Gradual encroachment of a rocky shoreline by an invasive sea during the Mississippian at the southeastern margin of the Maritimes Basin, Nova Scotia, Canada

Pierre Jutras, Robert J. Ryan, and Roger Fitzgerald

Abstract: Onlap of a rocky shoreline by marine beds of the Mississippian Windsor Group occurred at the southeastern margin of the composite upper Paleozoic Maritimes Basin in central Nova Scotia. The sedimentology of thin basal rudaceous deposits suggests that, although the transgression was rapid, there were times of prolonged shoreline stability. Boulder beach deposits indicate a high-energy coastline and a large marine basin. Clastic delta deposits were proximal to thick biohermal banks in shallow areas near the southeast margin of the sea while sulphate deposition was occurring basinward. According to their contained biota and stratigraphic relationships, the marginal banks evolved in a less saline environment than banks forming away from river inputs, on paleotopographic highs located farther offshore. Because diversity of the biota decreases with an increase in both water depth and distance from the paleoshore and because bank development in shallow or marginal areas was apparently synchronous with evaporitic deposition in deeper or less marginal areas, we conclude that both a vertical and a lateral gradient of salinity existed due to the thrusting of fluvial fresh water above salt water and its infiltration along the paleoshoreline. As salinity increased with time, bank building eventually aborted and sulphate deposition gave way to salt deposition in the deepest parts of the basin. Lastly, the onlap of evaporites above marginal clastic deposits indicates that evaporite deposition occurred in a transgressive context, although a gradual thinning of the water column may have simultaneously occurred due to basin infilling.

Résumé : Le recouvrement d'un socle rocheux par les lits marins du Groupe de Windsor (Mississippien) est observable dans la partie sud-est du bassin composite des Maritimes (Paléozoïque supérieur) au centre de la Nouvelle-Écosse. La sédimentologie des minces lits basaux de rudites suggère que la ligne côtière ait connu des temps prolongés de stabilité, malgré une transgression rapide. Des dépôts de plage très grossiers démontrent que l'énergie côtière pouvait être élevée, suggérant un bassin marin de grande étendue. Des dépôts deltaïques clastiques avoisinaient d'épais bancs biohermaux dans des régions de faible profondeur près de la marge sud-est de la mer, alors que l'intérieur du bassin recevait des dépôts de sulfates. D'après les organismes et les relations stratigraphiques qu'ils contiennent, les bancs marginaux ont évolué dans un environnement moins salin que les bancs s'étant développés plus loin des embouchures fluviales, sur des verrous paléotopographiques situés plus au large. En raison de la diversité décroissante des organismes avec la profondeur et la distance de la paléocôte, et en raison du développement apparemment synchrone de bancs carbonatés dans les régions marginales ou de faible profondeur et de la sédimentation de dépôts évaporitiques dans les régions plus profondes ou moins marginales, il est conclu qu'il existait un gradient de salinité à la fois vertical et latéral causé par le chevauchement d'eaux douces fluviales par-dessus les eaux salées et leur l'infiltration le long de la paléocôte. Puisque que la salinité croissait aussi avec le temps, la construction du banc finit par échouer, et la sédimentation de sulfates fût alors remplacée par la sédimentation de sels dans les régions les plus profondes du bassin. Finalement, le recouvrement des lits clastiques marginaux par les évaporites indique que la sédimentation évaporitique prit place dans un contexte transgressif, malgré qu'un amincissement graduel de la colonne d'eau ait possiblement eu lieu en même temps en raison du remplissage sédimentaire du bassin.

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Introduction

The onlap of a rocky shoreline by basal marine beds of the Viséan (Upper Mississippian) Windsor Group is well exposed in the Musquodoboit Valley of Nova Scotia (Fig. 1). Inherent to the sedimentology of these beds is a detailed record of paleoenvironments of deposition during this transgressive event. Moreover, because of its economic importance as a source of carbonate, gypsum, salt, barite, and base metals, the Windsor Group succession in the area has been drilled extensively, allowing a detailed reconstruction of the nearshore paleoenvironments to be made from the study of cores. Hence, sections in the Musquodoboit Valley provide an excellent record of the evolution of paleocoastal processes during the onset of marine sedimentation.

Although this is the first formal work specifically on the paleogeography of the basal Windsor Group in central Nova Scotia, many paleogeographic conclusions were formulated in the prolific work that was done on the complete Windsor Group succession over the past 30 years and that was recently compiled by Giles and Boehner (2006). In the present paper, the sedimentology of two significant exposures is combined with the study of 14 core logs and the paleontology of 23 basal Windsor biohermal banks to add detail to the previously proposed paleogeographic reconstructions and paleoenvironments of deposition. The main objectives of this study are (*i*) to understand the dynamics of the transgression, (*ii*) to differentiate Viséan paleotopographic elements from subsequently formed basement highs, (*iii*) to understand lateral variations in basal beds of the Windsor Group, and (*iv*) to compare the paleoenvironments and paleogeography of the Lower Windsor Group in central Nova Scotia with those of other studied areas in eastern Canada (McCutcheon 1988; Dix and James 1989; von Bitter et al. 1990, 1992; Schenk et al. 1994, 2001).

Geological setting

Regional geology

Late Precambrian to Early Devonian rocks of Nova Scotia were deformed by the Middle Devonian Acadian orogeny and form the basement of the composite, upper Paleozoic Maritimes Basin (Calder 1998) (Fig. 1). The latter developed as a series of continental graben fills (Belt 1968) with the onset of post-Acadian pull-apart tectonics during the Late Devonian in eastern Canada, at a time when compressional deformation was migrating towards New England (Jutras et al. 2003).

The marine Windsor Group (middle to late Viséan) overlaps but is for the most part concordant with underlying Late Devonian to Tournaisian beds of the Fountain Lake and Horton groups (Fig. 2), which were deposited in more restricted, fault-bound continental basins (Calder 1998; Giles and Boehner 2006). The Windsor Group was subdivided into two major faunal zones (Lower and Upper) and five subzones (A and B in the Lower, and C, D, and E in the Upper) by Bell (1929) (Fig. 2). Giles (1981) constrained the Lower Windsor Group to the A subzone and refers to the B subzone as the Middle Windsor Group. Because of their lack of biological diversity, Lower Windsor Group carbonates (sensu Giles 1981) are thought to have been deposited in more saline environments than were those of the Middle and Upper Windsor Group (Bell 1929; Ryan 1978; Giles 1981).

The basal Windsor Group carbonates of Nova Scotia are subdivided into two laterally equivalent formational units: the Macumber Formation (Weeks 1948) is a thin carbonate laminite unit (usually less than 5 m thick) deposited in central parts of the marine basin (Fig. 3); and the Gays River Formation (Giles et al. 1979), which includes a bank facies, an interbank facies, and a basal rudaceous facies, is a shallower water unit that can reach a thickness of 50 m (Fig. 3).

The Meaghers Grant Formation is a dominantly siliciclastic unit with carbonate and sulphate interbeds (Boehner 1977). Although mainly composed of grey beds, a distinctive red bed unit is found at the top of the Meaghers Grant Formation and was formally referred to as the Lindsay Brook Marker by Boehner (1977). Based on the combined presence of carbonate laminations, sulphate, red siliciclastics, and pedogenic overprints in that red interval in many of the wells, Harnish (1978) concluded that the Lindsay Brook Marker was deposited in a coastal sabkha evolving towards a coastal desert environment, whereas grey beds below would reflect alluvial to deltaic environments. Although Giles and Boehner (1979, 2006) consider the Meaghers Grant Formation to be stratigraphically above the Gays River Formation, we demonstrate in this paper that the latter unit is laterally equivalent to the lower part of the former (Fig. 3).

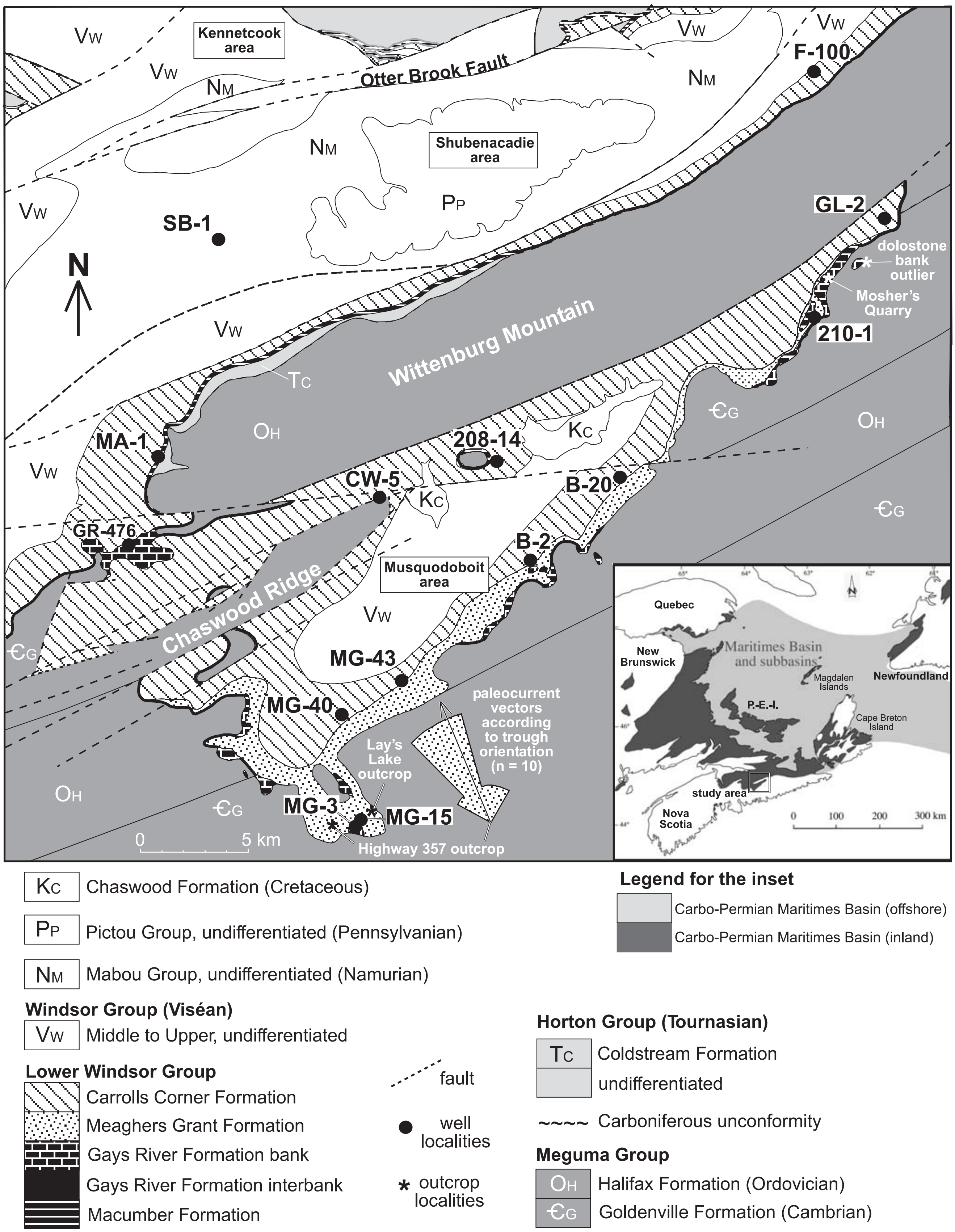
Giles and Boehner (1979, 2006) mention that the upper beds of the Meaghers Grant Formation interdigitate with sulphates of the Carrolls Corner Formation, which also overlie the former unit (Fig. 3). As shown in this study, up to 97% of the Meaghers Grant succession may interdigitate with sulphates, suggesting that sulphate deposition started soon after the onset of clastic deposition. According to Giles and Boehner (2006), the Carrolls Corner Formation is the result of a long period of regression that preceded the deposition of Middle Windsor Group carbonates, a conclusion that is also challenged in this paper.

The Carrolls Corner Formation is in part overlain by and in part laterally transitional to the Stewiacke Formation halite (Giles and Boehner 1979; Boehner 1984) (Fig. 3). These Lower Windsor Group evaporites have a minimum thickness of approximately 400 m and are overlain by successions of carbonates, clastic rocks, and evaporites of the Middle and Upper Windsor Group (Giles and Boehner 2006). The rest of the Carboniferous succession, above the Windsor Group, is dominantly clastic and almost entirely continental (Giles and Boehner 2006) (Fig. 2).

Study area

The study area (Fig. 1) includes the southeasternmost exposures of the Windsor Group at the margin of the Maritimes Basin. It covers the narrow Musquodoboit Basin and the southernmost part of the Shubenacadie Basin of Giles and Boehner (1979), which overlie Cambrian metagreywackes (Goldenville Formation) and Ordovician slates (Halifax Formation) of the Meguma Group (Fig. 1). It should be emphasized that the Musquodoboit and Shubenacadie successions are structural basins and do not necessarily represent separate sedimentary basins (Giles and Boehner 2006). They are herein referred to as areas (Fig. 1) rather than basins, as data

Fig. 1. Geology of the Musquodoboit and Shubenacadie areas (modified from Giles and Boehner 1982), with a rose diagram of paleocurrent vectors determined from trough orientations in the Viséan Meaghers Grant Formation, and localities of wells and sites referred to in the text. The inset situates the study area within the composite upper Paleozoic Maritimes Basin (modified from Gibling et al. 1992).



