Atlantic Geoscience
Journal of the Atlantic Geoscience Society

Termination of the Ganderian Cambrian–Ordovician Miramichi terrane in east-central Maine, northern Appalachian orogen, USA

Terminaison du terrane cambro-ordovicien gandérien de Miramichi dans le centre-est du Maine, nord de l'orogène des Appalaches, États-Unis

Allan Ludman and Amber T. H. Whittaker

Volume 59, 2023

URI: https://id.erudit.org/iderudit/1106342ar
DOI: https://doi.org/10.4138/atlgeo.2023.006

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Publisher(s)

Atlantic Geoscience Society

ISSN

2564-2987 (digital)

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Cite this article

Ludman, A. & Whittaker, A. (2023). Termination of the Ganderian Cambrian–Ordovician Miramichi terrane in east-central Maine, northern Appalachian orogen, USA. *Atlantic Geoscience*, *59*, 123–146. https://doi.org/10.4138/atlgeo.2023.006

Article abstract

The Ganderian Cambrian–Ordovician Miramichi terrane narrows in east-central Maine and terminates at the junction of faults that separate it from the mostly Silurian Central Maine/Aroostook–Matapedia basin (CMAM) to the northwest and Fredericton trough to the southeast. The terrane was emergent after Middle Ordovician recumbent folding and shed sediment to both adjacent depocenters. Its boundary faults are the youngest deformation events and play important roles in its termination, but do not by themselves explain it. The presence of distinctive CMAM strata southeast of the northwest boundary fault indicates that the first step in developing the current relationships was an episode of hitherto unrecognized late Silurian eastward thrusting. In the northern (Danforth) segment of the terrane, intermediate facies CMAM strata were thrust onto their Miramichi source rocks. The thrust sheet was deformed by Acadian upright folds, then dissected by dip-slip offset along boundary and internal faults prior to intrusion of the 409 ± 2 Ma Skiff Lake pluton. Subsequent erosion isolated a remnant of the thrust sheet as the Dill Hill klippe, its allochthonous CMAM strata isolated among Miramichi rocks. The southern (Greenfield) segment experienced similar events, but current relationships are different and timing of the late-stage faults is not well constrained. Allochthonous CMAM strata may have overridden the Miramichi terrane completely, so that a remnant of distinctive CMAM strata is now exposed east of the Miramichi terrane in fault contact with rocks of the Fredericton trough. The entire Greenfield segment is interpreted as a fault block exposed within the thrust sheet.

Termination of the Ganderian Cambrian–Ordovician Miramichi terrane in east-central Maine, northern Appalachian orogen, USA

Allan Ludman[1*] and Amber T.H. Whittaker[2]

1. School of Earth and Environmental Sciences (emeritus),
Queens College (CUNY), Flushing, New York 11367, USA
2. Maine Geological Survey, 93 State House Station, Augusta, Maine E 04433, USA
*Corresponding author <allan.ludman@qc.cuny.edu>

Date received: 21 March 2023 ¶ Date accepted: 29 June 2023

ABSTRACT

The Ganderian Cambrian–Ordovician Miramichi terrane narrows in east-central Maine and terminates at the junction of faults that separate it from the mostly Silurian Central Maine/Aroostook–Matapedia basin (CMAM) to the northwest and Fredericton trough to the southeast. The terrane was emergent after Middle Ordovician recumbent folding and shed sediment to both adjacent depocenters. Its boundary faults are the youngest deformation events and play important roles in its termination, but do not by themselves explain it. The presence of distinctive CMAM strata southeast of the northwest boundary fault indicates that the first step in developing the current relationships was an episode of hitherto unrecognized late Silurian eastward thrusting. In the northern (Danforth) segment of the terrane, intermediate facies CMAM strata were thrust onto their Miramichi source rocks. The thrust sheet was deformed by Acadian upright folds, then dissected by dip-slip offset along boundary and internal faults prior to intrusion of the 409 ± 2 Ma Skiff Lake pluton. Subsequent erosion isolated a remnant of the thrust sheet as the Dill Hill klippe, its allochthonous CMAM strata isolated among Miramichi rocks. The southern (Greenfield) segment experienced similar events, but current relationships are different and timing of the late-stage faults is not well constrained. Allochthonous CMAM strata may have overridden the Miramichi terrane completely, so that a remnant of distinctive CMAM strata is now exposed east of the Miramichi terrane in fault contact with rocks of the Fredericton trough. The entire Greenfield segment is interpreted as a fault block exposed within the thrust sheet.

RÉSUMÉ

Le terrane cambro-ordovicien gandérien de Miramichi se rétrécit dans le centre-est du Maine, et il prend fin à la jonction des failles qui le sépare du bassin principalement silurien du centre du Maine/Aroostook-Matapédia (CMAM) au nord-ouest et de la cuvette de Fredericton au sud-est. Le terrane a émergé après la formation de plis couchés de l'Ordovicien moyen et la diffusion de sédiments dans deux zones de dépôt adjacentes. Ses failles limitrophes constituent les épisodes de déformation les plus récents, et ils jouent des rôles importants dans sa terminaison, sans toutefois expliquer celle-ci par eux-mêmes. La présence de strates distinctives du bassin CMAM au sud-est de la faille limitrophe nord-ouest révèle que le premier stade de l'apparition des liens existants a été un épisode de chevauchement vers l'est du Silurien tardif qui n'avait pas été reconnu jusqu'ici. Dans le segment septentrional (Danforth) du terrane, des strates du faciès intermédiaire du bassin CMAM ont été charriées sur leurs roches mères de Miramichi. La nappe de charriage a été déformée par des plis droits acadiens, puis disséquée par un déplacement horizontal de rejet-pendage le long des failles limitrophes et internes avant l'intrusion du pluton de 409 ± 2 Ma du lac Skiff. Une érosion subséquente a isolé un vestige de la nappe de charriage pour créer la klippe de la colline Dill, ses strates allochtones du bassin CMAM isolées parmi les roches de Miramichi. Le segment méridional (Greenfield) a été touché par des phénomènes similaires, mais ses liens actuels sont différents et le moment de la formation des failles tardives n'est pas bien délimité. Les strates allochtones du bassin CMAM pourraient avoir complètement recouvert le terrane de Miramichi, de sorte qu'un vestige des strates distinctives du bassin affleure aujourd'hui à l'est du terrane de Miramichi en contact faillé avec les roches de la cuvette de Fredericton. L'ensemble du segment de Greenfield est interprété comme un bloc faillé découvert à l'intérieur de la nappe de charriage.

[Traduit par la redaction]

ATLANTIC GEOSCIENCE 59, 123–146 (2023)
doi: 10.4138/atlgeo.2023.006
2564-2987|23|00123–146 $4.60|0

INTRODUCTION

Maine and New Brunswick are underlain by several northeast-trending terranes of late Cambrian to Middle Ordovician strata isolated within extensive areas of Upper Ordovician to Middle Devonian cover rocks (Fig. 1). The Miramichi terrane is the largest of these terranes, extending more than 400 km from Chaleur Bay in northern New Brunswick near Bathurst to east-central Maine, where it narrows drastically and terminates abruptly southwest of the town of Greenfield. As the most extensive Cambrian–Ordovician terrane, it plays a critical role in deciphering the early Paleozoic tectonic evolution of the Northern Appalachian orogen.

Despite its tectonic significance, the critical Miramichi termination area has only recently been mapped in detail (Ludman 2020a, b, 2023; Ludman *et al.* 2021). This paper describes the stratigraphy and deformation history of the Miramichi terrane in Maine and its relationships with adjacent cover strata, and proposes an explanation for its rapid narrowing and abrupt termination.

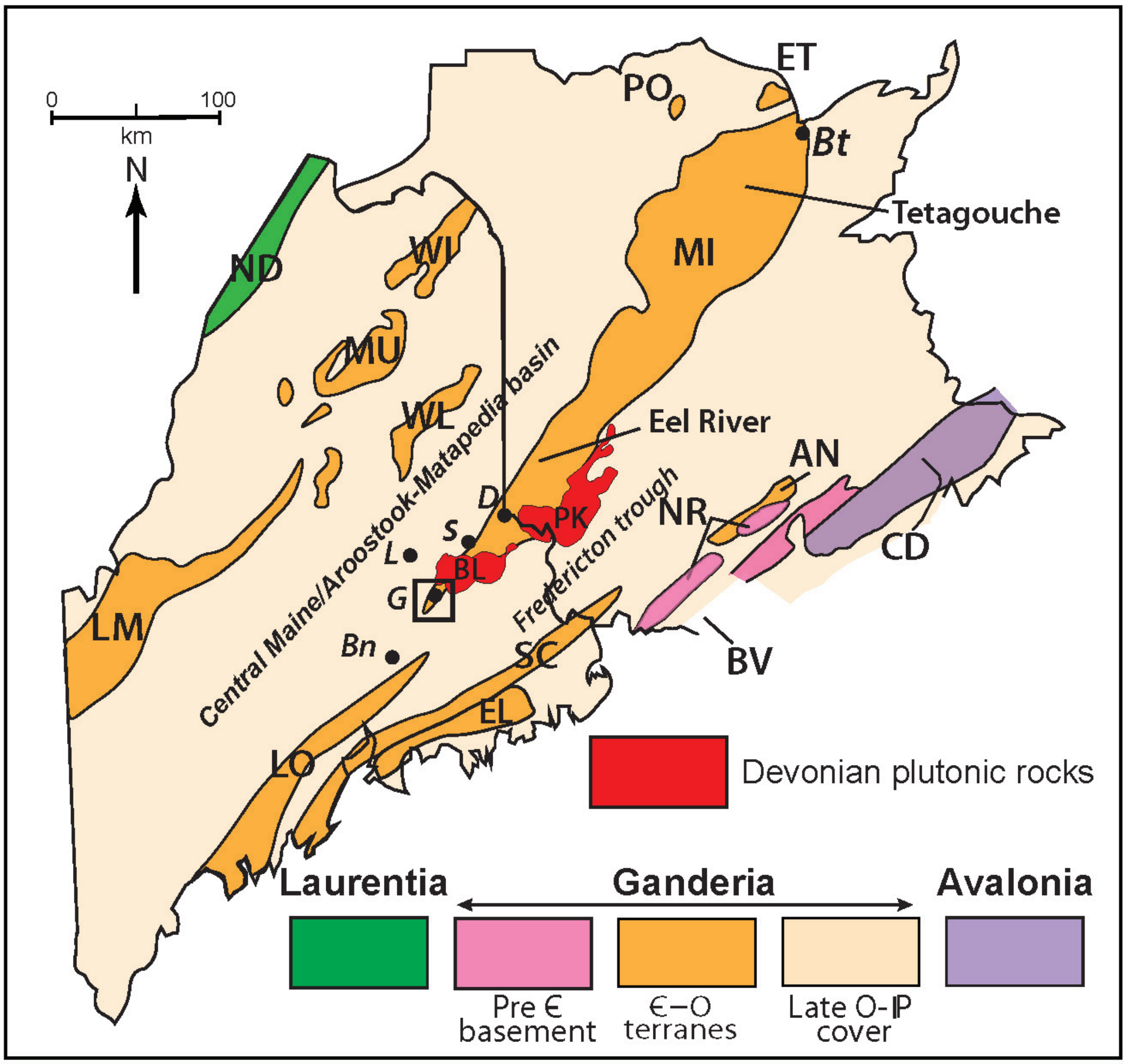

Figure 1. Lithotectonic framework of New Brunswick. Modified from Ludman *et al.* 2021; Fyffe *et al.* 2023). Rectangle outlines study area. Terranes: AN - Annidale; BV - Brookville; CD - Caledonia; EL - Ellsworth; ET - Elmtree; LM - Lobster Mountain; LO - Liberty–Orrington; MI - Miramichi; MU - Munsungun; ND - Notre Dame; NR - New River; PO - Popelogan; WI - Winterville; WL - Weeksboro–Lunksoos Lake. Plutonic complexes: BL - Bottle Lake; PK - Pokiok. *Towns: Bn - Bangor; Bt - Bathurst; D - Danforth; G – Greenfield; L - Lincoln; S - Springfield.*

PREVIOUS WORK

The Miramichi terrane in Maine had received little attention from mappers and was poorly understood at the time the most recent Maine bedrock map was published (Osberg *et al.* 1985). As a result, the northern (Danforth) segment on that map was based largely on a USGS regional reconnaissance study (Larrabee *et al.* 1965) and a single map of the Danforth 15' quadrangle (Larrabee and Spencer 1963). Even less was known about the southern Greenfield segment –a single Masters of Science thesis covering part of what is now the Greenfield 7½' quadrangle (Olson 1972). The terrane has been studied intensely over the past four decades, with initial results reported in New England Intercollegiate Geological Conference guidebooks (e.g., Ludman 1978, 1991) and an unpublished Masters of Science study of Miramichi volcanic rocks in the Danforth 15' quadrangle (Sayres 1986). The entire terrane has been mapped, most at 1:24 000-scale (Ludman 2003, 2023; Ludman and Hopeck 2020), with broader coverage in the Calais 1:100 000-scale sheet (Ludman and Berry 2003).

Years of mapping in the Greenfield segment were summarized in an initial report on the Greenfield 7½' quadrangle (Ludman 2020a), and the revised interpretation (Ludman 2023) will be included in a future compilation of the Lincoln 100 000-scale sheet by the first author. A recent study presented the geochemistry of volcanic rocks from both segments and U–Pb zircon ages of a lava and tuffs from the Greenfield segment (Ludman *et al.* 2021).

