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Complex interplay of faulting, glacioeustatic variations and halokinesis during deposition of upper Viséan units over thick salt in the western Cumberland Basin of Atlantic Canada

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ABSTRACT

The late Palaeozoic Cumberland Basin of Nova Scotia and New Brunswick (eastern Canada) developed as a strike-slip basin in the aftermath of the Middle Devonian Acadian Orogeny. Following deposition of thick salt during the middle Viséan (middle Mississippian), this basin mainly accommodated fault-controlled continental deposits during the late Viséan, which generated halokinesis from clastic loading. The Mississippian halokinetic history of this basin is cryptic, as it was severely distorted by subsequent tectonic and halokinetic overprints. After minor structural restoration, the study of upper Viséan minibasin units in wide coastal sections and deep wells allowed a fairly detailed reconstruction of the Mississippian halokinetic setting to be made. Paleoenvironments and depositional settings in the western part of the basin include sectors that were proximal to three fault-bounded source areas and characterized by alluvial fan systems transitioning laterally into gravelly to sandy braidplain environments. More central areas of the basin were characterized by tidal flats transitioning laterally into shallow marine environments. Because of halokinesis, the marine body was eventually forced to subdivide into three separate salt expulsion minibasins. Although late Viséan marine incursions were short-lived in the rest of eastern Canada due to ongoing glacioeustatic variations, there are sedimentologic and stratigraphic lines of evidence for the long-lasting entrapment of restricted marine bodies in salt expulsion minibasins of the western Cumberland Basin. In one minibasin that was characterized by especially high accommodation rates, NE of Hopewell Cape (New Brunswick), the proximal conglomerates and marine carbonates of a fan-delta setting transition laterally into thick sulphate over a short distance, away from freshwater inputs from the source area. The vertical continuity of the latter sulphate succession suggests that this entrapped evaporitic basin was cut-off from significant marine influxes, even at times of glacioeustatic highstands. This is in contrast with salt expulsion minibasins in open marine shelf settings, which always remain open to global marine transgressions and regressions.

INTRODUCTION

Most studies on the interactions between halokinesis and sedimentation are on modern settings or on relatively young rocks that did not go through major changes in tectonic regime since the onset of salt expulsion. Tectonic overprints tend to concentrate in the salt bodies and thus greatly obscure the original setting of those interactions (e.g. Dyson, 2004; Rowan & Vendeville, 2006). However, even after significant structural deformation, several clues to the nature of those interactions may still be derived from the sedimentology of ancient salt expulsion minibasin units.

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Late Viséan (middle Mississippian) halokinesis in the Carboniferous to Permian Cumberland Basin of New Brunswick and Nova Scotia (eastern Canada; Fig. 1) occurred in the context of active faulting along the outskirts of the Alleghanian Orogen (Gibling *et al.*, 2008; Waldron *et al.*, 2013), and in a region that was accommodating glacioeustatically controlled marine incursions at the time (Giles, 2009). This paper investigates the respective contribution and possible interplay of these tectonic, glacioeustatic and halokinetic variables in the well-exposed western part of the basin during the late Viséan by combining the study of large coastal sections with that of available well and geophysical data.

Although the interactions between glacioeustatically-controlled sedimention and halokinesis are well-documented

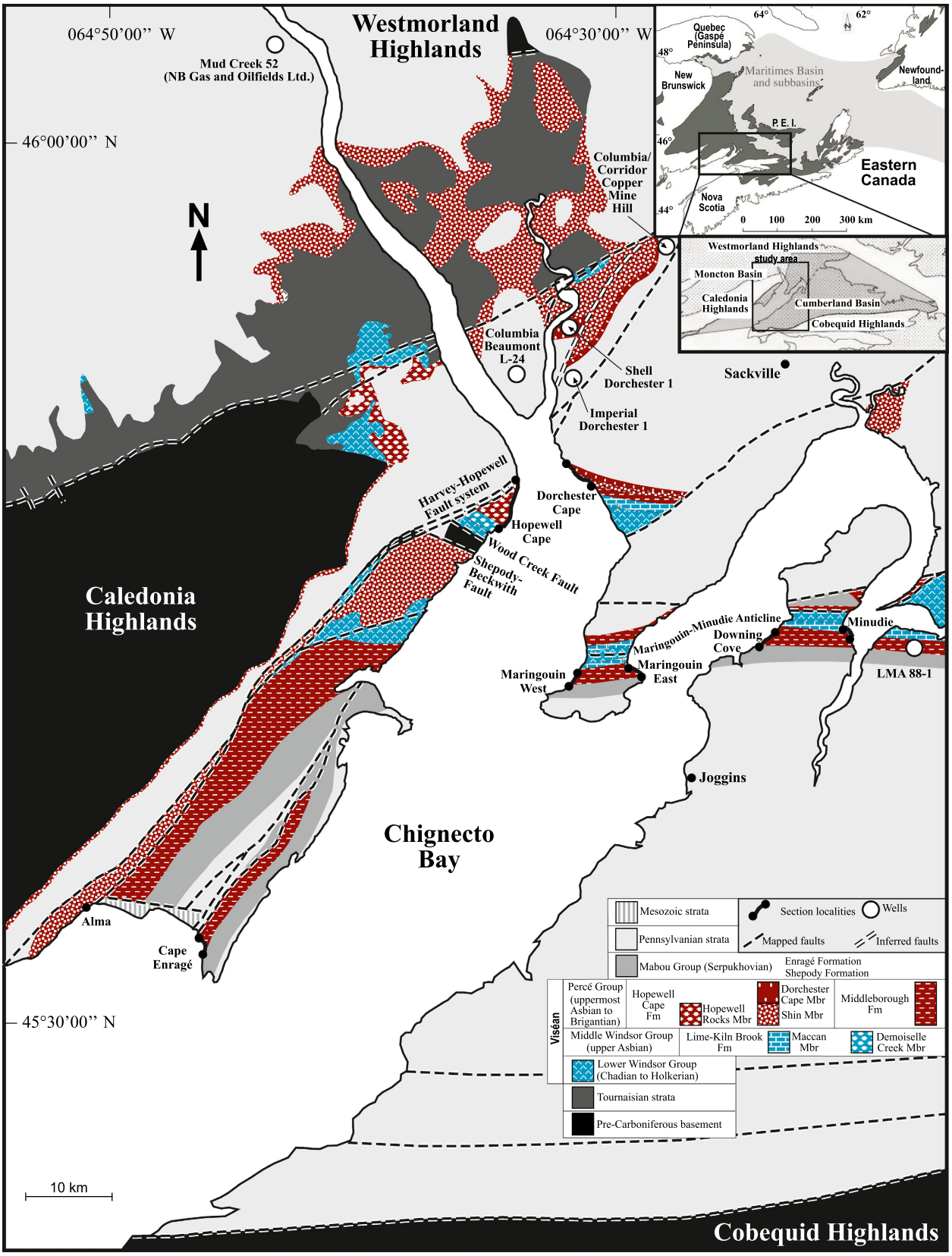

Fig. 1. Geology of the study area (modified from Ryan & Boehner, 1994; and St. Peter & Johnson, 2009), and studied localities. Inset: lateral extent of the Maritimes Basin, with close-up of the Cumberland Basin.

in more open marine environments (e.g. Mohriak *et al.*, 1995; Aschoff & Giles, 2005; Perov & Bhattacharya, 2011), this is the first study of such interactions in the restricted setting of a continental strike-slip basin. The paper also provides an example of methods that can be used to investigate ancient salt expulsion minibasins in which field relation-

ships may have been obscured by subsequent deformation events.

PREVIOUS WORK

Pennsylvanian salt structures involving middle Viséan evaporites have long been known in the Cumberland Basin from the seismic studies of Howie (1986) and Martel (1987), but the study of more recent seismic reflection profiles collected by Devon Canada in 2002 suggested that, in some areas of the basin, onset of salt expulsion occurred as early as late Viséan times (Waldron & Rygel, 2005; Waldron *et al.*, 2013). Clockwise rotation of compressive paleostress vectors occurred in eastern Canada near the Mississippian–Pennsylvanian boundary in relation with the evolving Alleghanian Orogeny (Faure *et al.*, 1996; Jutras *et al.*, 2003a). Hence, the tectonic context of Mississippian deposition differs drastically from that of the Pennsylvanian (Jutras *et al.*, 2005; Gibling *et al.*, 2008), and contrasts in Early vs. Late Carboniferous halokinesis are therefore to be expected.

Whereas Pennsylvanian halokinesis resulted in the formation of well-defined east-west striking salt walls separating minibasins of thick and rapidly deposited Pennsylvanian strata (Waldron *et al.*, 2013), the Mississippian portion of the story is more cryptic due to the Pennsylvanian overprint. Moreover, there are no previous reports on how Mississippian halokinesis influenced the sedimentology of coeval units, and on how it affected the western part of the basin, where these units are best exposed.

METHODS

To properly assess the lateral and vertical variations of sedimentary facies that are associated with the effects of late Viséan salt expulsion in the western Cumberland is complicated by limited exposure, lateral variations over short distances, and stratigraphic nomenclature complexities that evolved due to parallel development in two different provincial surveys (New Brunswick and Nova Scotia). To accommodate our efforts to produce a paleogeographic model that overlaps this provincial boundary, some formal correlations had to be made (defined in the next sub-section; Fig. 2).

To assist in defining basin architecture and identifying source areas, analytical data compiled by the Geological Survey of Canada (Canadian Geodetic Information System, 2006a,b) were used to render an image of Bouguer gravity anomaly data overlapped with first vertical derivative magnetic data and plotted with Generic Mapping Tools (Wessel & Smith, 1991) for the western part of the Cumberland Basin (Fig. 3).

Our paleogeographic reconstruction of the late Viséan halokinetic setting in the western Cumberland Basin is largely based on the study of eight coastal sections of well-exposed upper Viséan units at Minudie and Downing Cove, Nova Scotia, and at Maringouin East, Maringouin West, Dorchester Cape, Hopewell Cape, Cape Enragé and Alma, New Brunswick (Figs 1, 4 and 5), combined with the study of six deep boreholes in the area (Mud Creek 52 Well of New Brunswick Gas and Oilfields Ltd., Columbia Beaumont L-24, Shell Dorchester 1, Imperial Dorchester 1, Columbia/Corridor Copper Mine Hill F-88-2329, and LMA 88-1 (Figs 1 and 6). The study of outcrop sections focused on lateral and vertical variations of sedimentary facies as a means to identify successive paleoenvironments.

Paleocurrent vectors were obtained exclusively from scour-and-fill trough orientations at all outcrop sections (indicated on Figs 4 and 5) to help identify source areas and to investigate the influence of halokinesis on paleodrainage. Because the sections are dipping at different degrees, the vectors were projected in line with restoration to a flat surface.

All beds with a potential for spore preservation were collected from the interval of interest to obtain better control on lateral variations. A palynological study has been done on all productive samples (sample localities shown on Figs 4 and 5).

GEOLOGICAL SETTING AND STRATIGRAPHIC SUBDIVISIONS

The Cumberland Basin covers an area of approximately 3600 km^2 (Ryan *et al.*, 1987) in southern New Brunswick and northern Nova Scotia, with a large sector beneath the waters of the Bay of Fundy (Fig. 1; inset). It is a subbasin of the composite late Palaeozoic Maritimes Basin, which occupies a large portion of eastern Canada (Fig. 1; inset). This composite basin developed subsequent to the Middle Devonian Acadian Orogeny from wrench tectonics associated with closure of the Rheic Ocean to the south (Jutras *et al.*, 2003a).

Although predominantly continental, the Maritimes Basin was intermittently invaded by epicontinental seawater during the Viséan (Giles, 1981). The Windsor Group (Fig. 2) was deposited during multiple transgression/regression cycles that were caused by the waxing and waning of Gondwanan ice sheets in response to orbital forcing (Giles, 2009). Giles (1981) divided the marine to continental Windsor Group into three subgroups, namely the Lower, Middle and Upper. Macrofaunal assemblages in these three subgroups correspond to, respectively, the A, B and C–E subzones of Bell (1929). Based on macrofossils, spores, conodonts and stratigraphic relationships, the Lower Windsor Group is Holkerian to lower Asbian (middle Viséan), whereas the Middle Windsor Group is upper Asbian (upper Viséan), and the Upper Windsor Group is Brigantian (uppermost Viséan) (Utting & Giles, 2004; Richards, 2013; Fig. 2).