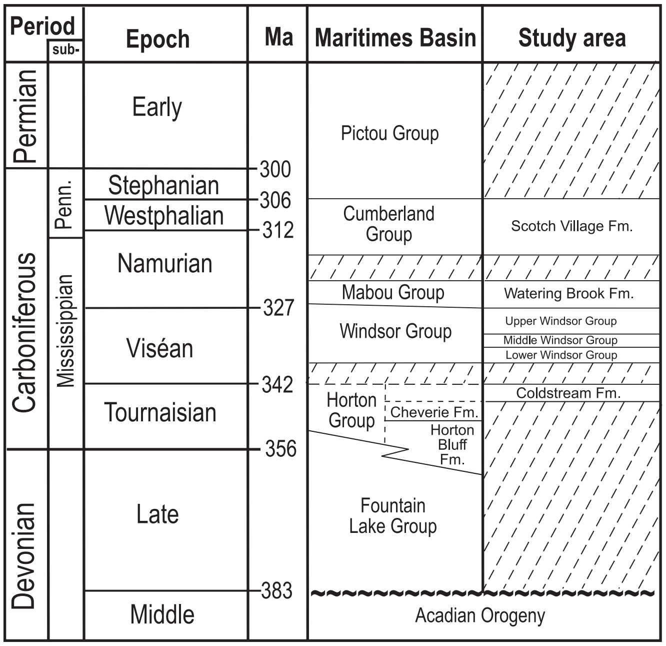


Fig. 2. Stratigraphy of the Maritimes Basin and the specific study area (Musquodoboit and Shubenacadie areas) according to Ryan et al. (1991), Calder (1998), Utting and Giles (2004), and Giles and Boehner (2006). Cross-hatching represents hiatuses.

presented in this paper suggest that they were not separate depocentres.

The Horton Group is very sparsely represented in the Musquodoboit area and present only as a thin and discontinuous veneer of up to 67 m in the Shubenacadie area. It is known to be over 900 m thick, however, north of the Otter Brook Fault, which separates the Shubenacadie area from the Windsor–Kennetcook area (Giles and Boehner 2006).

North of the Otter Brook Fault, the Tournaisian Horton Group succession is more complete, with coarse basal clastics of the lower Horton Bluff Formation overlain by lacustrine mudrocks of the upper part of this unit, which are in turn overlain unconformably by red beds of the Cheverie Formation (Martel et al. 1993; Martel and Gibling 1996). South of the fault, the Horton Group is restricted to the continental clastic rocks of the Coldstream Formation (Giles and Boehner 1979), which bears a slightly younger spore assemblage than the upper part of the Cheverie Formation in its type section (Utting et al. 1989) and is characterized by higher conglomerate to sandstone and grey bed to red bed ratios (Fig. 2).

In the study area, the uppermost Tournaisian Coldstream Formation is concordantly overlain by the middle Viséan Macumber Formation laminite in the Shubenacadie area and by the middle Viséan Meaghers Grant Formation in the Musquodoboit area, whereas the contemporaneous Gays River Formation bank, interbank, and rudaceous facies usually sit on pre-Carboniferous basement rocks in the Musquodoboit area and in the southeastern part of the Shubenacadie area (Giles and Boehner 2006) (Fig. 3). The Carrolls Corner Formation is present in both areas, whereas the Meaghers Grant Formation is restricted to the Musquodoboit area, and the Stewiacke Formation to the Shubenacadie area. Lastly, the five faunal subzones of the Windsor Group are at least partially represented in the relatively complete succession of this group that is found at the centre of both the Shubenacadie and Musquodoboit areas, below Namurian, Pennsylvanian, and (or) Cretaceous strata (Giles and Boehner 2006) (Fig. 1).

Outcrop analysis

Goldenville Formation – Gays River Formation contact at Mosher's Quarry

A recently cut section in the Mosher's Quarry of the Upper Musquodoboit area (Fig. 1) exposes rocks of the Gays River Formation onlapping basement rocks of the Goldenville Formation along south-facing (Fig. 4), north-facing (Fig. 5), and west-facing walls. The north- and south-facing walls are only separated by ~15 m. Boulder conglomerate and boulder breccia patches, up to 3 m thick, in places separate a thick Gays River Formation carbonate bank from a steeply dipping and highly irregular basement surface (Fig. 4).

Irregularities of the basement surface are tightly controlled by joint geometry. Sharp wedges of basement rocks are shaped by the 90° intersections of joints that are parallel or perpendicular to bedding (Fig. 4).

The boulder conglomerate is composed of well-rounded gravels of local Goldenville Formation lithologies (metagreywacke and phyllite) within a matrix of well-rounded siliciclastic material (Fig. 6). The sediment is poorly sorted and is a mixture of all clast sizes ranging from sand to large boulders. The boulder breccia is composed of the same clast lithologies, but the clasts are angular and float in a carbonate matrix.

The carbonate is an iron-rich, dolomitic, microsparitic algal boundstone with *Koninckopora* as the dominant faunal element. Fragments of brachiopods, ostracods, gastropods, bryozoa, and pelecypods are also found, along with 5%–10% quartz silt and subrounded sand. Small lenses of granular breccia with fragments of metagreywake and dolostone are found within the bank buildup near its base on the north-facing wall, above the coarse carbonate-supported breccia.

The lowermost exposure of basal beds is on the north-facing quarry wall, where boulder conglomerate is sharply overlain by carbonate-supported boulder breccia (Fig. 5). Massive carbonate overlies the breccia and sits directly on the basement upslope from it (Fig. 5). The carbonate also directly overlies the conglomerate in part, as it wraps the entire clastic package at a steep angle (Fig. 5).

At the same stratigraphic level where carbonate-supported breccia is present on the north-facing wall, carbonate overlies a fresh, flatter, but highly irregular bedrock surface with sharp wedges on the south-facing wall (Figs. 4, 7). A similar breccia is present a few metres upslope from there (Fig. 4) and probably correlates with that of the north-facing wall, although not reaching as far down due to a local break in the paleoslope. A large wedge of basement rock separates the carbonate-supported breccia from more conglomerate, upslope on the south-facing wall (Fig. 4), whereas a steep 50° contact between carbonate and basement rocks is found at the same level on the north-facing wall (Fig. 5, upper left corner). Similar to the lower patch described earlier, this upper conglomerate patch is also characterized by a well-rounded and poorly sorted siliciclastic matrix, but it includes smaller boulders, apart from a large cubic boulder of basement rock near the top of the patch, which seems to have slid along the bed-

Fig. 3. Stratigraphy of the pre-Middle Windsor Group units in the Musquodoboit and Shubenacadie areas (modified from Giles and Boehner 2006).

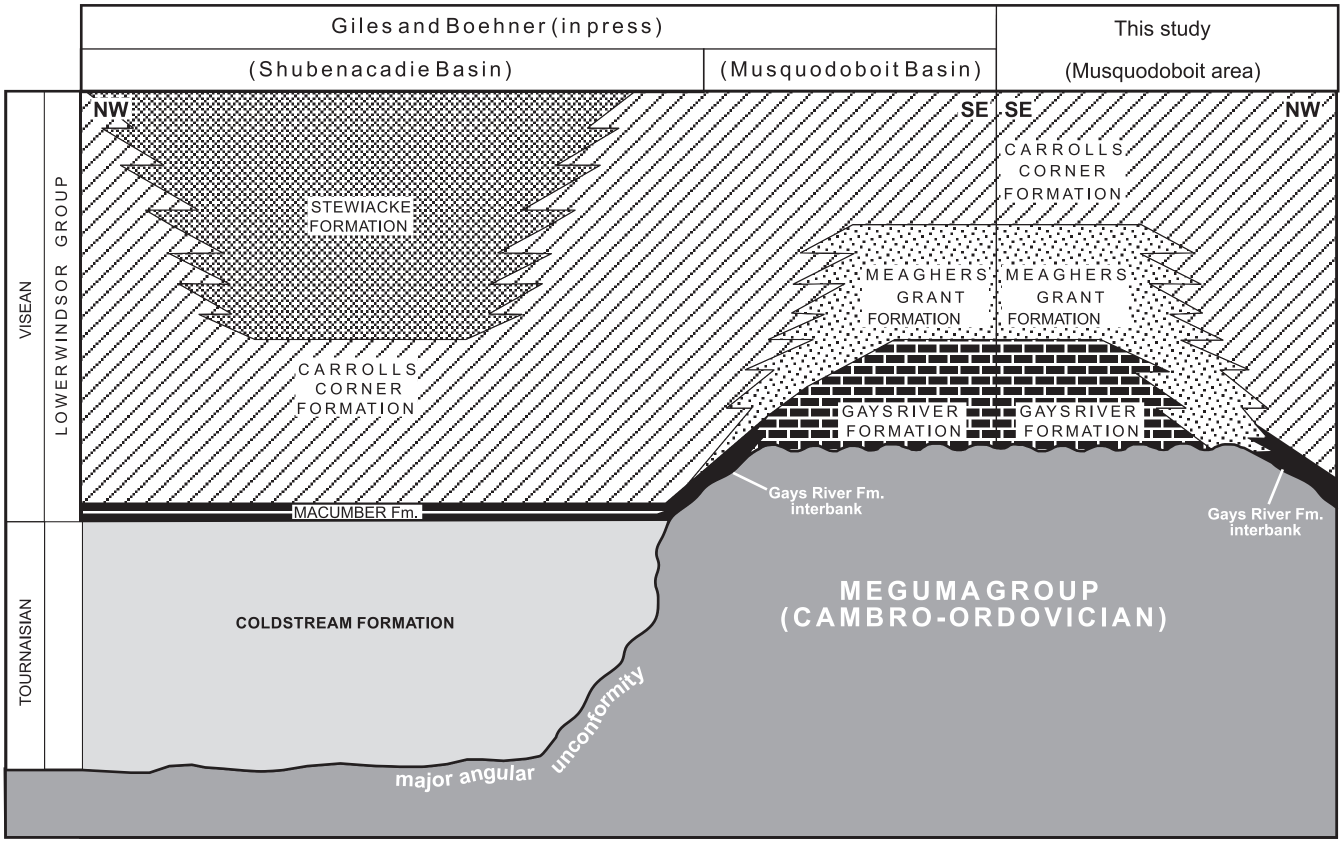
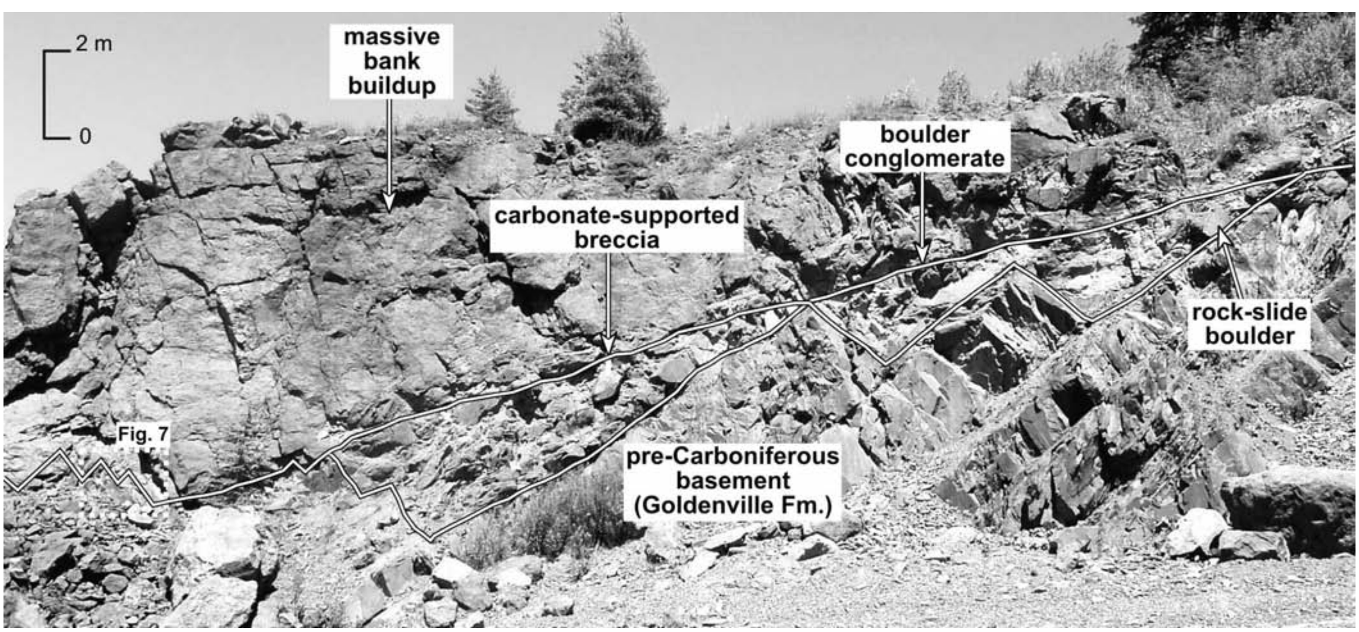


Fig. 4. South-facing wall of the studied cut section at Mosher's Quarry, showing patches of rudaceous rocks separating a massive carbonate bank buildup from basement rocks of the Cambrian Goldenville Formation.



ding plane that locally corresponds to the paleoslope (Fig. 4). The conglomerate–breccia deposit is entirely covered by boundstone (Fig. 4), which reaches a thickness of nearly 50 m in more complete sections of the quarry.

Highway 357 outcrop

The best exposure of the Meaghers Grant Formation is along the east side of Highway 357 (Fig. 1), where 16 m is observed at an unknown distance from basement. The lower

Fig. 5. North-facing wall of the studied cut section at Mosher's Quarry, showing a carbonate bank buildup (D) wrapping a talus of boulder conglomerate (B) and the carbonate-supported boulder breccia (C) that only locally separates it from basement rocks (A).