Revised geologic maps

Geologic maps in this paper reflect several improvements from the studies cited above, and Figures 2a and 2b compare current concepts with the 1985 Bedrock Geologic Map of Maine (Osberg *et al.* 1985). The most important changes pertinent to this paper include: (1) Cover rocks on both flanks of the Greenfield segment attributed by Osberg *et al.* (1985) to one formation deposited in a single basin are now assigned to several formations deposited in separate CMAM basin and Fredericton trough depocenters. (2) The southeastern contact of the Miramichi terrane with the Fredericton trough, shown as a normal stratigraphic contact by Osberg *et al.* (1985), presumably an unconformity, is now interpreted as a high-angle fault. (3) The northwestern contact of the Miramichi terrane with the CMAM basin, shown as a west-directed thrust on the 1985 bedrock map, is now interpreted as the high-angle, dip-slip North Bancroft and Stetson Mountain faults that modified an early east-directed thrust described below. (4) A thrust in the Miramichi terrane shown between the volcanic suites and underlying strata in both segments in 1985 is now interpreted as a normal stratigraphic contact.

TECTONIC CONTEXT

Evolution of the northern Appalachian orogen involved the progressive suturing to ancestral North America (Laurentia) of fragments broken from supercontinent Rodinia (Fig. 3a) through the early and middle Paleozoic, with orogenic events accompanying accretion of each fragment (Table 1). The current framework (Fig. 3b) was assembled by the Late Devonian after closure of the Iapetus and Rheic oceans. A later event, the late Paleozoic Alleghanian orogeny, sutured composite Laurentia to Gondwana to form the supercontinent Pangea, but although this was the climactic event in the central and southern Appalachians, it had little effect in the study area.

Tectonic setting of the Miramichi terrane

Researchers in Maine and New Brunswick agree that early Ordovician Miramichi volcanism occurred in a continental arc above a subduction zone terminated by the Middle Ordovician collision of Laurentia with the leading edge of Ganderia (Table 1; Fyffe *et al.* 2011; Ludman *et al.* 2021; Sayres 1986; Winchester *et al.* 1992; van Staal *et al.* 2016; Fyffe *et al.* 2023). Initial models envisaged a single subduction zone above which volcanism migrated toward the northwest (e.g., van Staal *et al.* 2016), but recent data from the Cambrian–Ordovician Miramichi, Weeksboro–Lunksoos Lake, and Munsungun–Winterville terranes in northeastern Maine suggest a more complicated scenario with at least two and possibly three coeval subduction zones (Ludman *et al.* 2021). This paper does not address the debate about Ordovician events (interested readers are referred to van Staal *et al.* (2016), Fyffe *et al.* (2023), and Ludman *et al.* 2021), but focuses on the later evolution of relationships of Miramichi and adjacent cover rocks in Maine leading to the terrane's termination.

GEOLOGIC SETTING

Extensive glacial, glaciofluvial, and fluvial deposits blanket the region, limiting bedrock exposures to less than 1% of the surface area. Both Cambrian–Ordovician Miramichi and adjacent CMAM and Fredericton trough strata experienced only low-grade regional metamorphism at supracrustal levels of the orogen (lower greenschist facies). As a result, even delicate primary sedimentary and volcanic features are generally well preserved, except in the inner parts of contact aureoles surrounding major plutons. Faults separate strata in the Miramichi terrane everywhere from the post-Middle Ordovician CMAM and Fredericton trough (Fig. 2b). Relationships are complex, as movement on the border faults was not coeval, and some faults experienced one or more reactivations

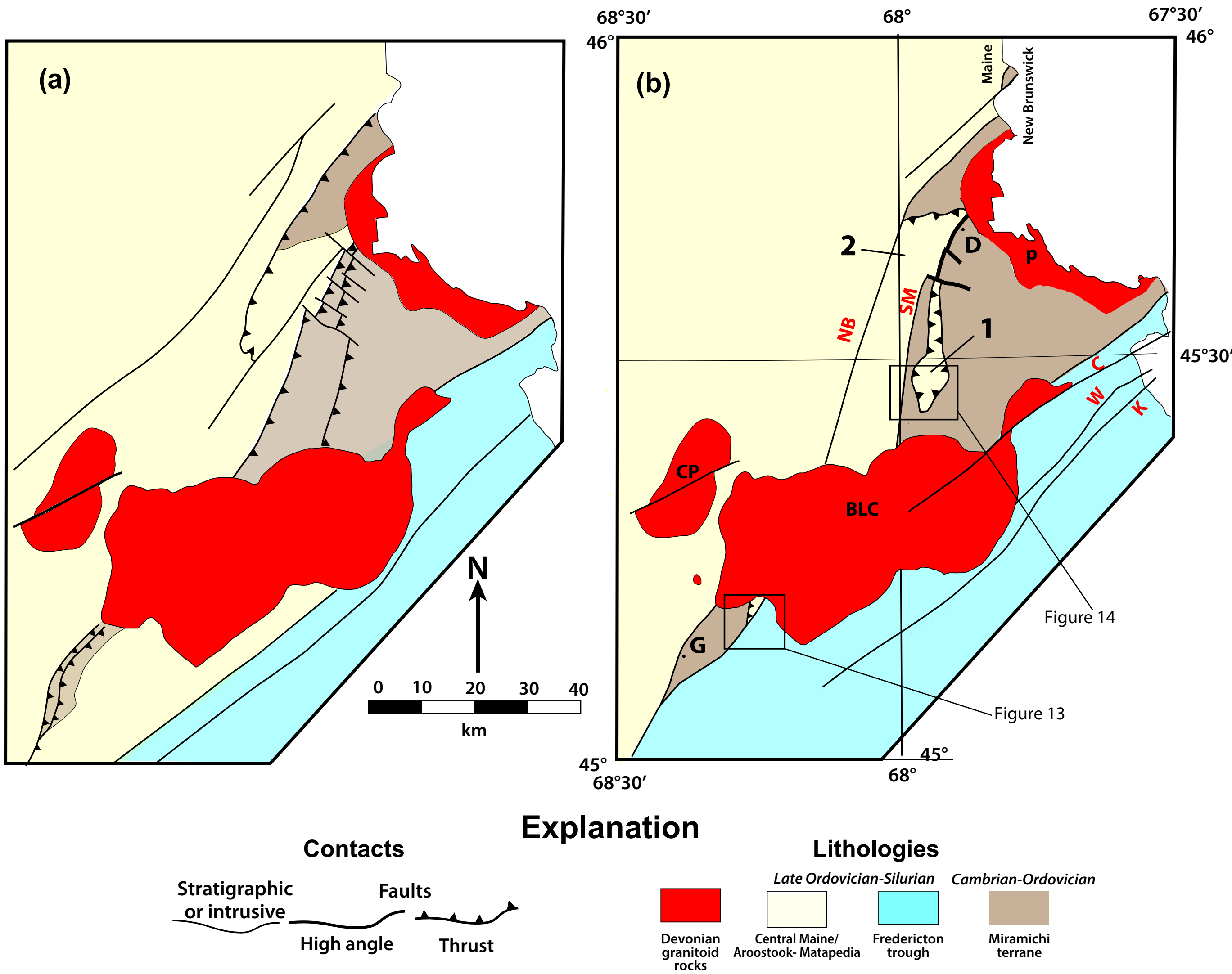

Figure 2. Simplified geologic maps comparing Miramichi geology as shown on the Maine bedrock map (Fig. 2a, after Osberg *et al.* (1985)) and current interpretation (Fig. 2b after Ludman *et al.* (2021)). GW - Greenfield window. Plutons: CP - Center Pond; BLC - Bottle Lake complex; P - Pokiok plutonic suite; Towns: D - Danforth; G - Greenfield. Faults: NB - North Bancroft; SM - Stetson Mountain. Norumbega fault strands: C - Codyville; W - Waite; K - Kellyland. 1 - Dill Hill klippe; 2 - eroded thrust remnant.

with different modes of offset. These complexities are responsible for the terrane's highly irregular boundaries in New Brunswick and Maine, and for the fact that internal structures are commonly not parallel to the border faults.

Two large plutonic complexes interrupt the continuity of the terrane (Fig. 2). The multiphase Pokiok plutonic suite spans the international border and separates Maine from New Brunswick components (New Brunswick Department of Natural Resources and Energy 2008; Osberg *et al.* 1985). The Bottle Lake plutonic complex further fragments the Maine Miramichi rocks into the Danforth and Greenfield segments. These plutons obscure stratigraphic correlations and connection of major structures like the North Bancroft and Stetson Mountain border faults to potential continuations in New Brunswick (Fig. 4). Indeed, depending on how those connections are drawn, the Greenfield and Danforth segments could lie on different fault blocks (e.g., Figs. 4a, b).

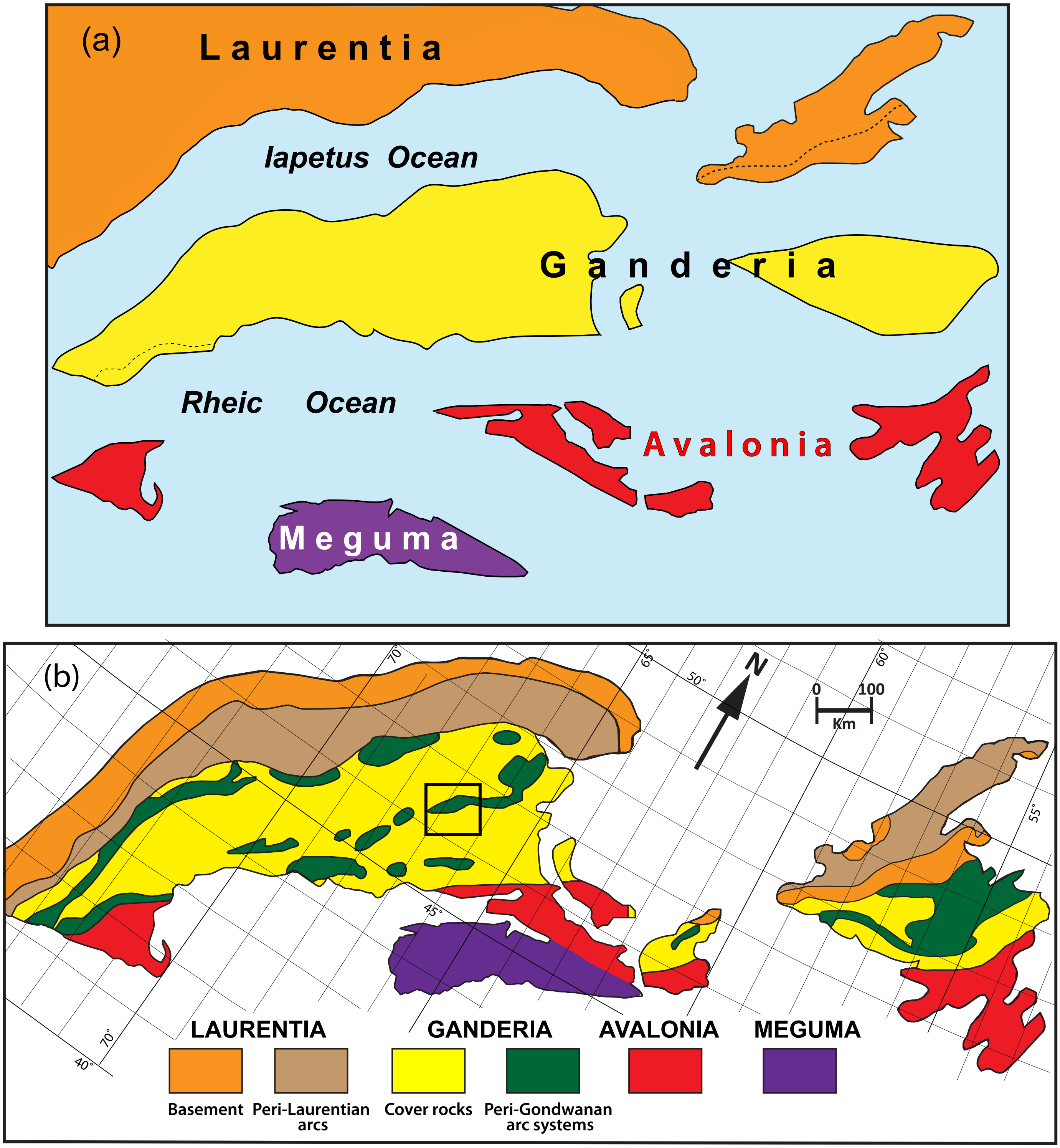

Figure 3. Tectonic framework of the study area. (a) Microplate fragments of supercontinent Rodinia prior to accretion to ancestral North America (after Ludman *et al.* 2022). (b) Current tectonostratigraphic framework of the Northern, Maritime, and Atlantic Appalachians (after Hibbard *et al.* 2006). Square outlines Miramichi terrane in Maine.

MIRAMICHI AND COVER ROCK STRATIGRAPHY

Most stratigraphic units in Maine lack fossil age control and several ages are assigned by correlation with sparsely fossiliferous strata in New Brunswick. Age ranges can only be approximations, because a single fossil locality in one formation is typically the only datum within a sequence of stratigraphic units thousands of metres thick. Maximum ages for some clastic units are constrained by the ages of their youngest detrital zircons, and eruptions of a few volcanic units are dated directly by U–Pb zircon geochronology.

Miramichi terrane

Concepts of stratigraphy in the Miramichi terrane of Maine have evolved slowly (Larrabee *et al.* 1965; Olson 1972; Sayres 1986; Ludman 1991, 2020a, b, 2023) but are now generally similar to those of Miramichi sections in west-central and northern New Brunswick (see Ludman *et al.* 2021). The stratigraphy exposed in the Danforth and Greenfield segments are similar but not identical (Fig. 5).

