A reappraisal of the allochthonous nature of the Rosenberg slice and Stanbridge Group of southern Quebec and northwestern Vermont

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Abstract: The Ordovician Stanbridge Group of Quebec has long been considered an allochthonous nappe. It is an internally coherent unit that consists of lower slaty limestone overlain by slate, which is correlated with the Highgate and Morses Line formations, respectively, in Vermont. In Quebec, the basal limestones have been inferred to be thrust over Cambrian dolomites (Gorge Formation in Vermont) of the Rosenberg slice, part of the parauthochthonous shelf, although this contact is not exposed there. In the Missisquoi River gorge of Vermont, a conformable sequence of upper Gorge–Highgate–Morses Line formations is exposed. The map distribution of rock units indicates that this conformable relationship probably extends up to at least the middle unit of the Stanbridge Group. Therefore, the relationships in Vermont require that the Stanbridge Group must be part of the parauthochthonous Taconic foreland rather than a far-traveled nappe. The Rosenberg slice in Quebec forms a large anticline (Highgate anticline) whose western limb is truncated by the Rosenberg thrust. In Vermont, the anticline is internally cut by the Highgate Falls Thrust, which is an out-of-sequence thrust that decreases in displacement northwards to the International Border.

Résumé : Le Groupe de Stanbridge au Québec (Ordovicien) a longtemps été considéré comme une nappe allochtone. Il s'agit d'une unité interne cohérente qui comprend un calcaire schisteux inférieur recouvert par de l'ardoise. Ces roches sont corrélées respectivement au Vermont avec les formations de Highgate et de Morses Line. Au Québec, les calcaires de base auraient été chevauchés par-dessus les dolomies cambriennes (la Formation de Gorge au Vermont) du copeau tectonique de Rosenberg, lequel fait partie de la plate-forme parautochtone, bien que ce contact n'affleure pas à cet endroit. Une séquence conforme des formations Gorge–Highgate–Morses Line affleure dans la gorge de la rivière Missisquoi au Vermont. Sur les cartes, l'étendue des unités rocheuses indique que cette relation concordante s'étend probablement au moins jusqu'à l'unité centrale du Groupe de Stanbridge. Les relations au Vermont exigent donc que le Groupe de Stanbridge fasse partie de l'avant-pays parautochtone taconique plutôt que d'une nappe provenant de loin. Le copeau tectonique de Rosenberg forme un grand anticlinal au Québec (anticlinal de Highgate) dont le membre ouest est tronqué par le chevauchement de Rosenberg. Au Vermont, le chevauchement de Highgate Falls recoupe l'intérieur de l'anticlinal; ce chevauchement est irrégulier et présente un déplacement qui décroît en direction nord vers la frontière internationale.

[Traduit par la Rédaction]

Introduction

In the Taconic foreland of the northern Appalachians, allochthonous, Cambrian to Upper Ordovician deep-marine mudrocks and flysch, originally deposited on the Laurentian lower slope and rise, are exposed discontinuously along-strike from, and directly east of, parautochthonous, thrust-imbricated shelf, slope, and foreland basin flysch sequences. From southwestern Vermont and eastern New York to the northeastern tip of Gaspé Peninsula and western Newfoundland these transported rocks are referred to as the Taconic Allochthons (in Quebec, allochthonous nappes of St. Julien and Hubert 1975). The parauthochthonous foreland of northwestern Vermont, which intervenes between the northern and southern allochthons, lacks far-traveled rocks and contains only east-dipping, thrust-imbricated (e.g., Champlain Thrust) sedimentary sequences of the Laurentian carbonate–siliciclastic shelf and upper slope. Although these rocks have undergone transport (i.e., the Champlain Thrust sheet), they are significantly less far-traveled than the more distal sedimentary rocks of the lower continental slope and rise. It is in this sense that we assign the terms "parautochthonous" and "allochthonous" to various rocks in the Taconic foreland.

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To the north of the parautochthonous foreland of northwest Vermont is the southernmost of the Quebec nappes identified by St.-Julien and Hubert (1975), the Ordovician Stanbridge Nappe (Stanbridge Group of Charbonneau 1980) that has been interpreted (Clark 1934; Charbonneau 1980; Globensky 1981) to extend south into Vermont as the calcareous Highgate and argillaceous Morses Line formations of the Rosenberg slice (Fig. 1). Quebec workers since St.-Julien and Hubert (1975) have interpreted the Stanbridge Nappe in Quebec as allochthonous (i.e., structurally detached from adjacent shelf strata and derived from the Laurentian rise), but workers in Vermont are divided as to whether the correlative Morses Line Formation is far-traveled. The contact in Vermont between the Morses Line Formation and underlying carbonates has been alternately interpreted to be depositional (Doll et al. 1961; Mehrtens and Dorsey 1987), unconformable (Keith 1923; Schuchert 1937), a thrust fault (Gore Thrust of Shaw 1958; Pingree 1982), or a normal fault (St. Albans Detachment of Haschke 1994). Also, nearly all studies by Vermont workers (Schuchert 1937; Shaw 1958; Landing 1983; Mehrtens and Dorsey 1987; Haschke 1994) concluded that the Highgate Formation was deposited on top of the parautochthonous carbonate platform. The results of our study confirm some of the previous work and indicate that the Highgate Formation and the lower part of the Morses Line Formation of Vermont are not allochthonous, but are a conformable part of the outer belt of parautochthonous, thrust-imbricated, shelf rocks. Furthermore, the Quebec section does not contain evidence contrary to this interpretation, and it is most plausible to conclude that at least the lower and middle units of the Stanbridge Group, and probably the upper unit are also parauthochthonous.

Regional geology

The Taconic foreland of eastern New York to southern Quebec records the formation of a Cambrian-to-Ordovician carbonate–siliciclastic passive margin during ocean basin development, followed by a diachronous sequence of events, including exposure of the margin (peripheral bulge), east-to-west foundering, and flysch overlap of the margin as the Taconic ocean closed during the Ordovician. Associated thrusting emplaced the Taconic Allochthons and associated mélange far onto the Laurentian margin, and these allochthons contain a variety of rock types, including flysch deposited as the margin approached and entered an east-dipping subduction zone during the Middle to Late Ordovician Taconic Orogeny (Rowley and Kidd 1981; Stanley and Ratcliffe 1985). Many of the Quebec nappes, and slices of the Taconic Allochthon in Vermont and New York, are present west of the strike of the easternmost exposures of shelf rocks and exposures of the Grenvillian Massifs (e.g., Green Mountain, Berkshire) indicative of long-distance transport. Connecting the allochthonous terranes of Quebec and Vermont is the regionally significant Champlain Thrust that for much of its extent in Vermont emplaces Cambrian carbonate platform rocks over Middle Ordovician flysch-related shales. Champlain Thrust-related shortening was accommodated by the Highgate Springs, Phillipsburg, and Rosenberg thrusts in northwest Vermont, and by Logan's Line in Quebec (Stanley 1987; Haschke 1994; Fig. 1).

Northwestern Vermont

The Champlain Thrust and related faults have stacked the shelf-related rocks of northwest Vermont into three distinct parautochthonous thrust slices, and include (from bottom to top) the Highgate Springs, Phillipsburg, and Rosenberg slices (Fig. 1). Clark (1934) originally defined the latter two slices for correlative, along-strike rocks in Quebec. The Middle to Late Ordovician Highgate Springs slice consists of carbonates of the Chazy, Black River, and Trenton groups and is thrust over the Ordovician Iberville Shale along the Highgate Springs Thrust (Kay 1958). The Phillipsburg slice, consisting of Late Cambrian to Early Ordovician carbonates and dolomites, has been correlated with the continental shelf units of the Clarendon Springs, Shelburne, Cutting, Bascom, and Chipman formations of west-central Vermont (Doll et al. 1961; Globensky 1981; also St.-Julien and Hubert 1975) and were carried over the younger Highgate Springs slice along the Phillipsburg Thrust. Both the Highgate Springs and Phillipsburg thrusts merge with the Champlain Thrust to the south and although the detailed relative timing of these three faults is not clear (compare Doll et al. 1961 with Stanley and Ratcliffe 1985), we think that in the most general terms they are coeval Ordovician structures.

The structurally higher Rosenberg slice is a succession of carbonates and slates, which comprises the northern part of the St. Albans Synclinorium (Fig. 1). In the region between Highgate Center and the International Border, the Rosenberg slice consists of the Dunham, Saxe Brook, Gorge, Highgate, and Morses Line formations, in ascending order (Fig. 2). The eastern boundary of the Rosenberg slice is marked by the Hinesburg Thrust that brings up from the east, the Early Cambrian Cheshire Quartzite and other more deformed rocks of the Oak Hill Group (e.g., Dennis 1964; Osberg 1965), part of the internal domain of St.-Julien and Hubert (1975). The slice has been the subject of numerous studies with conflicting results and the stratigraphic nomenclature has been repeatedly changed over nearly 200 years (see Fig. 2).

