

Article

The Role of Regional and Local Structure in a Late Ordovician (Edenian) Foreland Platform-to-Basin Succession Inboard of the Taconic Orogen, Central Canada

Ruth Gbadeyan ^{1,2} and George R. Dix ^{1,*}

¹ Ottawa-Carleton Geoscience Centre, Department of Earth Sciences, Carleton University, 2160 Herzberg Laboratories, Ottawa, ON K1S 5B6, Canada

² 2775 Crow Creek Road, Bettendorf, IA 52722, USA; E-Mail: gbadeys@gmail.com

* Author to whom correspondence should be addressed; E-Mail: gdix@connect.carleton.ca; Tel: +1-613-520-5633; Fax: +1-613-520-5613.

Received: 15 March 2013; in revised form: 26 April 2013 / Accepted: 9 May 2013 /

Published: 21 May 2013

Abstract: The Upper Ordovician (Edenian) Lindsay Formation of the Ottawa Embayment represents the final stage of carbonate platform development in the Taconic foreland periphery inboard of the northern Appalachian orogen. The succession overlies a narrow (~60 km) axis of a Neoproterozoic Laurentian rift extending across the Grenville orogen. The Lindsay Formation consists of a lower heavily bioturbated skeletal limestone that represents a warm-water shoal facies following an underlying outer ramp stratigraphy, and an upper division of renewed deep-water deposition with organic-rich shale and fossiliferous lime mudstone. Pyritic deep-water black shale of the westerly advancing Taconic foreland basin disconformably overlies this platform succession. Stratigraphic correlation through the central embayment identifies likely syndimentary faults and seaward-directed erosion bounding the Lindsay Formation in a region of older Ordovician faults and a change in the lithotectonic character of the crystalline basement. The Late Ordovician shallowing and localization of structural/erosional features are interpreted to record a structural hinge: a local accommodation to, first, foreland periphery uplift, then rapid subsidence related to westerly diachronous foreland subsidence through the platform interior. Spatial association of structures of differing ages suggests that reactivation of inherited weakened crust influenced Late Ordovician sedimentary patterns.

Keywords: carbonate platform-to-basin transition; Taconic foreland; inherited structure

1. Introduction

In the northern Appalachian orogen, Middle to Upper Ordovician stratigraphic successions of the Taconic foreland document westerly (in today's coordinates) diachronous foundering of a once prolific shallow-water carbonate platform in response to advancing foreland-basin sedimentation [1–4]. Collapse of the platform margin was not uniform but aided by local structure (faults, synsedimentary folds), areas of abrupt subsidence, and possible mass wasting [3,5–7]. As presented here, similar local structure, and related erosion were associated with the platform-to-basin transition inboard (~200 km) of the Laurentian paleomargin and western structural limit of the Appalachian orogen.

The Upper Ordovician (Edenian) Lindsay Formation is the final stage of a foreland platform succession in the Ottawa Embayment, an erosional remnant of the foreland periphery inboard of the Sutton Mountains salient [8] (Figure 1).

Figure 1. Regional distribution of sedimentary basins, Timiskaming graben (TG), local arches (A, Algonquin; F, Findlay; and, L, Laurentian), and trace of the Ottawa Bonnechere graben (OBG) west of the Sutton Mountains salient (SMS) of the Appalachian orogen [9]. Erosional limits of basins are shown by the heavy black line. Other abbreviations: B-O, Beauharnois-Oka arch; AH, Adirondack Highlands. The position of Locality 14 (see Table 1) is shown for reference.

