# Reactivation of prethrusting, synconvergence normal faults as ramps within the Ordovician Champlain-Taconic thrust system

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## ABSTRACT

**We present new geologic maps of the Lake Champlain region of west-central Vermont and east-central New York State. This region contains a shallow-crustal section of an Ordovician foreland basin and a far-traveled thrust system that transported the Upper Cambrian–Lower Ordovician platform-sequence, allochthonous rise-facies pelites and arenites and Middle Ordovician basinal shales and flysch. Early foreland and shelf sections are cut by postdepositional cross faults within the thrust system, and the required stratigraphic throw across the cross faults is not matched by the amount they offset the thrust planes. As thrust structures, these cross faults control structural style and kinematics by laterally bounding regions that contrast sharply in amount of thrust imbrication, duplexing, and net transport. The dominant set of normal faults in the autochthon, which had time-correlative slip with the thrust-system cross faults, is oriented parallel to the paleotrench, though there is also a subordinate transverse, linking set. The normal faults developed in response to the migrating flexural forebulge during convergence between the Laurentian margin and the accretionary prism above an outboard-facing subduction zone. Within the thrust system, any prethrust normal faults that were parallel to the paleotrench are largely masked by thrust structures. However, an out-of-sequence thrust, which emplaced shelf rocks above the westernmost allochthon and surrounding parautochthonous shale, may have localized on a paleotrench-parallel normal fault in the outer shelf. We also identify a postthrust normal fault that significantly obscures the original thrust map pattern. Reactivation of synconvergence, prethrust, flexure-induced normal faults adequately explains many otherwise puzzling stratigraphic and structural relationships in the Taconic foreland.**

**Keywords: Champlain Valley, foreland, reactivation, Taconic orogeny, thrust.**

## INTRODUCTION

The structure and stratigraphy of orogenic foreland thrust belts are partly the product of reactivation of preexisting normal faults (Jackson, 1980). Such reactivated normal faults are inherited from earlier phases of rift or aulacogen formation (Butler, 1989; Butler, 1997) or from the flexural bulge and outer foredeep of the synconvergence foreland basin (Scisciani et al., 2001; Blisniuk et al., 1998). Normal faults initiated in foreland basins develop in a domino style that is coeval with the deposition of the shales and flysch into the basin (Bradley and Kidd, 1991). Such faults dip dominantly toward the hinterland, have throws ranging from tens of meters to ≥1 km, and, where mapped in detail (Bradley and Kusky, 1986), are linked by transverse faults. Thrusts that propagate into and reactivate transverse structures incorporate them as sharp cross faults that function as displacement-partitioning lateral ramps, though the sharp cutoffs differ from typical lateral ramps that contain antiforms on the inside corners (e.g., Thomas, 1990; Tavarnelli, 1999). The reactivation of prethrust faults explains why some thrust belts are difficult, if not impossible, to restore. Unfortunately, demonstrating the history of such structures is difficult because, within the thrust sheet, reactivated normal faults are mostly subparallel to the trench and buried or masked by complicated imbricate and duplex geometries and out-of-sequence thrusting (Brown et al., 1999; Butler, 1989; Blisniuk et al., 1998; Scisciani et al., 2001).

The Ordovician Taconic collisional belt in New England is a widely cited example of a crustal section through a relict collisional margin (Stanley and Ratcliffe, 1985). Historically, several factors have prevented a completely consistent interpretation of the region, notwithstanding the models for the ancient tectonic environment that are widely accepted (Bird and Dewey, 1970; Rodgers, 1971; Rowley and Kidd, 1981). (1) In west-central Vermont, near Lake Champlain, the southern trace of the Champlain thrust system—the carbonate-rock–bearing foreland-thrust system—disappears where the flysch-molasse basin widens toward the south (Stanley, 1987; Bosworth et al., 1988; Kidd et al., 1995). (2) Throughout the Champlain thrust system, abrupt along- and across-strike changes in stratigraphic units and sedimentary facies as well as changes in structural style obscure the traces of major thrusts. (3) Between the Champlain thrust system and the Taconic thrusts, which carry more-distal pelites and arenites (Zen, 1967), out-of-sequence faulting and late normal faulting disrupt the orderly stacking sequence of thrusts. (4) Lastly, variable exposure and a lack of a consistent stratigraphy pose pragmatic obstacles.

We compiled new geologic maps of this region from our mapping between 1994 and 1997 (Hayman, 1997; Hayman and Kidd, 1997). We identify cross faults that were initially normal-sense faults—along which the largest finite increment of slip occurred during the development of the Taconic foreland, prior to thrusting—and that were subsequently reactivated as transverse thrust ramps. Although there are no clear examples of similarly re-

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activated faults oriented parallel to the paleotrench, there are significant nonrestorable thrust relationships across the strike of the foreland thrust belt that we attribute to the same synconvergence normal faulting. We also recognize a significant late- to post-Taconic normal fault that obscures original thrust-system relationships. We are able to trace the major thrusts through this problematic region by using our informal, lithology-based stratigraphy and recognition of multiple generations of structure.

Immediately prior to the development of the Champlain-Taconic thrust system there was normal faulting in the region associated with the passage of the flexural forebulge across the foreland (Bradley and Kidd, 1991). Thus, we suggest that the Champlain-Taconic thrust system contains examples of synconvergence, prethrust, normal faults that, as structures reactivated by thrusting, contributed to kinematic partitioning of the thrust system, created apparent tip lines of thrusts, and juxtaposed contrasting sedimentary facies.

In the following two sections we describe the tectonic setting in the Paleozoic and the resulting fault relationships. We then discuss the rock types in the platform and basinal sequences and introduce our informal stratigraphy. The later sections then describe the map pattern and cross sections from our efforts, pointing out key features that led us to the interpretations presented in the ensuing discussion.

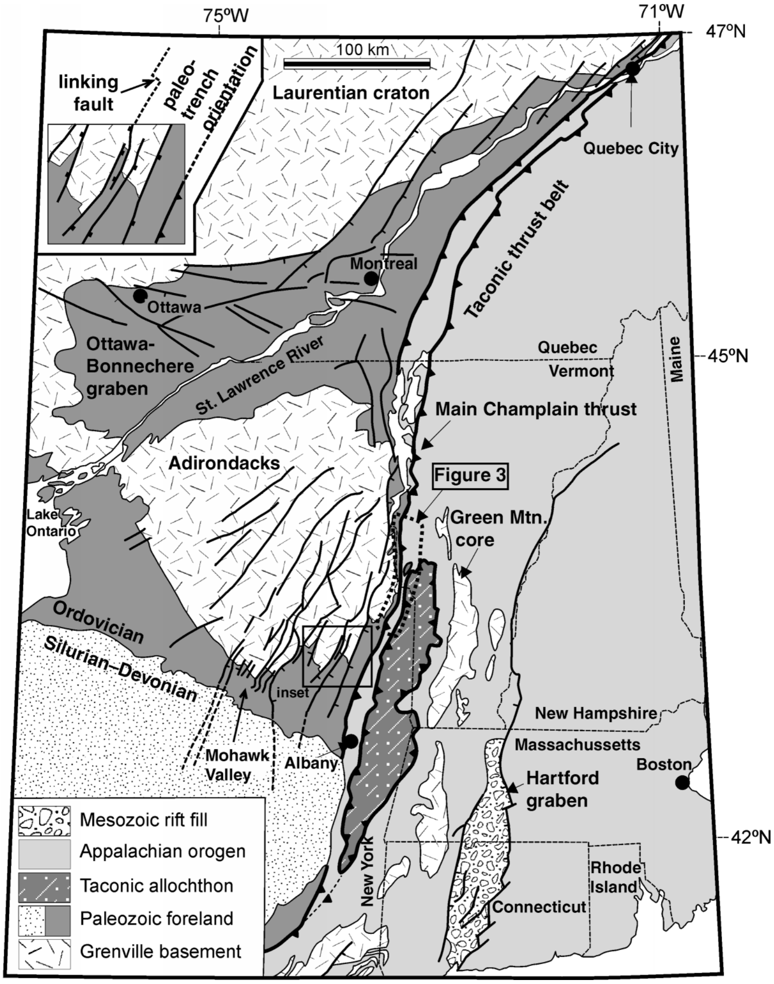


**Figure 1. Map of New England illustrating the relationships between geologic provinces. All of the faults depicted are normal faults except for the major thrusts of the Taconic thrust belt (shown as bold lines with teeth on hanging wall). The Hartford and Newark grabens (the latter is not depicted) 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 Middle Ordovician structures; no significant earlier or later slip occurred along them, and they are in paleotrench-parallel (and subordinate paleotrench-normal) orientations (inset shows detail from Mohawk Valley; location shown by outline box). The area of Figure 3 is indicated by a dotted line. Dashed lines indicating extensions of normal faults are beneath the Silurian–Devonian cover; they do not cut it.**

