Revised upper Paleozoic stratigraphy of the Blacks Harbour-Beaver Harbour area, New Brunswick, Canada: evidence from new bedrock mapping and palynology

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ABSTRACT

Upper Paleozoic sedimentary rocks form outliers delineated by large strike-slip faults in the Blacks Harbour-Beaver Harbour area in southwestern New Brunswick. Currently included in the Upper Devonian Perry Formation, and Visean–Pennsylvanian Mabou Group (Balls Lake Formation) and Cumberland Group (Lancaster Formation), these units have been subject to varied interpretations since the initial mapping during the 19th century. The Perry Formation, a red bed sequence consisting of coarse conglomerate, sandstone, minor shale, and mafic volcanic rocks, has yielded plant fossils (indeterminate debris and decorticated stem and root fossils) considered to be broadly Devonian, and most likely Famennian. The 'Carboniferous' strata have proven more intractable. Three units have been defined by mapping: Lighthouse Cove Formation (previously: 'Fish Plant Beds'), Cripps Steam Formation, and Russels Point Formation (previously: 'Beaver Harbour Formation'). These units have yielded plant fossils in the form of indeterminate debris and decorticated stem and root fragments that various workers have attributed to the Silurian, Devonian, Mississippian, or Pennsylvanian. New palynological analyses from the Perry Formation (at Tunaville) and Russels Point Formation (at Woodland Cove and Russels Point) have yielded stratigraphically significant assemblages. The Tunaville assemblage, the first miospores from anywhere in the Perry Formation, and roughly in the middle of the local sequence, is lower to middle Famennian. Two miospore assemblages are from near the base of the Russels Point Formation: one shows a possible range from Tournaisian to Holkerian (middle Visean), and the second is better constrained between Chadian and Holkerian (lower to middle Visean). Only the Lighthouse Cove Formation ('Fish Plant Beds') failed to yield any miospore assemblages; however, mapping and structural considerations are compatible with this unit being older than the Russels Point Formation and younger than the Perry Formation and most likely Tournaisian to lower Visean. One new stratigraphic relationship has been located along the southern shore of Deadmans Harbour where an angular unconformity occurs between red beds of the Perry Formation and grey beds of the overlying Russels Point Formation. Contrasting deformation styles in these units related to displacement on the Belleisle Fault constrain a major phase of strike-slip movement to the Famennian–Tournaisian interval.

RÉSUMÉ

Des roches sédimentaires du Paléozoïque supérieur forment des enclaves délimitées par de vaste failles décrochantes dans le secteur de Blacks Harbour-Beaver dans le sud-ouest du Nouveau-Brunswick. Ces unités, actuellement incluses dans la Formation du Dévonien supérieur de Perry, le groupe viséen-pennsylvanien de Mabou (Formation de Balls Lake) et le groupe de Cumberland (Formation de Lancaster), ont fait l'objet de diverses interprétations depuis leur cartographie initiale au cours du 19e siècle. La Formation de Perry, une séquence de couches rouges constituée d'un conglomérat grossier, de grès, de schiste modeste et de roches volcanomafiques, a livré des fossiles végétaux (débris indéterminés et fossiles de tiges et racines décortiquées) considérés comme des vestiges remontant d'une façon générale au Dévonien, et très probablement au Famennien. Les strates « carbonifères » se sont avérées plus insolubles. Trois unités ont été définies dans le cadre de travaux cartographiques : la formation de Lighthouse Cove (précédemment « les couches de l'usine de traitement du poisson »), la Formation de Cripps Steam et la Formation de Russels Point, (précédemment « la Formation de Beaver Harbour »). Les unités en question ont livré des fossiles végétaux sous forme de débris indéterminés et

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de fragments de tiges et racines décortiquées que divers chercheurs ont attribués au Silurien, au Dévonien, au Mississippien ou au Pennsylvanien. De nouvelles analyses palynologiques de la Formation Perry (à Tunaville) et de la Formation de Russels Point (dans l'anse Woodland et sur la pointe Russels) ont fourni des assemblages stratégiquement significatifs. L'assemblage de Tunaville, premiers miospores relevés à l'intérieur de la Formation Perry, qui sont présents vers le milieu de la séquence, sont du Famennien inférieur à moyen. Deux assemblages de miospores se trouvent près de la base de la Formation de Russels Point : l'un affiche une fourchette possible du Tournaisien à l'Holkérien (Viséen moyen) et le second se limite de façon plus précise entre le Tchadien et l'Holkérien (du Viséen inférieur à moyen). Seule la Formation de Lighthouse Cove (« couches de l'usine de traitement du poisson ») n'a pas présenté d'assemblages de miospores, mais les considérations cartographiques et structurales pertinentes sont compatibles avec un âge de l'unité supérieur à celui de la Formation de Russels Point et inférieur à celui de la Formation Perry, correspondant vraisemblablement à la période du Tournaisien au Viséen inférieur. Un nouveau lien stratigraphique a été découvert le long du rivage sud de Deadmans Harbour à l'endroit où une discordance angulaire s'inscrit entre les couches rouges de la Formation Perry et les couches grises de la Formation sus-jacente de Russels Point. Les modes opposés de déformation dans ces unités liés au déplacement sur la faille de Belleisle restreignent une phase déterminante du coulissage à l'intervalle du Famennien au Tournaisien.

[*Traduit par la redaction*]

INTRODUCTION

Upper Paleozoic sedimentary rocks form outliers adjacent to the Belleisle Fault, a major orogen-parallel strike-slip fault within the northern Appalachian orogenic collage in the Blacks Harbour to Beaver Harbour area of southwestern New Brunswick (Figs. 1, 2; Waldron *et al.* 2015 and references therein). Consensus on the distribution and age of the relatively undeformed Upper Devonian Perry Formation in southwestern New Brunswick had been relatively well established by 1960. However, delineating the extent and precise age of the younger, fault-bounded, plant-bearing Carboniferous units has been more problematic because of their degree of deformation and general lack of well-preserved fossils. As a result, these younger units have been variously referred to as 'Beaver Harbour Group' or 'Formation', Lighthouse Cove Formation ('Fish Plant beds'), and 'Cripps Stream Formation' ('Pennfield Station beds'). Due to the confused state of their stratigraphic nomenclature, the Carboniferous red-bed dominant and grey-bed dominant units in the Blacks Harbour–Beaver Harbour area are included, respectively, in the upper Mississippian Balls Lake Formation and Pennsylvanian Lancaster Formation of the Lepreau area (Fig. 1) on the most recent 1:20 000 compilation geological map (Fyffe *et al.* 2014). The evolution of the nomenclatural history of these units, summarized in Figure 3, is discussed in detail in the next section below.

Field mapping in the Blacks Harbour–Beaver Harbour area undertaken during the summers of 2020–2022 aimed to establish relationships among the various Upper Paleozoic units identified and defined during earlier studies. Samples for palynological analysis were collected at the same time from all these units (Fig. 2, Appendix A). These results clarify stratigraphic correlations that until now have been ambiguous and provide insight into the movement history of the Belleisle Fault.

Some revisions to the previous stratigraphic nomenclature were necessary due to a plethora of unit names, most of which have been applied without designation of type section or type locality, and therefore are not in compliance with the North American Stratigraphic Code. In some instances, place names have been employed multiple times; for example, 'Beaver Harbour Group' (Helmstaedt 1968), 'Beaver Harbour beds' (Rast *et al.* 1979), 'Beaver Harbour Formation' (McLeod and Johnson 1998) and 'Beaver Harbour Porphyry' (Bartsch and Barr 2005) were used despite the fact that the Beaver Harbour Group was a formally designated, albeit undivided, unit (Williams *et al.* 1985).

Here we propose a threefold subdivision for the plant-bearing rocks lying above the Late Devonian Perry Formation in the Beaver Harbour-Blacks Harbour area into (from oldest to youngest) Lighthouse Cove Formation, Cripps Stream Formation, and Russels Point Formation (new name). The Cripps Stream and Russels Point formations should be included in a formally reconstituted Beaver Harbour Group, consistent with the original definition of Helmstaedt (1968) and used by Williams *et al.* (1985). Formal definitions, detailed lithological descriptions, and type sections for these units are presented in Appendix B.

GEOLOGY OF THE BLACKS HARBOUR–BEAVER HARBOUR AREA

The four upper Paleozoic units recognized in the Blacks Harbour–Beaver Harbour area (Fig. 2)—the Late Devonian Perry Formation, and Carboniferous Lighthouse Cove, Cripps Stream and Russels Point formations—are described below.

Perry Formation

The red beds (pebble to boulder conglomerate, sandstone, shale, Figs. 4a, b, c) and minor basalts of the Perry Formation (Figs 1, 2) constitute the oldest of the upper Paleozoic sedimentary sequences in southwestern New Brunswick, studied since the middle 19th century on account of plant fossils, and documented by Gesner (1839), Dawson (1861, 1862), Hitchcock (1861), and described in more detail by Bailey and Matthew (1872). Detailed mapping identified

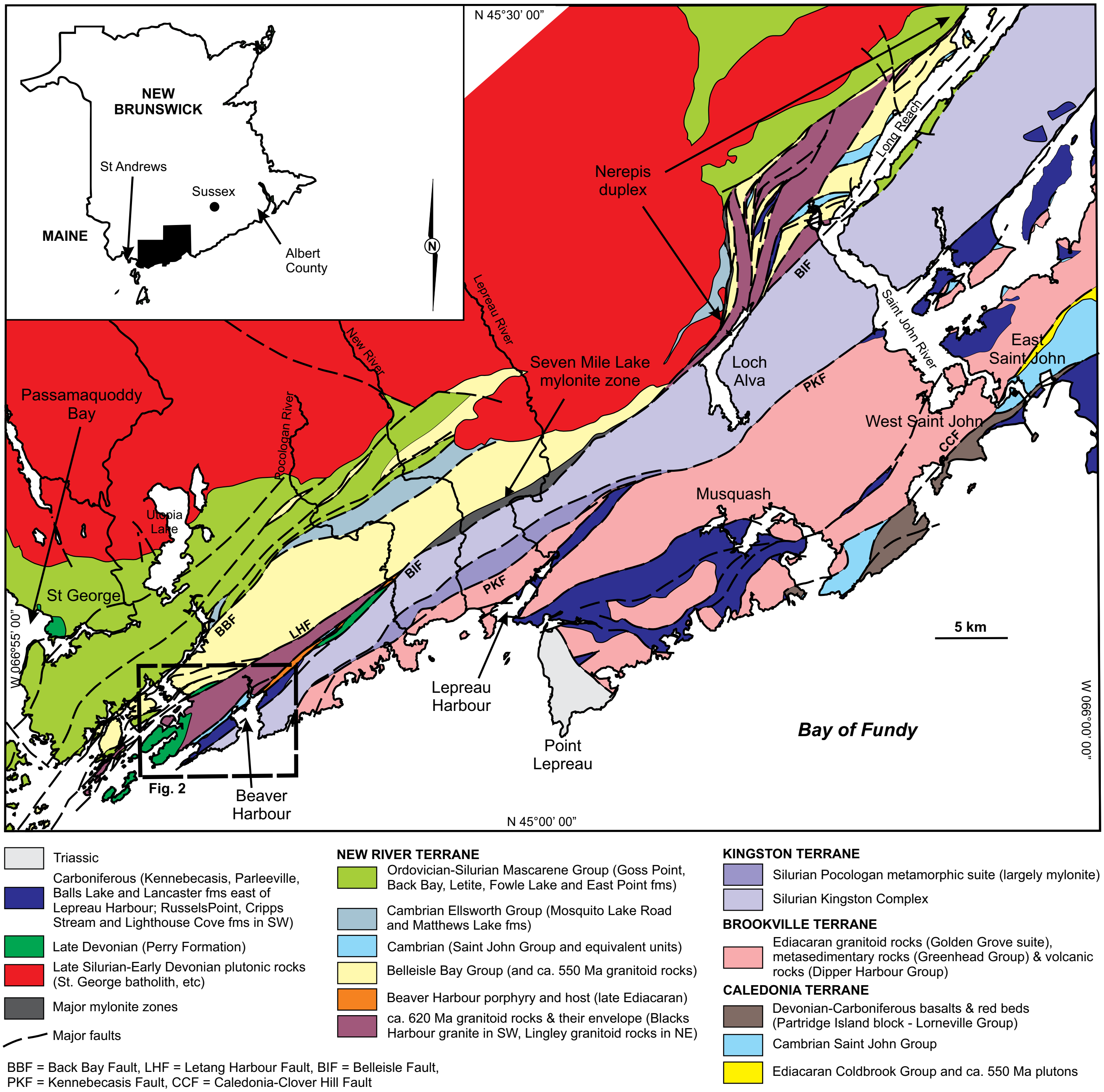


Figure 1. Outline geological map of southwestern New Brunswick based on McLeod *et al.* (2005), Johnson *et al.* (2005), and Barr and White (2005), modified after mapping for this study, with fault nomenclature after Waldron *et al.* (2015).

