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Basin inversion at the Mississippian–Pennsylvanian boundary in northern New Brunswick, Canada

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Abstract

Upper Paleozoic successions in the area of Bathurst, New Brunswick, were studied in an attempt to solve long-standing stratigraphic debates and to correlate the Carboniferous geology of this area with that of the adjacent Gaspé Peninsula of Quebec. Based on new spore dates and petrographic analyses, the abandoned Bathurst Formation is re-introduced. Paleogeographic reconstructions from facies analysis and provenance studies indicate that the Mississippian Ristigouche Basin formed the source area of the Pennsylvanian Central Basin due to a fault inversion event that occurred near the Mississippian–Pennsylvanian boundary. As a result, the Mississippian Bonaventure Formation, which was sourced from the south, is separated by the east–west striking Rocky Brook-Millstream Fault from the lower Pennsylvanian Bathurst Formation, which was sourced from the north with reworked detritus of the former unit. A possible correlation is made between Pennsylvanian sedimentation in northern New Brunswick and Pennsylvanian faulting in the adjacent Gaspé Peninsula of Quebec.

Résumé

Les successions du Paléozoïque supérieur de la region de Bathurst, au Nouveau Brunswick, furent étudiées pour tenter de résoudre de vieux débats stratigraphiques et pour tenter de corréler la géologie du Carbonifère de cette région avec celle de la Gaspésie, une région avoisinante du Québec. Sur l'appui de nouvelles données palynostratigraphiques et pétrographiques, la formation abandonnée de Bathurst est réintroduite. Les reconstructions paléogéographiques obtenues à partir d'analyses de faciès et d'études de provenance indiquent que le bassin Mississippien de Ristigouche formait la région source du bassin Central, d'âge Pennsylvanien, à cause d'un événement d'inversion de faille ayant eu cours près de la limite qui sépare le Mississippien du Pennsylvanien. En résultat, la formation mississippienne de Bonaventure, dont la source était au sud, est séparée par la faille est-ouest de Rocky Brook-Millstream de la formation pennsylvanienne de Bathurst, laquelle fut alimentée de par le nord par les sédiments remaniés de l'unité précédente. Un lien possible est proposé entre la sédimentation pennsylvanienne du nord du Nouveau Brunswick et le faillage pennsylvanien enregistré dans la région avoisinante de Gaspésie.

Introduction

Uncertainty about the Carboniferous stratigraphy of northern New Brunswick (Figs. 1, 2) has persisted over the past century, in part because of poor exposure and poor biostratigraphic control. Since the stratigraphic framework for that region was first established (Logan, 1863), several stratigraphic revisions have been proposed (Young, 1910; Alcock, 1935; Skinner, 1974; Ball et al., 1981; van Staal et al., 2003) (Fig. 3). Recent work on the lower Carboniferous successions of the adjacent Gaspé Peninsula of eastern Quebec (Jutras et al., 1999, 2001; Jutras and Prichonnet, 2002, 2005) (Fig. 4), and recent drilling in the study area have enabled new interpretations to be made of the poorly exposed succession that lies between the City of Bathurst and the Village of Janeville (Fig. 1).

A refined stratigraphic and paleogeographic framework for the local Carboniferous successions is proposed from new field, core and spore data. The sedimentary rock data is also used to reconstruct Carboniferous tectonic environments in correlation with scarce structural data for this time period in the Chaleur Bay region of northern New Brunswick and eastern Quebec. This paper presents evidence indicating that basin inversion occurred between sedimentation of the Mississippian Bonaventure Formation and deposition of the local Pennsylvanian succession. In the process, rocks of the Mississippian Ristigouche Basin (van de Poll, 1995) were uplifted and provided detritus for the Pennsylvanian Central Basin, which is also commonly referred to as the New Brunswick Platform (Fig. 1, inset).

This deformation correlates well with transpressive structures affecting rocks as young as early Namurian on the north shore of Chaleur Bay (Jutras et al., 2003a, b) and adds to our understanding of the tectonostratigraphic evolution of southeastern Canada during the upper Paleozoic. Moreover, contemporaneous fault breccia in eastern Gaspé is the host of the only productive oil well of the Chaleur Bay region (Well Galt #3 of JUNEX), and similar brittle fault zones of this Pennsylvanian system (Jutras et al., 2003a, b) are among the main petroleum exploration targets in the rest of the Gaspé Peninsula (J.-S. Marcil of JUNEX, pers. comm., 2005). Evidence presented here for Pennsylvanian faulting in northern New Brunswick is therefore of significant interest for petroleum exploration in that area.

Geological Setting

Carboniferous rocks of northern New Brunswick unconformably overlie lower to middle Paleozoic rocks. Cambro-Ordovician sedimentary and volcanic rocks of the area underwent deformation and high-pressure, low-temperature metamorphism during Ordovician to Early Silurian times (van Staal et al., 1990; van Staal, 1994). They are part of the Miramichi Anticlinorium, a tectono-stratigraphic belt that is unconformably overlain by a Siluro-Devonian volcano-sedimentary succession that was deformed by the Middle Devonian Acadian Orogeny (Wilson et al., 2004). The latter rocks are part of the Chaleur Bay Synclinorium of Malo and Bourque (1993).

Cambro-Ordovician rocks underlie most of the area to the south of the Rocky Brook-Millstream Fault (Fig. 1), whereas Siluro-Devonian rocks dominate the area to the north. However, rocks of both tectono–stratigraphic belts are represented on each side of the fault.

The lower to middle Paleozoic rocks of the Miramichi Anticlinorium (Elmtree Inlier north of the Rocky Brook-Millstream Fault) and Chaleur Bay Synclinorium were intruded by Late Devonian granites following the Acadian Orogeny (Fig. 1) (New Brunswick Department of Natural Resources and Energy (NBDNRE), 2000). The Cambrian to Devonian rocks are unconformably overlain by Carboniferous successions that occupy the northwestern end of the composite Maritimes Basin (Fig. 1, inset), which constitutes the entire upper Paleozoic succession of southeastern Canada.

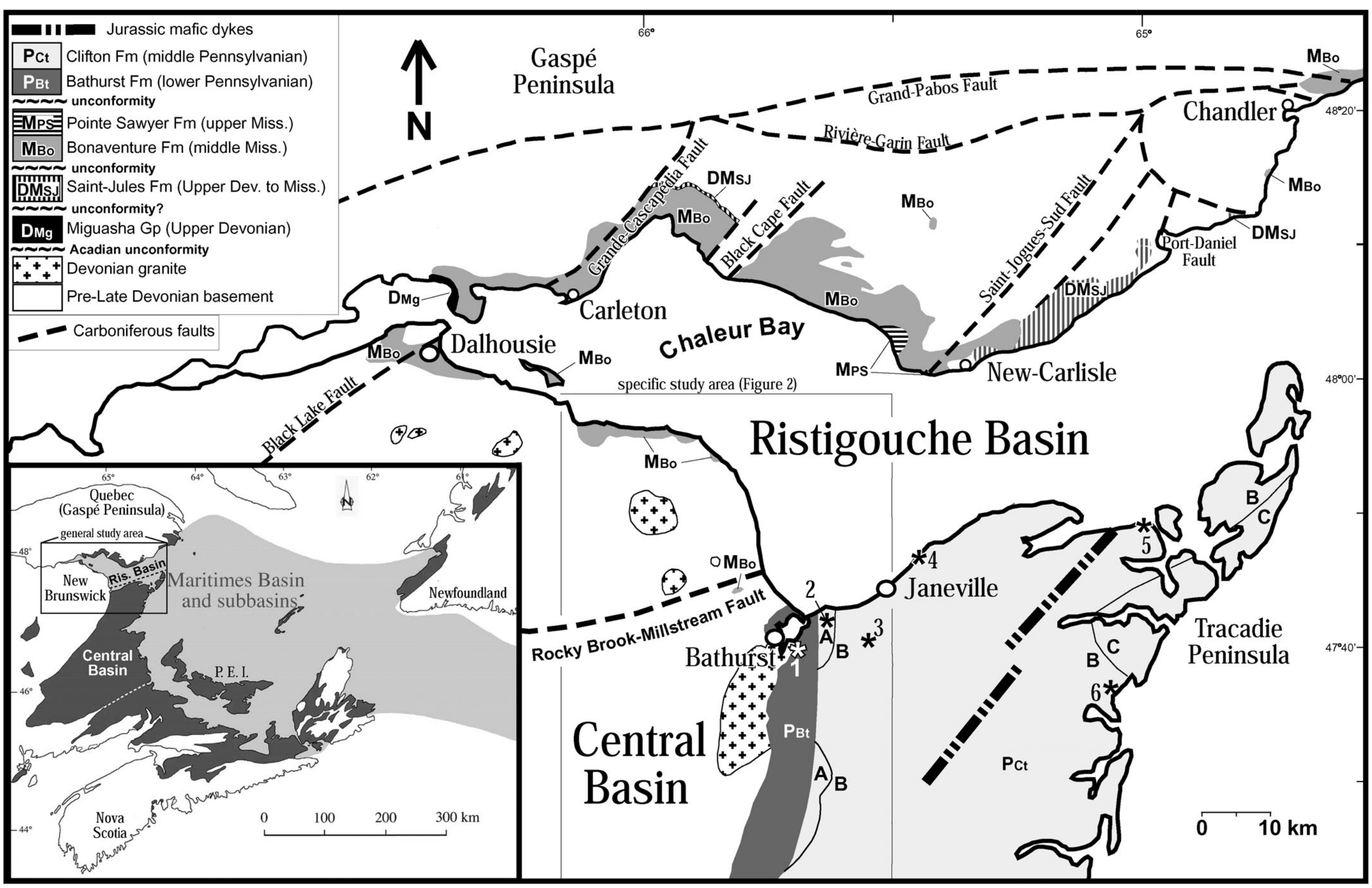

Fig. 1. Geology of the Chaleur Bay area (modified from Brisebois et al., 1992, NBDNRE, 2000 and Jutras et al., 2003b), with location of the study area. Localities 1 to 6 are referred to in the text. The cartographic limits of the three members of the Clifton Formation are delineated and labelled as **A**, **B** and **C**. Dark and light shades of grey in the inset (modified from Gibling et al., 1992) are, respectively, the onshore and offshore limits of the upper Paleozoic cover (Maritimes Basin) in southeastern Canada. Ris. Basin: Ristigouche Basin.