At the base of the Rosenberg slice is the Early Cambrian Dunham Dolomite that occurs as two approximately north-trending, discontinuous belts and forms the outer limbs of the St. Albans Synclinorium (Doll et al. 1961). The eastern belt crops out directly below the Hinesburg Thrust in Vermont and is present along-strike in Quebec at its type-section near Dunham, Quebec. The western belt forms the roof of much of the Champlain Thrust in northwestern Vermont (Stanley and Ratcliffe 1985).

Overlying the relatively continuous western belt of Dunham Formation is a series of Early Cambrian to Early Ordovician units that display a south-to-north lateral facies change from shallow-water continental-shelf carbonates and siliciclastics near Milton to deeper water shales in the St. Albans area (Fig. 1), finally grading into continental-slope carbonate breccias at Highgate Center (Shaw 1958; Landing 1983; Mehrtens and Dorsey 1987). All of these rocks are overlain by Early to Middle Ordovician calcareous slates (shales) of the Morses Line Formation that forms the core of the St. Albans Synclinorium. Shaw (1958), Landing (1983), and Mehrtens and Dorsey (1987) all interpreted the presence of a sedimentary basin ("Franklin Basin" of Shaw 1958), based on this stratigraphic relationship and the significant

Fig. 1. Regional map of significant structures and lithologic units in northwestern Vermont and southern Quebec. Based in part on Doll et al. (1961), Fisher (1968), Charbonneau (1980), Globensky (1981), and Avramtchev (1989). Fm., Formation.

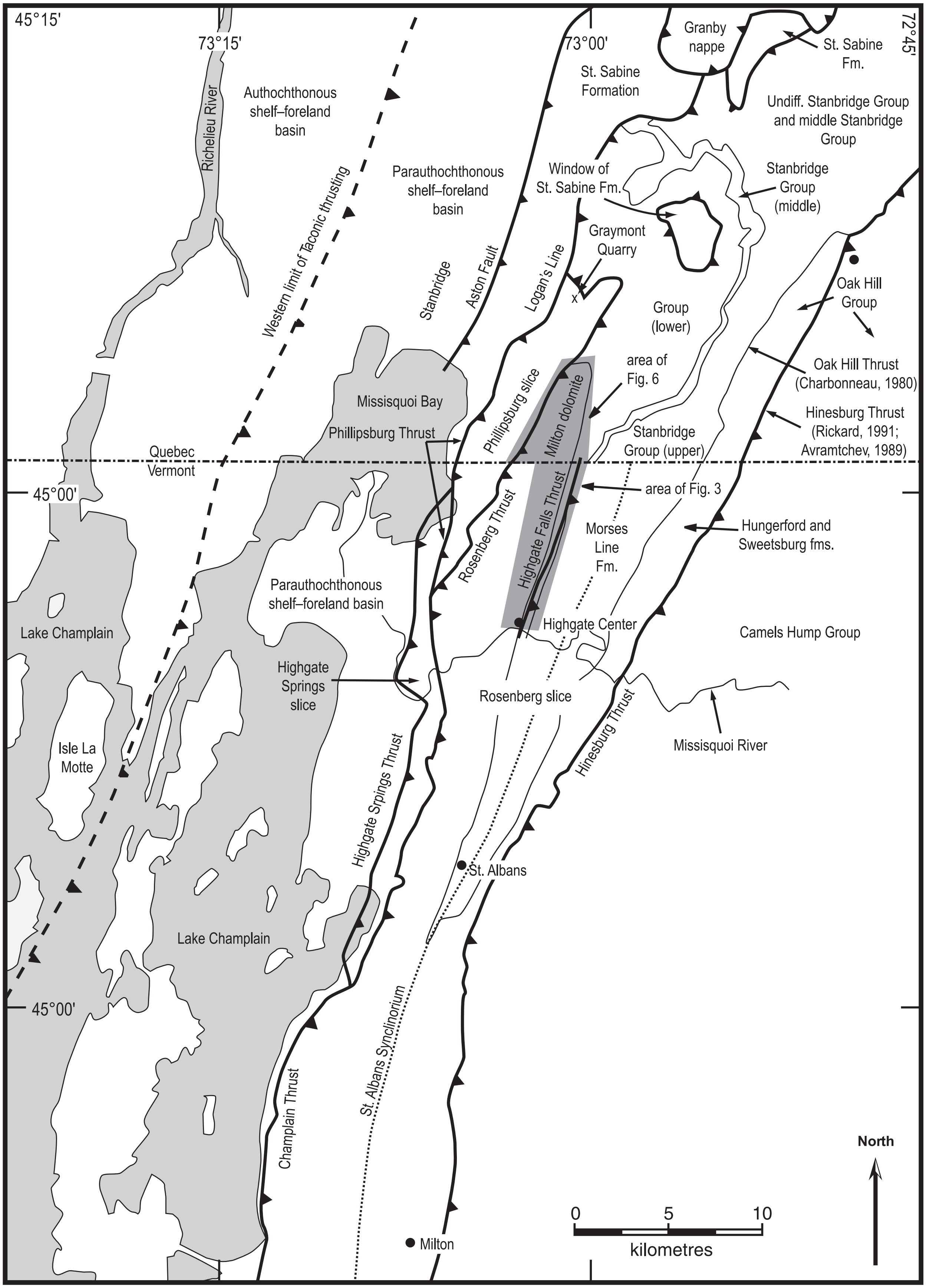
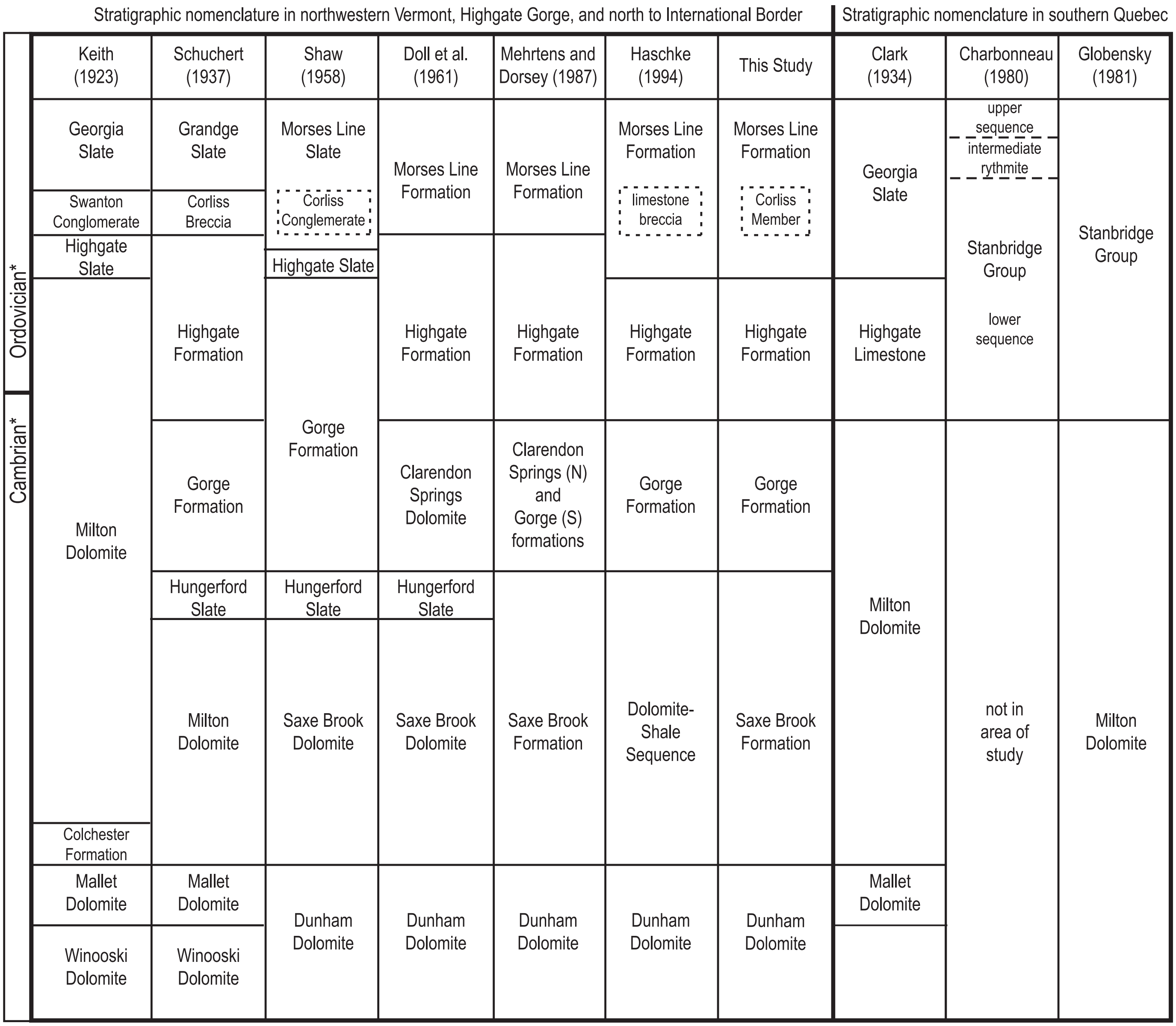