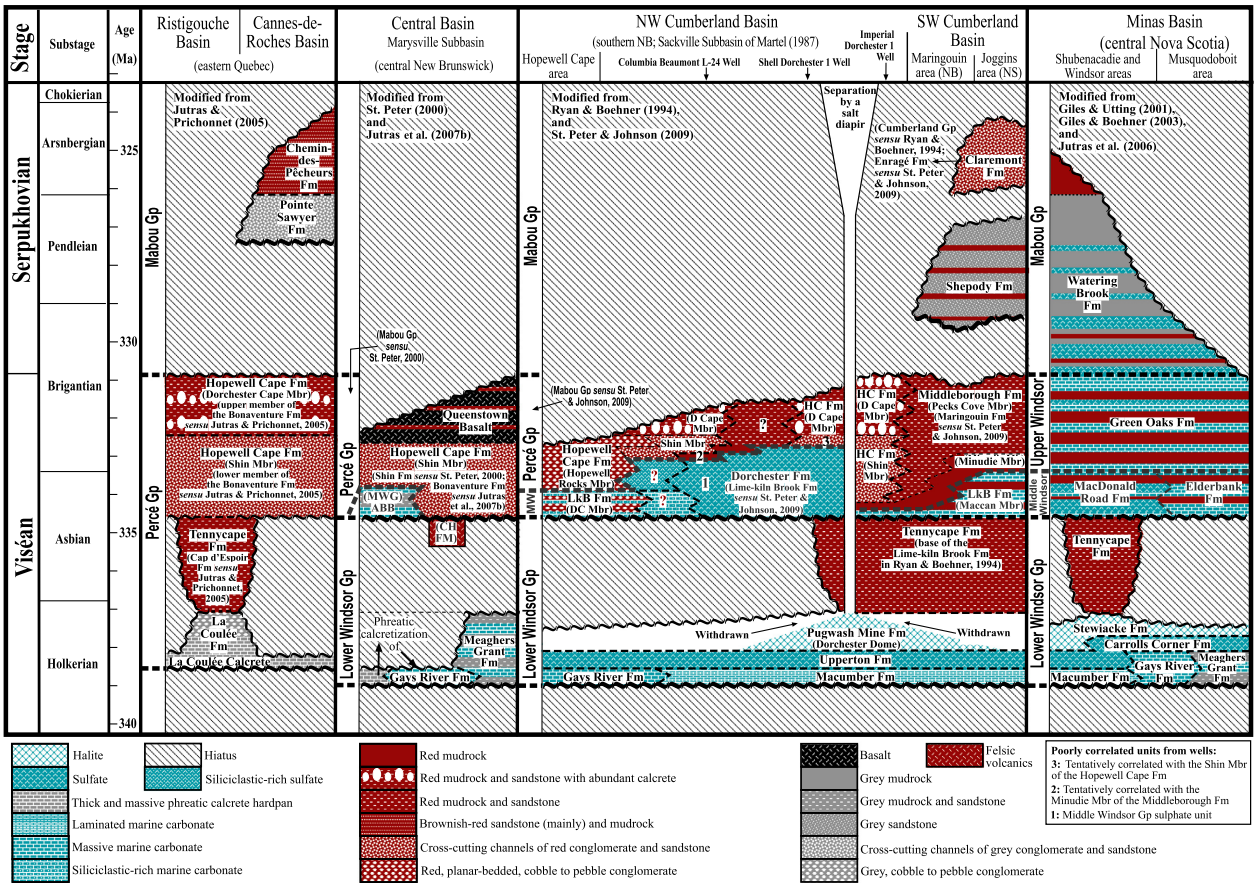

Fig. 2. Middle to upper Mississippian stratigraphy in the study area and adjacent areas of eastern Quebec, New Brunswick and Nova Scotia (time scale after Richards, 2013). All member attributions except the Dorchester Cape Member (St. Peter & Johnson, 2009) are new to this study. The stratigraphic boundary between the Middle Windsor and Percé groups is indicated in grey. CH, Cumberland Hill; D Cape, Dorchester Cape; HC, Hopewell Cape; LkB, Lime-kiln Brook; MWG, Middle Windsor Group.

Above a thin base of carbonates, the Lower Windsor Group consists mainly of evaporites with minor intervals of red beds and carbonates (Boehner, 1984; Ryan & Boehner, 1994; St. Peter & Johnson, 2009) (Fig. 2). Based on their estimates of minibasin subsidence between salt diapirs, Waldron *et al.* (2013) suggested that the original maximum thickness of Lower Windsor Group salt was 2–3 km in the Cumberland Basin. This is considerably thicker than in adjacent subbasins, where Lower Windsor Group salt is typically a few hundred metres thick (Gibling *et al.*, 2008). These greater accommodation rates characterized the Cumberland Basin throughout the middle to late Mississippian because of its position within the Minas Fault Zone (*sensu* Murphy *et al.*, 2011), the most tectonically active zone of eastern Canada at the time.

The Middle to Upper Windsor Group interval also includes evaporites, but is mainly characterized by thick alternations of carbonates and red beds (Giles & Utting, 2001; Giles & Boehner, 2003) (Fig. 2), which, in adjacent basins, are tightly correlated with Croll-Milankovitch cycles (Giles, 2009). In some areas, up to 250 m of fine red beds (the Tennycape Formation of Weeks, 1948) separate the Lower Windsor evaporites from the base of the Middle Windsor Group, which is marked by the first appearance of upper Asbian carbonates (Giles, 1981; Ryan & Boehner, 1994) (Fig. 2). The contact between the uppermost Lower Windsor (Tennycape Formation) and the Middle Windsor is in places interpreted as unconformable (Giles, 1981).

Only the Lower to Middle Windsor Group interval is present in the Cumberland Basin, where the time interval corresponding to the Upper Windsor Group is occupied entirely by continental red beds. Partly because they overlap a provincial boundary, the nomenclatural history of these upper Viséan red beds in the Cumberland Basin is rather complex and has been an ongoing subject of debate, even at the group level. For several decades, they have been assigned to the base the Hopewell Group on the New Brunswick side (e.g. Gussow, 1953; van de Poll, 1995) and to the base of the Canso Group in Nova Scotia (e.g. Bell, 1944; Kelley, 1967; Howie & Barss, 1975), terms that were since abandoned as group names (Ryan *et al.*, 1991). In more recent years, these upper Viséan red beds have been assigned to the base of the Mabou Group of Belt (1964) by some authors (e.g. Ryan & Boehner, 1994; St. Peter & Johnson, 2009), but to the top of the Percé Group of Jutras & Prichonnet (2005) by others (e.g. Jutras *et al.*, 2007b; Gibling *et al.*, 2008) (Fig. 2). The latter group is

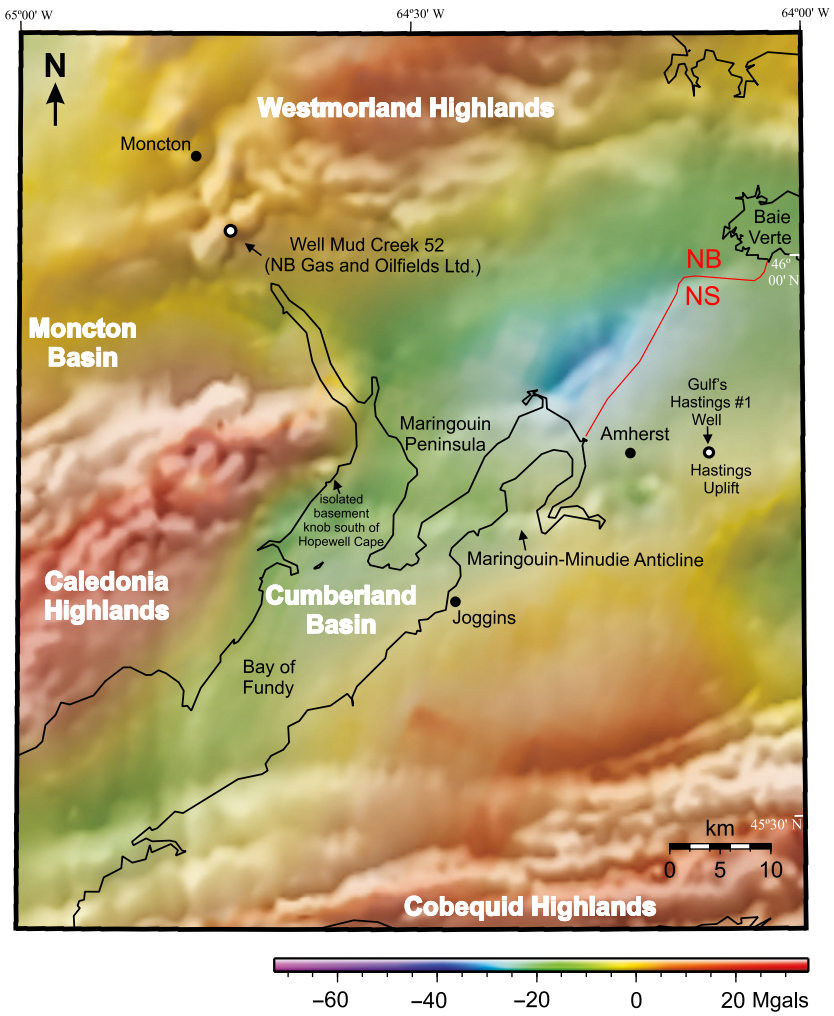

Fig. 3. Identification of basement highs in the Cumberland Basin from Bouguer gravity anomaly data (in Mgals translated to a color scheme; Canadian Geodetic Information System, 2006a) overlapped with first vertical magnetic derivative data (hillshaded with an illumination from the northwest; Canadian Geodetic Information System, 2006b).

thought to be time-equivalent to the entire Windsor Group in its type-area of eastern Quebec (Jutras & Prichonnet, 2005), whereas the Mabou Group overlies the uppermost Upper Windsor Group strata in its type-area of Cape Breton Island (northern Nova Scotia) and in central Nova Scotia (Hamblin, 2001; Fig. 2). In line with the subdivision criteria proposed by Hamblin (2001) for the Mabou Group and by Jutras & Prichonnet (2005) for the Percé Group, we here include the arid upper Viséan red beds of the Cumberland Basin within the Percé Group, and the sub-humid Serpukhovian grey and red beds that disconformably overlie them within the Mabou Group (Fig. 2),

Lower Windsor Group units in the study area

Sharply overlying Tournaisian continental strata, the base of the Windsor Group is occupied by laminated limestone of the Macumber Formation in the study area (Fig. 2). This basal carbonate interval is overlain by a few tens of metres of sulphate (the Upperton Formation) and a variable thickness of remnant salt (the Pugwash Mine Formation; Fig. 2). At least in the eastern part of the study area, this succession is topped by fine red beds of the Tennycape Formation (Fig. 2).

Middle Windsor Group units in the study area

As in other parts of the Maritimes Basin, the Middle Windsor Group interval is mainly characterized by alternations upper Asbian marine limestone and red beds in the western Cumberland Basin. The red bed intervals are conglomeratic on the New Brunswick side (McCutcheon, 1981), but muddy in Nova Scotia, where sulphate intervals are also found in wells (Ryan & Boehner, 1994). The mixed carbonate/conglomerate succession in New Brunswick (Demoiselle Creek Beds of McCutcheon, 1981) was lumped with the mixed carbonate/mudrock/sulphate succession of Nova Scotia (Lime-kiln Brook Formation of Ryan & Boehner, 1994) by St. Peter & Johnson (2009). We herein propose to distinguish these two contrasting successions as the coarse-grained Demoiselle Creek Member (type section: Hopewell Cape, New Brunswick, N 45°48′59″, W 064°34′47″) and the fine-grained Maccan Member (type section: Minudie, Nova Scotia, N 45°45′55″, W 064°20′15″) of the Lime-kiln Brook Formation (Figs 2 and 5).

St. Peter & Johnson (2009) noted that, in some wells, the Middle Windsor Group interval is occupied by thick sulphate. Although they included this thick sulphate

interval in the Lime-kiln Brook Formation, we argue that it is lithostratigraphically too distinct to warrant such correlation at the formation level. Hence, we herein propose to refer to it as the Dorchester Formation (type section: Shell Dorchester 1 Well, New Brunswick, N 45°54′51″, W 064°31′54″; Figs 2 and 6).

Percé Group units in the study area

Substantial lateral variability characterizes the red bed succession that separates the uppermost Lime-kiln Brook Formation carbonate from the lowermost grey bed with plant remains that marks the base of the Serpukhovian Mabou Group (*sensu* Hamblin, 2001; Jutras & Prichonnet, 2005; and Gibling *et al.*, 2008). This succession is conglomeratic in marginal areas (the Hopewell Cape Formation of Ami, 1902), but dominated by red sandstone and mudrock in more central areas of the basin (Maringouin Formation in New Brunswick side; Middleborough Formation in Nova Scotia). Based on their petrographic and stratigraphic equivalence, beds of the Maringouin Formation of Norman (1941) are herein assigned to the Middleborough Formation of Bell & Norman (1938), which has precedence (Fig. 2). The base of the Middleborough Formation is dominated by laminated red mudrock, herein referred to as the Minudie Member (type section: Minudie, Nova Scotia, N 45°45′55″, W 064°20′15″; Fig. 4), whereas the bulk of this unit is characterized by a monotonous alternation of planar-bedded sandstone and mudrock, herein referred to as the Pecks Cove Member (type section: Maringouin Peninsula, New Brunswick, N 45°45′00″, W 064°31′20″; Fig. 4).

St. Peter & Johnson (2009) assigned the finer and calcrete-rich upper part of the Hopewell Cape Formation to their Dorchester Cape Member, which is a petrographic and stratigraphic equivalent of the upper member of the Bonaventure Formation in eastern Quebec and northern New Brunswick (Fig. 2).[1] We herein refer to the coarser beds that underlie the Dorchester Cape Member as the Shin Member (cross-cutting channels of red sandstone and polymictic pebble conglomerate with pervasive pedogenic overprint; type section: Shin Creek, New Brunswick, N 45°34′15″, W 066°41′21″; described in van de Poll, 1967), which is a petrographic equivalent of the Shin Formation of van de Poll (1967; abandoned by Jutras *et al.*, 2007b) and the lower member of the Bonaventure Formation (Fig. 2). In the Cumberland Basin, this interval also includes a coarse, planar-bedded conglomerate facies that has not been documented in other basins of Atlantic Canada and that we herein refer to as the Hopewell Rocks Member of the Hopewell Cape Formation (Fig. 2). This member is laterally equivalent to the Shin Member and possibly the Dorchester Cape Member.

[1]Jutras et al. (2007b) proposed to formally correlate the Hopewell Cape Formation with the Bonaventure Formation of Logan (1846), which has precedence, but this stratigraphic simplification has not been adopted by other workers in the Cumberland Basin (e.g., St. Peter & Johnson, 2009). Because Logan mapped as Bonaventure Formation many units that were subsequently removed from it (e.g., the Middle Devonian Malbaie Formation of McGerrigle, 1950; the Upper Devonian to lower Mississippian St-Jules Formation of Jutras & Prichonnet, 2002; the middle Viséan La Coulée Formation of Jutras et al., 1999; the Serpukhovian Pointe Sawyer and Chemin-des-Pêcheurs formations of Jutras et al., 2001), and because his reference section at Bonaventure Island (eastern Quebec) is incomplete and was never formally measured, we herein propose to abandon this unit and correlate it with the better constrained Hopewell Cape Formation of St. Peter & Johnson (2009).

