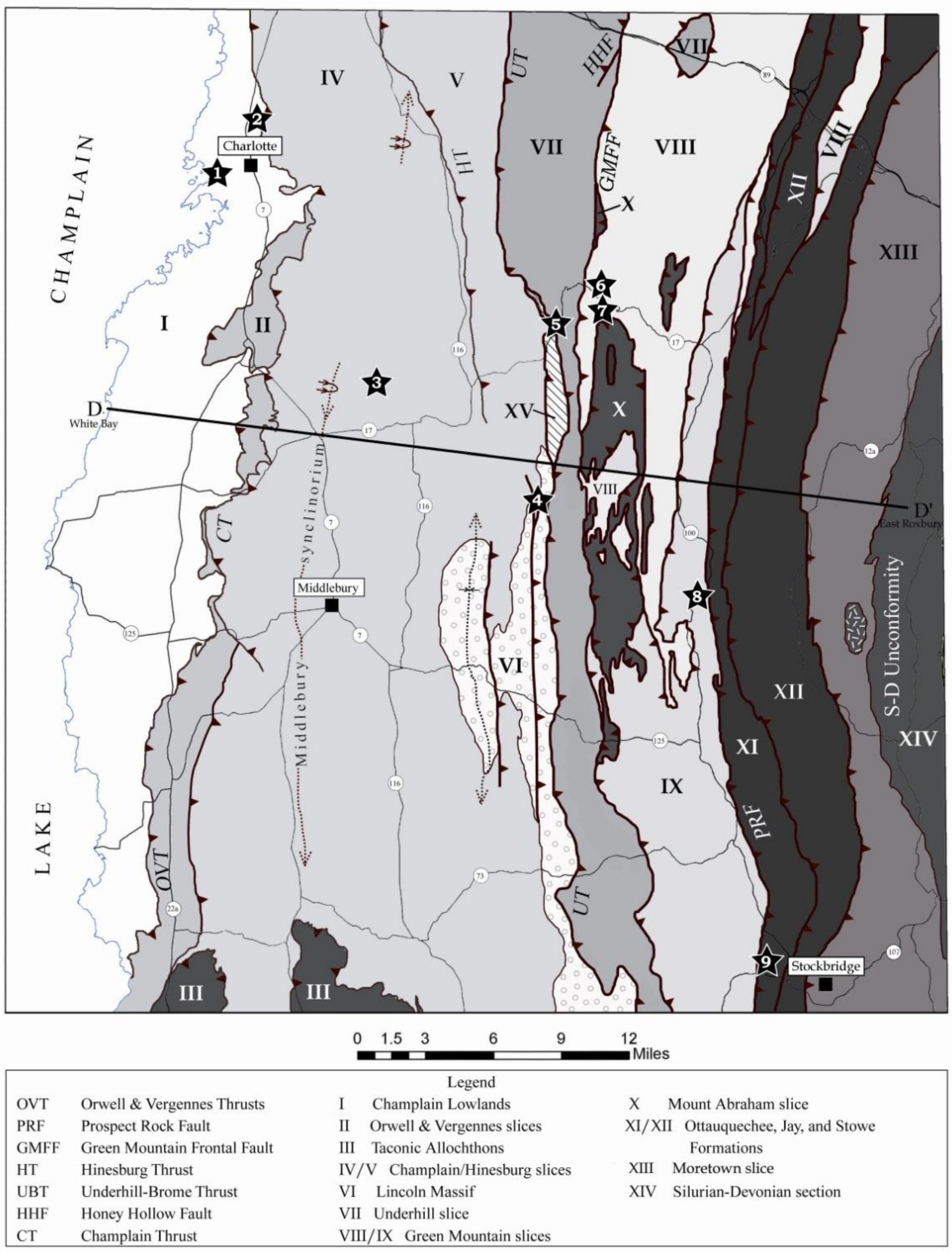

Figure 3. Lithotectonic packages (I-XIV), field trip stops (starred 1-9) and cross-section line D-D'. (XV, the Jerusalem slice, was numbered out of order; it lies between V and VII.)

I. Champlain Lowlands (Stops 1 & 2)

From the Adirondack massif east to the Vergennes and Champlain thrusts, stratigraphy in the autochthonous Champlain Lowlands is largely intact, with good fossil control. This package preserves rocks from the early Cambrian passive-margin shelf onlap up through Middle Ordovician flysch, which flooded westward from the advancing Taconian orogeny. Local Taconian thrusts thicken the section, especially in the younger shales. Cretaceous lamprophyre and trachyte dikes are abundant (McHone, 1987).

II. Vergennes Slice

The Vergennes thrust carries a thin slice of rocks that peer out from beneath the Champlain thrust south of our transect. The Highgate Springs slice in northern Vermont and the Orwell thrust still farther south occupy a similar position. In each case, the basal thrust places Ordovician carbonates on younger Ordovician shales.

III. Taconic Allochthons

The Taconic allochthons are imbricated thrust slices comprised of Late Proterozoic to Middle Ordovician metasedimentary and metavolcanic rocks, largely of continental slope origin and emplaced onto the carbonate platform during the Taconian Orogeny. They project into our line of section above the Middlebury synclinorium.

IV. Champlain Slice (Stop 3)

The Champlain slice extends from the Champlain thrust east to the Hinesburg thrust, and farther south, beyond where the Hinesburg thrust dies out, it includes the Middlebury synclinorium east to the Lincoln massif. The Taconic allochthons would project north above the synclinorium into the line of our section about two km above the present erosion surface. The Champlain thrust is a brittle fault surface dipping about 15° east, with displacement N60˚W of 60 to 80 km (Stanley, 1987). The rocks in the slice represent a more distal part of the carbonate shelf, including the Cheshire Quartzite, Dunham Dolomite, Monkton Quartzite and Winooski Formations, which are older than the basal Potsdam Sandstone of the Champlain Lowlands section, due to westward ocean transgression in the Cambrian (see fig. 4). The rocks are below chlorite grade and fossils are well preserved, except where dolomitized. At this latitude the Champlain thrust forms a prominent scarp where the Monkton overlies shales in the footwall. Although the displacement on the Champlain thrust becomes distributed among several faults farther south, all the rocks east of it, including the Green Mountain massif, are allochthonous relative to the Adirondack basement.

V. Hinesburg Slice

The Hinesburg thrust is shown on the new state map as a relatively short (80 km) fault, with at most six km of displacement, and dying out in both directions. The upper plate consists of Late Proterozoic to Cambrian rift clastics and volcanics of the Pinnacle and Fairfield Pond Formations, overlain by the basal drift or passive-margin units, Cheshire Quartzite and Dunham Dolomite. At the latitude of the Winooski River the Hinesburg thrust and underlying Muddy Brook thrust (Thompson et al., 2002a) occur right at the eastern edge of the carbonate bank in the Champlain slice; at Hinesburg the overturned Cheshire is faulted onto upright carbonates. In other words, the fault marks approximately the boundary between foreland and hinterland. The rocks east of the fault correlate with the Oak Hill slice of Quebec (Colpron et al., 1984), including the 554 Ma Tibbit Hill Volcanics (Kumarapeli et al., 1989). Metamorphism increases to greenschist facies across the Hinesburg thrust, but a coherent stratigraphy and primary structures are preserved within the slice. During the trip we will discuss evidence for the Hinesburg thrust cutting southeast, deeper into the clastic section and rooting along the east side of the Lincoln massif, rather than within steeply dipping Cheshire Formation northeast of Bristol as shown on the new state map. Stanley and Wright (1997) postulated that the Hinesburg thrust roots between the two anticlines of the Lincoln massif, but so far no one has identified the trace of such a connection on the ground.

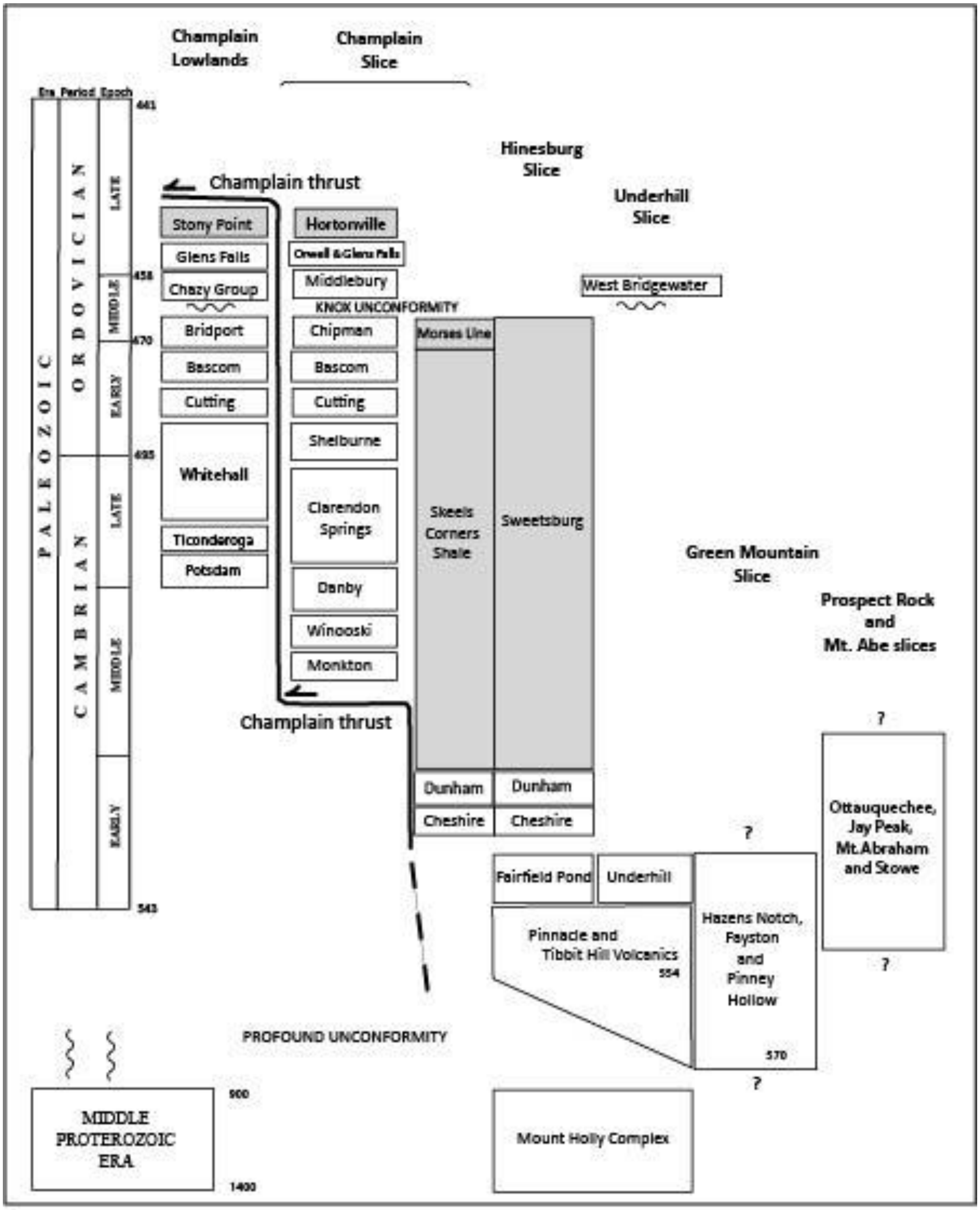

Figure 4. Stratigraphic Correlation Chart. Time scale is schematic. Gray shading indicates shales. Shelf facies from Monkton Quartzite upwards are coeval with deeper-water facies Skeels Corners Shale (OCsk under Hinesburg thrust on fig. 5c). Exact range in age of the eastern units is uncertain.