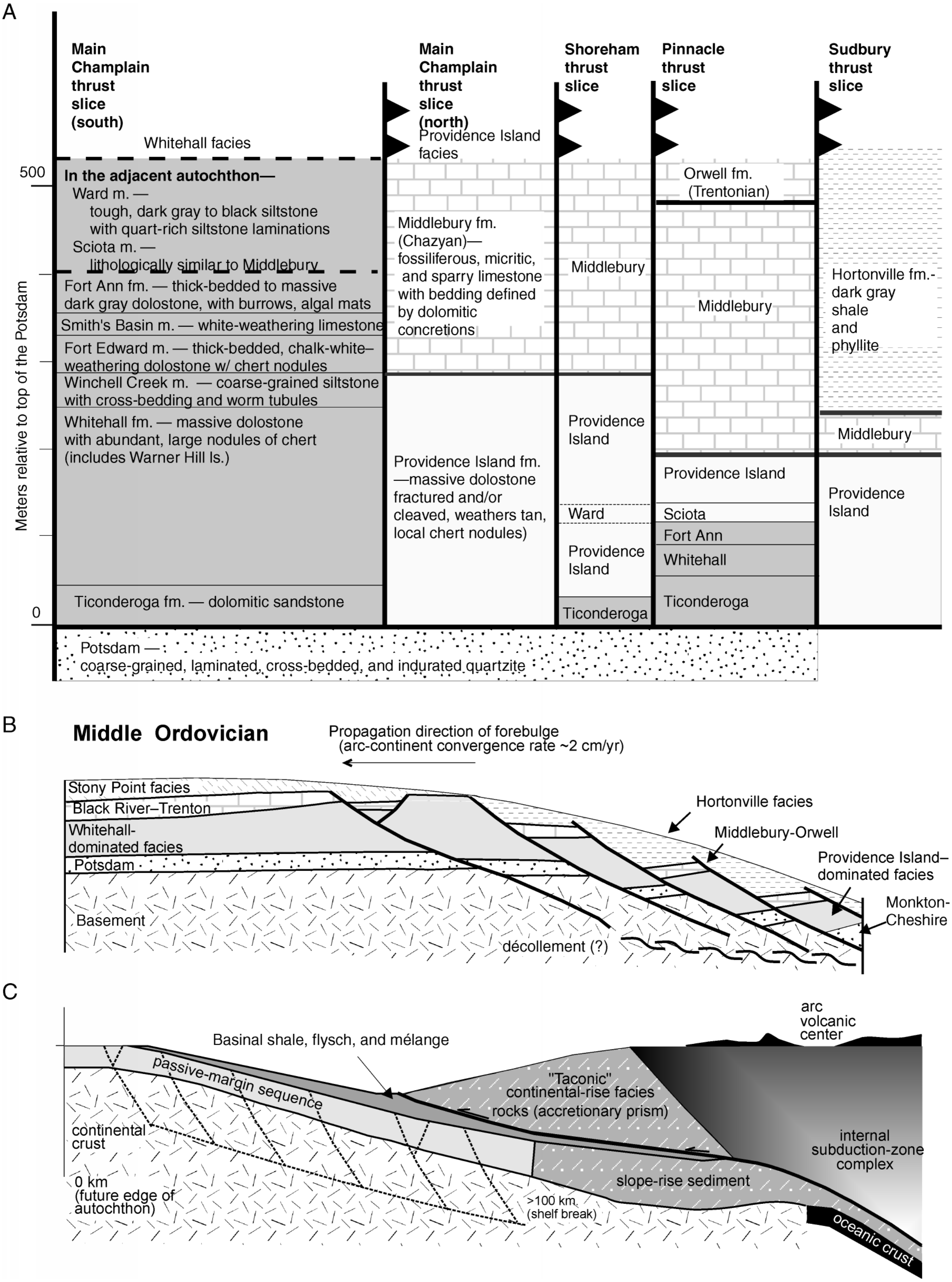
## GEOLOGIC SETTING

### Regional Paleozoic Tectonic Environment

Rocks within the autochthonous foreland of the New England Taconic orogenic belt constitute an Upper Cambrian–Lower Ordovician passive-margin sedimentary section that was deposited on the crystalline Grenville basement currently exposed in the Adirondack region (Fig. 1) (Rodgers, 1971). In addition to the autochthonous passive-margin section, there is a correlative thrust-transported passive-margin section east of Lake Champlain, structurally above Middle Ordovician basinal shale and flysch (Keith, 1932; Stanley, 1987). East of, and structurally above, this parautochthon are a series of allochthons that broadly consist of continental-rise-facies pelites and arenites of Late Proterozoic through Early Ordovician age (Zen, 1967; Rowley et al., 1979; Rowley and Kidd, 1981). East of the allochthons is the Green Mountain crystalline core of the Vermont Taconic mountains, consisting of Grenville basement rocks (Karabinos, 1984; Stanley and Ratcliffe, 1985).

The distribution of sedimentary rock types (Fig. 2A) with known fossil ages (Rodgers, 1971) and the structural relationships produced by thrusting (Zen, 1967; Bosworth and Rowley, 1984; Bosworth et al., 1988) support a tectonic model (Fig. 2, B and C) wherein the Middle Ordovician Laurentian margin collided with one or more island-arc terranes (Karabinos et al., 1998), perhaps built on crust with a continental affinity (Delano et al., 1990) above an outboard-facing subduction zone (Rowley and Kidd, 1981; Stanley and Ratcliffe, 1985). Modeling of the paleobathymetry of fossil assemblages, stratigraphic position of the time-transgressive unconformity between the platform and basin, and distribution of normal faulting across the autochthon support a model for a cratonward-migrating flexural bulge during the deposition of Trentonian basinal shale (Cisne et al., 1982; Bradley and Kusky, 1986; Bradley, 1989).

The normal faults that cut the foreland prior to thrusting are preserved in the Mohawk Valley autochthon (Fig. 1). The faults dominantly strike to the northeast, parallel to the paleotrench and dipping toward it. An approxi-



mately east-striking, linking, fault set is subordinate. Local sedimentary structures and regional map relationships indicate that normal faults are syn- to postdepositional with respect to the Middle Ordovician (Trentonian) foreland basin limestone and shale, and predepositional with respect to the youngest Middle Ordovician basinal shale and flysch (Bradley and Kusky, 1986). There is no evidence to attribute the Mohawk Valley normal faults to Late Proterozoic–Early Cambrian rifting of the Laurentian margin or to instability of the passive margin during the Late Cambrian–Early Ordovician (Bradley and Kidd, 1991). Thus, the free-end elastic flexure (Turcotte et

**Figure 2. (A) Stratigraphic sections and lithologic criteria for distinguishing map units within the platform sequence. The solid gray is the Beekmantown group that is dominantly dolostone but contains many limestone and siltstone horizons. These horizons are assigned informal formation (fm.) and member (m.) names (Fisher, 1985). The Whitehall formation is the characteristic unit consisting 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 different thrust slices is measured from cross sections; a direct measurement of section is not possible owing to inadequate outcrop and limited topographic relief. No age correlation is implied by this diagram. (B) A schematic profile of the shelf during the Middle Ordovician with a free-end load flexure arising from the encroaching trench and subduction zone. The change in sedimentary facies across the shelf is indicated; the Monkton-Cheshire, Providence Island, Middlebury-Orwell, and Hortonville on the right-hand side are the distal equivalents of the Potsdam, Whitehall, Black River–Trenton, and Stony Point. Facies transitions between the Middle Ordovician units (Black River–Trenton limestones and overlying shales) are partly dependent upon the development of the foredeep, the migration of the forebulge, and syndepositional normal faulting. Deposition of the younger shales continues after this normal faulting. (C) A schematic profile of the active margin of Laurentia during the Middle Ordovician, illustrating the tectonic environment of the different sedimentary facies.**

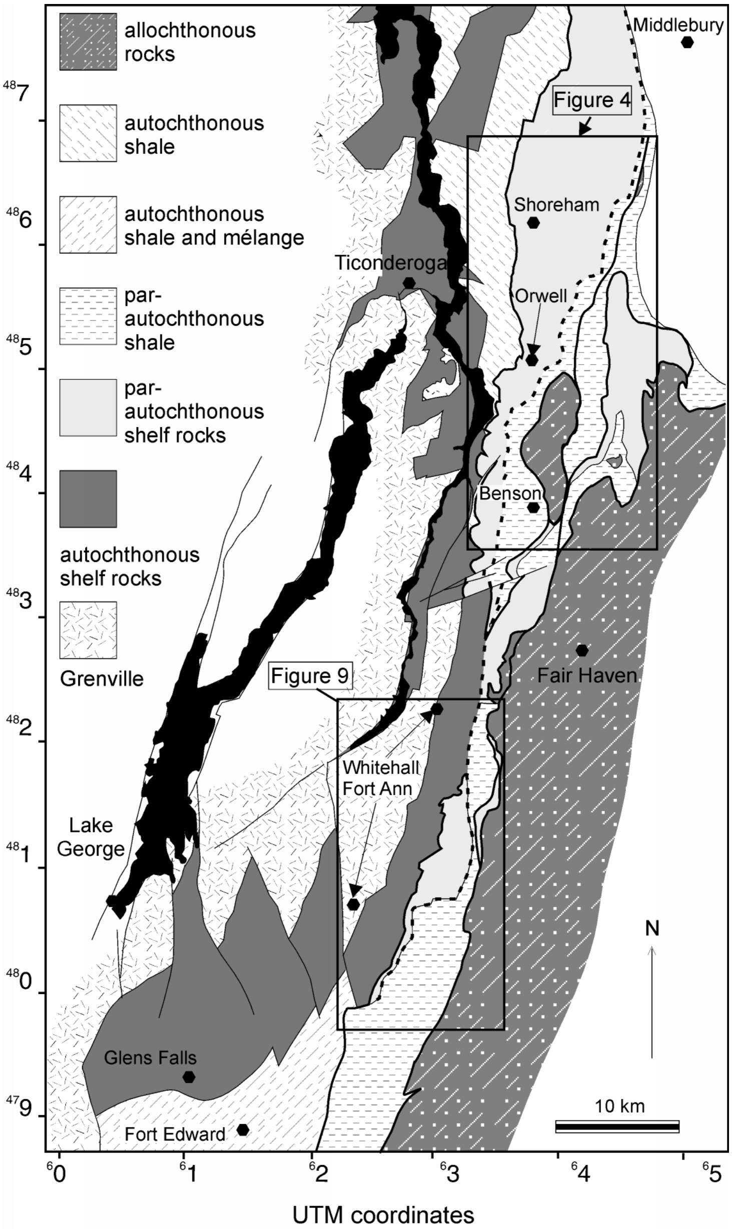


**Figure 3. Regional map of west-central Vermont to the upper Hudson River valley of New York, illustrating the trace of the Champlain thrust system. The Mettawee fault (dashed line) places, on the west, deformed and low-grade metamorphosed shale and flysch—and, to the north of Whitehall, imbricated parautochthonous upper-shelf carbonate rocks—against the parautochthon on the east. South of the disappearance of the parautochthonous carbonate rocks, it is unclear precisely where the trace of the Mettawee fault or that of the Champlain thrust run.**

al., 1978) with the load of the arc, basin fill, and thrust sheets (Ussami et al., 1999), and/or the slab pull of the sinking lithospheric slab (Royden, 1993), was sufficient to exceed the strength of the lithosphere and create a small-extension, domino-style, normal-fault system.