The Viséan/Serpukhovian transition in the Cumberland Basin

At Downing Cove, Maringouin (East and West) and Cape Enragé, the monotonous succession of planar-bedded red mudstone and sandstone of the Pecks Cove Member is sharply and disconformably overlain by grey to greyish coarse sandstones with grey mudclasts and coalified plant remains, which mark the base of the overlying Shepody Formation (Mabou Group). In the study area, the lower part of the Shepody Formation straddles the *Schopfipollenites acadiensis – Knoxisporites triradiatus* (AT) and *Grandispora spinosa-Ibrahimispores magnificus* (SM) concurrent range zones (Utting, 2008), which are, respectively, Brigantian and Pendleian (Utting *et al.*, 2010; Figs 4 and 5). Based on recent estimates of Carboniferous boundaries, which place the Viséan-Serpukhovian transition near the middle of the Brigantian, the AT zone is late Viséan to early Serpukhovian and the SM zone is early Serpukhovian (Richards, 2013).

Although previous data suggested that the transition from the Brigantian to the Pendleian occurs quite high in the Shepody Formation (Utting *et al.*, 2010), our new data indicate that the most basal beds of the Shepody Formation are Pendleian at Cape Enragé, Maringouin West and Downing Cove (Fig. 4). This age assignment is based on the diagnostic presence of *Ibrahimispores magnificus* within those beds, along with *Auroraspora magna, Calamospora* sp., *Colatispora decorus, Discernisporites micromanifestus, Rugospora minuta, Schopfites claviger, Shopfipollenites acadiensis, Spelaeotriletes windsorii, Spelaeotriletes bellii*, and abundant *Crassispora trychera* and *Punctatsiporites glaber*. However, basal beds of that unit at Maringouin East bear a similar assemblage, but without *Ibrahimispores magnificus*, suggesting a Brigantian age (Utting & Giles, 2004). The paucity of diagnostic taxa may result in zonal definitions that are tentative, and therefore the absence of *Ibrahimispores magnificus* in basal Shepody beds at Maringouin East does not in itself preclude a Pendleian age for these beds. However, tentative correlation of stratigraphic markers higher in the Shepody Formation (McLeod, 2010) supports the possibility that the most basal occurrences of the Shepody facies at Maringouin East may be slightly older than at other localities. Moreover, in its type-area of northern Nova Scotia, the base of the Mabou Group is characterized by grey mudrocks that

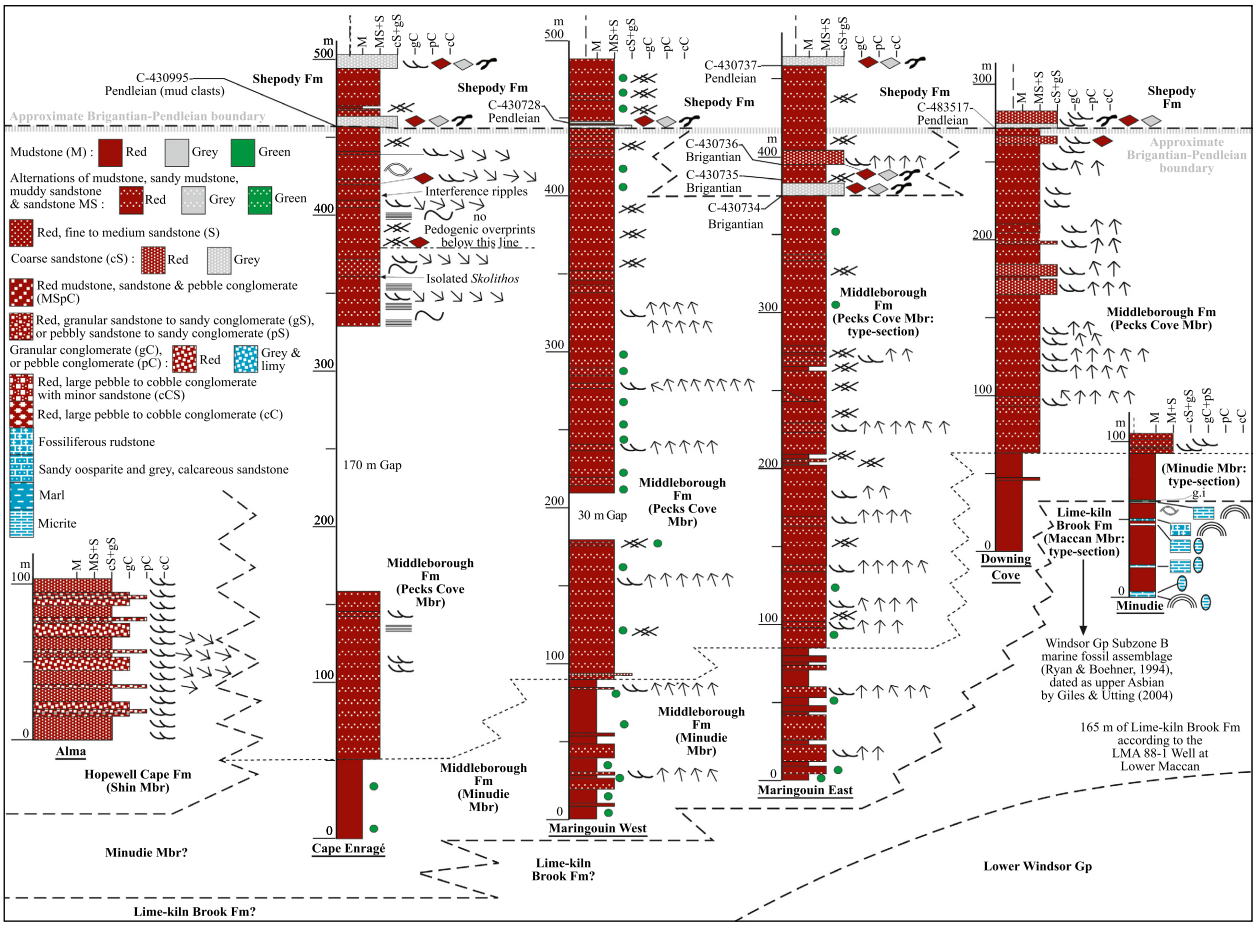

Fig. 4. Vertical and lateral transitions in the upper Viséan stratigraphy along an approximate SW–NE transect in the Cumberland Basin, with palynological localities (Geological Survey of Canada samples C-#) and results indicated on the left side of the columns. What is indicated as Brigantian and Pendleian correspond, respectively, to the *Schopfipollenites acadiensis – Knoxisporites triradiatus* (AT) and *Grandispora spinosa–Ibrahimispores magnificus* (SM) concurrent range zones of Utting *et al.* (2010). The symbol legend is on Figure 5.

are considered to be lateral equivalents of the Shepody Formation (Hamblin, 2001) and that also straddle the AT and SM zones (Utting, 2011).

A similar assemblage, without *Ibrahimispores magnificus*, was identified by Dolby (1997) from grey mudrock cuttings of the Shepody Formation in the Mud Creek 52 Well of New Brunswick Gas and Oilfields Ltd. (Figs 1 and 3), *ca.* 4 m below basal Pennsylvanian beds of the Boss Point Formation, and in the upper part of a thin (32 m) succession of upper Mississippian strata that onlaps basement rocks of the Westmorland Highlands (Fig. 3). Although Dolby (1997) considered the assemblage to be Pendleian, similar assemblages are here considered to be more probably Brigantian, although possibly Pendleian. The spore-bearing green to grey mudrock overlies red mudrock with calcretes (Dorchester Cape Member), and the well is therefore interpreted to penetrate the contact between the Hopewell Cape and Shepody formations. This contact is also observed at Dorchester Cape, where small lenses of grey mudrock, less than 30 cm thick and 1 m wide, are found below the very low-angle unconformity that separates the Dorchester Cape Member from the basal grey sandstones of the Pennsylvanian Boss Point Formation (Fig. 4). The mudrocks contain a Pendleian spore assemblage (Fig. 5) and are interpreted to represent small remnants of the Shepody Formation, which, as suggested by the high amount of reworked Pendleian spores in the basal beds of the Boss Point Formation at Dorchester Cape (Dolby, 1996), may have been largely eroded from that area in early Pennsylvanian times.

BASIN ARCHITECTURE

The composite gravity and vertical gradient magnetic image displays three well-defined basement highs within the study area, which are characterized by prominent positive Bouguer gravity anomalies and complex magnetic signatures, and which are mostly devoid of Mississippian strata: the Cobequid Highlands to the south, the Caledonia Highlands to the west, and the Westmorland Highlands to the north (Fig. 3). The latter basement high is buried beneath Pennsylvanian strata, but it is nonetheless quite prominent on the composite geophysical image. Large structures are well-defined by vertical gradient

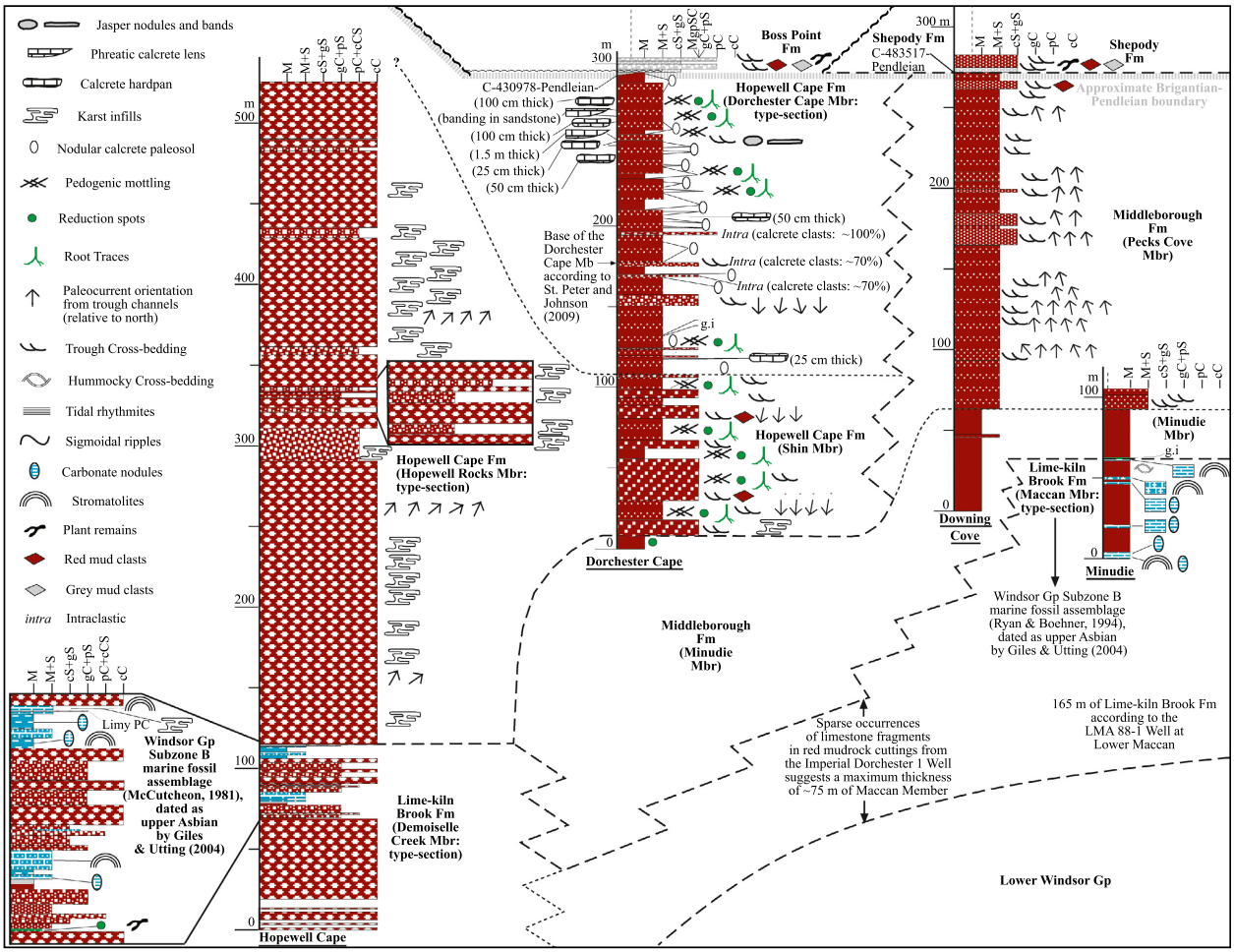

Fig. 5. Vertical and lateral evolution of upper Viséan stratigraphic units along an approximate NW-SE transect in the Cumberland Basin (see caption of Fig. 4 regarding spore dates). The lithological legend is on Fig. 4.

magnetic lineaments in the three basement highs, with E-W faults dominating in the Westmorland and Cobequid highlands, whereas the Caledonia Highlands show a more complex combination of E-W and SW-trending faults (Fig. 3).

Poorly defined on the composite geophysical image is the Hastings Uplift of Howie (1986), which is characterized by a lack of intervening Mississippian strata between basement rocks and Pennsylvanian strata in Gulf's Hastings #1 well, east of Amherst, Nova Scotia (Fig. 3). Martel (1987) used this minor basement high to divide his Sackville Subbasin to the northwest from his Cumberland Subbasin to the southeast, although Ryan & Boehner (1994) subsequently included both areas in their extended Cumberland Basin. Our gravity and magnetic data suggest that the Hastings Uplift is constrained to a small area to the east and south of Amherst, Nova Scotia (Fig. 3). Hence, it does not extend into New Brunswick, contrary with inferences made by St. Peter & Johnson (2009). What is here referred to as the Cumberland Basin therefore encompasses the Cumberland and Sackville subbasins of Martel (1987) and St. Peter & Johnson (2009), and corresponds to the limits proposed by Ryan & Boehner (1994).