VI. Lincoln Massif (Stop 4)

The Lincoln massif consists of two anticlines of Middle Proterozoic rocks, together covering about 80 square kilometers. The eastern part, the Lincoln anticline, mostly consists of granitic orthogneiss of the Mt. Holly Complex, locally with dark green amphibolite and minor metasedimentary rocks, all with faint Grenvillian schistosity. The massif is unconformably covered by the Late Proterozoic Pinnacle Formation, locally with a basal conglomerate, which we will see at Stop 4 where it is cut by the Cobb Hill thrust fault. Elsewhere, metamorphosed Late Proterozoic mafic dikes are preserved, which truncate the Grenvillian schistosity. The eastern margin of the massif is sheared by anastomosing fault zones that may follow reactivated normal faults inherited from early rifting (Warren, 1990).

XV. Jerusalem Slice (Stop 5)

The Jerusalem slice consists of mylonitic quartz-laminated schist up to 1500 meters wide and about 10 kilometers long, rooted along the east side of the Lincoln massif (Tauvers, 1982). The mylonitic zone pinches out both north and south, merging with the overlying Underhill thrust (DiPietro, 1983).

VII. Underhill Slice (Stop 6, viewed from VIII at Appalachian Gap)

The syn-metamorphic Taconian Underhill thrust was named for the predominant formation in the slice above it (Tauvers, 1982); the actual fault passes west of the town of Underhill and merges with the east-directed Brome thrust in northern Vermont and southern Quebec. At our latitude it is a west-directed Taconian fault, along which garnet-grade schists, metawackes and metavolcanics of the Underhill and Hoosac Formations truncate the inverted Lincoln anticline. The fault has several branches, locally decorated by slivers of basement. As in the "Mansville phase" of Quebec (Colpron et al., 1984) deformation is more intense in the Underhill slice than in those to the west, to the point where coherent stratigraphy is no longer certain, despite locally preserved graded beds. The fault-bounded Monastery Formation, which contains rock types common to several other formations, may represent a mélange zone internal to the Underhill slice. Middle Ordovician conodont-bearing deep water turbidites (now the West Bridgewater Formation graphitic schists with dolomite pods) that lie unconformably above the rift clastics are preserved in a few key places (Ratcliffe et al., 1999; Thompson et al., 2002b), one of which we'll pass in Buels Gore along the Appalachian Gap Road.

VIII & IX. Green Mountain Slice (Stop 7)

The Green Mountain slice lies between what Stanley and Wright (1997) referred to as the "western front fault zone" and the overlying pre-peak metamorphic Mt. Abraham and Prospect Rock slices. Stanley and Wright (1997) also proposed that the Taconic allochthons were ejected from beneath this slice, rather than from beneath the Underhill slice (Stanley and Ratcliffe, 1985). The Green Mountain slice contains several formations, including the Fayston Formation, Hazens Notch Formation and western Pinney Hollow Formation, which are interpreted as eastern rift- clastic correlatives to units in the Underhill slice. These rocks are Late Proterozoic to (?) Cambrian albitic schists, quartzites and greenstones. The Fayston and Pinney Hollow are silver-green to gray schists, often with magnetite, whereas the Hazens Notch is gray to black, graphitic and commonly sulfidic. The grouping of formations into slices that we present here is different from the "each formation in a different slice" approach (Stanley and Ratcliffe, 1985) and also different from the original interpretation of the hinterland at Lincoln Gap (Stanley et al., 1987b) whereby all black rocks (Sweetsburg, carbonaceous Hazens Notch and Ottauquechee) were assumed to be younger than all the green units (Underhill, silver-green parts of Hazens Notch = Fayston, Pinney Hollow and Stowe). As mapping proceeded during the 1990's it became clear that the albitic units such as Fayston and Hazens Notch lie structurally below the non-albitic Mt. Abraham, Ottauquechee and Stowe (Walsh, 1992; Thompson and Thompson, 1998; Thompson et al., 1999; Kim et al., 1999).

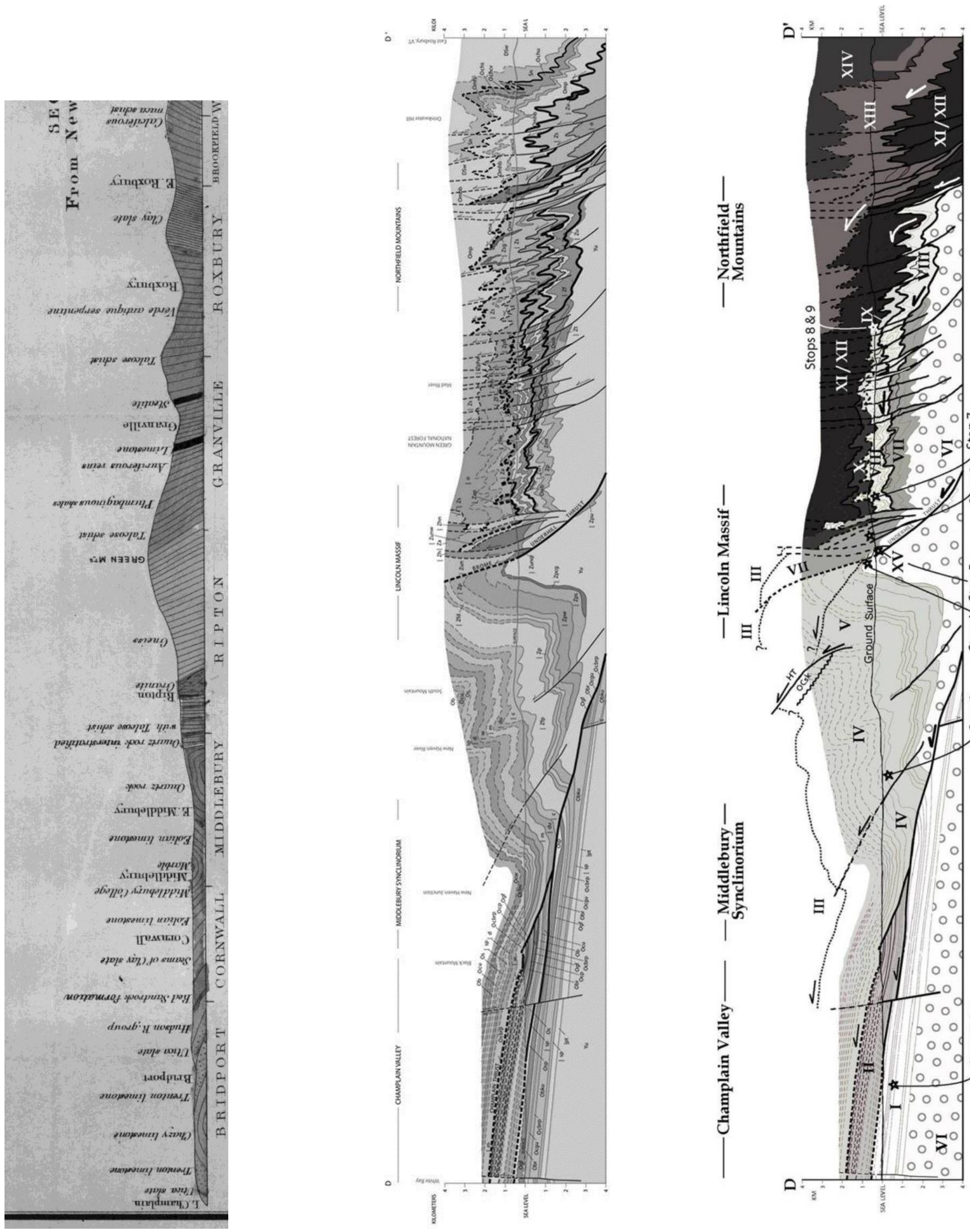

Fig. 5a Fig. 5b Fig. 5c

Figure 5a. Cross section from Bridport to Roxbury, from Hitchcock (1861) for historical context; 5b. Cross-section D-D' from Ratcliffe et al. (in press); 5c. Generalized D-D' showing lithotectonic packages and field trip stops. The Taconic allochthons (III) were projected north into the line of section. HT indicates Hinesburg thrust.

X. Mt. Abraham allochthon

The Mt. Abraham allochthon forms the long ridge of Lincoln Mountain between Appalachian Gap and Lincoln Gap, as well as Vermont's "Presidential Range" (Mts. Grant, Roosevelt, Cleveland and Wilson) south of Lincoln gap. It is almost entirely Mt. Abraham Formation: luminous silver-green to blue-black quartz-muscovite-chlorite phyllite +/- chloritoid, garnet, kyanite, magnetite, and locally staurolite (Albee, 1968). A few patches of Ottauquechee Formation at the north end of the allochthon link it to the Prospect Rock slice, and the two packages are shown as continuous on cross section D-D' (fig.5, X, XI, XII). O'Loughlin and Stanley (1986) mapped a coarse garnet-magnetite zone along what we now interpret as the thrust contact with the underlying Green Mountain slice. Similar rocks are exposed in a 100 to 300 m wide fault slice along the Battell Trail west of the main allochthon, interpreted as Mt. Abraham Formation brought relatively down by virtue of late, steep faults.

XI &XII. Prospect Rock Slice (Rowe slice): Ottauquechee, Stowe & Jay Peak Formations (Stops 8 & 9)

At the latitude of our transect the Prospect Rock slice is juxtaposed against the Green Mountain slice by steep Acadian faults, and the rocks are mostly Ottauquechee Formation: rusty-weathering, black quartzose phyllites with black quartzites. The Prospect Rock thrust itself is a folded, pre-metamorphic fault, which veers northwest away from Acadian faults north of the Winooski River and eventually makes its way across the Green Mountain anticlinorium to be truncated against the Honey Hollow fault (fig.2). The rocks above this thrust (Ottauquechee, Stowe and Jay Peak Formations) were likely deposited in the same ocean basin as rocks in the Green Mountain slice, but they were transferred to the upper plate of the subduction zone by underplating and thus have a different tectonic history (Thompson and Thompson, 2003) , discussed more fully in the next section. Ultramafic bodies are common along the fault and in adjacent rocks, both above and below. The Tillotson Peak Complex and Belvidere Mountain Complex lie above the Green Mountain slice and below the Prospect Rock slice.