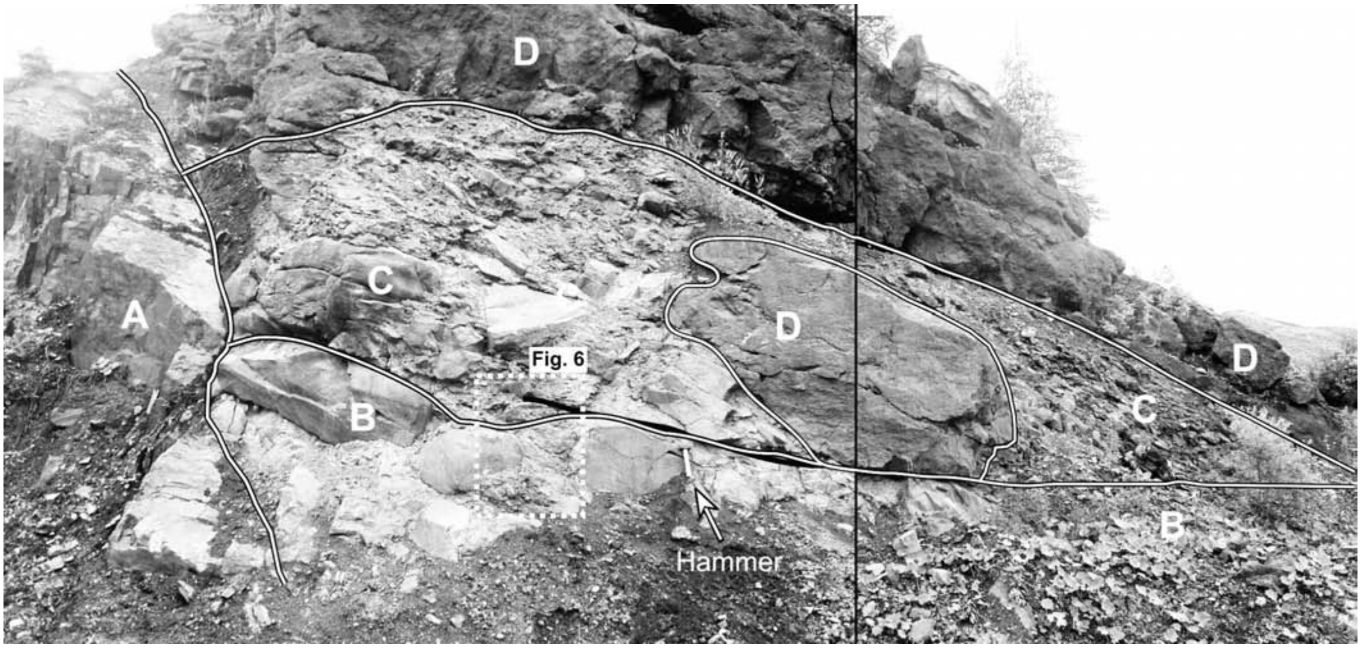
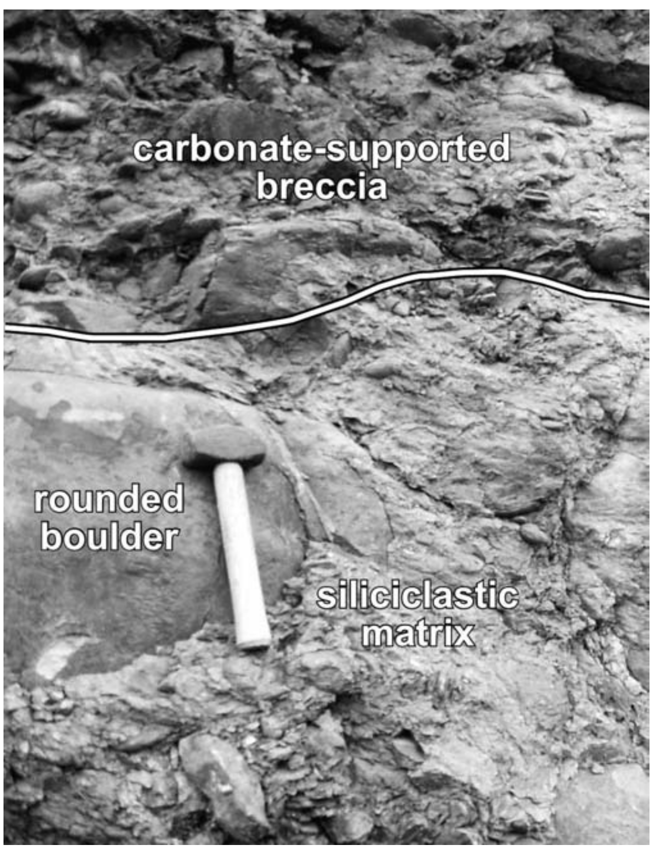


Fig. 6. Detailed view of the contact between boulder conglomerate and carbonate-supported breccia on the north-facing wall of the studied cut section at Mosher's Quarry (see Fig. 5).



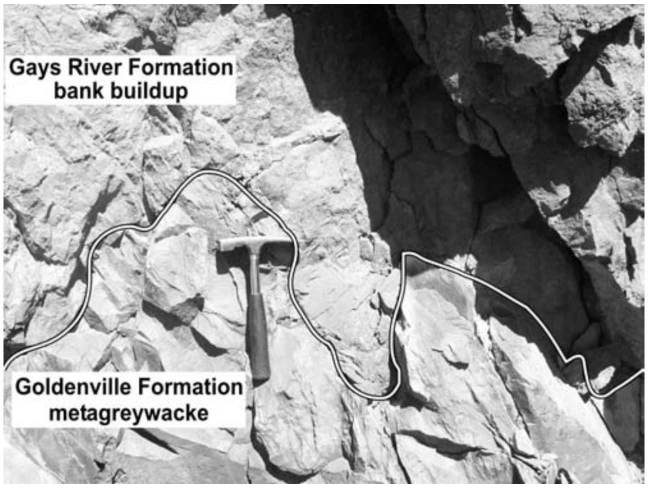
11 m is dominated by alternations of planar beds of grey mudstone and trough cross-stratified, buff calcareous wacke, with small and dispersed fragments of carbonized plant remains. These beds are truncated at a 10–20° angle by two trough fills of oolitic and ostracodal grey calcarenite, one of which is probably over 10 m wide (incompletely exposed) and at least 5 m thick. According to 10 measurements of orientated troughs, paleocurrents flowed in a north-northwest direction (Fig. 1).

Core analysis

The oldest Carboniferous beds in cores from the Musquodoboit and Shubenacadie areas are the uppermost Tournaisian grey and red siliciclastics of the Coldstream Formation, which are only found at the base of three of the 14 studied wells (Figs. 8 and 9, sections MG-43, MA-1, and SB-1). In the case of well MG-43, Boehner (1977) and Harnish (1978) were originally considering the entire clastic succession in this well as belonging to the Meaghers Grant Formation, making it the type section for this unit. Utting et al. (1989) retrieved late Tournaisian spores up to 80 m above the basement, however, suggesting that there is at least 80 m of Coldstream Formation beds in this well.

Although there are no significant lithostratigraphic differences that can be pointed out in the grey clastic succession that underlies the Lindsay Brook Marker in well MG-43, the thickness of Meaghers Grant clastics in nearby wells MG-40 and B-2 (in which the presence of sulphate and marine carbonate precludes an association with the Horton Group) strongly suggests that a large portion of the clastic interval in well MG-43 might be Viséan. Within the constraints provided by the few successful spore samples in this core, we tentatively place the Coldstream Formation – Meaghers Grant Formation boundary 81 m above basement, where an erosional contact with rip-up mudclasts separates a lower succession

Fig. 7. Detailed view of the direct contact between an irregular basement surface and the Gays River Formation carbonate bank buildup on the south-facing wall of the studied cut section at Mosher's Quarry (see Fig. 4).



with coarser sands and more abundant plant debris than the overlying beds. The Coldstream Formation in wells MA-1 and SB-1 (Fig. 9) includes some coarser and redder material, but also grey sandstones and mudrock with coaly remains, similar to those of well MG-43 (Fig. 8).

The presence of Tournaisian siliciclastics similar to those of the middle Viséan Meaghers Grant Formation in the Musquodoboit area calls for caution when assigning to a specific formation any undated clastic succession that is not underlain by carbonate or sulphate in that area, such as at the base of wells MG-40 and B-20 (Fig. 8). The fine nature of siliciclastic beds at the base of these two wells, however, and the presence of sulphate or carbonate less than 20 m from the base suggest that they most probably belong entirely to the Meaghers Grant Formation (Fig. 8).

Whereas the Meaghers Grant Formation can be entirely clastic at some localities (e.g., in wells MG-43 and B-2; Fig. 8), it can also include sulphates (well MG-40; Fig. 8), carbonates (Highway 357 outcrop and well MG-15; Fig. 8), or both (well B-20; Fig. 8). In the case of wells MG-15 and B-20, the carbonate intervals are characterized by a boundstone identical to that of the Gays River Formation buildups in the area, which can also include some clastic layers (e.g., well MG-3; Fig. 8). Hence, where carbonate buildups of substantial thickness alternate with siliciclastic layers, assignment to the Gays River Formation is given when the buildups encompass at least 50% of the basal succession (e.g., in well MG-3) and to the Meaghers Grant Formation when siliciclastics dominate the succession (e.g., in wells MG-15 and B-20). The same logic is applied to sulphates, which are assigned to the Carrolls Corner Formation only when they dominate the succession, such as above the Lindsay Brook Marker in wells MG-40 and MG-43; above non-oxidized siliciclastics in wells B-20 and 208-14; above the Gays River Formation boundstones in wells 210-1(?), GL-2, CW-5, and F-100; and above the Macumber Formation laminites in wells MA-1 and SB-1 (Figs. 8, 9).

Most lateral variations in the Lower Windsor Group of the study area occur below the Carrolls Corner Formation, where boundstone, siliciclastics, and sulphates alternate at nearly all levels of the basal succession. The very base of the Windsor Group succession can start with either siliciclastics (e.g., in wells MG-40, MG-43, and B-20; Fig. 8) or carbonate buildups (e.g., in wells MG-3, MG-15, B-2, and 210-1; Fig. 8) at the southeast margin of the Musquodoboit area. Away from this margin, bank buildups are only found on isolated topographic highs, such as at the Gays River Bank and Glenmore Knob localities (e.g., in wells GR-476 and 208-14; Fig. 9). Bank buildups are not found on all present-day basement highs, however. For example, along the Chaswood Ridge and Wittenburg Mountain areas, interbank boundstone lies directly on basement rocks (e.g., in wells CW-5 and F-100; Fig. 9) or peloidal laminites (i.e., the Macumber Formation) on Horton Group sediments (e.g., in well MA-1; Fig. 9). The latter stratigraphic relationship is also found at the base of well SB-1, farther into the Shubenacadie area (Fig. 9).

Sulphates are not known to occur at the very base of the Windsor Group succession at any locality, but they are present less than 5 m from the base in wells MG-40, GL-2, SB-1, CW-5, and F-100 (Figs. 8, 9). The Lindsay Brook Marker is found at the top of the Meaghers Grant Formation in wells MG-40, MG-43, and B-2 but is absent from the top of this unit in wells B-20 and 208-14. This red bed unit is sharply overlain by over 50 m of sulphate in wells MG-40 and MG-43 (Fig. 8).

Lastly, 277 m of mainly halite (Stewiacke Formation) is found in well SB-1 (Fig. 9) between 122 m of underlying sulphates and 440 m of post-Lower Windsor Group strata (i.e., the Viséan Middle and Upper Windsor Group and rocks of the Namurian Mabou Group). The Stewiacke Formation is not found below Middle and Upper Windsor Group rocks in any wells of the Musquodoboit area (Giles and Boehner 2006).

Gays River Formation bank fauna and flora

Twenty-eight Gays River Formation banks were identified by Giles et al. (1979) in the Musquodoboit and Shubenacadie areas (Fig. 10). The fauna and flora of 20 of these were studied, along with those of two banks from southern Nova Scotia (the East River and Springvale banks) and two banks from northern Nova Scotia (the Williams Point and Calpo Quarry banks) (Fig. 11).

The Gays River Formation bears a low-diversity, high-abundance fauna and flora (Fig. 11). There is an absence of major groups of organisms that are both common and widespread at higher stratigraphic levels of the Windsor Group. For example, the Phylum Echinodermata is absent in the Gays River Formation. In contrast, crinoid debris is ubiquitous and often prolific in the rest of the Windsor Group carbonates. Moreover, brachiopods are poorly represented in the Gays River Formation, also in contrast with the Middle and Upper Windsor Group (Fig. 12). Smooth-shelled brachiopods are relatively abundant in the Gays River Formation, but only two specimens of plicate or costate brachiopods have been reported from this unit (Giles et al. 1979), although they are abundant throughout the subsequent Windsor Group carbonates (Bell 1929; Moore and Ryan 1976).

Taxa that appear to be limited to the Gays River Forma-

Fig. 8. Lateral correlations between wells MG-3, MG-15, MG-40, MG-43 (Getty Mines, Ltd.), B-2, B-20 (Imperial Oil Ltd.), 210-1 (Noranda Exploration Company, Ltd.), and GL-2 (Imperial Oil Ltd.) in the Musquodoboit area. 1, upper Tournaisian spore dates (Utting et al. 1989).

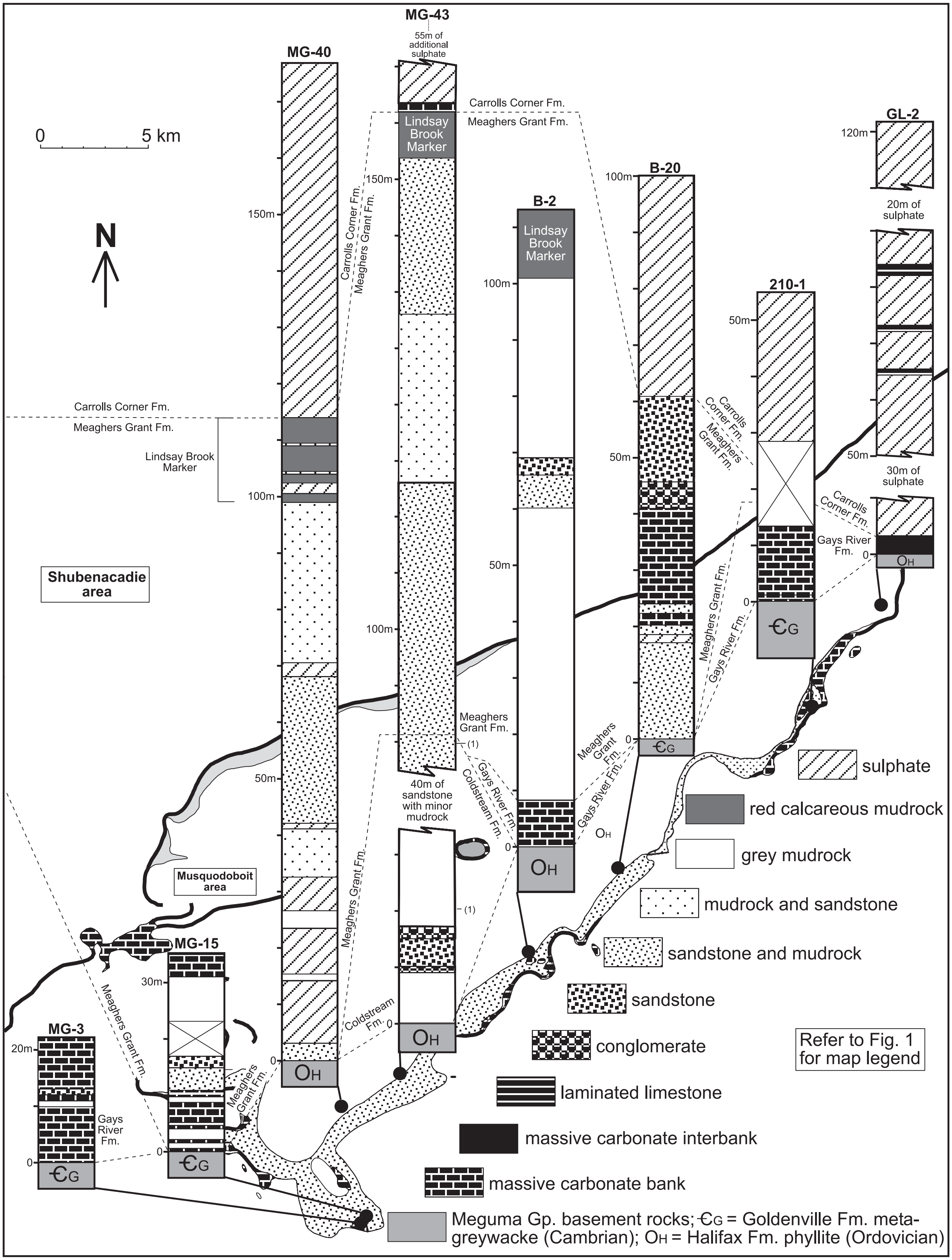


Fig. 9. Correlation of wells GR-476 (Imperial Oil Ltd.), MA-1 (Jorex – Imperial Oil Ltd.), SB-1 (U.S. Borax Ltd.), CW-5 (Imperial Oil Ltd.), 208-14 (Noranda Exploration Company, Ltd.), and F-100 (AMAX Exploration, Inc.) in the Musquodoboit and Shubenacadie areas. 1, upper Tournaisian spore dates (Utting et al. 1989).