this red bed unit mainly around St. Andrews and west of the United States border in Washington County, Maine (near Perry, the type section), with scattered outliers around the shores and islands of Passamaquoddy Bay, in the St. Stephen–St. Andrews area, and around Blacks Harbour (Ells 1905; MacKenzie 1940; Mackenzie and Alcock 1960; Alcock and Perry 1960; Figs. 1, 2). Dawson (1861, 1862) considered the plant fossils Devonian, but subsequently, these and other plant fossil occurrences in southern New Brunswick became the subject of often heated controversy, with suggested ages ranging from Silurian to Pennsylvanian (see Bailey 1865, 1890; Bailey *et al.* 1880; Bailey and Matthew 1919; Ells 1905). Part of the problem in the Blacks Harbour–Beaver Harbour area is that the Perry Formation is folded and locally cleaved (Figs. 4c, d) in contrast to relatively undeformed strata exposed around St. Andrews. Also, poor understanding of the distribution and age of the Mascarene Group and the Blacks Harbour granodiorite over which the Perry Formation

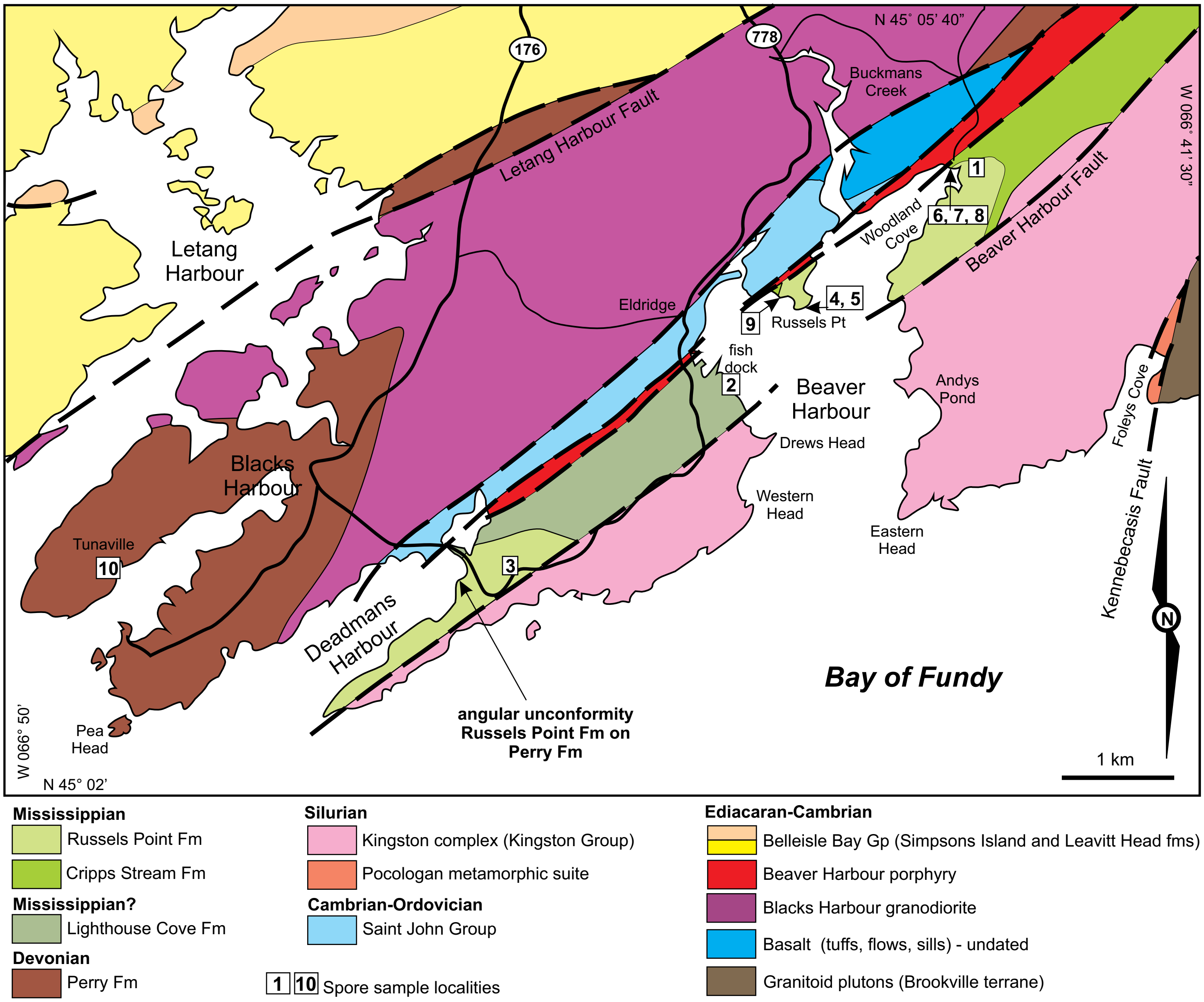


Figure 2. Geological map of the Blacks Harbour–Beaver Harbour area modified after McLeod *et al.* (2005) and Fyffe *et al.* (2014) with sample locations.

displays angular unconformity or nonconformity relationships in the Blacks Harbour–Beaver Harbour area further contributed to the problem (Fig. 4e; Helmstaedt 1968).

The Perry Formation was defined by Smith and White (1905) and formalized by Wilmarth (1938). Modern studies of the Perry Formation have included petrography and sedimentology (McIlwaine 1967, 1968; Schluger 1973, 1976), and stratigraphic revisions which subdivided the formation into various members with a schematic correlation between the St. Andrews, Maine, and Blacks Harbour areas. The most recent summary of this stratigraphy with minor revisions was compiled by Stringer *et al.* (1991, see Figs 3, 5). In these contributions, an Upper Devonian age for the Perry Formation was accepted, and Stearns and van der Voo (1987) concluded that despite evidence of remagnetization during the late Paleozoic, remanent magnetism in the Perry Formation was consistent with an Upper Devonian paleo-pole.

The basement to the Perry Formation lying beneath the angular unconformity on the St. Andrews peninsula and around Passamaquoddy Bay is largely composed of Silurian sedimentary and volcanic rocks of the Mascarene Group (Mackenzie and Alcock 1960; McLeod *et al.* 2005). A nonconformity on the Blacks Harbour granodiorite is preserved along the north shore of Deadmans Harbour (Helmstaedt 1968; Figs 1, 2, 4e). The Blacks Harbour granodiorite has yielded a Neoproterozoic (Ediacaran) U–Pb zircon age of 622 ± 2 Ma (Barr *et al.* 2003).

Lighthouse Cove Formation

The informal name 'Lighthouse Cove Formation' was introduced by McLeod and Johnson (1998), replacing the

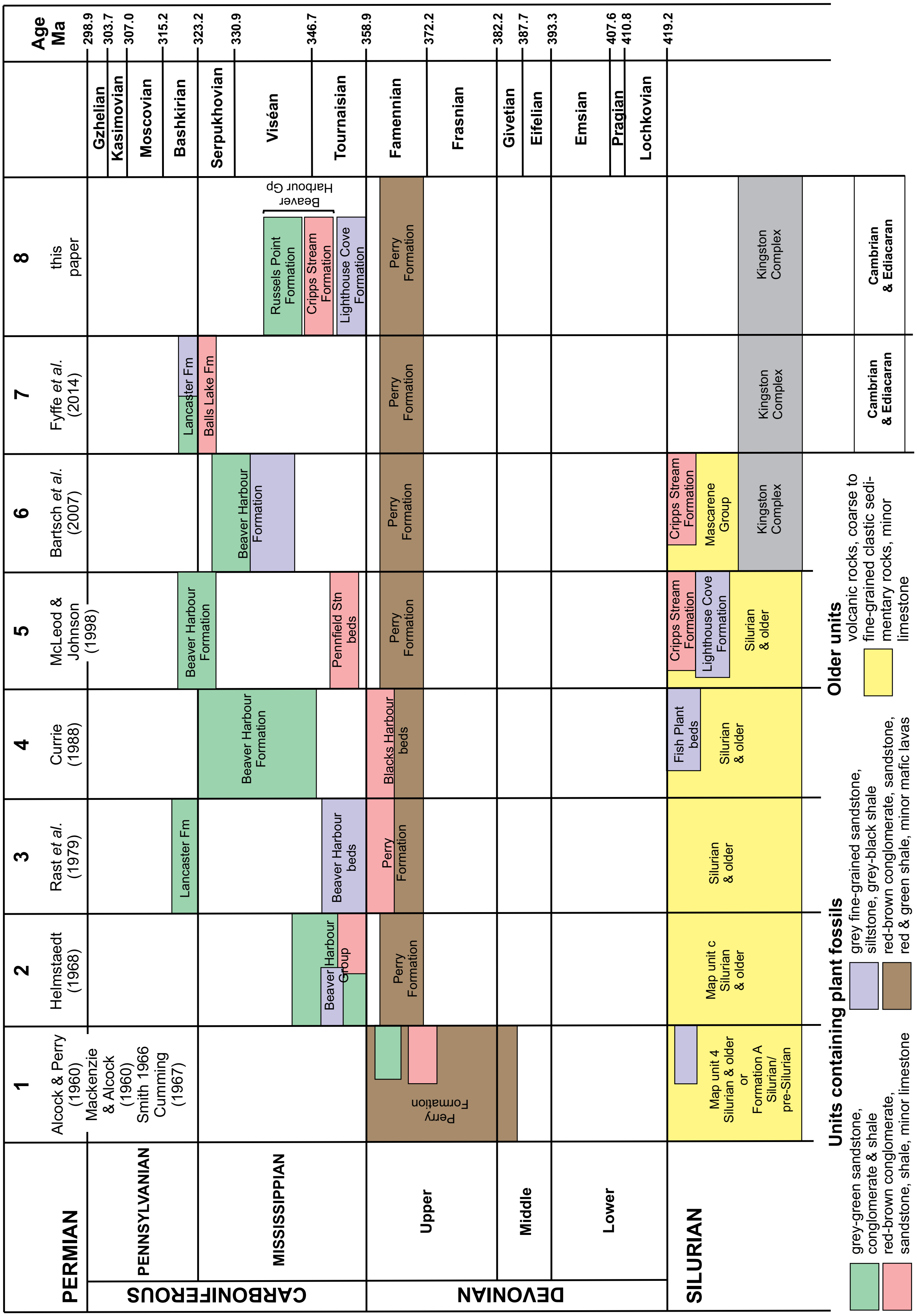


Figure 3. Schematic summary of the evolution of upper Paleozoic stratigraphic nomenclature in the Blacks Harbour–Beaver Harbour area, southwestern New Brunswick.

names “Beaver Harbour beds of Rast *et al.* (1979) and ‘Fish Plant beds’ of Currie (1988, Fig. 3). They followed Currie (1988) in assigning a Silurian age to the Lighthouse Cove Formation (Fig. 3, Columns 3–5). Formal status is given to the Lighthouse Cove Formation in this paper (Appendix B).

The Lighthouse Cove Formation comprises a ~500 m thick sequence of fine-grained light grey to white siliceous sandstone and siltstone, interbedded with thinly bedded to laminated and indurated dark grey to black, usually pyritiferous shale exposed along the western shore of Beaver Harbour between the Drews Head lighthouse and the fish plant dock (Figs. 2, 6a, b). Inland, sporadic outcrops of this unit can be traced to Deadmans Harbour, where they are also strongly indurated and underlie (with apparent angular unconformity—although the contact is not exposed) coarse to pebbly grey sandstone and grey to red shale of the Russels Point Formation (see below). Some plant fossils, largely fragmentary, from the Lighthouse Cove Formation were tentatively ascribed an Upper Devonian age (Cumming 1967), but earlier workers (Bailey and Matthew 1872) had suggested older ages. Helmstaedt (1968) noted that the fossiliferous Cambrian rocks he had identified along Buckmans Creek showed a more complex deformation history than those subsequently called Lighthouse Cove Formation. McLeod and Johnson (1998) followed Helmstaedt (1968) in tentatively assigning the Lighthouse Cove Formation a Silurian age (Fig. 3). Fyffe *et al.* (2014) implied that the Lighthouse Cove strata may represent an anoxic lacustrine facies variant of the Pennsylvanian Lancaster Formation (Fig. 3, Column 7), possibly analogous to the lacustrine beds in the Pennsylvanian Stellarton Formation in Nova Scotia (cf. Yeo 1989).

Cripps Stream Formation

This unit was identified and informally named ‘Pennfield Station beds’ by McLeod and Johnson (1998) (Fig. 3, Column 5) but was subsequently renamed Cripps Stream Formation by Fyffe (1998) because of the superior exposures on this stream. The formation consists of red and pale to dark grey shale, flaggy sandstone with interbedded red and green conglomerate, with layers of nodular carbonate (probably caliche) and limestone, unconformably beneath the Russels Point Formation (Figs. 6c, d, e, 7a, b). The thickest known section is at Woodland Cove (mouth of Cripps Stream), where 50 m of strata and the disconformity/unconformity with the overlying Russels Point Formation are preserved (Figs 2, 8). Some of the light and dark grey shales bear plant fragments and fossil burrows. Two more sections were identified during recent mapping along the southwestern and eastern shore of Russels Point (Fig. 2), consisting of red and grey shale, red sandstone, and conglomerate that appear to pass upward transitionally or with slight disconformity into grey shale and coarse-grained to pebbly sandstone of the Russels Point Formation (Figs 7b, 8). Plant fragments occur throughout the section.