Fig. 2. Lithostratigraphic correlation chart of the Cambrian through Middle Ordovician formations of the Rosenberg slice. *Cambrian–Ordovician boundary located after Landing (1983), as it applies to our study and does not necessarily represent placement of this boundary by other workers.



north-to-south change in continental shelf and slope facies. Landing (1983) interpreted a generally east–west shelf margin (largely siliciclastic–carbonate units) near Milton, Vermont (Fig. 1), with continental-slope rocks (shales and carbonate debris fans) extending north to Highgate Center. The interpretation of Mehrtens and Dorsey (1987) partly contrasts with this in that they additionally recognized the presence of shelf-derived carbonates (Gorge and Saxe Brook formations) north of Highgate Center to the International Border and extending into Quebec as the Milton Dolomite. Based on this, they proposed a model of a fault-bounded basin (St. Albans Reentrant) localized between Milton and Highgate Center. Mehrtens and Dorsey (1987) also interpreted the overlying Morses Line Formation as the conformable onlap of basinal shales during sea-level rise and drowning of the continental shelf, rather than transported continental rise units that make up much of the Taconic Allochthon.

Southern Quebec

Charbonneau (1980) and Globensky (1981) have conducted the most recent and detailed work along the International Border in Quebec (Fig. 1) and their study areas mutually adjoin approximately along the contact between the Phillipsburg and Rosenberg slices of Clark (1934). They recognize the Phillipsburg slice, but divide the Rosenberg slice into the Milton Dolomite and Stanbridge Group (Stanbridge Complex of Clark and Eakins 1968). The term "Milton Dolomite," according to Globensky (1981), refers to chert-bearing, sandy, massive dolomite and conglomeratic dolomite of Late Cambrian age and is composed of the Quebec equivalents to the Saxe Brook and Gorge formations of

Vermont. Its eastern contact with the Stanbridge Group is inferred to be a thrust fault that is folded at its northern end, south of Bedford, and truncated by the Rosenberg Thrust that separates it from the younger Phillipsburg slice (Figs. 1, 6). The structurally overlying Stanbridge Group is divided into three parts: the “lower sequence” comprises the Highgate Formation and lower part of the Morses Line Formation (Charbonneau 1980); the middle and upper parts, the “intermediate rhythmite” and “upper sequence,” respectively, are equivalent to the remaining Morses Line Formation (Charbonneau 1980). The group is broadly folded into a north-plunging anticline and forms the Stanbridge Nappe that is entirely composed of the Stanbridge Group and, according to Charbonneau (1980) and Globensky (1981), is a coherent, fault-bounded, lithostructural unit. Significantly, and in contrast to relationships observed in Vermont, this definition of the Stanbridge Group separates the Milton Dolomite and Highgate Formation into different structural units, separated by an inferred thrust (unnamed in Quebec). However, an internal part of the slate section of the lower sequence is observed thrust over the carbonates of the Phillipsburg slice (Graymont Quarry; Fig. 1), as well as calcareous shales of the Middle to Late Ordovician St. Sabine Formation (St. Sabine Window; Fig. 1). The latter unit structurally overlies the Iberville Formation, part of the foreland basin clastic section overlying the passive margin shelf sequence that lies directly on the Grenvillian crustal basement (Globensky 1981).

The Quebec nappes are internally consistent with respect to structure and lithology, composed of shale or mudstone with limestone conglomerate, argillaceous limestone, or arkosic sandstones (St.-Julien and Hubert 1975; St.-Julien 1977; Lebel and Kirkwood 1998). Additionally, several of the nappes are floored by mélange (Etchemin and Rivière Boyer mélanges) and contain olistostromal units (Citadelle and Anse St-Vallier). The nappes are stacked such that those containing older rocks always lie on those with younger strata (St.-Julien and Hubert 1975). The Stanbridge Group is broadly similar in lithology to some of the Quebec Nappes (Quebec Promontory, Pointe de Lévy, Bacchus, and St. Hénédine nappes) in that it is dominantly slate with thin limestone beds and thicker limestone-clast conglomerate units. In contrast however, the Stanbridge Group is of Early to Middle Ordovician age (Riva 1974) and rests on the older, or approximately coeval, rocks of the Milton Dolomite (= Early Ordovician age of the Gorge Formation (Landing 1983)), rather than younger ones. There is also a lack of any identified mélange or olistostromal units along its basal contact with the Milton Dolomite, Phillipsburg slice, or St. Sabine Formation.

The earliest interpretation of the Stanbridge Group as an allochthonous unit appears in the regional compilation of St.-Julien and Hubert (1975), where the group appears to include limestone and limestone breccias of the Highgate Formation with argillaceous rocks (= Stanbridge Nappe) of the inner belt of their External Domain. In their figs. 4 and 5, St.-Julien and Hubert correlate the calcareous Highgate Formation with the Lauzon Formation of the Point-de-Levy Nappe, and calcareous slates that overlie the Highgate Formation with the Levis, Pointe-de-la-Martinière, and St Hénédine formations of the Point-de-Levy, Bacchus, and St Hénédine nappes, respectively. This suggests that they consider this unit (Highgate Formation) to be part of the allochthonous Stanbridge Nappe. The Saxe Brooke Formation equivalent (and presumably the Gorge Formation), however, is shown as part of the thrust-imbricated shelf sequence, requiring a major tectonic break between the Gorge and Highgate Formation equivalents in Quebec. Williams (1978) tectonic lithofacies map continued this interpretation showing the Stanbridge Nappe (“transported rocks of continental slope/rise”) extending into Vermont, in the position occupied by the Morses Line Formation. Similarly, Charbonneau (1980) also interpreted the Stanbridge Group to be allochthonous, based on the observed thrust relationship with the Phillipsburg slice (Rosenberg Thrust) and the St. Sabine Formation (Fig. 1), which was correlated with the St. Germaine Complex, previously interpreted to be allochthonous (Charbonneau 1980).

Results of our field work

In northwestern Vermont and southern Quebec, the contacts between the Gorge, Highgate, and Morses Line formations, as well as the trace of the Highgate Falls Thrust, were remapped. The nature of these contacts, directly observed in the Missisquoi River gorge at Highgate Center (Fig. 1) forms the basis for interpreting the contact relationships in Quebec where these same contact relationships are obscured. Significant attention is given to the stratigraphic and structural relationships exposed in the gorge since the section there is the only place where these contacts are exposed and are variably interpreted by previous workers.

Northwestern Vermont

For this study, an area in Vermont consisting of an ~2 km wide strip extending north-northeast from the Missisquoi River to the International Border was remapped (Fig. 3). The rock units of interest include parts of the Saxe Brook, Gorge, Highgate, and Morses Line formations, including the Corliss Conglomerate of Shaw (1958). These units have been described by previous workers, and the reader is referred to Shaw (1958), Landing (1983), Mehrtens and Dorsey, (1987), and Haschke (1994) for detailed descriptions. Due to numerous conflicting interpretations of the stratigraphy by previous workers, the nomenclature of these workers, details of certain units, and criteria used for delineating units are given as follows.

The Missisquoi River gorge at Highgate Center exposes an ~120 m continuous section of east-dipping, conformable dolomites, dolomitic arenites, and dolomitic breccias of the Gorge Formation; bedded limestone breccias and argillaceous limestones of the Highgate Formation; and calcareous black slates with minor micritic limestone and pebbly breccias and individual micritic dolomite beds, formerly referred to as the upper Highgate Slate (Keith 1923) or the Highgate Formation (Schuchert 1937), but interpreted in this study to be the lower part of the Morses Line Formation (Fig. 2). The lower carbonate section of the river gorge, up to the base of the slates, was re-measured, and the positions of lithic units are shown in Fig. 4 and keyed to the appropriate part of Landing’s (1983) section E. The section is truncated farther upsection within the gorge by the Highgate Falls Thrust that has about 10 m of exposed dolomitic arenites and breccias (lower Gorge Formation) in its hanging wall.

A number of critical relationships are exposed in the

Fig. 3. Geologic map, Highgate Center area, Vermont. Loc., locality; Fm., Formation; Mb., Member; vert. exag., vertical exaggeration.