SALT STRUCTURES

Large salt structures were identified in the Cumberland Basin via seismic and well data (Howie, 1986; Martel, 1987; Ryan & Boehner, 1994; Waldron *et al.*, 2013), mostly east of the study area. The Dorchester Salt Dome of Martel (1987) is known from wells of the study area (Fig. 6), but does not have clear gravity and magnetic signatures (Fig. 3). In contrast, narrow salt walls that are associated with faults, such as the Maringouin-Minudie Anticline, have a well-defined magnetic signature (Fig. 3). According to Hayward *et al.* (2014), such localized magnetic anomalies at the margin of salt diapirs in the Maritimes Basin may be the result of alteration mineralization in salt-impregnated, iron-rich sedimentary rocks that were brecciated during salt mobilization, which are more likely to develop a strong magnetic signal when vertically concentrated along a narrow salt wall.

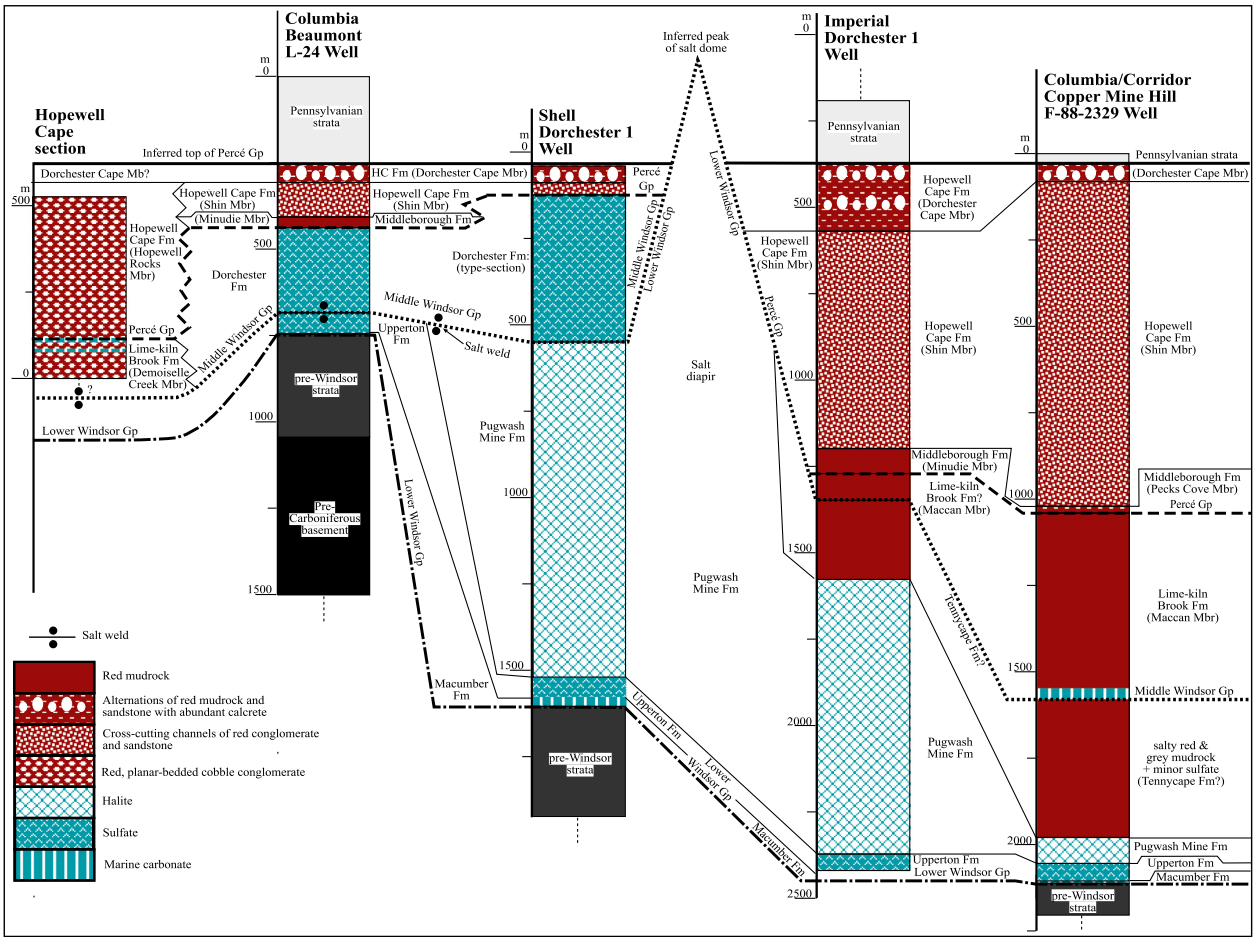

Fig. 6. Correlations between the Hopewell Cape section and nearby wells in the area of the Dorchester Salt Dome (localities are shown on Fig. 1, and the lithological legend is on Fig. 2). The wells are laterally placed in their inferred position prior to post-Viséan faulting (see discussion). Note that thicknesses in these non-cored wells are exaggerated to different degrees by unknown dip values.

SEDIMENTOLOGY OF UPPER VISÉAN UNITS IN SECTIONS OF THE WESTERN CUMBERLAND BASIN

Lateral and vertical variations were studied in eight coastal sections distributed along an approximate SW-NE transect from Alma to Minudie (Fig. 4), and along an approximate NW-SE transect from Hopewell Cape to Minudie (Fig. 5). The sections are positioned in line with our best estimation of the Brigantian-Pendleian boundary as a datum, which is based on available spore dates in the Shepody Formation of the Mabou Group (Figs 2, 4 and 5) and on a stratigraphic marker higher in this unit (McLeod, 2010). Lateral variations were also studied between Hopewell Cape and the deep boreholes at Beaumont, Shell Dorchester 1, Imperial Dorchester 1 and Copper Mine Hill (Figs 1 and 6).

The LMA 88-1 Well, Minudie, Downing Cove, and Maringouin East and West sections

The base of the Lime-kiln Brook Formation is nowhere exposed in the study area. In Well LMA 88-1 (Fig. 1), it shows alternations of carbonate rocks, anhydrite, red mudrock and fine sandstone (Ryan & Boehner, 1994), which we correlate with the Maccan Member. At the nearby Minudie section (Fig. 4), the Maccan Member includes a similar succession, but without the sulphate intervals, which are thought to have dissolved during uplift and exhumation (Ryan & Boehner, 1994). The clastic portion is characterized by laminations of mainly red mudrock (with occasional limestone laminae), but also minor green mudrock and thin beds of red or green fine sandstone. The carbonates include grey stromatolite intervals, grey nodular micrite, and dark grey massive micrite that occasionally houses cephalopods and algal tubes.

The second-from-uppermost carbonate interval is characterized at the base by a *ca.* 0.5 m thick planar cross-bed of mollusc-dominated biosparudite with cross-sets dipping towards the ESE (100°), laterally continuous over a *ca.* 20 m wide exposure at low-tide, and topped by stromatolite (Fig. 7). Hummocky cross-stratification occurs below the uppermost limestone in less disturbed areas of a severely brecciated muddy to sandy red bed interval. Above the uppermost carbonate interval of the Minudie section, the Minudie Member of the Middleborough Formation is characterized by the same facies as the red beds of the underlying Maccan Member of the Lime-kiln

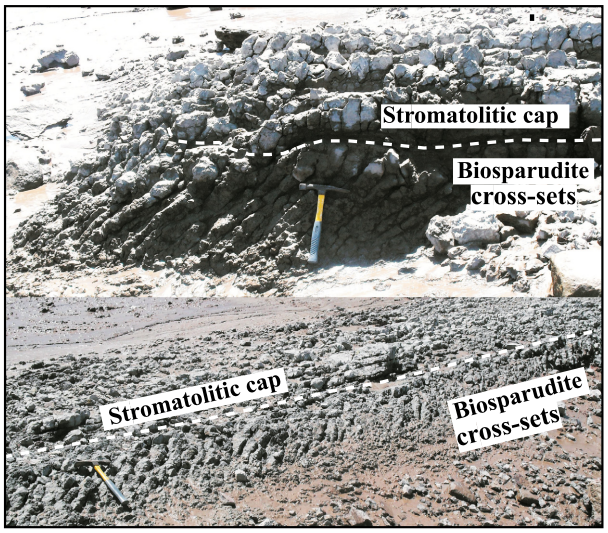

Fig. 7. Large cross-sets of fossiliferous biosparudite topped by stromatolite in the second-from-uppermost carbonate interval of the Lime-kiln Brook Formation (Maccan Member) at Minudie, Nova Scotia. Hammer for scale (30 cm).

Brook Formation, but occurring above its uppermost marine carbonate bed, which forms the upper limit of the Windsor Group (*sensu* Bell, 1929; Belt, 1964). This unit is composed of over 90% laminated mudrock, with thin (less than 1 m) and fine sandstone beds forming the remaining of the succession. It also includes sparse limestone laminae and many occurrences of lime-supported silts and fine sands.

The *ca.* 30 m thick Minudie Member at Minudie transitions upward into the more sandy Pecks Cove Member, which forms the bulk of the Middleborough Formation (Fig. 4). The Pecks Cove Member is still dominated by mudrock, but sandstone forms over 30% of the succession. Although most of the sandstone beds are still only a few centimetres thick (Fig. 8a), the Pecks Cove Member also includes sandstone beds that are over 1 m thick, some of which form tens of metres wide channels of trough cross-stratified sands (Fig. 4). In contrast with the laminated Minudie Member, mudrock of the Pecks Cove Member include adhesion ripples (Fig. 8b), minor mudcracks and non-penetrative pedogenic mottling, indicating relatively short periods of sub-aerial exposure.

The transition from the muddy Minudie Member to the sandier Pecks Cove Member is also observed in the Downing Cove and Maringouin East and West sections (Fig. 4). In all three sections, the top of this monotonous succession of fine red beds is disconformably truncated by coarse, grey to greyish sandstone with coalified plant remains and spore-bearing grey mudclasts, which were dated as Pendleian at Downing Cove and Maringouin West, but as Brigantian at Maringouin East (Fig. 4).

The Cape Enragé section

At Cape Enragé, pedogenic mottling and mudcracks only occur in the uppermost *ca.* 75 m of the Pecks Cove Member (Figs 4 and 8c). Below this point, the muddy to sandy succession is dominated by sigmoidal cross-sets and tidal rhythmites characterized by a near absence of bioturbation, although one *Skolithos* burrow was identified on outcrop (Fig. 8d). In the uppermost *ca.* 75 m, where evidence of sub-aerial exposure is common, there are still structures that are indicative of an intertidal or subtidal setting, such as interference ripples, hummocks and opposed tidal cross-sets (Figs 4 and 8e, f). This succession is disconformably overlain by the Shepody Formation, which bears basal mudclasts with a Pendleian spore assemblage (Fig. 4).

The Hopewell Cape section

In the lower *ca.* 70 m of exposure at Hopewell Cape, the Demoiselle Creek Member of the Lime-kiln Brook Formation is characterized by a monotonous, planar-bedded succession of red, polymictic, pebble to cobble conglomerate with occasional small boulders, and with little to no pedogenic overprint (Figs 5 and 7c). The conglomerates are coarse, poorly rounded, poorly sorted and matrix- to clast-supported, but they are mud-poor and show clear evidence of vertical aggradation, suggesting deposition by flash floods rather than debris flows (Fig. 9).

The upper part of the succession includes two *ca.* 10 m intervals of grey, limy clastic rocks and fossiliferous marine limestone with a Subzone B fossil assemblage (McCutcheon, 1981; dated as late Asbian by Utting & Giles, 2004), which are separated by *ca.* 25 m of coarse red beds that are analogous to the underlying conglomerate. The intervening red beds also include a previously undocumented *ca.* 0.25 m thick channel of oosparite that pinches-out towards the SW between red conglomerates (Fig. 5). The marine carbonates at Hopewell Cape are richer in siliciclastic material than the penecontemporaneous carbonates at Minudie, and these clastic grains are thickly coated with carbonate, suggesting nearshore marine agitation. Sandy oosparite and calcareous sandstone locally wrap steep columnar stromatolitic constructions (Fig. 10), which also suggest a nearshore environment.

The succession above the uppermost limestone of the Lime-kiln Brook Formation shows the same coarse, planar-bedded conglomerate facies as the one that underlies and separates the carbonate intervals, but in this case assigned to the Hopewell Rocks Member of the Hopewell Cape Formation as they overlie the uppermost Windsor Group carbonate (Fig. 5). These planar beds of conglomerate are laterally continuous over tens of metres of lateral exposure. Occasional scour-and-fills are wide and do not exceed 0.25 cm in depth of incision. Despite a siliciclastic composition with less than 5% carbonate material, this succession hosts relatively large paleokarstic structures (Fig. 5), which are described and discussed in P. Jutras & J. Mcleod (unpublished data). This monotonous succession is over 400 m thick, but incomplete (Fig. 5).

