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Field trip A-7
The Champlain Thrust System in the Whitehall-Shoreham area: influence of pre- and post-thrust normal faults on the present thrust geometry and lithofacies distribution
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The Champlain Thrust System in the Whitehall-Shoreham area: influence of pre- and post-thrust normal faults on the present thrust geometry and lithofacies distribution.

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Introduction

The Taconic foreland is an exemplar of collisional tectonics and the Champlain Valley of West-Central Vermont is a pivotal region for mapping and reconstructing this system (**figure 1**). This is because between the latitudes of Middlebury, VT and Whitehall, NY, the shelf sequence gives way to the foredeep and rise sequences along the strike of the eastward dipping range (Stanley, 1987; Kidd et al., 1995) (**figure 2**). Although many significant contacts between the sequences have been recognized as faults, the accrued transport on these faults, and the relationship between them in time and space, is ambiguous. This is partly due to the difficulty in determining the map trace of significant faults across regions of poor outcrop and sharp contrasts in stratigraphic units and sedimentary facies.

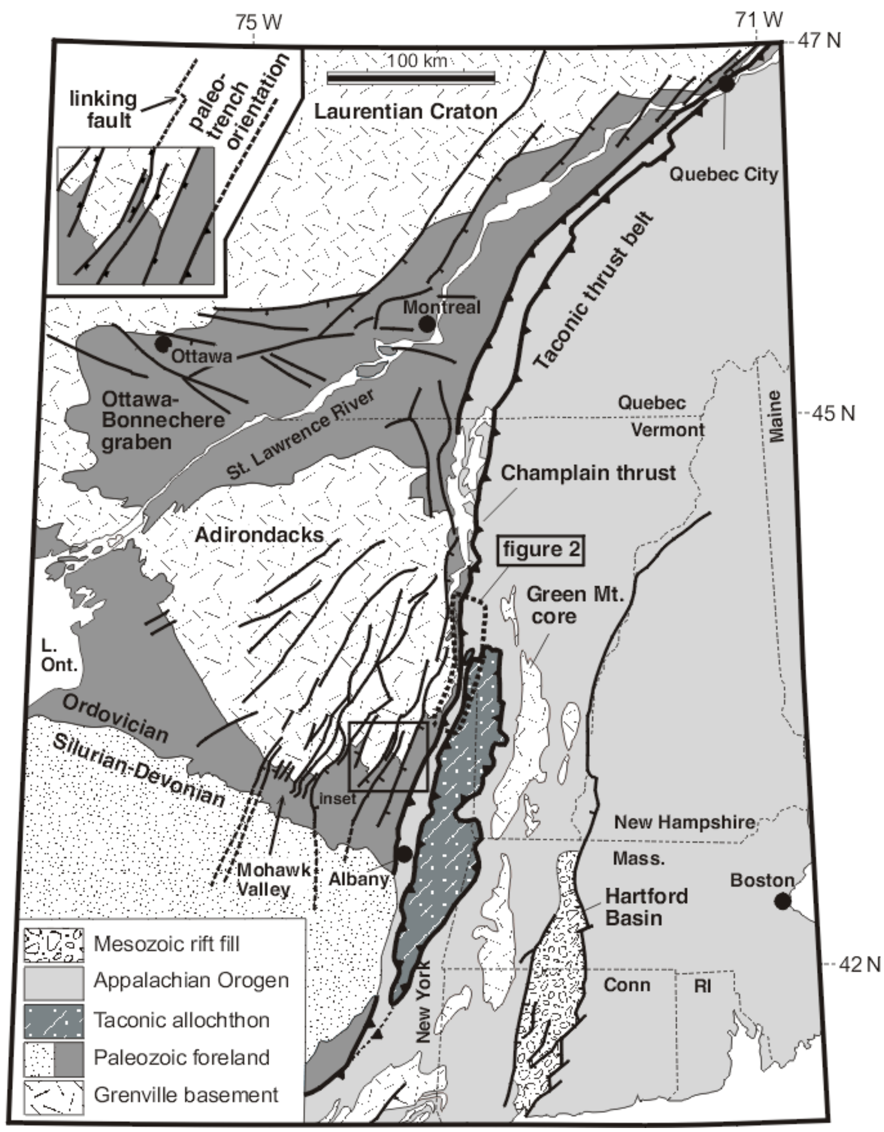

Figure 1. Map of New England illustrating the relationship between geologic provinces. All of the faults depicted are normal faults except for the major thrusts of the Taconic thrust belt. The Hartford and Newark grabens (the latter is not depicted) are Mesozoic structures. Many of the normal faults west of the Taconic thrust belt that cut the southern margin of the Adirondacks, and those in Quebec, are demonstrably medial Ordovician age, without significant earlier or later slip, and in paleotrench parallel, and subordinate paleotrench normal orientations (inset detail from Mohawk Valley; location outline shown by outline box). Dashed lines indicating extensions of normal faults are beneath the Silurian-Devonian cover, and do not cut it.

This field trip visits outcrops along the *Champlain thrust system* (*CTS*), including the *Mettawee* (River) fault, a late normal fault that significantly truncates thrusts of the CTS. These outcrops are from the areas discussed in Hayman and Kidd (2002), a synthesis of our work in the region. Our mapping focused on the CTS, which was responsible for large (>80 km) transport of the shelf section (Rowley, 1982). A cornerstone of our interpretation is that many abrupt changes in map units along-strike, and problems in restoration of cross-sections across the map area, are the consequence of reactivation of preexisting faults. The early (prethrust) faulting occurred in response to extension along the synconvergent flexural forebulge. Other significant lithic changes are the result of late (postthrust) normal faulting associated with one of the several phases of extension that affected the region. The thrust system projects to depth and thus is dynamically related to the overlying Taconic thrusts, and collectively forms a decollement beneath the Green Mountain crystalline core of the Taconic orogen (Rowley, 1982).

The Taconic Sequence

Building on the early work identifying the major faults and unconformities in the Taconic sequence (e.g. Dale, 1899; Keith, 1932; Zen, 1967), several workers refined the allochthonous stratigraphy, related the units to Cambrian-early Ordovician rise and middle Ordovician foredeep sedimentary facies, and recognized that most of the deformational fabric in the rocks post-dated lithification (Delano et al., 1979; Rowley and Kidd, 1983; Bosworth and Rowley, 1984). These observations and inferences provide a restoration of these rocks to their depositional site that requires far-traveled tectonically rooted thrusts such as are found in modern arc-continent collisions (Rowley and Kidd, 1983) (**Figure 3**). The simplest model of such a foreland thrust system predicts a forward-propagating system wherein, for the Taconic foreland, thrusts young to the west. However, many of the fold patterns, deformational fabrics, and cross-cutting relationships of thrusts found in the Taconic foreland require at least some late deformation (Zen, 1972; Rowley and Kidd, 1983; Stanley and Ratcliffe, 1985).

One explanation for late deformation derives from observations of outcrop structures, fabrics, and map patterns in the Taconic foreland requiring at least one out-of-sequence thrust towards the front of the Taconic thrust system. This thrust was awkwardly named *the Taconic frontal thrust* due to its position at the western front of the Taconic Allochthon near Whitehall, NY (Bosworth et al., 1988).

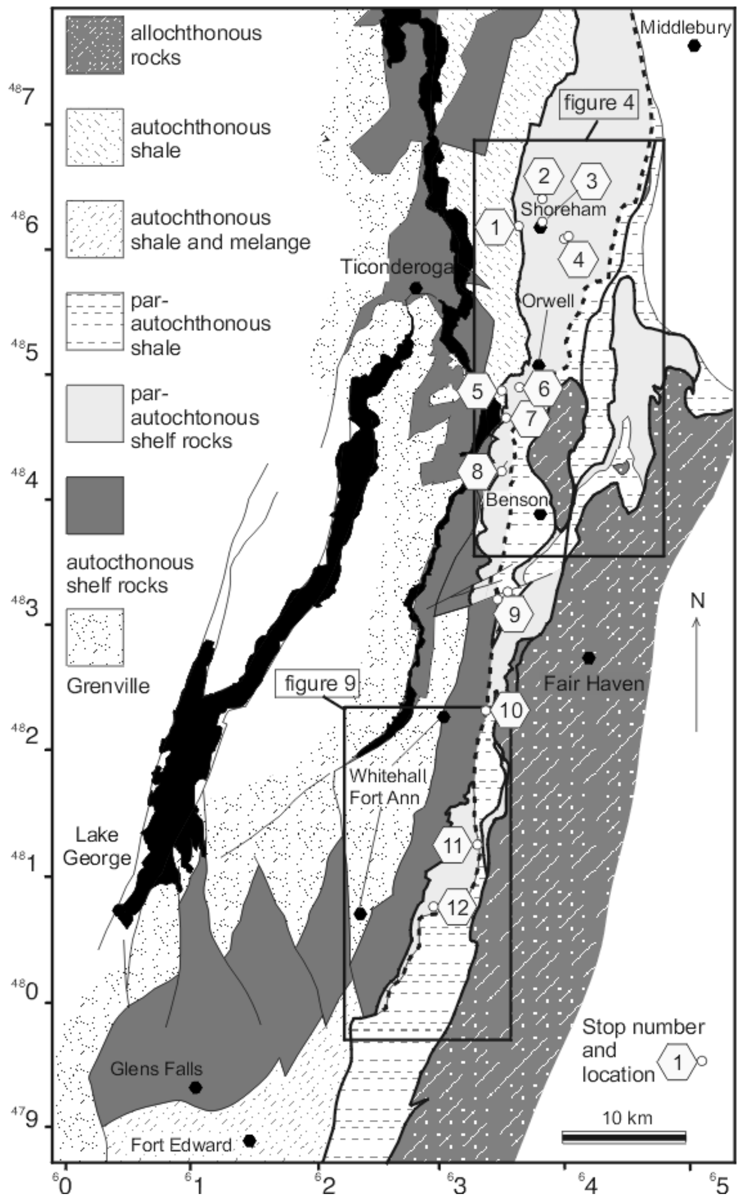

Figure 2. Regional map of west-central Vermont to the upper Hudson River valley of New York illustrating the trace of the Champlain thrust system. The Mettawee fault, in a dashed line, places deformed and low grade metamorphosed shale and flysch, and to the north of Whitehall, imbricated upper shelf carbonates, against the parautochthon. South of the disappearance of the parautochthonous carbonates, it is unclear precisely where the trace of the Mettawee fault or Champlain thrust run.

The Taconic frontal thrust cuts *the Taconic basal thrust*, the thrust responsible for the initial transport of the rise-facies Taconic sequence (Bosworth and Rowley, 1984). Most of the deformational patterns at both the outcrop and map scale can be explained with this model of Middle Ordovician forward propagating thrusting with a component of out-of-sequence thrusting. Two possible, but not preferred, alternative hypotheses for the causes of late foreland deformation are that: (*i*) they resulted from Devonian age tectonics such as the Acadian collision between Laurentia and Avalon (Zen, 1972), or (*ii*) that the system underwent a phase of *retrocharriage* (back- and hinterland-propagating- thrusting) with late Taconic deformation in the internal, eastern portions of the belt (Stanley and Ratcliffe, 1985).

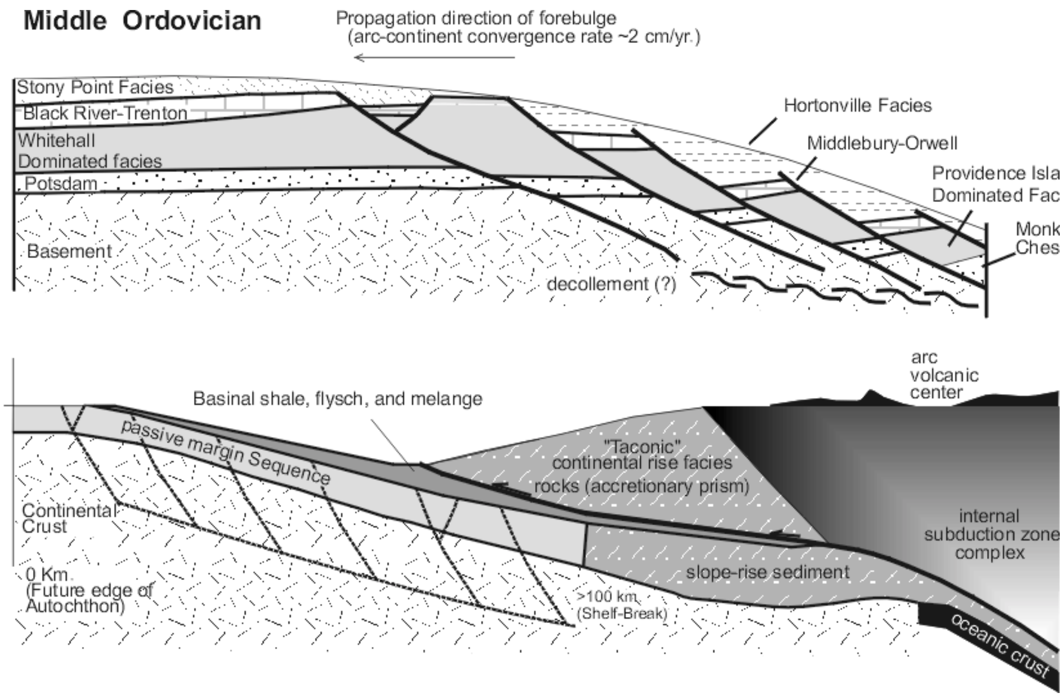

Figure 3. Schematic profiles of the pre- and syn-collisional shelf. The change in sedimentary facies across the shelf is indicated; the Monkton-Cheshire, Providence Island, Middlebury-Orwell, and Hortonville, are distal equivalents to the Potsdam, Whitehall, Black River-Trenton, and Stony Point facies, respectively. Facies transitions between the medial Ordovician units (Black River-Trenton limestones and overlying shales) are partly dependent upon the development of the foredeep, the migration of the forebulge, and syn-depositional normal faulting. Deposition of the younger shales continued after this normal faulting.