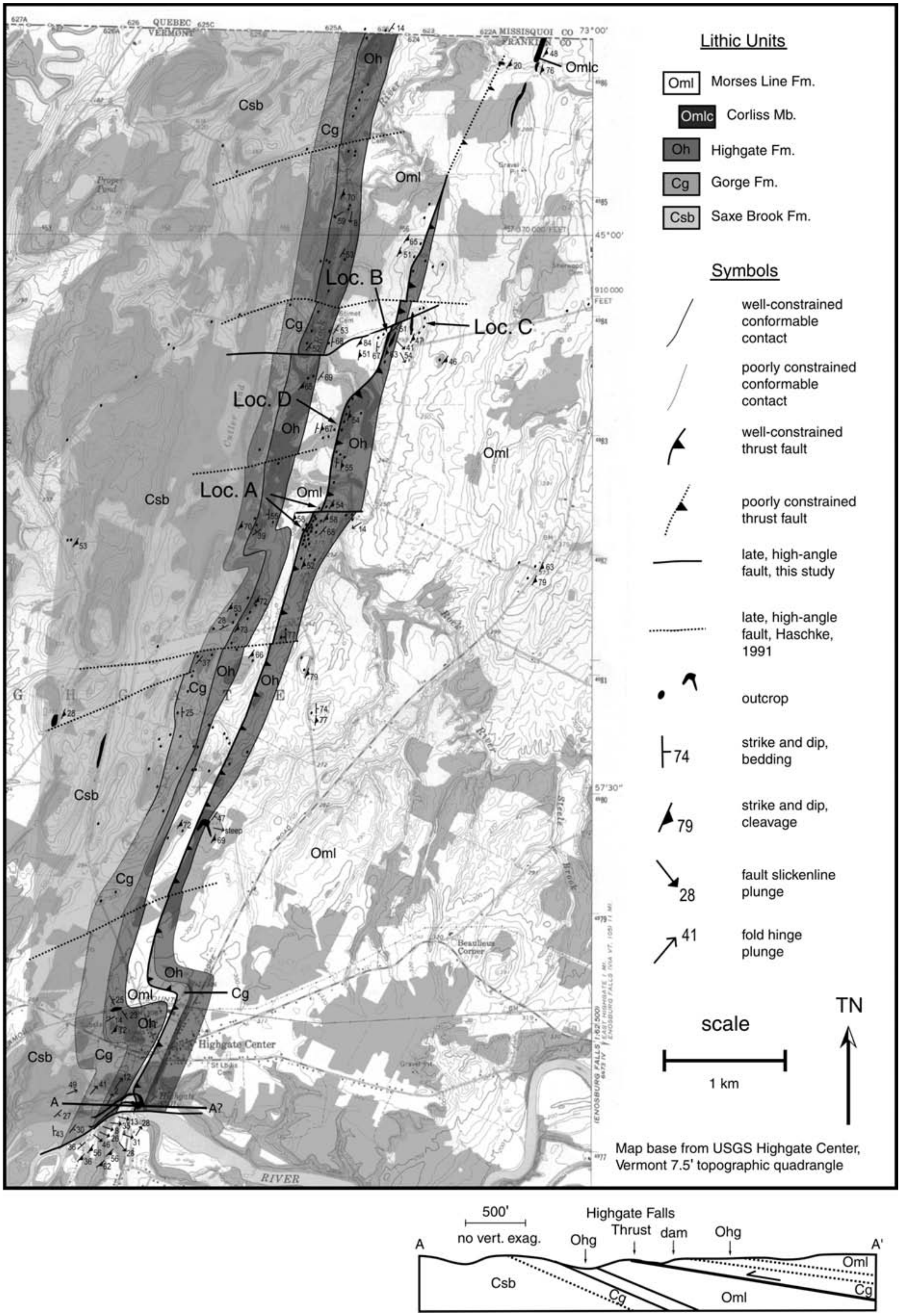
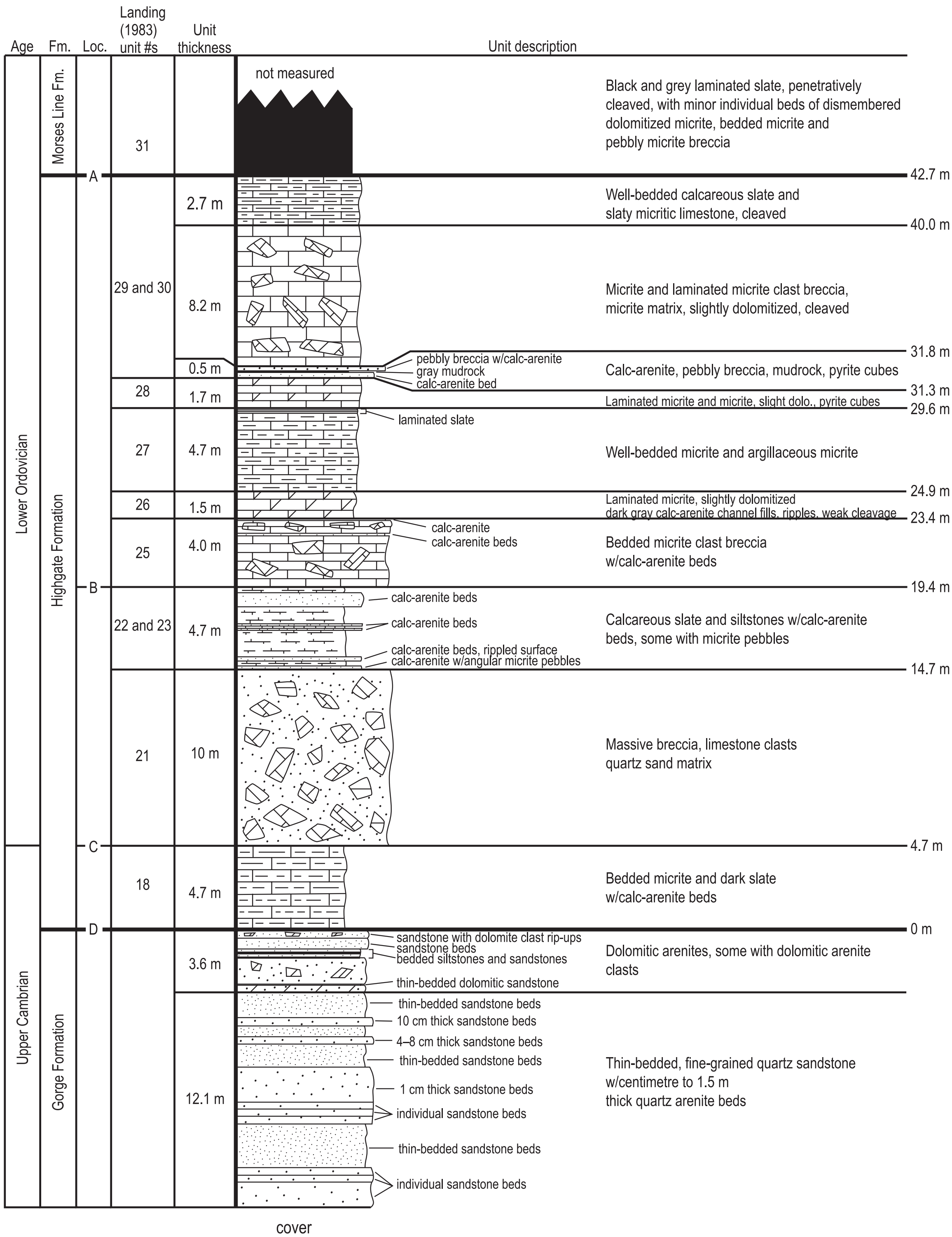


Fig. 4. Measured detailed lithostratigraphy of part of the continuously exposed section on the north shore of the Missisquoi River gorge at Highgate Center. Cambrian–Ordovician boundary from Landing (1983). Loc., locality; w/, with.



gorge or are inferred from mapping of these rocks north to the International Border and into Quebec, and these are discussed in the following subsections of text.