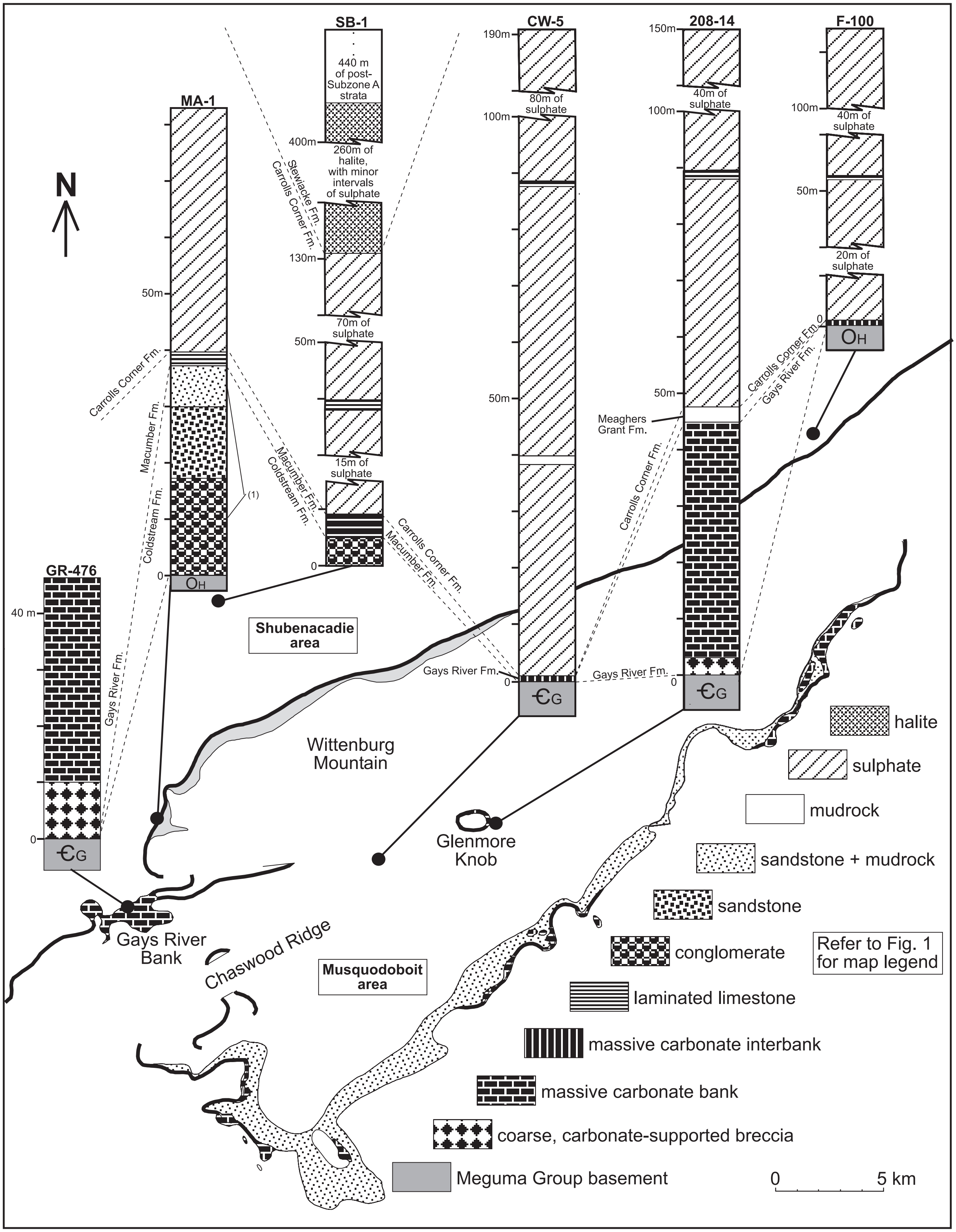
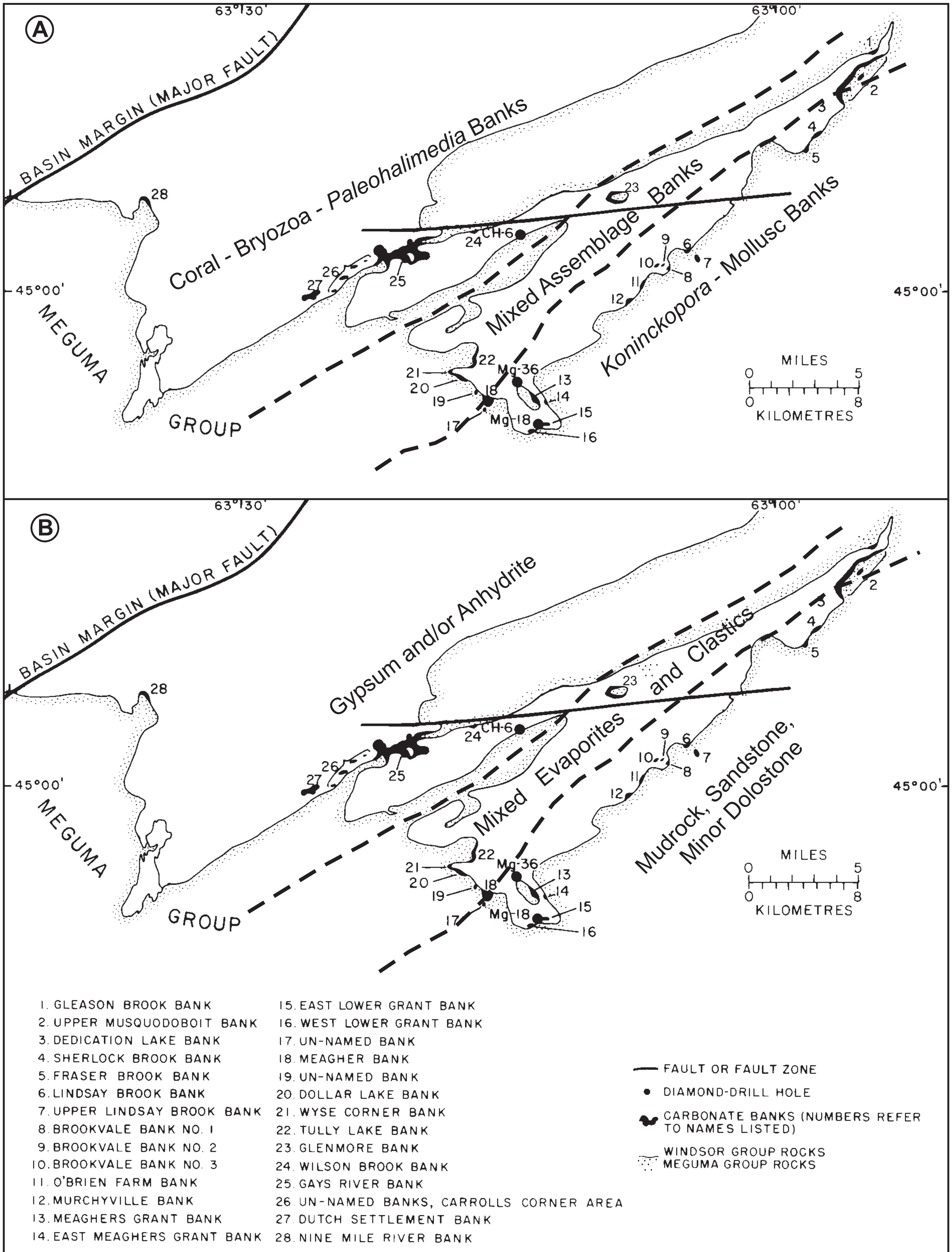


Fig. 10. Twenty-eight Gays River Formation bank localities in the Shubenacadie and Musquodoboit areas (after Giles et al. 1979): (A) associated lateral biotic zonations; (B) the nature of the interdigitating and overlying sediments.



tion include *Paleohalimedia* sp., *Koninckopora macropora*, *Cyclopora* sp., and *Turbonitella* sp. Most of the fossils in the Gays River Formation (Fig. 11) have also been reported from stratigraphically higher carbonates in the Windsor Group, however, which show greater diversity (Moore and Ryan 1976). This observed lack of diversity in the fauna of the Gays River Formation is thought to reflect a more stressed environment of deposition than that of the rest of the Windsor Group carbonates.

In terms of relative abundances in the fossil assemblage, the Gays River Formation is dominated by gastropods and pelecypods, which contrasts with the brachiopod-dominated carbonates at higher levels of the Windsor Group. Ryan (1978) quantified this by examining biotic diversity on bedding plane surfaces of equal area from the various biohermal buildups throughout the Windsor Group (Figs. 12A–12C).

Giles et al. (1979) suggested that the most plausible explanation for the mollusc domination of the Gays River Formation was paleoenvironmental in nature. Although all of the Windsor Group carbonates can be interbedded with evaporites at various localities, the Gays River Formation occasionally interfingers with (Hannon 1973), and is therefore in part laterally equivalent to, the thickest evaporite interval in the Windsor Group (over 400 m of the Carrolls Corner and Stewiacke formations). These evaporites were deposited under an arid climate in a large evaporating inland sea (Howie and Barss 1975).

As the younger Windsor Group carbonates are not laterally equivalent to thick evaporite intervals, it is reasonable to assume that the brachiopod domination in the bioherms of the Middle and Upper Windsor Group is a reflection of more normal saline conditions, and that the mollusc domination in the brachiopod-poor Lower Windsor Group is a result of more saline conditions. High salinity during Gays River Formation deposition is also suggested by the abundance of calcispheres associated with *K. macropora* (Mamet 1970). From these conclusions, relative fields of “more saline”, “mixed saline”, and “more normal saline” were drawn on the ternary diagrams (Fig. 12D), bearing in mind that truly normal saline marine conditions were possibly never achieved during deposition of the entire Windsor Group (Geldsetzer 1978).

For the younger stratigraphic intervals, 96% of the samples fall within the more normal saline field, and the remaining 4% fall within the mixed saline zone (Fig. 12D). In contrast, 75% of the Gays River Formation carbonate samples fall within the more saline zone, 20% in the mixed saline zone, and only 5% in the more normal saline zone (Fig. 12D). Interestingly, all the Gays River Formation samples that lie outside of the more saline zone come from areas where the Gays River Formation banks are overlain by or proximal to the Meaghers Grant Formation clastics.

Ryan (1978) suggested that faunal assemblage zones within individual Gays River Formation banks were controlled by water depth, wave agitation, and their position within the reefal buildups. Hatt (1978) demonstrated that the distribution of algal boundstone and associated bryozoa-coral bafflestone at the Gays River Bank (Fig. 9 and locality 25 in Fig. 10) was controlled by the –60 m structure contour on the pre-Carboniferous unconformity. This confirms the suggestion of Ryan that water depth and reefal position strongly influenced the biotic distribution.

In addition to the biotic variations within individual banks, regional variations in fossil distribution have also been observed (Giles et al. 1979). Although Giles et al. (1979) refer to only a twofold biotic zonation between “*Koninckopora*–mollusc banks” and “tabulate coral – bryozoa banks”, we consider that the faunal and floral distribution can be separated into three zones (Fig. 10A). The two contrasting zones of “coral–bryozoa–*Paleohalimedia* banks” and “*Koninckopora*–mollusc banks” are separated by a zone of “mixed assemblage banks” that contains a combination of fossils from the end members. Interestingly, the zones are parallel to the present southeastern margin of the Maritimes Basin in the Musquodoboit area and correspond to changes in the nature of sediments that interdigitate and overlie the bank buildups (Figs. 8, 9, 10B). These zones of associated sediments evolve from mainly clastics at the southeastern margin to a mix of clastics and evaporites basinward and evaporites only farther into the basin (Figs. 8, 9, 10B). The faunal zones therefore seem to correspond to a decrease in fluvial inputs from the southeast to the northwest, as reflected by an associated decrease in the abundance of clastic material in the succession (Fig. 10B).