The Champlain thrust system

A structure of considerable historic significance, the Champlain thrust is the westernmost thrust in New England with significant transport (Keith, 1932; Rowley, 1982; Stanley, 1987). However, at the latitude of Shoreham, VT, the trace of the Champlain thrust has been uncertain because south of Shoreham there is poor outcrop in the extensive fields separating widely-spaced and densely-forested ridges with better outcrop, and there are several significant along-strike changes in stratigraphic units and sedimentary facies. In this area the Champlain thrust was proposed (Coney et al., 1972) either: (*i*) to splay into a system of several thrusts with a main thrust continuing south as the Taconic frontal thrust or (*ii*) reach a point of zero displacement in the region south of Shoreham. Our mapping determined that thrusts could adequately be traced through the region provided that the stratigraphy was defined on a purely lithologic basis and that some of the along-strike facies changes were localised by reactivation of an earlier generation of faults (Hayman and Kidd, 2002).

Stratigraphy

One of the challenges in mapping the lower Champlain Valley is reconciling outcrop-scale observations of lithologic characteristics with the published stratigraphy. The Centennial map of Doll (1961) and numerous publications (e.g. Cady, 1945; Welby, 1961; Cady and Zen, 1960) define an accepted stratigraphy of the pre-Chazy shelf sequence that includes:

- two massive quartzite/sandstone units (the Cheshire & Monkton/Danby/Potsdam)
- an intermediate dolostone (Winooski)
- a rather complex interfingering of several Beekmantown Group dolostones (Ticonderoga, Whitehall, Cutting, Bascom, & Providence Island, the latter belonging to the Chipman formation)

In contrast, the stratigraphy proposed for the equivalent section in New York (e.g. Fisher, 1985) includes:

- Basal clastics (Potsdam sandstone, Ticonderoga dolomitic sandstone)
- Massive dolostones (Whitehall formation; and which includes a limestone unit, Warner Hill limestone, the cliff forming limestone near Whitehall, NY)
- A second sequence of mixed carbonate and clastic units (Great Meadows formation; which includes Winchell Creek arenite/siltstone, Fort Edward dolostone, & Smiths Basin limestone)
- A second mostly dolostone unit (Fort Ann formation; which includes many impersistent thin limestones)
- A second sequence of mixed carbonates and clastics (Fort Cassin formation; which includes the Ward siltstone, Sciota limestone, & the Providence Island dolostone).

Many of the stratigraphic units in adjacent areas undergo an along-strike facies change when they enter the Champlain lowlands (Cady and Zen, 1960). This complication is compounded by the problem that some of the stratigraphic section does correlate between northern Vermont and New York, but with the unpleasant result that physically similar units have two different names in the literature (Cady, 1945; Welby, 1961; Fisher, 1985). It is our proposal that the stratigraphy of the portion of the Champlain Valley we focus on in this trip is best kept simple – a basal quartzite, an overlying dolomitic section, capped by a Chazy and younger limestone section. Though there may be local exceptions to this simplest passive margin sequence, our mapping of the area between Shoreham and Whitehall has revealed little complication. One notable exception to the simple stratigraphy is that there is a structurally contiguous set of rocks within the Beekmantown Group that contain silty to sandy cross-beds, burrows, and thin limestone members indicative of a proximal shelf facies, and an equivalent section that contains massive dolostones with only *one* thin (less than ten meters) limestone and *one* thin siltstone horizon (**figure 4**). We have named the proximal sequence the *Whitehall facies* after the most prominent autocthonous and parautocthonous carbonate formation in the stratigraphy of Fisher (1984). In contrast, we interpret the massive dolostone with few clastic or limestone horizons to be a distal facies of the Whitehall. We named this the *Providence Island facies* as almost all of it most closely resembles descriptions of the Providence Island formation (Fisher, 1985) and is associated with a thin limestone and thin siltstone that closely resemble Sciota limestone and Ward siltstone. While the Sciota and Ward are defined in the autochthonous shelf near Whitehall, the lithic equivalents in the transported thrust slices near Shoreham appear to transgress stratigraphically (relative to the autochthon) and were probably transitional units forming channels and/or uneven platforms across the shelf.

Our stratigraphy differs from the “official” stratigraphy of Vermont or New York and should best be thought of as a lithologic classification to which we have provided names. This avoids reverting to Brainerd and Seeley’s (1890) *divisions a-e*, a difficult terminology to use in field discussions, but rather relates the lithologic traits and the relative stratigraphic position of the rocks to a passive margin sequence of quartzites, dolostones, and limestone. The complicated along-strike facies changes and across-strike repetition of units, such as the basal quartzite, are adequately explained by structural processes of thrust faulting superposed on a phase of prethrust normal faulting.

Reactivation of prethrust normal faults

The middle Ordovician outer trench slope was the site of normal faulting, between the synconvergence flexural forebulge and the trench (Cisne et al, 1982; Bradley and Kusky, 1985; Bradley and Kidd, 1991) (**figure 3**). We propose that these prethrusting faults localised many of the along- and across- strike lithic unit changes within the thrust sheets (Hayman and Kidd, 2002). Reactivation of these faults by thrusts compounds the difficulty in mapping

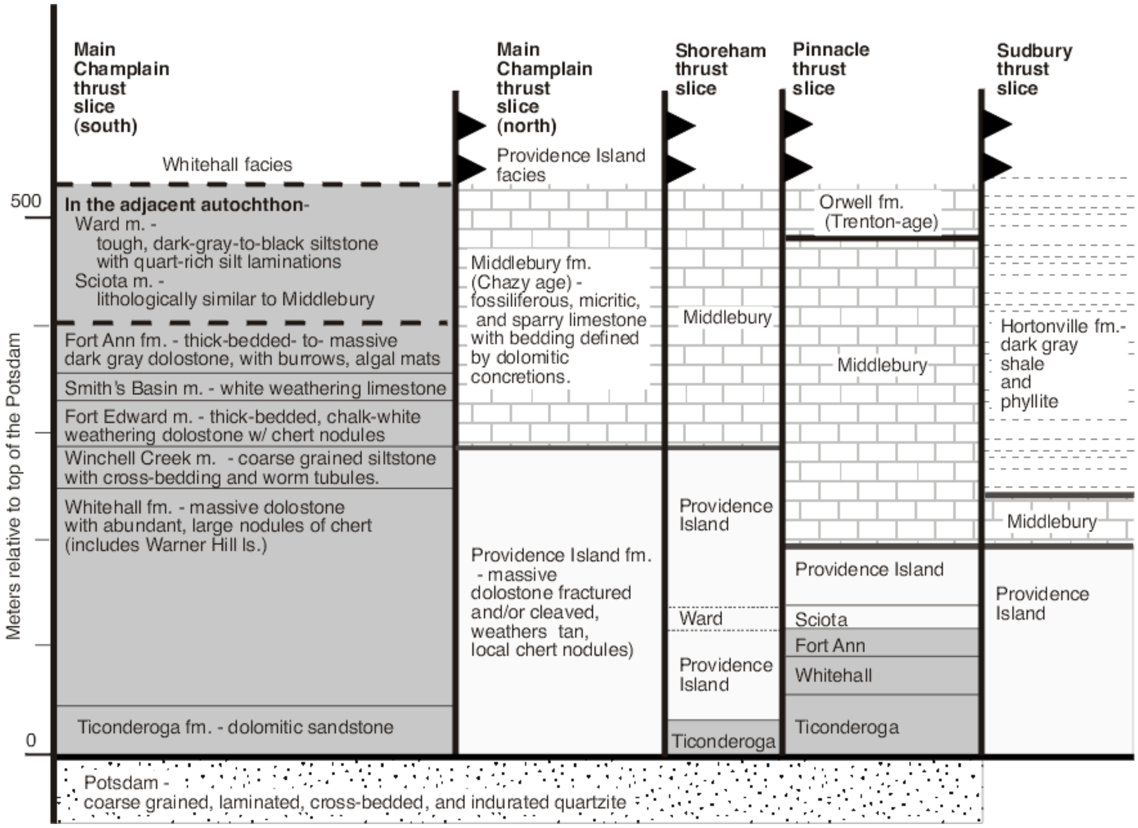

Figure 4. Stratigraphic sections and lithologic criteria for distinguishing map units within the platformal sequence. The solid gray is the Beekmantown Group that is dominantly dolostone but contains many limestone and siltstone horizons. These horizons are assigned formation (fm.) and member (mem.) names (Fisher, 1985). The Whitehall fm. is the characteristic formation of the Whitehall facies and includes the Warner Hill limestone, the cliff-forming limestone in the greater Whitehall region. The Ticonderoga sandstone, Ward siltstone, Whitehall dolostone (within the Pinnacle slice), and Sciota limestone have uneven distribution. The thickness of map units within the different thrust slices is measured from cross-sections; a direct measurement of section is not possible due to inadequate outcrop and limited topographic relief. No age correlation is implied by this diagram.

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this region because many of the prethrusting stratigraphic contrasts coincide with ramps in the thrusts. Our study is one of a growing number of examples of thrust-reactivation of synconvergence normal faulting (Blisniuk et al., 1998; Scisiani et al., 2001). A clear example of reactivation of early faults by thrusting occurs near Shoreham, VT (**figure 5, 6**) where there are three prominent thrusts, each of which transports a slice of shelf section. The three thrusts are *the Main Champlain* (also known as the *Orwell*), the *Shoreham*, and the *Pinnacle* thrusts (Coney, 1972). Each locally transported Potsdam quartzite, though the thrusts climb from north to south resulting in the disappearance of the quartzite in map-view. Along the Lemon Fair River, the Lemon Fair fault, a northwest-southeast striking cross-fault, cuts all of the thrusts and bounds the southern extent of a densely thrust-imbricated region containing the Shoreham duplex (Washington, 1985, 1987).South of the Lemon Fair, however, the thrust sheets consist of broad,, flat panels of structurally intact shelf sections. Additionally, north of the Lemon Fair there are several thin carbonate map units that are difficult to trace south of the Lemon Fair. An inescapable conclusion is that there is a subtle change in sedimentary facies across the Lemon Fair fault, and a rather striking contrast in structural style of the thrust system. Part of this change in structural style corresponds to an increase in displacement on some of the thrusts from north to south as local thrust-duplexes and zones of thrust-imbrication with hanging-wall anticlines are replaced by broad, flat thrust sheets with no hanging-wall cutoffs — horses and imbricates generally restore to a nearer position than broad, flat thrust sheets. We propose that the dual stratigraphic and structural control of the Lemon Fair is due to its origin as a cross-fault along the prethrusting flexural forebulge.