XIII. Moretown and Cram Hill Slice (Cambro-Ordovician forearc and arc rocks)

Metasedimentary and metavolcanic rocks of this slice are in fault contact with the Prospect Rock slice. The rocks are predominantly gray green pinstriped granofels and schist, gray and rusty schists, and quartzites. The section is intruded by Silurian (419-423 Ma) diorite, trondhjemite, and granite near Newport and Braintree (Ratcliffe, 2010).

XIV. Silurian & Devonian rocks

Silurian and Devonian metasedimentary rocks deposited in the post-Taconian Connecticut Valley trough include phyllites, sandy marble, calcareous quartzites, and quartz-muscovite schist. Throughout most of Vermont, the contact with the underlying Ordovician section is mapped as an unconformity. Acadian offset of the unconformity has been mapped locally in the Braintree and Montpelier areas (Westerman, 1987; Martin, 1994; Kim et al., 2003; Walsh et al., 2010).

TECTONIC HISTORY OF NORTH-CENTRALVERMONT

The story of how the various lithotectonic packages came to be where they are today starts in the Late Proterozoic, as rifting along normal faults in the continent Rodinia created rift valleys in the Grenvillian crust. Clastic sediments and volcanics were deposited in the valleys **(Stop 4**), at first as coarse subaerial fans and eventually as submarine deposits into the ocean that opened along the Laurentian margin. Rift volcanics range in age from 570 Ma in the Pinney Hollow Formation (Walsh and Aleinikoff, 1999) to 554 Ma in the Tibbit Hill Volcanics (Kumarapeli et al., 1989). The main transition from rift to drift, or passive margin conditions, is marked by the Lower Cambrian Cheshire Quartzite **(Stop 3**), which locally contains Olenellus Zone fossils that suggest a maximum age of about 542 Ma. A carbonate shelf built up on top of the Cheshire during the Cambrian and Lower Ordovician. Deposition in the ocean basin slowed during the drift stage, but turbidity currents continued to sweep sediments out onto the slope and rise. Some sediment may have been provided by longshore currents from rivers entering the ocean at the Quebec reentrant and the failed Ottawa rift graben. Other parts of the basin received little or no sediment (for example, where Middle Ordovician rocks lie directly on rift clastics, **Stop 6**). By at least 505 Ma (Laird et al., 1984), oceanic crust was getting subducted and metamorphosed far off the coast of Laurentia. How far away can be estimated by multiplying about 60 million years times your favorite average spreading rate – let's say 2 cm/year each way – which yields 2400 kilometers. Now the ocean basin began to close and the Taconian Orogeny got underway.

An accretionary wedge of sediments that were too buoyant to be subducted, largely derived from Laurentia, underplated the hanging wall of the subduction zone. These are preserved today as the Ottauquechee Formation **(Stop 8)**, Stowe Formation, and perhaps the eastern Pinney Hollow Formation, which correlate with the Rowe Formation in southern Vermont and Massachusetts. The earliest Taconian folds and faults (D1 in the Prospect Rock slice, for example) formed at this time - - far earlier than D1 structures in more western packages. As the fore-arc wedge grew toward the trench, the angle of the active subduction channel became less steep. Serpentinized ultramafic and mafic rocks, less dense than when they were subducted, rose along zones of weakness in the subduction channel - - along faults in both the upper and lower plates **(Stop 9)**. Meanwhile the carbonate shelf continued to grow upward (for example Chazy rocks at **Stop 1**). The conodonts from the West Bridgewater Formation at Buels Gore **(Stop 6)** are a Chazy cratonic species, *Leptochirognathus quadratus*, which lived only from about 463 to 460 Ma (Thompson et al., 2002b). The teeth were apparently swept from the shelf into deeper water by currents. Within five million years, the carbonate shelf began to receive flysch from the east, as seen in the shaly, dark limestones of the Glens Falls Formation and younger Middle Ordovician shales **(Stop 2)**. (An alternative to the starved-sequence explanation for the unconformity beneath the West Bridgewater would be that erosion, due to the rise of a foreland bulge in advance of the approaching orogen, removed any drift facies that had been deposited.)

Eventually subduction closed the ocean basin to the point where the accretionary wedge began to override the thicker rift clastics buried under the continental slope (Green Mountain slice), some of which were drawn down in the lower plate deeply enough to reach medium-high pressure metamorphic conditions. Folds and faults began to move these rocks westward onto more proximal rift clastics (Underhill slice), along the Green Mountain frontal thrust. D1 folds and faults in the Underhill slice cannot be any older than the rocks they deform, including the West Bridgewater Formation at about 462 Ma. All the faults discussed so far were initially ductile, relatively flat, west-directed thrusts. Somewhere to the west they may have reached higher levels in the crust, where they became brittle faults, and may even have broken the surface to form tectonic olistostromes, but we would have to take a detour to the Taconic klippen to see such structures.

As the accretionary prism met the resistance of the Laurentian margin, faults cut deeper into the crust, at some point involving basement, perhaps initially taking advantage of old normal faults from the time of rifting. The Hinesburg slice rode up over the distal shelf edge as the overturned limb of a large nappe failed (Dorsey et al., 1983). Close inspection of the fault itself reveals a transitional history between ductile and brittle behavior in stop-and-go activity dependent on water pressure (Stanley et al., 1999). The Champlain thrust brought a still larger slice of deeper basement into action and the fault cut up across the shelf units in a ramp. There is apparently also a lateral ramp between the Winooski River and our transect, for autochthonous basement here is closer to the surface. The Champlain thrust brought the assembled packages in the hanging wall along for the ride, although forward motion likely also continued along the earlier thrusts. When forward motion on the Champlain thrust locked up, a flower structure developed in northern Vermont, with both west- and east-directed D2 folds and faults **(Stop 7)**. The Honey Hollow back thrust is rooted just east of the Lincoln massif. Stanley and Wright (1997) suggested that the Lincoln anticline formed above an imbricated pile-up along the Champlain thrust below it. Forward motion of material farther east was forced upward. The Champlain thrust moved again in Acadian time, producing the Green

Mountain anticlinorium in northern Vermont, which is centered above the point where allochthonous basement ramped up over autochthonous basement. The anticlinorium dies out to the south, so that at our latitude D3 strain was taken up mainly along steep Acadian reverse faults east of the Lincoln massif, and east of the Green Mountains **(Stops 8 and 9)**. D3 fold axial planes and associated spaced cleavages are steep throughout the region, deforming older structures.

METAMORPHISM

In a note that accompanies previous NEIGC field trips (Stanley et al., 1987 b, c, d), Laird discussed the metamorphism along our traverse. Here we present the same data but with a better understanding of the tectonic setting and a more "user friendly" discussion of the mafic rocks. Honsberger's work at Stockbridge is new and addresses the metamorphism on the boundary between the Prospect Rock and Green Mountain slices farther south than any of the NEIGC trips in which we have been involved.

Metamorphism in the **Middlebury synclinorium** is weak with calcite-dolomite solvus and stable isotope temperatures between 210 and 295 ^{o}C (Sheppard and Schwarcz, 1970). Along the New Haven River west of the Lincoln massif, oxygen isotope quartz-calcite temperatures are between 400 and 420 ^{o}C, although the amount of retrograde exchange is in question (Schwarcz et al., 1970).

At our latitude, pelitic rocks in the **Underhill slice** reach garnet grade and mafic rocks are epidote amphibolite facies (hornblende+chlorite+epidote+albite+quartz). Temperature and pressure from calcite-dolomite and amphibole-plagioclase geothermobarometry are 450 to 489 ^{o}C and 7 to 8 Kbar. Amphibole is chemically zoned with rims showing more TK substitution (AlVI, AlIV for FM, Si) than the cores, indicating higher temperature metamorphism (along a reaction such as epidote + chlorite + quartz = amphibole + TK + H_2O Thompson and Laird, 2005) and consistent with conodonts from Buels Gore, which were heated to at least 500 ^{o}C (CAI 7 ½ to 8). 40Ar/39Ar total fusion ages on amphibole reported by Laird et al. (1984) are Taconian (471 +/- 5.8 Ma) along the Appalachian Gap road (VJL225) but Acadian (382 +/- 3Ma) along the Lincoln Gap road (VJL340). The latter is consistent with 384 to 387 Ma biotite ages and with the 386 +/- 4.5 Ma muscovite age reported by the same authors from chloritoid-kyanite grade pelitic schist in the Mt. Abraham allochthon south of Lincoln Gap (LA10K).

Petrographically and chemically, amphiboles in mafic rocks from the **Green Mountain slice** are distinctly different (fig. 6). Amphibole is discontinuously zoned, and cores have greater PL substitution (Na, Si for Ca, Al) than amphibole from the Underhill slice. This substitution is controlled by a reaction such as albite + actinolite + H_2O = chlorite + epidote + PL + quartz and is interpreted to increase with metamorphic pressure (Thompson and Laird, 2005). Rim compositions are actinolite (less TK and PL than cores) consistent with greenschist facies metamorphism (chlorite + epidote + actinolite + albite + quartz). 40Ar/39Ar amphibole ages reported by Laird et al. (1984) for the Pinney Hollow Formation at Stop 8 are 471 +/- 10.6 to 448 +/- 5.1 Ma.

East of our traverse in the **Rowe slice** (Northfield Mountains), amphibole cores have PL and TK substitutions intermediate in value between those in the Green Mountain and Underhill slices (fig. 6). Honsberger will discuss recent results from amphibole studies along the Green Mountain/Rowe slice boundary at Stop 9.