Paleoenvironmental and paleogeographic reconstructions

Coldstream Formation time slice (Fig. 13A)

Before deposition of the Windsor Group, most of the Musquodoboit and Shubenacadie regions must have been a source area for the conformably underlying siliciclastic beds of the Coldstream Formation, which are seemingly limited to small valley fills in the area, being absent in several wells (Figs. 8, 9, 13A). Because these beds bear a younger spore assemblage than the upper part of the Cheverie Formation near the town of Cheverie (type section of the latter unit) (Utting et al. 1989), ~50 km to the northwest of the study area, it is probably limited to narrow valley fills to the north of the Otter Brook Fault as well, cutting through Cheverie Formation strata (Fig. 13A). A disconformable erosional contact with the overlying Lower Windsor Group can be observed in the Cheverie area, supporting the hypothesis that this area may have been experiencing erosion while beds of the Coldstream Formation were being deposited in narrow valley fills cutting through the basin. Because both successions are nearly facies equivalent, such a stratigraphic relationship would be hard to detect given the lack of sufficiently continuous exposure. Beds of the Coldstream Formation therefore seemingly record a rise in base level following a period of base-level lowering and downcutting near the end of the Tournaisian.

Horton–Windsor transition

Although uncertainties remain regarding the age of Lower Windsor Group carbonates, age determinations from foraminifers (Mamet 1970), conodonts (von Bitter and Plint-Geberl 1982), and macrofauna (Bell 1929, 1960) all suggest that they do not begin in the lowermost Viséan, whereas the Coldstream Formation is bound to the Tournaisian according to its spore assemblage (the *Colatisporites decorus – Schopfites*

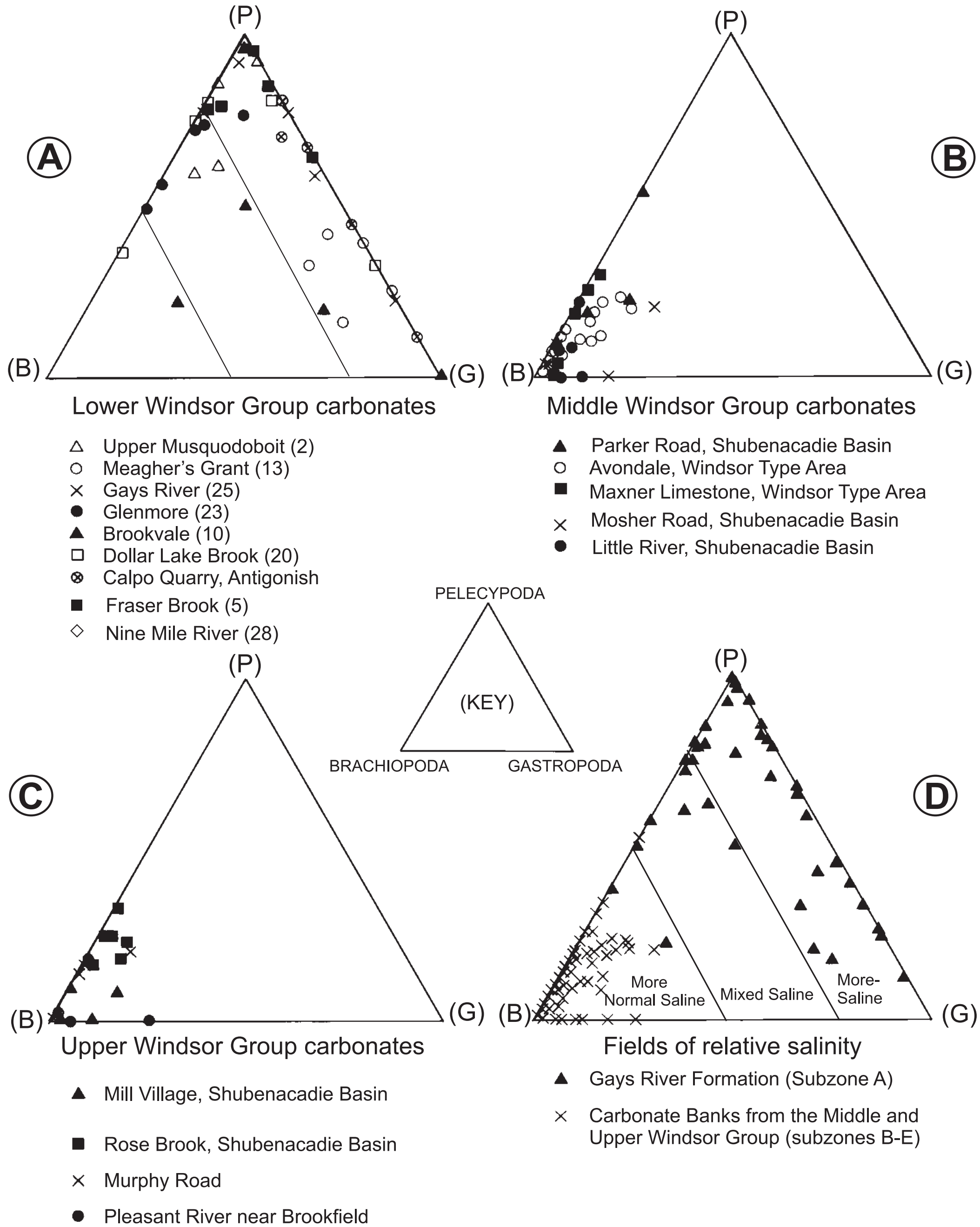
Fig. 11. List of faunal and floral species found in 23 Gays River Formation banks in Nova Scotia. The list of banks is ordered in terms of the clastics to evaporites ratio in the overlying beds, which decreases from left to right and is roughly proportional to the distance from the paleoshore. C, common; CC, very common; R, rare; RR, very rare.

Clastics ------------------- Mixed -----------> Evaporites

FAUNA AND FLORA / BANK LOCALITIES	UPPER MUSQUODOBOIT (NO. 2)	DEDICATION LAKE (NO. 3)	FRASER BROOK (NO. 5)	LINDSAY BROOK (NO. 6)	BROOKVALE (NO. 8)	O'BRIEN FARM (NO. 11)	MURCHYVILLE (NO. 12)	EAST LOWER GRANT (NO. 15)	WEST LOWER GRANT (NO. 16)	MEAGHERS GRANT (NO. 13)	MEAGHER (DILLMAN BK.) (NO. 18)	DOLLAR LAKE (NO. 20)	TULLY LAKE (NO. 22)	WILSON BROOK (NO. 24)	COOKS BROOK (NO. 25)	GLENMORE (NO. 23)	GAYS RIVER (NO. 25)	DUTCH SETTLEMENT (NO. 27)	NINE MILE RIVER (NO. 28)	WILLIAMS PT.-ANTIGONISH HARB.	CALPO QUARRY-ANTIGONISH	EAST RIVER-MAHONE BAY	SPRINGVALE	OVERALL ABUNDANCE
Aviculopecten sp.	X	X										X				X	X	X						C
Aviculopecten lyelli	X								X								X							R
Aviculopecten lyelliformis	X	X														X	X							R
Batostomella abrupta		X								X	X	X			X	X	X	X	X					RR
Batostomella exilis	X	X			X					X	X	X		X	X	X	X	X	X					C
Beecheria davidsoni	X	X		X	X		X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	CC
Cladochonus sp.	X	X					X			X	X	X			X	X	X	X	X			X	X	C
Cyclopora sp.		X									X	X	X	X	X	X	X	X	X		X	X		C
Diodoceras avonensis	X																							RR
Fenestrellina sp.	X	X									X	X		X	X	X	X	X	X					C
Koninckopora macropora	X	X	X	X	X	X	X	X	X	X	X	X	X				X		X			X		C
Leptodesma sp.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	C
Leptodesma acadica	X	X			X		X							X			X	X			X			C
Leptodesma borealis	X																X				X			R
Leptodesma dawsoni	X	X	X											X	X	X	X	X			X			CC
Paleohalimedia sp.	X	X					X					X		X		X	X	X						C
Paraconularia planocostata	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	CC
Pseudozygopleura cf. *cara*		X															X							RR
Pteronites gayensis	X	X															X							RR
Spirorbis caperatus	X	X		X		X	X				X	X	X		X		X	X	X		X	X		CC
Straparollus minutus	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	CC
Streblopteria debertianum							X																	RR
Turbonitella sp.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	CC

claviger Assemblage Zone of Utting et al. 1989). Hence, a hiatus may separate the Horton and Windsor groups in the study area (Fig. 2), although this hiatus is narrower than that in the Cheverie area. During this hiatus, basement rocks were subjected to mechanical and chemical weathering in the terrestrial environment, generating a regolith mantle

Fig. 12. Ternary diagrams showing the relative abundances of pelecypods (P), gastropods (G), and brachiopods (B) in (A) carbonate banks of the Gays River Formation (Lower Windsor Group; subzone A assemblage), (B) carbonate banks of the Middle Windsor Group (subzone B assemblage), and (C) carbonate banks of the Upper Windsor Group (subzones C–E assemblages). Relative fields of salinity are drawn in a summary diagram in (D).



(O'Beirne-Ryan and Zentilli 2003) (Fig. 14A). Due to the general aridity of the Viséan climate in that area (Utting 1987), mechanical weathering processes must have been important, and inefficient chemical weathering allowed coarse material to be preserved in the regolith.

Macumber – Gays River – Meaghers Grant formations time slice (Fig. 13B)

Rapid flooding of the Maritimes Basin occurred during the Viséan as more generalized subsidence affected the area and accommodated an invasive sea (Fig. 13B). According to Dewey (1988, 1989), the source of marine waters was the Northern Hercynian Ocean, a proto-Tethys ocean that closed during the Pennsylvanian, leaving a suture that can be traced across Europe and North Africa.

Macumber Formation

As was pointed out by Giles et al. (1979), the Macumber Formation laminites are mainly found above Tournaisian clastic rocks of the Horton Group, whereas the Gays River Formation typically lies directly on basement rocks (Figs. 9, 13B). Because Horton Group clastics are found only in the most depressed sectors of the basement surface in the Shubenacadie and Musquodoboit areas, this association may only reflect water depth, although slope gradient and the nature of the substrate (degree of induration) may also have been of influence during sedimentation.

Gays River Formation

As the sea transgressed and onlapped basement highs of the area, the regolith was reworked by wave action, as evidenced by patches of boulder conglomerate with well-rounded clasts, which are best interpreted as beach deposits (Figs. 4–6, 14B). During periods of sea-level stagnation, denudation must have occurred in the intertidal area, exposing the fresh bedrock below the regolith. At the same time, gravel beach deposits must have been concentrating in the lower reaches of the intertidal zone and in the upper reaches of the subtidal zone while being rounded and sorted by wave action (Fig. 14B). The poor degree of sorting and the preservation of sharp wedges of basement rocks in the washed-out intertidal zone (Fig. 7) imply that sea-level stagnation was insufficiently long to produce significant bedrock erosion. Coastal marine erosion was therefore limited to the ablation of a thin regolith mantle.

After formation of the lowermost gravel beach deposit, a sudden rise in sea level is necessary to explain the presence of a carbonate-supported breccia above the conglomerate (on the north-facing wall of the studied cut section at Mosher's Quarry; Fig. 5), or upslope from it on a fresh basement rock surface washed out of its regolith mantle (on the south-facing wall; Fig. 4). The subangular boulders had to be sourced from a regolith that was lying some distance upslope and was then being reworked by wave action (Fig. 14C).

The high angle of the basement surface allowed boulders and slabs of the regolith to be easily dislodged by wave action and transported downslope, via gravity-induced processes such as toppling, sliding, and rolling. Due to weathering along joints, the basement rocks were structurally weak and hence susceptible to detachment along the steep paleoshoreline. Dislodged rock boulders occasionally made their way down from a high-energy surf zone to a relatively calm area where carbonate buildup could occur between rock falls and where abrasion was ineffective. Over time, a carbonate-supported boulder talus deposit was formed through this process (Fig. 4). Similar breccias below the Gays River Formation at other localities of the Musquodoboit area have also been interpreted as submarine talus deposits (Schenk and Hatt 1984; Giles and Boehner 1979, 2006).

In late stages of the prolonged period of shoreline stability during which the carbonate-supported breccia of the Mosher's Quarry section was formed, and as the basement was still being washed out of its regolith mantle in the intertidal zone, rounded gravels started accumulating within basement wedge traps in the lower reaches of the intertidal zone and in the upper reaches of the subtidal zone (Fig. 14D).

The sea eventually took other transgressing steps (Fig. 14E), and up to 50 m of thick massive carbonate rock was deposited subsequently above the basal breccia and conglomerate deposits (Fig. 14F). The presence of a Gays River Bank outlier on top of the basement high that limits the Musquodoboit area to the southeast (locality shown in Fig. 1) indicates that the latter was eventually overstepped.

As noted earlier, the lower conglomerate is only exposed on the north-facing wall of the studied cut section at Mosher's Quarry, and the upper conglomerate only on the south-facing wall. This could be due to either the limitations of exposure or the lenticular nature of these deposits. The lower conglomerate is necessarily older than the upper conglomerate, however, due to the presence of the carbonate-supported breccia in between, which can be well correlated from one side of the quarry cut to the other.

The present disposition of the carbonate-supported talus breccia and overlying beach conglomerate necessitates a steep paleoslope to explain the juxtaposition of a low-energy environment (carbonate-supported talus) and a high-energy environment (boulder beach) (Fig. 4). If the paleoslope had been less steep, all the material would have been rounded and sitting in a siliciclastic matrix. Hence, a steep paleoslope on the southeast limit of the Musquodoboit area limited the Windsor Sea during the first stages of the initial transgression. Due to algal binding, carbonate accumulated at steeper angles than the angle of repose of clastic material (Fig. 5).

Lateral transitions observed between wells 210-1 and GL-2 (Fig. 8) and between wells 208-14 and CW-5 (Fig. 9) support the observation by Giles et al. (1979) that Gays River Formation biohermal banks thin very quickly to the dark and poorly fossiliferous interbank facies overlain by sulphates. The presence of a thick bank buildup along the Gays River Bank and Glenmore Knob localities (Fig. 9, wells GR-476 and 208-14) suggests that these present-day basement highs were also paleotopographic highs during sedimentation of the Gays River Formation, providing shallower marine conditions for the development of bank buildups (Fig. 13B). Geldsetzer (1978) and Ryan (1978) proposed that lower salinity in the upper part of a salinity-stratified water body may have favored Gays River Formation bank buildups on paleotopographic highs.