Historical Framework for the Carboniferous Stratigraphy of Northern New Brunswick

The undated Bonaventure Formation, which has its type section on the north side of Chaleur Bay (Logan, 1846), is the oldest upper Paleozoic succession of northern New Brunswick (van de Poll, 1995). In eastern Quebec, the Bonaventure Formation unconformably overlies a pro-evaporitic groundwater (or "phreatic") calcrete (a thick and massive type of calcrete that develops around evaporitic basins) and its underlying paleowave-cut platform, which are tentatively correlated with the first major transgression–regression cycle of the Viséan Windsor Sea (Jutras and Schroeder, 1999; Jutras et al., 1999) and disconformably underlies lowermost Namurian grey beds of the Pointe Sawyer Formation (Jutras et al., 2001). The Bonaventure Formation is therefore considered Viséan, largely due to its relative stratigraphic position (Fig. 4).

Several sections of the Bonaventure Formation were described by Zaitlin and Rust (1983) in the area of Dalhousie (Figs. 1, 5). Paleocurrent vectors obtained near Dalhousie are north-trending (Zaitlin and Rust, 1983), contrary to the south-trending paleocurrent vectors that were determined within this unit on the northern side of Chaleur Bay (Fig. 5). This allowed Zaitlin and Rust (1983) to draw the paleogeography of the western end of the Bonaventure Formation basin, which was later referred to as the Ristigouche Basin (sub-basin of the Maritimes Basin) by van de Poll (1995). The paleogeography of the northeastern end of the Ristigouche basin was later defined by Jutras et al. (2001) and the southeastern end of the basin is now described in this paper.

No contact was observed between the Mississippian Bonaventure Formation, which has its easternmost exposure to the northwest of Bathurst in northern New Brunswick, and the local Pennsylvanian succession, which has its westernmost exposure east of Bathurst (Fig. 1). The Upper Devonian Miguasha Group (Logan, 1846), the Upper Devonian to Tournaisian Saint-Jules Formation (Jutras and Prichonnet, 2002), the Viséan Cap d'Espoir (Jutras and Prichonnet, 2005) and La Coulée (Jutras et al., 1999) formations, and the lower Namurian Pointe Sawyer and Chemin-des-Pêcheurs formations (Jutras et al., 2001) on the north shore of Chaleur Bay were not recognized on the south side, in northern New Brunswick (Fig. 4). In places, however, thin remnants of fossil groundwater calcrete are observed unconformably below the Bonaventure Formation, indicating that the groundwater calcretization event that affected the La Coulée Formation of eastern Gaspé, prior to its pre-Bonaventure erosion (Jutras et al., 1999), also affected northern New Brunswick.

Until recent work by van Staal et al. (2003), the Carboniferous stratigraphy of northern New Brunswick included the Bonaventure Formation in the Ristigouche Basin, and the Bathurst and Clifton Formations in the Central Basin (Ball et al., 1981; Legun and Rust, 1982) (Fig. 1). The name Bathurst Formation was first used by Young (1910) (Fig. 3) in reference to Carboniferous red beds exposed along the Nepisiguit River in East Bathurst. Logan (1863) and Ells (1881) had previously correlated these red beds with the Bonaventure Formation (Fig. 3). The name Bathurst Formation was maintained by Alcock (1935) and Skinner (1974) (Fig. 3) but neither of them provided any petrographic criteria to differentiate this unit from the Bonaventure Formation, apart from

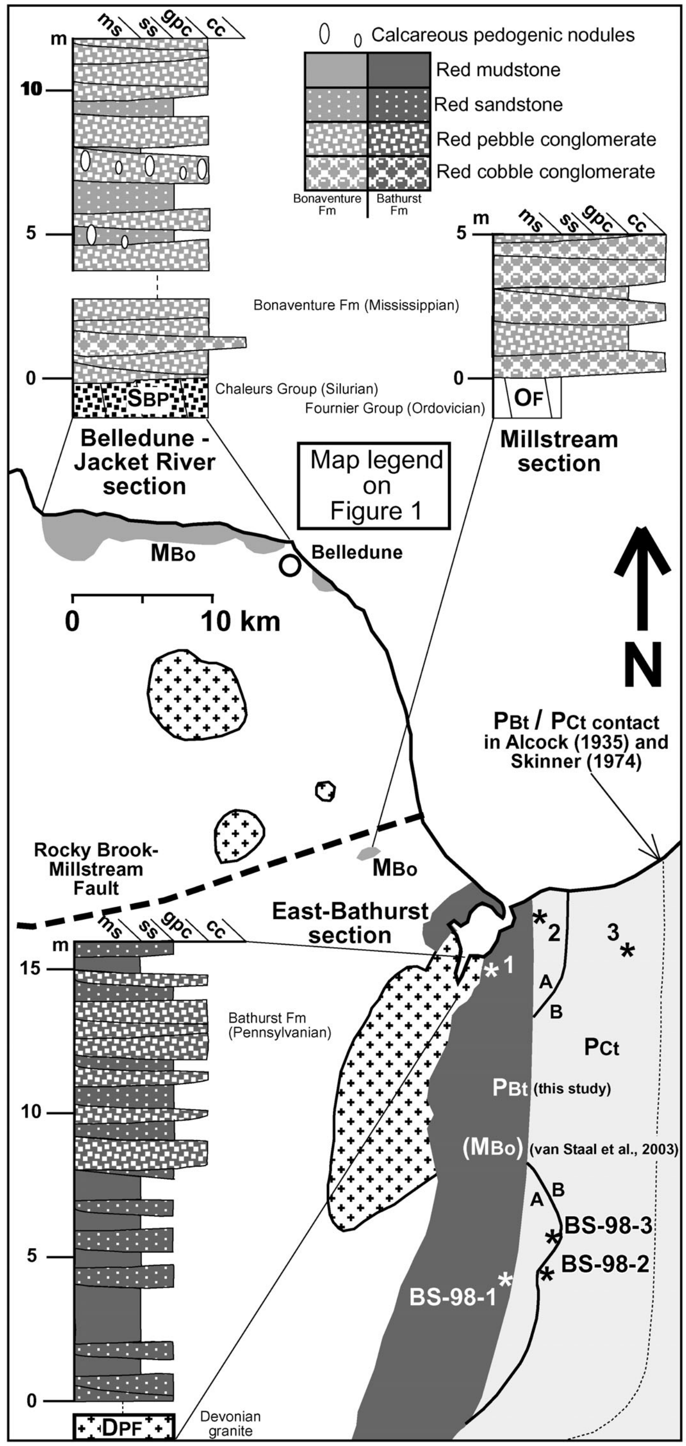

Fig. 2. Stratigraphic sections and localities of holes BS-98-1, -2 and -3 (Noranda Mining and Exploration Inc.). Refer to legend on Figure 1 for map symbols. OF: Ordovician Fournier Group slate; SBP: Silurian Bryant Point Formation conglomerate; DPF: Pabineau Falls Granite; ms: mudstone; ss: sandstone; gpc: granular or pebble conglomerate; cc: cobble conglomerate.