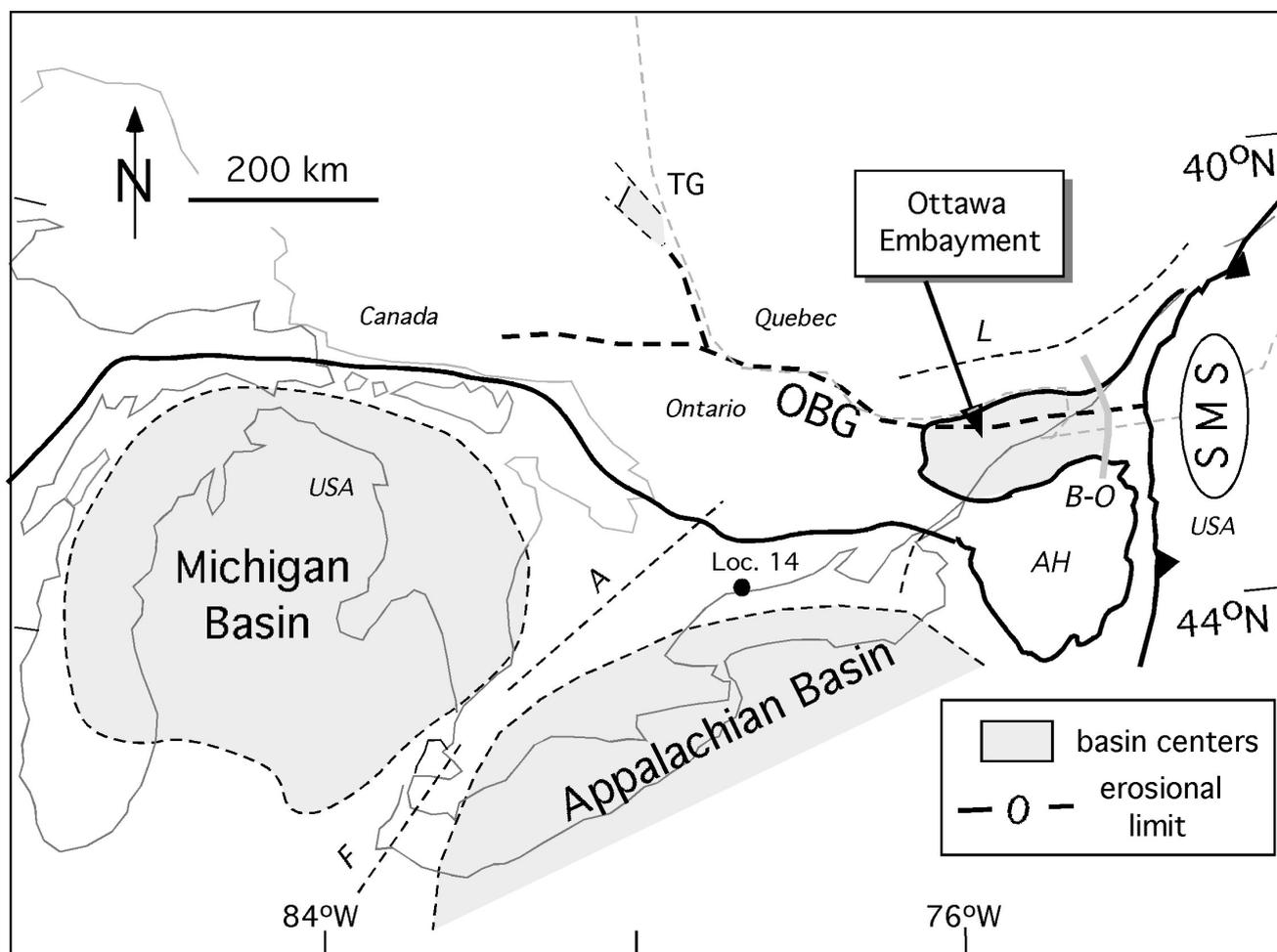


Table 1. Section localities, type (o, outcrop; c, core; q, quarry), and lithic succession. NTS easting and northing data (meters) from map sheet: Ottawa 31G, grid zone 18T.