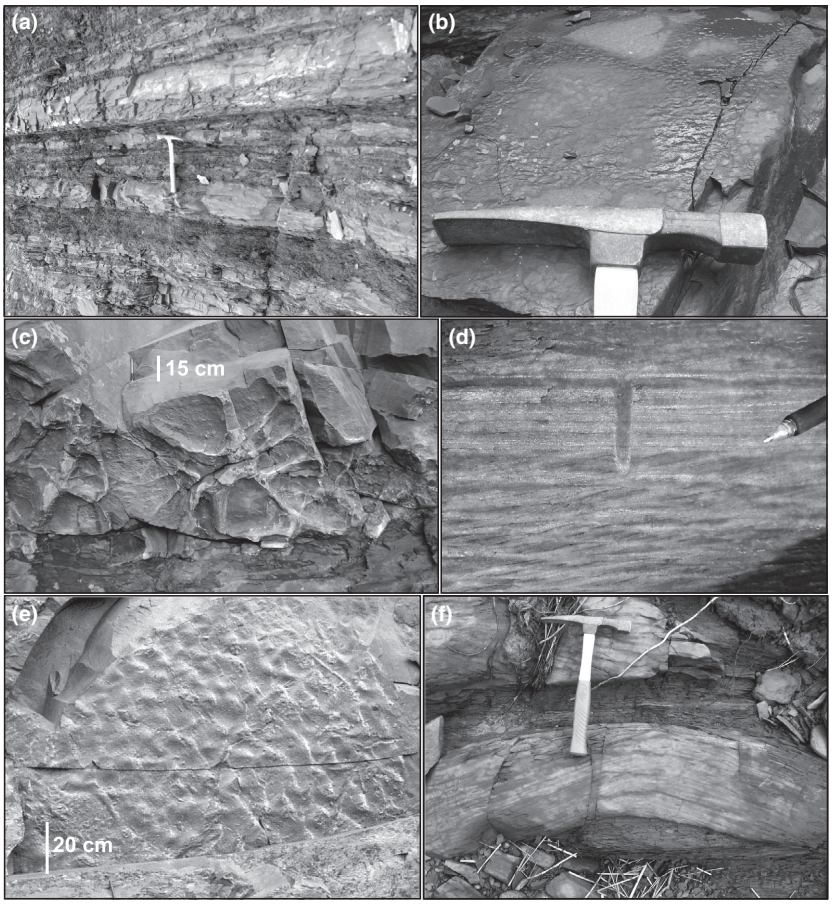

Fig. 8. Various sedimentary features in the Pecks Cove Member of the Middleborough Formation at Cape Enragé, New Brunswick (hammer is 30 cm): (a) intercalated red mudrock and fine sandstone (most common facies of this unit); (b) adhesion ripples at the top of a mudstone bed; (c) sandy desiccation crack infills; (d) *Skolithos* burrow cutting through tidal rhythmites and into a succession of sigmoidal cross-sets; (e) molds of interference ripple marks at the bottom of a fine sandstone bed; (f) hummocky storm erosion surface buried by large opposed tidal cross-sets.

The Dorchester Cape section

The uppermost 8 m of laminated red mudrock of the Minudie Member are exposed at the base of the Dorchester Cape section (Figs 1 and 5). At that locality, they are not overlain by the Pecks Cove Member (Middleborough Formation), but by coarse red beds of the Shin Member (Hopewell Cape Formation). The basal Shin Member conglomerate downcuts into the Minudie Member mudrock by *ca*. 0.5 m. It is characterized by intervals of cross-cutting channels of sandstone, pebbly sandstone and pebble conglomerate, which are separated by red to reddish-brown mudrock intervals that show well-developed pedogenic overprints in the form of mottling and abundant reduced root traces (Fig. 5). Deep oxidation and pervasive pedogenic calcite in those paleosols makes them analogous to modern Aridisols (USDA Keys to Soil Taxonomy; Soil Survey Staff, 2010).

The gradational contact between the Shin Member and the finer Dorchester Cape Member is tentatively marked at a level where the succession transitions upward from being dominated by pebbly sandstone and non-calcretic paleosols to being dominated by finer sandstone and mudrock with abundant calcretes (Fig. 5). Calcretes become increasingly ubiquitous up stratigraphy and are mainly in the form of 0.5 to 3 m thick nodular calcrete, and 0.25 to 1 m thick calcrete hardpans (Fig. 5). Also found near the top of the succession are 1 to 2 m thick phreatic calcrete lenses that include silcrete nodules and bands, and that tightly follow the internal structure of the sandstone lenses that host them, suggesting gradual precipitation by the lateral movement of groundwater between muddy aquicludes (Johnson & Jutras, 2004). As noted earlier, little remnant lenses of Shepody Formation grey mudrock with a Pendleian spore assemblage are found at the low angle unconformable contact with the overlying Pennsylvavian Boss Point Formation (Fig. 5).

The Alma section

A floating section of the Shin Member is present near the town of Alma, where it is overall coarser than at Dorchester Cape (Figs 1 and 5). In this section, the Shin Member is dominated by cross-cutting channels of pebble and cobble conglomerate with coarse sandstone lenses (Figs 1 and 5).

The Beaumont, Shell Dorchester 1, Imperial Dorchester 1 and Copper Mine Hill wells

Although in close proximity to each other, the Beaumont, Shell Dorchester 1, Imperial Dorchester 1 and Copper Mine Hill wells are characterized by substantial differences in their upper Mississippian interval (Figs 1 and 6). All wells go through the base of the Dorchester Cape Member (fine red beds with calcrete) near the top of the

Fig. 9. Planar-bedded sheetflood conglomerate in the Lime-kiln Brook Formation (Demoiselle Creek Member) at Hopewell Cape, New Brunswick. Metre stick for scale.

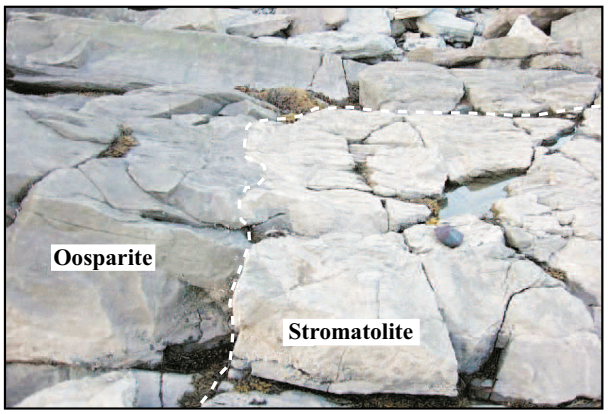

Fig. 10. Stromatolite buried by sandy oosparite in the Lime-kiln Brook Formation (Demoiselle Creek Member) at Hopewell Cape, New Brunswick. Camera bag for scale (10 cm).

well, and all but the Imperial Dorchester 1 Well reach the base of the Windsor Group (Fig. 6).

Above thin carbonate of the Macumber Formation, the Shell Dorchester 1 and Copper Mine Hill wells cut through 50 to 60 m of Upperton Formation sulphate (Lower Windsor Group), and it is inferred that a similar thickness must be found in nearby Imperial Dorchester 1 Well, in which the borehole does not quite reach the base of this sulphate unit (Fig. 6). In all three wells, the Upperton Formation sulphate is overlain by Lower Windsor Group salt (the Pugwash Mine Formation) in a diapiric structure referred to as the Dorchester Salt Dome (Martel, 1987). This salt interval is *ca.* 75 m at Copper Mine Hill, *ca.* 800 m at Imperial Dorchester 1, nearly 1 km thick at Shell Dorchester 1, and absent at Beaumont, where the basal Windsor carbonate is overlain directly by *ca.* 300 m of sulphate with minor red mudrock (Fig. 6). An even thicker sulphate is found at the Middle Windsor Group interval (Dorchester Formation) above the Lower Windsor salt in the Shell Dorchester 1 Well (Fig. 6). This uppermost sulphate is only separated from the Dorchester Cape Member by a very thin (less than 40 m) occurrence of Shin Member conglomerate (Fig. 6), suggesting that it occupies the full Middle Windsor interval and possibly extends within the time interval corresponding to the Percé Group in other parts of the study area. The red bed interval between the uppermost sulphate and the Dorchester Cape Member is also relatively thin at Beaumont (*ca.* 130 m; Fig. 6).

In the Imperial Dorchester 1 Well, which is separated by only *ca.* 6 km from the Shell Dorchester 1 Well, the interval between Lower Windsor salt and the basal Shin Member conglomerate is occupied by *ca.* 380 m of mainly fine red beds instead of sulphate, including a *ca.* 75 m interval of red mudrock with sparse limestone cuttings (less than 1% of the volume) that we tentatively assign to the Maccan Member of the Lime-kiln Brook Formation (Figs. 1 and 6; estimated thickness probably largely overestimated due to the caving of limestone cuttings). This fine red bed interval is overlain by *ca.* 630 m of Shin Member conglomerate, sandstone and mudstone, for a total of *ca.* 1010 m of mainly red beds between the top of the salt and the base of the Dorchester Cape Member (Fig. 6). At Copper Mine Hill, the latter interval is *ca.* 1890 m, which roughly compensates for its much thinner salt (Fig. 6). Also noteworthy in this well is a much thicker Lime-kiln-Brook Formation interval (*ca.* 530 m) with more abundant carbonate than at Imperial Dorchester 1 (Fig. 6).

Paleocurrents

Based on scour-and-fill trough orientations, the Maringouin (West and East) and Downing Cove sections show NNW-verging paleocurrent vectors (Fig. 11). This suggests a source to the SSE, which is presently occupied by the Cobequid Highlands. Paleocurrent data from Alma and Cape Enragé suggest a source to the NW, which is presently occupied by the Caledonia Highlands (Fig. 11). The Cape Dorchester section shows south-verging paleocurrent vectors (Fig. 11), which corroborate data from van de Poll & Sutherland (1976), and which suggests a source to the north, where the Westmorland basement high (Fig. 3) is buried beneath Pennsylvanian strata (Fig. 1). Paleocurrent data from the Hopewell Cape section indicate that it was sourced from the SW, away from a small inlier of basement rocks that we interpret as having been dislocated from the Caledonia Highlands subsequent to Mississippian deposition (see Discussion).

Clast composition

Clast contents in the Pecks Cove Member sandstones at Minudie, Downing Cove, Downing Head and Maringouin (West and East) include abundant rhyolite, phyllite, schist and polycrystalline quartz (McLeod, 2010). Gravel composition in the Lime-kiln Brook and Hopewell Cape conglomerates at Hopewell Cape, Dorchester Cape and Alma is dominated by low-grade metasedimentary rocks, with minor granitic, volcanic and metavolcanic rocks (St. Peter & Johnson, 2009; McLeod, 2010). Granite clasts are

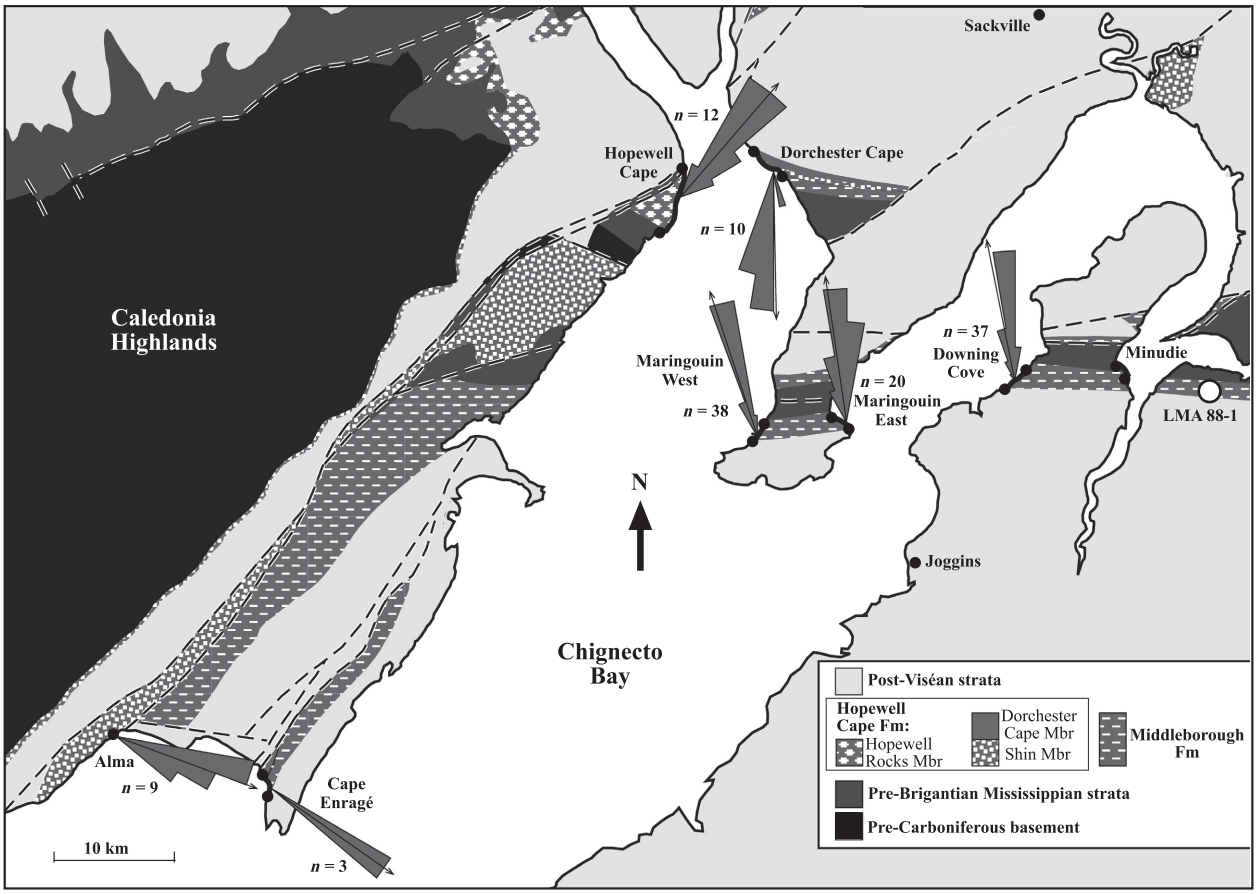

Fig. 11. Late Viséan paleocurrent vectors in the Cumberland Basin based on the measurement of scour-and-fill trough structures in the time-equivalent Hopewell Cape and Middleborough formations.

more abundant in the Hopewell Cape section, where they form *ca.* 20% of pebble and cobble contents. Based on mapping data (Donohoe & Wallace, 1982; Pe-Piper & Piper, 2002; St. Peter & Johnson, 2009), these clast compositions are compatible with basement high lithologies found upflow from the sites of measured paleocurrent vectors.