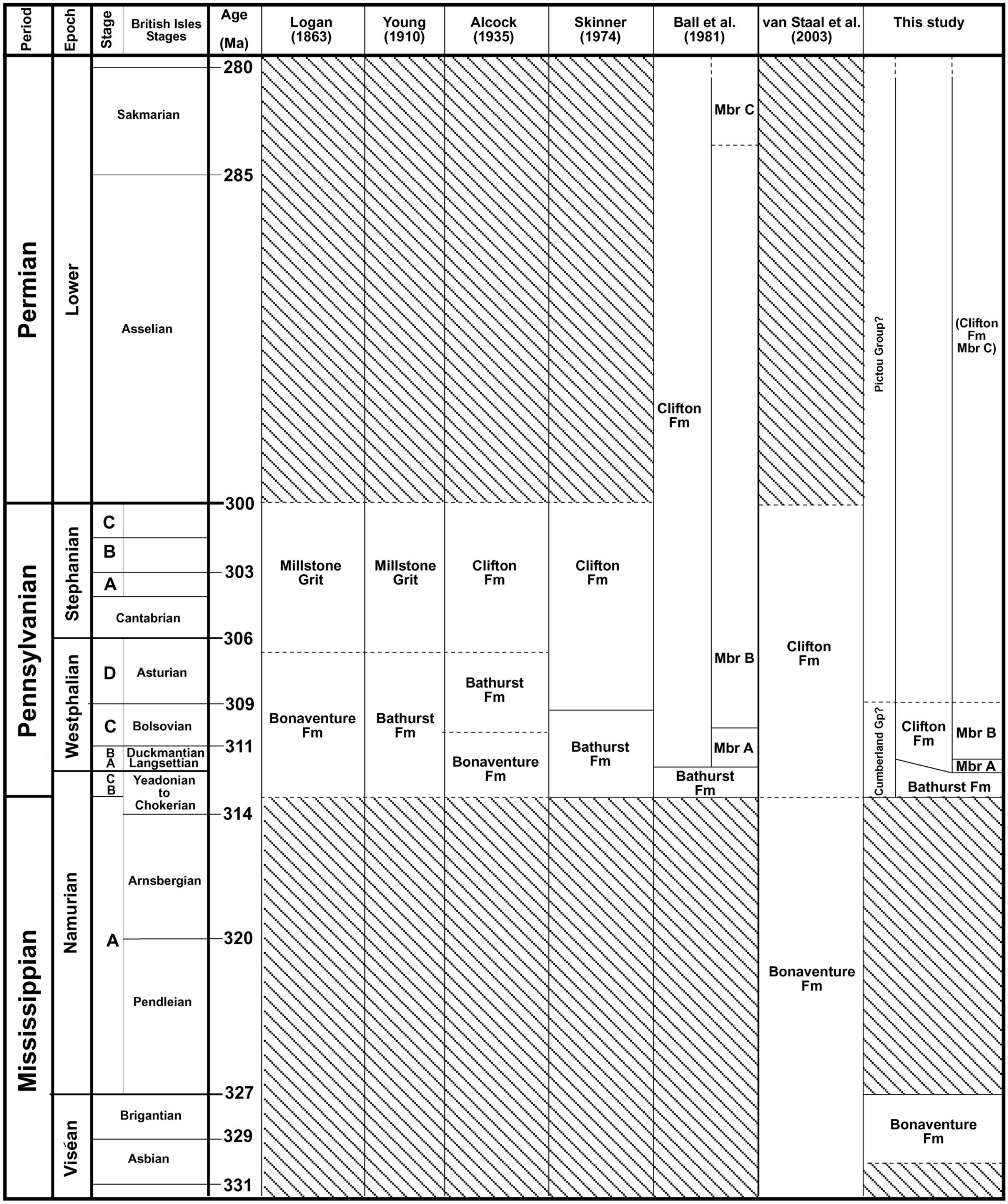

Fig. 3. Development of the stratigraphic nomenclature in the Bathurst area of northern New Brunswick. Time scale after Okulitch (1999). Stages after Harland et al. (1990). Full lines: dated boundaries. Dashed lines: uncertain boundaries. Cross-lined areas: hiatuses.

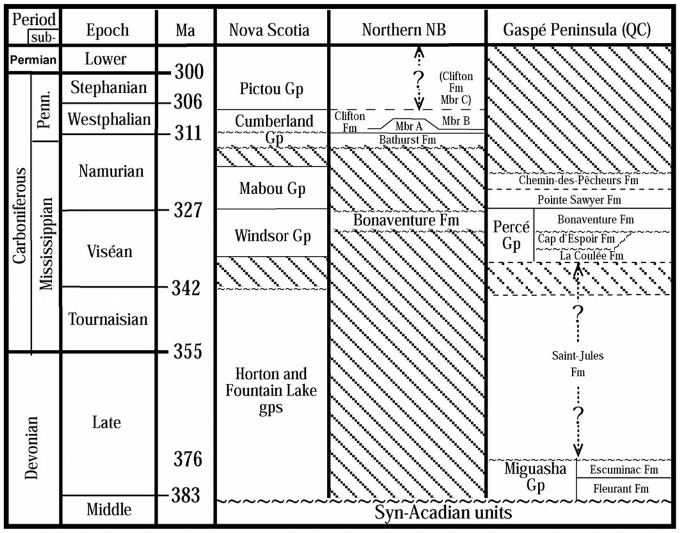

Fig. 4. Comparison between the upper Paleozoic stratigraphy of Nova Scotia (Ryan et al., 1991), northern New Brunswick (NB) (this study), and the Gaspé Peninsula of Quebec (QC) (Jutras and Prichonnet, 2002, 2005). Time scale after Okulitch (1999). Full lines: dated boundaries. Dashed lines: uncertain boundaries. Wavy lines: unconformities. Full cross-lined areas: hiatuses. Dashed cross-lined areas: postulated hiatuses.

a subtle difference in colour. The Bathurst Formation was recently abandoned by van Staal et al. (2003) and correlated with the undated Bonaventure Formation (Fig. 3) on the basis of precedence and of a lack of significant petrographic differences between the two units.

The abandoned Bathurst Formation mainly consists of red beds, but a grey mudstone lens, less than 1 m thick, is found near the base of this unit on the west bank of Nepisiguit River (Fig. 1, Locality 1). This mudstone was analyzed for spores by M.S. Barss in 1971 (GSC loc. 8881) and the results were later published in Skinner (1974). A late Namurian to early Westphalian age was determined.

The overlying Clifton Formation, which was introduced by Alcock (1935), comprises intercalations of red beds and coal-bearing grey beds (Ball et al., 1981; Legun and Rust, 1982). Ball et al. (1981) lowered the base of the Clifton Formation and subdivided it into three members, labelled A, B and C (Fig. 3).

Member A is nine to 18 m thick, has a limited lateral extent (Figs. 1, 2) and comprises a basal grey quartzose conglomerate overlain by quartz arenite. This unit was used by Ball et al. (1981) and van Staal et al. (2003) to mark the base of the Clifton Formation, although both Member A and the base of

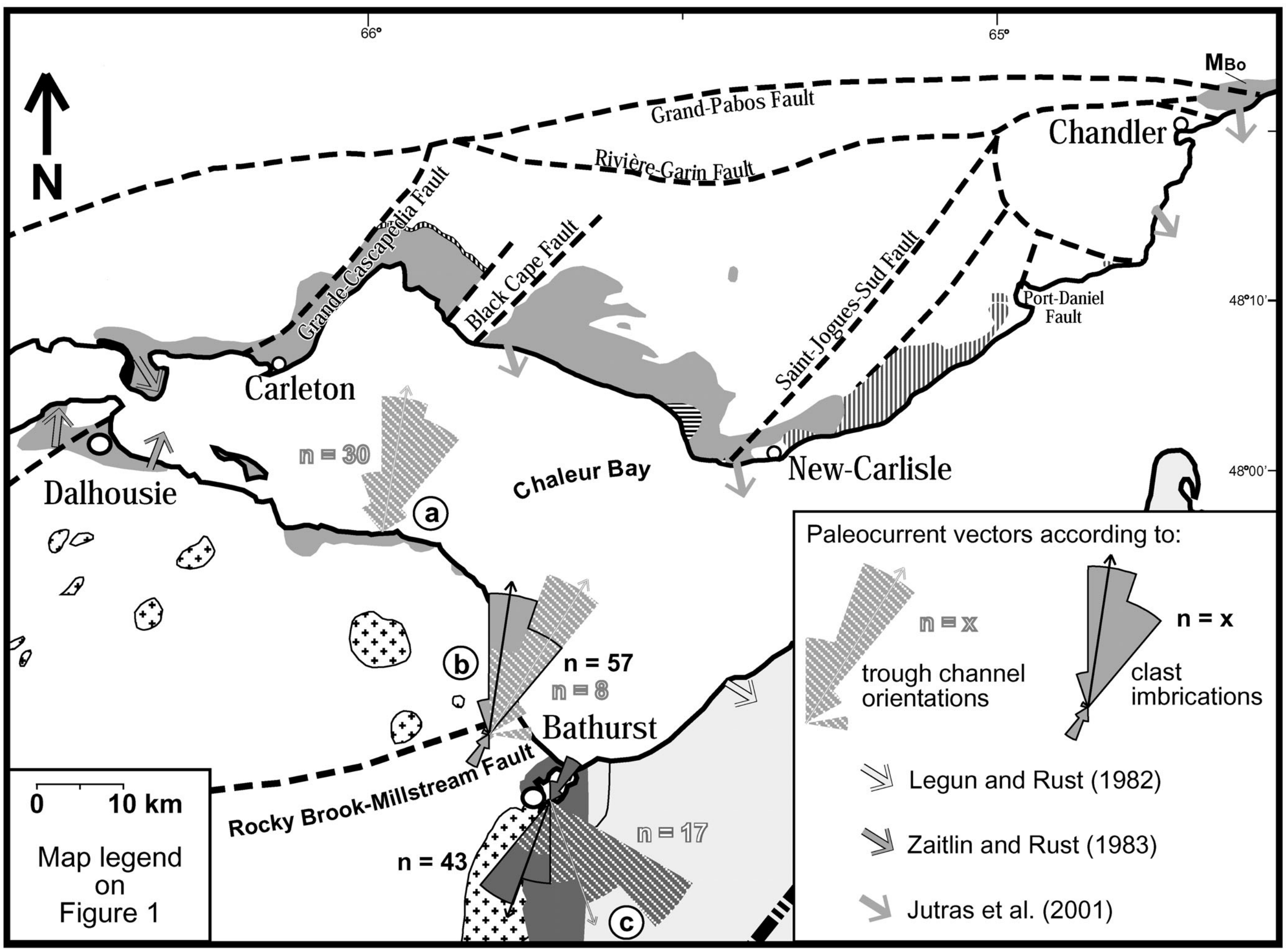

Fig. 5. Paleocurrent vectors in the Bonaventure (Zaitlin and Rust, 1983; Jutras et al., 2001; this study), Bathurst (this study) and Clifton (Legun and Rust, 1982) formations around Chaleur Bay.