The oldest unit in both segments is the Baskahegan Lake Formation (Ludman 1991, 2003, 2022; Ludman and Berry 2003; Ludman and Hopeck 2020), a thick, dominantly quartzose and quartzofeldspathic sandstone unit. Its Cambrian to Lower Ordovician range is based on the presence of the trace fossils *Circulichnus montanus* in the upper member in New Brunswick (Pickerill and Fyffe 1999) and *Oldhamia smithi* in the correlative Grand Pitch Formation of the Weeksboro–Lunksoos Lake terrane (Neuman 1967).

The youngest units, the Stetson Mountain Formation in the Danforth segment and Olamon Stream Formation in the Greenfield segment, are thick series of Early to Middle Ordovician volcanic rocks partially dated by U–Pb zircon ages in the Greenfield segment at ~469 Ma (lowest Dapingian; Ludman *et al.* 2021). Both volcanic suites are calc-alkaline, dominantly andesite-dacite-rhyolite assemblages

Table 1. Tectonic evolution of the study area in the northern Appalachians (after Ludman *et al.* 2021).

	AGE	OROGENY	TECTONIC EVENT(S)
APPALACHIAN WILSON CYCLE	Permian	Alleghanian	Gondwana accreted to previously amalgamated plates forming supercontinent Pangea
	Late Devonian	"Neoacadian"	Meguma terrane accreted to previously amalgamated plates
	Early Devonian	Acadian	Avalon terrane accreted to previously amalgamated plates
	Late Silurian	Salinic	Accretion of Ganderia to Laurentia completed by closure of remnant back-arc basin at trailing edge of Ganderia
	Silurian	Early Salinic	Continued Ganderia–Laurentia convergence by closure of Tetagouche back-arc basin (Miramichi inlier)
	Middle Ordovician	"Taconic"	Leading edge of Ganderia collides with Laurentia[1]
	Ordovician		Continued Ganderia–Laurentia convergence
	Cambrian–Ordovician	Penobscot	Ganderian components (Miramichi, Annidale) reunite near trailing edge of the Ganderian plate
	Cambrian-Early Ordovician		Ganderia rifted from Gondwana, drifts toward Laurentia, and is fragmented by extension during Iapetan subduction that produces island arcs and back-arc basins
	Latest Neoproterozoic		Rifting of Rodinia, opening of Iapetus Ocean
	Neoproterozoic (ca. 1 Ga)	Grenville	Assembly of supercontinent Rodinia

[1]In New Brunswick, this event is referred to as the Taconic orogeny (e.g., Fyffe *et al.* 2023) but it is a long way from the Taconic system and although the two are coeval, their deformation is different. Rather than add to the proliferation of names for orogenic events, we choose to simply refer to it by its timing as Middle Ordovician.

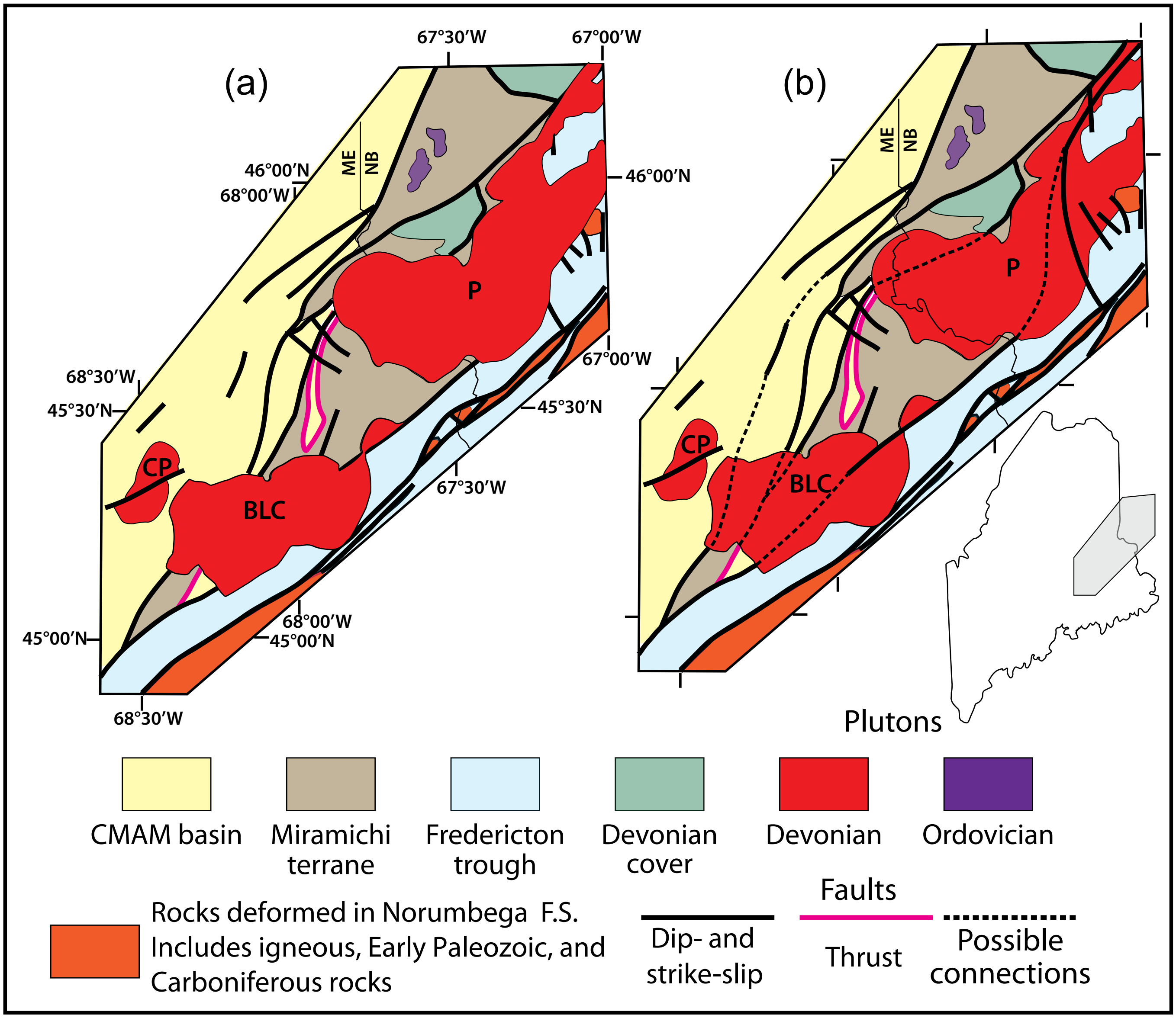

Figure 4. Two (of several) possible connections of major Miramichi faults in Maine and New Brunswick. (a) Greenfield and Danforth segments lie on same fault block. (b) Greenfield and Danforth segments lie on different fault blocks. Pluton labels as in Figure 2. Faults: NB - North Bancroft; WO - Woodstock; M - Meductic; SM - Stetson Mountain; C - Codyville strand; WA - Waite strands of the Norumbega fault system.

with distinctive but different manganiferous medial horizons. Subordinate basalts of uncertain stratigraphic position are restricted to the Olamon Stream Formation in the southwesternmost exposures of the terrane (Ludman *et al.* 2021). Sayres (1986) interpreted a transition in the Stetson Mountain Formation from cryptocrystalline basal ashfall tuffs to coarse ashflow tuffs, breccias, and volcaniclastic rocks, but this sequence is not recognized in the Olamon Stream Formation where both cryptocrystalline and coarsely fragmental volcanic rocks are present along with lava flows in several outcrops. The principal difference between the two segments is the presence in the Danforth area of a distinctive anoxic rusty-weathering quartzose sandstone- black shale unit (Bowers Mountain Formation) between the Baskahegan Lake and Stetson Mountain formations that is absent from all but the northernmost part of the Greenfield segment. The Baskahegan Lake–Bowers Mountain–Stetson Mountain sequence does emerge from the Bottle Lake plutonic complex into the northernmost part of the

Greenfield segment but the Bowers Mountain Formation is absent to the southwest. It is replaced there by the Lazy Ledges Road member of the Baskahegan Lake Formation, a unique unit of rhythmically bedded highly feldspathic quartzofeldspathic sandstone and siltstone (Ludman 2023; Ludman *et al.* 2021). This and other differences between the two segments are perhaps due to interfingering facies from different eruptive centers along the arc (Ludman *et al.* 2021), but structural complications may also play a role.

Cover rocks

Sediments in both cover rock depocenters are deep-water turbidites, and we focus here on post-Middle Ordovician rocks adjacent to the Miramichi terrane—the east flank of the CMAM basin and west flank of the Fredericton trough (Figs. 6 and 7, respectively). Clasts of characteristic Miramichi strata in the CMAM basin (Ho-peck 1998, 2013; Ludman and Hopeck 2020) and Fredericton trough (Fyffe and Fricker 1987) indicate that an emergent Miramichi terrane separated the two depocenters following Middle Ordovician deformation and shed sediment into both (Ludman *et al.* 2017). Deposition began in both in the Late Ordovician but ended in the Fredericton trough in the late Silurian prior to ~422 Ma (Ludman *et al.* 2018; West *et al.* 1992), while deposition continued uninterrupted in the center of the CMAM basin until Acadian deformation in Middle Devonian (Bradley *et al.* 2000).

Paleogeographic reconstructions conclude that the CMAM basin contained multiple submarine fans derived from the Cambrian–Ordovician terranes shown in Fig. 1 (Ludman *et al.* 2017). Individual fan morphologies are likely overlapping fan complexes suggest that "layer-cake" stratigraphic models are inappropriate and that without more extensive age control, detailed correlations within the basin will remain extremely difficult.

Although CMAM basin stratigraphy adjacent to the Danforth segment has been described in detail (Hopeck 1998, 2013), several questions remain about the ages of its strata bordering the Greenfield segment (see below). Fredericton trough strata immediately adjacent to both Maine Miramichi segments appear to be the same (Figs. 6, 7), but the adjacent CMAM basin rocks are not.

Central Maine/Aroostook Matapedia Basin

Danforth segment: Proximal, intermediate, and distal facies are recognized in the CMAM basin on the west flank of the Danforth segment (Hopeck 1998, 2013) but are locally disrupted by faults described below. Proximal boulder, cobble, and pebble conglomerates representing the entire Danforth segment stratigraphic section transition westward to granule sized clasts in the intermediate facies (Fig. 6). The intermediate facies in turn interfingers westward with silt-mud turbidites and argillaceous limestones of the distal facies. These relationships have proved critical to under-standing the termination of the Miramichi terrane, as discussed below.

Greenfield segment: CMAM strata adjacent to the Greenfield segment are less well understood, partly because of extremely sparse outcrops and partly because the rocks near the Miramichi boundary are different from well-defined CMAM sections on strike to the southwest in the nearby Bangor area (Fig. 7). The Miramichi terrane is absent from the Bangor area, as are facies relationships like those adjacent to the Danforth segment. As a result, CMAM

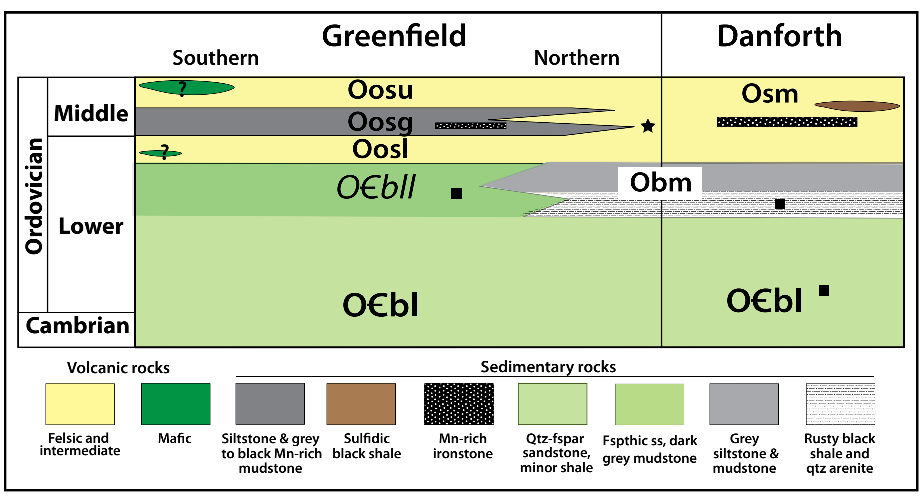

Figure 5. Stratigraphy of the Miramichi terrane in Maine (after Ludman 2023; Ludman *et al.* 2021). Squares indicate units with detrital zircon data, *not the actual ages*. Star indicates ages of dated volcanic rocks. OЄbl - Baskahegan Lake Formation; OЄbll - Lazy Ledges Road member; Oos - Olamon Stream Formation: l - (lower member), u - (upper member, g - (Greenfield member); Obm - Bowers Mountain Formation; Osm - Stetson Mountain Formation.