McLeod *et al.* (1994) and McLeod and Johnson (1998) included their ‘Pennfield Station beds’ within the Silurian (Fig. 3, Column 5), whereas Fyffe (1988) c onsidered h is Cripps Stream Formation to be Upper Devonian/Carboniferous. Smith (2005), however, included the Cripps Stream Formation in the Silurian on a 1:250 000 scale compilation map of southwestern New Brunswick. Bartsch *et al.* (2007) also considered the Cripps Stream Formation to be mainly Silurian but assigned a western tract of it to the Upper Devonian Perry Formation (Fig. 2; Fig. 3, Column 6). Fyffe *et al.* (2014) correlated the main part of the Cripps Stream Formation southeast of the Beaver Harbour Porphyry with the Pennsylvanian Lancaster Formation of the Cumberland Group, except red and grey conglomerates at Woodland Cove, which were termed ‘Balls Lake Formation’. The tract northwest of the Beaver Harbour Porphyry (Perry Formation of Bartsch *et al.* 2007) was correlated with the Upper Mississippian Balls Lake Formation of the Mabou Group (Fig. 3, Column 7). Formal status is given to the Cripps Stream Formation in this paper (Appendix B).

Russels Point Formation (new name)

The Russels Point Formation, a sequence of grey coarse- to medium-grained sandstone or pebbly sandstone with conglomerate lenses (Figs. 7b, c, d, 8), interlayered with dark grey to greenish shale, locally indurated, occurs at Woodland Cove and the coast to the south, and occupies most of Russels Point (Figs 2; Fig. 3, Column 8). The sequence contains red intervals, and some of the conglomerate contains cobbles. These rocks were included in the ‘Beaver Harbour Group’ by Helmstaedt (1968) and Brown and Helmstaedt (1970), and in the Lancaster Formation by Rast *et al.* 1979). Currie (1988) referred to these rocks as ‘Beaver Harbour Formation’ and followed Rast *et al.* (1979) in suggesting correlation with the Pennsylvanian Lancaster Formation

Figure 4. (next page) Field photographs of various features in the Perry Formation. (a) Polymictic cobble conglomerate, Perry Formation, Pea Head (GPS N 45.0409°, W 066.8061°); scale pen = 12 cm. (b) Greenish pebbly sandstone with red siltstone layers, Perry Formation, east of Deeping Cove, Deadmans Harbour (GPS N 45.0474°, W 066.7874°), scale hammer handle = 1 m. (c) Layer of greenish-brown siltstone in red shale and sandstone sequence, Perry Formation, Tunaville beach (GPS N 45.0521°, W 066.8081°), scale hammer handle = 1 m. Location #10, sample 186A is from this outcrop (see Appendix A). (d) Pebble coarse-grained sandstone with fine-grained sandstone-siltstone, Perry Formation, with pressure-solution cleavage (parallel to pen), Pea Head (GPS N 45.0409°, W 066.8061°), scale pen = 12 cm. (e) Nonconformity of basal Perry Formation (conglomerate-coarse-grained sandstone) on Blacks Harbour granodiorite, offset by small fault, east of Deeping Cove, Deadmans Harbour (GPS N 45.0492°, W 066.7853°), scale person = 1.75 m.


(a)
(b)
(c)
(d)
(e)
Perry Fm
fault
Blacks Harbour granodiorite
Perry Fm
nonconformity
Blacks Harbour granodiorite

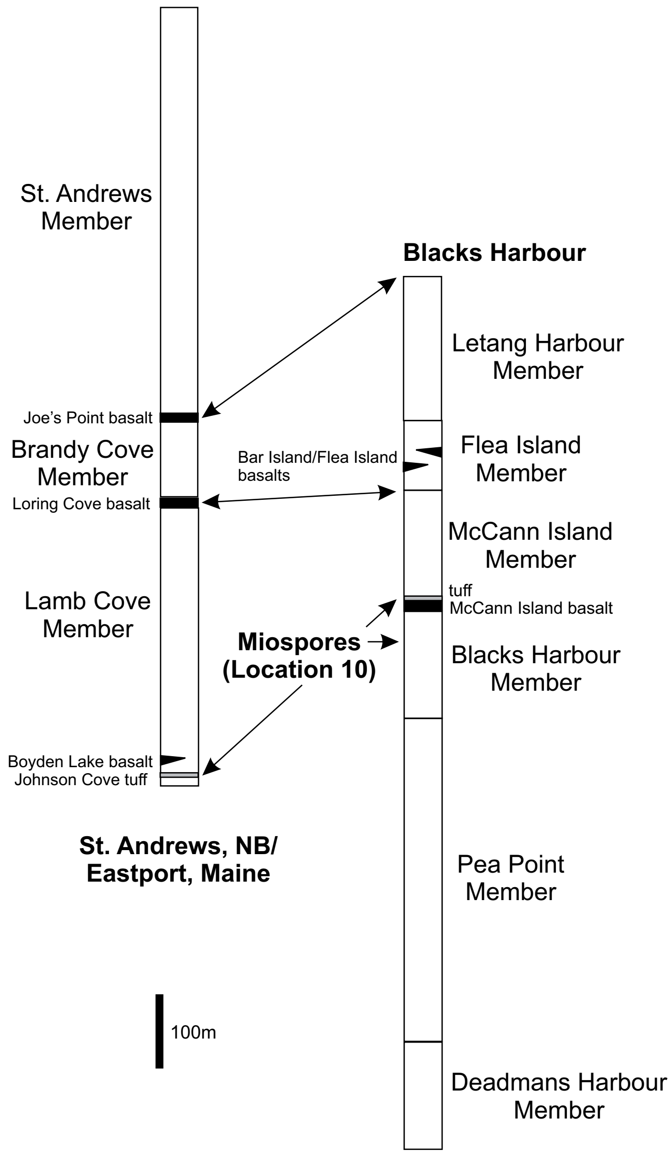


Figure 5. Correlated stratigraphy of the Perry Formation after Stringer *et al.* (1991) with the position of the palynology Sample 186B from location 10 in Figure 2).

(Fig. 3, Columns 2–4). McLeod *et al.* (1994) put the Beaver Harbour Formation in the Carboniferous, and McLeod and Johnson (1998) included it in the Lower Mississippian Horton Group (Fig. 3, Column 5), although the formation was not formally defined. Fyffe *et al.* (2014) subsequently correlated these rocks with the Lancaster Formation exposed farther to the east in the Lepreau area (Fig. 3, Column 7). Criteria for establishing the formal status of the Russels Cove Formation are summarized in Appendix B.

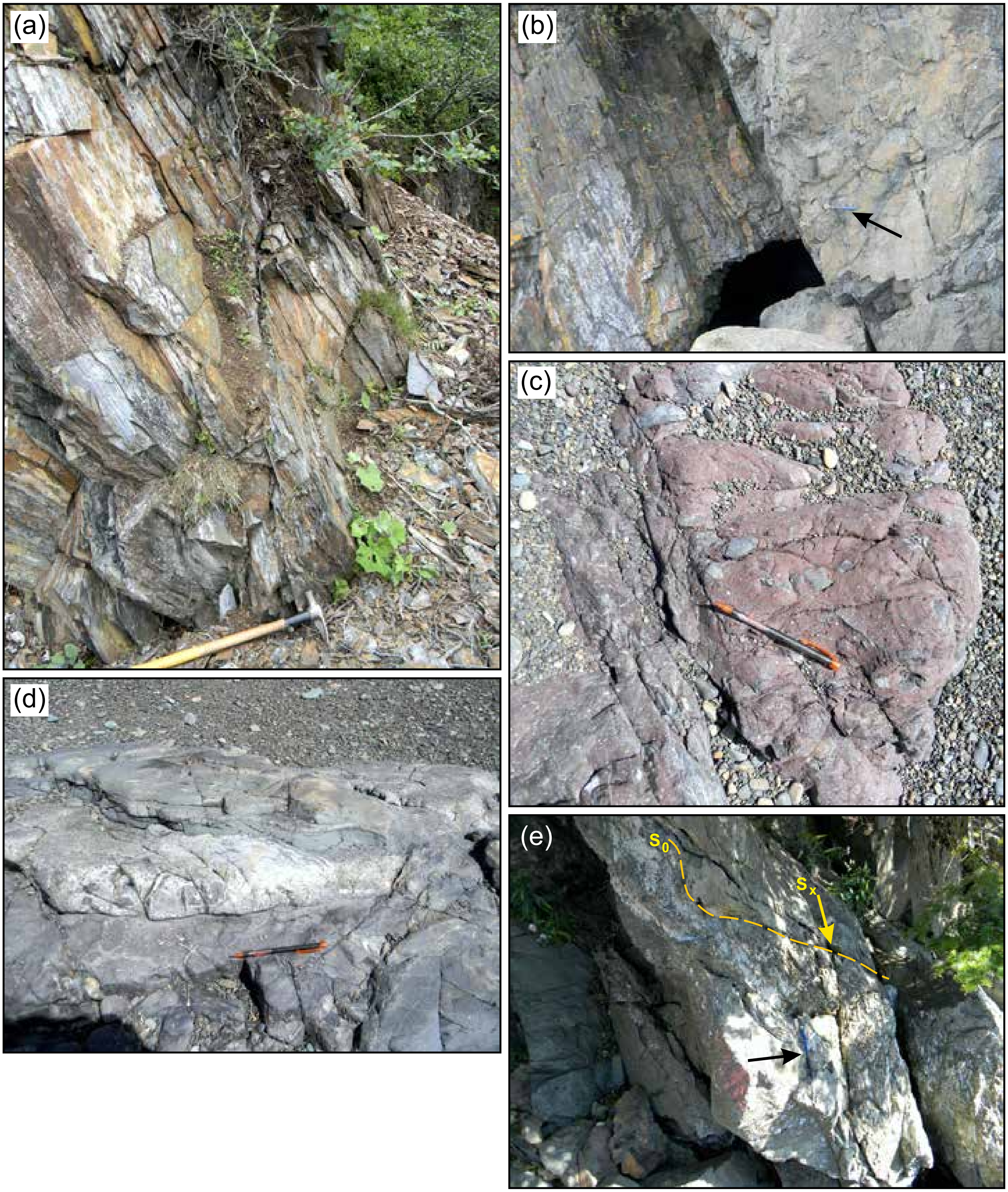
The Russels Point Formation also forms the northern side of Deadmans Point, exposed along the southern shore of Deadmans Harbour and sporadically outcrops inland to the east (Fig. 2). Along the shore section (near the low tide mark) an angular unconformity is preserved where this unit overlies steeply dipping red pebble to cobble conglomerate, sandstone, and siltstone of the Perry Formation (identified during this study, Fig. 9), whereas the exposed lowest 2 m of the Russels Point Formation include grey to red shale with carbonate nodules, and paleosol with roots in-growth position. Most of the succession at Deadmans Harbour is heavily indurated. No Cripps Stream Formation underlies the Russels Point Formation in this section.

The Russels Point Formation has yielded the most abundant (although still sparse) plant fossils (Figs. 7d, e), including specimens in growth position. Helmstaedt (1966) initially identified the plants as Devonian, but later revised this to Mississippian (Helmstaedt 1967, 1968).

Late Devonian and Carboniferous rocks in the Blacks Harbour–Beaver Harbour area occur within several northeast-trending, fault-bounded units adjacent to pre-Famennian rocks (Fig. 2). Mackenzie and Alcock (1960) and Alcock and Perry (1960), respectively, recognized the unconformable relationship of the Upper Devonian Perry Formation with the Silurian Mascarene Group in the St. George area (Fig. 2) and with undifferentiated 'Silurian and (?) earlier rocks of Map Unit '4' in the Blacks Harbour–Beaver Harbour area (Fig. 3, Column 1). Alcock and Perry (1960) also noted a fossil plant location within their Map Unit '4' on the western shore of Beaver Harbour (now part of the 'Lighthouse Cove Formation' of this study).

Cumming (1967), reporting on work in the early 1960s, recognized a narrow, un-named sequence of plant-bearing sedimentary strata extending from Deadmans Harbour northeastward to the head of Beaver Harbour (including the Lighthouse Cove, Cripps Stream and Russels Point formations of this study). This sequence was assigned a Devonian(?) age on the basis of plant fossils located in dark grey shale on the western shore of Beaver Harbour. To the northwest, the Devonian(?) rocks are faulted against older

Figure 6. **(next page) Field photographs of various features in the Lighthouse Cove and Cripps Stream formations. (a) Rusty weathering pyritiferous siltstone-shale, Lighthouse Cove Formation, fish plant and dock, west side of Beaver Harbour (GPS N 45.0671°, W 066.7376°), scale hammer handle = 1 m. (b) Laminated pyritiferous fine-grained sandstone-siltstone-shale between two thicker fine- to medium-grained sandstone layers, Lighthouse Cove Formation, fish plant and dock, west side of Beaver Harbour (GPS N 45.0671°, W 066.7376°), scale hammer handle = 35 cm (picked out by arrow). This is Location #2, sample 065C (see Appendix A). (c) Polymictic pebble conglomerate/breccia with red siltstone matrix, Cripps Stream Formation, cove west of Russels Point, Beaver Harbour (GPS N 45.0750°, W 066.7325°), scale pen = 13 cm. (d) Greenish-grey to red-brown siltstones with lenses of grey pebble conglomerate containing grey shale clasts, Cripps Stream Formation, cove west of Russels Point, Beaver Harbour (GPS N 45.0750°, W 066.7325°), scale pen = 13 cm. (e) Limestone layer with green-brown sandstone above, bedding (S0) and a weak cleavage (Sx) are indicated, Cripps Stream Formation, Woodland Cove (GPS N 45.0849°, W 066.7120°), scale pen (black arrow) = 13 cm.**


(a)
(b)
(c)
(d)
(e)
S_0
S_x

Silurian/pre-Silurian rocks of his Formation 'A' (more or less equivalent to Map Unit '4' of Alcock and Perry (1960). Map Unit '4' (Fig. 3, Column 1) and Formation 'A' (Fig. 3, Column 1) are now known to include Neoproterozoic volcanic and granitic rocks as well as sedimentary and volcanic rocks equivalent in age to Cambrian rocks in the Saint John Group (Helmstaedt 1968; Currie 1988; McLeod *et al.* 2005; Landing *et al.* 2008; Barr *et al.* 2014). In his stratigraphic column, Smith (1966) refers to Cumming's un-named Devonian(?) strata as the 'Beaver Harbour unit', locating it above the Silurian Mascarene Group and below the Upper Devonian Perry Formation.