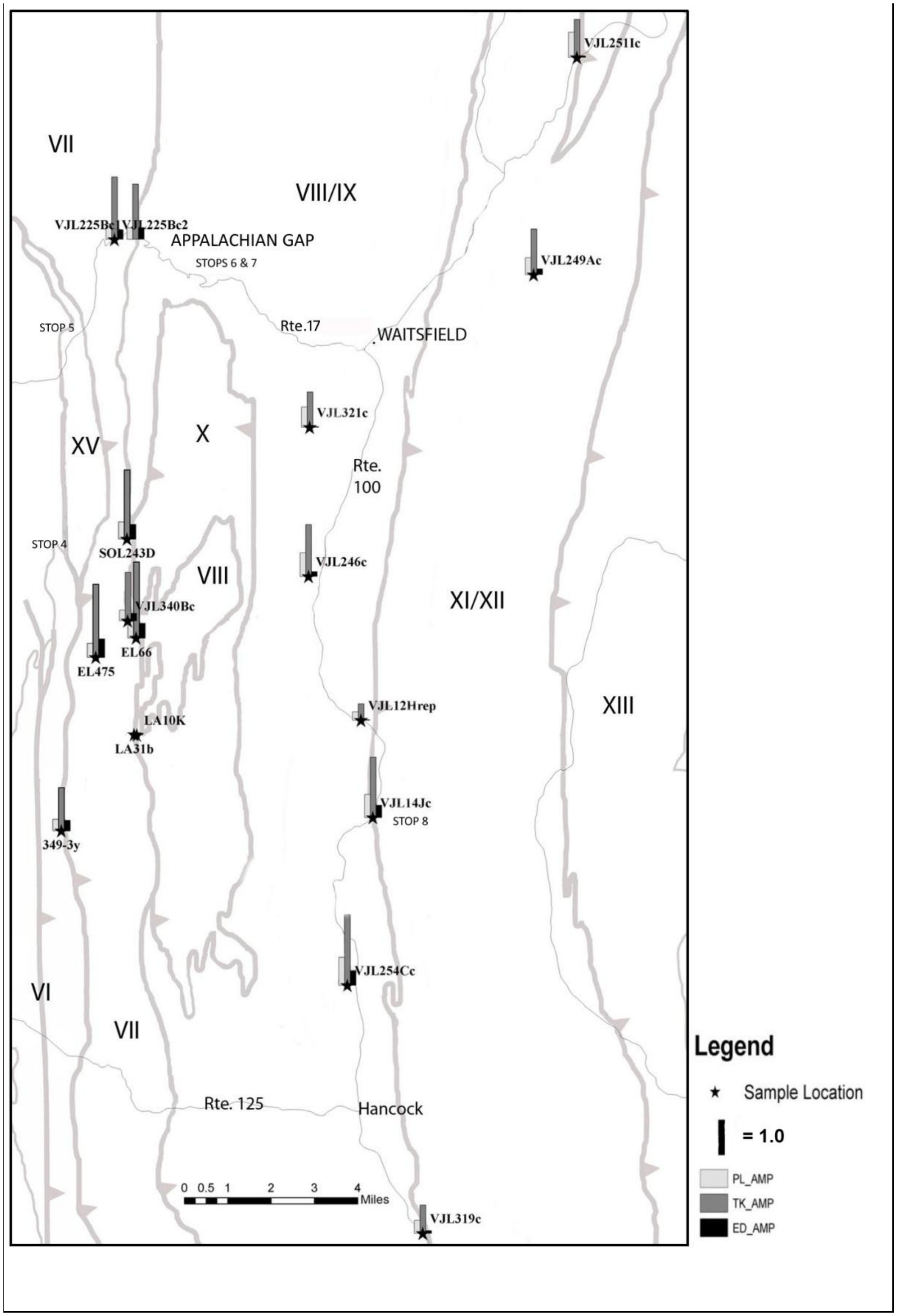

Figure 6. Bar graphs showing PL, TK and ED substitution in amphiboles collected from mafic rocks in the central Green Mountains. Higher PL is a proxy for higher pressure; higher TK is a proxy for higher temperature. Roman numerals indicate lithotectonic packages (see fig. 3).

ACKNOWLEDGMENTS

The authors would like to thank Arden Albee and Rolfe Stanley, whose ideas on the metamorphism and structure of this complicated corner of the world continue to inspire geologists working in Vermont today. Honsberger's field work was supported by a research grant from the Vermont Geological Society. Thanks to Wendy Kelly for her help with the figures.

ROAD LOG

Meeting point: Meet at 8AM Middlebury College, Bicentennial Hall parking lot S (Bicentennial Way is a right turn off Rt. 125, west of campus center) for 8:10 departure. We will consolidate vehicles and delay introductory remarks until the first stop in Charlotte.

Mileage
0.0 Set odometer at Bicentennial Hall parking lot.

0.2 Turn left on Rt. 125, which follows Main St. and College St., briefly right on Seymour St. to Rt. 7.

1.2 Turn left on Rt. 7 north.

21.6 Turn left on East Thompson's Point Road, Charlotte.

22.7 Bear right at yield sign, then turn left onto Thompson's Point Rd. at the stop sign. We pass the site from which the Charlotte Whale was excavated at 23.8 miles.

24.3 Turn right on Lake Road just after passing an outcrop of Bridport Fm. dolomite on the right.

26.4 Pull over and park along the road; walk back to the farmhouse on the west side of the road.

STOP 1. **CHAMPLAIN LOWLANDS: LAKE ROAD, CHARLOTTE** (30 minutes)

Stop 1 is located in the Champlain Lowlands west of the Champlain thrust (fig. 7). Our three reasons for stopping here are 1) to provide an overview of the trip from the relatively undeformed carbonates in the Champlain Lowlands to progressively older and more deformed rocks across each of the structurally higher fault slices to the east; 2) to relate the Chazy Group/Bridport contact to tectonic elements to the east; and 3) to discuss evidence for normal faults.

The Charlotte area was mapped by Welby (1961) at a scale of 1:62,500, compiled at a scale of 1:250,000 by Doll et al. (1961), compiled at a scale of 1:100,000 by Mehrtens et al. (1997), and mapped by Gale et al. (2009) at a scale of 1:24,000. The Champlain Thrust juxtaposes Early Cambrian Monkton Quartzite above Middle Ordovician Stony Point Formation in the Charlotte area. The gently dipping thrust fault is overprinted by upright, undulating, open, E-W striking folds and upright N-S trending open folds (Acadian). The intersecting fold sets produce a dome and basin map pattern which can also be observed in large exposures along the lake and in outcrop scale further east. A fracture cleavage is associated with the N-S folds. Numerous small bedding plane thrusts occur within rocks on both the upper and lower plates of the Champlain Thrust.

The unexposed contact of the Bridport Dolomite (Beekmantown Group) with the overlying limestones of the Chazy Group lies just downhill west of the farm. The Chazy Group has been divided into the Day Point, Crown

Point and Valcour Formations in northwestern Vermont but is mapped as "undivided" here in Charlotte. Please see Mehrtens (2011, this volume) for a discussion of the Chazy Group. The top of the Beekmantown Group corresponds regionally with the Knox unconformity, a period of subaerial erosion of the carbonate bank followed by deposition of the Chazy Group in the deepening foreland basin (see fig. 4). Evidence for the unconformity is not visible here at Stop 1although we do not doubt its existence. Ratcliffe et al. (1999) discussed the significance of Middle Ordovician conodonts (470-454 Ma) in the West Bridgewater Formation and the correlation of that formation with the Ira Formation below the Taconic allochthons. Subsequently, Thompson et al. (2002b) also recovered Middle Ordovician conodonts (460 Ma) unconformably above the Underhill Formation in the Underhill slice.

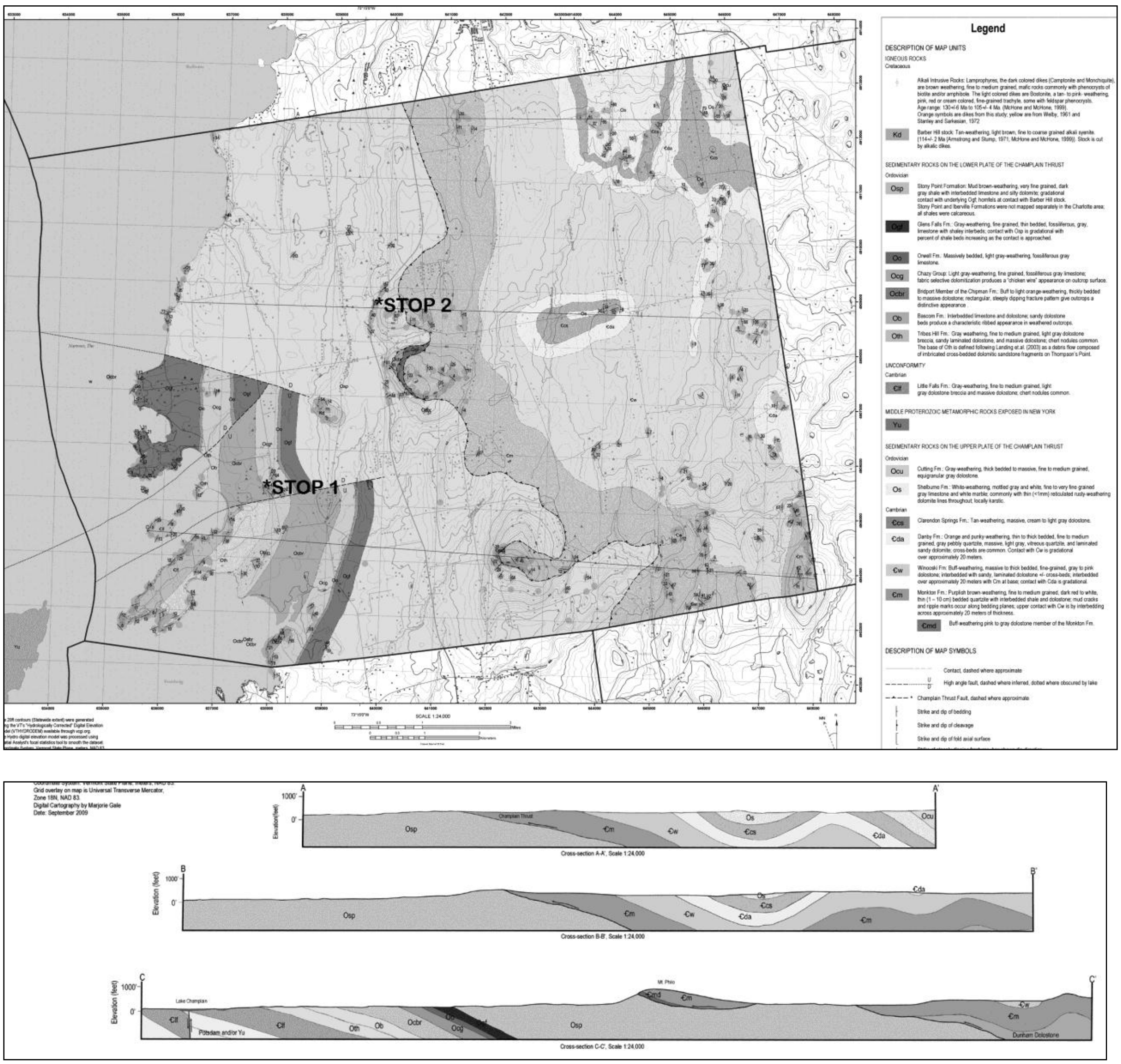

Figure 7. Bedrock map and cross-sections, Charlotte, VT (Gale et al., 2009)

Two major high angle faults are inferred from outcrop control at our current stop. The contact of the Bridport Dolomite with the underlying Bascom Formation occurs at the intersection of Lake Road and Thompson’s Point Road. Rocks there strike NW and dip gently east (318, 13) and are folded by open folds oriented 198, 81 with an associated fracture set. At Stop 1 however, the contact of the Bridport Dolomite with the overlying Chazy Group is inferred west of the farmhouse; again rocks strike NW and dip gently east. A steep fault striking east - northeast is required to account for this map pattern. The fault is interpreted as Mesozoic based on comparison to rare normal faults along the lakeshore which cut both bedding and F2. However, older ages cannot be ruled out. The strikes of the faults correspond well with analyzed fracture data (fig. 8 and see Kim et al., 2011, this volume). The estimated offset for the fault south of Stop 1 is 1000 feet.