Member B were previously included within the Bathurst Formation by Alcock (1935) and Skinner (1974). As a result, the Bathurst Formation was reduced from nearly 400 m (Skinner, 1974) to less than 200 m (Ball et al., 1981).

Member B is estimated to be up to 740 m thick and is dominated by coal-bearing grey beds, although red overbank deposits are also abundant (Ball et al., 1981; Legun and Rust, 1982). An early Bolsovian (Westphalian C) spore assemblage was identified by M.S. Barss (pers. comm., 1970, in Skinner, 1974) within the original limits of the Bathurst Formation (GSC Locality 7435; shown as Locality 3 on Fig. 1) at a stratigraphic level that is now included within Member B of the Clifton Formation (Ball et al., 1981; Fig. 3). The most basal spore dates within the original limits of the Clifton Formation (Locality 32 in Ball et al., 1981; shown as Locality 4 on Fig. 1) are late Bolsovian (Westphalian C) (M.S. Barss, pers. comm., 1979, in Ball et al., 1981; Fig. 3).

Spore dates from the uppermost outcrop samples in Member B of the Clifton Formation (Locality 41 in Ball et al., 1981; shown as Locality 5 on Fig. 1) are Asturian (Wesphalian D) (M.S. Barss, pers. comm., 1979, 1980, in Ball et al., 1981), but a Stephanian (late Carboniferous) to Sakmarian (Early Permian) age was determined for assemblages obtained from rock cuttings below the base of Member C in a testhole at Locality 65 of Ball et al. (1981) (shown as Locality 6 on Fig. 1) (M.S. Barss, pers. comm., 1979, 1980, in Ball et al., 1981). The latter unit is an incompletely exposed and undated succession of dominantly red beds.

Prior to this study, beds of the abandoned Bathurst Formation (upper Namurian to lower Westphalian, *sensu* Skinner, 1974) were assigned by the NBDNRE (2000) to the Mabou Group of Belt (1964) and those of the Clifton Formation (Bolsovian / Westphalian C to lower Permian, *sensu* Ball et al., 1981) to the Pictou Group of Bell (1944) (Fig. 4), which both have their type-sections in Nova Scotia. However, in the revised Carboniferous stratigraphy of Nova Scotia (Ryan et al., 1991), the Mabou Group is lower Namurian and the Pictou Group is Asturian (Westphalian D) to Lower Permian, whereas the Cumberland Group comprises upper Namurian to lower Asturian strata (Fig. 4). Moreover, the abandoned Bathurst Formation is mainly composed of red beds and is therefore lithostratigraphically distinct from the Mabou Group, which is dominantly composed of grey beds (Belt, 1964).

Finally, the coal-bearing grey beds of Clifton Formation Member B, assigned to the Pictou Group by the NBDNRE (2000), are lithostratigraphically distinct from rocks of that group in Nova Scotia, which are dominated by red beds (Ryan et al., 1991). They are, however, petrographically similar to the Cumberland Group (Ryan et al., 1991).

Methodology

Stratigraphic sections of the Carboniferous successions at Belledune, Millstream and East Bathurst, northern New Brunswick (Fig. 2), were measured in the field and analyzed petrographically. Paleocurrent vectors were obtained at these localities from upflow dipping clast imbrications in pebble or cobble conglomerate and from the convergent dip orientation of trough channel cross-beds (Fig. 5). Stratigraphic and petrographic analyses were also carried out on cores from three recent holes (BS-98-1, -2, -3) drilled by Noranda Mining and Exploration Inc. in the area of Bruce Siding, south of Bathurst (Figs. 2, 6).

Five outcrop samples from the East Bathurst locality (Fig. 1, Locality 1) and 22 core samples from Bruce Siding (Fig. 2, localities BS-98-1, -2, -3) were analyzed palynologically (stratigraphic level of spore samples indicated on Fig. 6). Four outcrop samples and four core samples were productive (Fig. 7).

Stratigraphic Sections

The Belledune – Jacquet River Section

The unconformable contact between the basal 12 m of the Bonaventure Formation and the Silurian Bryant Point Formation is well exposed near the Village of Belledune (Figs. 2, 8). The Bonaventure succession mainly comprises poorly-sorted (about 50% sandy matrix) and poorly-rounded polymictic pebble conglomerate, with minor sandstone (Fig. 2). The section exhibits the overall coarseness and rapid lateral variations that are typical of alluvial fan or proximal braidplain systems (Rust, 1984; Miall, 1996). According to the converging dip orientations of 30 measured trough channels, these sediments were sourced from the south-southwest (Fig. 5, Locality a).

Lithic clasts issued from Cambro-Ordovician rocks can be differentiated from those issued from Siluro-Devonian rocks on the basis of cleavage. Clast composition in the lower part of the profile includes 16% Cambro-Ordovician metagabbro and metabasalt, and 84% Siluro-Devonian clasts: red or grey sandstone (50%), grey limestone (14%), altered dacite and felsic tuff (10%), and basalt (10%). Similar clast compositions are found in the upper part of the profile, with the cleaved Ordovician rocks making up a higher proportion (50%) and Siluro-Devonian limestone being absent. Dark coloured Ordovician chert and quartz pebbles are rare (<1%) throughout the profile.

Notably, there are no rhyolite clasts, a lithology that forms a large part of the pre-Carboniferous geology on the north side of the Rocky Brook-Millstream Fault, but which is absent on the south side of the fault even though time-equivalent units are present. The absence of granite clasts in basal beds of the Bonaventure Formation is also noteworthy, although Devonian granites are abundant in the direction from which these sediments were sourced (Fig. 5, Locality a). A few granite clasts have been found in local exposures of the Bonaventure Formation that do not reach the basement contact and that are therefore at unknown stratigraphic levels.

The polymictic nature of the clasts is compatible with clast compositions in the Bonaventure Formation of eastern Quebec,

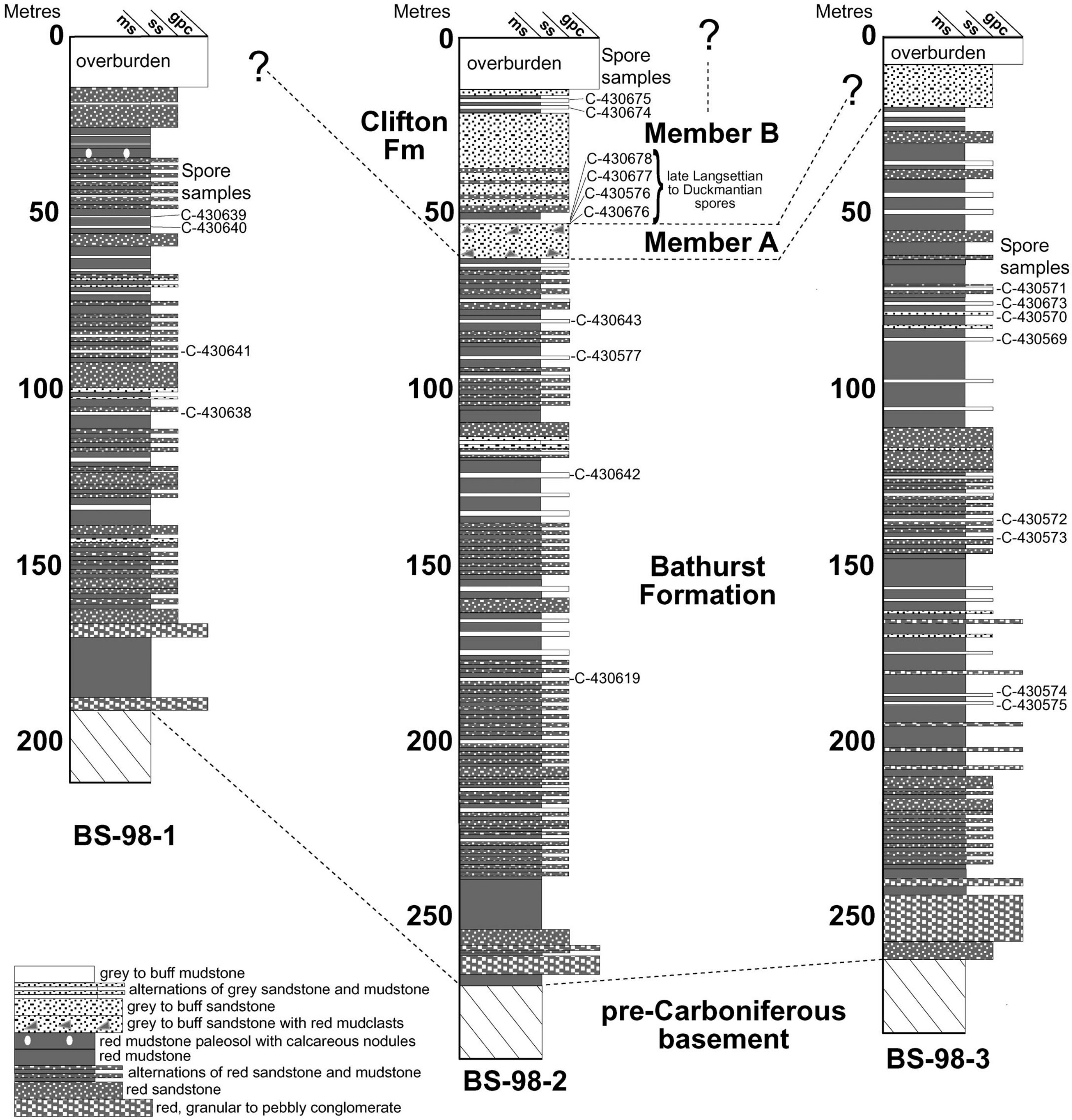

Fig. 6. Lithostratigraphic description of cores BS-98-1, -2 and -3 (localities on Fig. 2), with location of spore samples (results on Fig. 7).