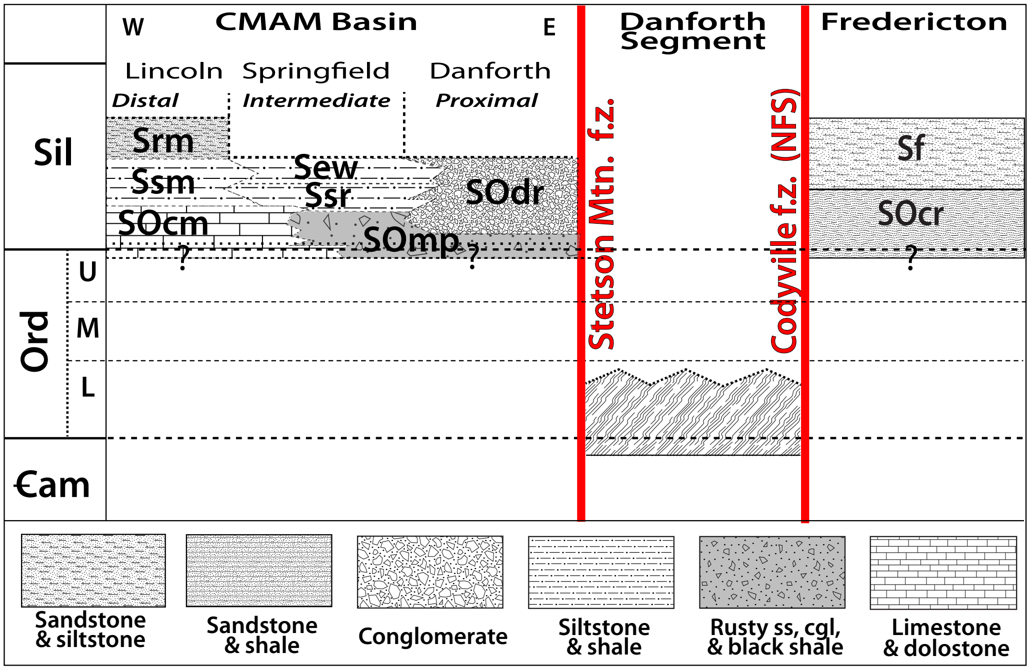

Figure 6. **Stratigraphy of cover rocks adjacent to the Danforth segment.** ***Fredericton trough:*** **SOcr - County Ridge Formation; Sf - Flume Ridge Formation.** ***CMAM basin:*** **SOdr - Daggett Ridge Fm; SOmp - Mill Privelege Brook Fm; Ssr - Sam Rowe Ridge; Sew - Ellen Wood Ridge; SOcm - Carys Mills; Ssm - Smyrna Mills; Srm - Rollins Mtn. After Ludman and Hopeck (2020).**

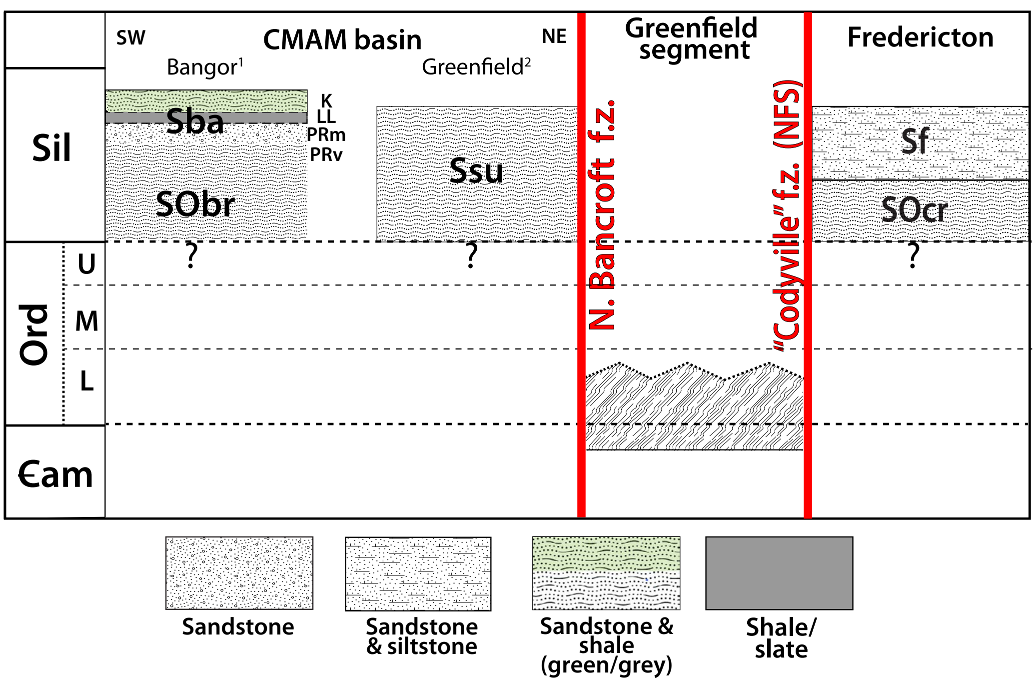

Figure 7. **Stratigraphy of cover rocks adjacent to the Greenfield segment.** ***Fredericton trough:*** **Sf - Flume Ridge; SOcr - County Road.** ***CMAM basin:*** **Ssu - undifferentiated Silurian strata; SObr - Brewer Formation; Sba - Bangor Formation: K - Kenduskeag member; LL - Lovers Leap member; PR - Penobscot River member (m - thick bedded; v - variably bedded). ([1]after Pollock 2011; [2]after Ludman 2023).**

basin and Fredericton trough rocks are juxtaposed across a late fault and even local correlations are moot (Figs. 3, 4; see below).

Fredericton trough

Fredericton trough strata in Maine adjacent to both segments of the Miramichi terrane are assigned to the County Road and Flume Ridge formations (Figs 6, 7). Although coarse Miramichi terrane-like clasts are reported in adjacent Fredericton trough units in New Brunswick (Fyffe and Fricker 1987), they are absent from the County Road and overlying Flume Ridge turbidites, as are facies relationships like those flanking the Danforth segment in the CMAM basin.

Fredericton trough strata in New Brunswick are assigned to the Kingsclear Group (Fig. 8) and those west of the Fredericton fault near the Miramichi terrane, especially the Burtts Corner and Taxis River formations, are coarser than their County Road and Flume Ridge formation counterparts in Maine (Fyffe 1995). The Fredericton fault is an extension of the Waite fault strand of the Norumbega fault system, and is interpreted in New Brunswick as a significant boundary between eastern and western components of the Kingsclear Group (Dokken *et al.* 2018). This is not the case in eastern Maine, where distinctive Flume Ridge formation rocks crop out west of the Waite fault zone (Fig. 8).

DEFORMATION HISTORY

Post-Middle Ordovician unconformities originally separated the Miramichi terrane from the CMAM basin and Fredericton trough but those contacts have been modified in most places by late Silurian, Devonian, and post-Devonian faulting, and intrusion of the Pokiok and Bottle Lake plutonic complexes. The blanket of glacial deposits further obscures even these contacts. The complex sequence of deformation events is discussed here, and evidence for their timing is presented below.

The Danforth and Greenfield segments of the Miramichi terrane record two episodes of penetrative folding (F_1, F_2). They were separated in time by an unconformity (see below), and only the second (F_2) is observed in the CMAM basin and Fredericton trough (Sayres 1986; Ludman 2003, 2023; Ludman and Berry 2003). The current boundary faults cut F_1 and F_2 folds and formed late in regional tectonic history.

Folding

Northeast- and north-northeast-trending tight to isoclinal F_2 folds are the dominant structural features throughout the region and generate relatively simple outcrop patterns in the CMAM basin and Fredericton trough. More complex patterns in the Danforth and Greenfield segments result from F_2 folds refolding earlier F_1 folds (see Fig. 9).

F_1 folding

Mesoscopic recumbent folds in the Danforth segment and inverted F_2 folds in both the Danforth and Greenfield segments reveal the nature of F_1 folding. The relationship between the two generations is also revealed by an outcrop-scale recumbent fold in the Stetson Mountain Formation in the Danforth quadrangle that has been folded by F_2 upright folds (Sayres 1986), and by inverted F_2 folds on the overturned limb of a mesoscopic recumbent fold involving the Bowers Mountain and Stetson Mountain formations in the Bowers Mountain quadrangle (Ludman and Hopeck 2020).

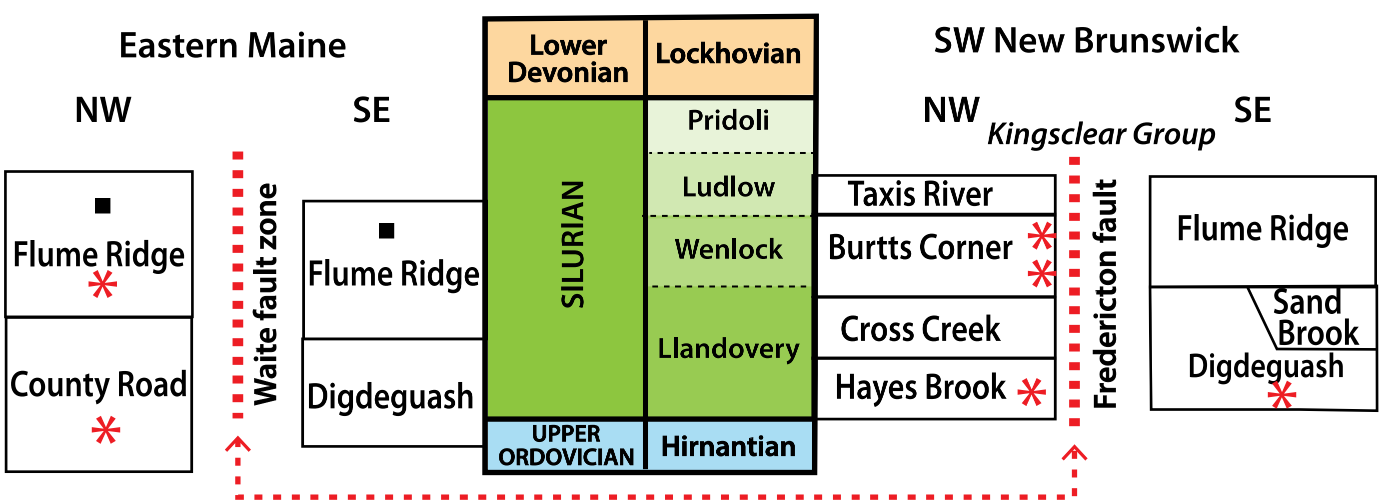

Figure 8. Fredericton trough stratigraphy in Maine and New Brunswick. Asterisks indicate macro- or microfossil age control. Squares indicate approximate maximum depositional age from youngest detrital zircons. New Brunswick data from Dokken *et al.* (2018) and Maine data from Ludman *et al.* (2018).

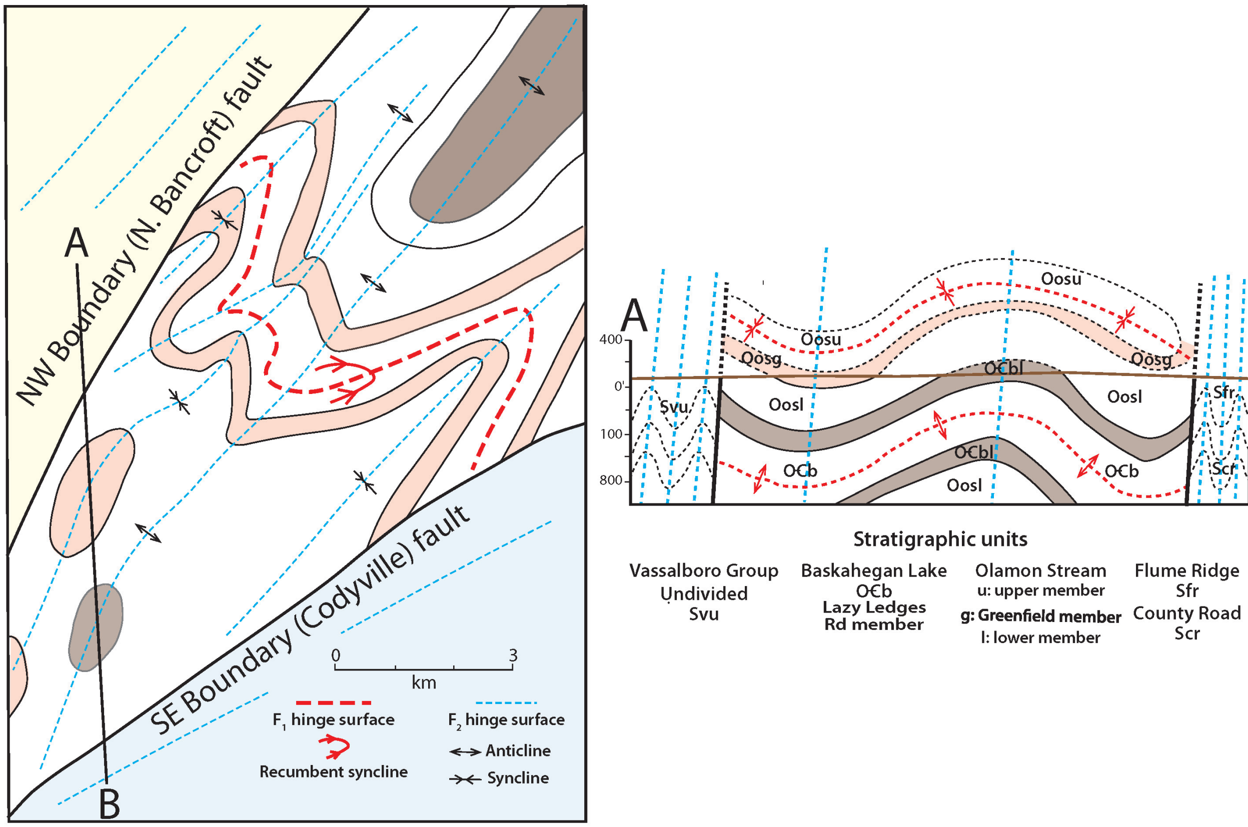

Figure 9. Simplified geologic map of the Greenfield 7½' quadrangle showing relationships among Greenfield segment folds and border faults. Left: Structural framework of the Greenfield quadrangle showing relationships of middle Ordovician (F_1) and Acadian (F_2) folds. Right: Cross-section showing absence of F_1 in CMAM basin and Fredericton trough. Elevations in feet.