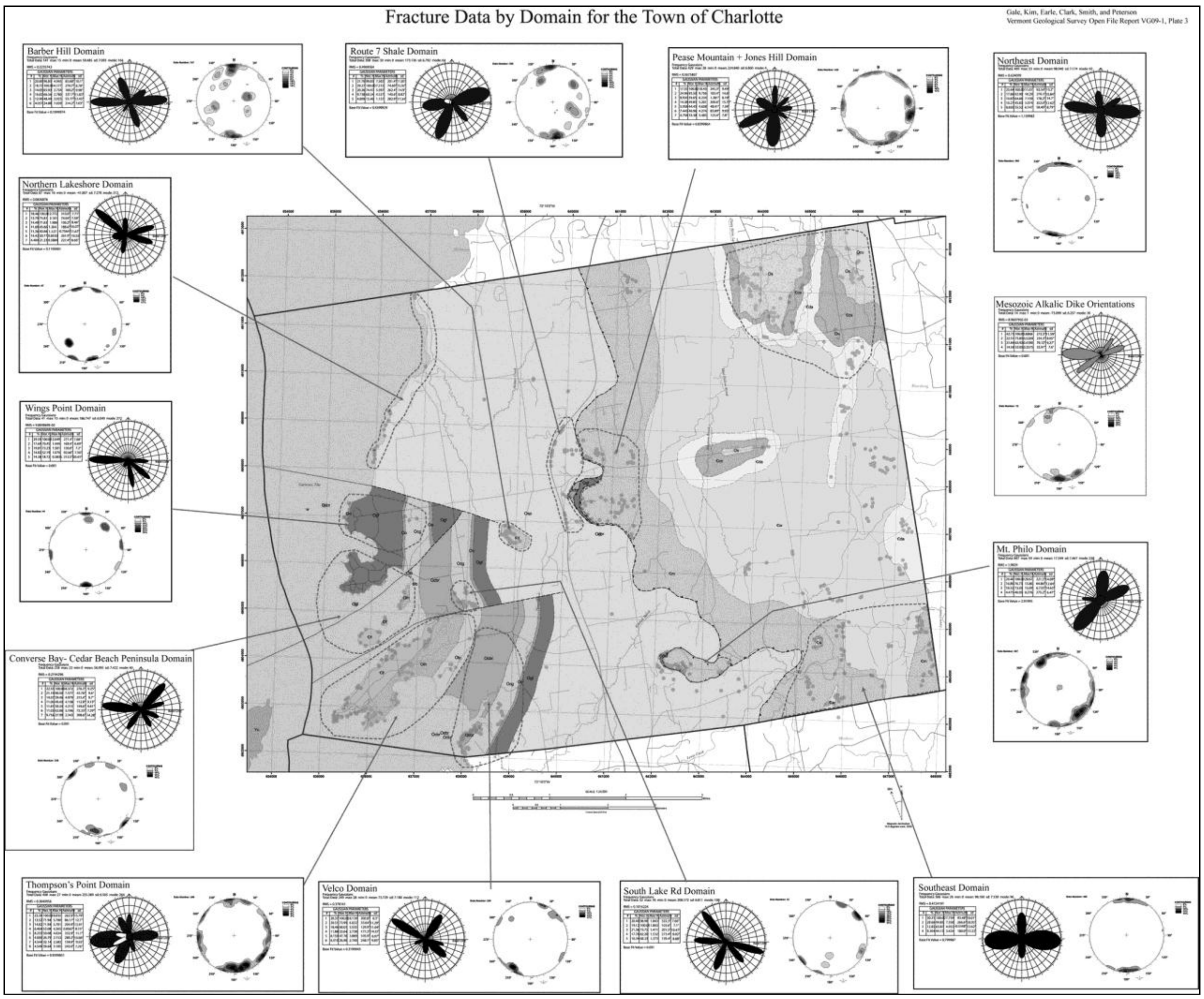

Figure 8. Fracture data for Charlotte, compiled by Jon Kim for Gale et al., 2009.

0.0 Continue north on Lake Road.

1.2 Stop sign; turn right on Ferry Road.

2.3 Blinking light; continue straight on Ferry Road.

2.6 Turn left at light onto Route 7 north.

3.1 Pass large roadcuts on the right and pull into driveway. Park at landing and walk back to roadcuts.

STOP 2. **CHAMPLAIN LOWLANDS BELOW THE THRUST: ROUTE 7, CHARLOTTE** (20 minutes)

At Stop 2 we will look at structures within the Ordovician shales on the lower plate of the Champlain thrust (see location on fig. 7). The Middle Ordovician Stony Point Formation (Trenton Group), a dark gray shale and interbedded limestone with white calcite veins, occurs at the top of the lower plate and is strongly deformed here, roughly 600 feet below the thrust as projected overhead. Recumbent folds with well-developed cleavage are transected by low angle thrusts. Although both Iberville and Stony Point Formations were previously mapped in Charlotte, we were not able to distinguish these formations; all the shales are calcareous. The limestone beds within the shales become thicker and more prevalent downwards toward the contact with the underlying Glens Falls Formation. See Kim et al. (this volume, stop 2) for a discussion of deformation in the shales.

Figure 9. Bedding and axial plane cleavage in recumbent fold, Route 7, Charlotte (photo: Jon Kim).

A comparison of section D-D’ (fig. 5b) with cross-sections farther north shows dramatic thickening of shales from less than 200 feet in the south to more than 3000 feet near the Canadian border, with much of the thickening due to structural repetition. Where exposed in northern Vermont, the shales are extensively folded and cut by numerous low-angle faults. Stanley (1990), in a study of the Cumberland Head Formation in the Champlain Islands, recognized the cumulative effect of small bedding plane thrusts and calculated total shortening of 11% -16% along predominantly northwest-directed imbricate faults.

0.0 Exit parking lot, turn left (south) onto Route 7.

10.3 Go through traffic light, start up the hill and stay in the left lane.

11.0 Turn left on Plank Road. At 12 miles, enjoy the views of the Bristol Cliffs (Cheshire Quartzite) and the Green Mountains beyond.

14.1 Stop sign; continue straight on Plank Rd.

14.8 Stop sign; continue straight on Plank Rd., now a dirt road.

15.7 Begin to round the sharp corner and pull into the small parking lot on the left. Follow signs to the anticline.

STOP 3. CHESHIRE QUARTZITE: WATERWORKS PROPERTY, BRISTOL (25 minutes)

Stop 3 is on the upper plate of the Champlain Thrust (fig. 4, slice IV) in the Cambrian Cheshire Quartzite. The light gray to white Cheshire Quartzite overlies the rift facies associated with the opening of Iapetus and represents a clean sandy beach deposit along the Laurentian margin. The area was mapped by Stanley (unpublished manuscript map).

The anticline on the Waterworks Property is an Acadian, upright, open fold that is likely coeval with the Acadian folds of the Green Mountain anticlinorium. Based on the map pattern (fig. 10), the upright fold deforms an older anticline with Dunham Dolomite both above and below the Cheshire Quartzite. The small anticline shows classic bedding/cleavage relationships; is an older foliation deformed across the anticline?

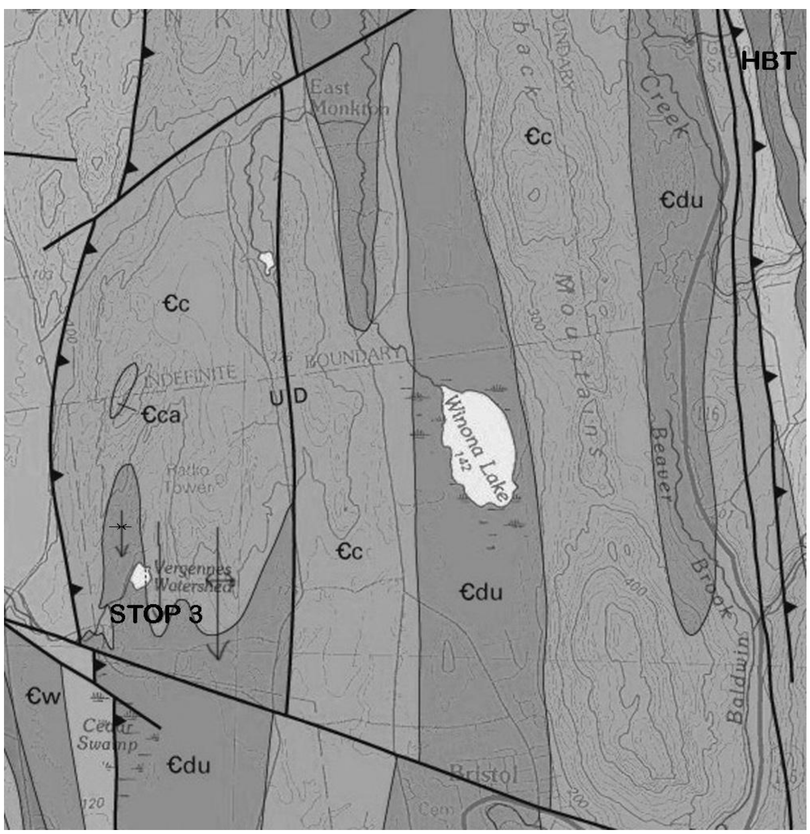

Figure 10 . Map of the Vergennes waterworks area as shown on the new Bedrock Map of Vermont. The area around Stop 3 was mapped by Stanley (manuscript map). Note the southern terminus of the Hinesburg thrust in the northeast corner (HBT).

0.0 Turn left out of the parking lot, continuing east on Plank Road.

1.5 Stop sign; turn right onto Sawyer Road.

2.7 Stop sign; Turn left onto Route 17/Main St. and head to Bristol.

3.9 Traffic light; continue straight on Routes 17 and 116.

5.1 Continue straight through light in downtown Bristol. As you cross bridges and pass Rocky Dale Gardens, note view to left (north) of east-dipping Cheshire Quartzite on Hogback Mountain.

6.6 Turn right on Lincoln Road. The New Haven River to the right of the road cuts through a syncline in the Cheshire, and then deeper into rift clastic rocks beneath the Cheshire.

10.0 Continue straight, following signs for Lincoln Gap and Warren.

10.9 Just before the second bridge beyond Lincoln, turn right onto Revell Drive; continue up the hill, stay to the right and park in the field on the right.

Walk back down the hill, WATCH TRAFFIC and cross the road first, <u>then</u> cross the bridge to the east, and follow the footpath to the left. (We want to avoid an accident like the one on a previous field trip, which gave the bridge its informal name!)

Walk first upstream to see outcrops under the bridge.