The contact between the Gorge and Highgate formations is depositional

The formal nomenclature of the section exposed in the Missisquoi River gorge has been controversial (see Landing 1983, pp. 1153–1154). Schuchert (1937) introduced the name Gorge Formation for a series of dolomite and limestone breccias, thin-bedded dolomites and limestones, and dolomitic slate in the lower part of the river gorge, equivalent to the upper part of Keith's (1923) Milton Formation, and restricted the Highgate Formation of Keith (1923) to the

Fig. 5. Field photos are all from the north bank of the Missisquoi River in the gorge at Highgate Center; see text for discussion. (A) The sedimentary breccia identified as "fault breccia" by Schuchert (1937). Pocketknife is 9 cm long. (B) Large arrow indicates contact between the lowest beds of the Highgate Formation (above) and the uppermost sandstone bed of the Gorge Formation (below) (loc. D, Fig. 7). Small arrow points to 15 cm tall notebook. (C) Minor, locally impersistent thrust fault at contact between Highgate (HG) and Morses Line (ML) formations. Arrow A points to calcite slickenfiber vein, ~1 cm thick. Arrow B points to dime for scale, only partially visible. Large bi-directional arrow indicates cleavage orientation. (D) Minor thrust faults and en echelon fractures in Morses Line Formation. A arrows point to deformed fault, slip surface parallels ground surface in photo. B arrows indicate relatively undeformed planar thrust that cuts oblique to ground surface. Both faults are surrounded by extension fractures (C arrows). Pocketknife is 9 cm long. (E) Highgate Falls thrust exposed in the Missisquoi River Gorge. Geologist (A.S.) points to slip surface. Upper block has moved to the west (left in photo). Photo courtesy of Marjorie Gale.

overlying limestone breccias, bedded limestones, and slate, with rare dolomites and overlying black slates (also Pingree 1982). Schuchert (1937) considered the contact between these two formations to be the base of a massive limestone breccia (locality (loc.) C, Fig. 4), which he interpreted as a thrust breccia. However, all subsequent workers (Shaw 1958; Landing 1983; Mehrtens and Dorsey 1987; Haschke 1994), including us, have interpreted this as a depositional contact and consider the breccia to be of sedimentary origin (Fig. 5*a*), based on a lack of slip-related hard-rock structures, cleavage, offsets, or truncations at its upper and lower contacts, or internally, and its conformable relationship with bedding. Landing (1983), following Keith (1923), redefined the Gorge–Highgate contact to loc. B (Fig. 4), thereby placing the lower quartz sand-bearing rocks in the Gorge Formation and the upper quartz sand-free rocks into the Highgate Formation. Later, Haschke (1994) moved the formation contact to the base of the first occurrence of limestone beds (loc. D, Fig. 4; Fig. 5*b*). We agree with Haschke's (1994) definition because the change in lithology from sandy dolomites to limestones is a more readily recognizable lithic marker in the field than the presence or absence of quartz sand, since some parts of Landing's (1983) upper Gorge Formation is quartz sand-free. This also corresponds to the change in depositional environment from a dolomite–quartz-sand shelf environment to a lime-mud–breccia continental-slope environment, as proposed by Landing (1983) and Mehrtens and Dorsey (1987). In any case, none of these contacts show evidence of faulting.

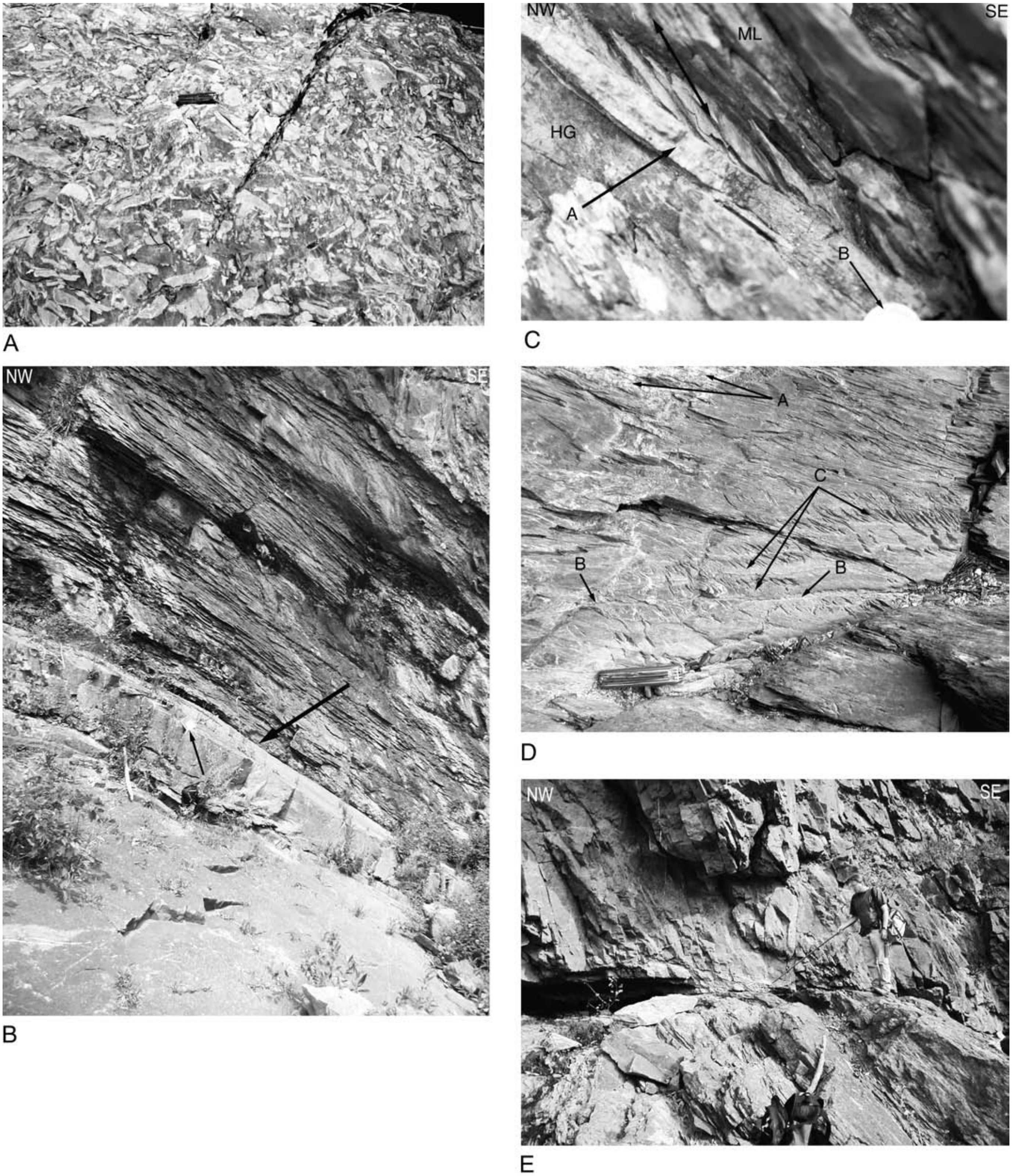
The contact between the Highgate limestones and overlying black slates is depositional

Keith (1923) assigned the black slates in the upper part of the Missisquoi River gorge, beneath the Highgate Falls Thrust (above loc. A, Fig. 4), and the underlying well-bedded calcareous slates and slaty limestones (below loc. A, Fig. 4) as the upper and lower Highgate Slate, respectively. Rocks at the top of the Highgate slate were designated as the Swanton Conglomerate (Corliss Conglomerate of Schuchert 1937; Fig. 2) and are overlain by the Georgia Slate (now Morses Line Formation). The Highgate Formation of Schuchert (1937) includes all the rocks between this conglomerate and the top of the sandy dolomites (loc. D, Fig. 4). However, Shaw (1958) only designated the slate section as the Highgate Formation. Haschke (1994) later redefined the lower calcareous slates and slaty limestones to be the uppermost section of the Highgate Formation and the overlying black slates as basal Morses Line Formation, a name introduced by Shaw (1958) for the large expanse of slates found east of the village of Highgate Center. We agree with Haschke's (1994) proposal because of the relative ease of separating the dominantly bedded, gray limestone and limestone breccias from the dominantly gray-black slates along an observable and mappable contact within the study area. This contrasts with the difficulty of separating the slates similar to those in the river gorge (upper Highgate Slate) from black and gray, and in-part calcareous, slates that underlie large areas along the eastern part of Fig. 4, generally attributed to the Morses Line Formation (see Doll et al. 1961). In no part of the lower calcareous section (Highgate Formation) do slates make up more than a small percentage of the rock, and slate or silt beds are typically <1 cm thick. In the upper slate section (Morses Line Formation), slates make up more than 90% of the rock, and thin limestone-dominated sections are interspersed between slates sections many metres to tens of metres thick.

The Highgate – Morses Line formation contact may be considered an alternative fault surface to emplace allochthonous slates over parauthochthonous carbonate rocks (loc. A, Fig. 4). It has been alternately interpreted as conformable (Shaw 1958; Pingree 1982), a thrust fault (Landing 1983), or a normal fault (Haschke 1994). Landing (1983) interpreted the thick breccia near the top of the carbonates of the Highgate Formation (Landing's units 29 and 30; Fig. 4) as a tectonic breccia and inferred that it marks a thrust boundary. However, the breccia is clearly of sedimentary origin because there are no significant faults, fault-zone cleavage, slickenlines, fault gouge, or other slip indicators present in or bounding this unit. Also, large coherent and conformable bedded limestones are present, not bounded by slip surfaces, above and below this breccia.

The top of Landing's unit 30 (limestone–slate contact) is deformed by a single mesoscopic, angular, open fold in bedding (but not cleavage) whose hinge lies along the shore of the Missisquoi River and extends across it. The contact along the northern shore limb is a minor reverse fault with a stepped, slickensided surface parallel to bedding and cuts the penetrative cleavage (Fig. 5*c*). It is associated with rotated en echelon calcite-filled veins and has a slip surface < 2 cm thick with an offset that varies but is not more than several centimetres. However, on the southern shore, the contact is observably depositional, lacking any slip-related features, truncations, fault-zone cleavage, or offsets like those on the north shore.