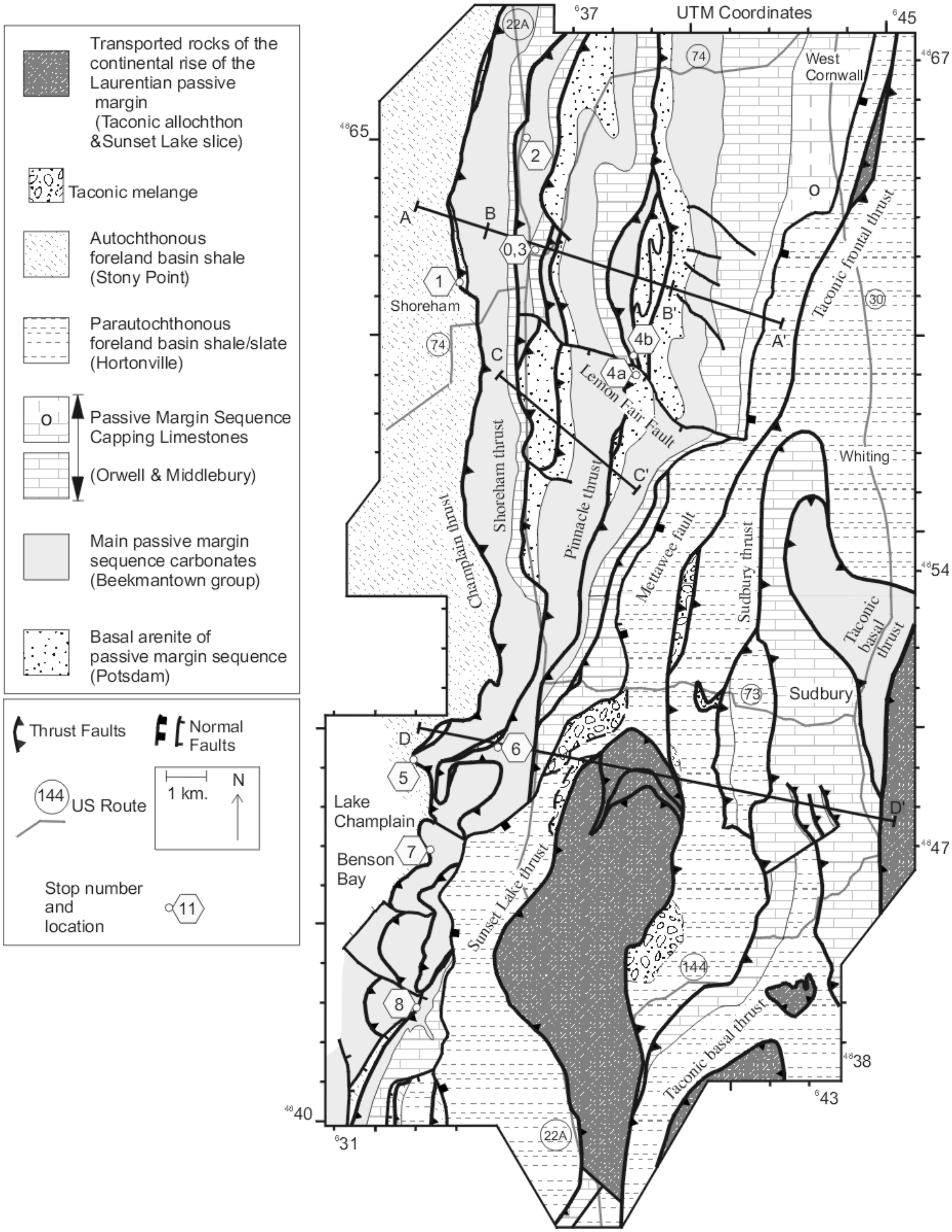

Figure 5. Geologic map of the Shoreham-Benson region illustrating the map trace of faults, significant stratigraphic contacts, and the relationship of different thrust systems to one another, and relationship to the surrounding autochthonous and parautochthonous basinal shales. Thicker lines with no ornaments are cross-faults in the thrust system.

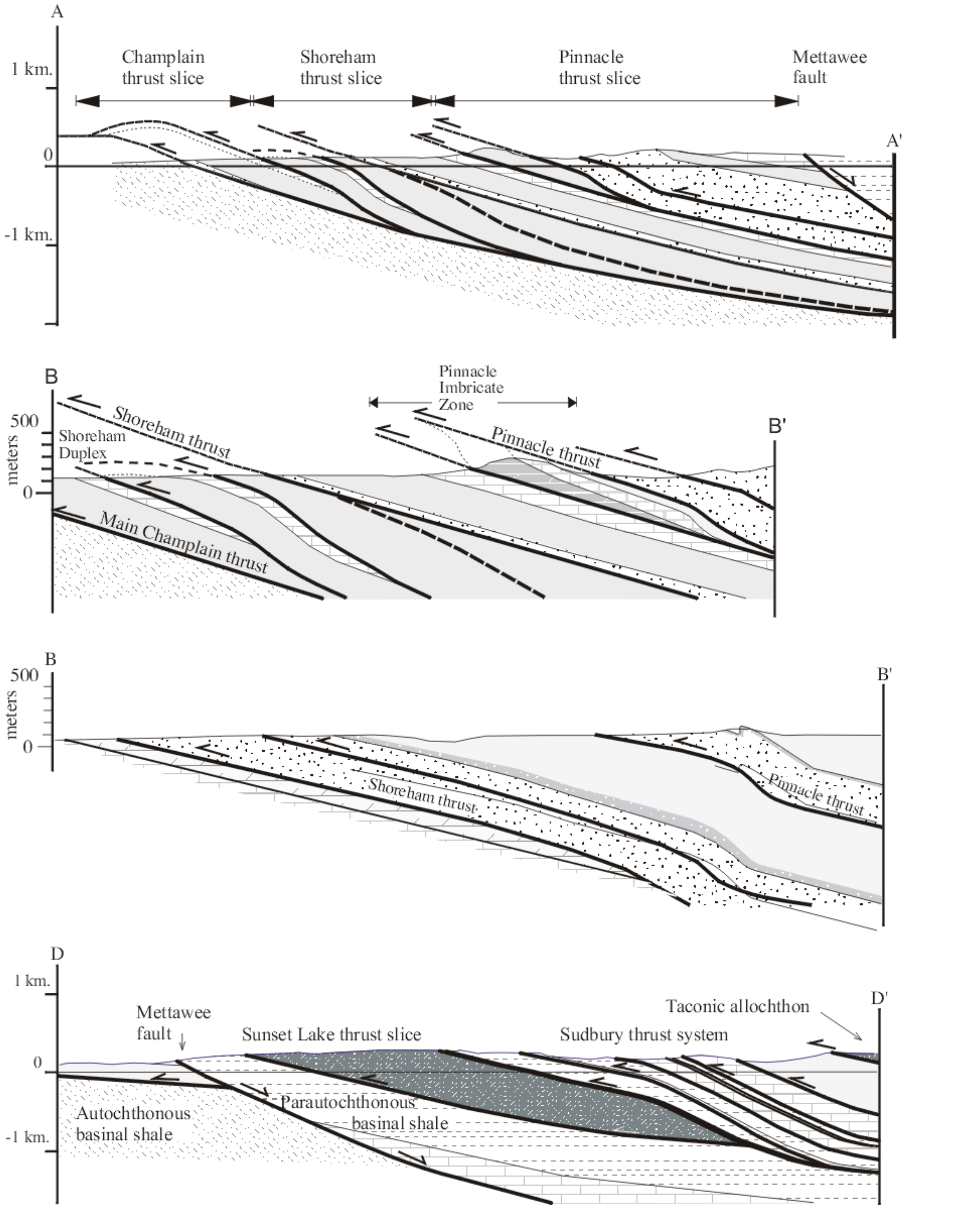

Figure 6. Cross-sections across figure 5. Sections are not formally balanced due to a lack of match points and tip lines, and along and across strike changes in stratigraphic thickness. Bedded unit thickness is conserved as much as possible, and there is no vertical exaggeration.

The other clear example of reactivation of prethrust faults as thrust-structures occurs near Benson Bay, VT (**Figure 7, 8**). Here, the Main Champlain thrust crosses a cross-fault and climbs a few tens of meters in elevation. However, the footwall of the thrust changes abruptly here from the Stony Point facies basinal shale to autochthonous Beekmantown Group carbonates, an order of magnitude larger displacement. A few kilometers to the south, the next thrust to the east, the Shoreham thrust, intersects a small, km^2, basin of Stony Point-facies shale and we propose that the Main Champlain thrust ramps up across the northeast striking normal fault that bounds the western margin of the basin. This is because, south of this place, the Shoreham thrust continues as the basal thrust of the system, and the lower thrust (Orwell, or Main Champlain) is not present, so its displacement must have been transferred up the lateral ramps to the Shoreham thrust by these cross-fault structures. The Benson example underscores behavior of the thrust system also exhibited near Shoreham. In the northern portion of the area the Main Champlain thrust transported massive Providence Island facies dolostones. In contrast, in the southern portion of the area the Main Champlain thrust transported Whitehall facies. South of the amalgamation of the Champlain and Shoreham thrusts, the footwall of the Shoreham thrust is autochthonous Beekmantown Group, but the hanging wall is far-traveled Providence Island facies. Thus, from north to south, the Main Champlain decreases in net transport while the Shoreham thrust increases. We propose that the cross-faults at Benson and Shoreham not only control the distribution of map units due to their prethrust origin but, once reactivated, kinematically partitioned the thrust system by controlling where thrusts decreased and increased transport, transferring displacement from one thrust to another. This behavior is found worldwide where thrusts reactivate earlier structures (e.g. Brown et al., 1999; Butler, 1997; Thomas, 1990).

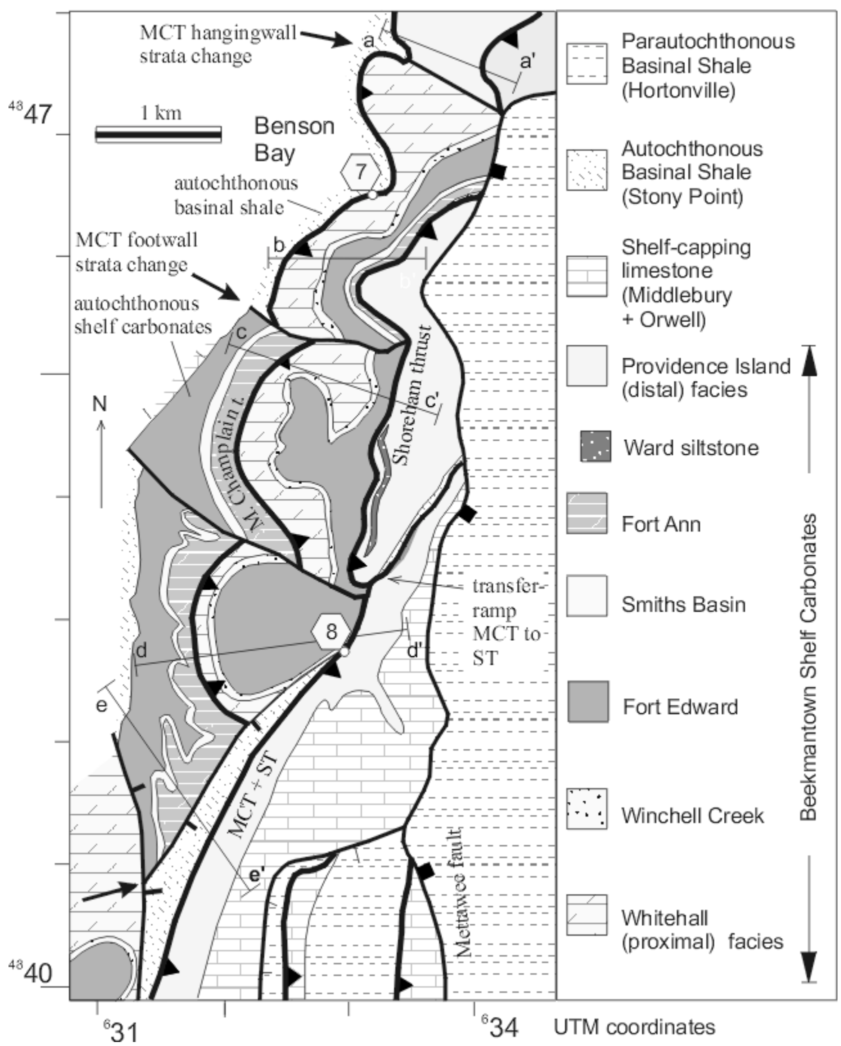

Figure 7. Detailed geologic map of the Benson Bay area with the trace of thrusts and detailed stratigraphy shown. Geologic relationships demonstrating interaction with and/or reactivation by thrusts, of Ordovician normal faults, are indicated.