STOP 4. BASAL LATE PROTEROZOIC UNCONFORMITY, "CRASH BRIDGE", LINCOLN (60 minutes)

This is a much-visited exposure of the western contact of the eastern lobe of the Lincoln massif, first presented as an NEIGC stop by Stanley et al. (1987c, p. 301-302), from which fig. 11 is taken. It is one of four designated Rolfe Stanley teaching outcrops, dedicated during a memorial field trip in 2001. We will look first at Middle Proterozoic foliated orthogneiss (granitic gneiss) under the bridge, and look upstream across the New Haven River to foliated amphibolite. We will have a sample of the mafic rock for you to look at. A similar rock from south of Cobb Hill in the Lincoln massif records a maximum temperature of metamorphism less than in any of the rocks from the overlying Underhill slice, indicated by much lower TK substitution in amphiboles (fig. 6). The Ti cores may reflect original igneous compositions. Weak Grenvillian foliation is preserved in the gneisses, striking NW parallel to the stream and dipping steeply NE. Superimposed Taconian foliation striking NNE becomes more pronounced downstream under the bridge toward a shear zone of muscovite and biotite schist. Stanley et al. (1987b) interpret the shear zone as a branch of the west-directed Cobb Hill thrust.

Downstream from the bridge, near the plaque honoring Rolfe, several strands of mylonitic muscovite schist cut the protomylonitic gneiss, and layers of biotite schist (more abundant on the west bank under the bridge) represent sheared amphibolite. Stanley et al. (1999, p. 152) pointed out that the large quartz pods in the fault zone suggest that silica-rich fluids played an important role in the dynamics of thrusting. Immediately downstream, zones of metaconglomerate within magnetite-bearing metawacke of the Pinnacle Formation are interpreted as paleochannel deposits above the unconformity. The cobbles and boulders of granitic gneiss are elongated parallel to Paleozoic, SE-plunging fold axes. The folds tighten toward the faulted unconformity. DelloRusso and Stanley (1986) suggested that they initially plunged more gently, but were rotated during faulting toward the line of transport.

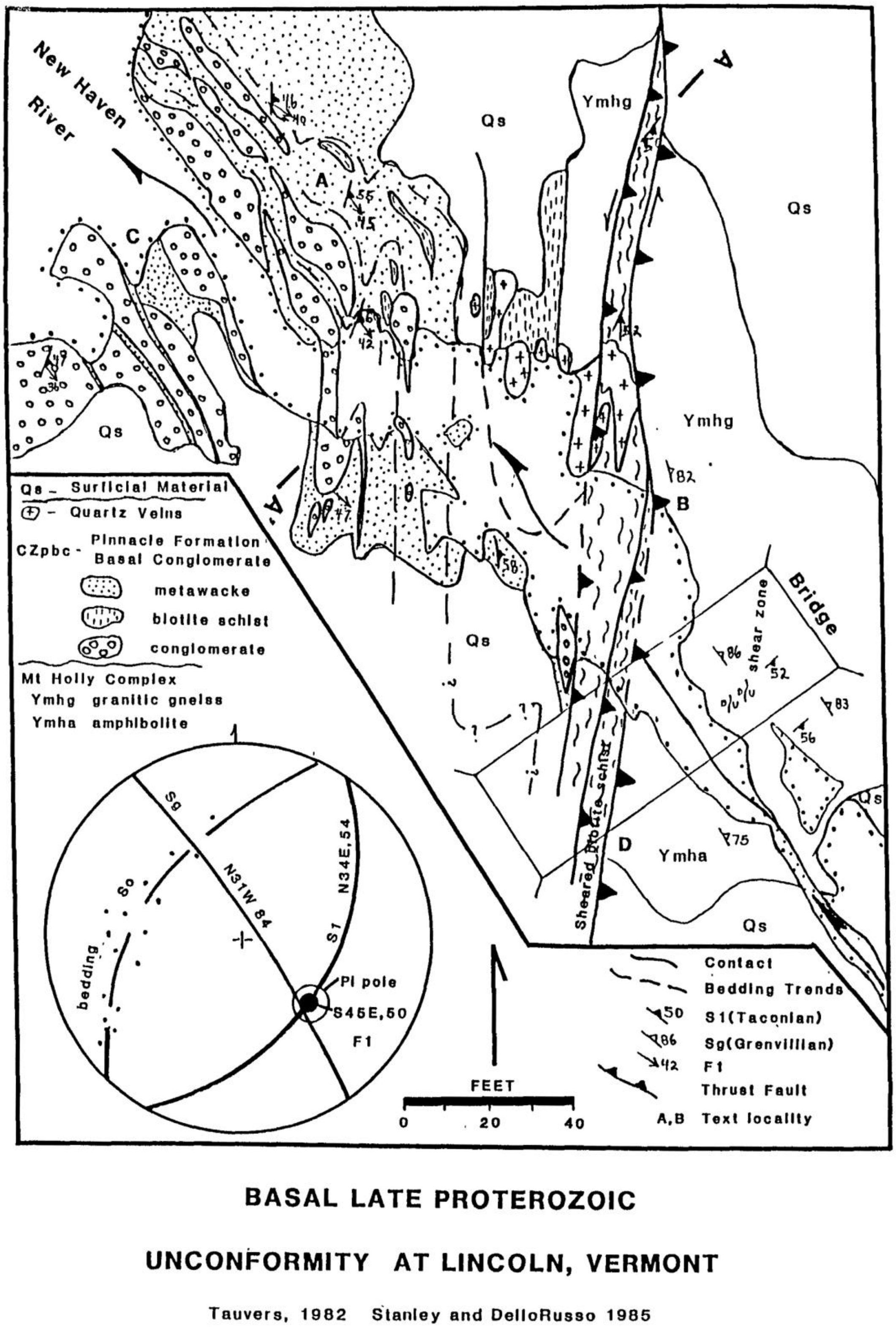

Figure 11. "Crash Bridge", Lincoln (from Stanley et al., 1987c).

0.0 Return to vehicles, turn left at the base of the driveway onto Lincoln Road.

1.0 Turn right on Quaker Street just past the Lincoln General Store.

1.9 Quaker Street turns to dirt; continue on to South Starksboro.

5.0 Stop sign; turn right (east) on Route 17 towards Appalachian Gap.

8.3 Turn right into driveway at Ghyll-Fen Farm (yellow house). Park here and walk back to 3423 Lincoln Rd.; go up driveway, bearing right until we get to the outcrops. Please ask permission of the landowners.

STOP 5. QUARTZ - LAMINATED SCHIST OF THE JERUSALEM SLICE (30 minutes)

The Jerusalem slice as mapped by Tauvers (1982) and DiPietro (1983) consists almost entirely of quartz-laminated schist such as you see at this stop. Prior to their work, the units from the Hinesburg thrust east across the Green Mountains were considered part of a normal stratigraphic sequence. Although shown on the new bedrock map of Vermont as a member of the Underhill Formation, the quartz-laminated schist is interpreted as a mylonite, which indicates a major fault zone at the base of the Underhill slice. The laminated schist is a fine-grained sericite-chlorite-quartz-epidote-albite schist. The quartz laminations are mainly recrystallized quartz of metamorphic origin although some sandy layers are also preserved and are likely original bedding (DiPietro, 1983). DiPietro described the mylonitic fabric as an incipient to pervasive foliation. Development of the mylonite ranges from a phacoidal foliation, to a foliation that truncates intrafolial isoclines (fig.12), to a strongly foliated rock in which the older fabric has been completely destroyed.

It's worth remembering that in the early 1980's relatively few faults were mapped in northern Vermont until a number of MS theses under Stanley, Doolan and Mehrtens at the University of Vermont made it clear by detailed mapping that numerous faults must be present, especially on the basis of truncation of map units. Gradually as the individual maps were compiled into the regional picture, units were redefined and faults were connected south to north. For example, the Underhill thrust heads northwest from here (fig. 13) and eventually connects to the Brome thrust in northern Vermont.

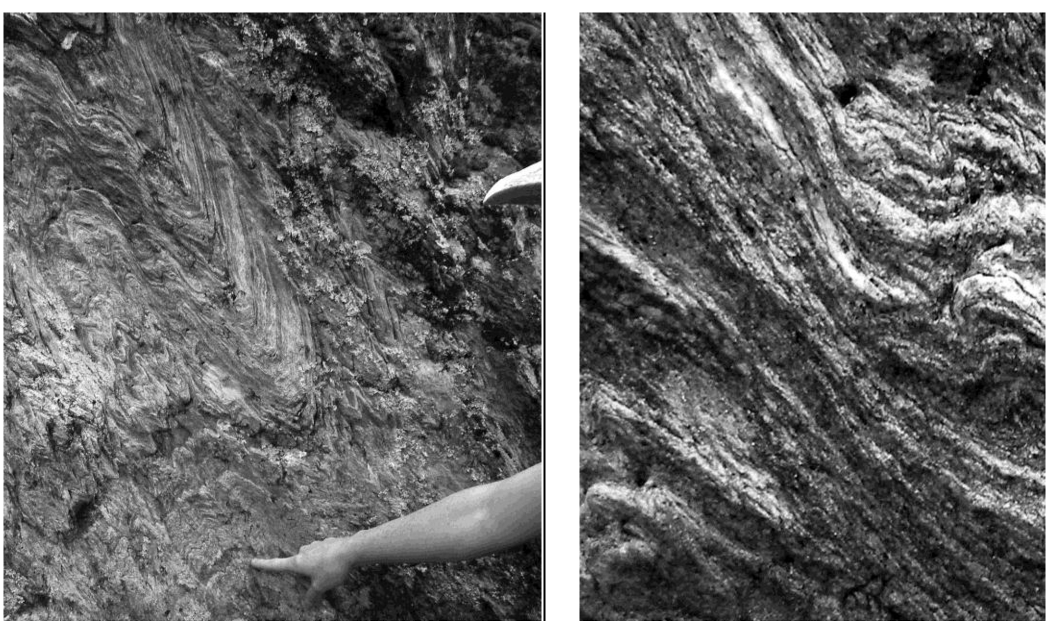

Figure 12. Bedding in the quartz-laminated schist (left); incipient development of mylonite (right).