One steep to moderately east-dipping slaty cleavage is well developed in the slates of the Morses Line Formation; this cleavage decreases rapidly in intensity down-section through the Highgate Formation limestones and is not developed in the massive dolostones of the Gorge Formation. The



variable intensity and spacing of this cleavage (a solution cleavage) in the Highgate limestones appear to depend on both the argillaceous component of a particular bed and on its height in the east-dipping section.

A number of minor reverse faults (Fig. 5*d*) cut the exposed slates and limestones of the Morses Line and Highgate formations in the Missisquoi River gorge (excluding the Highgate Falls Thrust). They have thin fault zones, typically about 1 cm thick or less, that are of short lateral extent as many of these faults die out within the exposed outcrop, and the displacements are estimated to be on the order of millimetres to < 1 m. Reverse sense is determined from steps in slickenfiber surfaces and en echelon fracture orientation and rotation. A spectrum of faults with similar characteristics range from planar thrusts to highly contorted faults; all are marked by calcite-filled veins with slickenfiber slip surfaces and are associated with calcite-filled, en echelon extension fractures. Thin fractures with millimetre displacements linking individual unrotated extension fractures appear to be early, whereas later faults have up to 1 cm thick slickensided veins and cut several generations of extension fractures, some of which show variable amounts of rotation. Older, highly contorted faults generally contain annealed calcite veins, but some still show slickenfiber surfaces. These are also associated with sets of en echelon extension fractures that have also been folded. Most folded fault surfaces have axial planes parallel to cleavage in the surrounding rocks indicating that shortening strain associated with cleavage generation was responsible for folding. In contrast, the younger faults crosscut the penetrative cleavage in the slate and, although similar to the earlier faults, may have formed from a separate event.

Disrupted beds of dismembered, orange-weathering, fine-grained dolomite in the dark slates are displaced, at least in part, by small normal faults that were developed pre-cleavage. These faults were the primary evidence of Haschke (1994) for a large-scale normal fault at the Highgate – Morses Line contact, which we discount as soft-sediment slump-related structures.

In the Missisquoi River gorge, the black slates extend laterally ~100 m east of their conformable contact with the Highgate Formation to where they are truncated by the Highgate Falls Thrust. Along strike to the north, they are present west of a discontinuous ridge that forms the hanging wall of the Highgate Falls thrust (locs. A, B, and D, Fig. 3). The slaty beds of limestone of the Highgate Formation, and the black slates (including dismembered dolomite beds) of the lower Morses Line Formation, are then repeated on the eastern flank of the thrust-floored ridge (loc. C, Fig. 3). Based on this, and regardless of how the black slates are designated, the depositionally continuous section (excluding the Highgate Falls thrust) exposed in the Highgate gorge continues across strike at least as far east as the along-strike position of location C in Fig. 3.

The Highgate Falls Thrust in Vermont

The Highgate Falls Thrust is well exposed in the Missisquoi River gorge (Fig. 5*e*) and emplaces dolomitic arenites and sedimentary arenitic breccias of the lower Gorge Formation over black slates containing intercalated bedded limestones and limestone breccias of the lower Morses Lines Formation. The slip surface is undulatory but, on average, dips shallowly to the east. The fault zone is cataclastic with a locally developed fault-zone foliation. Folds in the bedding of the lower block and cleavage of both the upper and lower blocks, as well as the orientation of the fault-zone fabric, indicate a generally westerly transport direction for the upper block. The Highgate Falls Thrust is a late, out-of-sequence thrust and may possibly be coeval with many of the minor thrusts seen in the underlying slates since slip surfaces along the fault cut the penetrative cleavage in the lower block.

North of the Missisquoi River, the Highgate Falls Thrust can be traced along the western base of a series of discontinuous low ridges underlain by limestones of the Highgate Formation. At locs. A, B, and D (Fig. 3), limestone breccias and bedded limestones and slates similar to those seen in the Missisquoi River gorge are thrust over black slates of the Morses Line Formation. At these locations, fault-zone breccias containing carbonate slivers are present along the contact between the two units. Approximately 200 m south of the International Border, a thrust fault emplaces slates over slates, and no rocks below the lower Morses Line Formation are present. The along-strike change in the rocks of the upper plate (Gorge Formation in the Missisquoi River gorge to Highgate Formation at locs. A and B (Fig. 4), to Morses Line Formation near the border) suggests that the thrust ascends along-strike to the north, possibly along lateral ramps.

The Corliss Member of the Morses Line Formation is present near the International Border

The Corliss Member (Fig. 3), a discontinuous, limestone boulder conglomerate horizon within the Morses Line Formation, originally the Corliss Conglomerate of Schuchert (1937), was named for a series of outcrops (Corliss ledge) south of the Missisquoi River (not shown in Fig. 3). Because we consider the slates beneath this limestone conglomerate to be part of the Morses Line Formation, rather than the upper Highgate Slate, we consider the conglomerate to be an internal member of the Morses Line Formation (Corliss Member).

Nearby and stratigraphically above the conglomerate in Quebec is the “intermediate rhythmite” of the Stanbridge Group. Haschke (1994) correlated this unit with lithologically similar rocks in a railway cut on the northern outskirts of the village of Highgate Center. We have observed similar rocks there and along-strike to the north, structurally below the Highgate Falls Thrust. Based on this distribution, it is likely that the Corliss Member conformably overlies the black slates seen in the Missisquoi River gorge, although this cannot be demonstrated with certainty.

Southern Quebec

The area remapped in Quebec includes the rocks previously assigned to the Milton Dolomite and the adjoining western slaty part of the “lower sequence” of the Stanbridge Group (Fig. 6). All of the formations seen in Vermont are present in Quebec and, additionally, the Dunham Formation occurs in the western part of the area. It is proposed that the name Milton Dolomite be dropped in recognition that the dolomites and breccias of the Dunham, Saxe Brook, and Gorge formations, which make up the lower part of the Rosenberg slice of Vermont, can be delineated in Quebec (Fig. 6). Furthermore, the name has been abandoned in Vermont (Shaw 1958).

The dolomites of the Dunham Formation closely resemble those of the Saxe Brook Formation, but are distinguished by the absence of well-rounded quartz sand. Along the contact between the two units, there are several alternating layers of sandy dolomite and quartz-free dolomite, which represent a section of at least several metres thickness. In many places, the near-horizontal bedding makes placement of the formational contact difficult, and consequently, its position in Fig. 6 should be viewed as an approximation. The Saxe Brook Formation typically contains abundant well-rounded white and

Fig. 6. Geologic map, St. Armand Station area, southern Quebec. FM., Formation; Mb., Member. For geological unit abbreviations see Fig. 3.