DISCUSSION

Although the late Viséan geology of the western Cumberland Basin is quite complex and fragmented, a clear picture can be drawn by combining all available data. First- and second-order elements of discussion on source areas, lateral variations, and successive sedimentary environments will be used as building blocks to produce a paleogeographic model of that basin at that time interval, with emphasis on the role of salt tectonics. To facilitate communication, the discussion on sedimentary environments is subdivided by stratigraphic unit.

Source areas

Paleocurrent vectors, clast composition and the distribution of coarse clastic facies altogether suggest that the three major basement highs that were identified by a combination of mapping, gravity and magnetic data (the Caledonia, Westmorland and Cobequid highlands on Fig. 3) were active source areas during late Viséan deposition. However, nothing suggests that the much smaller Hastings Uplift was present and active at the time. We therefore correlate the Hastings Uplift with other post-Viséan uplifts of similar size that are found in central Nova Scotia, such as the Chaswood Ridge and Wittenburg Mountain (Jutras *et al.*, 2006).

Lateral variations

At Hopewell Cape (Fig. 5), intercalation of upper Asbian marine carbonates with the coarse red bed facies that characterizes the Hopewell Rocks Member suggests that this coarse conglomeratic unit is laterally equivalent to at least part of the much finer red bed facies that characterizes the Middleborough Formation, which is also intercalated with upper Asbian carbonates at its base. At Dorchester Cape (Fig. 5), the Shin Member facies is underlain by the fine, laminated facies that characterizes the base of the Middleborough Formation (the Minudie Member), suggesting that the Shin and overlying Dorchester Cape members are equivalent to the Pecks Cove Member of the Middleborough

Formation, as both successions are constrained below the Shepody Formation.

No concordantly overlying unit is known above the Hopewell Rocks Member, which is either fault-bounded at the top or unconformably overlain by Pennsylvanian strata (St. Peter & Johnson, 2009). Because the uppermost exposures of the Hopewell Rocks Member are no finer than its basal beds, it is possibly altogether older than the Dorchester Cape Member, which marks a drop in sediment coarseness in the nearby Dorchester Cape section (Fig. 5). It is noteworthy that this fine, calcrete-bearing facies of the Dorchester Cape Member also typically overlies the conglomeratic base of the Bonaventure (now Hopewell Cape) Formation in eastern Quebec (Jutras & Prichonnet, 2005; Fig. 2) and in the Moncton Basin of southern New Brunswick (Jutras *et al.*, 2007b). However, this fining-upward pattern is not observed in the time-equivalent Middleborough Formation, which coarsens upward slightly (Fig. 5).

Towards the Caledonia Highlands, the distal fine beds of the Middleborough Formation at Cape Enragé transition over a short distance into coarse, proximal beds of the Hopewell Cape Formation at Alma (Figs. 1 and 4). A similar lateral transition is also observed towards the Westmorland Highlands, between Downing Cove and Dorchester Cape (Figs. 1 and 5).

According to correlations with the Shell Dorchester 1 and Beaumont boreholes (Fig. 6), the Demoiselle Creek and Hopewell Rocks members at Hopewell Cape transition laterally into sulphate and minor red mudrock of the Dorchester Formation towards the northeast (Figs. 1 and 6). In the Shell Dorchester 1 Well, as noted earlier, this thick Middle Windsor Group sulphate is separated from thin Lower Windsor Group sulphate (the Upperton Formation) by nearly 1 km of salt, which is missing (i.e., expelled) from the nearby Beaumont Well (Figs. 1 and 6). It is therefore interpreted that the sulphate interval in the latter well combines Lower and Middle Windsor Group sulphates separated by a salt weld. Moreover, no trace of evaporites can be found less than 5 km to the northwest of Shell Dorchester 1 in a large and poorly exposed area where, according to a combination of mapping and zshallow borehole data, the Hopewell Cape Formation sits directly on lower Mississippian strata, with no intervening Windsor Group strata (St. Peter & Johnson, 2009) (Fig. 1). This area is interpreted to be part of the salt weld that is inferred in the nearby Beaumont Well. The few hundred metres of sulphate that were left behind were probably dissolved subsequently in near-surface conditions.

The Viséan succession above the salt is over 700 m thicker in the Copper Mine Hill Well than in the Imperial Dorchester 1 Well, which is located *ca.* 18 km to the northeast (Figs. 1 and 6). This excess thickness is at the expense of salt, strongly suggesting syn-halokinetic deposition.

The relatively sharp vertical transition from the sandstone-poor Minudie Member to the sandstone-rich Pecks Cove Member of the Middleborough Formation can be traced from Minudie (*ca.* 30 m above the uppermost Lime-kiln Brook carbonate) to the Downing Cove section, less than 5 km to the west (Fig. 4). However, no marine carbonate beds occur in the *ca.* 65 m of exposed laminated mudrock and minor thin sandstone beneath that contact at the latter section, which suggests that the thin carbonate beds at Minudie pinch-out between the two sections (Fig. 4). This is consistent with the observation that the Lime-kiln Brook Formation and each of its carbonate intervals thin substantially from east to west in drill holes of Nova Scotia (Ryan & Boehner, 1994). It is also consistent with the lack of a significant or definitive presence of marine carbonate in the stratigraphic interval that would correspond to the Lime-kiln Brook Formation in the Imperial Dorchester 1 Well near Dorchester Cape, only *ca.* 40 km NW of Minudie and *ca.* 18 km SW of its much thicker occurrence at Copper Mine Hill (Fig. 6). However, marine carbonates of the Lime-kiln Brook Formation become again an important component of the succession farther west at Hopewell Cape (Figs. 1 and 6). It is therefore interpreted that marine intervals of the Middle Windsor Group are thickening away from the Dorchester Salt Dome on either side.

Sedimentary environments of the Lime-kiln Brook Formation

Maccan member

Alternations of marine carbonates and fine red beds in the Lime-kiln Brook Formation at Minudie (Fig. 4) are interpreted to reflect, respectively, times of low and high siliciclastic inputs into a subtidal environment. The conclusion that even the red bed intervals at Minudie are subtidal is based on the lack evidence for a sub-aerial disturbance of their laminated structure, which includes occasional limestone laminae, and it is also supported by the presence of hummocky cross-stratification in one of those intervals (Fig. 4). Because most of the Maccan Member transitions to the west into the Middleborough Formation, which shows evidence of fluvial inputs from the Cobequids throughout its succession (Figs. 4), its depositional setting is inferred to have been proximal to a river mouth. In the restricted setting of a continental strike-slip basin that was abutting basement highs, macrotidal conditions are inferred. The thick and laterally continuous cross-sets of biosparudite that are observed at Minudie (Fig. 7) may therefore be a product of the combined energy of fluvial and ebb flows in a tide-dominated delta.

Demoiselle creek member

The very coarse nature of the Demoiselle Creek sheet-flood conglomerates at Hopewell Cape suggests that this site was proximal to a source area. The presence of marine carbonates interbedded with coarse red beds suggests

that, despite proximity to the source area, this locality was also close to sea-level and therefore part of a fan-delta setting that was at times marginally if not entirely submerged. Normal fault movement along the NW-striking Wood Creek Fault (St. Peter & Johnson, 2009; Fig. 1) would best provide the high subsidence rates necessary to maintain the presence of a nearby marine body while depositing large quantities of coarse sediment. This fault separates the Hopewell Cape section from the isolated basement knob that stands upflow from it according to paleocurrent vectors (Fig. 11). As will be further discussed below, these high accommodation rates may have been also enhanced by syndepositional expulsion of Lower Windsor Group evaporites from that area of the Cumberland Basin.

Implications of vertical variations and lateral transition into the Dorchester formation

The presence of sulphate intervals in the Maccan Member in wells of Nova Scotia (Ryan & Boehner, 1994) and the basinward transition from Demoiselle Creek limestone at Hopewell Cape to Dorchester Formation sulphate in wells of the Dorchester area of New Brunswick (Fig. 6) altogether suggest that the late Asbian marine setting was strongly restricted in the western Cumberland Basin. The carbonate rocks at Hopewell Cape therefore owe their existence to dilution by freshwater close to the source area, as the receiving basin was otherwise depositing sulphate.

A restricted seawater context is also consistent with the observation that biosparudite beds in the upper part of the Maccan Member at Minudie are dominated by salt-tolerant molluscs, whereas Middle Windsor carbonates are typically dominated by salt-sensitive brachiopods (Ryan, 1978; Giles *et al.*, 1979; Jutras *et al.*, 2006). At Minudie, the transition from fossiliferous limestone at the base of the carbonate intervals to stromatolites at the top (Fig. 7) is interpreted to reflect an upward increase in salinity at each of these intervals. Despite such indications of occasional influxes of closer to normal marine water, the significant increase in sulphate/carbonate ratio that is observed from the base to the top of the Lime-kiln Brook Formation in Well LMA 88-1 (Ryan & Boehner, 1994), near Minudie (Fig. 1), suggests a gradual increase in general restriction. At Hopewell Cape, this may imply that the lateral transition from carbonate to sulphate deposition was occurring closer and closer to the source area over time.

Sedimentary and eodiagenetic environments of the Hopewell Cape Formation

Hopewell Rocks member

The very thick and coarse succession of red sheetflood conglomerates at Hopewell Cape, in the Demoiselle Creek Member of the Lime-kiln Brook Formation and in the overlying Hopewell Rocks Member of the Hopewell Cape Formation (Figs. 5 and 9), is interpreted as having been part of a fault-bounded, arid alluvial fan system. However, the lateral and vertical consistency of the sheetflood deposits, which resulted in several hundred metres of mostly undisturbed planar-bedding, is very unusual in alluvial fan settings and suggests that base-level remained high during deposition of the succession that overlies the uppermost Demoiselle Creek limestone. A high water-table would have favoured rapid ground saturation and efficient lateral dispersion of surface runoff during heavy rainfall and associated flash flood deposition. Hence, although the Hopewell Rocks Member lacks the marine limestone intervals of the underlying Demoiselle Creek Member, it includes the same planar conglomerate facies that we associate with a fan-delta setting. It is therefore interpreted that, through its entire thickness, the Hopewell Cape succession was deposited near a remnant arm of the Windsor Sea. This is consistent with well correlations, which suggest that a large portion of the Hopewell Rocks Member transitions basinward into sulphates over a short distance (Fig. 6).

Shin member

The Shin Member is characterized by cross-cutting channels of red sandstone and conglomerate, which are interpreted as sandy to gravelly braidplain deposits, and by well-developed Aridisols in the finer portions, which are interpreted as muddy alluvial plain deposits. This member is therefore interpreted to have evolved farther from the sea than the planar-bedded Hopewell Rocks Member and the time-equivalent Middleborough Formation (discussed below). At Dorchester Cape, many coarse braidplain deposits are observed to pinch-out into fine alluvial plain deposits, suggesting that the two sedimentary environments were coeval.

The Alma section (Fig. 4) also shows sandy to gravelly braidplain deposits. However, they are coarser, include a tighter network of cross-cutting channels, are less deeply affected by pedogenic overprint, and are not intercalated with muddy alluvial plain deposits, suggesting that the depositional environment was subjected to higher rates of sedimentation due to a closer proximity to its source area, which was also possibly more rapidly rejuvenated.

Dorchester Cape member

The fine sediments and well-developed calcretes of the Dorchester Cape Member, which gradationally overlies the conglomeratic Shin Member (Fig. 5), indicate that the succession was by then experiencing lower rates of deposition. The occasional calcrete hardpans indicate times of especially low sedimentation rates.

The transition from the Shin Member to the Dorchester Cape Member implies that the depositional environment was gradually evolving from braidplain-dominated to alluvial plain-dominated. Because of the presence of

pedogenic calcite cement and root traces throughout both members, this gradational transition is interpreted to be more probably related to decreasing rates of source area rejuvenation than to climate change.

Sedimentary environments of the Middleborough formation

Minudie member

The base of the Middleborough Formation (Minudie Member), from Minudie to Cape Enragé, is almost exclusively composed of laminar mudstone, with no pedogenic overprint, much like the mudstone components of the underlying Maccan Member of the Lime-kiln Brook Formation, suggesting a continued subtidal setting. The presence of limestone laminae and lime-supported siltstone and fine sandstone also supports the interpretation of a subtidal setting and suggests that, although the 'carbonate factory' remained active, it was flooded by high siliciclastic inputs. The occasional thin and wide lenses of sandstone are interpreted as sparsely distributed subtidal channels.

Pecks Cove member

Transition to the sandier remainder of the Middleborough Formation (Pecks Cove Member), which is still mainly planar-bedded, but which shows modest pedogenic overprint, is interpreted to represent a progression towards a dominantly supratidal mudflat environment that was cut by wide fluvial channels. Hence, the greater presence of sandstone beds is interpreted to be most likely related to base-level lowering and an associated increase in channelling because of gradual sea withdrawal from the area, and less likely related to greater inputs from the source area. This would best explain the observed lack of correspondence between the coarsening-upward succession of the Middleborough Formation and the coeval, fining-upward Hopewell Cape Formation at Dorchester Cape (Fig. 5). The latter was altogether deposited farther from the sea and closer to its source area. It was therefore more influenced by changes occurring in the source area and less influenced by minor changes in base-level.