### Regional Fault Relationships

The thrust that juxtaposes the parautochthonous passive-margin section (on the east) above the Middle Ordovician basinal shale (on the west) is the Main Champlain thrust, whose map trace continues from north of the United States/Quebec border to south of the Hudson Valley of New York (Fig. 1) (Stanley, 1987). In west-central Vermont, the Champlain thrust is the basal thrust of a system of thrusts, collectively termed ‘‘the Champlain thrust system’’ (Figs. 3 and 4) (Bosworth et al., 1988; Kidd et al., 1995). Our mapping demonstrates that the Champlain thrust system is cut by a late- or post-Taconic extensional structure, the Mettawee fault, which is known to cut shelf rocks in the Whitehall, New York, region (Fisher, 1985). The downthrown side of the Mettawee fault is a wide belt of Middle Ordovician shale, flysch, and imbricated carbonate rocks. Within this belt is the westernmost, or structurally lowest, Taconic allochthon, the Sunset Lake slice of continental-rise–facies slates and arenites of Late Proterozoic to Early

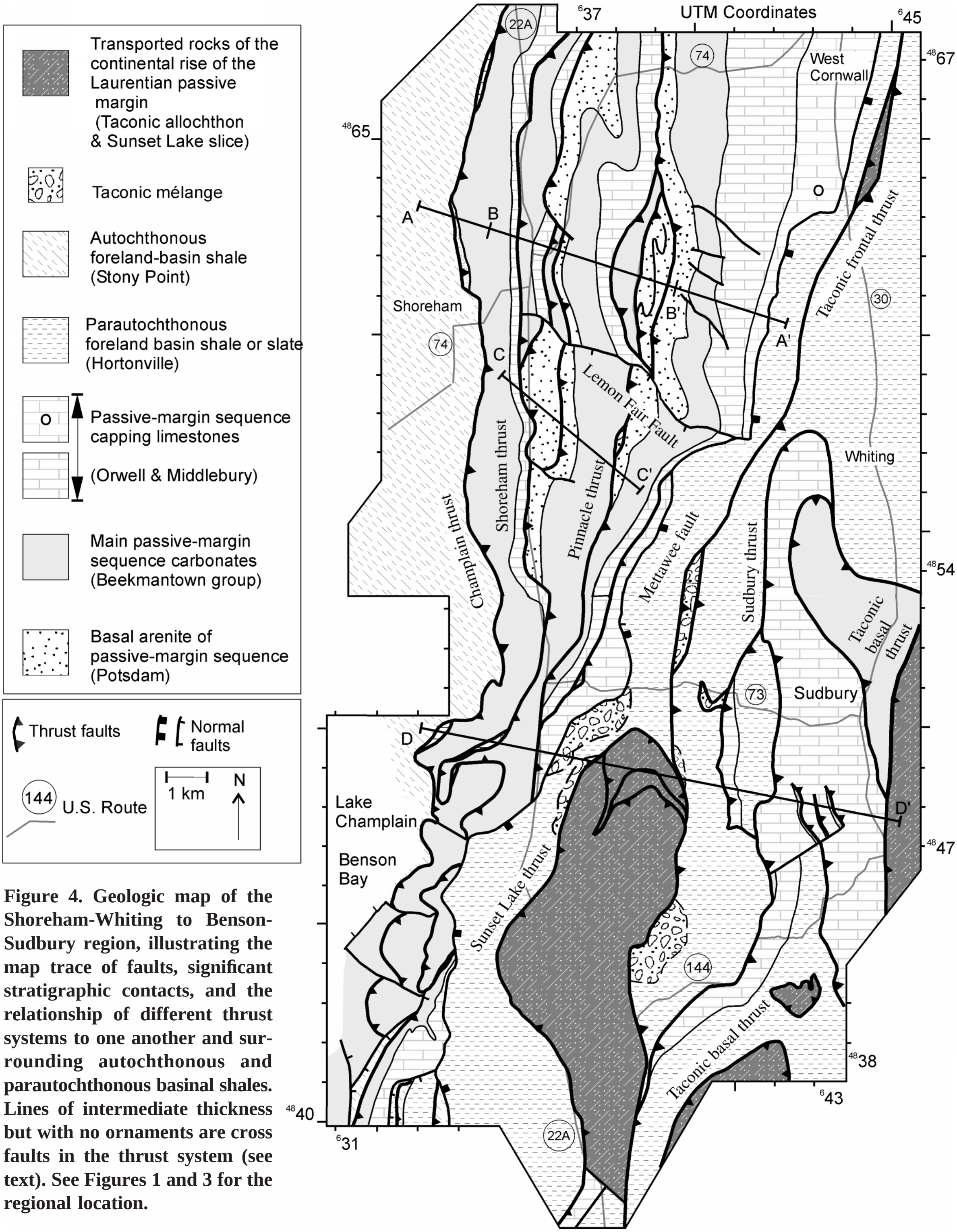


**Figure 4. Geologic map of the Shoreham-Whiting to Benson-Sudbury region, illustrating the map trace of faults, significant stratigraphic contacts, and the relationship of different thrust systems to one another and surrounding autochthonous and parautochthonous basinal shales. Lines of intermediate thickness but with no ornaments are cross faults in the thrust system (see text). See Figures 1 and 3 for the regional location.**

Cambrian age (Zen, 1967, 1972). We suggest that the east side of the Sunset Lake slice is cut by the Taconic frontal thrust, which to the south is a well-defined thrust that forms the eastern boundary of the main belt of Middle Ordovician shale, flysch, and mélange (Fig. 3) (Bosworth et al., 1988). Above this structurally high belt of basinal rocks is a small system of carbonate-bearing thrusts, the Sudbury thrust system (Zen, 1972; Bird, 1969), and above the Sudbury system is the Taconic basal thrust that transported the largest Taconic allochthon (Bosworth and Rowley, 1984; Bosworth et al., 1988). Given comparisons with modern passive margins (Rowley, 1982a) and estimates of rates of Middle Ordovician convergence of stratigraphically controlled markers (Cisne et al., 1982; Bradley and Kusky, 1986; Bradley, 1989), the Champlain-Taconic thrust system transported the parautochthon >80 km from its original position, and the main allochthon, >120 km.

There are some apparent discrepancies in relationships between fault-bounded rocks of distinctive sedimentary facies. The Taconic basal thrust (Rowley and Kidd, 1981) is the thrust that initially juxtaposed the Taconic allochthon against the Middle Ordovician shales, flysch, and mélange. The rocks immediately below the Taconic basal thrust, such as the Sudbury slices, contain second-generation folds and tectonic fabrics that indicate that the thrusts beneath the main allochthon are younger than the Taconic basal thrust (i.e., thrusts are younger toward the west) (Zen, 1972). The Taconic basal thrust is folded and cut by the Taconic frontal thrust (Bosworth et al., 1988); this later, out-of-sequence thrusting partially reactivated the basal thrust such that the basal thrust now appears to cut the Sudbury thrusts (Zen, 1972). The terms *Taconic frontal thrust* and *Taconic basal thrust* refer solely to the faults bounding the rock types of the Taconic allochthon that are highly distinct from the shelf rocks. However, as the Champlain thrust system, which carried shelf rocks, is broadly part of the same system as the Taconic thrusts, ''the Main Champlain thrust'' is the frontal and basal thrust of the overall Champlain-Taconic thrust system. We prefer the proposal for out-of-sequence thrusting in a forward-propagating thrust system (Rowley and Kidd, 1981) to the alternative proposals that Taconic thrusting propagated eastward toward the hinterland (Stanley and Ratcliffe, 1985).

The Taconic frontal thrust and the southern continuation of the Champlain thrust system can be traced beneath the Silurian cover in New York State (Fig. 1). Therefore, they cannot be Devonian thrusts. However, there have been suggestions that a crenulation cleavage associated with the Taconic frontal thrust and, therefore, some of the shortening provided by the thrust are Devonian in age and associated with Acadian contraction (Zen, 1972; Chan et al., 2001; Hayman, 2001).

## ROCKS WITHIN THE CHAMPLAIN THRUST SYSTEM

We divided the passive-margin sequence into map units based upon lithologic criteria without regard to previously proposed stratigraphic divisions. We independently arrived at map units that are very similar to the earliest maps of the region (Brainerd and Seely, 1890) and, when placed in a stratigraphic framework (Fig. 2), correlate well with a combination of formation names formalized by Fisher (1985), Cady (1945), and Welby (1961) (see Hayman, 1997). We propose an informal stratigraphic nomenclature for use in this paper, using the terms ''group,'' ''formation,'' and ''member'' only to describe the basic stratigraphic hierarchy within the areas we mapped.