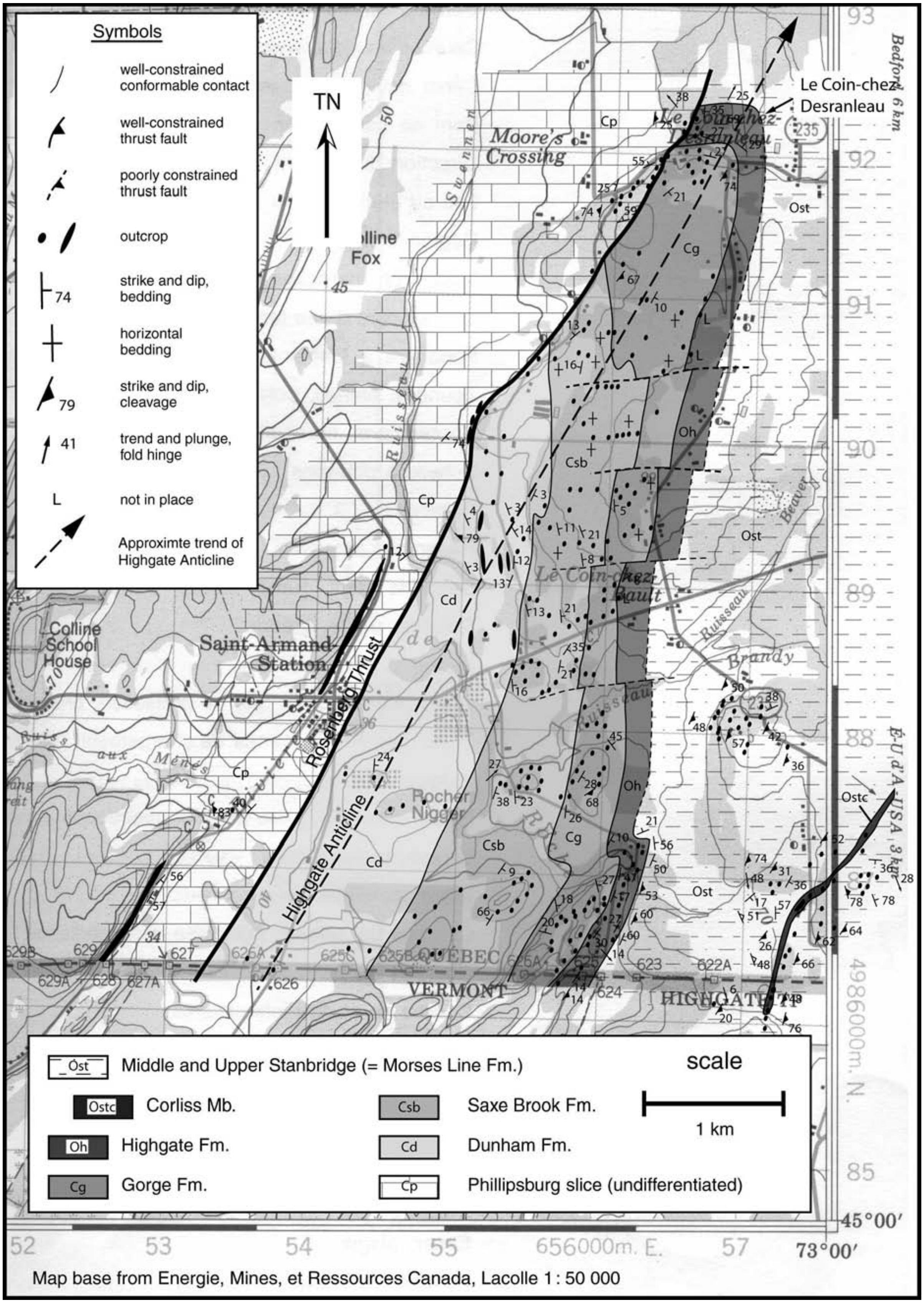
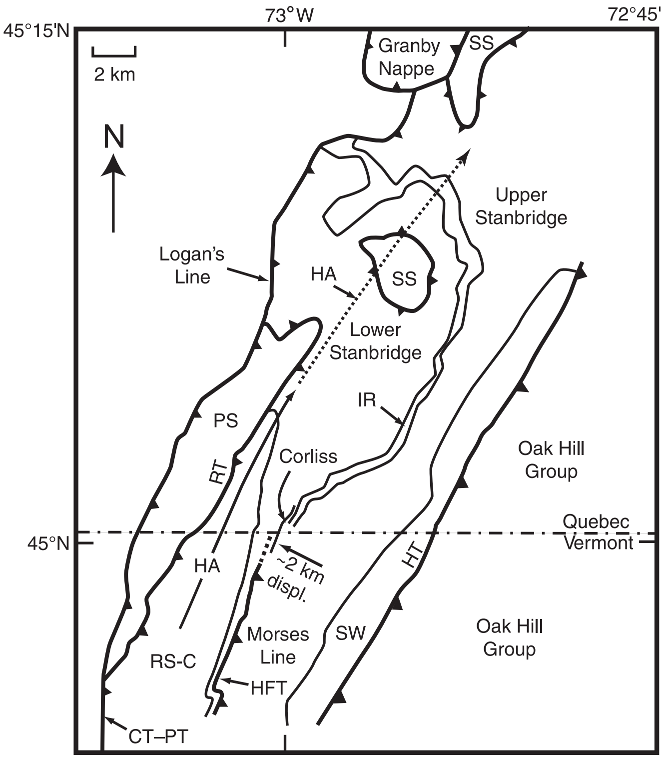


Fig. 7. Generalized geology and structure of southern Quebec and northwestern Vermont. CT–PT, Champlain–Phillipsburg Thrust; HA, Highgate Anticline; HFT, Highgate Falls Thrust; HT, Hinesburg Thrust; IR, intermediate rhythmite unit of the Stanbridge Group, PS, Phillipsburg slice; RS-C, Carbonates of the Rosenberg slice (up to the top of the Highgate Formation); RT, Rosenberg Thrust; SS, Saint Sabine windows; SW, Sweetsburg, Dunham, and Cheshire formations east of the Hinesburg Thrust. Adapted from Doll et al. (1961); Charbonneau (1980); Globensky (1981); Avramtchev (1989); this study.



clear quartz sand. This unit is massively bedded but in places display beds of 0.5 m or more thickness. Weathered surfaces are generally smooth (excluding the quartz sand grains) and brown to yellow in color.

Although well-bedded in the Missisquoi River gorge, the Gorge Formation in Quebec is not. It comprises fractured, variably arenaceous, massive dolomites and sedimentary breccias composed of dolomitic clasts in an arenaceous dolomitic matrix, with varying abundances of broken arenite beds and rare cobbles of mature white quartz sandstone.

The Highgate Formation in Quebec comprises ribbon-bedded slaty limestones but lacks the numerous breccia units seen in Vermont (Fig. 4). Exposures of these beds are present at the International Border and north to the Rock River, where they are folded westward and dive beneath a thick blanket of till. Northward, they do not reappear in definite outcrop until Le Coin-chez-Desranleau, where good outcrops of bedded limestones wrap around the northernmost exposures of the underlying dolomitic rocks of the Gorge Formation and are crosscut by the Rosenberg Thrust.

The Corliss Member of the Morses Line Formation extends into Quebec along a typical north-northeastern strike, but north of the border turns to the east and passes off into a series of low ridges in fields. Charbonneau (1980) noted these outcrops on his map and showed them paralleling, and beneath, his middle unit of the Stanbridge Complex.

Two significant conclusions arise from the distribution, orientation, and contact relations of the rocks in Quebec and are described as follows.

The conformable relationships in Vermont are likely present in Quebec

In previous studies, the contact between the Gorge and Highgate formations in Quebec (= base of "lower sequence" of the Stanbridge Group) has been inferred to be a thrust (Charbonneau 1980; Globensky 1981). However, at no place is the contact between the Highgate and Gorge formations directly observed, although the two formations are separated by only a few metres, both in the north (Le Coin-chez-Desranleau) and south (Rock River to International Border). Furthermore, there is no evidence, in the form of slivers of exotic material, mélange, fault rock, fault-zone-localized cleavage, or related deformational structures, of a fault contact. The sedimentary breccias in the Gorge Formation of Vermont (Mehrtens and Dorsey 1987; Landing 1983; this study) are similar in nature in Quebec. Because the relationships are clear in Vermont, and there is no evidence to the contrary in Quebec, we think it is reasonable to infer that no thrust is present at the base of the Stanbridge Group.

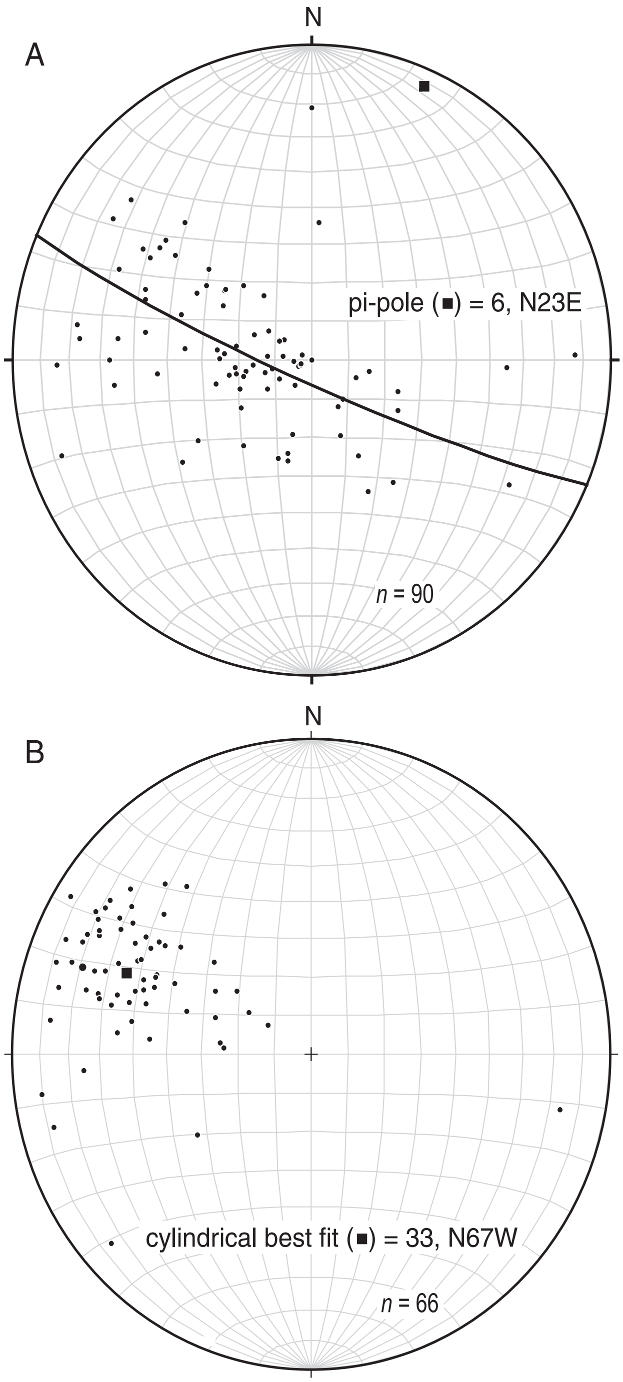
In Vermont, the Corliss Member of the Morses Line Formation and rocks correlated with the "intermediate rhythmite" unit of the Stanbridge Group occur within the Morses Line Formation (Haschke 1994; this study). East of the Highgate Falls thrust, beginning near the International Border, the Corliss Member (see Fig. 3) and "intermediate rhythmite" unit lie close to one another and are mapped in parallel for at least 2 km northeastward in Quebec (Fig. 7), suggesting that no fault exists between the two. Also in Quebec, these two units both turn sharply to the east, and while the conglomerate disappears under cover, the "intermediate rhythmite" unit extends nearly to the eastern boundary of the Stanbridge Group before turning north and finally trending back to the west (Charbonneau 1980; Figs. 1, 7).