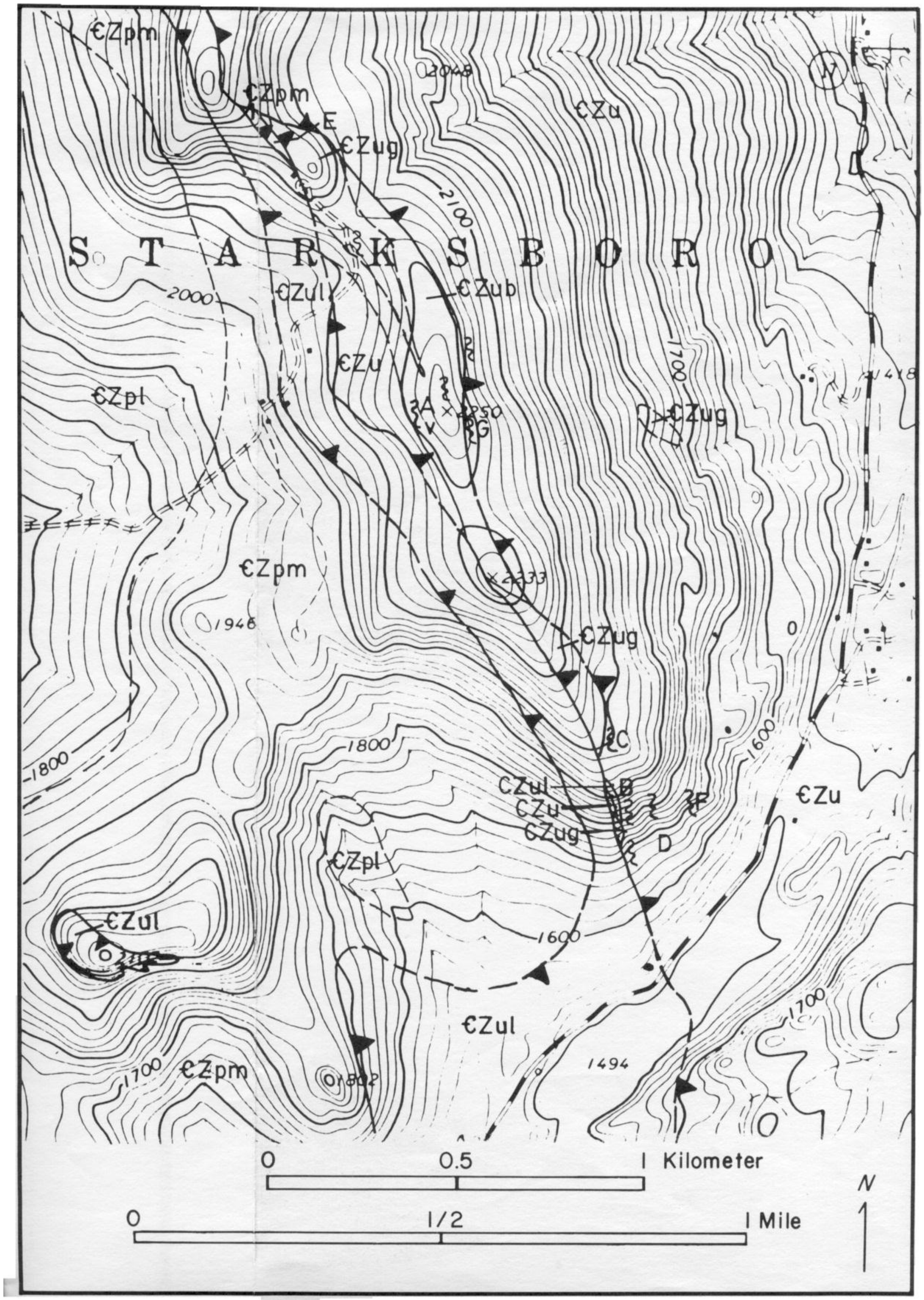

Figure 13. Northern end of the Jerusalem slice (CZul) and continuation of eastern contact (Underhill thrust) north. CZpl Lower Pinnacle Fm.; CZpm Middle Pinnacle Fm.; CZu Underhill Formation; CZul quartz-laminated schist; CZug Underhill, greenstone member; CZub Underhill, biotite metagreywacke member. From DiPietro (1983).

0.0 Leave Ghyll-Fen Farm and turn right on Route 17.

4.2 Pull into the parking lot on the left at Appalachian Gap.

STOP 6. VIEW OF UNDERHILL SLICE FROM APPALACHIAN GAP (10 minutes)

As we look west from Appalachian Gap, the hills in the middle ground are underlain by a folded pattern of Underhill and Pinnacle Formations in the Underhill slice (fig. 3, VII). On a clear day one can see the Adirondack Mountains in the distance. Partway up the steep road in Buels Gore we passed road cuts with greenstones in the Underhill. Sample VJL225 came from a nearby brook, with Taconian 40Ar/39Ar total fusion ages on amphibole (471 +/- 5.8 Ma, Laird et al., 1984). A bit higher but still in the Underhill slice we passed through the Monastery Formation, locally with infolds of graphitic schist and dolomite pods of the West Bridgewater Formation. Conodonts recovered from one dolomite pod are *Leptochirognathus quadratus,* a species that has the tightest age constraints (460-463 Ma) of any yet found in the West Bridgewater. (More isotopic work on the amphiboles might resolve the slight discrepancy between the conodont and metamorphic ages.) The conodonts are encrusted by overgrowths of apatite (fig.14b) and are clear and translucent, which indicates that they were heated to at least 500˚C (CAI 7 ½ to 8), compatible with garnet in the pelitic rocks. Farther up the mountain we crossed into the Green Mountain slice, so that all the roadcuts visible from the overlook are Fayston and Hazens Notch albitic schists.

Fig. 14a. View west from Appalachian Gap.

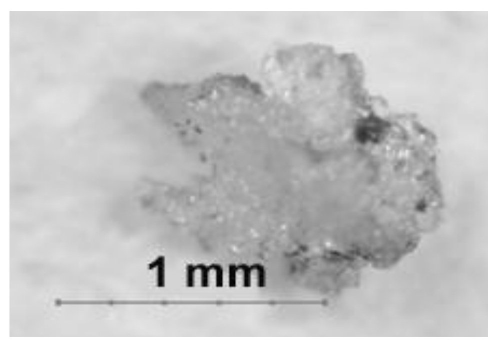

Fig. 14b. Conodont from Underhill slice at Buels Gore (photo: John Repetski).

0.0 Walk east along the north side of the highway down to the next turnout on the left and then cross to the best roadcut for seeing structures. WATCH TRAFFIC!

STOP 7. GREEN MOUNTAIN SLICE AT APPALACHIAN GAP (20 minutes)

The main point of this stop is to compare the structural style to previous stops. This is Fayston Formation: silver-green quartz-muscovite-chlorite schist with garnet, albite and magnetite porphyroblasts. Here we are near the crest of the Green Mountain anticlinorium. Sn (local S2) dips 35 to 50 degrees NE, associated with west-verging, tight, Taconian folds. Quartz veins help define the folds; older foliation and bedding are hard to see. Sn locally lends a "pinstriped" aspect to the rock, with 2 cm quartz-feldspar domains alternating with thinner, more micaceous domains. Weak spaced cleavage is parallel to the axial planes of upright, open Fn+1 folds; they are likely Acadian. On the north side of the road east of the turnout, foliation surfaces show S2 X S3 crinkle lineations and very faint S2 X S1.

0.0 Return to vehicles and continue east on Route 17.

6.1 Outcrops in river (left) as you approach Irasville: Pinney Hollow Formation - - note foliation dips east.

6.2 Turn right on Route 100 south. At first the road stays in the Green Mountain slice, but then bends east into the Ottauquechee Formation (Prospect Rock slice). Rely on the very consistent N-S foliation to keep your bearings.

17.3 Height of land in Granville Notch - - divide between Lake Champlain and Connecticut River watersheds.

18.5 Pull into parking area on the right before sharp bend back toward the west.

STOP 8. FAULTS BETWEEN OTTAUQUECHEE & PINNEY HOLLOW FORMATIONS (20 minutes)

WATCH TRAFFIC AND STAY OFF THE PAVEMENT BECAUSE THIS IS A DANGEROUS CURVE IN THE HIGHWAY!

Small outcrops east of the roadcut are black, carbonaceous schist of the Ottauquechee Formation, with foliation dipping steeply east. Next you will encounter strongly foliated, tan-weathering "papery schist" dipping 55 degrees east, interpreted as a late or post-Taconian fault.

In the main roadcut to the west carbonaceous rocks are in contact with the Pinney Hollow Formation, composed of silver-green chlorite-muscovite-albite-quartz schist with two darker green mafic layers. An epidote-rich layer outlines Fn folds plunging 50 to 60 degrees ESE. Stanley et al. (1985d) suggested that the actual contact between silver-green and carbonaceous rocks, west of the papery schist zone, might be an older, syn-metamorphic fault, because in thin section albite porphyroblasts can be seen growing across the foliation. They also noted that fold axes and mineral lineations here are far less variable than those farther from the fault zone, suggesting rotation into the transport direction. Fn+1 folds have axial planes and spaced cleavage nearly parallel to the papery schist (345, 55). One pinkish layer (dolomite?) in the mafic rock seems to form an Fn-1 isocline, deformed by Fn into a hook.

Most of the green-colored rocks at this roadcut are primarily chlorite rich, but in the middle of the outcrop greenstone contains epidote, zoned amphibole (fig. 15), and green biotite, as well as chlorite and albite, quartz, sphene, calcite, and magnetite. Amphibole cores contain up to 0.74 formula proportion of Na(M4) and are similar in composition to barroisite from Belvidere Mountain. At this stop the barroisite cores are interpreted to be Taconian based on a 40Ar/39Ar total fusion amphibole age of 471 +/- 10.6 Ma (Laird and others, 1984). The youngest age that these authors report for barroisite cores with actinolite rims from this outcrop is 448 +/- 5.1 Ma.

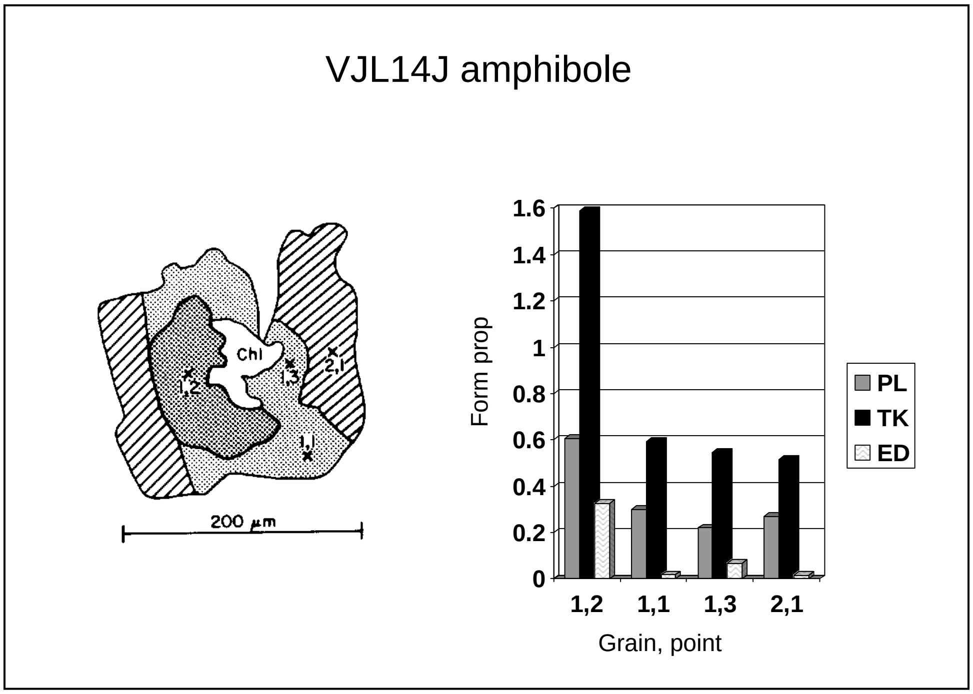

Figure 15. Line drawing and composition of zoned amphibole at Stop 8. Between the barroisite core (dark stipple) and actinolite rim (light stipple) is an anhedral chlorite grain. On either side of the zoned amphibole are actinolite grains (diagonal lines). PL is formula proportion Na(M4), TK is Al(VI)+Fe3+2Ti+Cr , and ED is Na(A)+K .