The main shelf-carbonate sequence along the entire Taconic foreland is the Upper Cambrian–Lower Ordovician Beekmantown group, a name inherited from the late-nineteenth-century New York State Geological Survey under James Hall (King, 1977, p. 23–24). In west-central Vermont, the Beekmantown group is extremely thin, ~200–400 m total (the thickness cannot be directly measured owing to limited exposure and/or structural complexity). Within this section are several limestone, dolostone, and siltstone formations and members summarized in Figure 2. The Beekmantown group is dominated by one of two facies, the Whitehall facies or the Providence Island facies. The Whitehall facies is associated with prominent clastic map units (the Winchell Creek siltstone) and carbonate rocks (the Fort Edward dolostone and Smith's Basin limestone) that have autochthonous correlatives. The Providence Island facies has no known autochthonous lithologic correlative; however, there are some rocks within the Providence Island facies that are present in the autochthon, though at least one of these (the Ward siltstone) changes apparent stratigraphic level across strike. There is a contrast in lithology between the two facies. The Whitehall facies is sparry and micritic, weathers to buff-white, and in some units has layers of chert, whereas the Providence Island facies is mostly micritic, weathers to a distinctive tan, and has only local, minor chert. The Providence Island is everywhere heavily fractured in outcrop and in places has a cleavage. The lithologic characteristics of the two facies, their associated formations, and their respective regional distribution in autochthonous and transported sections have led us to suggest that the Whitehall facies was deposited on the proximal shelf and that the Providence Island facies is a distal facies of the Whitehall.

## THE MAP PATTERN OF THE CHAMPLAIN-TACONIC THRUST SYSTEM

### The Map Trace of the Champlain Thrust System

In west-central Vermont, the Champlain thrust is densely imbricated, warranting its description as a system of several splays, each juxtaposing a nearly complete shelf-sequence section upon one another (Figs. 4 and 5). We refer to these fault-bounded blocks as thrust slices. The major thrust splays are the Main Champlain, Shoreham, and Pinnacle thrusts, although there are other, historically used names for these thrusts (Coney et al., 1972). The corresponding thrust slices have the same names—Main Champlain thrust slice, Shoreham thrust slice, and Pinnacle thrust slice. Other unnamed, locally exposed, thrust slices are likely preserved mainly in the subsurface of the eastern part of the map area, concealed beneath the parautochthonous basin shale (Hortonville facies). An alternative name for the Main Champlain thrust is the ''Orwell thrust''—a useful name where the Main Champlain thrust is the frontal, least-far-traveled thrust splay of a larger system. However, we define the ''Main Champlain thrust'' as the thrust that bounds the top of the autochthon, and we hope to avoid confusion by defining the Main Champlain thrust within a footwall reference frame.

In the north, all of the thrust slices contain some part of the basal passive-margin sandstone (Potsdam), a section of the main passive-margin carbonate rocks (Beekmantown), and at least the lower part of the sequence-capping limestone units. There are significant facies changes that occur within this general stratigraphic division and between thrust slices. For example, the Main Champlain slice, in the northern part of the area we examined, contains only minor parts of Ticonderoga sandstone, a transitional clastic unit. However, the southernmost part of the Main Champlain slice contains Whitehall facies dolostones, and the section correlates lithologically to an autochthonous section. In contrast, the carbonate sections within the Shoreham thrust slice are dominated by Providence Island facies and only roughly correlate to the autochthon. The Shoreham and Pinnacle thrust slices contain thin clastic and carbonate units unique to these slices. Because of the cumulative effect of subtle stratigraphic variations, there is a significant contrast in lithologic sequence of the Beekmantown group section between thrust slices, as well as significant thickness variations (Fig. 2). One general property of most of the larger faults is that they climb section to the south, shown most clearly by the distribution of the basal Potsdam sandstone (Fig. 4).

The Sudbury thrust system, structurally separate from the Champlain thrust system, contains substantial parts of parautochthonous basinal shale (Hortonville facies). The Middle

Ordovician unconformity between carbonate rocks and shales stratigraphically eliminates a large part of the limestone section in the Sudbury thrust system. Nonetheless, a stratigraphic contact between the Providence Island facies dolostone and overlying Middle Ordovician limestones correlates to the same contact within the Champlain thrust systems, indicating that the two thrust systems have correlative map units. We interpret the across-strike contrasts in sedimentary facies to indicate that the eastern Champlain thrust slices were derived from the more distal shelf than the western slices.

## The Mettawee Fault

The Champlain thrust system is regionally truncated by a large-displacement, east-side-down normal fault, the Mettawee fault, first identified in New York State near Whitehall (Fisher, 1985). This fault minimizes the map width of the Champlain thrust system and decreases the difference in present structural level between the Champlain thrust system and adjacent thrust slices. Near Whitehall, the map trace of the Mettawee fault eliminates all but the base of the lowermost thrust sheet from map view (Fig. 3). In west-central Vermont (Fig. 4), the Mettawee fault cuts thrusts of the Champlain system and juxtaposes the basinal shale (Hortonville facies) against the Champlain thrust system. The fault is exposed at two localities between Whitehall and Benson in west-central Vermont (Granducci, 1995).

In west-central Vermont, from north to south, the Mettawee fault eliminates ~1.5 km of vertical section from map view, including the entire Pinnacle and Shoreham thrust slices (Figs. 4 and 5). A similar offset estimate comes from the cross sections (Fig. 5). However, its total offset could be significantly more than ~1.5 km as there are no observable structural or stratigraphic match points or tip lines across the fault, and there are no other constraints on the net slip accrued along the fault. The Mettawee fault could be a late Taconic structure, though its age is unknown, and could have developed any time after the assembly of the Champlain thrust system and the formation of locally truncated cleavage in the slates. In the area we examined, the Mettawee fault forms the western boundary of rocks that show a well-defined slaty cleavage. Thus, the Mettawee fault juxtaposes terranes with different low metamorphic grades. The Mettawee fault may be traceable to the Vermont-Quebec border in the equivalent geologic position (Haschke, 1995).

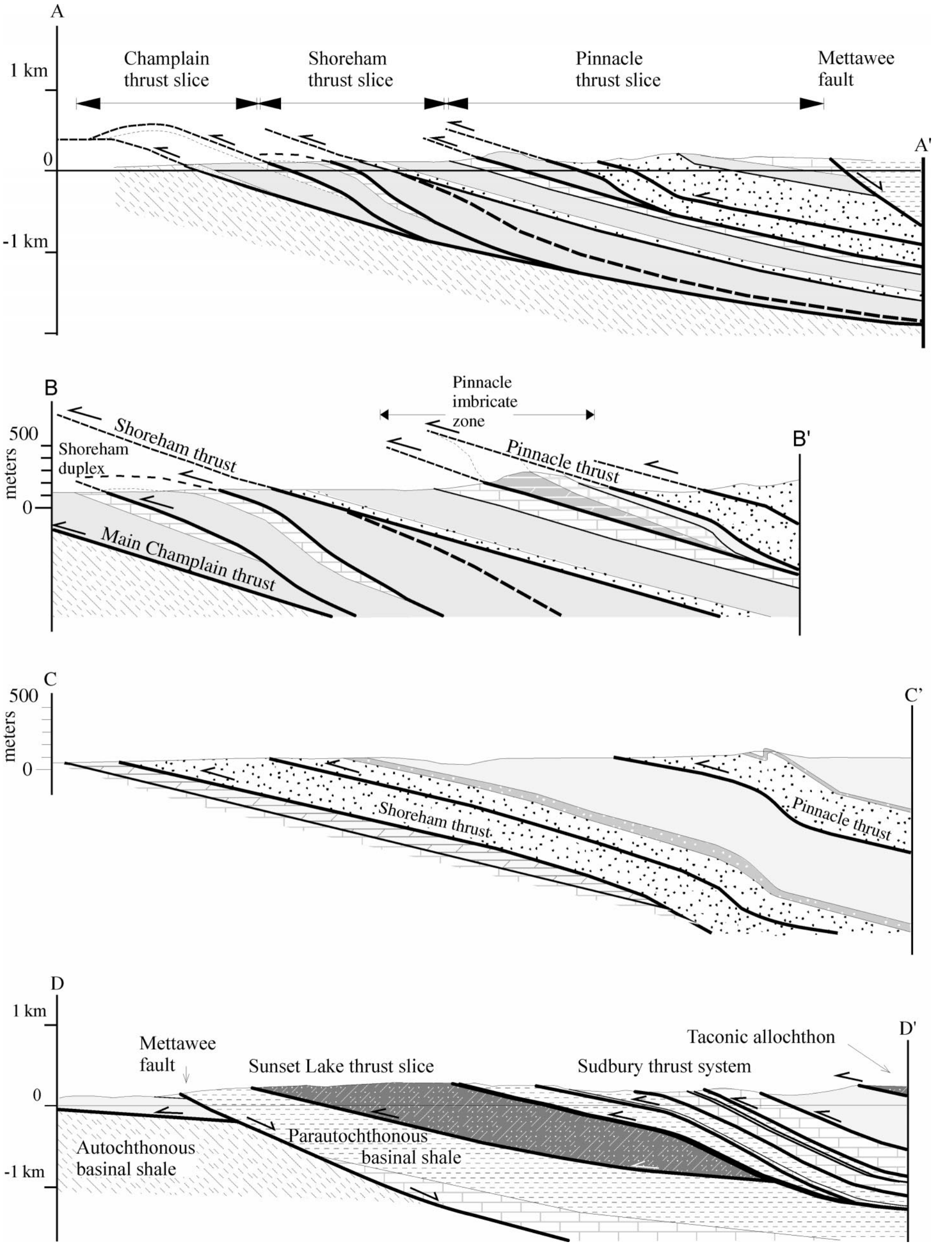


**Figure 5. Cross sections A–A′, B–B′, C–C′, and D–D′ (located in Fig. 4), illustrating the thrust-stacking geometry and relationships of thrust systems to surrounding autochthonous and parautochthonous basinal shales. The detailed map units depicted on B–B′ and C–C′ are described in Figure 2A; they are shown in map view in Figure 8. Sections are not formally balanced owing to a lack of match points and tip lines and to along- and across-strike changes in stratigraphic thickness. Bedded-unit thickness is conserved as much as possible, and there is no vertical exaggeration.**