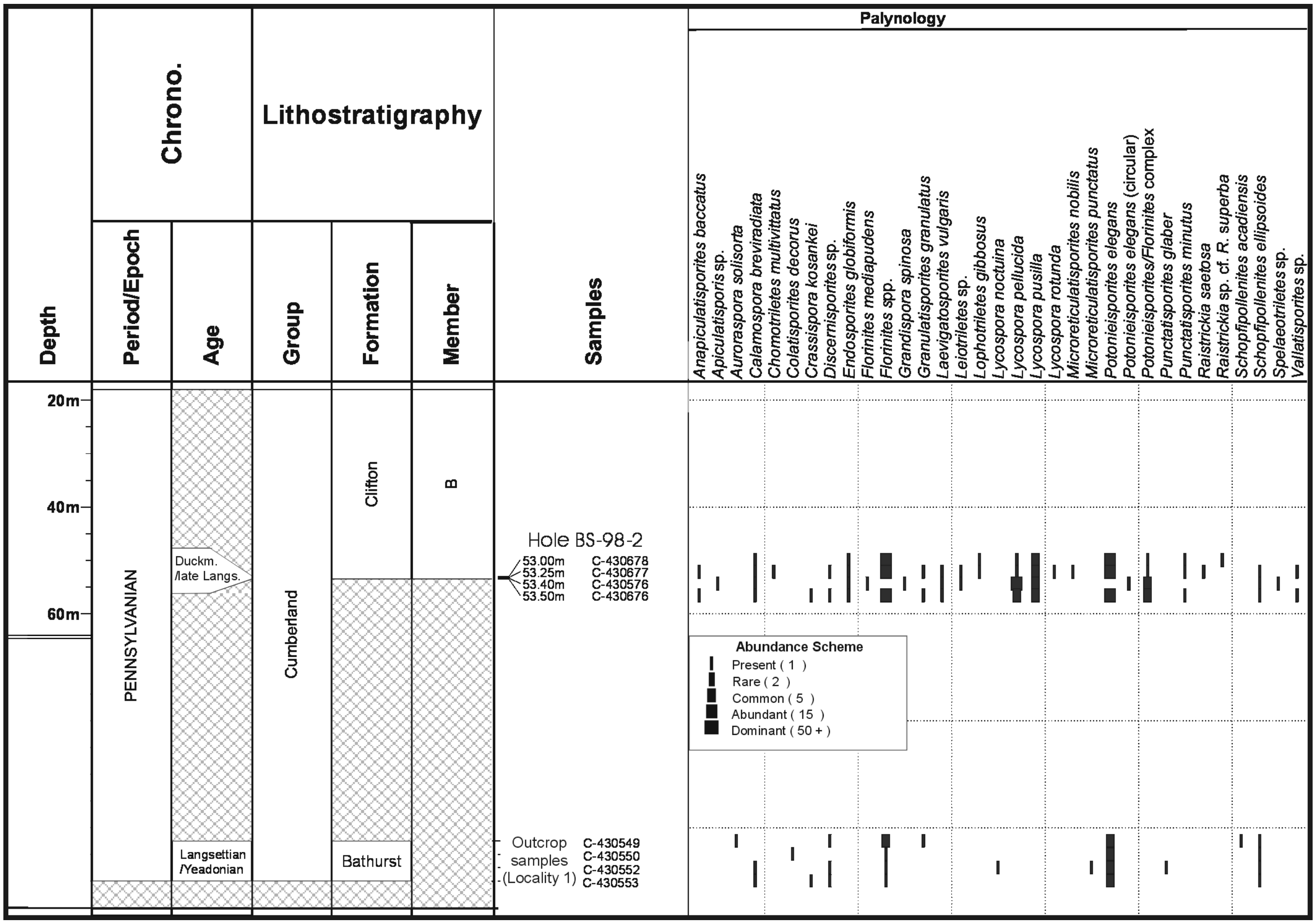

Fig. 7. Spore assemblages in outcrop samples of the Bathurst Formation and in core samples (hole BS-98-2 by Noranda Mining and Exploration Inc.) of the basal beds in Member B of the Clifton Formation.

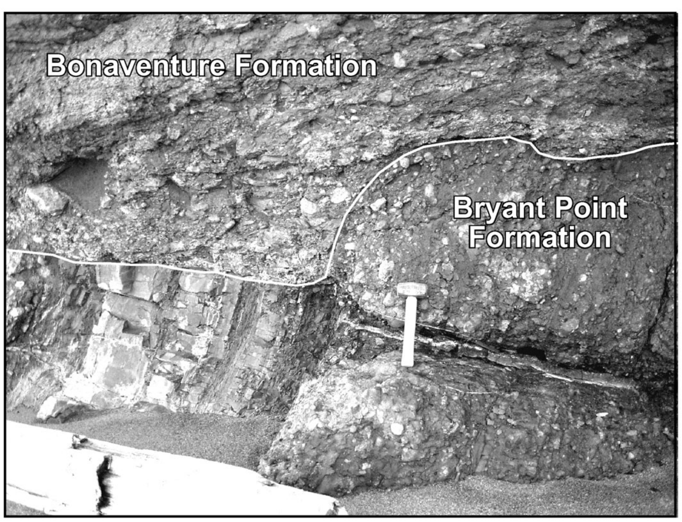

Fig. 8. Unconformable contact between the Viséan Bonaventure Formation and the Silurian Bryant Point Formation at the base of the Belledune–Jacquet River section. A calcite vein (partly hidden by hammer) cuts through irregularities of the contact surface.

although this unit is typically richer in quartz pebbles (about 10–20% of gravel content) (Jutras et al., 1999, 2001; Jutras and Prichonnet, 2002, 2005). Calcrete nodules, green reduction haloes and a high content of lithic fragments within the sandstones and mudstones of the Belledune–Jacquet River section are also typical of the Bonaventure Formation. Thin remnants of groundwater / phreatic calcrete developed in basement regolith are found unconformably below thin coastal outcrops of the Bonaventure Formation in the area of Belledune, which is also typical of this unit in the Gaspé area.

The Millstream Section

Less than 10 km to the north-northwest of Bathurst, a 5 m succession of trough cross-bedded red cobble conglomerate (Fig. 2) is exposed along the Millstream River. Alcock (1935) correlated this conglomerate patch with the Bonaventure Formation, but Skinner (1974) and Ball et al. (1981) included it within the Bathurst Formation. According to a combination of trough channel orientations (n=8) and clast imbrications (n=57), the sediments were sourced from the south-southwest (Fig. 5, Locality b).

The conglomerate is poorly-sorted and comprises about 15% quartz granules, pebbles and cobbles, along with various fine-grained sedimentary rock clasts, mafic and felsic volcanic clasts, but only rare granite clasts, although the latter lithotype is widely exposed in the direction from which these gravels were sourced (Fig. 5, Locality b). The overall composition of the conglomerate is typical of the Bonaventure Formation as defined by Zaitlin and Rust (1983), Jutras et al. (1999, 2001), and Jutras and Prichonnet (2002, 2004).

It is noteworthy that the Bonaventure conglomerate is abutting a basement high at the Millstream section, with no evidence of a fault. The beds are therefore still confined by one of their original valley walls.

The East Bathurst Section

Red beds are exposed east of Bathurst, along the Nepisiguit River (Fig. 2). They were assigned to the Bonaventure Formation by Logan (1863), Ells (1881), NBDNRE (2000) and van Staal et al. (2003), but to the abandoned Bathurst Formation by Young (1910), Alcock (1935), Skinner (1974) and Ball et al. (1981).

The 16 m East Bathurst section, exposed on the east side of the Nepisiguit River, unconformably overlies the Late Devonian Pabineau Falls Granite (Figs. 2, 9). It is dominated by red mudstone and trough cross-bedded sublitharenite with carbonaceous partings and fragments of *Calamites* between some of the beds. It also includes minor red quartzose conglomerate channel fills, with about 20% dark Ordovician chert clasts and about 80% quartz pebbles. Although rather mature in composition, the gravels are neither well-rounded nor well-sorted.

The sediments were sourced from the north-northwest according to trough channel orientations (n=17), or from the north-northeast according to clast imbrications (n=43) (Fig. 5, Locality c). All the clast imbrications were taken from the same scour-and-fill body, whereas the trough channel measurements were recorded from several of them. Therefore, we consider the latter to be more statistically representative of the overall paleocurrent patterns, and hence, a source to the north-northwest is inferred.