Two clear examples of ramping of the Champlain thrust system across preexisting normal faults are also exhibited at the southern end of exposed parautochthonous shelf rocks near Whitehall, NY (**figure 9**). In this area the belt of flysch and mélange to the east of the Champlain thrust system changes from north to south, from dominantly shelf limestone thrust slices with thin shale-mélange fault zones to carbonate-deficient shale-dominated mélange. We suspect that this is also a product of the thrusts intersecting a shelf dissected by Ordovician-age flexural normal faults. Farther south, near Fort Ann, the Champlain thrust-transported shelf rocks disappear from map view entirely, though thrusts continue south in the mélange and flysch (Kidd et al, 1995). The cross-faults in the Champlain thrust system cut the entire middle Ordovician shelf section, and the base of the overlying basinal shale/flysch section. Therefore, these faults must be middle Ordovician in age, yet predate the formation of the thrust faults. The prethrust faults thus belong to the generation of faults mapped in theautochthonous Mohawk Valley area (Cisne et al, 1982;

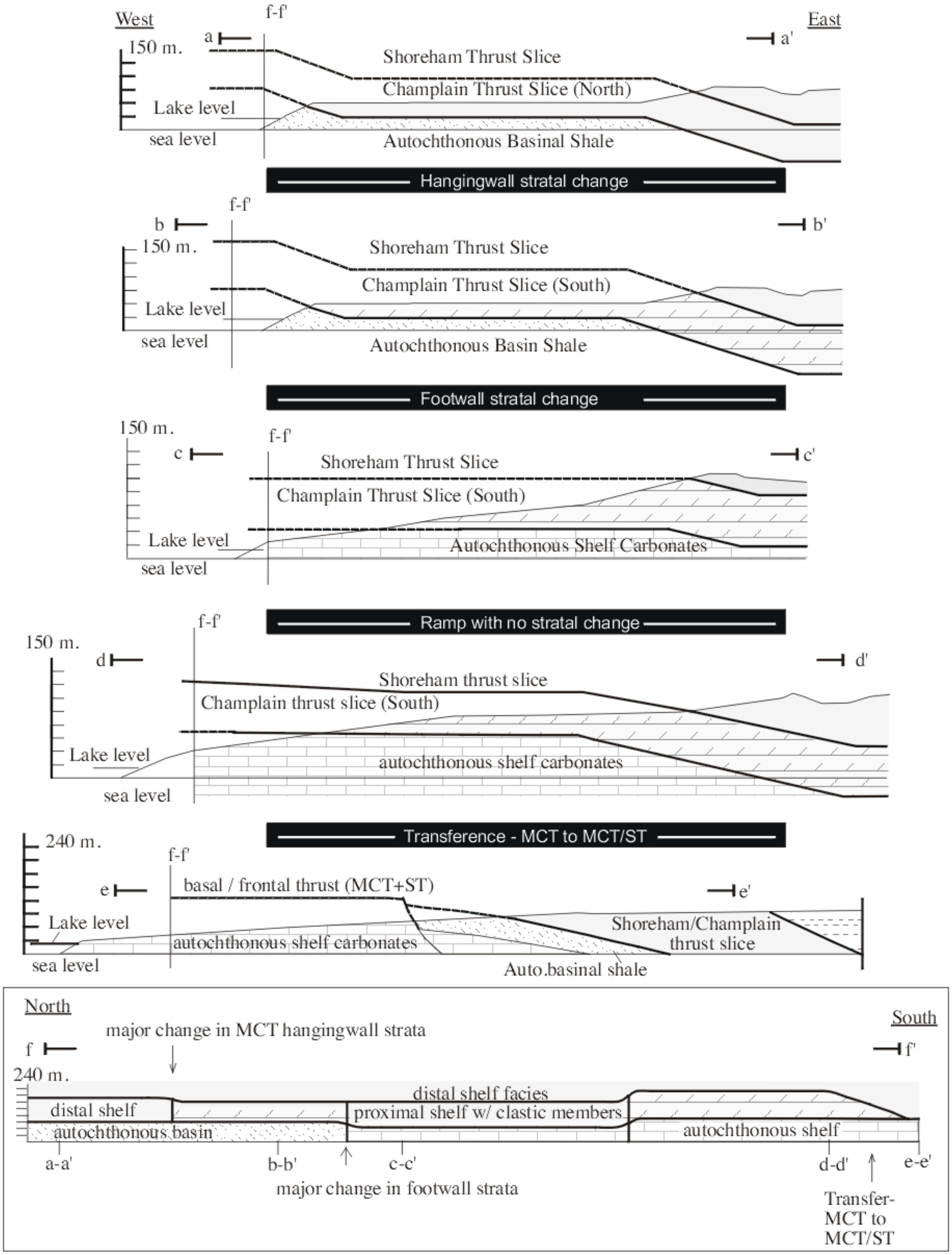

Figure 8. Cross-sections from north to south, and along-strike, for figure 7 - the Benson Bay region.

Bradley and Kusky, 1985). In the Mohawk Valley these faults formed between the flexural forebulge and the trench, and strike roughly NNE (parallel to the paleotrench), dip ESE (towards the paleotrench), and increase in throw to the east (towards the paleotrench). The cross-faults in the Champlain thrust system strike oblique to the thrust front and therefore must have been linking faults within the prethrust fault system, and not the dominant trench-parallel faults. Reactivation of trench-parallel parallel faults tends to form frontal ramps in thrusts that are rarely exposed (Baker et al., 1988; Butler, 1989) and can only be resolved by the deficit in restorable transport. Many of the slivers of carbonates, shale, and mélange within the Champlain thrust system may indicate such frontal ramp formation. However, we propose that the larger scale map pattern of this region provides a more impressive example of reactivation of prethrust, trench-parallel normal faults as frontal thrust-ramps. To explain this relationship we have to briefly outline our map and interpretation of the eastern boundary of the Champlain thrust system.

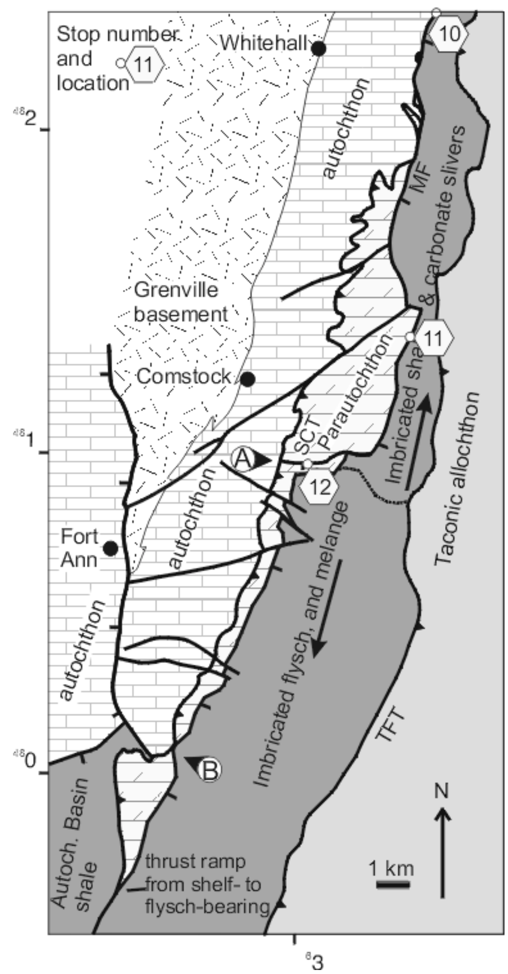

Figure 9. Generalized map of the trace of thrusts and normal faults in the Whitehall area, New York, between the Taconic frontal thrust (TFT) and the autochthonous Cambro-Ordovician shelf sequence. This is the northern end of the extensive Taconic flysch basin of the Hudson Valley. The Champlain thrust system continues through this basin as flysch-bearring thrusts (Kidd et al., 1995). At points marked with labeled triangles, the westernmost thrust of the Champlain system (SCT) climbs section abruptly (A), and changes footwall lithology (B), across faults with normal sense slip prior to thrusting. MF - Mettawee (normal) fault. Geology modified after compilation by Fisher (1985).

East of the Champlain thrust system

The contact between the limestone and shale in the Taconic foreland is a regional unconformity that changes stratigraphic level across the shelf and flexural forebulge. Near Whitehall, NY, the contact is a normal fault that cuts the Champlain thrust system, and cuts the cleavage planes in the overlying shale and mélange. The Mettawee fault (Fisher, 1985) is only locally exposed, and in places has been traditionally mapped as the regional unconformity. We have been able to trace the Mettawee fault through the Champlain Valley where it (*i*) places cleaved Hortonville shale against only moderately strained Middlebury and Orwell limestone and Stony Point shale, (*ii*) cuts thrusts, and (*iii*) is locally exposed or constrained to be a normal fault due to moderate to high dips and a younger-over-older stratigraphic relationship. The Metawee fault is a significant structure in that it is the only recognized post-Taconic extensional structure in the area. There is a growing understanding of the several Paleozoic and Mesozoic extensional phases to affect New England (Hames et al., 1991), though we do not yet know the age of the Mettawee fault and therefore cannot relate it to a particular phase.

A consequence of the Mettawee fault is that it minimizes the apparent separation between the Champlain thrust system and rocks to the east. Furthermore, it eliminates at least one additional Champlain thrust slice from map view, and could eliminate several others (**figure 10**). East of (above) the Mettawee fault, north of the NY-VT border at the Poultney River, is a wide belt of shales, slates, mélange, and other pelites. Though this belt likely contains tectonically mixed Cambrian-early Ordovician slates and middle Ordovician pelites, the only clearly mappable contact within it is the Sunset Lake thrust that places the Sunset Lake slice over Hortonville shale (Zen, 1967). The Sunset Lake slice contains Cambrian through middle Ordovician arenites and pelites that are stratigraphically correlative with rocks found within the main Taconic allochthon (Zen, 1967, 1972). Though the Sunset Lake slice is a south-plunging syncline, this fold pattern is related to an early phase of thrusting that is cut to the east by a mélange and shale-bearing thrust. Thus, the *east* margin of the Sunset Lake slice is the Taconic frontal thrust that cuts the *west* margin of the main allochthon to the south (Bosworth et al., 1988). The Taconic frontal thrust continues north of the Sunset Lake thrust where it locally carries small slivers of allochthonous slate but is otherwise untraceable.

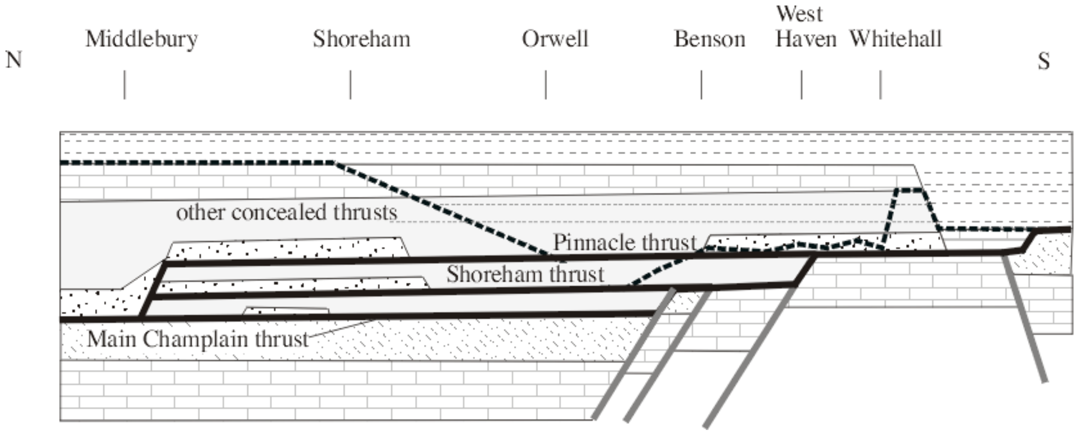

Figure 10. Along-strike cross-section across figure 4 demonstrating the change in stratigraphic level of thrusts across transverse cross-faults. The Mettawee fault is drawn with a dashed line, and the geology now cut-out by the fault is interpreted.

East of the Taconic frontal thrust is a local thrust system in carbonates and shales, the Sudbury slice (Voight, 1965; Zen, 1972). Though highly strained, the rocks in this area are in stratigraphic terms roughly correlative with the rocks found within the Champlain thrust system and they contain locally exposed stratigraphic contacts between Providence Island facies dolostones and overlying Middlebury/Orwell limesones, and between the limestones and overlying Hortonville shale.

The structural position of this slice above the Sunset Lake slice but below the main allochthon is an unresolved restoration problem in the Champlain Valley that was initially explained with the model of gravity sliding that was in vogue in the 1960's and 1970's (Bird, 1969; Zen, 1972). However, even Zen (1972) seemed to find such an explanation unacceptable and his discussion alluded to a model wherein the Sudbury slice was separated from its correlatives to the west before the Taconic allochthon was emplaced. We agree with this assessment, and we speculate that the Sudbury slice was initially a horst on the outer shelf produced by the same phase of synconvergence prethrust faulting that affected the western portions of the foreland. This would require the presence of a foreland (west)-dipping normal fault in addition to one or more major east-dipping faults; faults with this sense of throw are not common, but recognized, in such a setting (Bradley and Kidd, 1991; Scisciani et al, 2001). It is difficult to confirm this restoration problem due to the combined effects of the Mettawee fault and Taconic frontal thrust. However, the separation between the Main Taconic allochthon and the Sunset Lake slice does not match the separation between the Sudbury slice and the Champlain thrust system, indicating that even with the added separation of the Mettawee fault, some prethrusting separation of the Sudbury and Champlain thrust system is required. Thus, we propose that the Sudbury thrusts developed a frontal ramp on an outer shelf normal fault, but otherwise soled at depth into the same detachment as the later Champlain and Taconic frontal thrusts.