## The Sunset Lake Slice

A large belt of parautochthonous basinal shale (Hortonville facies) dominates the downthrown eastern side of the Mettawee fault (Figs. 3 and 4). This domain has classically been interpreted as the core of a southward-plunging regional synclinorium, containing the Taconic allochthon, the Sunset Lake slice, and the Sudbury thrust system (Doll et al., 1961; Zen, 1967). In contrast, we suggest that the Sunset Lake slice is a predominantly east-dipping structure. Within the Sunset Lake slice, exposed contacts between Taconic-sequence rocks (undifferentiated in Fig. 4) generally dip to the east, and folds at the

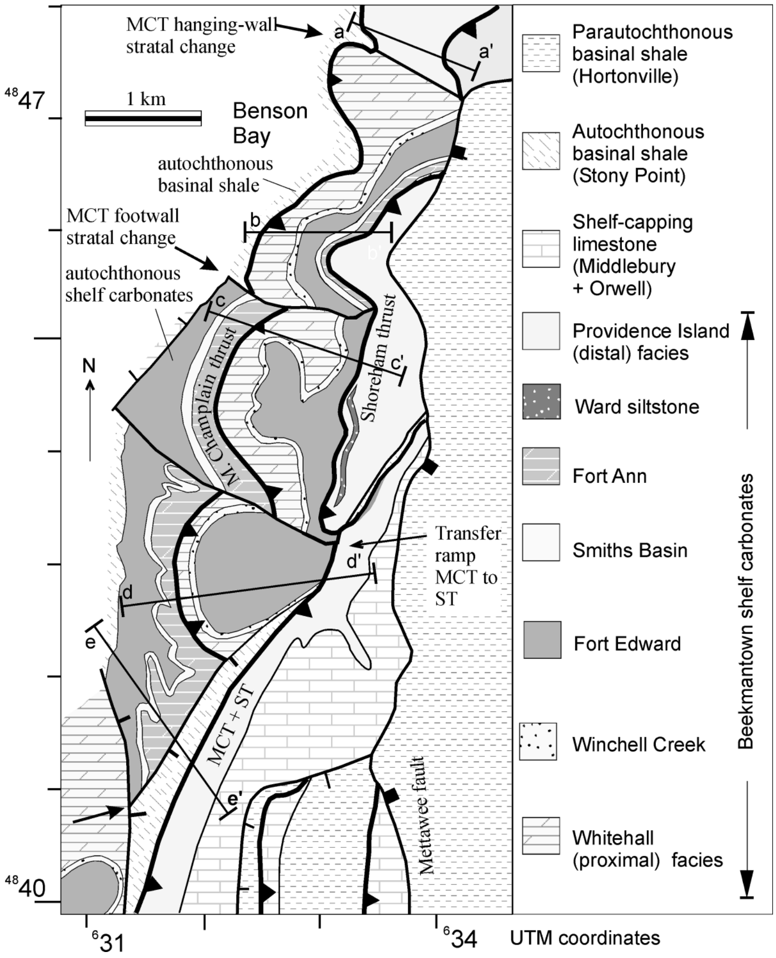


**Figure 6. Detailed geologic map of the Benson Bay area with the trace of thrusts and detailed stratigraphy shown. Arrows indicate sites of geologic relationships demonstrating thrust-fault interaction with and/or thrust-sense reactivation of Ordovician normal faults. Geology of the southern part of this area modified after Granducci (1995) MCT—Main Champlain thrust, ST—Shoreham thrust.**

north end of the slice predate its emplacement. Furthermore, the Sunset Lake thrust, the fault that transports the slice, is also present east of Whitehall, New York, where it juxtaposes allochthonous Taconic slate against mélange (Bosworth and Kidd, 1985). The locally mélange-bearing thrust that cuts the east margin of the Sunset Lake slice is the Taconic frontal thrust, an out-of-sequence thrust (Bosworth et al., 1988). Linearly distributed lenses of Taconic mélange and small slices of Taconic slate mark the trace of the Taconic frontal thrust north of the Sunset Lake slice.

### The Northern Benson Bay Region

The Benson Bay region (Figs. 6 and 7) has long been considered the location of the southern termination of the Main Champlain thrust, marking essentially a pivot point where the thrust was proposed to reach zero displacement (Coney et al., 1972). We agree with this assessment only in that the continuous trace of the thrust is interrupted by a segmenting ramp, south of which the thrust continues as an amalgamation of the Main Champlain and Shoreham thrusts. The cross faults that serve as these thrust ramps also juxtapose contrasting sedimentary facies.

In the northernmost section of the area (a–a′ in Fig. 7), the exposed, flat-lying Main Champlain thrust juxtaposes massive shelf carbonate rocks (Beekmantown group) against autochthonous calcareous shales (Stony Point facies). The Main Champlain thrust crosses a cross fault and climbs 30–40 m in structural level from north to south, whereas the footwall of the thrust changes from the Middle Ordovician autochthonous basinal shale (Stony Point facies) to the middle part of the Upper Cambrian–Lower Ordovician autochthonous shelf carbonate rocks (Beekmantown group). This is a change in stratigraphic level of at least several hundred meters, nearly the entire thickness of the autochthonous carbonate passive-margin sequence, including the sequence-capping limestone units. There is no corresponding change in thickness or facies of the thrust's hanging-wall units, however.

There are several other cross faults in the Benson region similar to the one just described. Across the northernmost structure, the Main Champlain slice changes from a massive, micritic dolostone in the north (a–a′; Figs. 6 and 7), to the lower-autochthon-correlative carbonate sequence (Winchell Creek sandstone through Fort Edward dolostone) in the south (section b–b′; Figs. 6 and 7). The dolostones to the north are most plausibly characterized as Providence Island facies, an interpretation that requires that the northern and southern Main Champlain slices are derived from very different parts of the shelf. There must be a sharp contrast in the amount of structural and stratigraphic offset provided by the cross fault.

In the southern part of the Benson Bay region, the continuous map trace of the Main Champlain thrust terminates against a down-thrown fault block of (Stony Point facies) shale. However, the adjacent Shoreham thrust, and its overriding thrust slice, continues unsegmented south of this location. The thrust-terminating cross fault links the tip line of the Main Champlain thrust with the Shoreham thrust. Although this cross fault functions in effect as a synthrusting lateral ramp, the age of most of the slip on the fault is prethrust as demonstrated by its juxtaposition of Middle Ordovician basinal shale against Lower Ordovician carbonate rocks. This relationship is the same as that involving the northernmost ramp that functions as a lateral ramp in the Main Champlain thrust. Each of these cross faults must have had large amounts of normal-sense throw in the Middle Ordovician; the cross faults were then reactivated as lateral ramps (in the loose sense) in the Champlain thrust system.

### The Shoreham-Whiting Region

The broad tract of farmland between Shoreham and Whiting (Fig. 8) has been considered to contain the southern extent of the Shoreham and Pinnacle thrusts, the two other significant thrusts of the Champlain thrust system (Coney et al., 1972). In this area near Shoreham we define the Shoreham and Pinnacle thrusts as