Palynology

Sample GSC No. 8881, collected from a mudstone lens near the base of the Bathurst Formation (*sensu* Skinner, 1974) on the west side of the Nepisiguit River, was investigated by M.S. Barss (in Skinner, 1974). The assemblage included a number of taxa, but stratigraphically significant were *Florinites diversiformis, F. visendus, Potonieisporites elegans, Auroraspora solisorta, Schopfipollenites ellipsoides* and *Lycospora* spp. The assemblage was assigned to spore zone D of Hacquebard (1972), which was recorded from the boundary of the Canso–Riversdale groups (Mabou–Cumberland groups in present day terminology) of Nova Scotia, and dated as late Namurian.

A similar assemblage was recorded by Dolby (unpublished report, 1998) from a sample collected at the same locality as GSC No. 8881 by C. St. Peter (CS98-008b). In addition to the identifications of spore taxa, semi-quantitative data were provided, indicating an abundance of *Colatisporites decorus* and *Potonieisporites* spp., and common *Schopfipollenites* spp. and *Florinites visendus*. Dolby pointed out that the assemblage had some characteristic taxa of the Windsor–Mabou groups, and that although *Potonieisporites* spp. and *Florinites visendus* can occasionally occur in the Mabou Group, their relative abundance in this sample suggested a correlation with the lower part of the Cumberland Group. A relatively long age range of "Namurian, no older than late Arnsbergian" was assigned. Such an age range is longer than the late Namurian age proposed by Barss (in Skinner, 1974). For example, rocks as old as Arnsbergian would correlate with the upper Mabou Group (Utting and Giles, 2004) rather than with the lower Cumberland Group. Based on the assumption that the Bathurst Formation is Arnsbergian, van Staal et al. (2003) correlated it with the Bonaventure Formation, although the latter unit predates Pendleian (lowermost Namurian) units of the basal Mabou Group (Jutras et al., 2001).

In an attempt to resolve the uncertainties concerning the age interpretations, the same outcrop of the Bathurst Formation that was sampled by Skinner (1974) and C. St. Peter (written comm., 2004) was revisited. Four samples were collected (C-430549; C-430550; C-430552; C-430553), and all were productive. The assemblage (Fig. 7) is similar to that recorded by previous workers, with *Potonieisporites elegans / Florinites* spp. complex, *Lycospora pellucida* and *L. pusilla* being abundant to common, and *Schopfipollenites elegans* and *Auroraspora solisorta* being consistently present. *Crassispora trychera*, which is a common constituent of the upper Horton, Windsor and Mabou groups (Utting and Giles, 2004), is absent; a characteristic also noted by Dolby (unpublished report, 1998). The assemblage is qualitatively and quantitatively typical of the lower Cumberland Group, and current data suggest that deposition of these beds probably commenced in the late

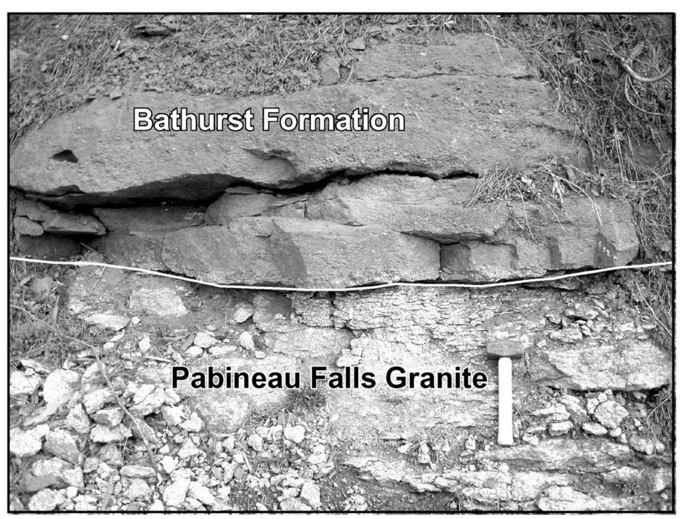

Fig. 9. Unconformable contact between the Pennsylvanian Bathurst Formation and the weathered, underlying Devonian Pabineau Falls Granite basement along the Nepisiguit River.

Namurian, after the major palynofloral change that took place at the Mississippian–Pennsylvanian boundary (Figs. 3, 4). Thus, the upper Namurian Bathurst Formation is considerably younger than the Bonaventure Formation, which disconformably underlies the lower Namurian Pointe Sawyer Formation (Jutras et al., 2001).

The BS-98-1, -2 and -3 Core Sections

Drill holes BS-98-1, -2 and -3 (localities shown on Fig. 2), respectively, intersected 177, 254 and 255 m of Carboniferous clastic rocks overlying Ordovician metasediments (Fig. 6). Hole BS-98-1 is limited to the Bathurst Formation (*sensu* Ball et al., 1981), whereas holes BS-98-2 and -3 also include the base of the Clifton Formation.

The Bathurst Formation in the cores is largely dominated by red mudrock, which explains why this part of the Carboniferous succession crops out so poorly. The base of the succession includes red, granular to pebbly quartzose conglomerate interbedded with red mudstone and sandstone. Conglomerate beds are limited to the basal 25 m and 12 m, respectively, in holes BS-98-1 and -2, but are found as far up as 98 m from the base in hole BS-98-3, which intersected more than twice as much conglomerate as the other two holes.

The first grey beds appear at 60, 41 and 75 m from the base in holes BS-98-1, -2 and -3, respectively, and become more common up section, especially in the mudrock components (Fig. 6). However, red beds remain dominant throughout the succession. Calcitic nodules are found only near the top of hole BS-98-1, although pedogenic marmorosis is common throughout the succession.

The subdivisions of Ball et al. (1981) are clearly recognizable in hole BS-98-2, with a 9 m thick unit of grey quartz arenite and pebbly sandstone (Member A of the Clifton Formation) serving as a sharp stratigraphic marker to separate a lower succession that is dominated by red beds (the Bathurst Formation) from an upper succession that is dominated by grey beds (Member B of the Clifton Formation). Floating in a quartz arenite matrix at various levels of Member A are angular, pebble-size, red mud clasts that were probably scavenged from the underlying Bathurst Formation, which is dominantly muddy in its upper part. A similar quartz arenite with red mud clasts was observed around a flooded quarry near Bass River, closer to Bathurst, where a laterally extensive channel sand body assigned to Member A was once exploited for silica (locality 2 on Figs. 1, 2). These observations suggest that the Bathurst–Clifton contact may be disconformable. The overlying Member B in hole BS-98-2 shows alternations of red and grey sandstone and mudstone, dominated by grey sandstone (Fig. 6).

The upper 13 m of hole BS-98-3 are occupied by a grey sandstone that sharply overlies red beds of the Bathurst Formation (Fig. 6). The sandstone is assigned to Member A of the Clifton Formation, which occurs 30 m higher above basement than in hole BS-98-2.

Although holes BS-98-1, -2 and -3 are located less than 5 km away from each other, no internal stratigraphic marker exists within the Bathurst Formation to allow correlation from one core to the next, apart from the basal contact with basement rocks and the upper contact with the Clifton Formation (Fig. 6). These rapid lateral variations are somewhat unusual for such a fine-grained succession. Thickness varies rapidly as well, with the Bathurst Formation totalling only 205 m in hole BS-98-2, but over 235 m in hole BS-98-3 (Fig. 6), which is located less than 4 km to the north (Fig. 2). Hence, core data indicate that the Bathurst Formation not only coarsens towards the north, hole BS-98-3 being considerably more conglomeratic than the other two, but also thickens rapidly in that direction.

Palynology

As noted above, several grey mudstone intercalations occur in the subsurface Bathurst Formation below Member A of the Clifton Formation (Fig. 6), and although 16 samples were processed, none was productive. However, four core samples from the base of Member B in the Clifton Formation were productive (C-430576; C-430676; C-430677; C-430678). The assemblage shows a slight increase in diversity relative to that found in the Bathurst Formation (Fig. 7). *Lycospora pellucida* and *L. pusilla* are abundant, and *Potonieisporites elegans* is common. The presence of *Endosporites globiformis*, which appears in the upper Langsettian in the British Isles (Smith and Butterworth, 1967) and in the North Sea (McLean et al., 2005), is significant. Thus, if the range is similar in Atlantic Canada, the assemblage from Member B is probably late Langsettian (late Westphalian A) at the oldest. The absence of diagnostic taxa of the Bolsovian (Westphalian C) such as *Vestispora costata* and *V. fenestrata,* which are known to occur in the Bolsovian of New Brunswick (Kalkreuth et al., 2000), suggests that the base of Member B is no younger than the Duckmantian (Westphalian B). These are the first pre-Bolsovian Westphalian dates to be obtained from the New Brunswick Platform.

Discussion

Stratigraphy

The Bonaventure and Bathurst formations

Several petrographic traits distinguish the Bonaventure Formation from the abandoned Bathurst Formation. Conglomerates of the Bonaventure Formation are petromictic, typically including less than 20% quartz gravels (Jutras et al., 1999, 2001; Jutras and Prichonnet, 2002, 2004), whereas the Bathurst Formation is characterized by quartzose conglomerate. A higher maturity is also found in the sandstones of the Bathurst Formation, which are sublitharenites, whereas those of the Bonaventure Formation are true lithic arenites that are commonly dominated by limestone grains (Jutras et al., 2001).