In contrast with the basement highs at Gays River Bank and Glenmore, the Chaswood Ridge and Wittenburg Mountain are fault bound (Horne et al. 2000). The absence of bank buildups along them (Fig. 9, wells CW-5, MA-1, and F-100) suggests that they were not paleotopographic highs during deposition of the Windsor Group, but rather that they are the result of subsequent structural deformation. Also supporting the latter conclusion is evidence of high-energy coastal conditions in the sedimentology of the Mosher's Quarry section, which suggests that the southeast margin of the Musquodoboit area was that of a large open basin, certainly much larger than the present configuration of the structural basin. Hence, although knobs of paleotopographic highs seemingly existed, the Musquodoboit, Shubenacadie, and Windsor areas were most likely part of the same open sedimentary basin (the Minas subbasin of Bell 1929) during Windsor Group deposition.

Meaghers Grant Formation

In a detailed sedimentologic study of the Meaghers Grant Formation clastics, largely based on well MG-43, Harnish (1978) concluded that this unit evolved from an alluvial to a deltaic environment below the Lindsay Brook Marker. Based on subsequently obtained spore dates from well MG-43 (Utting et al. 1989), we interpret the subtle petrographic changes on each side of an erosional surface, located 81 m

Fig. 13. Schematic paleogeographic reconstructions during (A) the Coldstream Formation time slice, (B) the Macumber – Gays River – Meaghers Grant formations time slice, (C) the Gays River – Meaghers Grant – Carrolls Corner formations time slice, (D) the Meaghers Grant – Carrolls Corner – Stewiacke formations time slice, (E) the Lindsay Brook Marker time slice, and (F) the Carrolls Corner – Stewiacke formations time slice. 1, Goldenville Formation (Cambrian); 2, Halifax Formation (Ordovician); 3, Horton Bluff Formation clastics (Tournaisian); 4, Cheverie Formation clastics (Tournaisian); 5, Coldstream Formation clastics (uppermost Tournaisian); 6, Macumber Formation carbonate laminites (Viséan); 7, Gays River Formation interbank carbonate (Viséan); 8, Gays River Formation carbonate bank buildup (Viséan); 9, Meaghers Grant Formation clastics (Viséan); 10, Carrolls Corner Formation sulphates (Viséan); 11, Stewiacke Formation halite (Viséan).

above the basement contact in this well, as representing the transition between fluvial sandstones of the Coldstream Formation and delta-front sandstones of the Meaghers Grant Formation.

As stated earlier, bank buildups interdigitate with clastic sediments in many wells (e.g., wells MG-3, MG-15, and B-20; Fig. 8), and either type of lithology can be found at the base of the Windsor Group succession (Figs. 8, 9). Hence, although Giles and Boehner (2006) consider the Meaghers Grant Formation to be younger than the Gays River Formation banks, core data suggest that onset of Viséan clastic sedimentation is synchronous with bank development and that the Gays River Formation is entirely transitional to the Meaghers Grant Formation (Fig. 13B). The Musquodoboit Valley region therefore evolved rapidly in Viséan times from an eroding source area (Fig. 13A) to a sedimentary basin, which from then on was receiving clastic material from a source area displaced to the southeast (Fig. 13B). How far to the southeast the sea reached during its maximum extent is unknown. The large quantity of siliciclastic material being conveyed into the Musquodoboit area during deposition of the Meaghers Grant Formation implies, however, that a large subaerial topographic high (the Nova Scotia Uplands of Harnish 1978) existed nearby to the southeast. Given this and the apparent absence of Windsor Group strata in offshore Nova Scotia, it can be argued that the Windsor Sea probably did not extend much farther to the southeast than the present margin of the Musquodoboit area.

The abundance of sands and the absence of pure carbonates below the Lindsay Brook Marker in well MG-43 imply that this locality was closest among the well localities to the main fluvial input into the marine basin (Fig. 8). However, the passage from basal carbonates in well B-2 to basal sands in well B-20 (Fig. 8), which is farther from well MG-43 than the former, implies that secondary tributaries were also feeding the basin with terrigenous clastics along the margin (Fig. 13B). Because clastic material of the Meaghers Grant Formation fines and disappears to the northwest (Figs. 8, 9), and because paleocurrent vectors are also oriented in that direction (Fig. 1), it is concluded that the source area was to the southeast and that the paleocoastline had an overall southwest–northeast strike.

Gays River – Meaghers Grant – Carrolls Corner formations time slice (Fig. 13C)

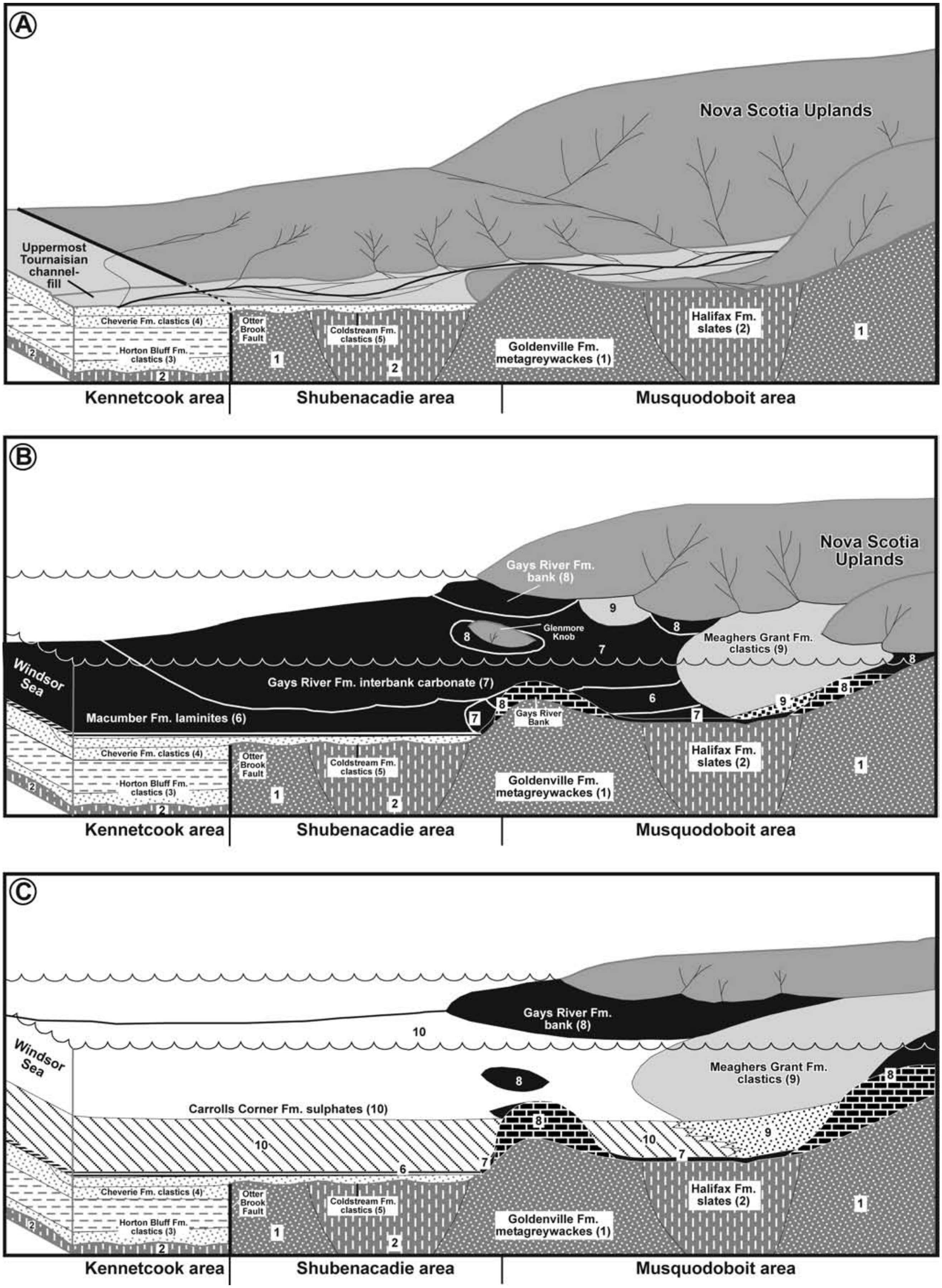
The presence of Macumber Formation laminites or Gays River Formation interbank carbonate directly below the Carrolls Corner Formation, away from the southeast margin of the Minas Subbasin (well GL-2, Fig. 8, and wells MA-1, SB-1, CW-5, and F-100, Fig. 9), implies that evaporitic deposition was initiated after a period of more normal marine conditions. Slow sedimentation rates can be inferred to justify the thinness of carbonates below the sulphates, but in the case of well MG-40 the sulphates are underlain by only 3 m of sandstone and mudrock (Fig. 8), suggesting that this initial period of more normal marine conditions was very short-lived in the epicontinental marine basin.

The presence of only 3 m of siliciclastic material between the lowermost sulphate and basement rocks in well MG-40, whereas at least 18 m of siliciclastics interdigitate with bank buildups 5 km to the south in well MG-15 (Fig. 8), suggests that the Carrolls Corner Formation is a lateral equivalent not only of the upper Meaghers Grant Formation beds, as proposed by Giles and Boehner (2006), but also of the upper beds of the Gays River Formation. This is also suggested by the presence of sulphate below the first occurrences of carbonate bank buildups in well B-20 (Fig. 8). In other words, bank buildups may have bordered the evaporitic basin during most of their formation (Fig. 13C).

The relationship between variations in the faunal assemblages and the proximity of fluvial inputs into the Minas Subbasin from the southeast (Figs. 1, 10) suggests that water salinity and (or) turbidity may have been responsible for these variations. From the observation that faunal assemblages near the basin margin have more similarity to those which developed under the less saline conditions of the Middle and Upper Windsor Group, which bear more species and relative abundance of brachiopods (Figs. 10, 12), it is postulated that salinity variation was a controlling factor for the lateral biotic zonation, although turbidity may also have been an important factor. The absence of echinoderms and the abundance of calcispheres suggest that salinity fluctuations were also of importance (Casier et al. 2005) during Gays River Formation deposition, which corroborates with the conclusion that fluvial inputs had a strong influence on the environment.

Giles et al. (1979) correlated algal boundstones and associated bryozoa-coral bafflestones of the Gays River Bank (Fig. 9; locality 25, Fig. 10) with *Koninckopora* algal boundstones and bafflestones of the southeast margin of the Musquodoboit area on the basis of the similar reefal position of these units within the banks, the petrography of the carbonates, and the similar water depths interpreted from the contained biota. The correlation of these units suggests that some of the biotic variations must be controlled by environmental influences other than water depth and position within the reefal banks of the formation. Hence, salinity increased not only with depth, but also with distance from sources of freshwater, which, due to its lower density, was probably forced to both thrust over more saline water and infiltrate along the basin margin.

The higher diversity of banks that are located close to fluvial inputs suggests that average salt contents had more


A
Nova Scotia Uplands
Uppermost Tournaisian channel-fill
Cheverie Fm. clastics (4)
Horton Bluff Fm. clastics (3)
Otter Brook Fault
Coldstream Fm. clastics (5)
Goldenville Fm. metagreywackes (1)
Halifax Fm. slates (2)
Kennetcook area
Shubenacadie area
Musquodoboit area
B
Nova Scotia Uplands
Gays River Fm. bank (8)
Glenmore Knob
Meaghers Grant Fm. clastics (9)
Windsor Sea
Gays River Fm. interbank carbonate (7)
Macumber Fm. laminites (6)
Gays River Bank
C
Gays River Fm. bank (8)
Meaghers Grant Fm. clastics (9)
Carrolls Corner Fm. sulphates (10)