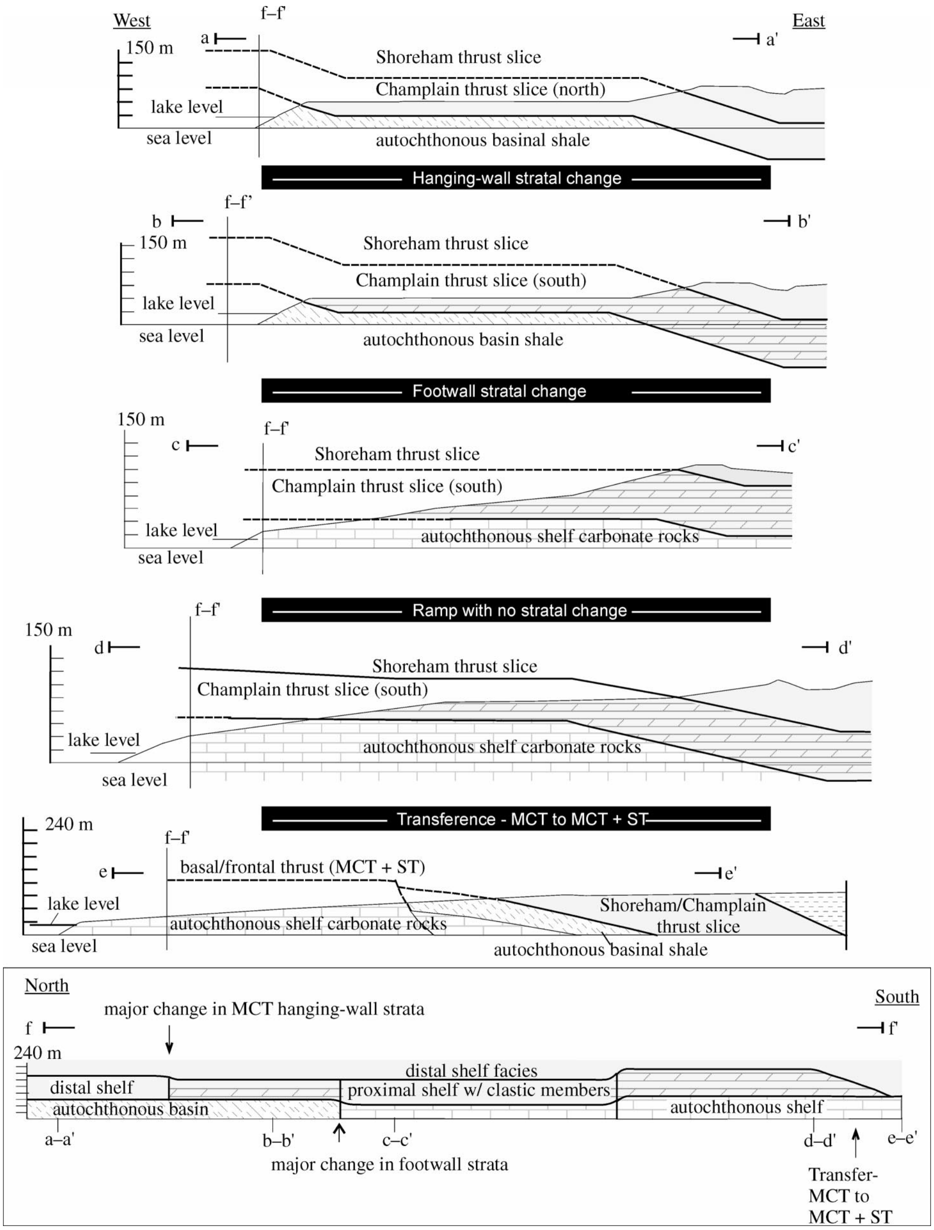


**Figure 7. Qualitatively balanced cross sections (locations are from north to south in Fig. 6) and a representative composite along-strike section. Ramp-flat geometry is necessary to roughly maintain consistent unit thickness for bedded units. Arrows indicate sites of geologic relationships demonstrating thrust-fault interaction with and/or thrust-sense reactivation of Ordovician normal faults. MCT—Main Champlain thrust, ST—Shoreham thrust; MCT + ST is the combined frontal and basal thrust south of the amalgamation of the two.**

those thrusts that carry the Potsdam formation. The Main Champlain and Shoreham thrust slices contain two complicated imbricate systems, collectively referred to as ‘‘the Shoreham duplex’’ (Washington, 1985). Within the Main Champlain slice (section B–B′ in Fig. 5) there is a repetition of stratigraphic sequence across two thrust splays. Thus, there is a thrust duplex with the Main Champlain thrust as the floor thrust and the Shoreham thrust as the roof thrust, and the splays define strike-restricted horses. The Shoreham slice preserves no clear repetition of stratigraphic sections across thrust splays, nor does it have a roof or floor thrust, per se. Rather, lithologic units found more extensively in the Pinnacle thrust slice are internally imbricated by thrust faults within a strike-restricted domain.

The dense imbrication near Shoreham is laterally segmented and bound by an east-trending fault, the Lemon Fair fault. Slickenlines on the fault plane indicate that the fault is a south-side-down normal fault though its structural role is far more complicated. Tracing the Shoreham and Pinnacle thrusts across the Lemon Fair fault involves matching several minor thrust splays, some of which were sites of transport of limestone sections, to two significant thrusts, neither of which were sites of transport of limestone sections (sections B–B′ and C–C′ in Fig. 5). South of the Lemon Fair fault, the trace of the Pinnacle thrust contains at least one lens of Taconic shaly mélange, another observation that the Lemon Fair fault marks an abrupt change in prethrust lithologic units. Across the region between the Lemon Fair fault and the Sunset Lake slice near Orwell, the dense thrust imbrication gives way to an absence of internal imbrication of the Main Champlain and Shoreham thrust slices.

Similar to our map of the Benson Bay region, the fault-related lithologic changes signify that the transverse structures (in this case the Lemon Fair fault) have a prethrust origin, and as they cut the entire shelf sequence with local lenses of flysch, the final slip on them must postdate the deposition of the Middle Ordovician shelf sequence and earliest basinal rocks. As in the Benson Bay region, the along-strike variation in the thrust slices across cross faults signifies that the cross faults partly control the thrust kinematics. Splays of thrusts will generally restore to more proximal locations than broad, shallowly dipping thrust sheets. This circumstance requires an increase in net displacement on the thrusts from the north to the south. This geometry is consistent with an overall decrease in net displacement from north to south on the Main Champlain thrust as the overlying thrusts have to accommodate the deficit in its displacement. Because there must have been significant and abrupt changes in lithic units, and their thicknesses, across the Lemon Fair fault and because it shows discrete partitioning of structural style, we suggest that the Lemon Fair fault was a dominantly normal-sense fault formed prior to thrusting and that it was reactivated as a displacement-partitioning cross fault in the thrust system.

## Southern Continuation of the Frontal Champlain Thrust

As most previous workers have tacitly assumed that the Lemon Fair fault and the Benson cross faults constitute an overprinting, late generation of normal faults (Welby,

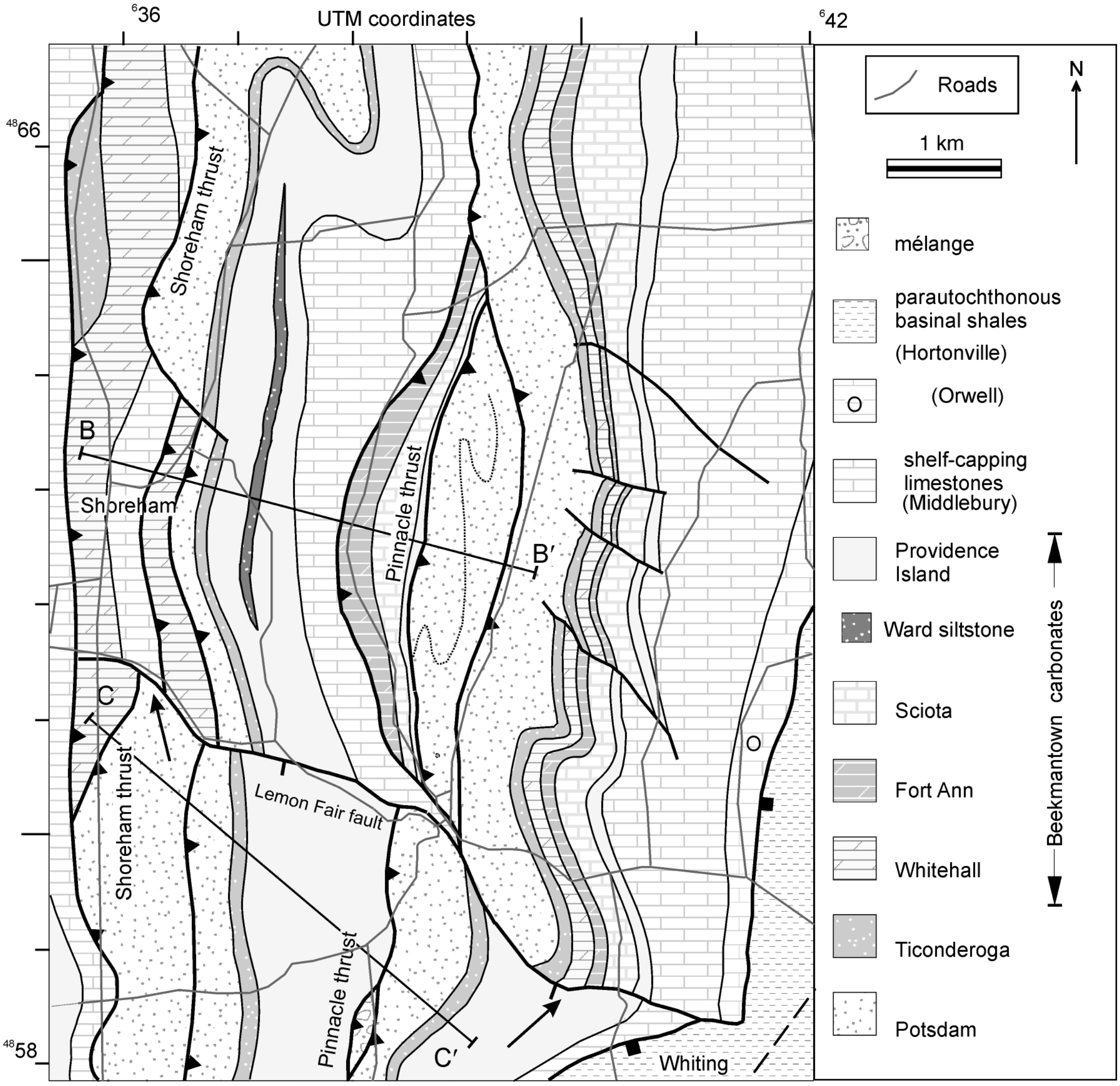


**Figure 8. Detailed geologic map of the Shoreham-Whiting area with the trace of thrusts and full stratigraphy shown. The Lemon Fair fault is the roughly east-striking south-side-down normal fault that laterally bounds the southern margin of the Shoreham duplex and Pinnacle imbricate-thrust zone. In addition, the sequence-capping limestone and the middle-shelf limestone disappear across the Lemon Fair fault (arrows point to the location of these changes on the Lemon Fair Fault). See Figure 5 for sections B–B′ and C–C′.**

1961), there has been neither the suitable stratigraphy, nor the structural framework to warrant tracing the Champlain thrust system south of the Shoreham-Benson region. Our stratigraphy and identification of the reactivated cross structures allow us to do this tracing.