In summary, although some of the thicker intervals of trough cross-bedded sandstone in the Pecks Cove Member may indicate times of lower sea-level and a temporary evolution towards a continental braidplain system, the absence of substantial downcutting or well-developed pedogenic overprint in even its most continental facies suggests that no bed of this member was deposited very far from base-level. This is especially true for the Cape Enragé section, in which evidence for an intertidal to subtidal setting still dominates in the sandy Pecks Cove Member (Fig. 8d–f), although some pedogenic mottling and mudcracking are observed in the uppermost part of the section (Fig. 8c). Finally, the near absence of bioturbation in subtidal intervals of the Pecks Cove Member at Cape Enragé, with only one trace fossil identified in thick and well-exposed successions of tidal rhythmites (Fig. 8d), suggests that subtidal conditions were not only turbid, but probably hypersaline as well, and generally unfavorable to macrofauna.

Paleogeographic model (latest Asbian)

Based on mapping, geophysical, paleocurrent, provenance and sedimentary facies distribution data, a paleogeographic model for the western sector of the Cumberland Basin and its associated fault scarps was constructed for the late Viséan interval (Fig. 12). The time-slice chosen for the model corresponds with deposition of the uppermost carbonate bed of the upper Asbian Lime-kiln Brook Formation at Minudie, with interpreted lateral equivalences that are based on tentative correlations from one section to the next (Figs. 4–6). Each studied section was placed on the model based on its inferred approximate position at the time of deposition, prior to post-Viséan fault dislocations.

Restoration of post-Viséan displacements

Substantial post-depositional displacement is only inferred for some sectors of the study area. Mapping (St. Peter & Johnson, 2009) and sedimentologic data suggest that the Alma section has been telescoped towards the Cape Enragé section to the southeast along a series of NE-striking reverse faults, bringing closer together the proximal Hopewell Cape Formation and its distal equivalent, the Middleborough Formation (Figs. 1 and 4). A more complex fault history is necessary to explain the present position of the Hopewell Cape section, which was dislocated away from the Caledonian massif along with a knob of basement rocks that was part of its source area according to paleocurrent vectors (Fig. 11). Moreover, the Imperial Dorchester 1 and Dorchester Cape sections had to be originally farther from the Hopewell Cape, Beaumont and Shell Dorchester 1 sections than they are today to account for the significant sedimentologic inconsistencies that they have with them at time-equivalent intervals if only their present position is considered (Figs. 1 and 6).

The deformation history of eastern Canada suggests that the main shortening direction rotated clockwise from NW-SE (Fig. 13a) to NNW-SSE (Fig. 13b) near the Mississippian-Pennsylvanian boundary in response to plate readjustments that were related to the final closure of the Rheic Ocean to the south (Faure *et al.*, 1996; Jutras *et al.*, 2003a,b, 2005). This is interpreted to have caused the eventual dislocation of the Hopewell Cape section and of part of its source area along the Shepody-Beckwith Fault, a WNW-ESE-trending dextral strike-slip fault (Fig. 13b) that is inferred from both mapping (St. Peter & Johnson, 2009) and geophysical data (Figs. 1 and 3). Subsequent faulting along the SW- to N-S-striking Harvey-Hopewell Fault system further isolated the knob (Figs. 1 and 13c). The latter fault system has experienced

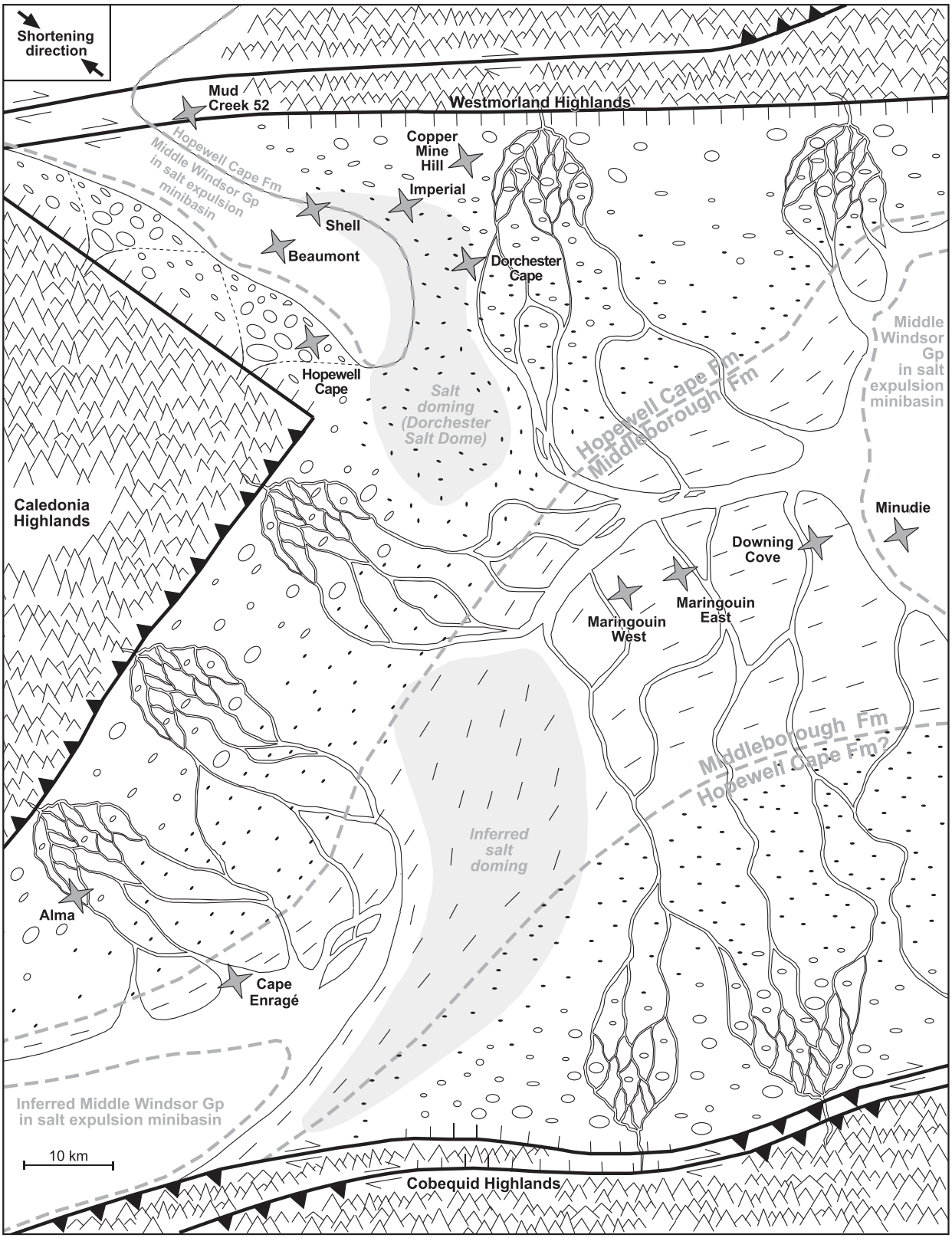

Fig. 12. Paleogeographic model for the Cumberland Basin in latest Asbian times based on mapping data (Ryan & Boehner, 1994; St. Peter & Johnson, 2009), geophysical and sedimentological data (this study), and estimates of the principal shortening direction by Faure *et al.* (1996), Jutras & Prichonnet (2005), and Wilson & White (2006).

a complex history of normal, reverse, dextral and sinistral motions, of which only some of the reverse history predates the Pennsylvanian, and of which dextral displacement largely dominates (Martel, 1987). It is therefore interpreted that the Mississippian sections that are located in and around the Harvey–Hopewell Fault system

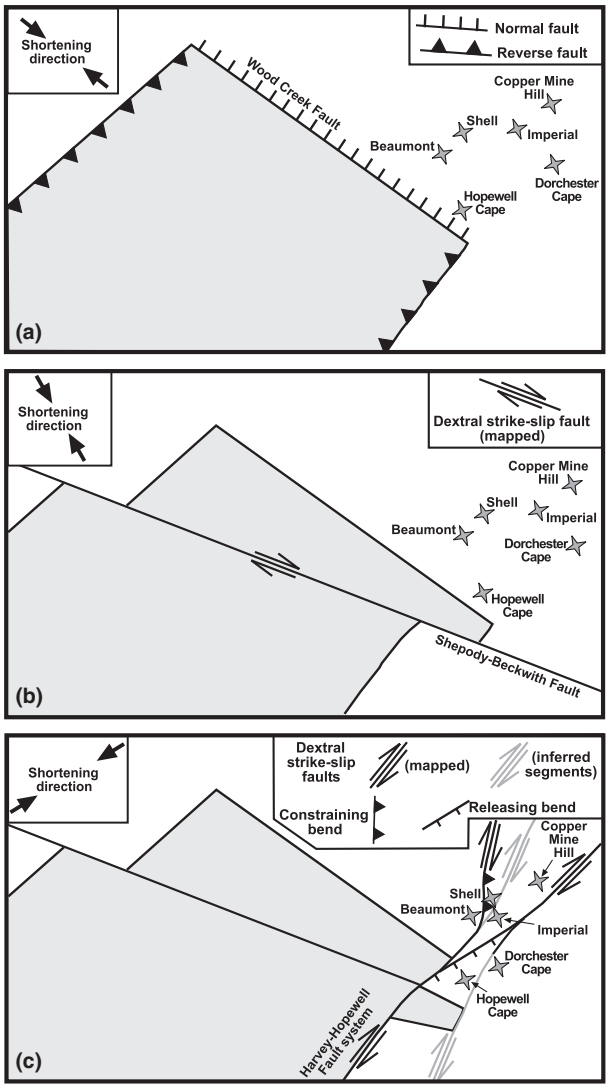

Fig. 13. (a) Hypothetical geometry of the Caledonia Highlands at the time of Viséan deposition (see Fig. 13); (b) post-Viséan displacement of the Hopewell Cape section and immediate source area along a WNW-ESE-trending dextral strike-slip fault due to the clockwise rotation of compressive paleostress vectors from NW-SE to NNW-SSE shortening near the Mississippian-Pennsylvanian boundary (Faure *et al.*, 1996; Jutras *et al.*, 2003a, b, 2005, 2007a); (c) dextral displacement of fault blocks involving the Beaumont, Shell Dorchester 1, Imperial Dorchester 1, Copper Mine Hill, Hopewell Cape and Dorchester Cape sections along segments of the Harvey-Hopewell Fault system.

were subsequently telescoped closer together through dextral displacement along different segments of that fault corridor, with minor reverse and normal motion along restraining and releasing bends (Fig. 13c), as correlations between these sections are only consistent in terms of paleogeography if they are pictured as originally farther apart (Figs. 6, 12 and 13a). This dominantly dextral displacement along the SW- to N-S-striking fault system may have occurred in response to NE-SW shortening, which is the youngest tectonic event recorded in Mississippian rocks of eastern Quebec (Jutras *et al.*, 2003a), and which may correspond to the post-Early Jurassic sinistral reactivation of the E-W trending Minas Fault Zone. Although post-Appalachian deformation events in eastern Canada are still poorly constrained, this reactivation best correlates with Early Cretaceous deformation associated with rifting of the northwest Atlantic Ocean between Newfoundland and Ireland-Iberia (Pe-Piper & Piper, 2012).

Tectonic control on deposition

During the late Asbian and the early Brigantian, the western Cumberland Basin margins were characterized by very coarse siliciclastic material that was being deposited near three source areas and that showed a basinward transition into finer continental deposits and marine deposits (Fig. 12). The proposed Mississippian fault scarps are linked to known structures that strike perpendicular to paleocurrents and that correspond well in terms of distance (when structural telescoping is taken into account) to the observed facies and sediment coarseness in the sections. have been controlled by NW-SE shortening based on the study of Mississippian rocks in the northwest sector of the Maritimes Basin (Jutras & Prichonnet, 2005; Wilson & White, 2006; Jutras *et al.*, 2007a). In this scenario, only the NW-striking fault that sourced the Hopewell Cape section would have acted as a purely extensional fault, which is compatible with the greater accommodation rates that are indicated by the stratigraphy of that section. Just as in the Ristigouche and Central basins of eastern Quebec and New Brunswick (Jutras & Prichonnet, 2005; Jutras *et al.*, 2005, 2007a,b), SW-striking faults are interpreted as syndepositional reverse faults, and E-W trending faults as syndepositional dextral strike-slips faults with a normal component. Matching kinematics are well registered in the faults that border the Caledonia (St. Peter & Johnson, 2009) and Cobequid (Gibling *et al.*, 2008) highlands, whereas E-W striking faults bordering the Westmorland Highlands are buried by Pennsylvanian strata, but are inferred to have a similar history to that of E-W striking faults in the Cobequid Highlands.

Continental to marine transitions

Available data do not allow us to determine whether the Windsor Sea ever occupied the entire Cumberland Basin during deposition of the Middle Windsor Group. However, the marine presence was increasingly limited in extent with time, as suggested by both an eastward and westward thinning of the Lime-kiln Brook Formation towards the Dorchester Cape area, with an accompanying decrease of carbonate intervals (this study and Ryan & Boehner, 1994). Hence, the Windsor Sea was subdivided into at least two arms in latest Asbian times (i.e. near the transition between the Lime-kiln Brook and Hopewell Cape formations), leaving more central areas of the basin mostly free of marine deposits (Fig. 12).

It is inferred that the Cape Enragé section was closer to the sea than more central sections in the basin, such as those of the Maringouin Peninsula. This inference is based on its finer grain-size and on the absence of evidence for supratidal conditions in most of its succession, which is dominated by tidal rhythmites and sigmoidal cross-sets from a subtidal to intertidal setting (Fig. 8d). This inference is also based on its greater proximity to coeval Middle and Upper Windsor Group marine carbonate occurrences in the adjacent Minas Basin (*sensu* Bell, 1929; and Jutras *et al.*, 2006; encompassing the Windsor-Kennetcook, Shubenacadie and Musquodoboit basins of Giles *et al.*, 1979), which is only separated from the Cumberland Basin by the narrow Cobequid Highlands. Hence, while large portions of the Cumberland Basin were continental throughout the Viséan portion of the Brigantian, the nearby Minas Basin was more widely accommodating marine transgressions during warm orbital cycles (Giles, 2009; Fig. 2). Evidence of nearshore subtidal environments in lower Brigantian beds of the Cape Enragé section therefore suggests that a connection to the Minas Basin may have existed west of the Cobequids (Fig. 12). This is supported by the observation of a relatively steep attenuation of both gravity and magnetic anomalies in that direction (Fig. 3).