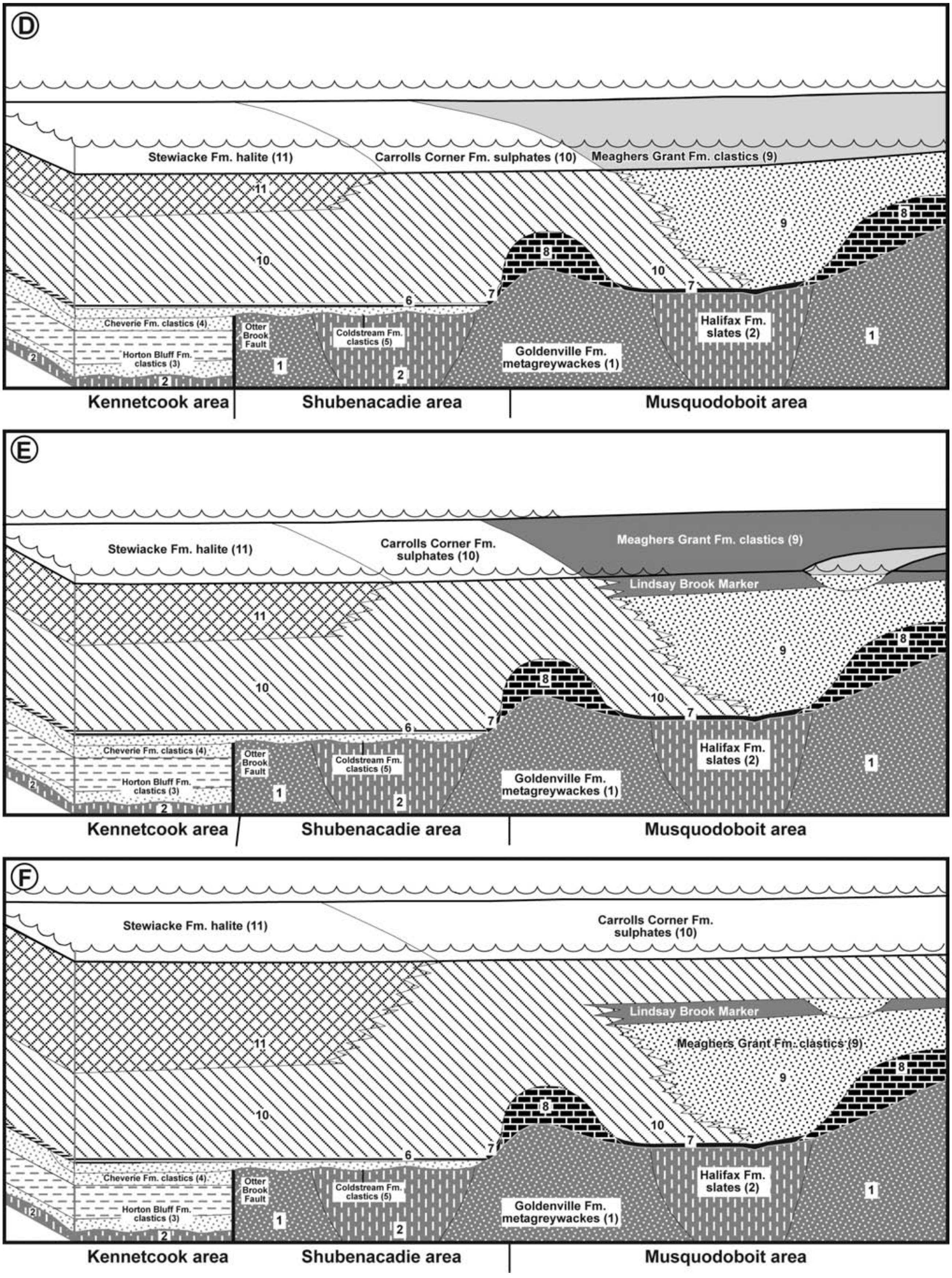
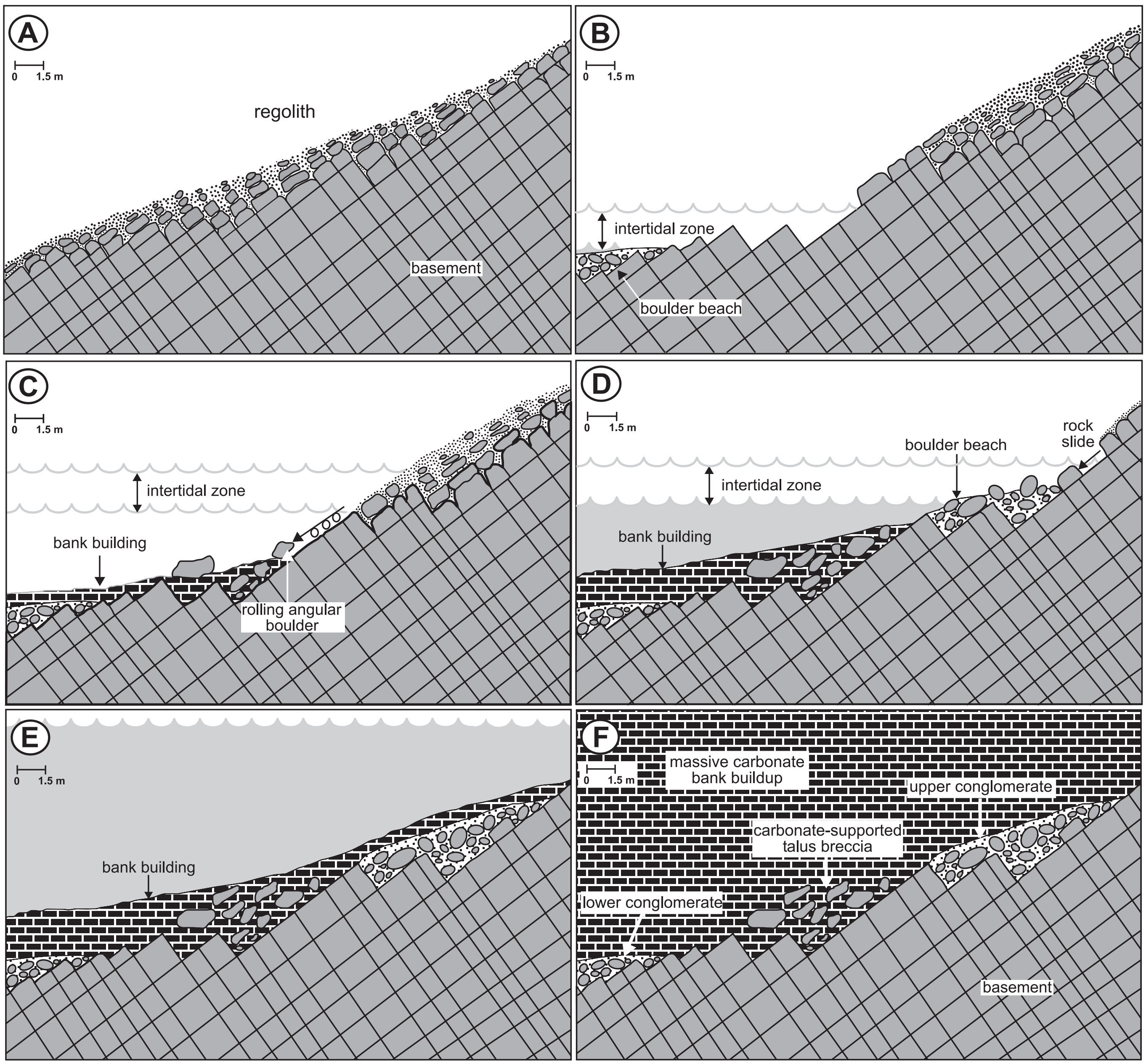

D
Stewiacke Fm. halite (11)
Carrolls Corner Fm. sulphates (10)
Meaghers Grant Fm. clastics (9)
Cheverie Fm. clastics (4)
Horton Bluff Fm. clastics (3)
Otter Brook Fault
Coldstream Fm. clastics (5)
Goldenville Fm. metagreywackes (1)
Halifax Fm. slates (2)
Kennetcook area
Shubenacadie area
Musquodoboit area
E
Stewiacke Fm. halite (11)
Carrolls Corner Fm. sulphates (10)
Meaghers Grant Fm. clastics (9)
Lindsay Brook Marker
Cheverie Fm. clastics (4)
Horton Bluff Fm. clastics (3)
Otter Brook Fault
Coldstream Fm. clastics (5)
Goldenville Fm. metagreywackes (1)
Halifax Fm. slates (2)
Kennetcook area
Shubenacadie area
Musquodoboit area
F
Stewiacke Fm. halite (11)
Carrolls Corner Fm. sulphates (10)
Lindsay Brook Marker
Meaghers Grant Fm. clastics (9)
Cheverie Fm. clastics (4)
Horton Bluff Fm. clastics (3)
Otter Brook Fault
Coldstream Fm. clastics (5)
Goldenville Fm. metagreywackes (1)
Halifax Fm. slates (2)
Kennetcook area
Shubenacadie area
Musquodoboit area

Fig. 14. Sedimentology of the studied cut section at Mosher's Quarry. (A) Development of a regolith mantle during prolonged subaerial exposure. (B) Transgression, removal by wave action of regolith material in the intertidal zone of a newly formed shoreline, and accumulation of abraded regolith material in the lower reaches of the intertidal zone and the upper reaches of the subtidal zone. (C) Rise of sea level, removal by wave action of regolith material in the intertidal zone of a newly formed shoreline higher upslope, and rolling of displaced regolith material down into a quieter zone, where abrasion does not occur and where carbonate can precipitate. (D) Entrapment and abrasion of regolith material between wedges of fresh basement rocks. (E) Rise of sea level and burial of the basal rudaceous material by carbonate. (F) Buildup of a thick carbonate bank as sea level keeps rising.



influence on biotic zonations than short-term salinity fluctuations. This and the apparently long duration of coeval bank development and evaporitic deposition within the same basin suggest that fluvial inputs within that basin were relatively persistent, implying that the source area lying to the southeast was considerably large and perhaps extending into less arid areas. This conclusion is also suggested by the abundance of coaly material in the Meaghers Grant Formation, although this unit interdigitates with evaporites.

Meaghers Grant – Carrolls Corner – Stewiacke formations time slice (Fig. 13D)

Due to a combination of basinward and temporal increases in salinity, the lateral transition between the proximal Gays River Formation bank buildups and the distal Carrolls Corner Formation sulphates gradually gave way to a lateral transition between these sulphates and the Stewiacke Formation halite (Figs. 3, 13D), where Meaghers Grant Formation clastic inputs were low. The lateral transition between sulphate and salt is suggested by the interfingering of both lithologies in some wells of the Shubenacadie area (Giles and Boehner 2006) and by a greater thickness of sulphate near the southeast basin margin (e.g., in well CW-5; Fig. 9) compared with that in the Shubenacadie area (e.g., in well SB-1; Fig. 9). The temporal transition from the previous time slice must have occurred when salinity in the Minas Subbasin became high enough to result in the abortion of bank building in marginal parts of the basin and to initiate salt deposition in the centre of the basin (Fig. 13D).

Lindsay Brook Marker time slice (Fig. 13E)

We concur with the conclusions of Harnish (1978) that the limestone laminites, sulphates, red clastics, and paleosols of the Lindsay Brook Marker reflect an intertidal to supratidal environment near the end of Meaghers Grant Formation deposition. By this time, the Nova Scotia Uplands may have been quite subdued by prolonged erosion; furthermore, basin infilling may have forced the shoreline to migrate basinward, away from remaining highlands (Fig. 13E). The absence of the Lindsay Brook Marker below the Carrolls Corner Formation in some wells, such as well B-20, may be due to erosion, as the sea kept regressing. Channel fills of non-oxidized clastic material may have cut the supratidal flats during this time slice, however, making the red bed cover discontinuous (Fig. 13E).

Carrolls Corner – Stewiacke formations time slice (Fig. 13F)

Sulphates overlie the Meaghers Grant Formation clastics even in the most marginal areas of the basin (Fig. 8, wells MG-40, MG-43, and B-20). We therefore conclude that, after a short period of regression during deposition of the Lindsay Brook Marker, basin waters resumed their transgressive trend during deposition of the overlying evaporitic succession. This is contrary to the conclusions of Giles (1981) and Giles and Boehner (2006), who regarded the evaporites as having formed during a long period of regression. As the evaporation of 1000 m of seawater can produce only ~15 m of evaporite deposits (Warren 1999), a connection with an open oceanic basin during most of the deposition time is necessary to explain the thickness of the evaporite deposit, which exceeds 400 m. Even in a transgressive context, high evaporation rates could gradually concentrate the brines of the restricted epicontinental sea and lead to thick evaporitic deposition through constant refluxing of oceanic water into the system.

Hence, we conclude that the shoreline was farthest to the southeast during deposition of the upper part of the Lower Windsor Group in the study area, in which there is no record of marginal deposits, but only that of a lateral transition between the Carrolls Corner Formation sulphates and the Stewiacke Formation chlorides. The overall surface area of the Windsor Sea may have been contracting at that time, however, as it was tectonically forced to regress away from the northwest margin of the Maritimes Basin shortly after the initial transgression (Jutras and Schroeder 1999; Jutras et al. 1999, 2001; Jutras and Prichonnet 2005). Due to tectonic constraints, the Windsor Sea may have been forced to migrate towards the southeast while becoming simultaneously more restricted.

At the southeast margin of the Maritimes Basin, during deposition of the upper beds of the Stewiacke and Carrolls Corner formations, gradual thinning of the water column may have accompanied these late stages of the local transgression due to the gradual sedimentary infilling of topographic lows and the associated flattening of the basin floor. The presence of small potash patches at the top of the Lower Windsor Group in dispersed areas of the Maritimes Basin (Boehner 1985) is best explained by thinning of the water column, which eventually must have forced the water body to divide into isolated basins near the very end of Lower Windsor Group deposition, before the major influx that marks the base of the Middle Windsor Group.

Comparisons with time-equivalent units in other areas of eastern Canada

Our paleoenvironmental and paleogeographic model for the Lower Windsor Group in the Musquodoboit and Shubenacadie areas concurs in many ways with that of Dix and James (1989) for the Port-au-Port Peninsula of western Newfoundland. The latter authors concluded that the initial Windsor transgression flooded steep paleorelief, with adjacent fluvial inputs providing intermittent coarse clastic detritus and salinity fluctuation during mound building in the Big Cove Formation (a Gays River Formation equivalent). McCutcheon (1988) also concludes that steep paleorelief must have existed during the initial Windsor transgression to justify the abundance of coarse clastics in the Parleeville Formation (Lower Windsor Group) of southern New Brunswick.

Finding evidence for water depths exceeding 100 m in some of the Big Cove Formation mounds at Port-au-Port, von Bitter et al. (1990, 1992) did not agree with the conclusions of Dix and James (1989) concerning the proximity of a rocky shoreline during mound development but did not provide arguments to explain the vicinity of contemporaneous alluvial-fan deposits (Lower Cove Formation) without involving nearby subaerial basement highs. Moreover, von Bitter et al. did not present convincing arguments to disprove the many indications of fluvial inputs provided by Dix and James for the Big Cove Formation itself. In the context of the highly dissected paleokarst topography described by Dix and James below the basal Windsor Group in the Port-au-Port Peninsula, we find that the presence of moderately deep water mounds is not inconsistent with the nearby presence of a rocky shoreline.

According to von Bitter et al. (1990, 1992) and Schenk et al. (1994, 2001), mounds of the Big Cove and Gays River formations in southern Newfoundland and northern Cape Breton Island (Fig. 1; inset) were formed around deep-water hydrothermal vents. We agree that the abundance of tube worms, the lack of fossil fragmentation, and the nearby presence of Viséan volcanics in the Magdalen Islands (Fig. 1; inset) support this conclusion for these localities. We do not agree with von Bitter et al. (1992), however, that this model may apply to all Gays River Formation buildups. In the Musquodoboit area, type locality of the Gays River Formation (Giles et al. 1979), tube worms are absent and the buildups are in the form of wide banks. Moreover, the ~1 km exposure of a 50 m bank at the Mosher's Quarry locality shows no evidence of hydrothermalism, and the studied cut section shows evidence instead of shallow-water, high-energy conditions in the form of fragmented fossils, rounded siliciclastic sand grains, and a lateral transition with gravel beach deposits. Hydrothermal alteration exists at other localities of the Gays River Formation, such as at Gays River Bank (Fig. 10, locality 25), but all studies conducted in the Musquodoboit area agree that this alteration post-dates bank formation and that the buildups represent a shallower water facies than the Macumber Formation laminites (Lavoie and Sami 1998; Giles and Boehner 2006).