South of Benson Bay, the frontal and basal thrust of the Champlain thrust system (the Main Champlain thrust) is an amalgamation of the Shoreham and Main Champlain thrusts to the north. The southernmost exposure of this thrust is just south of West Haven, Vermont. However, in the area south of Whitehall, New York (Fig. 9), there is a thrust that transported parautochthonous sections similar to those in the Pinnacle slice of the Shoreham area, including the basal quartzite (Potsdam formation). Thus, a structural equivalent to the Main Champlain thrust is present in the Whitehall, New York, region, though its hanging-wall units are equivalent to those carried by the Pinnacle thrust near Shoreham.

At two places south of Whitehall there are abrupt changes in the arrangement of lithologic units along strike. In one case (labeled A in Fig. 9) there is an east-striking cross fault where the westernmost thrust (SCT in Fig. 9) abruptly changes stratigraphic level along strike, from near the base to the top of the Beekmantown, from north to south. There is no accompanying major change in structural level of the thrust, or thrust ramp, with this along-strike lithic change. On the downthrown side of the Mettawee fault, there is a lithic change in the imbricate-thrust slices within the Taconic mélange from mixed upper-shelf carbonate rocks and shale in the north to all shale in the south (Bosworth et al., 1988). This change is spatially coincident with this hanging-wall fault preserved in the parautochthon on the upthrown side of the Mettawee fault. The other along-strike lithic change (labeled B in Fig. 9) is where the thrust footwall passes southward abruptly from shelf carbonate rocks to flysch-basin shales across the mapped west-dipping normal fault. South of here (Fig. 9) is arguably the southernmost extent of the Main

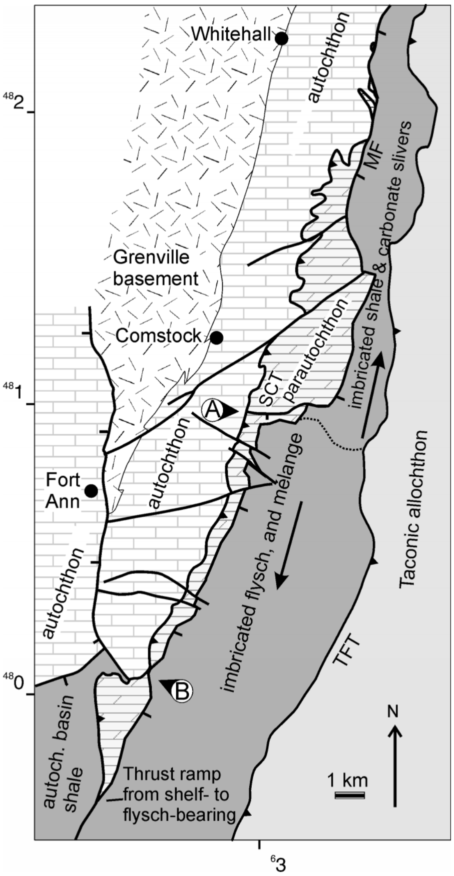


**Figure 9. Generalized map of the trace of major thrusts and normal faults in the Whitehall area, New York, between the Taconic frontal thrust (TFT) and the autochthonous Cambrian–Ordovician shelf sequence. This is the northern end of the extensive Taconic flysch basin of the Hudson Valley. The Champlain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

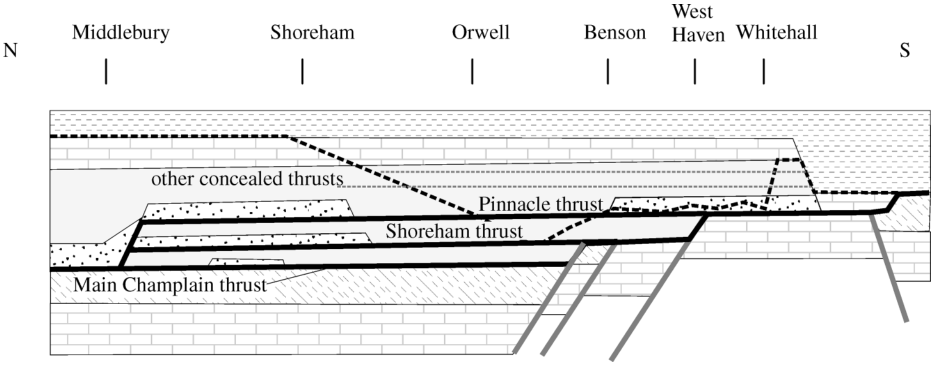


**Figure 10. Along-strike cross section demonstrating the changes in stratigraphic level of thrusts across transverse cross faults. The Mettawee fault is drawn with a dashed line, and the geology now cut out by the fault is interpreted.**

Champlain thrust, as south of this point there are no extensive carbonate-bearing thrusts. However, it is clear that the Main Champlain thrust (here the westernmost thrust, SCT in Fig. 9) must ramp up into the Middle Ordovician flysch, and it and related thrusts are projected south along the mélange zones and the western thrust-controlled deformation boundary of the Hudson River Valley flysch basin (Stanley, 1987; Bosworth et al., 1988; Kidd et al., 1995).

## DISCUSSION

West-central Vermont is typified by moderate-to-poor outcrop, few indicators to differentiate between rocks of similar sedimentary facies, and low grades of deformation and metamorphism. Attempts to delineate the structural evolution of the area have produced conflicting stratigraphies (Rodgers, 1971), interpretations of relative ages of structures (Stanley and Ratcliffe, 1985), and amounts of transport of thrust slices, including the Green Mountain crystalline core (Rowley, 1982b; Karabinos, 1988). We propose that many of the complications that historically have puzzled other workers, and provide incongruities in our map pattern, are the result of reactivation within the thrust system of synconvergence, Middle Ordovician normal faults that initially nucleated near the migrating foreland flexural bulge.

### Cross Faults in the Champlain-Taconic Thrust System

The cross faults in the Benson and Shoreham region, and those more cryptically present in the Whitehall region, had a significant increment of slip in the Middle Ordovician, after deposition of both inboard basinal shales (the Stony Point formation) and outboard flysch, but prior to thrusting. Near Benson, the overall sense of slip was normal sense, as basinal rocks are juxtaposed against the lower shelf. Elsewhere the kinematics of cross faults are more complicated though there must have been a normal-slip component to provide the postdepositional juxtaposition of flysch and shale-bearing rocks against shelf rocks. In the Whitehall region, if the spatial coincidence of lithic change in the mélange zone is related to the cross fault defined in the parautochthon, then the age of cross-fault activity was remarkably close to that of early thrusting. At the southern end of the Sunset Lake slice, shelf carbonate rocks are juxtaposed directly against the allochthonous slates (Fig. 4), indicating that sedimentary facies–bounding cross faults are present in the structurally low sections of the allochthonous slates. Thus, cross faults are present in all parts of the Taconic foreland and had a significant episode of prethrusting activity, but continued during (to at least in one case, after) deposition of the Trentonian basinal shales and flysch.

The contrast in sedimentary facies and structural characteristics along strike are partly controlled by these cross faults. Between Middlebury and Shoreham, Vermont, the Main Champlain thrust laterally splits into the overlying Shoreham and Pinnacle thrusts, and other thrusts are cut out of map view by the Mettawee fault (Fig. 10). This imbrication and duplexing of the thrust system in the Shoreham region is sharply segmented by cross faults and coincident with stratigraphic variation. One such variation is within the Pinnacle thrust slice where Whitehall facies stratigraphic units (Whitehall formation, Fort Ann formation, Sciota member—see Fig. 2) are overlain by Providence Island facies dolostone, the distal equivalent to the Whitehall facies. The Shoreham thrust slice to the west contains no Whitehall facies units. The shelf environment probably had local stratigraphic complexities such as local variations in sediment supply (Mehrtens, 1987), barrier islands, channels, and eustatic effects (Rowley, 1982a). Thus, the local reappearance of the Whitehall facies east of Providence Island facies may result from stratigraphic control. However, the trace