Influence of salt tectonics on paleodrainage systems

The inferred three-part division of the Windsor Sea was possibly controlled by clastic infilling issued from the three above-mentioned source areas, but more importantly by its effect on salt expulsion and diapirism. The latter were already active in parts of the Cumberland Basin at the time according to the seismic study of Waldron *et al.* (2013), and must have been stimulated by differential depositional rates within the basin. Northeast-verging paleocurrents at Hopewell Cape, away from the Caledonia Highlands, and south-verging paleocurrents at Dorchester Cape, away from the Westmorland Highlands, suggest that these paleodrainage systems were not converging towards the same depocentre, possibly due to syndepositional diapirism of the Dorchester Salt Dome between the two areas, which would have divided and redirected drainage (Figs 11 and 12). An intervening salt diapir would also explain the convergent thinning and at least partial pinchout of Lime-kiln Brook carbonates in the area between Hopewell Cape and Minudie (Fig. 5). As noted earlier, syn-halokinetic Viséan deposition is also suggested by the observation that thickness of the Viséan succession above the salt grows at the expense of remnant salt thickness between the Imperial Dorchester 1 and Copper Mine Hill wells (Figs 1 and 6).

Paleocurrent vectors obtained at the Maringouin (West and East) and Downing Cove sections suggest a steady flow towards the north, quite far from their Cobequid Highlands source (Figs 11 and 12). Without involving syndepositional salt diapirsm to the west (i.e., in the present day Bay of Fundy), it would be unexpected to see drainage patterns not converging with those flowing away from the nearby Caledonia Highlands along a southeast vector (Fig. 12). The inferred presence of this second syndepositional salt diapir in the study area remains to be verified by seismic exploration, as this area of the Bay was never surveyed. Based on the work of Waldron *et al.* (2013), the northward funnelling of these rivers could have also been stimulated by a syndepositional diapir to the east, which transitions westward into a large salt weld below the Downing Cove and Minudie sections. Similar instances of river systems funnelled between syndepositional salt diapirs have been reported by Matthews *et al.* (2007), Mosher *et al.* (2009) and Trudgill (2011).

These north-flowing rivers, sourced from the Cobequid Highlands, must have been converging with south-flowing rivers from the Westmorland Highlands before draining into the Windsor sea arm present at Minudie and east from there (Fig. 12). The resulting convergence would have created a trunk river system transitioning into a large tidal channel and flowing directly into the Windsor sea arm (inferred environment of the large and laterally persistent east-dipping cross-sets of biosparudite near the top of the Lime-kiln Brook Formation at Minudie; Figs 7 and 12). As these opposing sets of fluvial paleocurrents also converge towards the Maringouin-Minudie Anticline (east-west striking exposure of Lower Windsor evaporites just north of Minudie on Fig. 1, and also observable on Fig. 3), it is unlikely that this and other similar east-west striking salt walls that partly controlled Pennsylvanian sedimentation (Waldron *et al.*, 2013) were already active in the Cumberland Basin in late Viséan times. However, our data suggest that a less linear system of salt expulsion and diapirism was influencing late Viséan deposition in the basin, interplaying with an active fault system to produce a complex and rapidly evolving paleogeography.

Interplay of salt tectonics and glacioeustatic variations in the Cumberland Basin

In the nearby Minas Basin of central Nova Scotia, where Lower Windsor Group strata were relatively undisturbed by salt tectonics, the Middle to Upper Windsor Group is characterized by orbitally forced transgression-regression cycles, each well-defined by thick carbonate intervals that show evidence for gradual deepening followed by gradual shallowing towards a continental red bed facies (Giles, 1981, 2009). Such clear cyclicity is not recognized in Middle Windsor Group and Percé Group rocks in our study area, where gradual regression is inferred between the late Asbian and the Serpukhovian (i.e., over millions of years) without much evidence for significant, shorter scale sea-level variations. For instance, although the Enragé, Hopewell Cape, Minudie-Downing Cove and Maringouin sections are for the most part devoid of marine carbonates, they appear to have never evolved very far from base-level at any given time during the late Asbian and the early Brigantian. In the case of Cape Enragé, most of the section is interpreted to have been deposited below base-level

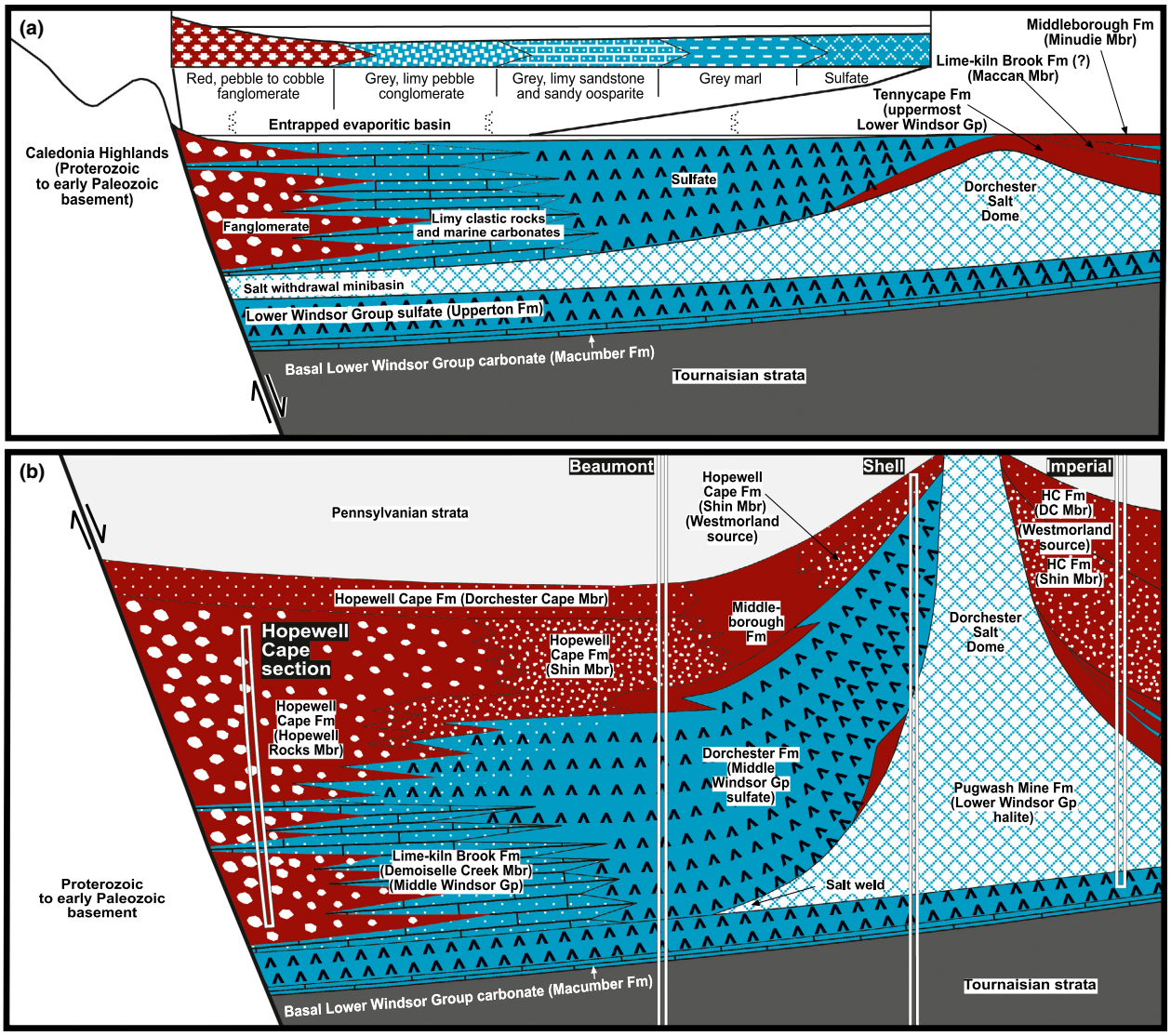

Fig. 14. Stratigraphic evolution around the Dorchester Salt Dome: (a) sedimentation in the minibasin at Hopewell Cape late Asbian times, with an evaporitic basin entrapped between the rising diapir and a normal fault (Wood Creek Fault) along the Caledonia Highlands. The basin was characterized by coarse fanglomerates and siliciclastic-rich marine carbonates near fluvial inputs from the source area, and by sulphates away from these fluvial inputs. Based on the lithologies observed at Hopewell Cape, it is interpreted that red cobble to pebble conglomerate transitions laterally into grey, limy pebble conglomerate and sandstone, sandy oosparite, marl, and eventually sulphate, with increasing distance from the source area. (b) Position of the sections of Fig. 6 in early Pennsylvanian times, prior to their dislocation by subsequent faulting. HC, Hopewell Cape; DC, Dorchester Cape.

during these intervals. At Minudie, although each carbonate interval of the Lime-kiln Brook Formation may be the result of minor marine influxes, the red bed intervals of that unit do not show any evidence of shallowing towards a continental facies, and upward transitions between carbonate and red mudrock may mostly be explained by supratidal to intertidal channel avulsion.

Transition over a short distance between interbedded fanglomerates and marine carbonates at Hopewell Cape to nearly continuous sulphate in the Shell Dorchester 1 and Beaumont boreholes may be the result of salt expulsion in response to clastic loading. This would have forced an entrapped evaporitic basin to abut the fault-bounded source area and its proximal fanglomerates to the southwest, while the rising Dorchester Salt Dome would have constrained the evaporitic basin to the northeast, with the lowest part of the sea floor basin forming a moat between the diapir and the highlands (Figs 12 and 14a). The exceptionally fast accommodation rates that are to be expected in this context may have prevented regression from the salt expulsion minibasin to fully occur during glacioeustatic lowstands (Fig. 14a). This would have resulted in the long-term entrapment of the evaporitic basin, although vertical transitions from conglomerate to limestone near the source area may have still been the result of minor base-level variations in response to ongoing global glacioeustatic fluctuations.

A similar scenario is projected for the two other sea arms (Fig. 12), although lower fault movement rates in

those areas would have provided lower clastic sedimentation rates, lower salt expulsion rates, and therefore lower overall accommodation rates. Still, due to their entrapment in salt expulsion minibasins, standing water bodies may have remained in those areas as well during glacioeustatic lowstands, keeping base-level high and preventing well-defined sedimentary cyclicity from occurring during the entire late Asbian and early Brigantian intervals.

The inferred minibasin at Minudie is characterized by a substantial lateral continuity of some of its carbonate intervals (Ryan & Boehner, 1994), many of which are fossiliferous at the base and stromatolitic at the top, suggesting that they are the result of minor marine influxes. Moreover, both that minibasin and the one inferred at Cape Enragé are dominated by tidal flat deposits, which suggest that, although restricted, these minibasins remained at least intermittently connected to the open ocean. Greater restriction is inferred for the minibasin at Hopewell Cape, where sulphate deposition seemingly remained uninterrupted for the entire late Asbian to early Brigantian interval.

SUMMARY AND CONCLUSIONS

The transtensional Cumberland Basin is located within the Minas Fault Zone, which was the most tectonically active area of eastern Canada in mid- to late Mississippian times. Due to this, it has accommodated thicker Lower Windsor Group salt and was subsequently affected by more significant clastic loading than adjacent basins that are located outside of this zone. As a result, whereas late Viséan deposition in adjacent basins was characterized by a monotonous sedimentary cyclicity controlled by glacioeustatic variations (Giles, 2009), the Cumberland Basin was strongly influenced by salt tectonics during that interval, which resulted in a much more complex stratigraphy.

Our study indicates that salt diapirs were diverting drainage and subdividing the marine basin, leaving large areas mostly free of marine deposits, whereas salt expulsion was preventing marine waters from fully leaving minibasins during global sea-level lowstands, thus obscuring glacioeustatic cyclicity. The entrapped water became increasingly hypersaline due to insufficient marine influxes in the context of the warm and arid climate that prevailed at the time.

In the case of the minibasin at Hopewell Cape, where salt expulsion was paired with rapid subsidence along a normal fault, the entrapped marine basin was forced to abut the coarse fanglomerates of a rapidly evolving source area (Fig. 14a). Inputs of freshwater from the latter created a lateral gradient of salinity, which resulted in a lateral transition from the coarse clastics and marine carbonates of a fan-delta to the sulphates of a restricted marine basin in just a few kilometres (Fig. 14a).

The lack of lateral continuity of marine carbonates in the minibasin at Hopewell Cape, each transitioning laterally into sulphates in nearby wells (Figs. 6 and 14b), suggests that this area of rapid salt expulsion and diapirsm may have been cut off from significant marine influxes, whereas the vertical continuity of sulphates away from the source area suggests that the entrapped sea never fully regressed out of the minibasin during glacioeustatic lowstands. Such thorough entrapment of the marine body in the salt expulsion minibasin greatly reduced the influence of ongoing glacioeustatic variations. This is in contrast with minibasins from open marine shelf settings, which always remain connected to the open ocean during glacioeustatic highstands, and from which the sea might fully regress during glacioeustatic lowstands (e.g. Mohriak *et al.*, 1995; Aschoff & Giles, 2005; Perov & Bhattacharya, 2011). Although it is an obvious possibility, such thorough entrapment of an epicontinental marine body by the combined effects of faulting, clastic loading and halokinesis had never been reported before.

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