Helmstaedt (1968) introduced the term 'Beaver Harbour Group' for the Lower Carboniferous plant-bearing beds in the Blacks Harbour–Beaver Harbour area. Brown and Helmstaedt (1970) used Map Unit 'h' (Beaver Harbour Group) for Carboniferous rocks, and Map Unit 'c' for Silurian and older rocks in the Blacks Harbour–Beaver Harbour area, equivalent to Formation 'A' of Cummings (1967). Although Brown and Helmstaedt (1970) mentioned that Bailey and Matthew (1872) included some of these rocks in the Mascarene Group, Map Unit 'c' was not labelled as such on their map legend. Their Map Unit 'a' (Neoproterozoic Coldbrook Group) on the southern side of the Beaver Harbour Group is now known as the Silurian Kingston Complex (Barr *et al.* 2002). Helmstaedt (1967, 1968) reported that flora contained in the grey-green sandstone, conglomerate, and shale of the Beaver Harbour Group were Lower Carboniferous (Mississippian) rather than Upper Devonian as previously stated (Helmstaedt 1966) (Fig. 3, Column 2).

Rast *et al.* (1979) suggested that their 'Beaver Harbour Beds' could correlate with the Tournaisian Horton Group to the east (Fig. 3, Column 3), following a suggestion by Helmstaedt (1968) that a correlation with the Kennebecasis Formation north of Saint John was possible, although at the time, the age of the Kennebecasis Formation was not well constrained. Rast *et al.* (1979) took the grey-green sandstone, conglomerate, and shale unit on Russels Point out of the 'Beaver Harbour Group' and correlated it with the Pennsylvanian Lancaster Formation in the Saint John area (Fig. 3, Column 3).

Currie (1988) used the term 'Blacks Harbour beds' in the Blacks Harbour–Beaver Harbour area for rocks equivalent to the Upper Devonian Perry Formation in the St. Andrews area (Mackenzie and Alcock 1960). He introduced his 'Fish Plant beds', extending from Deadmans Harbour northeastwards to Beaver Harbour (Fig. 2). He considered them to be Silurian and thus much older than the Upper Devonian–Mississippian Beaver Harbour Formation (Fig. 3, Column 4).

McLeod and Johnson (1998) introduced the term 'Lighthouse Cove Formation' to replace 'Fish Plant beds' of Currie (1988). McLeod *et al.* (1994) and McLeod and Johnson (1998) also mapped strata in the continuation of the Blacks Harbour–Beaver Harbour fault-bound belt, northeast from Woodland Cove on Beaver Harbour to Pennfield Station on Rte 175 (old Hwy 1), naming them 'Pennfield Station beds'. The 'Pennfield Station beds' were assigned a Silurian age like that of the Lighthouse Cove Formation (Fig. 3, Column 5).

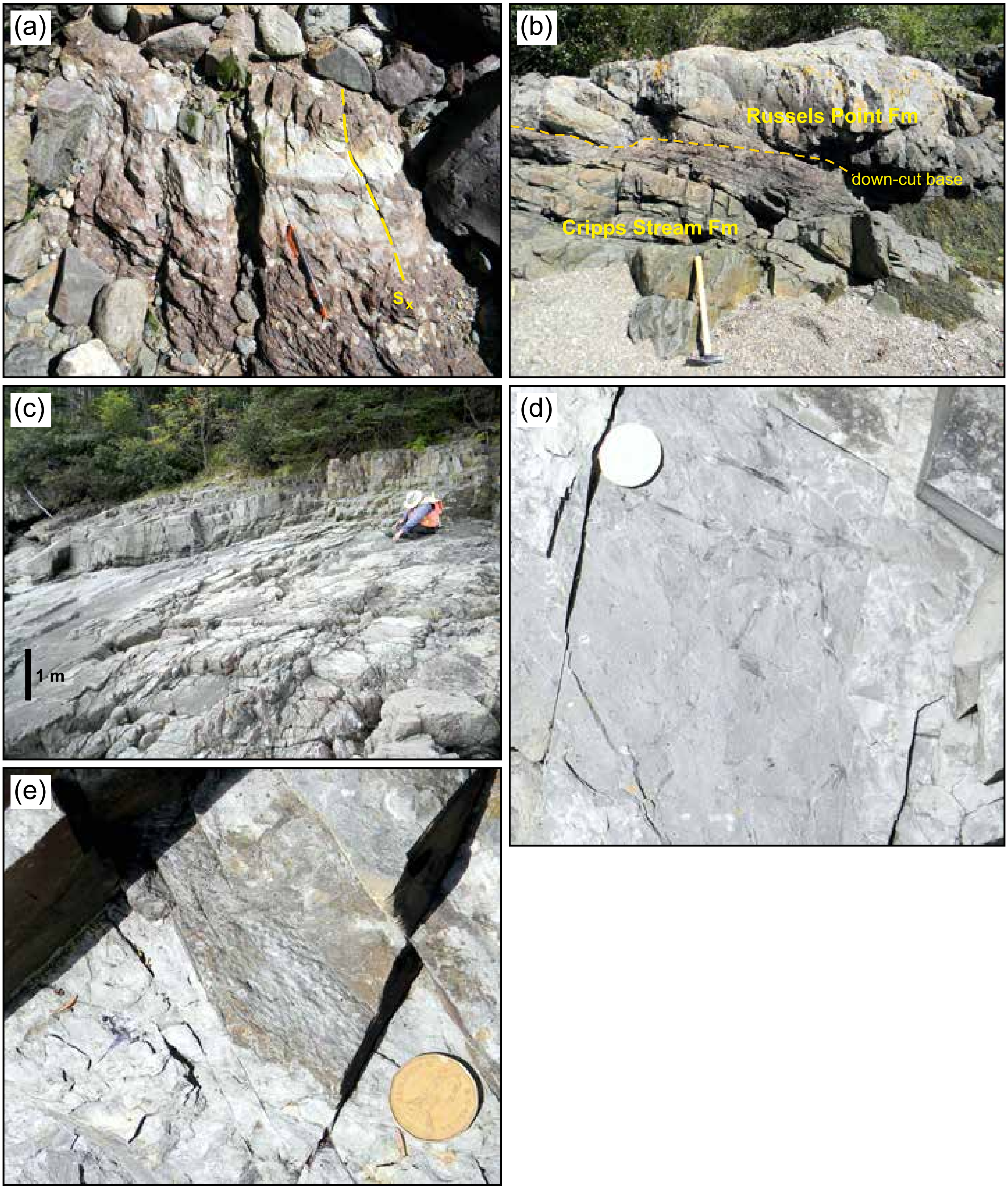
Fyffe (1998) introduced the 'Cripps Stream Formation' of Devonian or Carboniferous age to refer to the supposed Silurian 'Pennfield Station beds' of McLeod *et al.* (1994) and McLeod and Johnson (1998). Fyffe (1998) noted small outcrops of grey sandstone and shale exposed during construction of the new Highway 1 south of Pennfield Station. This exposure lies in the watershed of Cripps Stream along trend from good exposures mapped as 'Pennfield Station beds' at the mouth of Cripps Stream, mapped by McLeod *et al.* (1994) and McLeod and Johnson (1998).

The distribution of the Cripps Stream Formation from Woodland Cove to Pennfield Station is shown on the revised 1:250 000 scale compilation map of southwestern New Brunswick, where it is considered to be Silurian (Smith 2005). However, Bartsch *et al.* (2007) suggested that the red conglomerate and sandstone exposures at Pennfield Station are part of a distinct fault-bounded sliver that could be traced to the southwest, north of Woodland Cove, separated from the Cripps Stream Formation of the Deadmans Harbour–Beaver Harbour fault-bounded tract by a narrow outcrop of Late Proterozoic Beaver Harbour Porphyry (Bartsch and Barr 2005; Barr *et al.* 2014). Bartsch *et al.* (2007) therefore placed the exposures at Pennfield Station in the Upper Devonian Perry Formation, an interpretation that is adopted in this study (Fig. 2). We retain the term 'Cripps Stream Formation' herein but restrict it to include only strata that lie on the southeast side of the Beaver Harbour Porphyry (Figs. 2, 3, Column 8). Our palynological collections at the mouth of Cripps Stream prove that the rocks in that area are Mississippian (see below).

Based on lithological similarities, Fyffe *et al.* (2014) correlated the red conglomerate and sandstone exposures at

Figure 7. (next page) Field photographs of various features in the Cripps Stream and Russels Point formation. (a) Red siltstone-shale with carbonate nodules and discontinuous layers (caliche), with weak cleavage (Sx), Cripps Stream Formation, Woodland Cove (GPS N 45.0849°, W 066.7120°), scale pen = 13 cm. (b) Contact of red and grey sandstone-siltstone, Cripps Stream Formation with overlying grey pebbly sandstone, Russels Point Formation showing down-cutting base, mouth of Cripps Stream, Woodland Cove (GPS N 45.0745°, W 066.7314°), scale hammer handle = 1 m. (c) Grey feldspathic quartz arenite and grey shale layers, shallow channels with minor quartz pebble conglomerate lenses, Russels Point Formation, east shore of Russels Point, Beaver Harbour (GPS N 45.0744°, W 066.7288°), 1 m scale lower left. (d) Carbonized stem fragments, unidentified, in fine-grained quartz arenite, Russels Point Formation, east shore of Russels Point, Beaver Harbour (GPS N 45.0744°, W 066.7288°), scale coin = 2.5 cm diameter. (e) Stem fragment Lepidodendropsis sp. in fine-grained quartz arenite, Russels Point Formation, east coast of Russels Point, Beaver Harbour (GPS N 45.0744°, W 066.7288°), scale coin = 2.5 cm diameter.

Pennfield Station (Perry Formation of Bartsch *et al.* 2007) with the upper Mississippian (Visean–Serpukhovian) Balls Lake Formation. The Lighthouse Cove and Beaver Harbour formations on Russels Point and west of Beaver Harbour were included in the Pennsylvanian Lancaster Formation (Fig. 3, Column 7). Although the Russels Point and Lancaster formations have similarities, they also have important differences, such as the type and abundance of plant fossils.



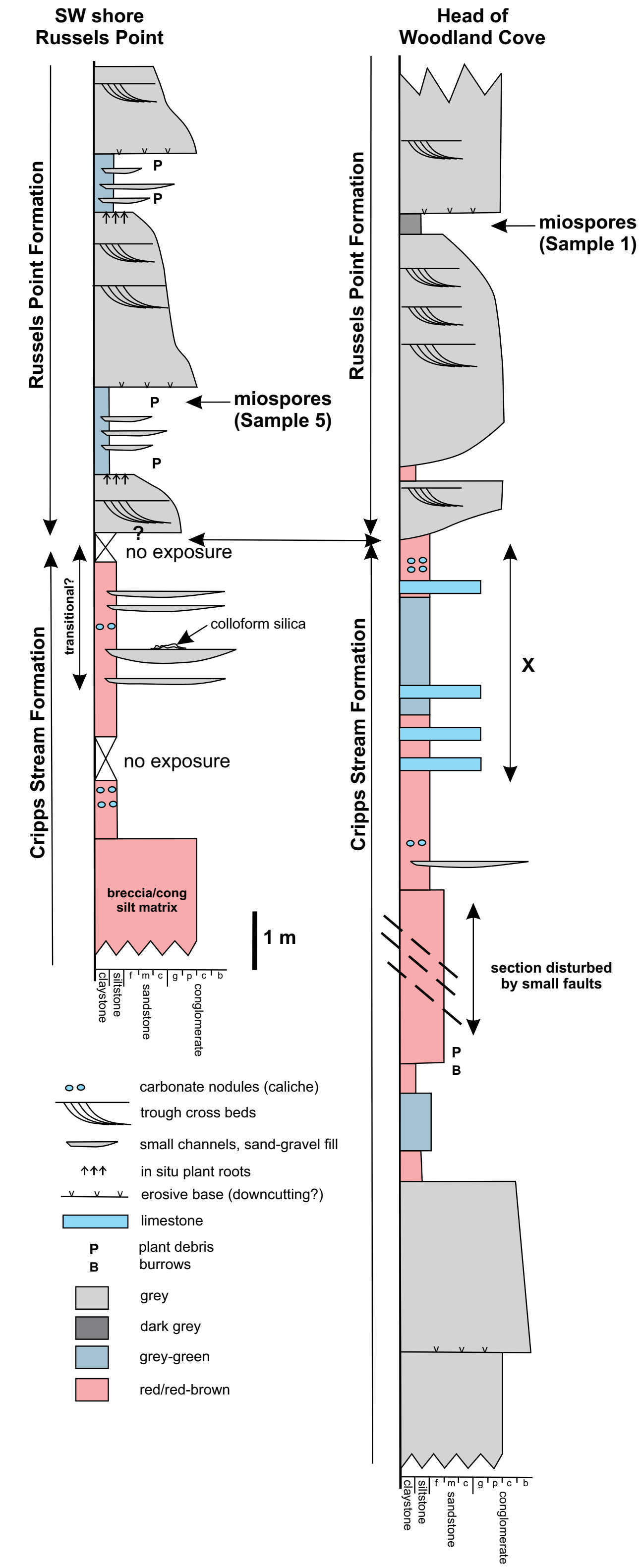


Figure 8. Schematic stratigraphic-lithological sections across the Cripps Stream Formation/Russels Point Formation contact at Cripps Steam (Woodland Cove) and on the southwest coast of Russels Point. Location of palynology samples 064A (from location 1) and 167 (from location 5) indicated (Fig. 2).