Based on this, most of the areal extent of the Stanbridge Group (including the "lower sequence" and "intermediate rhythmite" units) is likely a conformable sequence, although definite evidence is lacking for the "upper sequence."

The northern termination of the Gorge and Highgate formations is an anticlinal hinge, truncated by the Rosenberg thrust

The bedding relationships and the outcrop distribution at Le Coin-chez-Desranleau show that the units are folded around a large anticlinal fold, whose western limb is truncated along the Rosenberg thrust (Fig. 6). The name Highgate Anticline is proposed for this structure. In outcrop, the limestones of the Highgate Formation wrap around the northernmost exposures of dolomite and show extensive mesoscopic folding in the macroscopic hinge area. The π-pole to bedding indicates a north-northeast-trending fold hinge (Fig. 8*a*). Its axial surface (assuming the cleavage is axial planar to this large-scale fold,) dips to the east (Fig. 8*b*).

Fig. 8. Structural data from Vermont and Quebec. (A) poles to bedding; (B) poles to penetrative cleavage.



Discussion and implications

The evidence in Vermont and southern Quebec indicates that most of the Stanbridge Group, relative to the carbonates of the Rosenberg slice, is not part of a continental rise-derived allochthonous nappe but was deposited as the upper part of the continental shelf- and upper slope-derived Rosenberg slice (after Landing 1983; Mehrtens and Dorsey 1987). Regardless of the accepted position of the Gorge–Highgate–Morse Line formation contacts, the rocks in the Missisquoi River gorge are a fully exposed section that is depositionally continuous from Late Cambrian sandy dolomites of the Gorge Formation, through the Early Ordovician limestones of the Highgate Formation, and into black slates beneath the Highgate Falls Thrust. Consistent with this interpretation is (1) the Early to Middle Ordovician age of the black slates relative to underlying Cambro-Ordovician strata (Gorge and Highgate formations), which contrasts with all of the other allochthons in Quebec that place older transported rocks on younger rocks of the Laurentian shelf; and (2) a lack of mélange or flysch associated with transport. Charbonneau (1980) considered the entire Stanbridge Group to be a complete, relatively unfaulted lithostratigraphic unit, and with no evidence to the contrary. We propose that the entire Stanbridge Group is a part of the parauthochthonous domain and not part of the Quebec Taconic Allochthons.

While no evidence was observed in Quebec to support the existence of a major thrust fault at or near the basal contact of the Stanbridge Group, thrust faults between internal slates of the Stanbridge Group and other units are seen in Quebec. In the Graymont quarry (Fig. 1), west of Bedford, an inlier of Stanbridge Group rocks is thrust over the Corey Formation of the Phillipsburg slice (Globensky 1981). This fault occurs 4 km north of Le Coin-chez-Desranleau (Fig. 6) and is most likely the northern extension of the Rosenberg Thrust that imbricates the Laurentian shelf and shelf edge rocks. Charbonneau (1980) reported Stanbridge Group rocks thrust over Middle Ordovician turbidites (bedded slates and calcareous slates and mudstones) of the Saint Sabine Formation (Fig. 1), previously Iberville Shale, along the northward extension of the Phillipsburg Thrust (Logan's Line according to Riva 1974), which is in turn thrust over Iberville Shale to the west. Charbonneau (1980) indicated that the St. Sabine Formation might be either an allochthonous nappe or a slice of the parauthochthonous foreland (see his figs. 68, 75 and p. 77) and correlated it with the Courval Formation and St. Germaine Complex father north. These rocks are now considered to be part of the autochthonous and parautochthonous St. Rosalie Group (Globensky et al. 1993; Stephan Séjourné, personal communication, 2005), and thus the Stanbridge Group need not be allochthonous, but more likely it is part of the imbricated continental shelf and slope.

An alternative hypothesis, in which the Phillipsburg thrust is an out-of-sequence thrust that post-dates emplacement of an allochthonous St. Sabine Formation, is unlikely since the allochthonous Granby Nappe that occurs farther north (Fig. 1) crosscuts the Phillipsburg Thrust. The Cambrian Granby Nappe contains volcanic horizons, is probably related to the Sillery Group, and is thrust over the younger Stanbridge Group and St. Sabine Formation (St.-Julien and Hubert 1975; Charbonneau 1980).

Hayman and Kidd (2002) suggested that the normal fault interpreted by Haschke (1994) at the contact between Highgate and Morses Line formations in the Missisquoi River gorge (loc. A, Fig. 4) is correlative with the normal-sense Mettawee Fault that cuts the Champlain Thrust system in west-central Vermont. However, the depositional contact exposed in the Missisquoi River gorge does not support this interpretation.

According to some workers (e.g., St.-Julien and Hubert 1975), Logan's Line is defined as the western boundary of the "nappes emplaced by gravity sliding", but not the "western limit of the outer belt of the thrust-imbricated structures" (p. 351). They drew this line at the western limit of the Stanbridge Nappe (their figs. 1, 2). Regardless of the mechanism of nappe emplacement, we do not consider the Stanbridge Group a far-traveled nappe. Accordingly, our study implies that Logan's Line does not extend south of the Granby Nappe. This is, especially historically, a rather unsatisfying interpretation, and therefore we suggest that Logan's Line should be placed at the significant structural break that occurs along the Champlain and Highgate Springs thrusts in Vermont, and their continuation as the Phillipsburg Thrust in southern Quebec. Only where the internal slates of the Stanbridge Group are thrust over the St. Sabine Formation does the western limit of the Stanbridge Group delineate Logan's Line. This interpretation acknowledges that Logan recognized the presence of a significant break in the faunal record of the Taconic foreland between Logan's Quebec Group (= Highgate Springs, Phillipsburg, and Rosenberg slices) and Ordovician shales (Logan 1861).

The distribution of the Stanbridge Group in southernmost Quebec is anomalous compared with the typical north-northeastern strike of units in Vermont, as shown by the meandering nature of the outcrop belt of Charbonneau's (1980) "intermediate rhythmite" unit of the Stanbridge Group and Corliss Member of the Morses Line Formation (Fig. 7). The Corliss Member strikes north-northeast in Vermont but bends to the east-northeast just north of the International Border and parallels the intermediate rhythmites for about 2 km before disappearing under cover. The rhythmites then continue to the northeast until they bend around a window of the St. Sabine Formation and are finally truncated at the Rosenberg Thrust. This distribution is generally parallel to the Highgate Anticline (Fig. 8), but the atypical change in strike (NNE to ENE) north of the International Border may be the result of west-directed displacement of the upper block of the Highgate Falls Thrust. Stratigraphic throw, and thus displacement on the thrust, decreases northward and dies out near the International Border forming a hinge point at the termination of the Highgate Falls Thrust (Fig. 7). The progressive decrease in upper block displacement, indicated by the rise in stratigraphic level of the upper block cut by the thrust in Vermont, suggests a gradual bending of the upper plate stratigraphy may be more likely. The relative strike position of the "intermediate rhythmite" unit near the International Border to its position southwest of the St. Sabine window suggests a minimum of ~2 km of displacement along the Highgate Falls Thrust in Vermont (Fig. 7).

The interpretation that the Stanbridge Group is part of the parauthochthonous Rosenberg slice has significant implications for its eastern boundary. Clark (1934) and Charbonneau (1980) drew this boundary at the Oak Hill Thrust, separating the Stanbridge Group to the west from the Sweetsburg Formation to the east (Fig. 7). In contrast, Doll et al. (1961) show the equivalent contact in Vermont to be conformable. The Hinesburg Thrust occurs a short distance to the east, underlying the Cheshire Formation in Vermont and Quebec (Doll et al. 1961; Avramtchev 1989; Rickard 1991). According to our work, the eastern contact of the Stanbridge Group and equivalent Morses Line Formation is conformable, with the Morses Line Formation forming the core of the St. Albans Synclinorium (Fig. 1) and the Sweetsburg Formation occurring along its eastern limb, although it is possible that other, unrelated thrusting may have occurred there.

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