Perhaps the most distinguishing petrographic difference between the two units is the local presence of carbonaceous partings and fragments of *Calamites* between some of the mudstone and sandstone beds of the Bathurst Formation. To date, no organic material has been recognized in the thoroughly oxidized beds of the Bonaventure Formation. Moreover, calcrete nodules are pervasive in beds of the Bonaventure Formation

(Zaitlin and Rust, 1983; Jutras et al., 1999; 2001; Jutras and Prichonnet, 2002, 2004), but were not found in exposures of the Bathurst Formation and were found only in one of the three analyzed cores (BS-98-1 on Fig. 6).

Spores from the basal part of the Bathurst Formation (Fig. 7) indicate a late Namurian to early Westphalian (early Pennsylvanian) age, consistent with that proposed by M.S. Barss (in Skinner, 1974), which makes the Bathurst Formation considerably younger than the lower Namurian beds that overlie the Bonaventure Formation in its type area (Jutras et al., 2001). Hence, beds of the Bathurst Formation are neither the lithostratigraphic nor the biostratigraphic equivalents of the Bonaventure Formation, and the two units should therefore not be correlated. Furthermore, the Bathurst Formation cannot be correlated with any unit in southern New Brunswick or Nova Scotia. Time equivalent beds of the Boss Point Formation, at the base of the Cumberland Group, are lithologically quite distinct, being dominated by grey sandstone (Ryan et al., 1991). However, the Bathurst Formation postdates the middle Namurian major palynofloral change and therefore correlates better with the upper Namurian to Asturian (Westphalian D) Cumberland Group than with the lower Namurian Mabou Group (Fig. 4), which predates this hiatus (Ryan et al., 1991).

While abandoning the Bathurst Formation, van Staal et al. (2003) introduced the term Bathurst Supergroup to define Cambro-Ordovician rocks in the general area of Bathurst. Because the Bathurst Formation has precedence and a longer history of usage in the literature, we propose its reintroduction. It follows that the Bathurst Supergroup should be renamed.

The Clifton Formation

Although the Bathurst–Clifton contact may be in part disconformable, there are neither lithostratigraphic nor biostratigraphic indications for any significant hiatus within the Pennsylvanian succession of northern New Brunswick. The previously observed absence of Duckmantian (Westphalian B) strata (Ball et al., 1981) is attributed to the paucity of rock exposures, core data and spore bearing beds in the lower part of the Pennsylvanian succession. During this study, four samples from the base of the Clifton Formation Member B (samples C-430576, C- 430676, C- 430677 and C- 430678 in hole BS-98-2; Fig. 7) were dated as late Langsettian to Duckmantian (late Westphalian A to Westphalian B) and partly fill the biostratigraphic gap that was previously separating upper Namurian to Langsettian beds along the Nepisiguit River (Fig. 1, Locality 1) from lower Bolsovian (lower Westphalian C) beds along Curries Brook (Fig. 1, Locality 3) (Ball et al., 1981).

The Bathurst–Clifton contact, as defined by Ball et al. (1981), is fairly easy to recognize in core and corresponds to an abrupt change from Bathurst Formation type lithologies to Clifton Formation type lithologies, as defined by Alcock (1935). The Bathurst Formation is more red and conglomeratic near the base, but its upward evolution is too irregular and gradational for it to be subdivided into members.

As for the upper Carboniferous Clifton Formation, time and facies equivalent beds in the Cumberland Basin of Nova Scotia are subdivided into seven formations (Polly Brook, Joggins, Springhill Mines, Ragged Reef, Malagash, Balfron and Tatamagouche) that are part of two groups (Cumberland and Pictou) (Ryan et al., 1991). Further stratigraphic work is, therefore, necessary in the Tracadie Peninsula of northern New Brunswick to correlate the local Pennsylvanian succession with the rest of the Maritimes Basin and to position appropriately the Cumberland–Pictou contact. However, preliminary spore analysis of a sample (C-430682) from the uppermost beds of Member B in a testhole (Fig. 1, Locality 6) suggests that they could be as old as Bolsovian (Westphalian C). This is considerably older than the Stephanian to Sakmarian age proposed by Ball et al. (1981) for these beds, but closer to the estimated transition between Cumberland Group grey beds and Pictou Group red beds, which typically occurs in the early Asturian (Westphalian D) in the rest of the Maritimes Basin (Ryan et al., 1991), and which is petrographically similar to the members B–C transition.

Paleogeography

The Mississippian Ristigouche Basin

The coarseness and high lateral variability of the Bonaventure Formation suggest a proximal alluvial fan environment controlled by active fault scarps. Jutras and Prichonnet (2005) gathered structural and sedimentological evidence from Viséan rocks of eastern Gaspé, indicating that the Ristigouche Basin did not evolve from pure extension, but from transtension along oblique, east–west striking dextral faults that responded to a northwest–southeast trending maximum compressive paleostress (Fig. 10A).

Paleocurrent vectors derived from the Belledune–Jacquet River and Millstream sections corroborate with data from the Dalhousie area (Zaitlin and Rust, 1983) and indicate a source area to the south (Fig. 5). The Rocky Brook-Millstream Fault (Fig. 5), a major east–west striking structure, is considered the best candidate for limiting the Ristigouche Basin to the south during Mississippian times (Fig. 10A). However, the Siluro-Devonian rocks that dominate clast composition in the Bonaventure conglomerates of northern New Brunswick are poorly represented south of that fault, where mainly Cambro-Ordovician rocks are exposed due to the stripping of Siluro-Devonian rocks by erosion. The observation that clasts from Cambro-Ordovician metamorphic rocks and Devonian granites increase in abundance going up the profile suggests that these rocks were gradually being exhumed from their Siluro-Devonian cover during deposition of the Bonaventure Formation.

The Millstream exposures of the Bonaventure Formation are less than 2 km south of the Rocky Brook-Millstream Fault (Fig. 1). As was noted earlier, the beds abut one of their valley walls, suggesting that this local coarse cobble conglomerate may be the remnant of a valley fill that was located upstream from an alluvial fan of the Ristigouche Basin, within the basement high that was sourcing the basin. In this view, the basal

Bonaventure conglomerate at Millstream may be considerably younger than that at Belledune, which may explain why it includes more quartz pebbles and some granitic clasts, as Late Devonian plutons may have been partly exhumed by then.

The Pennsylvanian Central Basin

Apart from the Millstream exposures, no Bonaventure Formation beds were identified south of the Rocky Brook-Millstream Fault in the area of Bathurst. The fault separates Mississippian rocks of the Ristigouche Basin from Pennsylvanian rocks of the Central Basin, starting with the Bathurst Formation (Fig. 1).

Paleocurrents in the Bathurst Formation indicate a source area to the north-northwest (Fig. 5), i.e., towards the Rocky Brook-Millstream Fault and the Mississippian rocks of the Ristigouche Basin that lie to the north. This may explain why the Bathurst Formation conglomerates are more mature than those observed in the Bonaventure Formation (Zaitlin and Rust, 1983; Jutras et al., 1999; 2001; Jutras and Prichonnet, 2002, 2004), as they may be the product of reworking of the latter formation. This would explain why the bright red beds of the Bathurst Formation are in places separated by carbonaceous partings, an unusual occurrence in thoroughly oxidized strata. The environmental conditions during deposition of the