The Lancaster Formation characteristically contains abundant plant trash, *Stigmaria* sp. roots, lycopsid and cordiatalean logs, and *Calamites* stem fragments, whereas identifiable specimens in the Russels Point Formation are sparse, far smaller, and generally identified as *Adiantites, Lepidodendropsis,* and *Dadoxylon*, not typically considered Pennsylvanian species and more likely Mississippian, specifically Tournaisian (e.g., Stopes 1914; Bell 1927, 1960; Falcon-Lang and Miller 2007). The genus *Adiantites* is restricted to the Carboniferous, and specimens formerly identified as Upper Devonian *Archaeopteris* and *Cyclostigma* were reclassified as Mississippian *Lepidodendropsis* (Helmstaedt 1966, 1967, 1968).

PALYNOLOGY

Rationale

Given the ambiguity and poor biostratigraphic resolution of the macroflora collected from the Perry, Lighthouse Cove, Cripps Stream, and Russels Point formations, and the lack of any marine deposits, palynology offers the possibility of stratigraphically useful data. Consequently, ten samples were collected from around Blacks Harbour, Deadmans Harbour, and Beaver Harbour from all four formations (Figs. 2, 3, 4; Table 1). In each case dark grey shale units as fine-grained as possible, without visible plant fragments, pyrite, or reddening, were chosen (see Appendix A for sample details and Fig. 2 for locations).

Analytical method

For palynological preparation sample material was washed, subjected to cold HCl and HF treatment for several days, and then sieved to neutrality (Wood *et al.* 1996). Organic residues from clastic samples were oxidized in Schulze's solution for between 6 and 8 hours before being treated with KOH (Smith and Butterworth 1967). Residues were strewn in PVA on coverslips and then mounted on two microscope slides using Petropoxy. Permanent mounts from the preparations were conserved and a set supplied to the Geological Surveys Branch, New Brunswick Department of Natural Resources and Energy Development. This material will eventually be archived in the New Brunswick Museum, Saint John.

Some samples provided poor quality assemblages but with common or abundant thermally mature, dark, opaque organic material. Four of these (64A, 65C, 167A and 186B, Table 1) which had common or abundant organic material on coverslips from the first oxidation were selected for extended oxidation, being treated with Schulze's solution for 170 hours. After this period the residue was split, with half treated in KOH and the other half not. Residues were mounted in Aquamount for analysis. Aquamount produces a non-permanent mount, allowing for rapid examination of the oxidized material without the application of any heat (as

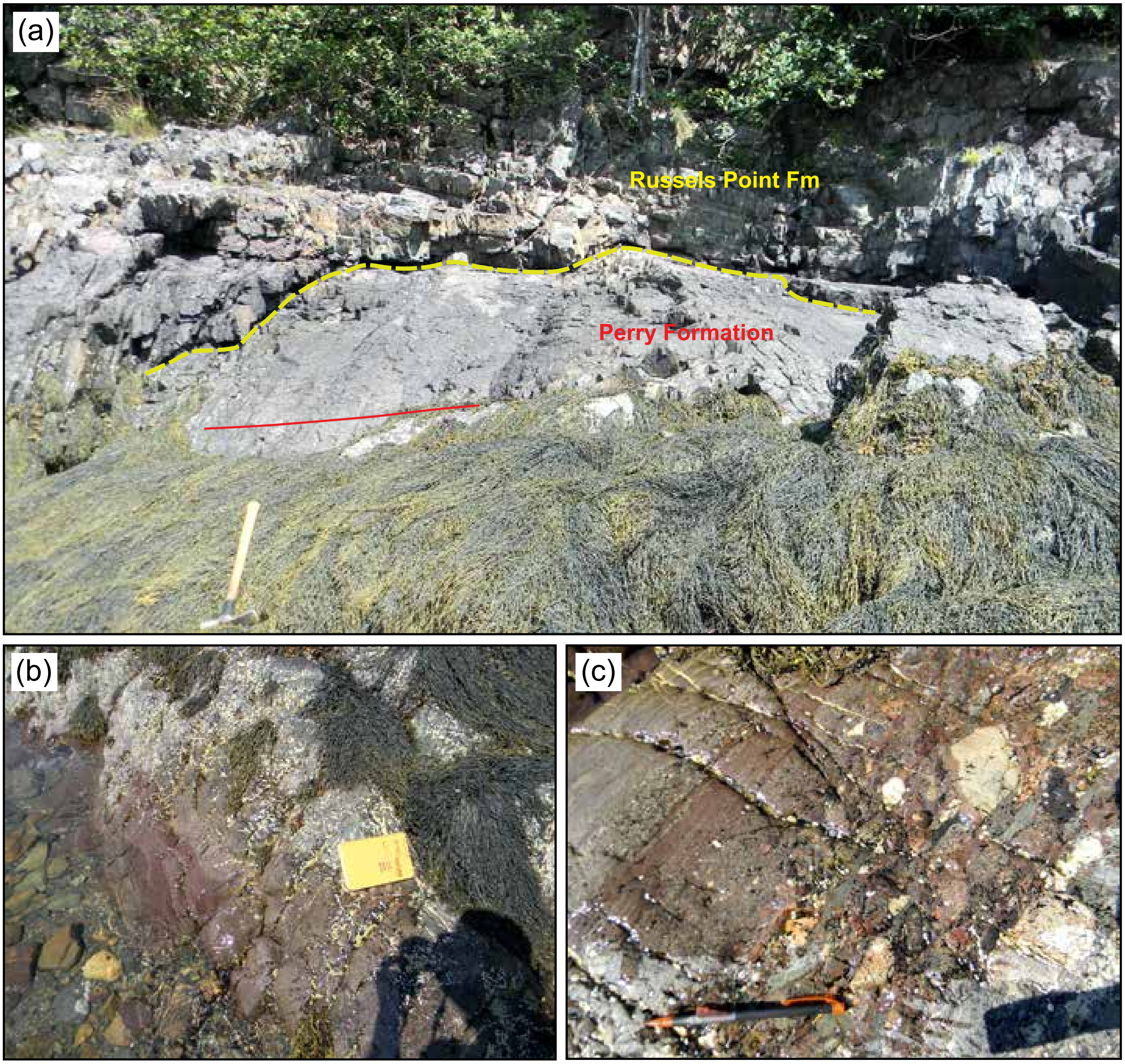


Figure 9. Angular unconformity with Russels Point Formation overlying steeply dipping Perry Formation, south shore of Deadmans Harbour (GPS N 45.0503°, W 066.7695°). (a) Overview of unconformity, Russels Point Formation is indurated grey feldspathic sandstone overlying red sandstone cobble conglomerate of Perry Formation. Solid red line indicates strike of bedding in the Perry Formation with dip of 70–75˚ toward the camera. Scale hammer handle = 1 m. (b, c) Detail of cobble conglomerate and red sandstone, Perry Formation, beneath the seaweed in foreground of (a). Scales: notebook = 18 cm along spine, pen = 13 cm.

used for other mounting media). Any heat (including, in extreme cases, that from a microscope light bulb) will hasten the eventual return to opacity of the miospore material. A rapid analysis is required as the material, even at room temperature, will eventually return to opacity. For this reason, cold mounting media that take many hours to cure (e.g., Elvacite) are not used.

Biostratigraphy

Palynological assemblages are assigned to the miospore biozonations for the Carboniferous of Maritimes Canada (Hacquebard 1972; Utting 1987, 1989; Utting *et al.* 1989, 2010; Dolby in St. Peter and Johnson 2009) and to the Devonian miospore biozones of Richardson and MacGregor (1986, see Fig. 10). There are few points in the Mississippian

Table 1. Tabulated samples and results of palynological analysis, Blacks Harbour - Beaver Harbour area, southwestern New Brunswick.

Sample #	Location #	GPS: latitude - longitude	Location name	Notes
20-SJH-064A	1	N 45.0852°, W 066.7112°	Cripps Stream dam	Grey shale in Russels Point Fm
20-SJH-065C	2	N 45.0671°, W 066.7376°	Beaver Harbour fish dock	Black shale in Lighthouse Cove Fm
20-SJH-135A	3	N 45.0520°, W 066.7631°	Road south of Deadmans Harbour	Grey shale in Russels Point Fm
20-SJH-165B	4	N 45.0745°, W 066.7314°	South end of Russels Point	Grey shale in Russels Point Fm
20-SJH-167A	5	N 45.0748°, W 066.7322°	South end of Russels Point	Grey shale in Russels Point Fm
20-SJH-169B	6	N 45.0851°, W 066.7126°	Beach at NE end of Woodland Cove	Grey shale in Cripps Stream Fm
20-SJH-170A	7	N 45.0850°, W 066.7125°	Beach at NE end of Woodland Cove	Grey shale in Cripps Stream Fm
20-SJH-172C	8	N 45.0849°, W 066.7123°	Beach at NE end of Woodland Cove	Grey shale in Cripps Stream Fm
20-SJH-185A	9	N 45.0737°, W 066.7296°	Beach W side of Russels Point	Grey shale in Russels Point Fm
20-SJH-186B	10	N 45.0521°, W 066.8081°	West end of beach at Tunaville	Grey-green shale in Perry Fm

Notes: Sample numbers (first column) refer to the specimen collection maintained by Geological Surveys Branch, New Brunswick Department of Natural Resources and Energy Development (Fredericton, New Brunswick). Location numbers (second column) are those shown in Figure 2.

biostratigraphy where range tops of miospore taxa are useful, which means that the presence of a single biozone is inferred based on the absence of any of the critical taxa from the overlying biozone. This approach is not wise when dealing with non-ideal, relatively low-diversity assemblages, or assemblages with some unusual paleoecological or facies control: the absence of key taxa may reflect such controls other than evolutionary distribution. Given the nature of the material in this present study, the absence of key taxa has not been given any biostratigraphical significance. This approach has resulted in the predominance of relatively long proven age range interpretations for individual samples.

Results

Of the ten samples examined in this study (Fig. 2, Table 1), one (location 8) proved barren, six samples (locations 2, 3, 4, 6, and 7) yielded material of poor quality of indeterminate age, and three samples (locations 1, 5, and 10) yielded useful assemblages (Fig. 5). Complete results for all samples are tabulated in Appendix A.

Sample 64A

Collected at location #1 from the Russels Point Formation at the head of Woodland Cove (Figs. 2, 8) yielded a poor-quality assemblage with species showing a maximum age of Tournaisian Biozone 1A to a minimum age of the lower part of the *K. stephanephorus* Biozone (Visean, middle Holkerian).

Sample 167A

Collected at location 5 from the lowest part of the Russels Point Formation on the southwest coast of Russels Point (Figs. 2, 8) yielded a good quality assemblage consistent with the *L. pusilla – D. columbaris* Biozone (Visean, Chadian– Holkerian) (Fig. 10).

Sample 186B

Collected at location 10 from the Perry Formation at Tunaville (Figs 2, 4c, 5) yielded a good quality assemblage consistent with the *R. flexuosa – G. cornuta* Biozone, and possibly the lower part of the *V. pusillites – R. lepidophyta* Biozone (Upper Devonian, lower to middle Famennian) (Fig. 10).

STRATIGRAPHIC INTERPRETATION

The samples from the Russels Point Formation (locations 1 and 5) constrain the age of this unit quite well. Sample 64A at location 1 is from a grey to blue-grey shale layer within a sequence dominated by coarse to pebbly sandstone approximately 10 m above the contact with the Cripps Stream Formation, at the dam on Cripps Stream at Woodland Cove (Figs. 2, 7b, 8). At the contact here the first pebbly sandstone is downcutting into the red shale and siltstone at the top of the Cripps Stream Formation. Sample 167A at location 5 is from a grey shale beneath the first thick coarse sandstone-pebbly sandstone of the Russels Point Formation, west of Russels Point, where the transition from Cripps Stream Formation appears to be gradational (the contact is poorly exposed but can be placed within 2 m (Figs. 2, 8). Given the nature of the contact, the top of the Cripps Stream Formation could be as young as Chadian or Arundian (lower Visean). The assemblage in Sample 167A at location 5 places the basal part of the Russels Point Formation in the Chadian–Holkerian interval (Figs. 8, 10). This result demonstrates unequivocally that the suggested correlation of the Cripps Stream Formation and the Russels Point Formation with Lancaster Formation (Fyffe *et al.* 2014) is untenable because the latter is Langsettian (Bashkirian, lower Pennsylvanian).