Involvement of the Baskahegan Lake Formation in both segments is evidenced by outcrops containing both upright and inverted F_2 folds, indicating their positions on the upright and overturned limbs, respectively, of F_1 recumbent structures (Fig. 10). A map-scale F_1 syncline in the Greenfield segment is outlined by the distinctive Greenfield member of the Olamon Stream Formation (Fig. 9).

F2 upright folding

Gently plunging tight to isoclinal folds affect all stratigraphic units. Hinge surfaces range from 020° to 060° but are distorted locally close to the Bottle Lake and Pokiok complexes. A transposed F_2 axial planar layering (S_2) in limestones and thin-bedded pelitic units locally obscures or obliterates bedding (Fig. 11) but has proved helpful in deciphering details of later fault history.

Faulting

The Stetson Mountain and North Bancroft faults separate the Danforth and Greenfield segments, respectively, from the CMAM basin to the northwest. The North Bancroft fault is also present in the Danforth area but lies there entirely within the CMAM basin (Fig. 4). The southeastern contact with the Fredericton trough in both segments is interpreted to be an extension of the Codyville fault, the northernmost strand of the Norumbega fault system (Fig. 4).

All three were brittle, characterized by coarse cataclastic fabrics in which fragments of the host rocks and broken quartz veins are cemented in a dark gray to black fine-grained matrix (Fig.12). The host rocks are normally non-sulfidic, but pyrite derived from fluids during faulting locally yields a thick rusty weathering rind.

Northwest boundary faults (Miramichi/CMAM): Stetson Mountain (Danforth segment) and North Bancroft (Greenfield segment) faults

The Stetson Mountain fault appears to have experienced two episodes of displacement. Map relationships, described in Figure 13 below, indicate that the first, and dominant, activity was as a high-angle dip-slip fault. Small-scale, nearly vertically plunging drag folds that deform S_2 axial plane transposed layers suggest reactivation in a later episode of dextral strike-slip offset.

The North Bancroft fault is less well understood in the study area. In its type locality to the north, it lies within

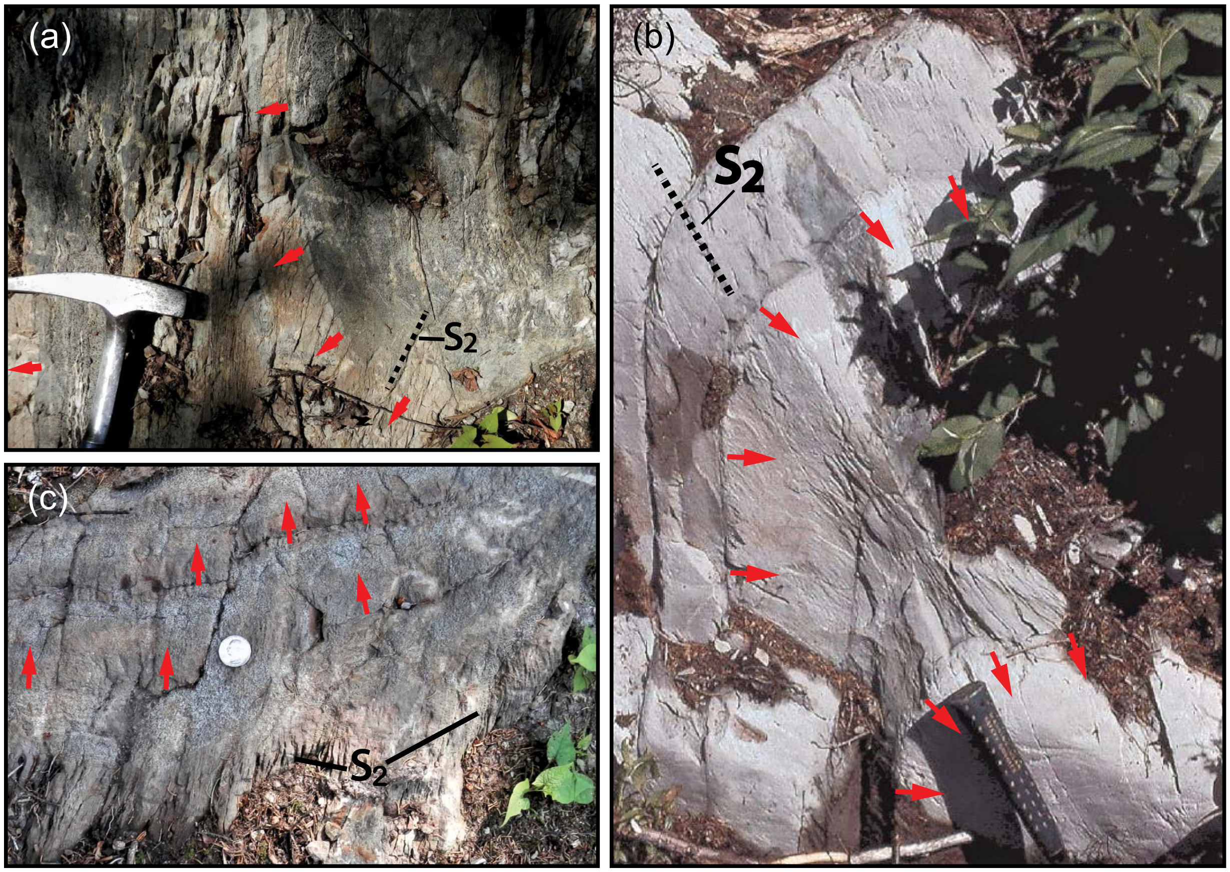

Figure 10. **Inverted (a, b) and upright (c) F_2 folds in the Baskahegan Lake Formation showing S_2 cleavage. Red arrows at base of sandstone beds indicate facing. (a) inverted anticline and (b) inverted syncline on overturned limbs of F_1 folds in the Greenfield and Danforth segments, respectively. (c) upright syncline on upright limb of an F_1 fold in the Greenfield segment.**

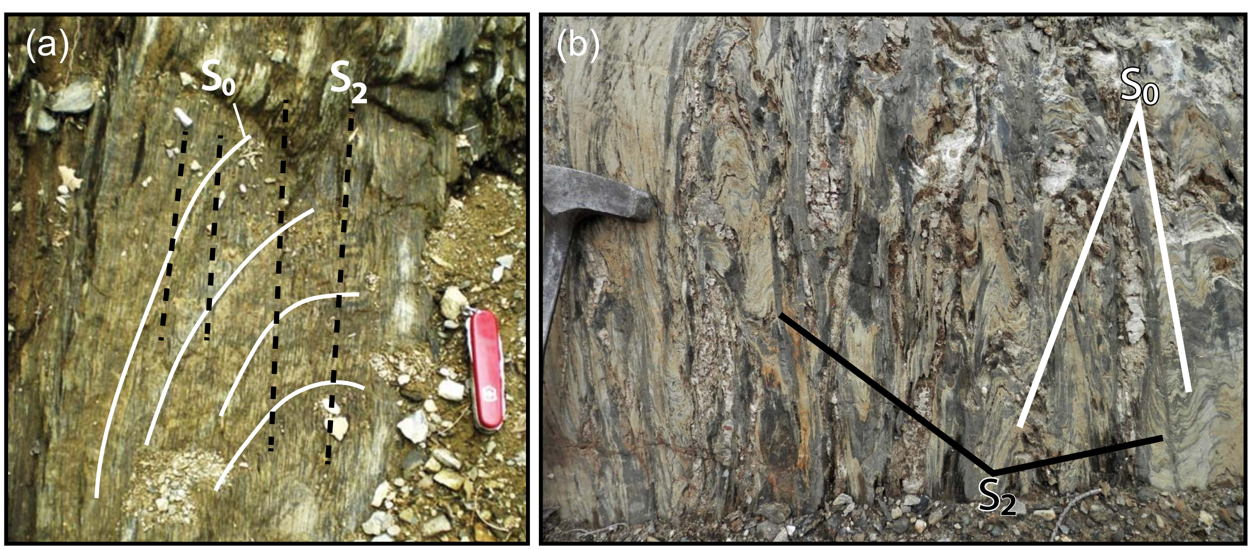

Figure 11. **Acadian F_2 folds showing bedding (S_0) and axial plane transposed layering (S_2) in the CMAM basin. (a) Smyrna Mills Formation siltstone and mudstone; (b) Carys Mills Formation limestone and dolostone.**

the CMAM basin and has a history involving two episodes of activity similar to that of the Stetson Mountain fault. The earliest involved high angle reverse dip-slip offset that brittlely deformed host proximal and distal CMAM strata, the later dextral oblique offset (Hopeck 1998).

The CMAM/Miramichi boundary fault in the Greenfield quadrangle was similarly brittle and drag folds indicate a similar episode of late dextral offset. The two are probably connected, but the lack of outcrops along the most likely trace in the gap between them makes it impossible to confirm the link.

Absent a cross-cutting pluton in either the Greenfield segment or its type locality, activity of the northwest boundary/North Bancroft fault is constrained only to be younger than F_2. The fault continues eastward in New Brunswick as the Woodstock fault, which shears the Hawkshaw granite of the Pokiok suite northwest of Fredericton (L. R. Fyffe 2022 personal communication). At least one episode of movement along the fault would therefore be younger than 411 ± 2 Ma based on the U–Pb sphene age of that pluton (Bevier and Whalen 1990). The timing of the youngest potential activity is not known.

Southeast boundary fault [Miramichi/Fredericton trough] (Codyville?)

The southeast boundary with the Fredericton trough in both segments is a fault thought to be an extension of the Codyville fault zone, northernmost strand of the Norumbega fault system. Kinematic indicators along the Codyville fault east of Topsfield and in the proposed extension in the Greenfield and Olamon quadrangles indicate dextral strike-slip offset consistent with early activity of the Norumbega fault system.

Relationships between NW and SE boundary faults

The County Road and Flume Ridge formations crop out east of the Southeast Boundary/Codyville fault. These units continue to the southwest, beyond the intersection of the Codyville and North Bancroft faults (Fig. 14), indicating that the Codyville fault truncates the North Bancroft fault and is the youngest structure in the study area. Reactivations of the Norumbega fault system continued through at least the Alleghanian orogeny (Wang and Ludman 2001) and

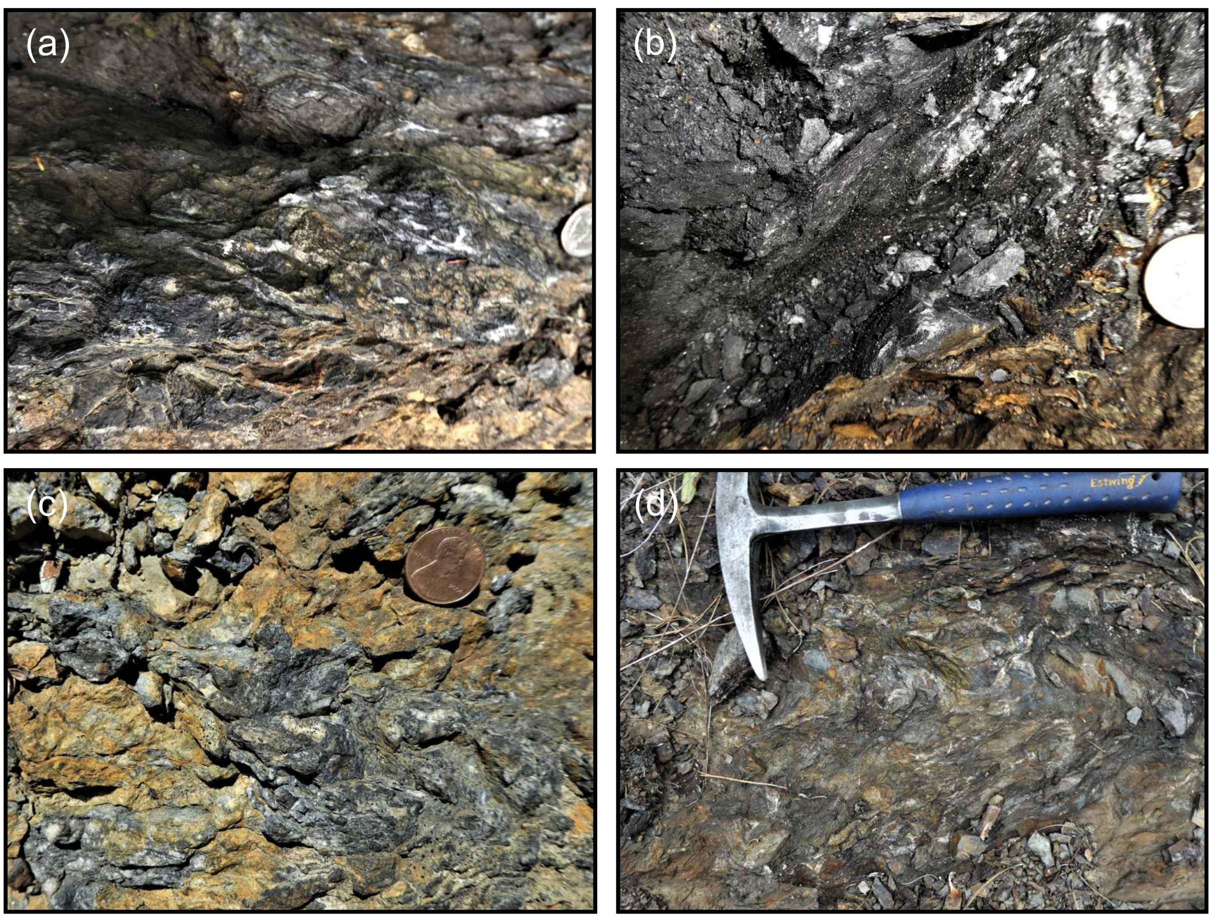

Figure 12. Exposures of the North Bancroft fault in the Olamon quadrangle (a, b), and Codyville fault (c, d) in the Greenfield quadrangle.