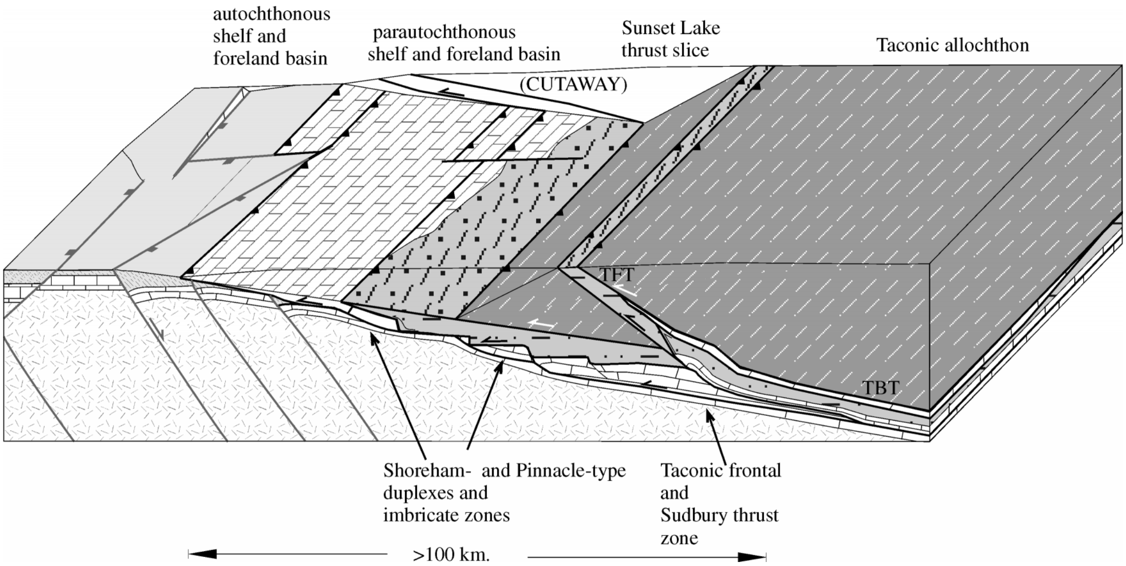


**Figure 11. Schematic representation of the Middle Ordovician shelf and trench during obduction of parautochthonous basinal shale and carbonate rocks over the Sunset Lake thrust slice by the out-of-sequence Taconic frontal thrust (TFT). Diagram modeled on a figure in Bradley and Kusky (1986). Note that proposed trench-parallel normal faults controlling frontal-ramp geometry (such as the Taconic frontal thrust) are rooted farther outboard. TBT—Taconic basal thrust.**

of major structures and the overall change in facies and thrust kinematics along strike led us to suggest that the Champlain thrust system in the Shoreham-Whiting area is controlled by prethrust normal faulting (Figs. 10 and 11). We propose that a horst on the middle shelf brought a stratigraphically low, older, and more outboard part of the Whitehall facies to the structural level of the major thrusts. The Pinnacle thrust intersected an uplifted block of the Whitehall facies beneath the facies transition (we assume that the facies transition is related to shelf deepening and/or sea-level transgression) and the younger Shoreham thrust propagated forward into the unfaulted stratigraphic level more typical of that shelf location. Similar local horsts occur beneath the thrust sheets in the Whitehall region.

The same cross faults that provided tens to hundreds of meters of throw prior to thrusting partitioned net displacement along the strike of thrusts. Near Benson Bay, the change from the northern Main Champlain thrust slice of dominantly Providence Island (distal shelf) facies, to the southern Main Champlain thrust slice of dominantly Whitehall (proximal shelf) facies leads to the interpretation that the Main Champlain thrust decreases in displacement from north to south and terminates near Benson Bay (Coney et al., 1972). Oblique faults that had significant prethrust, Middle Ordovician, normal-sense slip link this termination line with the Shoreham thrust, and the amalgamation of the two thrusts is the basal/frontal thrust of the Champlain system south of the Benson Bay region. We suggest that the Shoreham thrust increases in net displacement from north to south, accommodating the deficit in transport created by the termination of the Main Champlain thrust. South of Shoreham, a decrease in thrust imbrication from north to south reflects this displacement gradient. Therefore, the cross faults, active just prior to thrusting, were reactivated during thrusting and incorporated as kinematically significant structural elements—transverse structures that functioned as lateral ramps and linked thrust segments with different amounts of net displacement.

## Frontal Faults in the Champlain-Taconic Thrust System

The only known episode of normal faulting that occurred during foreland basin development, but prior to thrusting, is the normal faulting that occurred during and after the passage of the flexural forebulge (Cisne et al., 1982; Bradley and Kusky, 1986; Bradley and Kidd, 1991). The best explanation for the cross faults' activity during this period is that they were initially linking structures for the more dominant trench-parallel set of normal faults that developed along the lithospheric flexure and foredeep of the convergent margin (Fig. 11). Though poorly mapped in the parautochthon or allochthon, it is possible that any reactivated, paleotrench-parallel, synconvergence normal faults are masked by thrust structures and have been incorporated as duplexes and frontal ramps within the far-traveled thrust sheet (e.g., Baker et al., 1988; Coward et al., 1988). Lenses of shale, mélange, and carbonate found along the Champlain and Taconic frontal thrusts may have been plucked from irregularities along the faulted shelf. Folded normal faults that expose crystalline basement and certain lithologic and/or stratigraphic discontinuities in the equivalent lower Paleozoic sections adjoining the western margin of the Green Mountain crystalline core are adequately explained by prethrust normal faulting (Rowley, 1982b; Herrmann, 1982; Herrmann and Kidd, 1992). Middle Ordovician normal faults in the autochthon near the thrust front have throws of up to a few hundred meters (Bradley and Kusky, 1986). Examples of trench-parallel normal faults along the more outboard shelf and shelf break in other locations, notably the Arkoma basin, are documented to have accumulated throws in excess of 1000 m (Bradley and Kidd, 1991).

We suggest that a significant synconvergence normal fault was active between the restored position of the Sudbury thrust system and the Champlain thrust system prior to thrusting. The Sunset Lake slice is roughly correlative with the Taconic allochthon, and the Sudbury thrust system is roughly correlative with the Champlain thrust system. Yet the initially continuous suites of shelf rocks are now vertically separated by ~3 km—the thickness of the Sunset Lake slice, the surrounding basinal shale, and the estimated thickness of the buried thrust stack, corrected for the minimum separation provided by the Mettawee fault (Figs. 4 and 5). The vertical offset between the Sunset Lake thrust and the Taconic basal thrust is ~2 km if a constant dip on all of the thrusts is assumed (again, measured from Figs. 4 and 5). The paradox is that whereas the Taconic frontal thrust may have inverted the structural section, placing shelf rocks above the Sunset Lake slice, the maximum separation between the two allochthons is less than the minimum separation between the two shelf-bearing thrust systems (Bird, 1969). We suggest that this mismatch of structural and stratigraphic offset is evidence for a prethrust offset of map units of Ordovician age. Thus, the Taconic frontal thrust and overriding Sudbury system likely ramped across a significant trench-parallel normal fault within the outer shelf (Fig. 11). This normal fault would have had many hundreds of meters, and perhaps >1000 m, of throw.

The hypothesis we have described is speculative for several reasons. Regionally, direct exposures of the Taconic frontal, basal, and Sudbury thrusts yield a variety of eastward dips, and in places even flat-lying, to shallowly west-dipping attitudes are observed. There are neither the adequate tip lines, match points, nor the predictable stratigraphic section necessary to balance a section properly and determine total transport on each thrust. Significant parts of the basinal shale and slate may be local slivers of allochthonous rocks (Zen, 1972), suggesting that the region between the Sudbury and Champlain thrust systems is even more densely imbricated than presented here. That the shelf-bearing thrusts are separated by more than the allochthon-bearing thrusts also indicates that there must have been some component of normal faulting away from the trench (foreland-dipping or antithetic faulting). Such faulting is not widely recognized in such a tectonic setting, although there are notable exceptions (Scisciani et al., 2001). Most important, the Sudbury thrusts are locally cut by the Taconic basal thrust and affected by postemplacement deformation (Zen, 1972). None of these reservations precludes our hypothesis, although they may yield local alternative hypotheses, given further investigation.

### Timing and Extent of Reactivated Normal Faulting

There are indications of prethrust normal faults within the farthest-traveled thrust sheets of the Champlain-Taconic thrust system. These faults would have been roughly parallel to the paleotrench, and located in the outboard part of the shelf, and it is possible, although not required, that the Sudbury carbonate rocks could have been plucked from the horsts of one of these particular faults. It is conceivable that such faults are longer-lived faults inherited from the rifting of the Laurentian margin or from the syndepositional collapse of the passive margin and that they already had a large increment of slip by the Middle Ordovician. However, there is no evidence to support this possibility, and faults in the autochthon on which time-equivalent slip occurred are solely Middle Ordovician structures and of a flexural-bulge origin (Bradley and Kidd, 1991). Given this identification of prethrust, synconvergence, normal faults extending across the foreland of the west-central Vermont Taconic orogenic belt, there may have been a décollement at middle-crustal level for this normal-fault system. As the Champlain-Taconic thrust system is responsible for >80 km of net transport of the distal shelf rocks (Rowley, 1982a), any restoration of the far-traveled foreland-thrust system requires that the Green Mountain core be somewhat equivalently restored to a position to the southeast. A décollement at middle-crustal level could have served as an ideal detachment for the crystalline core.

## CONCLUSION

We present an improved map of a region in west-central Vermont that has traditionally been considered the southern extent of the Ordovician Champlain thrust system, a system of thrusts that transported the parautochthonous Laurentian passive-margin shelf sequence. The continuity of the Champlain thrust system is demonstrated through the Champlain Valley of Vermont, to the northern end of the Hudson River Valley of New York, where an equivalent to the Champlain thrust ramps into the Middle Ordovician flysch basin. Cross faults that link thrusts along the length of this thrust system juxtapose different map units of Ordovician age with stratigraphic offsets that mismatch structural offsets of the thrusts. The cross faults separate the thrust system into kinematically somewhat independent domains with contrasting structural style and amounts of net displacement. We identify a restoration problem across strike between the Champlain thrust system and Sunset Lake slice, on the one hand, and the equivalent Sudbury thrust system and Taconic allochthon, on the other. A late normal fault and an out-of-sequence thrust separate the different terranes. Despite such late and out-of-sequence faulting, we suggest that early normal faulting parallel to the paleotrench, during development of the foreland basin prior to thrusting, is required for the amount of separation observed. We propose that the cross faults, and potentially the Taconic out-of-sequence frontal thrust, were localized by normal faults that developed along the flexural forebulge and its outer slope during Middle Ordovician convergence between the Laurentian margin and one or more island-arc terranes.

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