Discussion / Conclusion

Our maps and interpretations of the Taconic foreland have several implications for collisional tectonics and the regional geology of the Champlain Valley. Firstly, as noted by Bradley and Kidd (1991), synconvergence faulting along the flexural forebulge, demonstrates that the strength of lithosphere can be reached via elastic flexure (Ussami et al., 1999) producing large-scale extensional structures in an otherwise contractional field. The patterns of foreland sedimentation and thrust-development were influenced by the pre-collisional, but synconvergence phase of deformation, with local fault-bounded basins controlling the sites of deposition of particular carbonate or flysch facies.

We find that most of the deformation in the foreland can be explained by the model of frontal accretion and underplating, and, that given the protracted evolution of the foreland, the multiple generations of thrusts can account for the multiple generations of folds and cleavages as well. The foreland thrusts must form a decollement that extends beneath the Green Mountain crystalline core of the orogen and the thick-skinned portion of the thrust belt must restore to an equivalent position eastward. One might speculate that the localization of this decollement might also have nucleated on a preexisting mid-crustal detachment produced by the earlier normal fault system (Bradley and Kidd, 1991).

Even at the more speculative fringes of our interpretation there are still untouched problems in the Taconics. For example, we have little control on the age of the Mettawee fault and therefore do not know if the orogen reached a configuration that might have induced extension, or if extension was imposed by later Paleozoic or Mesozoic phases. Furthermore, although the Taconic deformation front passes beneath the Silurian-Devonian cover near Albany, NY, we cannot exclude the possibility that some of the deformation in the Taconic fold-and-thrust belt was Devonian in age, part of the Acadian event (Hames et al., 1991; Chan and Crespi, 2001; Hayman, 2001). Nonetheless, we prefer our map and model of the Taconic foreland to older alternatives (e.g. Doll et al, 1961) and think it is most consistent with the data, and with modern models of collisional tectonics.

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ROAD LOG

Participants arriving early Friday from MA, CT, RI, Quebec, VT, NH, ME and points farther east should choose their own direct way to the meeting point of the field trip, in Shoreham, VT, at the Mobil station at the intersection of Routes 22A and 74 east. For those staying Thursday night in Lake George, take Route 9 south to the intersection with 149; turn left.

From south: take Exit 20 northbound ramp from Interstate 87; turn left at light at end of exit ramp; go north ~0.4mi to intersection of Route 9 and Route 149 at light turn right onto 149

From north: take I-87 Exit 20 southbound ramp, turn left at end of ramp; go ~0.1mi to intersection with Route 9; turn left at light; go north ~0.5 mi to light at intersection of Route 9 and Route 149; turn right.

	Mileage Increment	Mileage Total
Intersection of Route 9 and Route 149 at light; go east on 149	0.0	0.0
Intersection with Route 4 in Fort Ann; turn left onto Route 4 at light	11.5	11.5
Follow Route 4 across intersection (with light) with Route 22 (east/south) at Comstock	3.8	15.3
Turn half right at light in Whitehall following Route 4 at junction with Route 22 (north)	6.7	22.0
NY-VT border (Poultney River)	6.3	28.3
Take Exit 2 ramp from Route 4	1.5	29.8
End of exit 2 ramp; intersection with Route 22A; turn left onto 22A north	0.2	30.0
Intersection with Route 73 by Orwell; continue north on 22A	14.3	44.3
Intersection with Route 74 (west) in Shoreham; continue north on 22A	6.2	50.5
Intersection with Route 74 (east) in Shoreham; turn right into Mobil station	0.4	50.9

STOP 0 - Meeting Point of Field Trip A-7

From intersection of Route 74 (east) and Route 22A, turn left and go south on 22A		
Intersection with Route 74 (west); turn right onto 74 (west)	0.4	51.3
Leave Route 74, going straight ahead onto Watch Point Road	0.4	51.7
Park on right at Slateledge Farm.	0.7	52.4

STOP 1 - Orwell/Main Champlain Thrust at Shoreham – ASK PERMISSION AT SLATELEDGE FARM

Continue west on Watch Point Road to intersection with Basin Harbour Rd; turn right	0.5	52.9
Turn to half right onto N. Cream Hill Road	1.2	54.1
Intersection with Lapham Bay Road; turn right	1.8	55.9
Intersection with Route 22A; turn right	0.8	56.7
Park on right at end of driveway - PARK COMPLETELY OFF THE HIGHWAY	1.1	57.8

STOP 2 - Potsdam/Ticonderoga quartzites/arenites at base of Shoreham Thrust Duplex – ASK PERMISSION AT THE GARAGE, OR AT THE HOUSE ON THE CORNER OF THE 74/22A INTERSECTION

Continue south on Route 22A into northern part of Shoreham village; turn left into vast parking area 100 yards before Route 74 (east) intersection.	1.2	59.0

STOP 3 - Middlebury Limestone in the Shoreham Duplex

From the parking area, turn left out onto Route 22A		
Pass intersections with Route 74 (east) [0.1 mi] and Route 74 (west) [0.5 mi]; then turn left at intersection onto Richville Road	0.9	59.9
Junction with N. Orwell Road on the right; parking area on the left, opposite the junction	2.1	62.0

STOP 4A - Potsdam quartzites of the Pinnacle Thrust slice adjacent to the Lemon Fair Fault

Continue east on Richville Road; across the bridge, turn sharp left onto Buttolph Rd.	0.1	62.1
Park at roadside next to the roadcut	0.1	62.2

STOP 4B - Carbonates adjacent to the Lemon Fair Fault, and just beneath the Pinnacle Thrust

Continue along Buttolph Road; turn right at intersection to follow it	0.2	62.4
Turn right onto Philion Road	0.1	62.5
Take half left returning to Buttolph Road	0.2	62.7
Turn right onto Richville Road	0.05	62.75
Intersection with Route 22A; turn left	2.2	65.0
Intersection with Route 73 by Orwell; turn right onto 73	5.7	70.7
Go straight onto Mt Independence Rd, leaving Route 73	0.4	71.1
Turn left at intersection onto Bascom Road	1.3	72.4
Turn right at intersection with Stevens Orchard Road	0.5	72.9
Park at roadside by house and barn	1.0	73.9

STOP 5 - Champlain/Orwell Thrust at Stevens Orchard

Continue to end of road at orchard buildings,and turn around	0.4	74.3
Continue straight, past Bascom Road junction on left	1.4	75.7
Park on right, before curve to right and roadcut	0.3	76.0

STOP 6 - Shoreham Thrust near Orwell

Continue to intersection with Old Stage Road; turn right	0.2	76.2
Junction with Singing Cedars Road; turn right	1.8	78.0
Park on right near house and barns	1.2	79.2

STOP 7 - Orwell/Main Champlain thrust sheet at Benson Bay/Blue Ledge

Go down to end of road at Benson Bay boat launch; turn around	0.1	79.3
Return to Old Stage Road; turn right	1.3	80.6
Junction with Frazier Hill Road (and N. Cross Road); turn right	0.7	81.3
At bottom of hill, left turn at junction with Turkey Farm Road	1.5	82.8
Junction with N. Lake Road; turn left	0.9	83.7
Park on roadside; enter field on south side through gate	0.2	83.9

STOP 8 - Shoreham Thrust and end of Orwell/Main Champlain Thrust near Benson Landing – AFTER GETTING PERMISSION AT FARM ON N. LAKE ROAD 0.4 MILES WEST OF FRAZIER HILL ROAD JUNCTION

Continue east/south on N. Lake Road to intersection with Lake Road;	1.8	85.7
Go across and continue south, now on Park Hill Road; this changes name again to Best Road before coming to:		
Junction with Main Road (aka West Haven Turnpike); turn right	3.7	89.4
Junction with Book Road in West Haven; turn left	0.9	90.3
Park on right near entrance to private unpaved road	0.3	90.6

STOP 9A - Shoreham Thrust at West Haven, and

STOP 9B - Mettawee River Fault at West Haven - ASK PERMISSION AT BOOK FARM BEFORE ENTERING - FIND BOOK FARM ALONG BOOK ROAD 1.1 MILES SOUTH OF STOP

Continue south along Book Road; pass Book Farm	1.1	91.7
Poultney River Bridge; NY-VT border; road changes name to Sciota Road	0.6	92.3
Junction with County Route 11; turn right	2.5	94.8
Junction to left with Stalker Road [no sign]; turn left	2.0	96.8
Junction with Fair Haven Turnpike [no sign]; turn left	0.5	97.3
Park just before junction on right with Buckley Road [no sign]	1.0	98.3

STOP 10 - Pinnacle/Comstock Thrust, and Mettawee River Fault, at Fish Hill - OBTAIN PERMISSION FROM HARMONY HILL FARM [0.5 MILE DOWN BUCKLEY ROAD FROM JUNCTION; enter field to north through gateway/over electric fence

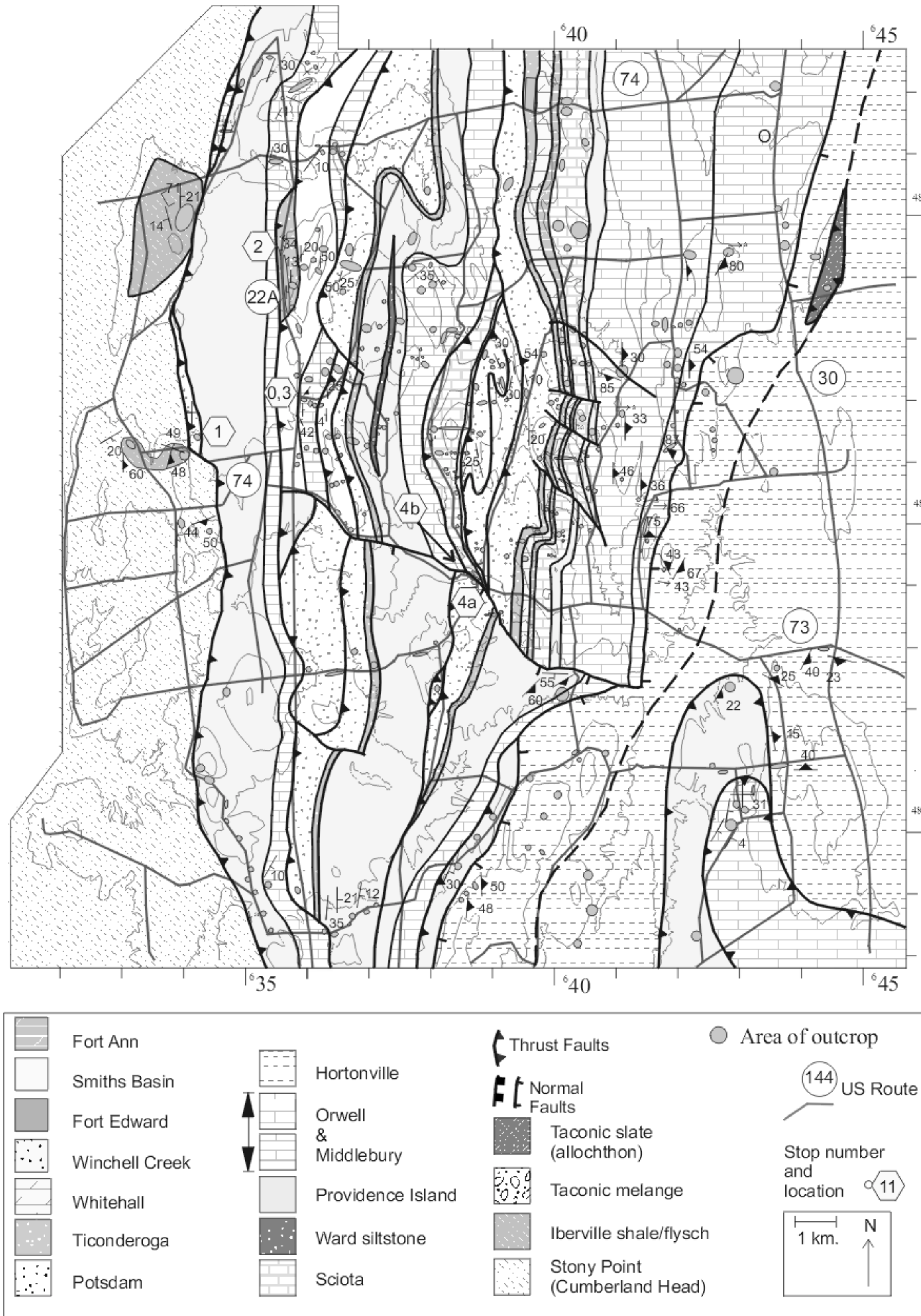
Turn right onto Buckley Road, pass Harmony Hill Farm	0.5	98.8
Junction with Route 4; turn right	1.3	100.1
Junction at light with Williams/S. Williams Street; turn left	0.7	100.8
Continue straight onto Upper Turnpike, leaving County Route 12 (turns sharp left)	1.6	102.4
Mettawee River Bridge [slowly!!]	0.3	102.7
Follow paved road - Upper Turnpike - sharp left, blind hill crest, sharp right	0.7	103.4
Follow paved road - sharp left at junction with dirt road	0.7	104.1
Follow paved road - sharp left, blind hill crest, sharp right	2.5	106.6
pavement ends	0.2	106.8
Pull into parking area on left, just beyond low point in road	0.3	107.1