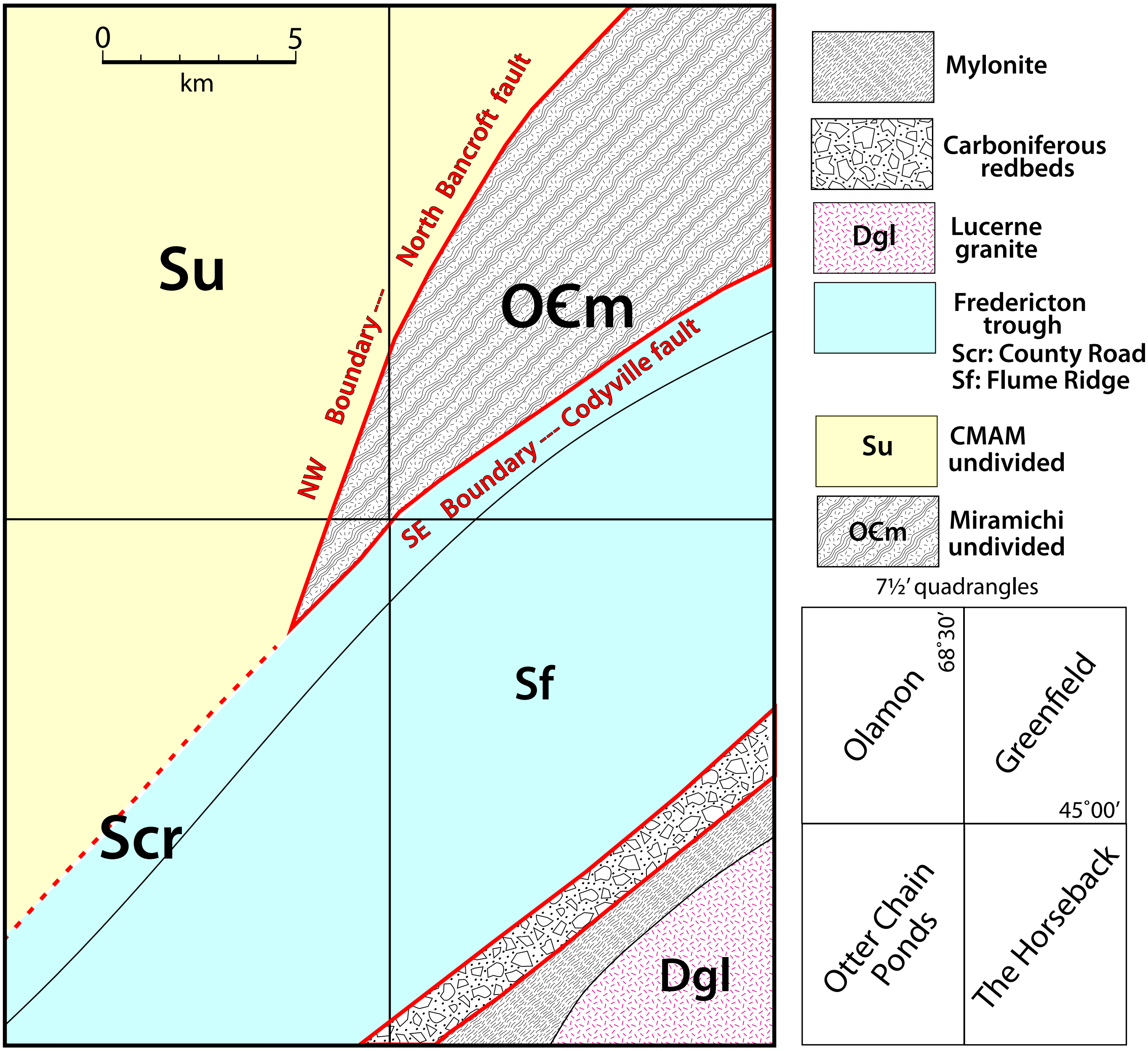

Figure 13. Simplified map showing the Southeast Boundary/Codyville fault truncating the Northwest Boundary/North Bancroft /fault and continuation of Fredericton trough strata into the Otter Chain Ponds quadrangle.

some activity in the central part of the fault system (Waite fault zone in eastern Maine, Norumbega fault zone in south-central Maine) is recognized as recently as Cretaceous time (West and Roden-Tice 2003). These latest events have not been documented in either the northernmost (Codyville) or southernmost (Kellyland) strands of the Norumbega system.

PROPOSED NORTHWEST-OVER-SOUTHEAST THRUSTING

The boundary faults are the youngest tectonic events that affected relationships with the adjacent CMAM basin and Fredericton trough, but they alone cannot explain current Miramichi/cover rock relationships. Mapping along the west flank of the Miramichi terrane suggests a hitherto unrecognized event in which CMAM strata were thrust

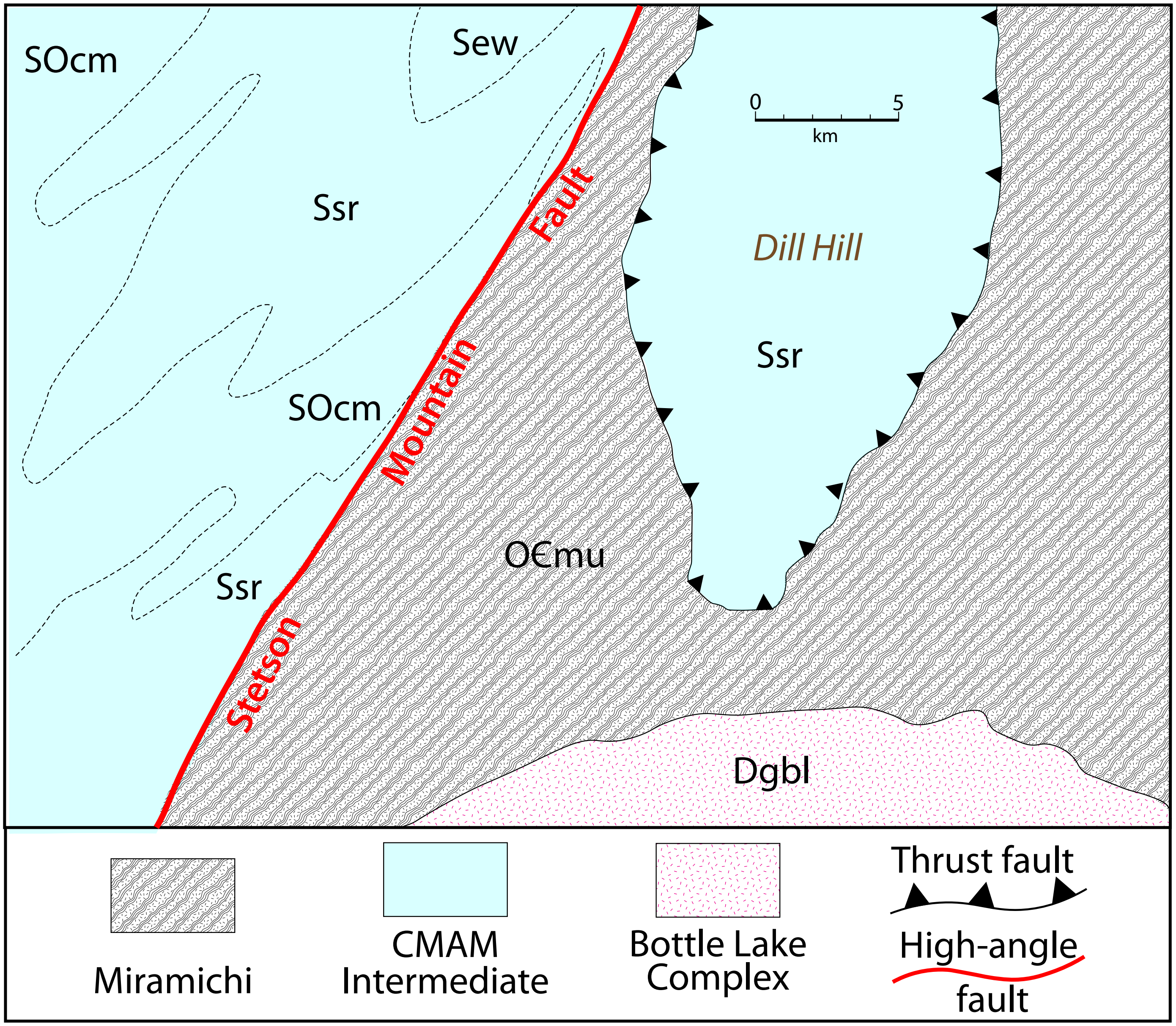

Figure 14. Southern part of the Dill Hill klippe. OЄmu - Miramichi terrane undifferentiated; Ssr - Sam Rowe Ridge; SOcm - Carys Mills; Sew - Ellen Wood Ridge; Dgbl-Bottle Lake plutonic complex (after Ludman 2003).

onto and, in at least one instance, over both segments of the Miramichi terrane.

The key to recognizing this event was recognition of the anomalous presence of CMAM strata east of the Stetson Mountain fault – enclosed within Miramichi units in the Danforth segment and sandwiched between Miramichi rocks and distinctly different Fredericton trough strata east of the Greenfield segment. Details of these two areas, referred to below as the Dill Hill klippe and Greenfield "window", respectively, and the series of steps producing the current relationships are described below.

Dill Hill klippe

An area of thin-bedded turbidites isolated within the Danforth segment of the Miramichi terrane has been known for some time (Ludman 2003) but its significance was not recognized until the stratigraphy of the east flank of the CMAM basin was fully understood (e.g., Ludman and Hopeck 2020). Figure 2b provides an overview of its relationships within the Danforth segment and Figure 14 is a detailed map of the southern part of that area on Dill Hill.

CMAM rocks isolated on Dill Hill belong to the Sam

Rowe Ridge Formation, an intermediate facies prominent west of the Stetson Mountain fault. Figure 15 shows the series of events responsible for the current relationships: initial eastward thrusting of intermediate CMAM rocks onto the Miramichi terrane (Fig. 15b); F_2 folding of the thrust sheet and underlying strata (Fig. 15c); uplift of the Miramichi terrane on the Stetson Mountain fault (Fig. 15d); and subsequent erosion that produced the current relationships (Fig. 15e). The absence of anomalous CMAM strata in the adjacent Fredericton trough makes it impossible to determine the original eastern extent of the thrust sheet in the Danforth segment. Late-stage dextral strike-slip reactivation of the Stetson Mountain fault mentioned above does not appear to have modified these relationships.

Figure 2b shows the full extent of the Dill Hill klippe (#1) and an unnamed fragment of the dissected thrust sheet to the west (#2). Most of the contacts of this fragment are today the Stetson Mountain and North Bancroft faults, but a remnant of the thrust contact is exposed at the southern boundary of the isolated part of the Danforth segment (# 2 in Fig. 2b).

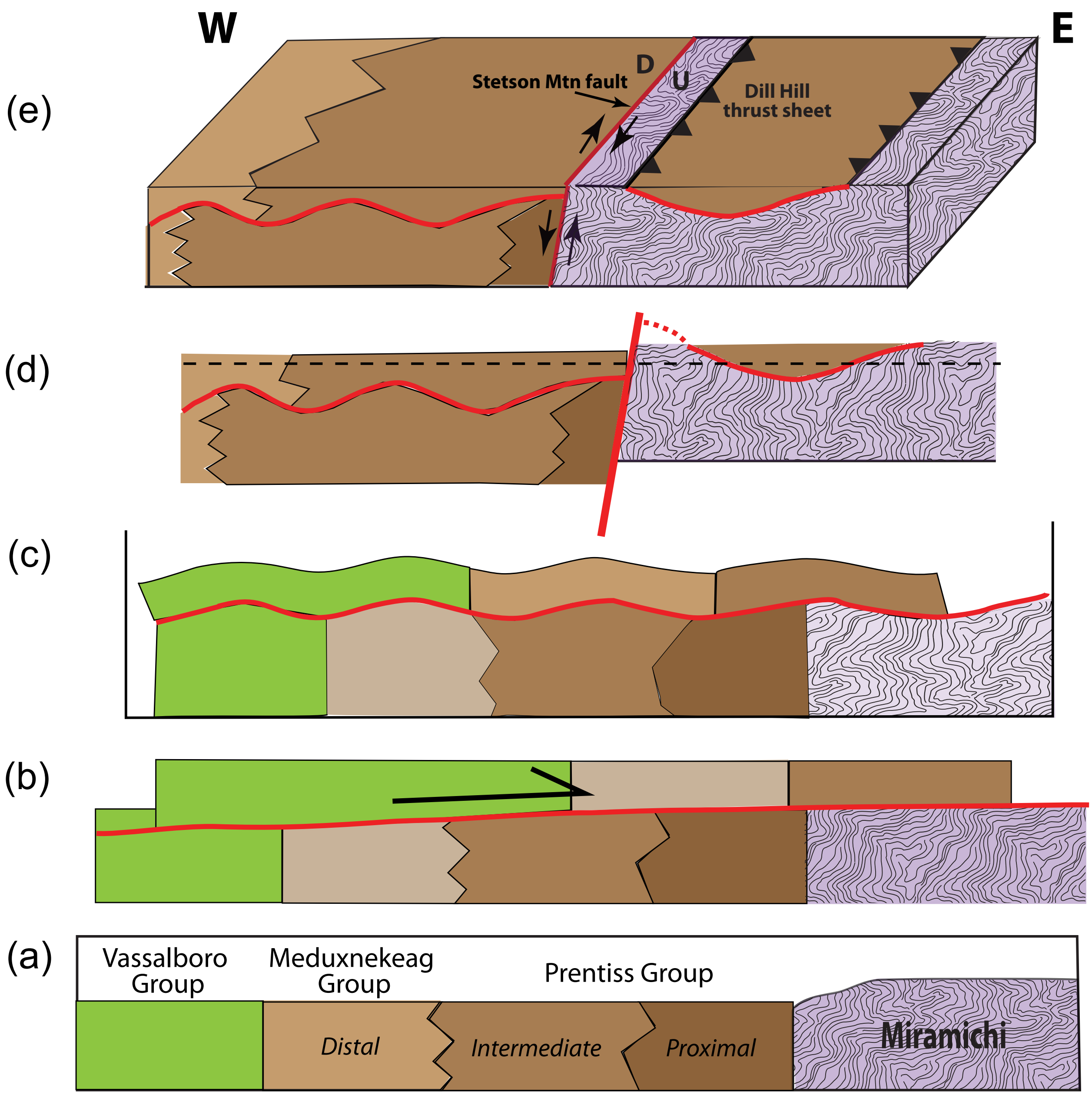

Figure 15. Evolution of the Dill Hill klippe. See text for details.