Regional biostratigraphy suggests correlation of the Cripps Stream and Russels Point formations with the lower part of the Windsor Group, and a similar succession can be

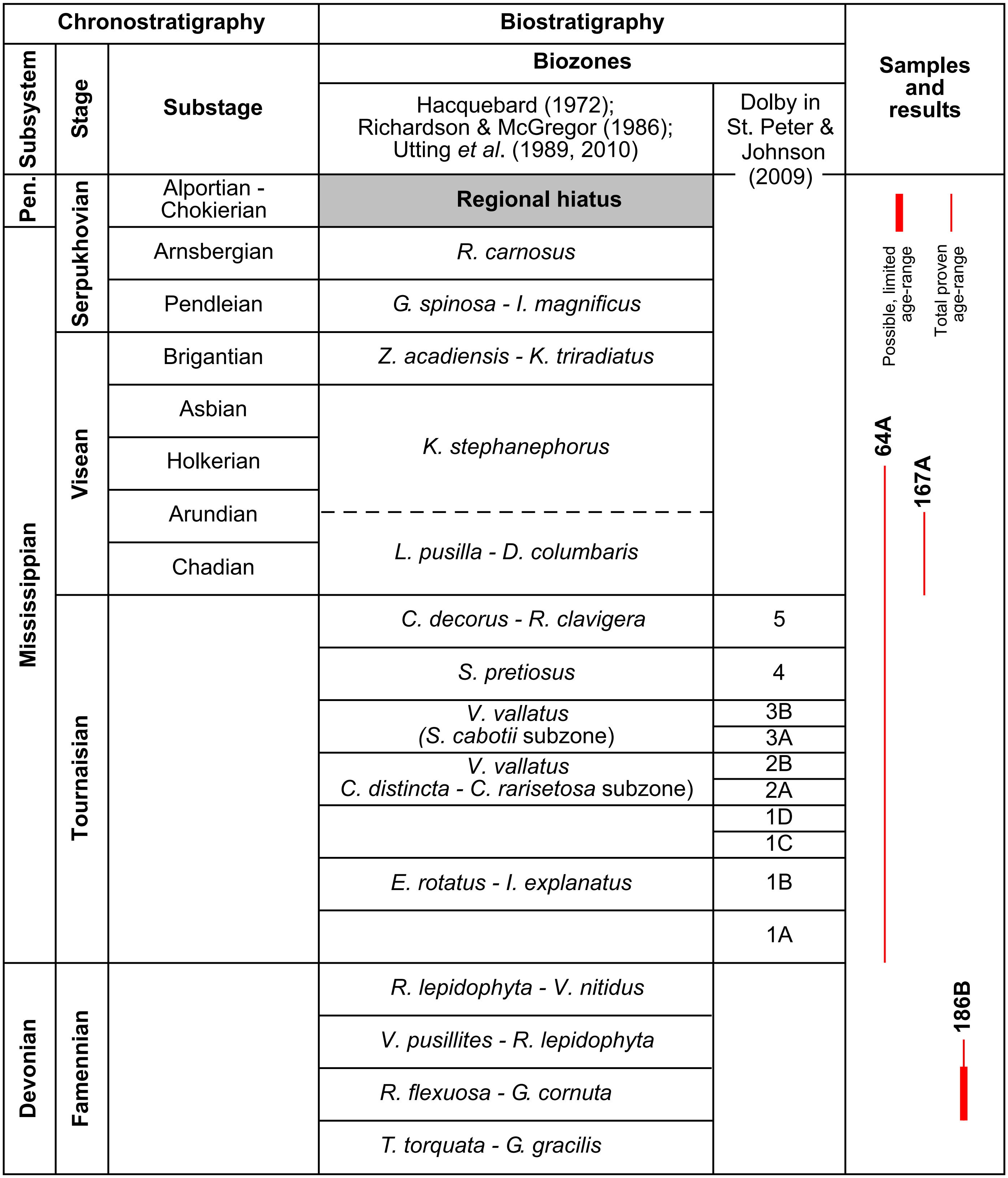


Figure 10. Miospore biozones of the Upper Devonian and Carboniferous rocks of eastern Canada after Hacquebard (1972), Richardson and McGregor (1986), Utting *et al.* (1989, 2010), and Dolby in St. Peter and Johnson (2009). Samples and results from this study are included.

seen to the east of Beaver Harbour around Lepreau Harbour (Stimson *et al.* 2016; Fig. 1). Here, the bioclastic to algal limestone and red breccia of the Parleeville Formation (Windsor Group), lies on granitic basement, and is overlain by a sequence of red sandstone, pebble to cobble conglomerate, and shale with caliche nodules. Grey intervals of this upper sequence (shale, sandstone, pebble conglomerate) have yielded Asbian–Brigantian miospores (upper Visean, Stimson *et al.* 2016; Park *et al.* 2016).

The carbonate-bearing upper 10 m of the Cripps Stream Formation at Woodland Cove ('x' on Fig. 8) may well be equivalent to the limestone beds of the Parleeville Formation and overlying red bed sequence, with the Russels Point Formation the equivalent of one or more of the upper grey intervals but more substantially developed (Fig. 8). This suggestion is a broad lithostratigraphic comparison rather than an exact correlation and is contingent on ongoing studies of the biostratigraphy around Lepreau Harbour.

The discovery of an angular unconformity below the Russels Point Formation around Deadmans Harbour (where the Cripps Stream Formation is absent, Fig. 2) sheds some light on the age of the Lighthouse Cove Formation. The Lighthouse Cove Formation is not present at the outcrop of the unconformity, and shallowly dipping beds of the Russels Point Formation directly overlie steeply dipping beds of the Perry Formation. On the edge of the marsh northeast of the causeway, grey shale/sandstone correlated with Lighthouse Cove Formation (McLeod and Johnson 1998) have vertical dip and strike directly toward nearly horizontal Russels Point Formation rocks, with the same strike as the exposed Perry Formation. A similar mapped relationship occurs between Lighthouse Cove Formation and Russels Point and Cripps Stream formations across the northwest arm of Beaver Harbour (Fig. 2)—steeply dipping Lighthouse Cove Formation strikes directly toward nearly horizontal to shallow-dipping Cripps Stream and Russels Point formations on Russels Point. The possibility of a north to northwesterly trending fault beneath the northwest arm of the harbour seems unlikely given the continuity of Cambrian units and the Beaver Harbour Porphyry across this branch of the harbour with little or no offset (Fig. 2). An angular unconformity explains both exposed relationships and those mapped between older Perry and Lighthouse Cove formations and younger Cripps Stream and Russels Point formations, with the latter locally overstepping directly onto the older units.

All the Paleozoic units around Beaver Harbour and Blacks Harbour show evidence of deformation, generally folding and cleavage(s), with these features being more profound and complex in the older units (see Helmstaedt 1968; Currie 1988). The Cambrian rocks display complex fold interference from two overprinted structures with at least two cleavages (Helmstaedt 1968). The Perry Formation and Lighthouse Cove Formation display one set of folds with steep to vertical dipping limbs and a single slaty cleavage in suitably fine-grained rocks. The Cripps Stream and Russels Point formations are tilted into open, shallow-limbed folds (dips rarely exceed 20°) with the absence of consistently orientated or penetrative cleavage.

In the absence of palynological evidence, the age of the Lighthouse Cove Formation remains speculative. However, circumstantial evidence (deformation style and map distribution) suggests a shared post-depositional history with the Famennian Perry Formation which predates the Visean Cripps Stream and Russels Point formations. One possibility, given the anoxic, probably lacustrine depositional environment, is that the Lighthouse Cove Formation is a Tournaisian succession and the local equivalent of the lacustrine rocks of the Horton Group to the northeast around Sussex and in Albert County (cf. Rast *et al.* 1979).

UPPER PALEOZOIC ROCKS AND THE BELLEISLE FAULT

The Devonian Perry Formation around Blacks Harbour and Deadmans Harbour, the Tournaisian(?) Lighthouse Cove Formation, and the Visean Cripps Stream and Russels Point formations around Beaver Harbour all occur in fault-bounded outliers along the trend of the regional Belleisle Fault. Although the Belleisle Fault and other orogen-parallel faults through New England and the Maritime Provinces are considered major strike-slip faults (Waldron *et al.* 2015 and references therein), in southwestern New Brunswick, detailed studies have proven more equivocal. Helmstaedt (1968), Brown and Helmstaedt (1970), and Garnett and Brown (1973) all concluded that exposed faults and exhumed mylonite zones between Blacks Harbour, Beaver Harbour, and Loch Alva (including the Seven Mile Lake mylonite zone) carry no evidence of major strike-slip movement, but rather display dip-slip mechanisms related to thrusts or steeper reverse faults (see discussion by Webb 1969 and Brown *et al.* 1969). Subsequent studies (Leger and Williams 1986) demonstrated widespread evidence of strike-slip movement along both the Belleisle and Kennebecasis faults, illustrating complex movement histories. Complicating matters in the Blacks Harbour – Beaver Harbour area, several exposed faults have been defined as the 'Belleisle Fault' (e.g., Helmstaedt 1968; Brown and Helmstaedt 1970; Greenough *et al.* 1985; Landing *et al.* 2008; Barr *et al.* 2014). Part of this problem stems from the form of the Belleisle Fault along its outcrop. From Loch Alva to the Pocologan River the Belleisle Fault is a narrow belt of deformation marked by the Seven Mile Lake mylonite zone and a later brittle structure along its southern margin (Fig. 2, see Garnet and Brown 1973). West of the Pocologan River, the brittle structure breaks into several splays with the same general trend, of which the Letang Harbour Fault is considered the northernmost (see McLeod *et al.* 2005), and the fault termed 'Beaver Harbour Fault' (Landing *et al.* 2008) is the southernmost (see Figs 1, 2).

A similar complex pattern of splays affects the Belleisle Fault east of Loch Alva into the Belliesle Bay/Long Reach area on the Saint John River (Johnson *et al.* 2005), termed the 'Nerepis strike-slip duplex' by Waldron *et al.* (2015; Fig.

1). The panels within the duplex include Ediacaran granitoids (the Lingley granites, considered the equivalent of the Blacks Harbour granodiorite to the southwest; Johnson 2001), Ediacaran volcanic-sedimentary assemblages (Belleisle Bay Group), Cambrian Saint John Group sedimentary sequences, and the Sagwa Formation, a possible late Devonian–Carboniferous unit (Johnson 2001). To the northeast of Long Reach (Fig. 1), the Belleisle Fault has a less dramatic effect on a younger Carboniferous sequence, beginning with the Visean Windsor Group and extending up-sequence to the Pennsylvanian Minto Formation—the main influence of the Belleisle Fault on these younger sequences appears to have been as much topographic as tectonic. Waldron *et al.* (2015) concluded that the main strike-slip displacement (in excess of 160 km) on the Belleisle Fault and the Nerepis duplex was Tournaisian, possibly Famennian–Tournaisian.

Fault movement within the splay structures in the Blacks Harbour – Beaver Harbour area has juxtaposed deformed and steeply dipping panels of the Famennian Perry Formation and Tournaisian (?) Lighthouse Cove Formation alongside the Cambrian Saint John Group, over which the lesser deformed, open-folded Visean Cripps Stream and Russels Point formations are draped. Major displacement on the Belleisle Fault here would be pre-Visean, whereas faults such as the 'Beaver Harbour Fault' of Landing *et al.* (2008) represent post-Visean reactivation on a smaller scale, possibly showing only dip-slip displacement (Fig. 2). Such later (Pennsylvanian) reactivation of major strike-slip faults is documented in detailed geochronology/petrographic studies of the parallel Kennebecasis Fault and adjacent mylonites to the east (Massone *et al.* 2018) and demonstrated in structural studies (Park and Hinds 2020).