STOP 11 - Mettawee River Fault at the type locality - NO HAMMERS/SAMPLING - NYDEC REGULATIONS

Continue south on Upper Turnpike; pavement resumes	0.6	107.7
Turn half-right at intersection [NOT 3/4 right] onto Sheehan Road Extension	0.3	108.0
Junction with Route 22; Stop, then cross onto Route 40	0.3	108.3
Intersection onto County Route 17 [no name; direction sign to West Granville]; turn right	0.5	108.8
Junction with Dewey's Bridge Road; turn right	1.1	109.9
Park at roadside; Tyler Farm, house on right, barn on left.	1.7	111.6

STOP 12 - Pre-thrust normal fault in Comstock/Pinnacle Thrust slice at Tyler Farm - ASK PERMISSION AT TYLER FARM

Continue west on Dewey's Bridge Road; follow sharp left bend near Champlain Canal	2.1	113.7
Bridge over Champlain Canal	2.6	116.3
Railroad crossing at grade	0.1	116.4
Crossroads junction with Route 4 and Route 149 in Fort Ann; go across onto Route 149	0.1	116.5
Junction of Route 149 with Route 9; turn right for Lake George Village; end of log	11.5	128.0



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Fort Edward
Winchell Creek
Whitehall
Ticonderoga
Potsdam
Hortonville
Orwell
&
Middlebury
Providence Island
Ward siltstone
Sciota
Thrust Faults
Normal Faults
Taconic slate (allochthon)
Taconic melange
Iberville shale/flysch
Stony Point (Cumberland Head)
Area of outcrop
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Stop number and location
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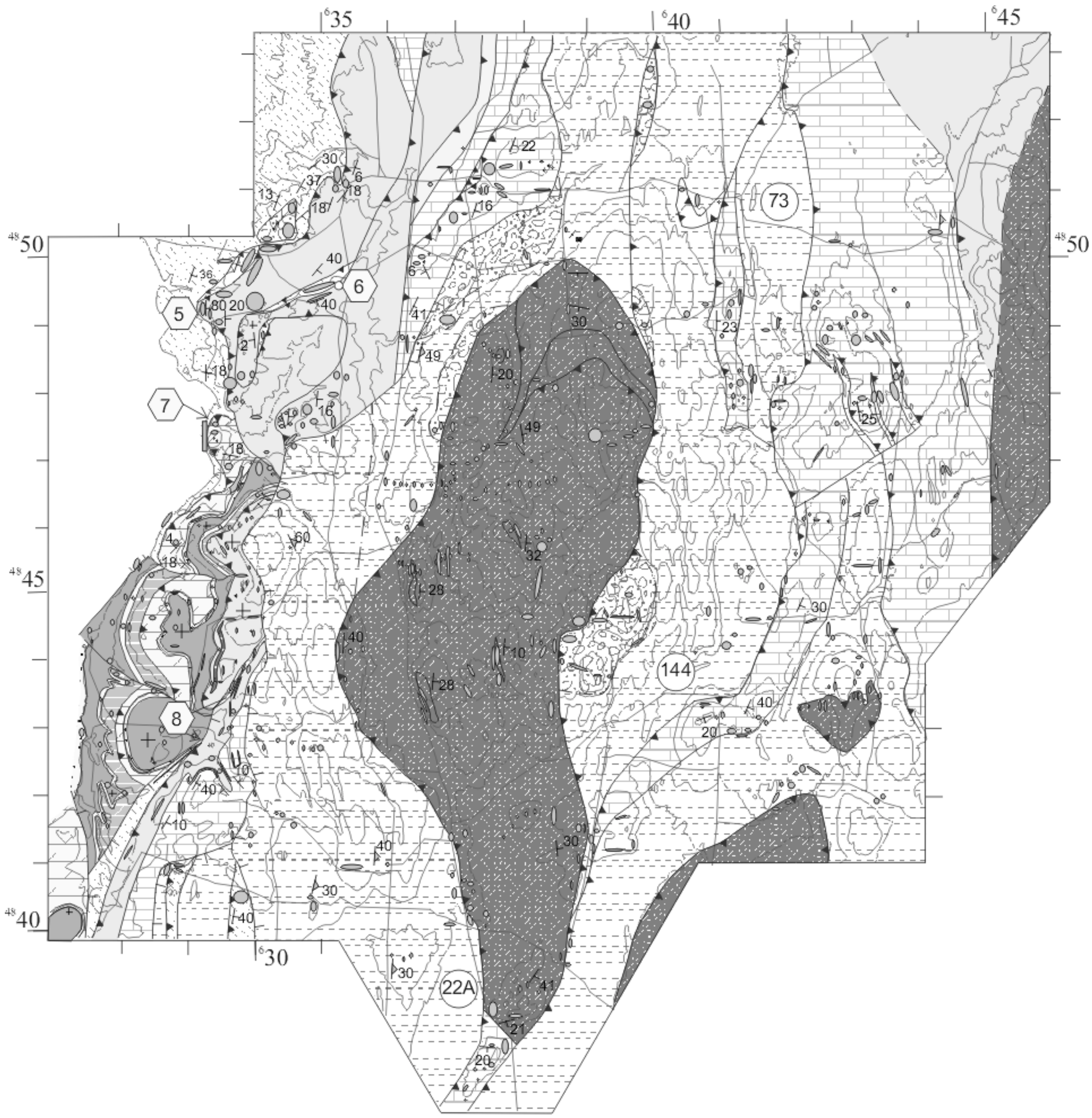

Figure RL-1. Outcrop and geologic maps of the Shoreham and Benson regions with field trip stops 1-8 indicated.

STOP DESCRIPTIONS

STOP 1 - Orwell/Main Champlain Thrust at Shoreham

ASK PERMISSION AT THE FARMHOUSE to visit this outcrop. Unplanned encounters with an unfriendly bull may result if you ignore this instruction.

From Slateledge Farm house, walk east along the road passing the track to the barn nearest the house, and take the next track which heads toward the low ridge extending north from the second barn. About 100 meters from the road, small exposures of dark grey shales/slates occur at the side of the track. After passing a fence line (and maybe crossing an electric fence across the track, small exposures of steeply east-dipping calcareous dark shale, and more extensive loose material, occur on the western slope of the ridge [43º 53.740'N, 73º 19.723'W]. Based on lithic correlation, these are mid-Ordovician in age, termed Stony Point Formation in this region. They represent the transition to deep-water deposition from the previous shallow passive margin carbonate sedimentation as the Laurentian margin subsided rapidly on entering the Taconic subduction system. On top of the ridge here are outcrops of pale tan-weathering, grey quartzite, gently east-dipping at this position, becoming flat and then moderately west-dipping in a small ramp anticline on going north along the ridge. This quartzite is identified as Potsdam Fm., of mid-Cambrian age. The westernmost major thrust of the Champlain Thrust System at this latitude is located between the quartzite and the dark shale. This fault to the north of the Shoreham area is termed the Champlain Thrust; in the area of Shoreham, where several major splays occur, this one has been called the Orwell Thrust, although we have placed the name "Main Champlain Thrust" on it. The fault surface itself is not exposed here, although the position can be constrained to an interval less than 10 meters wide. Looking east from the ridge towards Shoreham village, no outcrops occur in the lowlands, but extrapolation from outcrops along strike imply that this belt is underlain by Cambrian-early Ordovician Beekmantown carbonates, largely dolostones, which are stratigraphically above the Potsdam. In Shoreham Village, and farther east, imbricate slices of the Shoreham and Pinnacle Thusts occur, which are examined in subsequent stops. To the west, the Champlain lowlands, under the blanket of Quaternary lake clays, contain a few outcrops of mid-Ordovician shaly strata which are the Taconic trench/foredeep sediments. Walk back to the road, and slates, siltstones and fine-grained greywacke arenites of these mid-Ordovician flysch sediments can be seen in outcrops by the road opposite the farmhouse, and in the small quarry adjacent [43º 53.639'N, 73º 19.832'W]. A well-developed moderately east-dipping slaty cleavage cuts moderately NW-dipping bedding, and excellent slate pencils formed by this oblique intersection weather out. The bedding strikes obliquely towards the N-S trace of the Main Champlain Thrust . We infer from the strong cleavage and down-plunge lineation that this is probably an imbricate thrust slice attached to and considerably transported by the Main Champlain Thrust; more autochthonous flysch west of the Champlain Thrust in this region tends not to have prominent cleavage.

STOP 2 - Potsdam/Ticonderoga quartzites/arenites at base of Shoreham Thrust Duplex

This stop has DANGEROUS TRAFFIC CONDITIONS (high speeds and limited sight distance) - please park as far off the paved road as possible, be extremely careful crossing the road, and do not stand on or step into the pavement when contemplating the outcrop.

From the parking place specified, cross the road and walk north to the roadcut [43º 55.241'N, 73º 18.743'W]. Pale tan-weathering, grey, well-indurated quartzites and local dolomitic arenites dip gently east. These can be identified as either the upper part of the Potsdam and/or the arenite-rich part of the overlying unit, the Ticonderoga Fm. Small-scale cross-bedding occurs locally. Mapping shows that they form an imbricate slice on the Shoreham Thrust. In this area near Shoreham, the Shoreham Thrust Slice is a complex imbricated stack of slices, forming the Shoreham Duplex.

STOP 3 - Middlebury Limestone in the Shoreham Duplex

ASK PERMISSION to park and view this outcrop AT THE GARAGE, OR AT THE HOUSE ON THE CORNER OF THE 74/22A INTERSECTION.

From the east side of the parking area, walk to the north-east corner, then go east to the nearest outcrop. This is massive limestone, showing a fairly well-developed steep east-dipping cleavage in places. About 50 meters east of the first outcrop, another ridge of limestone [43º 54.144'N, 73º 18.377'W] contains locally prominent large coiled gastropod fossils, probably *Maclurites*, which is common in autochthonous sections of Chazy Group mid-Ordovician limestones. In these transported rocks this limestone is usually termed Middlebury Limestone. These outcrops map as imbricate slices within the Shoreham Duplex. Recent expansion of the parking area has unfortunately resulted in the best outcrop being buried by bulldozed trees, soil and trash. If time is short, or permission is refused, a smaller roadcut outcrop of this limestone can be viewed just east of the Mobil Station parking lot on Route 74 east, but the gastropods are not clearly seen there.

STOP 4A - Potsdam quartzites of the Pinnacle Thrust slice adjacent to the Lemon Fair Fault

From the parking place, cross the road, and view tan-weathering, grey indurated quartzites, locally dolomitic, of the Potsdam Fm. East of the intersection [43º 52.386'N, 73º 16.321'W] they dip steeply southwest; in the outcrop west of the intersection, they dip gently southwest. The monoclinal fold outlined by this dip change, and the oblique strike, we interpret as due to proximity to the Lemon Fair Fault, and the lateral ramp it defines in the thrust geometry. These quartzites are regionally part of the Pinnacle Thrust Slice; this thrust is not exposed here, but its position can be constrained by mapping to the south. The Lemon Fair Fault runs here along the river; looking across from the parking place, limestones on the other side of the fault can be seen at the base of the old bridge abutment. The outcrop of Stop 4B is just beyond this through the trees.

STOP 4B - Carbonates adjacent to the Lemon Fair Fault, and just beneath the Pinnacle Thrust

Roadcut outcrop [43º 52.398'N, 73º 16.280'W] of limestones, dolomitic limestones, and minor dolostones which are adjacent to the Lemon Fair Fault. The generally rather fractured appearance, and the common presence of calcite veins, are indicative of this proximity. The dominant fractures and veins strike NW, dipping steeply north to vertical, subparallel with the Lemon Fair Fault. One vein shows prominent steeply pitching slickensides. These rocks are part of a slice of early-mid Ordovician limestone-dominated carbonates localised immediately under the Pinnacle Thrust in the area north of the Lemon Fair Fault, but not present to the south. This and other substantial changes in structural geometry that occur across the Lemon Fair Fault show that it was used as a major lateral ramp structure by the thrusts of the Champlain System. Because facies and stratigraphic thickness variations only occur in mid-Ordovician units across this structure, we infer that it was generated as a mid-Ordovician cross-strike "flexural" normal fault, and then converted to use as a lateral ramp in the Champlain Thrust System.