Greenfield "window"

A similar scenario is interpreted for the Greenfield segment. There, however, a remnant of the thrust sheet is exposed east of, rather than within the Miramichi terrane, juxtaposing CMAM Rollins Mountain and Smyrna Mills formations with Fredericton trough rocks (Figs. 2, 16) across the Codyville fault. We interpret the current relationships shown in Figure 16 to have resulted from a series of events similar to that which created the Dill Hill klippe. (1) CMAM strata, in this case the Rollins Mountain and Smyrna Mills formations, were thrust over the Miramichi terrane. (2) The thrust contact was cut by an extension of the Stetson Mountain fault that today forms the western boundary of the thrust sheet remnant. The thrust was cut by the Codyville fault. (3) erosion following uplift between the two faults removed the allochthonous rocks and exposed the autochthonous Greenfield segment of the Miramichi terrane – similar to a window through the thrust. (4) Intrusion of the Passadumkeag River pluton further modified the eastern margin of the thrust sheet.

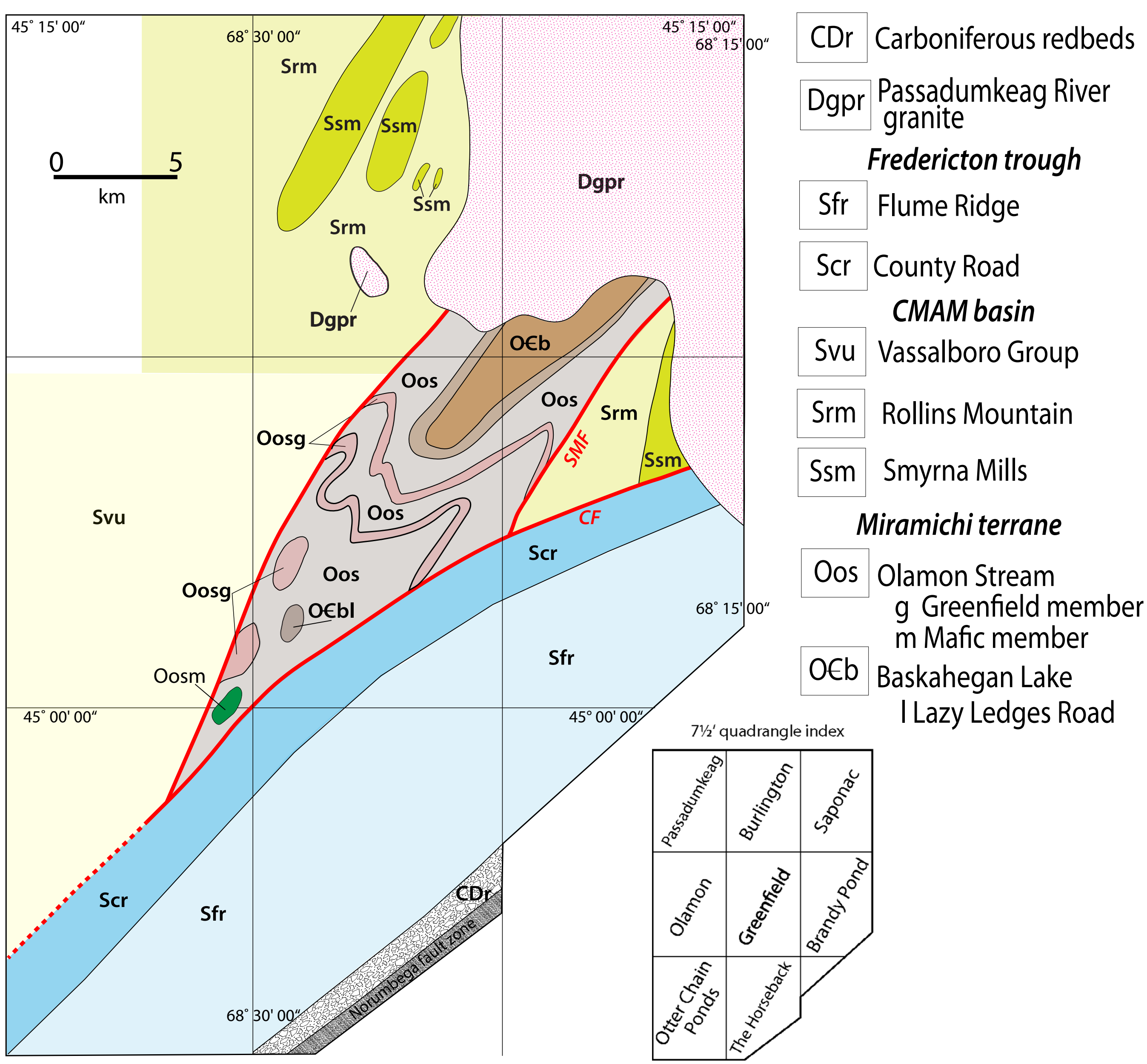

Figure 16. Geologic map of the Greenfield terrane termination zone. SMf - Stetson Mountain fault; CF - Codyville fault.

Deformation timeline

Several factors make it impossible to determine the precise timing of the deformation events described above. Several *caveats* make even imprecise estimates of minimum and maximum ages based on paleontologic and geochronologic information difficult.

Most formations lack fossil age control and, where present, it typically consists of a single site of uncertain stratigraphic position within a unit thousands of metres thick. In addition, neither the tops nor bases of the most critical fossiliferous units are exposed so that the full ranges of the units are poorly constrained. The ages of the youngest detrital zircons in a rock limit its maximum depositional age but do not reveal the span over which it was deposited. Stages in the Silurian and much of the Middle and Upper Ordovician only span a few million years, in many instances less than the reported zircon age analytic error. With these caveats in mind, Figure 17 shows our interpretation of the deformation timeline. Detrital zircon data reported below are SHRIMP ages with 1σ errors.

F_1 folding

F_1 folding is constrained to between the ~470 Ma age of the youngest affected Olamon Stream Formation (Ludman *et al.* 2020a) and the oldest unaffected cover rocks – the Upper Ordovician to early Silurian Carys Mills Formation in the CMAM basin (Pavlides 1968; Rickards and Riva 1981), and the early Hayes Brook and Digdeguash formations in the Fredericton trough. All three are fossiliferous, but the *caveats* mentioned above apply: none of their bases are exposed and the stratigraphic positions of the fossiliferous rocks are not known precisely. Data from neither Maine segment nor the Meductic Group in the Eel River area in New Brunswick date F_1 precisely, but a composite of the most useful data indicates that F_1 was Middle Ordovician (Fyffe 2001; Ludman 2023).

F_2 folding

F_2 folding in the Fredericton trough must have occurred after crystallization of the youngest detrital zircons in the folded Flume Ridge Formation and their incorporation in the formation, and before the 421.9 ± 2.4 Ma emplacement of the Pocomoonshine gabbro-diorite that intrudes those folds (Ludman *et al.* 2018; West *et al.* 1992). A cluster of the eight youngest Flume Ridge detrital zircons spans the Homerian–Sheinwoodian boundary, ranging from 433 ± 3 to 424 ± 3 Ma and averaging 429 Ma (earliest Homerian). The depositional age must be younger and, considering analytical error in both the detrital and plutonic zircons, a late Silurian age and Salinic tectonic affinity is evident for F_2.

By the same reasoning, the timing of F_2 folding in the CMAM basin appears to be less well constrained. The youngest affected unit in the area is the informally named Rollins Mountain Formation, which lies above the middle Silurian Smyrna Mills Formation (Ludman 2020b). A cluster of the six youngest detrital zircons ranges from 435 ± 4 to 423 ± 7 Ma and averages 430 Ma (again at the Homerian–Sheinwoodian boundary). Folded Rollins Mountain sandstones are intruded by the Center Pond pluton, with a U–Pb zircon age of 377 ± 3 Ma (Bradley *et al.* 2000) and a $^{40}Ar/^{39}Ar$ biotite age of 372 ± 2 Ma (Ghanem *et al.* 2016).

However, Ghanem *et al.* (2016) were able to date F_2 directly, reporting a ~410 Ma $^{40}Ar/^{39}Ar$ age for neocrystallized muscovite in S_2 cleavage, and thus an Acadian affinity for the event. F_2 upright folds in the Fredericton trough are thus older than those in the CMAM basin, supporting the proposal by Bradley *et al.* (2000) of a 40-m.y. continuum of Acadian deformation from a late Silurian ("Salinic") phase in the Fredericton trough to the Middle Devonian in central Maine.

Stetson Mountain fault

The timing of Stetson Mountain faulting is bracketed between F_2 folding and intrusion of the Skiff Lake granite of the Pokiok plutonic suite. A sample of the Skiff Lake granite dated in Maine yielded a K–Ar (biotite) age of 400 Ma (Faul *et al.* 1963). Multiple attempts were made to date the Skiff Lake granite in New Brunswick between 1963 and 1990, using varied techniques and materials: K–Ar (biotite and muscovite), Rb–Sr (muscovite and whole-rock) and, most recently, U–Pb (zircon). Reported ages ranged from 389 to 430 Ma, but the preferred age cited in the New Brunswick Bedrock Lexicon (New Brunswick Department of Natural Resources and Energy 2022) is a U–Pb zircon age of 409 ± 2 Ma (Bevier and Whalen 1990). The northwest boundary of the Danforth segment was thus set by the early Devonian.

North Bancroft/Northwest Boundary fault

Absent a cross-cutting pluton in either the Greenfield segment or its type locality in the Danforth segment, the age of the North Bancroft fault/Northwest Boundary fault is constrained only to be younger than F_2. The fault continues into New Brunswick as the Woodstock fault which shears the Hawkshaw granite of the Pokiok suite northwest of Fredericton (L. R. Fyffe 2022 personal communication). At least one episode of movement along the fault would therefore be younger than the 411 ± 2 Ma U–Pb sphene age of that pluton (Bevier and Whalen 1990). The timing of the youngest potential activity is not known.

Codyville/southeast boundary fault

Ayuso (1984) reported that the Codyville fault cuts the Whitney Cove pluton of the Bottle Lake Complex but not the Passadumkeag River pluton to the southwest. Both plutons were dated at ~380 Ma (Ayuso *et al.* 1984), apparently pinpointing faulting precisely at 380 Ma. However, there are few outcrops within the Passadumkeag River pluton along the projected trace of the fault, leaving ample opportunity for the fault to continue undetected to the Greenfield segment.

NW-SE thrusting

The proposed thrusting occurred after F_1 and before F_2 folding. Because the thrusting involved both the Fredericton trough and CMAM basin, the timing is constrained to the late Silurian, most likely Pridoli. Because the thrust sheet was deformed by F_2 folds, the thrusting event was probably an early phase of the Salinic orogeny.