Conclusions

(1) Paleogeographic and paleoenvironmental reconstructions suggest that the Musquodoboit and Shubenacadie areas represent marginal regions of the Minas Subbasin of Bell (1929), as paleocurrent vectors and lateral variations of facies in both regions are consistent with the presence of a common paleoshoreline to the southeast, with no substantial intervening basement high. Moreover, evidence of high coastal energy in the basal Gays River Formation deposits at the southeast margin of the Musquodoboit area necessitates a more open basin than the present configuration of the Musquodoboit Valley (i.e., the “Musquodoboit Basin” of Giles and Boehner 1979).

(2) Basal beds of the Gays River Formation along the southeast margin of the Minas Subbasin record evidence for a rapid, but intermittent marine transgression onto paleotopographic highs, probably due to a sudden increase in subsidence rates within the Maritimes Basin. This conclusion differs slightly from that of Giles and Boehner (2006), who hypothesized a nearly instantaneous transgression resulting from a breach into a preexisting, subsea-level continental basin. We argue that the transgression breaks recorded by superimposed beach deposits are not compatible with catastrophic scenarios.

(3) Core and outcrop analyses suggest that lateral variations between bank buildups, interbanks, and laminated limestones of the Gays River and Macumber formations are related to water depth at the time of deposition, with the bank buildups representing the shallowest, near-surface facies, as suggested by Giles and Boehner (2006). This conclusion challenges the thesis of von Bitter et al. (1992) that all Gays River Formation buildups may have formed in deep-water conditions. Moreover, contrary to studies conducted in southern Newfoundland and northern Cape Breton Island (von Bitter et al. 1990, 1992; Schenk et al. 1994, 2001), we found no evidence of hydrothermal activity as a control to bank development in the Gays River Formation of central Nova Scotia.

(4) According to core correlations, clastic sedimentation of the Meaghers Grant Formation along river deltas was synchronous with bank development in the Gays River Formation, away from these deltas and along the southeast margin of the Windsor Sea.

(5) Core correlations also suggest that sulphate deposition of the Carrolls Corner Formation was synchronous with all but the very base of clastic and carbonate material. Hence, we conclude that the Gays River Formation banks are significantly thicker than the interbank facies of this unit and the Macumber Formation laminites not only because of higher sedimentation rates, but also in part because they formed during a much longer time frame, while bordering an evaporitic basin.

(6) Lateral and vertical biotic variations in the bank buildups suggest that salinity was increasing with depth and with distance from the paleoshore due to freshwater input from rivers that were partly thrusting over salt water and partly infiltrating along the shoreline due to their lower density.

(7) The passage from a basinward transition between bank buildups and deeper water laminites to a basinward transition between bank buildups and sulphates and finally to a basinward transition between sulphates and halite suggests that salinity was increasing with time, probably due to insufficient influxes for the existing evaporation rates.

(8) Because coarse marginal clastic deposits of the Meaghers Grant Formation are directly overlain by thick evaporites, we conclude that the Windsor Sea was still transgressing during most of the evaporitic deposition, demonstrating that the latter environment is not restricted to regressive settings.

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References

Bell, W.A. 1929. Horton–Windsor district, Nova Scotia. Geological Survey of Canada, Memoir 155.

Bell, W.A. 1960. Mississippian Horton group of type Windsor–Horton District, Nova Scotia. Geological Survey of Canada, Memoir 314.

Belt, J.R. 1968. Post-Acadian rifts and related facies, Eastern Canada. *In* Studies in Appalachian geology, northern and maritime. *Edited by* E.-A. Zen, W.S. White, and J.B. Hadley. Interscience Publishers, New York, pp. 95–113.

Boehner, R.C. 1977. The lower Carboniferous stratigraphy of the Musquodoboit Valley, central Nova Scotia. M.Sc. thesis, Acadia University, Wolfville, N.S.

Boehner, R.C. 1984. Stratigraphy and depositional history of marine evaporites in the Windsor Group, Shubenacadie and Musquodoboit structural basins, Nova Scotia, Canada. *In* Ninth International Carboniferous Congress, Urbana, Ill., 19 May 1979, Proceedings Volume. *Edited by* H.H.J. Geldsetzer, W.W. Nassichuk, E.S. Belt, and R.W. Macqueen. Southern Illinois University Press, Carbondale, Ill., Compte Rendu 3, pp. 173–178.

Boehner, R.C. 1985. Salt and potash resources in Nova Scotia. Nova Scotia Department of Mines and Energy, Bulletin 5.

Calder, J.H. 1998. The Carboniferous evolution of Nova Scotia. *In* Lyell: the past is the key to the present. *Edited by* D.J. Blundell and A.C. Scott. Geological Society Special Publication (London), No. 143, pp. 261–302.

Casier, J.-G., Lebon, A., Mamet, B., and Preat, A. 2005. Ostracods and lithofacies close to the Devonian–Carboniferous boundary in the Chanxhe and Rivage sections, northeastern part of the

Dinant Basin, Belgium. Bulletin de l'Institut Royal des Sciences Naturelles de Belgique, Sciences de la Terre, **75**: 95–126.

Dewey, C.P. 1988. Lower Carboniferous ostracod assemblages from Nova Scotia. Developments in Palaeontology and Stratigraphy, **11**: 685–696.

Dewey, C.P. 1989. Lower Carboniferous ostracodes from the Maritimes Basin of eastern Canada: a review. Atlantic Geology, **25**: 63–71.

Dix, G.R., and James, N.P. 1989. Stratigraphy and depositional environments of the Upper Mississippian Codroy Group: Port au Port Peninsula, western Newfoundland. Canadian Journal of Earth Sciences, **26**(6): 1089–1100.

Geldsetzer, H.H.J. 1978. The Windsor Group in Atlantic Canada — an update. *In* Report of activities, part C. Geological Survey of Canada, Paper 78-1C, pp. 43–48.

Gibling, M.R., Calder, J.H., Ryan, R., van de Poll, H.W., and Yeo, G.M. 1992. Late Carboniferous and Early Permian drainage patterns in Atlantic Canada. Canadian Journal of Earth Sciences, **29**(2): 338–352.

Giles, P.S. 1981. Major transgressive–regressive cycles in middle to late Viséan rocks of Nova Scotia. Nova Scotia Department of Mines, Paper 81-2.

Giles, P.S., and Boehner, R.C. 1979. The Windsor Group stratigraphy in the Shubenacadie and Musquodoboit Basins of central Nova Scotia. Nova Scotia Department of Mines and Energy, Open File Report 410.

Giles, P.S., and Boehner, R.C. 1982. Shubenacadie and Musquodoboit basins, central Nova Scotia. Nova Scotia Department of Mines and Energy, Map 82-4.

Giles, P.S., and Boehner, R.C. 2006. Geology of the Shubenacadie and Musquodoboit basins, Hants, Halifax and Colchester counties, Nova Scotia. Nova Scotia Department of Natural Resources, Mineral Resources Branch, Open File Report. In press.

Giles, P.S., Boehner, R.C., and Ryan, R.J. 1979. Carbonate banks of the Gays River Formation in central Nova Scotia. Nova Scotia Department of Mines and Energy, Paper 79-7.

Hannon, P. 1973. Base metal exploration of the Nine Miles River area; NM73-2 well-log. Nova Scotia Department of Mines and Energy, Assessment Report 07I62.

Harnish, S.A. 1978. Stratigraphy and depositional environment of the Meaghers Grant Formation of the Musquodoboit Valley, Central Nova Scotia. B.Sc. thesis, Dalhousie University, Halifax, N.S.

Hatt, B.L. 1978. An interpretation of the carbonate geology exposed in the decline at Gays River, Nova Scotia. M.Sc. thesis, Dalhousie University, Halifax, N.S.

Horne, R.J., King, M.S., and Young, P. 2000. Geology of the Wittenburg Mountain Slate Belt, Centre Musquodoboit Area (NTS 11E/03), Nova Scotia. *In* Minerals and Energy Branch, Report of Activities 1999. Nova Scotia Department of Natural Resources, Report 98-1, pp. 15–25.

Howie, R.D., and Barss, M.S. 1975. Upper Paleozoic rocks of the Atlantic provinces, Gulf of St.-Lawrence and adjacent continental shelf. *In* Offshore geology of eastern Canada: a collective study. *Edited by* B.R. Pelletier, W.J. Van der Linden, and J.A. Wade. Geological Survey of Canada, Paper 74-30, Vol. 2, pp. 35–50.

Jutras, P., and Prichonnet, G. 2005. Record of Late Mississippian tectonics in the new Percé Group (Viséan) of eastern Gaspésie, Quebec. Canadian Journal of Earth Sciences, **42**(5): 815–832.

Jutras, P., and Schroeder, J. 1999. Geomorphology of an exhumed Carboniferous paleosurface in the southern Gaspé Peninsula; paleoenvironmental and tectonic implications. Géographie physique et Quaternaire, **53**: 249–263.

Jutras, P., Prichonnet, G., and von Bitter, P. 1999. The La Coulée Formation, a new post-Acadian continental clastic unit bearing groundwater calcretes, Gaspé Peninsula, Québec. Atlantic Geology, **35**: 139–156.

Jutras, P., Prichonnet, G., and Utting, J. 2001. Newly identified Carboniferous units (the Pointe Sawyer and Chemin-des-Pêcheurs formations) in the Gaspé Peninsula, Quebec; implications regarding the evolution of the northwestern sector of the Maritimes Basin. Canadian Journal of Earth Sciences, **38**(1): 1–19.

Jutras, P., Prichonnet, G., and McCutcheon, S. 2003. Alleghanian deformation in the eastern Gaspé Peninsula of Quebec. Geological Society of America Bulletin, **115**: 1538–1551.

Lavoie, D., and Sami, T. 1998. Sedimentology of the lowest Windsor carbonate rocks: base metal hosts in the Maritimes Basin of eastern Canada. Economic Geology, **93**: 719–733.

Mamet, B.L. 1970. Carbonate microfacies of the Windsor Group (Carboniferous), Nova Scotia and New Brunswick. Geological Survey of Canada, Paper 70-21.

Martel, A.T., and Gibling, M.R. 1996. Stratigraphy and tectonic history of the Upper Devonian to Lower Carboniferous Horton Bluff Formation, Nova Scotia. Atlantic Geology, **32**: 13–38.

Martel, A.T., McGregor, D.C., and Utting, J. 1993. Stratigraphic significance of Upper Devonian and Lower Carboniferous miospores from the type area of the Horton Group, Nova Scotia. Canadian Journal of Earth Sciences, **30**(5): 1091–1098.

McCutcheon, S.R. 1988. Algal buildups of Visean age in southern New Brunswick. *In* Reefs of Canada and adjacent areas. *Edited by* H.H.J. Geldsetzer, N.P. James, and G.E. Tebutt. Canadian Society of Petroleum Geologists, Memoir 13, pp. 677–681.

Moore, R.G., and Ryan, R.J. 1976. Guide to the invertebrate fauna of the Windsor Group in Atlantic Canada. Nova Scotia Department of Mines, Paper 76-5.

O'Beirne-Ryan, A.M., and Zentilli, M. 2003. Paleoweathered surfaces on granitoids of southern Nova Scotia: paleoenvironmental implications of saprolites. Canadian Journal of Earth Sciences, **40**(6): 805–817.

Ryan, R.J. 1978. The paleontology and paleoecology of the Gays River Formation in Nova Scotia. M.Sc. thesis, Acadia University, Wolfville, N.S.

Ryan, R.J., Boehner, R.C., and Calder, J.H. 1991. Lithostratigraphic revisions of the upper Carboniferous to lower Permian strata in the Cumberland Basin, Nova Scotia, and their regional implications for the Maritimes Basin in Atlantic Canada. Bulletin of Canadian Petroleum Geology, **39**: 289–314

Schenk, P.E., and Hatt, B.L. 1984. Depositional environment of the Gays River Reef, Nova Scotia, Canada. *In* Ninth International Carboniferous Congress, Urbana, Ill., 19 May 1979, Proceedings Volume. *Edited by* H.H.J. Geldsetzer, W.W. Nassichuk, E.S. Belt, and R.W. Macqueen. Southern Illinois University Press, Carbondale, Ill., Compte Rendu 3, pp. 117–130.

Schenk, P.E., von Bitter, P.H., and Matsumoto, R.R. 1994. Deep-basin/deep-water carbonate–evaporite deposition of a saline giant, Loch Macumber (Visean), Atlantic Canada. Carbonates and Evaporites, **9**: 187–210.

Schenk, P.E., von Bitter, P.H., and Matsumoto, R.R. 2001. Carbonate mud flows and other indicators of excess pore-fluid pressure in the Macumber Formation (Lower Carboniferous, Viséan) at Ingonish, Nova Scotia, Canada. Carbonates and Evaporites, **16**: 185–209.

Utting, J. 1987. Palynology of the Lower Carboniferous Windsor Group and Windsor–Canso boundary beds of Nova Scotia, and their equivalents in Québec, New Brunswick and Newfoundland. Geological Survey of Canada, Bulletin 374.

Utting, J., and Giles, P.S. 2004. Biostratigraphical implications of new palynological data from the Mississippian of Newfoundland

and Nova Scotia, Canada. Memoirs of the Association of Australasian Palaeontologists, **29**: 115–160.

Utting, J., Keppie, J.D., and Giles, P.S. 1989. Palynology and stratigraphy of the Lower Carboniferous Horton Group, Nova Scotia. *In* Contributions to Canadian paleontology. *Edited by* L. Reynolds. Geological Survey of Canada, Bulletin 396, pp. 117–143.

von Bitter, P.H., and Plint-Geberl, H.A. 1982. Conodont biostratigraphy of the Codroy Group (Lower Carboniferous), southwestern Newfoundland, Canada. Canadian Journal of Earth Sciences, **19**(1): 193–221.

von Bitter, P.H., Scott, S.D., and Schenk, P.E. 1990. Early Carboniferous low-temperature hydrothermal vent communities from Newfoundland. Nature (London), **344**: 145–148.

von Bitter, P.H., Scott, S.D., and Schenk, P.E. 1992. Chemosynthesis: an alternate hypothesis for Carboniferous biotas in bryozoan/microbial mounds, Newfoundland, Canada. Palaios, **7**: 466–484.

Warren, J.K. 1999. Evaporites. Blackwell Science, Oxford, UK.

Weeks, L.J. 1948. Londonderry and Bass River map area, Colchester and Hants counties, Nova Scotia. Geological Survey of Canada, Memoir 245.