STOP 5 - Champlain/Orwell Thrust at Stevens Orchard

Walk up the road from the parking place by the house and barn/garage. On the east side, an outcrop of calcareous dark shale/slate, with a local phacoidally cleaved fault zone, is mid-Ordovician Stony Point Formation. Farther up on the same side just above a driveway there is a smaller outcrop and loose material of the same unit. About 20 feet above this, seen in the roadcut and the ridge going south from it, are dolostones of the Beekmantown Group forming the base of the Main Champlain (or Orwell) Thrust here. A little farther up on the north side of the road [43º 47.077'N, 73º 20.586'W], similar dolostones, showing not very prominent medium to thick-bedding and homogeneous brown-weathering, are exposed. This outcrop also shows the characteristic "fretted" weathering pattern produced by differential removal of abundant narrow calcite veins that are ubiquitously and abundantly developed in these transported dolostones, but are not usually seen in autochthonous dolostone sections in areas to the south. Dolostones like these form all of the body of both the Main Champlain (Orwell) and Shoreham Thrust Slices at this latitude; the Potsdam quartzites are absent because the thrusts have ramped up laterally to within the late Cambrian-early Ordovician carbonate section. Rocks like these are conventionally termed "Providence Island Formation", but we have little confidence that this is stratigraphically meaningful in the sense of strict correlation to the type section on Providence Island. The map pattern of the Main Champlain Thrust in this local area shows that it is very gently east-dipping, or almost flat.

STOP 6 - Shoreham Thrust near Orwell

On the corner with the roadcut outcrop [43º 47.439'N, 73º 19.236'W], east of the parking spot specified, deformed calcareous shales ("Stony Point Fm") make up most of the exposure, although at the western end a contact can be observed with fractured tan-weathering Beekmantown (late Cambrian/early Ordovician) dolostone above the shales. This dolostone forms a low ridge in the woods that parallels the road westwards to beyond the Bascom Road junction and, back along the road in this direction, smaller outcrops of both calcareous and non-calcareous deformed shales can be found locally, with dolostones near or in contact above the shales. The thrust fault defined by this contact is the Shoreham Thrust; the local map pattern demonstrates that this fault also is near flat-lying here. As for the Main Champlain Thrust, the absence here of Potsdam Fm is due to the thrust climbing section southwards, in part across the lateral ramp structure of the Lemon Fair Fault. A much better, even excellent outcrop of this fault exists 20 meters west into the woods near the end of Wilcox Road, about 1.0 mile SW of this outcrop, but the current landowner is most unwelcoming and is quick to display a gun.

STOP 7 - Orwell/Main Champlain thrust sheet at Benson Bay/Blue Ledge

ASK PERMISSION AT THE HOUSE.

The main part of the outcrop visible from the parking area is now only accessible through the pig mud wallow, unfortunately. We recommend viewing it from the road, from where the nearly flat-lying well-defined planar bedding in the dolostones is clearly seen. To see rocks closer up, walk east along the road, to a large oak tree on the corner [43º 45.889'N, 73º 20.399'W], and then go into the bushes a short distance where the same well-bedded sugary-textured dolostones continue to outcrop. Here the existence of common dark chert as nodules and patches in the dolostones can be seen, both in the outcrop and in the talus fragments. This unit is clearly identifiable in the Beekmantown stratigraphy of Fisher (1985) as the Whitehall Formation. Nearby, on White Ledge, the cliff visible to the east of the road, more Whitehall Formation is exposed; above it one can find in the woods good outcrop that shows overlying Beekmantown units matching those of Fisher (1985), including the unmistakeable Winchell Creek cross-bedded arenites. Structurally, we are back down in the Main Champlain Thrust slice (the fault is well-constrained by outcrop on Blue Ledge a few hundred meters to the northwest of this outcrop), yet the whole section carried by the Thrust here is utterly different from the homogeneous, poorly-bedded, veined dolostones at and just south of Stop 5, no more than 1-2 km. away. We identify this change to occur across a NW-trending valley just to the northeast of this stop location, and interpret this to be a lateral ramp in the thrust system inherited from a flexural Ordovician normal fault. The change in the shelf facies that occurs in the "Main Champlain" Thrust sheet here is by far the most pronounced anywhere, and it must represent a very substantial relative distance (we think many tens of kilometers) between the sites of detachment of the stratigraphic sequences north and south of this change. Because the sequence in the MCT slice from here south so closely matches the autochthonous stratigraphic sequence defined by Fisher (1985), we think it is unlikely to have been displaced very far (<10km?). Because it is likely the MCT to the north has significantly larger displacement (at least several tens, and perhaps >80km - Rowley, 1982) we think there must be a large displacement transfer here from the MCT north of this site, along the lateral ramp fault up to the next thrust, the Shoreham Thrust. Not only is there a substantial change in the MCT hanging wall here, but the footwall also contains a similar (and we think closely related) feature about 1 km. SW of this stop. There is an abrupt change, from mid-Ordovician shales and calcareous shales of the Stony Point Fm as the footwall strata, to an autochthonous shelf carbonate/clastic section of the "Whitehall" sequence. This change takes place across a mapped cross-fault which affects the MCT as a small-offset lateral ramp/tear fault, but which has a much larger stratigraphically-defined offset in the footwall. We think this is also a mid-Ordovician normal fault used soon after to localise a ramp in the lowest part of the thrust system.

STOP 8 - Shoreham Thrust and end of Orwell/Main Champlain Thrust near Benson Landing

GET PERMISSION AT FARM ON N. LAKE ROAD 0.4 MILES WEST OF FRAZIER HILL ROAD JUNCTION
This stop may be omitted if time becomes short.
Enter field on south side of road [43º 43.781'N, 73º 20.562'W] through gate [OPEN AND CLOSE IT BEHIND YOU - PLEASE DON'T CLIMB OVER IT]

About 50 meters from gate [43º 43.751'N, 73º 20.599'W] dark calcareous shales of Stony Point Fm. Follow the track on the east side of the valley for another 50 meters or so; small outcrops of calcareous shales occur at the foot of the ridge to the east, while massive fractured dolostones occur up the slope and at the crest of the ridge. This defines the Shoreham Thrust here (to the south this has been called the Shaw Mountain Thrust). On the hillsides and tableland to the west of this valley, on a longer walk than we have time for, flat-lying shelf strata of "Whitehall facies" that map in the MCT slice are sparingly exposed; there has to be a normal fault bounding these against the Stony Point Fm. shales which continue down this valley in and near the stream. The Main Champlain Thrust terminates against this normal fault, and is not present farther south. We think that this normal fault originated as an Ordovician "flexural" normal fault, and was subsequently reactivated with reverse displacement sense and used by the Champlain Thrust System as a "terminal ramp" including the transfer of the residual displacement on this southernmost part of the MCT up to the Shoreham Thrust.

If desired by those on independent schedules, continue walking down the valley until the stream enters a continuous section exposing dark calcareous shales [43º 43.575'N, 73º 20.934'W]. Outcrops of near flat-lying dolostones (Fort Edward) or cross-bedded arenites (Winchell Creek) are found on the northwestern slope of the valley, e.g. dolostones at [43º 43.636'N, 73º 20.895'W], at an elevation significantly above the shales in the stream bed.

STOP 9A - Shoreham Thrust at West Haven

From the parking place [43º 38.727'N, 73º 20.888'W] walk about 120 meters south along Book Road [43º 38.663'N, 73º 20.929'W] to roadcut on east side. In the center portion of this exposure, black non-calcareous shale (mid-Ordovician) up to 1 meter thick, with a pronounced phacoidal cleavage indicative of large shear strain, occurs below a sharp contact with highly fractured massive dolostones ("Providence Island" lithology). This is the Shoreham Thrust, and mapping of the surrounding area shows unequivocally that it is here the westernmost thrust in the Champlain System - in other words that the "Main Champlain Thrust" farther north has disappeared. To the south across the Vermont-New York border at the Poultney River, the Shoreham Thrust too disappears as a discrete mappable structure, although minor folding and incipient ramps can be detected in shelf rocks at its expected position as far south as the latitude of Whitehall. A major WSW-ENE cross-fault passing north of this outcrop cuts and displaces the autochthonous shelf section and the Champlain Thrust System stack, crossing Book Road at the parking spot. The Shoreham Thrust is offset by this structure with an apparent left lateral displacement of about 2 kilometers. Two other faults like this one pass through the next valley north near West Haven hamlet. These cross faults are discussed in the description of Stop 9B below.

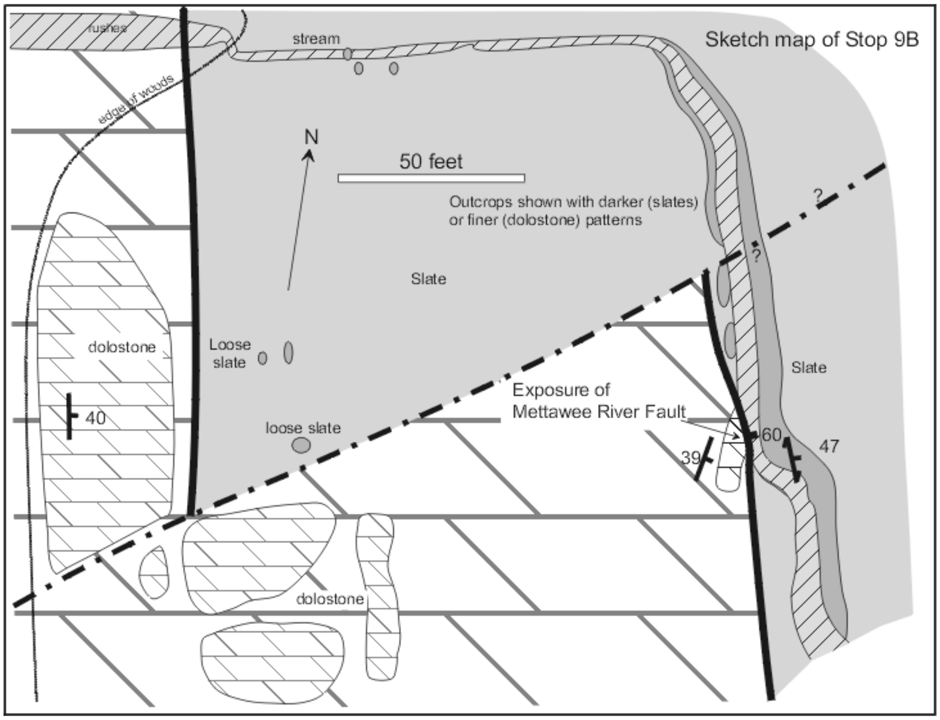

Figure RL-2. Outcrop and geologic map of Stop 9B – the Mettawee fault at West Haven.

STOP 9B - Mettawee River Fault at West Haven

ASK PERMISSION AT BOOK FARM BEFORE ENTERING - FIND BOOK FARM ALONG BOOK ROAD 1.1 MILES SOUTH OF STOP

From parking place [43º 38.727'N, 73º 20.888'W], enter field on east by walking between the two fences, opening the gate if necessary. Follow the grassed-over track into the edge of the woods (about 100 meters), then along the edge of the woods (about another 200 meters), then angle down the crest of a low ridge in the meadow (about another 100 meters) to the edge of the woods crossing the low ridge [43º 38.850'N, 73º 20.513'W]. Outcrop of fractured tan-weathing dolostone ("Providence Island" lithology) is found just inside the woods at this point. Use the sketch map below to navigate and understand the geology from this point on. About 200 feet east of the first dolostone outcrop, in the bed of the stream near the south end of the small ravine, dark slates ("Hortonville"), of presumed mid-Ordovician age, are exposed in contact with the dolostones [43º 38.853'N, 73º 20.473'W]. This contact is clearly a steep (60º) east-dipping fault, truncating the moderately east-dipping thick bedding in the dolostones, and the cleavage in the slates. Given the regional context, with no thick dark slates occurring west of this point, but rather the carbonates of the Shoreham Thrust slice, then the underlying autochthonous Cambro-Ordovician "Whitehall facies" sequence, with Potsdam sandstone/quartzite at its base lying unconformably on Grenville Basement, this fault must be a normal fault, and is in fact the Mettawee River Fault first proposed by Fisher (1985) in New York. It is the only complete exposure of this fault, although our mapping demonstrates that it runs continuously from the Mettawee River (to be seen at stop 12) north through this locality at least as far north as the latitude of Shoreham, and all along this length it regionally truncates the thrust stack of the Champlain Thrust System. We suspect that it extends significantly farther north and south than this, but this falls outside our mapping area, and there is a lack of clear truncation of components of the Champlain Thrust System beyond these extents. One reason for suspecting a larger along-strike extent is the minimum displacement, which can be constrained from accurately drawn cross-sections, and which demand at least 1000 meters of throw, and perhaps more than 1500 meters. This fault cuts out very significant parts of the Champlain Thrust stack, and is one of the main reasons why previous attempts to trace the major thrust faults of the System failed. What age is this normal fault? We have no direct younger age limit in the mapped area, other than the observation that it is cut and displaced by the WSW-ENE faults which also cut the Shoreham Thrust. In fact this set of local outcrops (see sketch map) shows that relationship directly, with a smaller splay of the larger WSW-ENE fault displacing in an apparent left-lateral sense the dolostone-slate contact (the Mettawee River Fault). Despite the prominence of the WSW-ENE faults, we have seen no direct evidence in outcrops near the fault valley indicating whether they are really left-lateral strike slip faults or whether the displacements are created by dip slip movement (in this case, it would require north side down) working on consistently east-dipping strata and faults. Thus these ENE-WSW faults, and the Mettawee River Fault, could be Taconic in age, although they might be younger, e.g. Acadian, or even Mesozoic, and they do not necessarily have to belong to the same orogenic episode.