Return to vehicles and continue south on Route 100. Watch for Moss Glen Falls on the right - - ledges at the falls are albitic, carbonaceous layers within the Pinney Hollow Formation.

2.3 Leaving Granville Gulf. Route 100 roughly parallels the lithotectonic boundary we saw at Stop 8.

4.8 Lower Granville. Syn-metamorphic thrusts (Stanley et al., 1987d) and medium-high pressure metamorphism in Pinney Hollow greenstones west of the church (VJL254, fig.6).

7.7 Hancock (junction with Route 125 west over Middlebury Gap).

9.7 Note big iron kettle in yard on left - - likely used in the potash industry - - Vermont’s first cash crop.

10.1 Alluvial fans along slope to west. One of these was shown by Paul Bierman’s UVM students to postdate early settlements, when erosion rates increased due to clearing of the forests (in part to produce potash).

10.2 Quarry Hill Road leads left to an active serpentine quarry - - one of many ultramafic bodies along faults in the Prospect Rock slice and adjacent packages.

11.2 Roadcut left: greenstone in Pinney Hollow Fm.; medium-high pressure metamorphism (VJL319, fig. 6).

12.0 Rochester. Austin Hill to west: felsic volcanics in Pinney Hollow (570 Ma, Walsh and Aleinikoff, 1999).

14.6 Liberty Hill Road to right leads to old quarry in Devonian granite.

19.5 Turn right on Route 100 in center of Stockbridge.

19.8 Sharp right turn directly after bridge onto Pit Road (may not be labeled) and sign for Peavine state wayside.

20.8 Park to left at private camp. Seek landowner permission if you come here on your own.

STOP 9. STOCKBRIDGE TALC MINES (60 minutes)

Pre-Silurian metavolcanic, metasedimentary and serpentinized ultramafic rocks in Stockbridge are part of a polymetamorphosed and multiply deformed zone between the core of the Green Mountain anticlinorium and the Silurian unconformity and were mapped by Walsh and Falta (2001) at a scale of 1:24,000. The lens-shaped ultramafic body here is in contact with intercalated greenstone and muscovite schist, all of which are bound by quartzose graphitic phyllite and albite schist of the Ottauquechee Formation. The albitic rocks are identical to Hazens Notch Formation, which suggests that the ultramafics may occur along a pre-peak metamorphic fault analogous to the Prospect Rock thrust.

If time permits, we will stop along Pit Road at an outcrop of graphite-chlorite-quartz-muscovite phyllite of the Ottauquechee Formation, which is juxtaposed against ultramafics farther west. Steeply dipping S3 foliation strikes N-S and moderately dipping S2 foliation strikes E-W. Lineations on S3 plunge moderately to the northeast.

The main stop is at the end of Pit Road, where we will have a fairly easy traverse to the mine at the north end of the ultramafics. Watch your footing in the mine. A much rougher, steeper traverse leads to the greenstone. The northern part of the ultramafics is a 100-meter wide continuous body that is 400 meters long N to S and contains three pits (we will visit only the northernmost pit). A fourth, isolated pit 400 meters south of the main body is about 30 m wide and 10 m long and contains more carbonate than the northern pits.

S3 foliation cross-cuts S2 foliation in the northern pit and coarse-grained tremolite, chromite and carbonate occur with chlorite along the eastern wall of the serpentine deposit. The mineral compositions are as follows:

tremolite $Ca_{1.9}Na^{M4}_{0.05}Fe^{2+}_{0.7}Mg_{4.3}Si_{7.9}Al^{IV}_{0.1}O_{22}(OH)_2$

chlorite $Fe^{2+}_{0.9}Mg_{4.1}Al^{VI}Si_{3.1}Al^{IV}_{0.8}O_{10}(OH)_8$

chromite $Cr_{1.1}\ Fe^{3+}_{0.8}Fe^{2+}_{0.9}Mn_{0.1}O_{4.}$

In the interior of the ultramafic body, dolomite veins strike parallel to the S2 foliation. Petrographic data for the interior portion of the ultramafics will be available the day of the trip. West of the ultramafics muscovite-chlorite-quartz schist is intercalated with epidote-chlorite-albite-amphibole-sphene-calcite and minor apatite-bearing greenstone. Is the origin of the intercalation tectonic or depositional?

Electron microprobe analyses of chemically zoned amphiboles from greenstone in Stockbridge reveal magnesio-hornblende cores and actinolite rims. Representative PL (Na^{M4} site) and TK ($Al^{VI} + Fe^{3+} + 2Ti + Cr$) values are 0.25PL and 1.1TK for cores and 0.09PL and 0.3TK for rims, suggesting that the cores grew at higher temperature and pressure (fig. 16). PL, TK and ED values of actinolite rims closely resemble actinolite rims at Granville Notch (Stop 8) and are most likely Acadian. PL and TK values of cores are lower than in amphibole cores at Granville Notch (compare point 4 on figure 17 with point 1,2 on figure 15). Some amphiboles preserve three chemical zones, as shown in figure 17.

Data from amphibole cores may indicate that this lithologic package was formed in the Taconian subduction zone but at shallower depths than rocks in the Green Mountain slice. Perhaps these rocks were part of the accretionary prism.

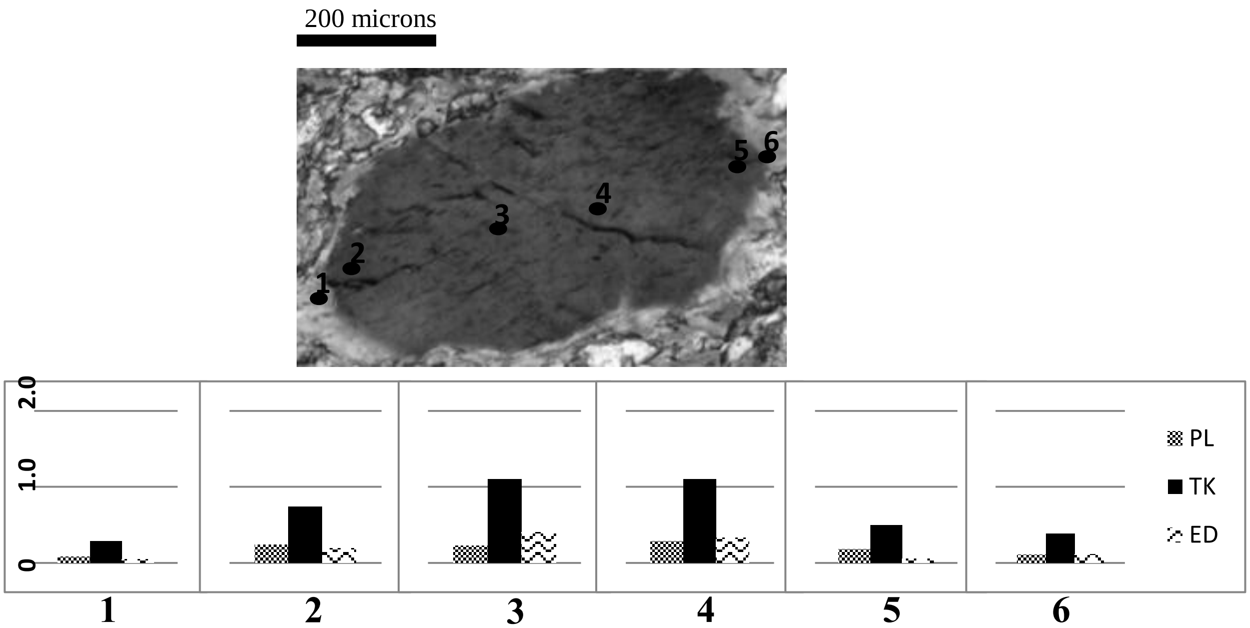

Figure 16. PL, TK and ED transects across amphibole grain from greenstone in Stockbridge that preserves two chemical zones. Image taken in plane polarized light and converted to grayscale.

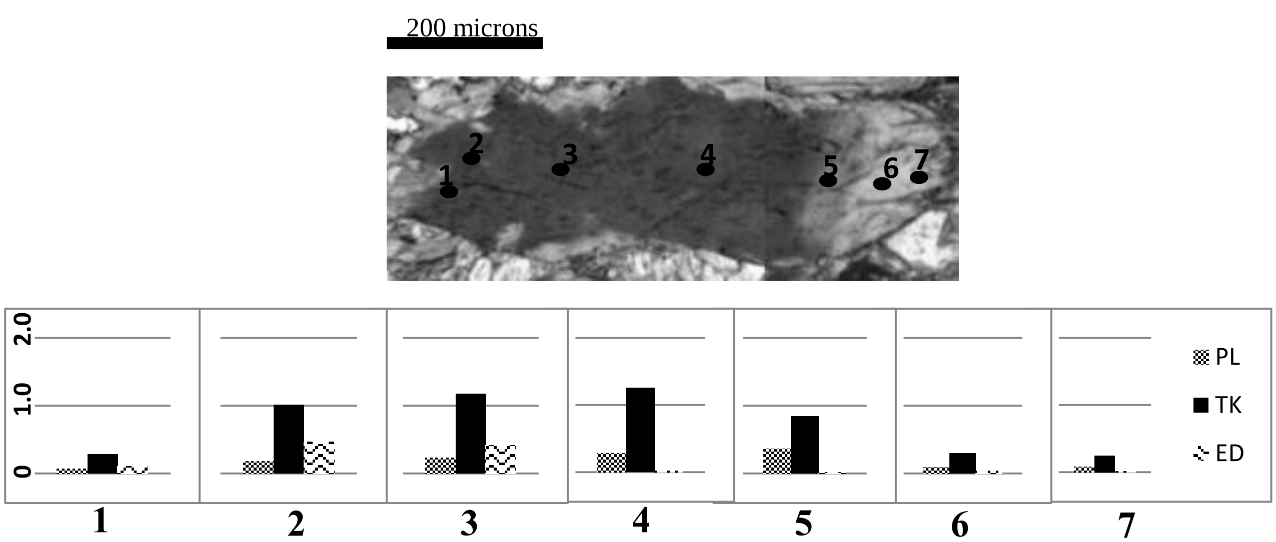

Figure 17. PL, TK and ED transects across amphibole grain that preserves three chemical zones. Image taken in plane polarized light and converted to grayscale.

0.0 Return to vehicles and retrace route north to Hancock.

12.0 Left on Rt. 125 over Middlebury Gap.

27.6 East Middlebury. Stay straight on Rt. 125 and then north on Rt. 7 to Middlebury, where you follow signs for Rt. 125, west to the college campus.

33.5 Bicentennial Hall parking lot, Middlebury College. (About 50 minutes from Stop 9 to Middlebury.)

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