CONCLUSIONS

1. Biostratigraphically useful miospore assemblages have been recovered from three of ten samples collected from Upper Devonian–Carboniferous strata in the Blacks Harbour–Beaver Harbour area of southwestern New Brunswick.
2. The Perry Formation at Tunaville (Blacks Harbour) contains miospores consistent with the *R. flexuosa – G. cornuta* Biozone, and possibly the lower part of the *V. pusillites – R. lepidophyta* Biozone (Upper Devonian, lower to middle Famennian).
3. Miospores from the lowest part of the Russels Point Formation (SW of Russels Point and at Woodland Cove) indicate a Chadian–Holkerian age (*L. pusilla – D. columbaris* Biozone), indicating that the underlying Cripps Stream Formation may be as young as Chadian–Arundian.
4. The Cripps Stream and Russels Point formations are too old to be the lateral equivalents of the Balls Lake and Lancaster formations (the latter being Langsettian). Biostratigraphy suggests that these units are the lateral equivalents of the Windsor Group, with the limestone-bearing uppermost Cripps Stream Formation possibly correlative with the Parleeville Formation seen to the east around Lepreau Harbour.
5. The Lighthouse Cove Formation ('Fish Plant Beds' of Currie 1988) has not yielded any usable miospore assemblages, but mapping of structural trends indicates that the Russels Point and Cripps Stream formations overlie this unit with angular unconformity (as they also overlie the Perry Formation). The most probable interpretation is that the Lighthouse Cove Formation is Tournaisian, and a lacustrine depositional environment suggests a correlation with the Horton Group in southeast New Brunswick, as previously suggested by Rast *et al.* (1979).
6. Different deformation style between the Visean Cripps Stream and Russels Point formations and older Perry and Lighthouse Cove formations implies that major strike-slip displacement on the Belleisle Fault system in this area was pre-Visean, probably Famennian–Tournaisian. Faulting affecting the Visean rocks relates to later reactivation and was largely dip-slip.

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Editorial responsibility: Sandra Barr

APPENDIX A

Miospore samples with details (sample numbers in parentheses refer to the New Brunswick Department of Natural Resources and Energy Development, Geological Surveys Branch collection).

Sample Location #1 (20-SJH-64A)
Locality. Above the dam on Cripps Stream, Woodland Cove, GPS N 45.0852°, W 066.7112°
Stratigraphic unit. Russels Point Formation
Lithology. Dark blue-grey micaceous silty mudstone. Indurated. Orange weathering.
Proven age. Tournaisian to middle Holkerian
Biozone. Within the range Biozone 1A to lower part of the *K. stephanephorus* Biozone.
Sample quality. Poor.
Palynomorph assemblage. The sample provided fairly common smooth or apiculate, opaque miospore silhouettes. Even after oxidation for >1 week the palynomorphs remained dark. Identifiable miospores are usually only recognizable due to their distinctive silhouette outline (e.g. *P. gibberosus, V. nitidus*). Rare specimens of *Indotriradites* sp., *Knoxisporites* cf. *literatus, Pulvinispora scolecophora, Pustulatisporites gibberosus, Retusotriletes* spp., *Vallatisporites* sp., *Verrucosisporites* sp., *Verrucosisporites nitidus* and *Verrucosisporites* cf. *nitidus* are recorded.
Palynofacies. The sample contained common structured and irregular inertinite and vitrinite with fairly common smooth or apiculate opaque miospores silhouettes. Even after oxidation for >1 week the palynomorphs remained dark. Identifiable miospores are usually only recognizable due to their distinctive silhouette outline (e.g. *P. gibberosus, V. nitidus*).
Critical palynomorph taxa. *P. gibberosus, V. nitidus*

Sample Location #2 (20-SJH-65C)
Locality. Cliff face south of fish plant, Beaver Harbour GPS N 45.0671°, W 066.7376°
Stratigraphic unit. Lighthouse Cove Formation
Lithology. Dark blue-grey micaceous silty mudstone, laminated. Indurated. Orange weathering.
Proven age. Unknown
Possible biozone. Not identified
Sample quality. Poor
Palynomorph assemblage. The sample provided very rare palynomorphs, mostly fragmentary, unidentifiable, circular or rounded-triangular, laevigate or apiculate, opaque silhouettes. Questionably identified specimens of *Deltoidospora* spp.?, *Punctatisporites* spp., *Pustulatisporites* spp.?, *Raistrickia* spp.? and *Retusotriletes* spp. are recorded.
Palynofacies. The sample provided very dark structured and irregular vitrinite and inertinite fragments. Miospores scarce.
Critical palynomorph taxa. None

Sample Location #3 (20-SJH-135A)
Locality. On Route 778 south of Deadmans Harbour, GPS N 45.0520°, W 066.7631°
Stratigraphic unit. Russels Point Formation
Lithology. Dark grey mudstone. Ironstone? Possible palaeosol textures.
Proven age. Unknown
Possible biozone. Not identified
Sample quality. Poor
Palynomorph assemblage. The sample provided very rare palynomorphs including the taxa *Calamospora* sp., *Knoxisporites* sp.? and *Prolycospora* sp.?
Palynofacies. The sample provided very rare irregular inertinite and vitrinite. Modern contaminants (fungi and angiosperm pollen) are rare.
Critical palynomorph taxa. None

Sample Location #4 (20-SJH-165B)
Locality. South end of Russels Point, GPS N 45.0745°, W 066.7314°
Stratigraphic unit. Russels Point Formation
Lithology. Red quartzo-feldspathic coarse sandstone with medium grey-green fine sandstone layers and intraclasts
Proven age. Unknown
Possible biozone. Not identified
Sample quality. Poor
Palynomorph assemblage. The sample provided very rare palynomorphs including a single specimen of *Verrucosisporites* cf. *nitidus*.
Palynofacies. The sample provided very rare irregular inertinite and vitrinite. Modern contaminants (fungi) are rare.
Critical palynomorph taxa. None

Sample Location #5 (20-SJH-167A)
Locality. Small cove on Russels Point, west of last, GPS N 45.0748°, W 066.7322°
Stratigraphic unit. Russels Point Formation
Lithology. Pale blue-grey siltstone/mudstone. Irregularly laminated with carbonaceous laminae. Plant debris. Indurated.
Proven age. Carboniferous, Mississippian, Chadian to early Arundian
Biozone. *L. pusilla – D. columbaris* Biozone
Sample quality. Poor.
Palynomorph assemblage. The sample provided scarce palynomorphs, mostly fragmentary, unidentifiable, circular or rounded-triangular, laevigate or apiculate, opaque silhouettes. The assemblage appears to be dominated by the taxa *Retusotriletes* spp. and *Vallatisporites* spp. *Calamospora* spp.? and *Vallatisporites vallatus* occur as common. A low-diversity accessory assemblage includes the taxa *Anapiculatisporites* spp., *Auroraspora* spp., *Ceratosporites* sp. A, *Crassispora trychera, Cristatisporites* spp., *Cyrtospora cristifera?, Deltoidospora* spp., *Dictyotriletes* cf. *equigranulatus, Endoculeospora gradzinskii, Indotriradites* cf. *viriosus, Lycospora pusilla, Neoraistrickia* cf. *loganensis, Punctatisporites* spp., *Raistrickia* cf. *baculosa, Spelaeotriletes* spp.?, *Spelaeotriletes balteatus, Spelaeotriletes pretiosus, Spelaeotriletes* cf.

pretiosus, Stenozonotriletes spp., *Umbonatisporites* cf. *abstrusus, Vallatisporites drybrookensis, Vallatisporites splendens, Vallatisporites verrucosus, Vallatisporites* cf. *verrucosus, Velamisporites* spp. and *Waltzispora* spp.
Palynofacies. The sample provided scarce, dark and fragmentary structured and irregular vitrinite and inertinite with largely fragmentary miospores.
Critical palynomorph taxa. *C. trychera, L. pusilla, S. pretiosus, V. vallatus*
Remarks. The biozonations of Utting (1989) and Dolby *in* St Peter & Johnson (2009) indicate that *Spelaeotriletes pretiosus sensu stricto* and *Vallatisporites vallatus* are restricted to the *C. decorus – R. clavigera* Biozone (Biozone 5) and deeper, whereas *Lycospora pusilla* is restricted to the *L. pusilla – D. columbaris* Biozone and higher. The co-occurrence of these taxa in this assemblage may suggests proximity to the boundary of the two biozones. The assemblage is assigned to the *L. pusilla – D. columbaris* Biozone because the stratigraphical first appearance of *L. pusilla* is a well-constrained biostratigraphical event of global significance (Clayton 1985) whereas the upper range limits of *S. pretiosus sensu stricto* and *V. vallatus* are less well constrained.

Sample Location #6 (20-SJH-169B)
Locality. Beach at northeastern end of Woodland Cove, north side of Cripps Stream, GPS N 45.0851°, W 066.7126°
Stratigraphic unit. Cripps Stream Formation
Lithology. Medium blue-grey mudstone. Hackly. Indurated.
Proven age. Unknown
Possible biozone. Not identified
Sample quality. Poor
Palynomorph assemblage. The sample provided a single specimen of a smooth, opaque and indeterminate miospore silhouette.
Palynofacies. The sample provided rare amorphous organic material, with irregular inertinite/vitrinite. Some of the amorphous organic material is arranged in unusual circular forms. Modern contaminants (gymnosperm pollen) are present.
Critical palynomorph taxa. None

Sample Location #7 (20-SJH-170A)
Locality. Beach at northeastern end of Woodland Cove, north of Cripps Stream, GPS N 45.0850°, W 066.7125°
Stratigraphic unit. Cripps Stream Formation
Lithology. Olive-grey-brown mudstone, laminated. Possible plant debris. Indurated.
Proven age. Unknown
Possible biozone. Not identified
Sample quality. Poor
Palynomorph assemblage. The sample provided very rare palynomorphs including *Punctatisporites* spp., *Pustulatisporites* spp., *Retusotriletes* spp. and *Verrucosisporites spp*.
Palynofacies. The sample provided rare irregular and structured inertinite and vitrinite with very rare, fragmentary, dark brown miospores. Modern contaminants (phytoclasts) are rare.
Critical palynomorph taxa. None

Sample Location #8 (20-SJH-172C)
Locality. Beach northeastern end of Woodland Cove, north of Cripps Stream, GPS N 45.0849°, W 066.7123°
Stratigraphic unit. Cripps Stream Formation
Lithology. Grey green, olive-brown silty mudstone, laminated. Indurated.
Proven age. Unknown
Possible biozone. Not identified
Sample quality. Poor
Palynomorph assemblage. The sample proved barren of miospores.
Palynofacies. The sample provided rare irregular inertinite. Modern contaminants (phytoclasts, gymnosperm pollen, fungi) are common.
Critical palynomorph taxa. None

Sample Location #9 (20-SJH-185A)
Locality. Beach west of Russels Point, GPS N 45.0737°, W 066.7296°
Stratigraphic unit. Russels Point Formation
Lithology. Dark blue-grey mudstone, irregularly laminated. Very indurated.
Proven age. Unknown
Possible biozone. Not identified
Sample quality. Poor
Palynomorph assemblage. The sample provided very rare miospores with a single identifiable specimen questionably assigned to *Diducites poljessicus?*
Palynofacies. The sample provided rare irregular inertinite. Modern contaminants (phytoclasts, gymnosperm pollen, fungi) are common.
Critical palynomorph taxa. None

Sample Location #10 (20-SJH-186B)
Locality. Western end of beach at Tunaville, Blacks Harbour, GPS N 45.0521°, W 066.8081°
Stratigraphic unit. Perry Formation
Lithology. Olive- dark grey silty mudstone, carbonaceous laminae. Plant debris.
Proven age. Devonian, Famennian
Biozone. *R. flexuosa – G. cornuta* Biozone to lower part of the *V. pusillites-R. lepidophyta* Biozone, possibly restricted to the *R. flexuosa – G. cornuta* Biozone
Sample quality. Good
Palynomorph assemblage. Miospores are dark but well-preserved. The assemblage is dominated by *Retusotriletes* spp. with common *Apiculiretusispora* spp., *Auroraspora macra, Auroraspora* spp., *Diducites mucornatus, Diducites poljessicus, Diducites radiatus, Endoculeospora gradzinskii, Pulvinispora scolecophora, Punctatisporites* spp., *Rugospora* spp., A moderately diverse accessory assemblage includes the taxa *Ancyrospora* cf. *furcula, Ancyrospora* spp., *Aneurospora goensis, Aneurospora greggsii, Camptotriletes* spp., *Chelinospora* spp., *Cristatisporites* spp., *Diducites plicabilis, Diducites versabilis, Discernisporites micromanifes-*

tus, Endoculeospora cf. *rarigranulata, Geminospora* spp., *Grandispora* cf. *cornuta?, Hystrichosporites multifurcatus, Hystrichosporites* spp., *Latosporites* spp., *Lophozonotriletes lebedianensis, Plicatispora quasilabrata, Retispora* cf. *lepidophyta, Retusotriletes crassus, Retusotriletes incohatus, Retusotriletes leptocentrum, Rugospora flexuosa, Samarisporites* cf. *triangulatus, Samarisporites* spp., *Spelaeotriletes* cf. *crustatus* and *Teichertospora torquata.*

Palynofacies. The sample provided common, thermally mature organic material dominated by miospores with lesser structured vitrinite.

Critical palynomorph taxa. *H. multifurcatus, R. flexuosa,* common *Diducites* spp.

Remarks. The proven age range is determined by the co-occurrence of *H. multifurcatus* and *R. flexuosa.* The stratigraphical range of *H. multifurcatus* extends into the lower part of the *V. pusillites-R. lepidophyta* Biozone (Richardson & McGregor 1986; McGregor & McCutcheon, 1988). In the absence of taxa (*R lepidophyta, V. pusillites*) restricted to this and higher biozones, the assemblage can possibly be restricted to the older *R. flexuosa – G. cornuta* Biozone. Note that specimens assigned to *Retispora* cf. *lepidophyta* have faint, poorly developed lumina associated with rugulae and should not be considered to be morphologically close to *R. lepidophyta sensu stricto*.