STOP 10 - Pinnacle/Comstock Thrust, and Mettawee River Fault, at Fish Hill

OBTAIN PERMISSION FROM HARMONY HILL FARM [0.5 MILE DOWN BUCKLEY ROAD FROM JUNCTION]

Enter field to north of parking point through gateway/over electric fence. Go round pond on western side, loop round north end, crossing dry bouldery bed of stream, and head NE up slope toward outcrops just into the woods. [Cross electric fence at edge of woods]. Find contact between grey indurated quartzites above and tan-weathering crudely bedded dolostones below [43º 33.942'N, 73º 21.398'W], all dipping gently east. About 1 meter below the base of the quartzites, there is a projecting ledge exposing a bedding-parallel surfaceof fractured and veined dolostones, smears of limestone, and loose fragments of dark shale coming from the 10-30 cm unexposed interval between the dolostone above and the ledge with limestone smears below. This is the Comstock Thrust, which we maintain corresponds with the Pinnacle Thrust to the north of Orwell (or more precisely here it is the lowest fault surface in a zone which places imbricated Potsdam and Ticonderoga/Whitehall quartzites and dolostones over Fort Ann and Providence Island dolostones). Walk east along the base of the hillside outcrop; an ~10 meter section mostly of quartzites is conformably overlain by dolostones which extend to near the west end of the barn, where there are some dark cherty patches in the dolostones. Climb up on the outcrop to avoid the manure piles and to find another imbricate fault contact placing the quartzites back on top of the dolostones, with truncation of the dolostone bedding in the footwall as a thrust ramp. Near the east end of the barn [43º 33.920'N, 73º 21.305'W], the quartzite outcrop ends, with locally steep and folded bedding probably reflecting accomodation to the ramp/imbricate geometry underneath. Walk north up into the field over quartzite outcrop, then curve to the east across exposure gap of about 40 meters to outcrop of dark and strongly deformed, melangy mid-Ordovician shales [43º 33.957'N, 73º 21.281'W]. You have just crossed the Mettawee River Fault, which again must have substantial normal, down to east displacement. You may find the evidence here for the existence of the Comstock/Pinnacle Thrust not wholly compelling, but raise your eyes to the view towards the southwest, where, in the hills south of Whitehall, the map of Fisher (1985) unquestionably demonstrates a) the existence of the Pinnacle/Comstock Thrust duplicating most of the Cambrian-Ordovician shelf stratigraphy from the Potsdam upward, and b) the unquestionable fact that this thrust is truncated on a large scale by the Mettawee River Fault.

To the east of the shale outcrop, up the slope of Fish Hill, limestones and dolostones of early-mid Ordovician age form another of several thrust slices involving only the upper part of the outer Laurentian shelf and the overlying mid-Ordovician dark shales. These slices rest below the westernmost fault bounding the Taconic Allochthon, which outcrops only about a kilometer to the east.

STOP 11 - Mettawee River Fault at the type locality

[NO HAMMERS OR SAMPLING PLEASE - NY DEC REGULATIONS]

From parking area [43º 28.259'N, 73º 22.153'W], walk from northeast corner along path which quickly descends to a bouldery small stream bed. If wet, the path down can be slippery since it passes through well-rounded fluvial pebble gravel and underlying lake clays; the sloping bedding surfaces of the carbonate outcrops can also be treacherous in places. Cross the stream bed near/at the Mettawee River bank and get onto the outcrop along the west bank of the River [43º 28.283'N, 73º 22.103'W]. These carbonates are mapped by Fisher as Providence Island Formation, and dip about 10-20 degrees east. The lowest part of the section here consists of dolostones; the upper 4 meters contains substantial limestones; we think it is possible that the part of the section containing limestones is either basal Chazy or Black River. This shows some bedding surfaces with well-developed ripples, and small mudcracks, and selectively dolomitized burrows. Local meter-scale folding of periclinal type affects these beds near this end of the section. Walk north along the west bank on the outcrop; mostly dolostones are exposed farther north. About 70 meters north, dark highly deformed mid-Ordovician shales extend from the east bank across the river to an almost complete section at the small rapids. Depending on the streamflow, it may or may not not be possible to examine the shale closely. The contact of the deformed shale with the dolostone beds at the west side of the stream is not quite fully exposed (even at the lowest water we have seen, there is a gap of 10 cm or so), but is clearly sharp, and parallel with bedding in the dolostones. This is somewhat surprising, for a contact which maps out a short distance to the north as a sharp fault that unquestionably truncates strata of the carbonate shelf stratigraphy, as well as the major thrust fault which duplicates this sequence (see the map of Fisher, 1985). Also surprising, for a fault that must have substantial normal sense displacement, is the fact that most or all quartz fiber slickensides in the shale here give thrust sense of displacement!

We infer either that the normal fault mapped to the north passes east of this outcrop within the shale belt, or that the motion is confined to a surprisingly narrow zone along the contact; the full exposure at Stop 9B suggests the latter possibility is more likely than one might be inclined to think based on this outcrop at Stop 11 alone.

STOP 12 - Pre-thrust normal fault in Comstock/Pinnacle Thrust slice at Tyler Farm

ASK PERMISSION at Tyler Farm house [43º 26.849'N, 73º 24.432'W] before going into fields to north of road. If visiting the western part of the ridge, also ask at the old stone house about 0.2 mi west of Tyler farmhouse.
This stop may be skipped if time runs short.
Refer to the outcrop map to navigate. Outcrops on the slope above the Tyler farmhouse, and above the old stone house 0.2 miles west of this, begin with mid-Ordovician limestones of Black River and/or Trenton age; the thin-bedded shaly ones are termed Glens Falls Fm, the more massive ones stratigraphically below are Orwell Fm. They strike about E-W and dip steeply south. Units of the upper Beekmantown (Providence Island, Sciota Limestone, and Ward Siltstone) are found on and near the crest of the first ridge, with decreasing dips towards the valley to the north in which a fault is located. The zone of steep dips is interpreted as a bend fold ["drag fold"] against the hanging wall of (inferred from its straight trace, and the limestone maximum dips) a steeply south-dipping normal fault, and perhaps also is partly an accomodation to the lateral ramp this fault has provided to the Comstock Thrust. North of this ~E-W striking fault, various units of the older parts of the Beekmantown are found forming mostly a moderately east-dipping panel truncated at the normal fault. These strata are in the hanging wall of the Comstock Thrust (=Pinnacle Thrust), which here is the last and only thrust fault in the exposed part of the Laurentian shelf sequence between the autochthonous Grenville basement and mid-Ordovician shales of the Taconic foredeep. The Comstock Thrust is included on the map of Fisher (1985), although he shows its continuation by joining it to the E-W fault referred to above, which we think is geometrically and kinematically unlikely. Our map (based on mapping by Y. Pan and W. Kidd), instead interprets the E-W normal fault to intersect the Comstock thrust and to be truncated by it. In addition, we interpret the Comstock Thrust to continue south across the point of this truncation, and the map pattern requires that it abruptly climb stratigraphic level from the Ticonderoga or Potsdam sandstone to near the base of the mid-Ordovician limestones despite no change in its structural level. This requires the thrust to have truncated an existing normal fault that had a throw of several hundred meters, nearly the full thickness of the shelf sequence. Since there is no indication approaching the E-W fault of any thickness or facies change in the pre-Black River section, we infer that this normal fault too is a mid-Ordovician age structure, generated during flexure of the Laurentian continental margin as it approached the Taconic trench and subduction system. (As a additional note on the structure of the local faults, we find no evidence of the existence of the rootless klippen of Potsdam-Whitehall Fm strata shown not far southwest of this locality on Fisher's 1985 map. We think he confused gently dipping autochthonous Winchell Creek and stratigraphically conformable dolostones with the lower units here; there is in our view no stratigraphic or structural evidence requiring this peculiar object to exist).

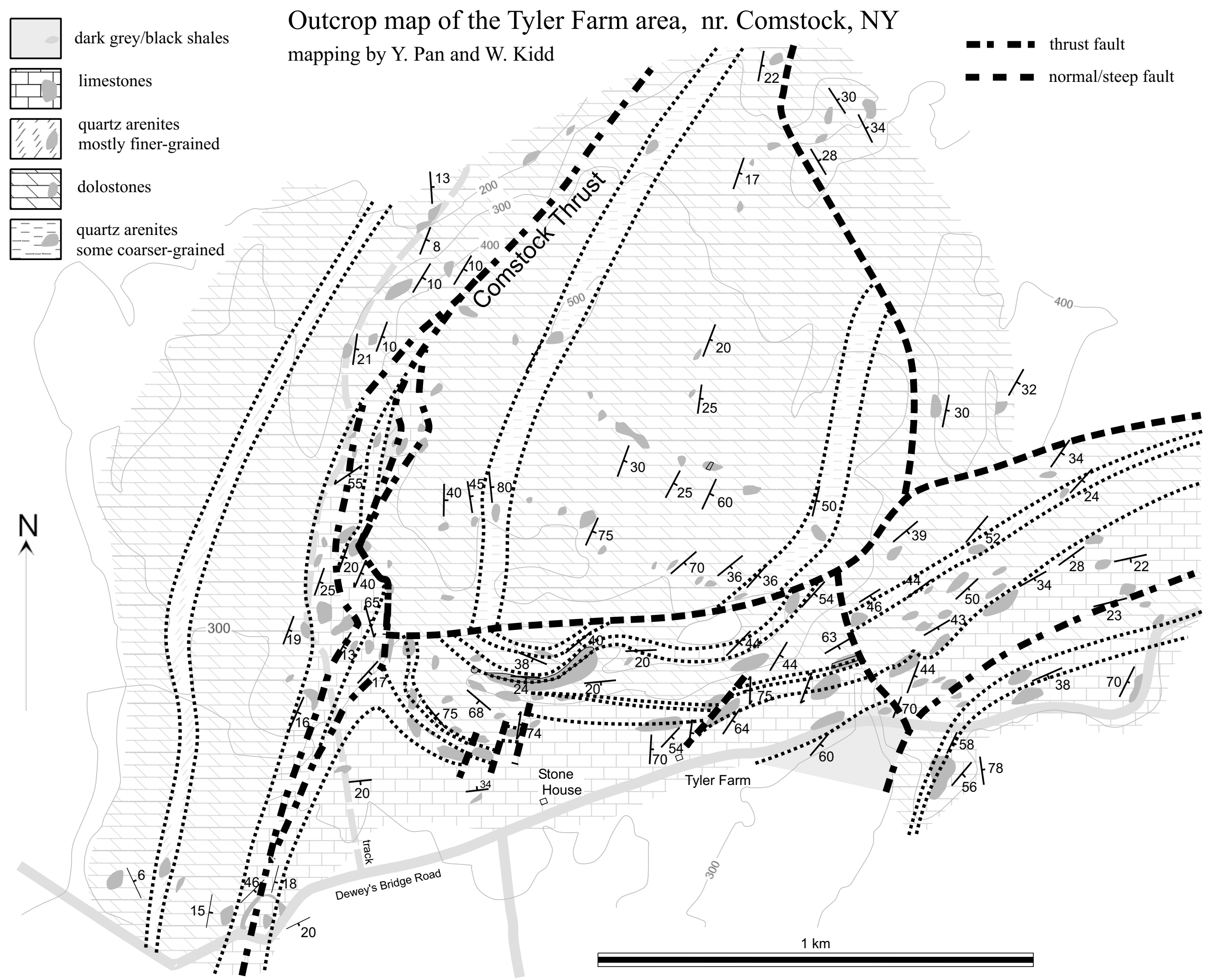

Figure RL-3. Outcrop and geologic map of Tyler farm, stop 12.