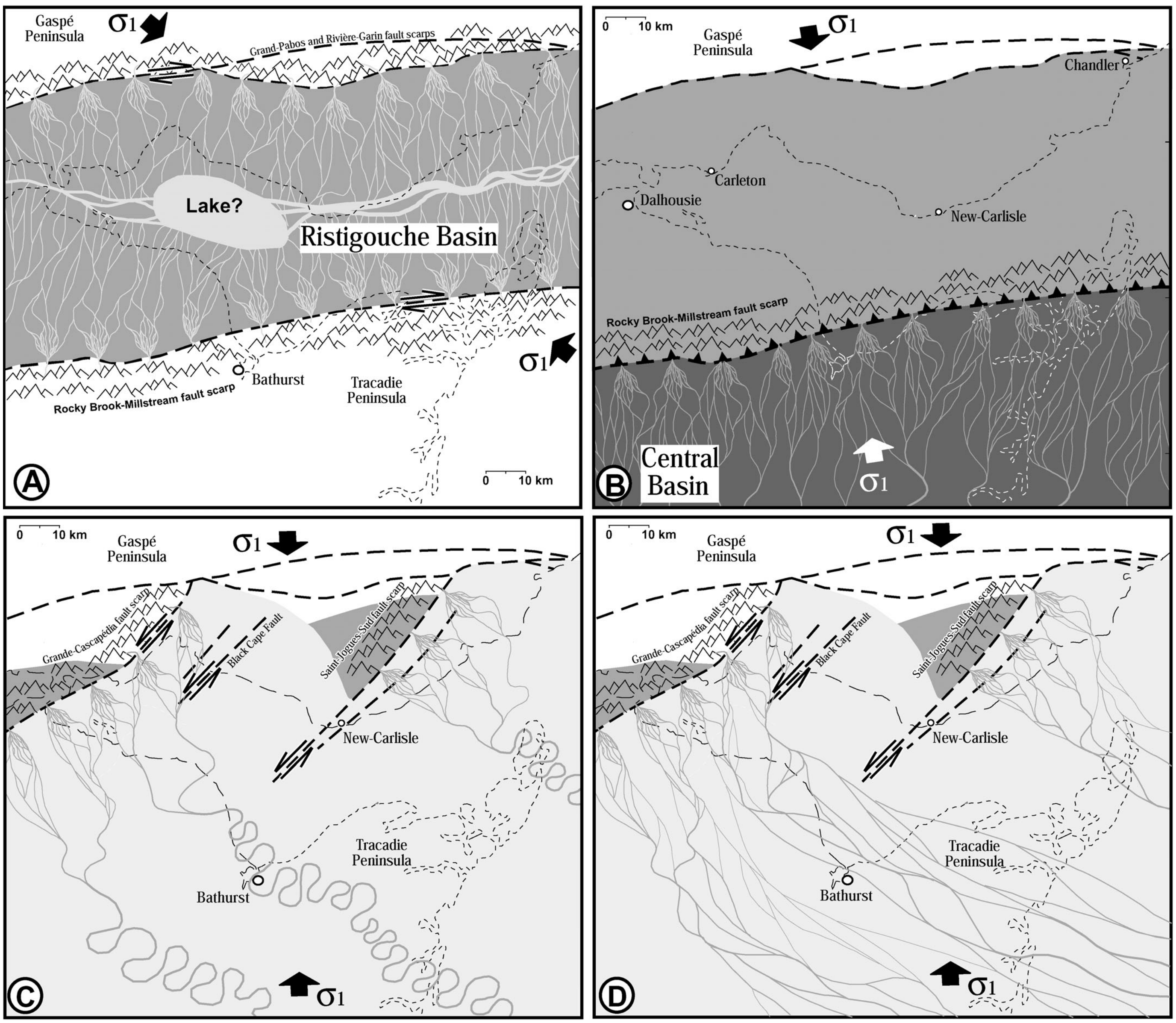

Fig. 10. Paleogeography, tectonic environment and inferred maximum compressive stress (σ1) during deposition of **A)** the Viséan Bonaventure Formation (medium grey); **B)** the upper Namurian to Langsettian Bathurst Formation (dark grey); **C)** the upper Langsettian to Duckmantian Member A of the Clifton Formation (light grey); and **D)** the upper Langsettian to Bolsovian Member B of the Clifton Formation (light grey). Based on data from this study, Ball et al. (1981), Legun and Rust (1982), Zaitlin and Rust (1983), Jutras and Schroeder (1999), Jutras et al. (2001, 2003a, b), and Jutras and Prichonnet (2005).

Bathurst Formation may not have been as oxidizing as they appear, because much of the red material may have been reworked from the Bonaventure Formation. The paucity of calcrete nodules and the preservation of some organic matter in the Bathurst Formation suggest that the Bathurst Formation was deposited under a less arid and oxidizing environment than that prevailing during deposition of the Mississippian Bonaventure Formation.

Unlike the Bonaventure Formation, the Bathurst Formation is dominated by fine-grained beds, suggesting that its source area may have been more remote or less steep. However, if the Bathurst Formation was indeed sourced from reworked Bonaventure Formation beds, which are still poorly-consolidated today, much finer material is to be expected at the same distance from the source area, especially under a more humid climate and, therefore, more efficient chemical weathering conditions.

Proximal deposition from a well and easily weathered source area would explain the apparent dichotomy between the compositional maturity of the Bathurst Formation conglomerates and their poor sorting. It would also explain the rapid lateral variations observed in the succession, both in outcrop and within closely spaced cores. Hence, we agree with Ball et al. (1981) that the Bathurst Formation may include the toe portion of an alluvial fan system, transitional to a fluvial floodplain system, although we do not consider the available data on this unit sufficient to derive rigorous paleoenvironmental conclusions beyond the simple statement that the river system was braided.

Mississippian rocks experienced north-northwest contraction in the Gaspé Peninsula, less than 50 km north of the study area (Faure et al., 1996; Jutras et al., 2003a, b). Resulting deformations affect rocks as young as early Namurian and are distal expressions of the Carbo-Permian Alleghanian Orogeny that resulted from the collision between Africa and the southern U.S.A. (Faure et al., 1996; Jutras et al., 2003a, b). Many structures related to Pennsylvanian shortening are recorded in the rest of the Maritimes Basin and contrast with the dominantly extensional tectonics that the latter experienced throughout the Late Devonian and the Mississippian (e.g., Howie and Barss, 1975; Fralick and Schenk, 1981; Bradley, 1982; Ruitenberg and McCutcheon, 1982; Gibling et al., 1987, 2002; McCutcheon and Robinson, 1987; Calder, 1998; Pascucci et al., 2000).

Structural data along the unexposed Rocky Brook-Millstream Fault are unavailable. However, considering the constraints provided by structural data in the adjacent Gaspé Peninsula (Faure et al., 1996; Jutras et al., 2003a, b; Jutras and Prichonnet, 2005), we propose that this west-southwest striking fault, an inherited Acadian strike-slip, may have been reactivated as an oblique dextral fault during sedimentation of the Mississippian succession in the Ristigouche Basin (Fig. 10A), and then experienced reverse movement during the above-mentioned, post-early Namurian north-northwest contraction event. As a result, Ristigouche Basin rocks were uplifted and eroded, feeding a new basin developed in what used to be the source area of the Ristigouche Basin with deposits of the lower Pennsylvanian Bathurst Formation (Fig. 10B).

As was pointed out by Koopman et al. (1987), reverse movement along faults that limit a graben during its inversion is mainly effective in early stages of compression tectonics, because sliding friction along the fault increases during shortening and it eventually becomes mechanically easier to develop new faults to accommodate the stress. It is possibly at this point that a series of southwest striking sinistral to reverse faults developed in Mississippian rocks of the southern Gaspé Peninsula (Jutras et al., 2003b) (Fig. 10C), which are perpendicular to southeast-trending paleocurrent vectors recorded in the Clifton Formation by Legun and Rust (1982) (Fig. 5). Uplift of the northwest block is observed on all of these faults (Jutras and Schroeder, 1999; Jutras et al., 2003b) and may have generated sufficient relief and erosion to source the Clifton Formation strata exposed on the south shore of Chaleur Bay (Fig. 10C). Hence, counterclockwise rotation of paleocurrent vectors from a south-southeast trend in the Bathurst Formation to a southeast trend in the overlying Clifton Formation may be related to the onset of southwest striking sinistral to reverse faulting in the Ristigouche Basin during Westphalian B (Duckmantian) times (the Maritimes Disturbance), which corresponds to the best recorded Alleghanian phase in the Maritimes Basin (Piqué, 1981; Ruitenberg and McCutcheon, 1982; Nance, 1987; Nance and Warner, 1986; Gibling et al., 1987; Yeo and Ruixiang, 1987; Ryan et al., 1988; Thomas and Schenk, 1988; Keppie, 1993; Reed et al., 1993).

Although the lack of continuous outcrops of Member A makes its sedimentological interpretation speculative, a meandering river model (Fig. 10C) is compatible with the large width of this channel body, its apparent isolation (only observed as a "shoestring" body of limited lateral extent in the northwestern part of the Central Basin), its high maturity, and the presence of red mud clasts at two localities, which were most likely scavenged from receding banks. Legun and Rust (1982) concluded that an anastomozing river system in the lower part of Member B, which is not as mature as Member A, evolved upward into a braidplain system in the upper part of that member, reflecting increased aridity. It is, therefore, proposed that the anastomozing river system of the lower Member B (Fig. 10D) may have itself evolved from a meandering river system (Member A) because of a gradual increase in aridity and an associated decrease in phytostabilization during younger parts of the Westphalian. In this view, the base of Member B would include overbank deposits that are time equivalent to Member A channel sands and gravels where the latter are not found. Petrographically, the observed transitions from quartzose conglomerate at the base of Member A to quartzose sandstone in the upper part of this member near Bathurst (Ball et al., 1981), to sublitharenites in Member B and barren red beds in Member C, are all compatible with an inferred gradual decrease in precipitation rates during deposition of the Clifton Formation.

Conclusions

The lower Pennsylvanian Bathurst Formation is petrographically and biostratigraphically distinct from the Viséan Bonaventure Formation, to which it was mistakenly assigned by van Staal et al. (2003). The former unit is, therefore, re-introduced to the stratigraphic record of northern New Brunswick.

The Bonaventure Formation was sourced from the south in northern New Brunswick, probably from a paleoscarp that was generated by tectonic movement along the Rocky Brook-Millstream Fault. The latter structure apparently experienced reverse movement during subsequent basin inversion at the Mississippian–Pennsylvanian boundary. The Bonaventure Formation then became part of the source area for the upper Namurian to Langsettian (Westphalian A) Bathurst Formation, which was deposited to the south of the Rocky Brook-Millstream Fault under a less arid climate.

Evidence for a disconformity between the Bathurst Formation and the overlying Clifton Formation is found in outcrop and in drill cores, but no major hiatus is recorded, as a late Langsettian to Duckmantian (late Westphalian A to Westphalian B) spore assemblage was identified in basal beds of the Clifton Formation Member B. The transition between the Bathurst and Clifton formations is interpreted as reflecting the onset of sinistral to reverse southwest-striking faulting in the adjacent Gaspé Peninsula of Quebec (Jutras et al., 2003b) during the Duckmantian (Westphalian B) Maritimes Disturbance. Facies and paleocurrent vectors within the Clifton Formation (Legun and Rust, 1982) are compatible with the hypothesis that these faults may have limited the source area of this unit to the northwest. Finally, although the Bathurst–Clifton transition may reflect a substantial increase in climatic humidity, facies changes above this contact suggest that gradual aridification occurred during deposition of the Clifton Formation.

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