APPENDIX B

Formal definition of stratigraphic units

Lighthouse Cove Formation

Authors: The Lighthouse Cove Formation was introduced by McLeod and Johnson (1998), but not formally defined (Fig. 3, Column 5). This name replaced Silurian (?) 'Fish Plant beds' of Currie (1988) (Fig. 3, Column 4) and 'Beaver Harbour beds' of Rast *et al.* (1979)(Fig. 3, Column 3). The Lighthouse Cove Formation is shown as Silurian on the compilation map of southwestern New Brunswick (Smith 2005). Fyffe *et al.* (2014) considered the unit to be a lacustrine facies of the Lancaster Formation (Fig. 3, Column 7).

Type section: Sea cliffs from the fish plant and dock on the west shore of Beaver Harbour (GPS N 45.0687°, W 066.7424°) south toward the Drews Head lighthouse (GPS N 45.0647°, W 066.7364°) expose this unit. A sequence around 500 m thick is exposed in these cliffs with no obvious evidence of large-scale folds, however there is abundant evidence of bedding-parallel slip and fault zones in rocks that dip steeply (from 60˚ to vertical and overturned). Thickening by repetition exaggerates measured thickness to an unknown degree. Grey to white fine-grained sandstone, siltstone and interlayered to laminated dark grey, pyritiferous shale comprise this unit.

Reference section: Owing to the restricted occurrence of the Lighthouse Cove Formation no reference sections have been designated.

Definition and description: The Lighthouse Cove Formation consists of interbedded white to grey medium-grained to fine-grained siliceous sandstone, siltstone and laminated dark grey to black organic-rich mudstone and shaly mudstone. The finer-grained units carry a poorly developed slaty cleavage. Sandstone layers are generally 0.1 to 0.5 m thick, but a few are up to 3 m thick. Siltstone and shaly claystone are notably pyritiferous, and the entire unit takes on a rusty weathering. Fragmentary plant fossils have been reported from this section (Bailey and Matthew 1872, Cumming 1967). There is a complete lack of any evidence for bioturbation. The thicker sandstone layers show evidence for soft-sediment deformation related to slumping.

Distribution and thickness: Aside from the type section of the Lighthouse Cove Formation, where a 500 m thick section is exposed, outcrop of this unit is limited to small roadside and ditch excavations around Beaver Harbour settlement and along a forestry road near Deadmans Harbour, the only other occurrence mapped is along the creek and marsh NE of the causeway at Deadmans Harbour, and this correlation is questionable.

Upper and lower boundaries: No depositional boundaries of the Lighthouse Cove Formation are exposed. The southern boundary is the Beaver Harbour Fault against the Andys Pond gabbro/West Branch Reservoir granite, part of the Silurian Kingston Group (mapped originally as a fault, but no longer exposed), and the northern boundary is assumed to be the Belleisle Fault against the Ediacaran Beaver Harbour Porphyry (Helmstaedt 1968, Bartsch *et al.* 2007) beneath the beach north of the dock.

Age: Highly fragmented plant fossils occur sporadically in the Lighthouse Cove Formation, originally documented by Bailey and Matthew (1872), but the age has remained contentious. Bailey and Matthew (1872) considered the fossils upper Devonian, but subsequently (Bailey and Matthew 1919, Bailey *et al.* 1880) revised this estimate to Silurian. Rast *et al.* (1979) considered the possibility, based on an anoyxic lacustrine environment, that these rocks were comparable to the Albert Formation in the Horton Group of southeastern New Brunswick and therefore Tournaisian (Fig. 3, Column 3). McLeod and Johnson (1998) tentatively assigned a Silurian age to their 'Pennfield Station beds' (Fig. 3, Column 5), whereas Fyffe *et al.* (2014) grouped them as a lacustrine facies of the Lancaster Formation (and therefore Pennsylvanian, Langsettian sub-stage, Fig. 3, Column 7). Samples for miospores taken during this study proved barren. These rocks are less deformed than the upper Devonian Perry Formation, but more deformed than the Visean Cripps Stream and Russels Point formations, which suggests (but does not prove) their age lies between Famennian and lowest Visean. Mapping shows that this formation occupies a steeply dipping panel that around the area strikes beneath the sub-Visean unconformity.

Depositional environment: Characteristics of this formation are consistent with an open water, low-energy and anoxic environment of deposition. A deep and stagnant lake, or a lake subject to eutrophy and anoxic bottom conditions is most probable.

Cripps Stream Formation

Authors: The Cripps Stream Formation was introduced by Fyffe (1998), but not formally defined, for a red bed unit containing polymictic cobble to boulder conglomerate, sandstone, siltstone and limestone found at the northeastern head of Woodland Cove. McLeod *et al.* (1994) and McLeod and Johnson (1998) referred to the same beds and those occurring in fault-bound strips to the northeast as far as Highway 175 near Pennfield Station as the 'Pennfield Station beds' (Fig.3, Column 5). The distribution of the 'Silurian' Cripps Stream Formation is shown on the compilation map of southwestern New Brunswick (Smith 2005). Fyffe *et al.* (2014), suggested a correlation with the 'Balls Lake Formation' (Fig. 3, Column 7).

Type locality: Northeastern head of Woodland Cove north of the mouth of Cripps Stream (GPS N 45.0849˚, W 066.7118˚). 200 m of cliff gives a continuous section through 50 m of the sequence below the contact with the overlying Russels Point Formation. The base of the formation is not exposed.

Reference section: Similar sections below the contact with the Russels Point Formation are expose in sea cliffs along the east shore of Russels Point west of Buckmans Creek (between GPS N 45.0744°, W 066.7288° and N 45.0757°, W 066.7293°, and in an unnamed cove west of Russels Point (GPS N 45.0750°, W 066.7325°). These sections include covered intervals and are disturbed by faulting, though neither section contains thicknesses greater than 25 m.

Definition and description: Red to grey-green polymictic pebble to boulder conglomerate with clasts recognizable as local rock types, such as the Blacks Harbour granodiorite, Beaver Harbour Porphyry and a distinctive dark red-brown rhyolite from the Silurian Eastport Formation (Mascarene Group). Red-brown or greenish-grey medium- to fine-sandstone and siltstone, grey shale partings, are interbedded with the conglomerate. Carbonates preserved as nodules in red siltstone after caliche, bedded carbonate and carbonate-rich sandstone occur especially in the top 5 m of the type section. Minor beds with rootlets in siltstone and possible burrows. A distinctive laminated siltstone—fine-grained sandstone has alternating bands of purplish-red and buff coloured material especially preserved in the reference section east of Russels Point. A pebble conglomerate with a red-brown siltstone matrix occurs in the reference section west of Russels Point.

Distribution and thickness: The Cripps Stream Formation is only known from four locations: the type section at the northeastern head of Woodland Cove, cliffs along the east side of Russels Point, an unnamed cove west of Russels Point and scattered small outcrops along the old Cripps Stream road northeast of Woodland Cove. The fault-bound strip of red cobble conglomerate along Highway 175 at Pennfield Station is considered Perry Formation in agreement with Bartsch *et al.* (2007). As no base to this formation is exposed total thickness is unknown, but at least 50 m thickness is exposed at the type section (though faulted). The Cripps Stream Formation is not seen along the SE shore of Deadmans Harbour, where the Russels Point Formation oversteps directly onto the Upper Devonian Perry Formation.

Upper and lower boundaries: The top of the Cripps Stream Formation is marked by the first grey-green-brown cross-bedded sandstone of the Russels Point Formation. Where channel-forms are visible (such as in the type section) the Russels Point Formation downcuts into the Cripps Stream Formation. Overall the upper boundary appears to be conformable. The base of the Cripps Stream Formation is not exposed though outcrops along the Cripps Stream road, northeast of the type section, imply the base is an angular unconformity on the felsic volcanic rocks of the Silurian Kingston Group.

Age: When McLeod and Johnson (1998) used 'Cripps Stream Formation' the age was regarded as ill-defined, though older than Russels Point Formation and possibly as old as Silurian. Fyffe *et al.* (2014) made the correlation with the Balls Lake Formation (Mabou Group) implying a Mississippian to Pennsylvanian age (Serpukhovian to Bashkirian, Fig. 3). No samples for miospores taken as part of this study yielded viable assemblages. Given the conformable relationship with the overlying Chadian–Arundian Russel Point Formation a similar slightly older age is assumed.

Depositional environment: Interbedding of coarse, poorly sorted cobble- boulder conglomerate with fine-grained sandstone and siltstone implies a fluvial or lacustrine environment adjacent to small alluvial fans. Caliche nodules and red beds suggest a semi-arid climate with deep oxidation.

Russels Point Formation (new name)

Authors: The Russels Point Formation was referred to in general terms as the 'Beaver Harbour Group' by Helmstaedt (1968) and 'Beaver Harbour beds' by Rast *et al.* (1979), then 'Beaver Harbour Formation' by Currie (1988), and McLeod and Johnson (1998), but not formally defined (Fig. 3, Column 2–6). This unit was correlated with the Lancaster Formation by Fyffe *et al.* (2014), see Fig. 3, Column 7).

Type section: Eastern shore of Russels Point along Buckmans Creek in Beaver Harbour (between GPS N 45.0747°, W 066.7289° and N 45.0737°, W 066.7296°). Continuous section is exposed in sea cliffs to Russels Point lighthouse. Contact with the underlying Cripps Stream Formation (see below) is preserved at the north end of the section (GPS N 45.0747°, W 066.7289°). The top of the formation is not preserved.

Reference section: Reference sections with less complete sequences but preserving the lower contact with the Cripps Stream Formation are present on the western shore of Russels Point (GPS N 45.0745°, W 066.7314°) and at the northeastern head of Woodland Cove along Cripps Stream (GPS N 45.0849°, W 066.7118°) and the sea cliffs to the southwest. The sea cliffs along the south shore of Deadmans Harbour (GPS N 45.0503°, W 066.7695°) preserve a lower contact that is an angular unconformity on Perry Formation and the Cripps Stream Formation is absent.

Definition and description: The Russels Point Formation consists mainly of medium-grained to coarse-grained grey, greenish-grey to brown sandstones (quartz arenite to feldspathic quartz arenite) with dark grey to grey-green siltstone-shale-claystone partings or thicker intervals, some of which are reddened. Conglomerate layers and lenses occur throughout and both polymictic and quartz-dominated types occur. Grain size is generally pebble, but minor cobble clast populations are present. Pebble lags are generally dominated by vein quartz clasts. Paleosol surfaces are buff-coloured or reddened and contain in situ roots. Sand dikes into siltstone-shale are associated with some paleosols. The sandstones form layers up to 5 m thick and are typically cross-bedded with sets up to 2 m thick, averaging 0.75 to 1.0 m thick. Channel-forms, downcutting into siltstone-shale intervals (or the underlying Cripps Stream Formation) occur throughout the section.

Distribution and thickness: The thickest section of the Russels Point Formation is preserved on Russels Point, measuring at least 70 m thick. Lesser thicknesses are preserved along the southeastern shore of Woodland Cove, and along the southeastern shore of Deadmans Cove between the causeway and Deadmans Point. Total outcrop distribution of the Russels Point Formation is restricted to an area between the Belleisle Fault and Beaver Harbour Fault from Cripps Stream/Woodland Cove in the northeast to Deadmans Point in the southwest.

Upper and lower boundaries: The upper boundary of the Russels Point Formation is the present erosion surface and no younger formations are preserved. The base of the formation, defined by the first grey-green-brown cross-bedded sandstone with or without pebble lags, forms downcutting channels over the Cripps Stream Formation from the northeastern head of Woodland Cove to Russels Point. Downcutting channels are localized, and the contact is considered conformable overall. In Deadmans Harbour the Russels Point Formation rests with marked angular unconformity on the Upper Devonian Perry Formation and the Cripps Stream Formation is absent.

Age: Plant fossils have been reported from the Russels Point Formation since the work of Gesner (1839) and Bailey and Matthew (1872). The specimens were fragmentary, consisting of pinnule, leaf, stem and root segments, and their age was contentious, with estimates ranging from Silurian to Pennsylvanian. A more systematic study by Cumming (1967) suggested Upper Devonian to lower Mississippian, whereas Helmstaedt (1966, 1967, 1968) considered Mississippian more likely. This contrasts with the correlation with the Pennsylvanian Lancaster Formation (Langsettian sub-stage) proposed by Fyffe *et al.* (2014). Two miospore assemblages recovered from shales within 5 m of the lower boundary of the Russels Point Formation (this study) yielded Mississippian microflora, with one restricted to the Chadian–Arundian sub-stages in the lower Visean.

Depositional environment: Fluvial, with both channel-fill and overbank deposits present. Overbank areas contain paleosols and rooted beds generally associated with reddening, suggesting a braid-plain with emergent areas colonized by vegetation. In situ plant fossils (roots and stems) are small, no larger than 2–3 cm diameter.

Beaver Harbour Group

Authors: 'Beaver Harbour Group' was a term introduced by Helmstaedt (1968) for the map units that are now termed Russels Point Formation and Cripps Stream Formation. The term did not include the map unit now called Lighthouse Cove Formation. We recommend the term Beaver Harbour Group as used by Helmstaedt (1968) be retained. This definition of Beaver Harbour Group includes the Russels Point Formation and Cripps Stream Formation, but not the Lighthouse Cove Formation.