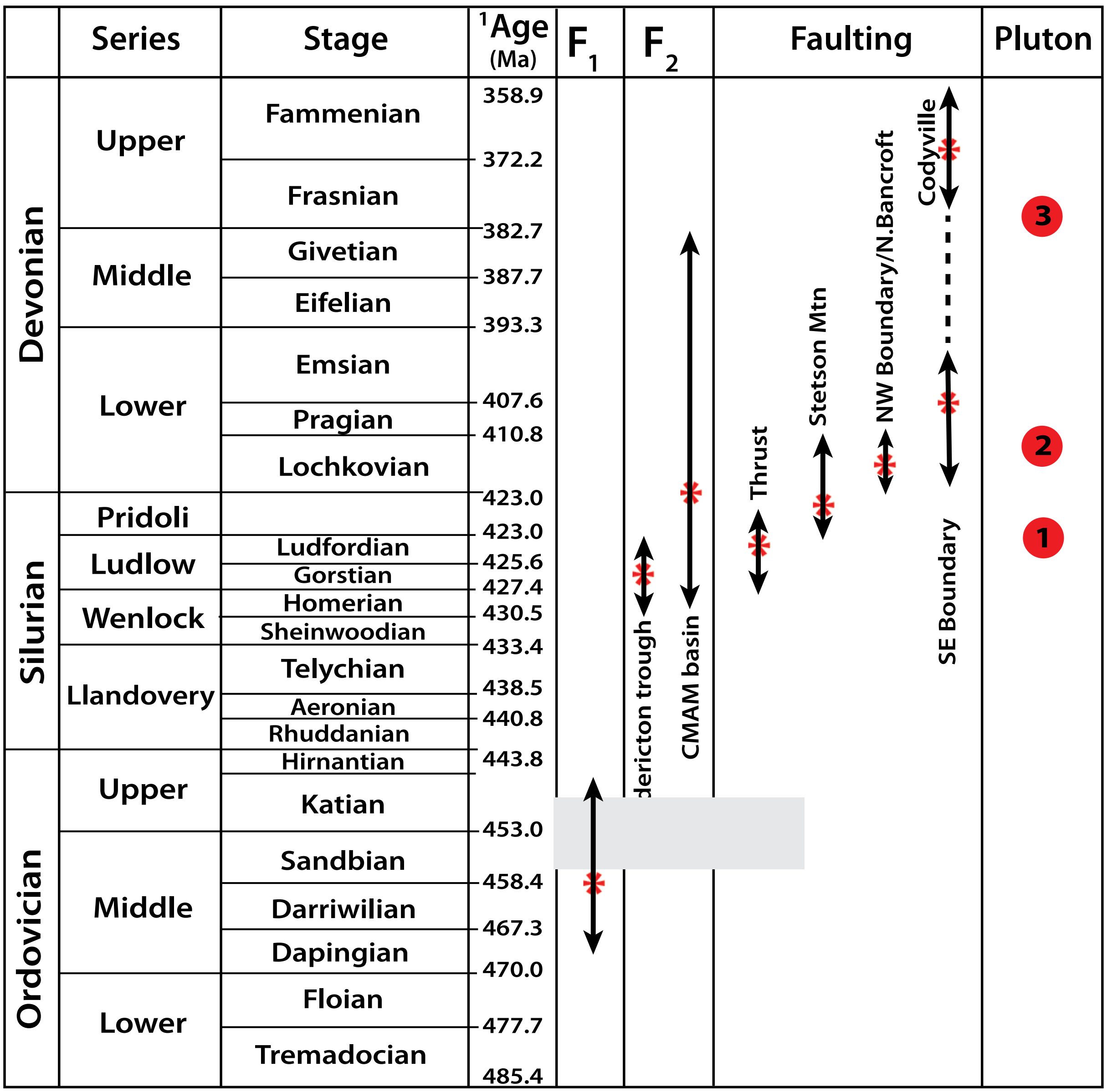

Figure 17. Sequence of deformation events. Arrows indicate possible ranges, asterisks the proposed timing. Shaded area indicates post-F_1 unconformity between Miramichi and cover rocks. FT - Fredericton trough; CMAM - Central Maine/ Aroostook–Matapedia basin. Red circles - plutons: 1 - Pocomoonshine gabbro-diorite; 2 - Skiff Lake phase, Pokiok plutonic suite; 3 - Bottle Lake complex (Passadumkeag River and Whitney Cove plutons). 1Numerical ages after Cohen *et al.* 2013 (2022 modification).

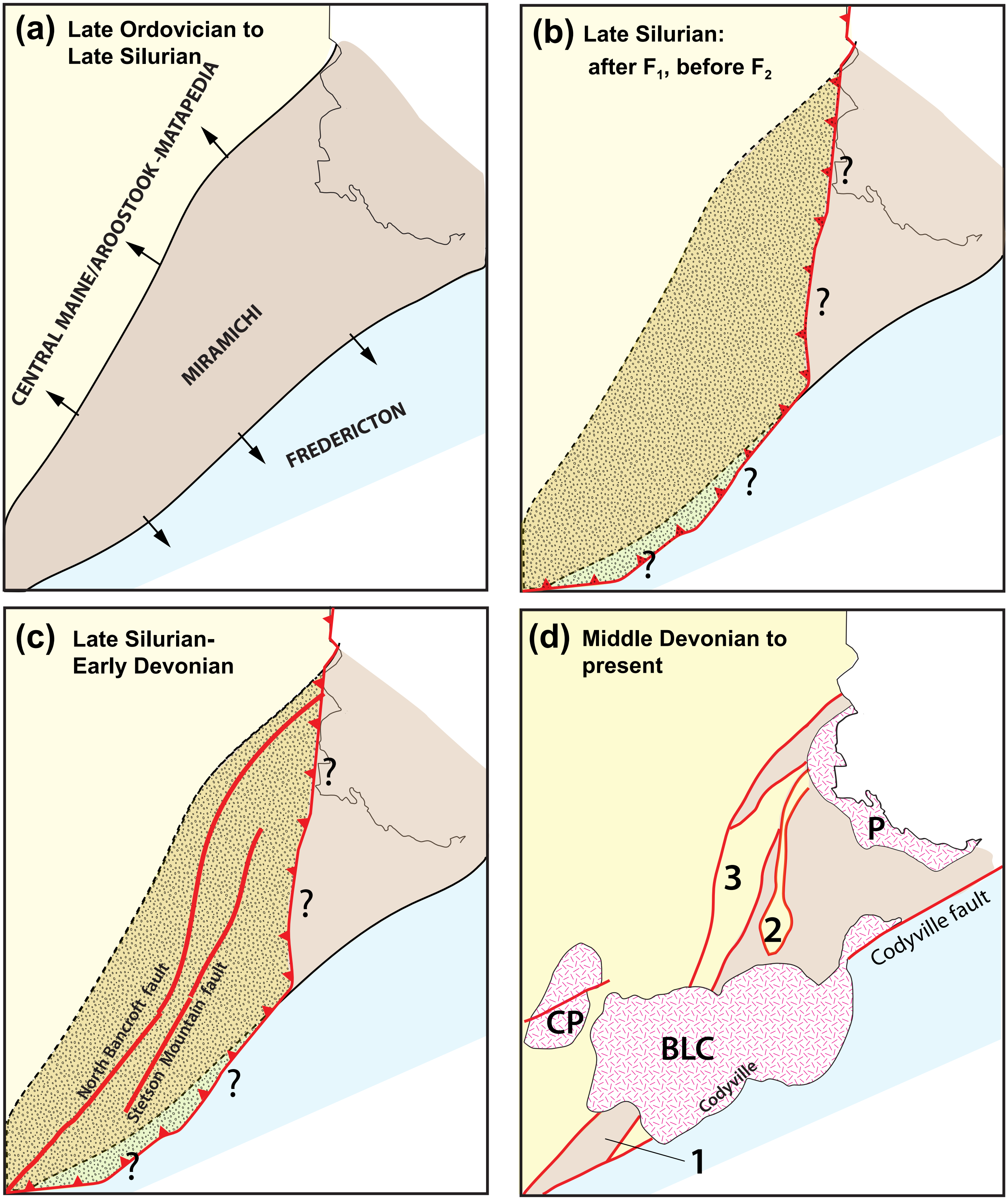

Figure 18. Stages in the termination of the Miramichi terrane. See text for details. Sawtooth pattern indicates uncertain leading edge of thrust sheet. Pattern shows possible extent of thrust sheet over the Miramichi terrane. 1 - Greenfield segment; 2 - Dill Hill

TERMINATION OF THE MIRAMICHI TERRANE

Evidence presented above indicates that a complex series of tectonic and magmatic events, listed below, interspersed with erosion and deposition during quiet intervals, was largely responsible for truncating the Miramichi terrane in eastern Maine. These are summarized in Figure 18, beginning with Step 3 below.

1. Late Cambrian to early Middle Ordovician (Dapingian): Deposition and eruption of Miramichi strata.
2. Middle to early Late Ordovician: F_1 recumbent folding.
3. Late Ordovician through Late Silurian (Fig. 18a): Sediment eroded from a post-F_1 emergent Miramichi terrane was deposited in the Fredericton trough and CMAM basin.
4. Late Silurian: CMAM strata were thrust onto (Danforth segment) and locally over (Greenfield segment) their Miramichi source (Fig. 18b). The maximum eastern extent of the thrust sheet is unknown.
5. F_2 upright folds deform both the thrust sheet and autochthonous Miramichi terrane.
6. Late Silurian–Early Devonian: Thrust sheet dissected by high-angle, dip-slip North Bancroft and Stetson Mountain faults. (Fig. 18c).
7. Middle Devonian:Whitney Cove and Passadumkeag River plutons of the Bottle Lake complex emplaced. Offset on the Codyville fault initiated. (Fig. 18d).
8. Devonian to present: Sporadic reactivation of Norumbega fault system. Erosion created the Dill Hill klippe and and unnamed thrust fragment and exposed the Greenfield segment through the thrust (Fig 2b).

DISCUSSION

The Miramichi terrane is bounded by faults throughout its ~400 km length and terminates at the convergence of two of these boundary faults. The proximal cause of its termination today is therefore tectonic, but because those faults are the youngest structural features, they may have only modified earlier relationships rather than being the primary cause of the termination. For example, the outcrop pattern associated with the Dill Hill klippe could result from an unconformity in which a sedimentary sequence was deposited unconformably on the Miramichi terrane. Indeed, CMAM rocks on Dill Hill were initially described as "lying unconformably above Miramichi strata, but possibly modified by thrusting" (Ludman 2003). A similar scenario could also explain the presence of CMAM rocks between the Greenfield segment of the Miramichi terrane and Fredericton trough (Figure 16).

Thrust fault or unconformity?

A model in which an unconformity caused the current outcrop patterns rather than a thrust fault is reasonable, but for reasons described below we submit that it cannot explain relationships in the Danforth segment and is unlikely for the Greenfield segment.

Several lines of evidence demonstrate that the Miramichi terrane from southwestern New Brunswick to at least the Danforth area was emergent from the Late Ordovician to as recently as the late Silurian. In New Brunswick, distinctive Miramichi terrane clasts in the Fredericton trough are reported from the Burtts Corner Formation (Wenlock to Ludlow) and the overlying Taxis River grits (Fyffe and Fricker 1987). In the Danforth area, Miramichi terrane clasts were deposited in the CMAM basin — in the Mill Privilege Brook Formation (correlated with the Late Ordovician Belle Lake Formation in New Brunswick), and in the overlying Daggett Ridge Formation, where the entire Miramichi section is represented by clasts ranging in size from a centimetre to a few metrer (Hopeck 1998).

The Fredericton trough was folded during the late Silurian Salinic orogeny and before intrusion of the post-Salinic Pocomoonshine gabbro-diorite at 421.9 ± 2.4 Ma (Ludman *et al.* 2021). The Miramichi terrane was thus emergent during Salinic deformation of the Fredericton trough, leaving no time for deposition of younger rocks above the Miramichi strata.

Hopeck (2013) also demonstrated that recognizable Miramichi terrane clasts get progressively finer grained westward in the CMAM basin, where the proximal/intermediate Sam Rowe Ridge Formation interfingers with a more distal Smyrna Mills Formation (at least as young as Wenlockian).

Therefore, an emergent Miramichi terrane shed sediment into the adjacent CMAM basin and Fredericton trough well into the Silurian and could not have been overlain unconformably by a blanket of post-Middle Ordovician sediment. The presence of sedimentary rock derived from the Miramichi terrane and now surrounded by its Miramichi source rocks thus cannot be explained by an unconformity. The thrust model is therefore the best explanation for the current relationships.

Greenfield segment

Evidence for the proposed thrust involving the Greenfield segment is not as strong, and while we acknowledge that an unconformity cannot be ruled out, the thrust interpretation is preferred for two reasons. (1) The absence of a proximal facies like those at Miramichi–CMAM and Miramichi–Fredericton trough contacts described above, and (2) The proximity of the Greenfield area to coeval east-directed thrusts in both the Danforth segment to the northeast and mid-coastal Maine to the southwest. Late

Silurian east-vergent thrust faults are reported southeast of the Norumbega fault system in amphibolite facies rocks of mid-coastal Maine (West *et al.* 2021) and are also deformed by Acadian folding. We submit that it is unlikely that the Greenfield area escaped a regional episode of eastward thrusting recorded in mid- and upper crustal levels, and therefore that the relationships are not caused by what would be a uniquely preserved unconformity.

Regional implications

On a larger scale, a non-tectonic explanation has been suggested to explain the absence of the Miramichi terrane southwest of the current termination (Tucker *et al.* 2001). They proposed that although the Miramichi terrane was emergent in eastern Maine and New Brunswick in the Middle and Upper Ordovician, it was completely submerged in mid-coastal and central eastern Maine where the Miramichi terrane is absent today. In this model, a submarine Miramichi arch was, and still is, buried beneath Silurian sediment deposited in a combined CMAM/Fredericton trough depocenter. The thrust model proposed here could potentially offer a tectonic explanation for the burial and absence of the Miramichi terrane beyond the Greenfield segment termination area. A detailed discussion of this issue is far beyond the scope of this paper, and we leave it to others more familiar with the geology of the area in question.

CONCLUSIONS

1. Sediments in the CMAM basin and Fredericton trough were derived from an emergent Miramichi terrane after Middle Ordovician deformation.
2. Relationships between the Miramichi terrane and adjacent cover rocks evolved over a complex series of tectonic events spanning early Silurian through at least Lower Devonian times.
3. A previously unrecognized event occurred between Middle Ordovician and Lower Devonian folding in which CMAM basin strata were thrust eastward onto and locally over the Miramichi terrane.
4. The faults that separate the Miramichi and cover rock belts today were the final tectonic events that modified those relationships.

ACKNOWLEDGEMENTS

USGS StateMap 2013–2014 funding through the Maine Geological Survey supported early work in the Greenfield quadrangle, and Allan Ludman is grateful to the Maine Geological Survey for its logistic support and encouragement over nearly six decades. Queens College Masters of Science student Mindy Sayres and undergraduates John Damanti, Frances Dragan, Charles LoBue, and Neal Madnick made important contributions to understanding the Danforth segment, and Garrett Beaulieu and Charles Rodda provided able field assistance during recent work in the Greenfield segment. Conversations with John Hopeck, Henry Berry, Robert Marvinney, and Les Fyffe have helped to shape the ideas expressed in this paper. We are grateful to Dykstra Eusden, Robert Marvinney, and Dave West whose comments on an earlier version have greatly improved this paper.

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Editorial responsibility: David P. West, Jr.