| Location Name | Type | Formation(s) * | Easting | Northing |
|----------------------------|------|--------------------|---------|----------|
| 1 Royal Mint of Canada | o | L (NPM)/V | 445261 | 5031151 |
| 2 National Art Gallery | o | L (NPM)/V | 445430 | 5030887 |
| 2A Chateau Laurier Hotel | o | L (NPM) | 445400 | 5030500 |
| 3 GSC Billings Bridge | c | B/L(E, NPM)/V | 447360 | 5025840 |
| 4 Consumers #12417 well | c | B/L/V | 469800 | 5015200 |
| 5 GSC #2 Russell well | c | B/L(E, NPM)/V | 469400 | 5017600 |
| 6 Consumers #1772 well | c | B/L/V | 468800 | 5021000 |
| 7 Aviation Parkway | o | L (E/NPM) | 449300 | 5032050 |
| 8 Canaan Quarry | q | L (NPM)/V | 477550 | 5033200 |
| 9 SIS 10 | c | B/L (E) | 472100 | 5028000 |
| 10 Navan Quarry | q | L (NPM)/V | 469750 | 5031500 |
| 11 St. Isidore Quarry | q | L (NPM)/V | 508000 | 5022150 |
| 12 Richier Quarry | q | L (NPM)/V | 494875 | 5012780 |
| 13 Apple Hill Quarry | q | L (NPM)/V | 517760 | 5002400 |
| 14 St. Mary's Cement Plant | q | L (unnamed member) | 685350 | 4868550 |

Notes: * B, Billings Formation; L, Lindsay Formation; NPM, Nepean Point Member; E, Eastview Member; V, Verulam Formation.

The formation records initial shallowing from an underlying outer ramp facies, then conformable deepening culminating in local expression of a regional source rock, the Collingwood shale, that occurs in the Michigan and northern Appalachian basins [10–13]. The foreland platform-to-basin transition in the Ottawa Embayment is marked by local synsedimentary faulting and erosion spatially associated with the traces of older Ordovician and Precambrian structures. Reactivation of inherited crustal structures in response to distal orogenic events can be of significant influence on younger intraplate sedimentary patterns [14,15]. We interpret the Upper Ordovician facies succession and local structural and erosional events as accommodations to regional foreland periphery uplift, then subsidence driven by westerly diachronous subsidence.

2. Geological Setting

The westward curvature of the Sutton Mountains salient (SMS) [8] of the northern Appalachian orogen (Figure 1) represents a structurally modified regional indentation, the Quebec Embayment, of the original rifted Laurentian margin [16]. The Ottawa Embayment lies west of the apical region of the salient, and forms a WNW-ESE-oriented structural depression containing an ?Eldiacaran—Upper Ordovician sedimentary succession [17] that cuts across the NE-SW structural grain of the Precambrian Grenville orogen. The axis of the embayment is a narrow (~60 km) fault zone, the intracratonic Ottawa-Bonnechere graben (Figure 1) [18]. It follows the trace of a similarly narrow intracratonic structural corridor of faults, mafic dykes, and alkaline/syenitic intrusions interpreted as an aborted Neoproterozoic rift [8,9,19–21].

The ?Eldiacaran to Middle Ordovician sedimentary succession of the Ottawa Embayment contains platform-interior facies contiguous with the St. Lawrence epicontinental trailing margin of eastern

Laurentia [22]. By the Middle Ordovician, a peripheral foreland basin developed outboard of the Quebec Embayment. By the Late Ordovician, reversal of subduction polarity established a retroarc foreland basin [23]. Westerly directed diachronous foundering of the regional foreland platform spanned the Chatfieldian to early Maysvillian interval [1–4] extending as far west as the Timiskaming graben [24] in the craton interior (Figure 1). Along the Laurentian margin, initial deep-water black shale represented by the regional Utica or Indian Castle facies [1,5] is replaced by a northwesterly directed, shallowing-upward succession of oxic siliciclastic facies, an expression of a northwesterly progradational clastic wedge from the Taconic orogen [25,26].

Ottawa Embayment Stratigraphy

Post-Ordovician structure and erosion have greatly limited the distribution of the Middle to Upper Ordovician foreland succession in the Ottawa Embayment (Figure 2). The Upper Ordovician platform succession is of Turinian to Edenian age and is represented by the Ottawa Group [27] (Figure 3), a mostly limestone succession overlain by a structural remnant of a once more expansive (Maysvillian—lower Richmondian) siliciclastic foreland-basin succession (Figure 2). Initial dysoxic foreland basin deposits are represented by pyritic black shale (Billings Formation) equivalent to the Utica or Indian Head facies in Quebec and New York State, respectively (Figure 3).

Figure 2. Regional bedrock geology [9,17] showing distribution of the foreland sedimentary succession, section locations, and section transect (see Figure 5). Abbreviations: G, Gloucester Fault; RR, Rigaud-Russell Fault.

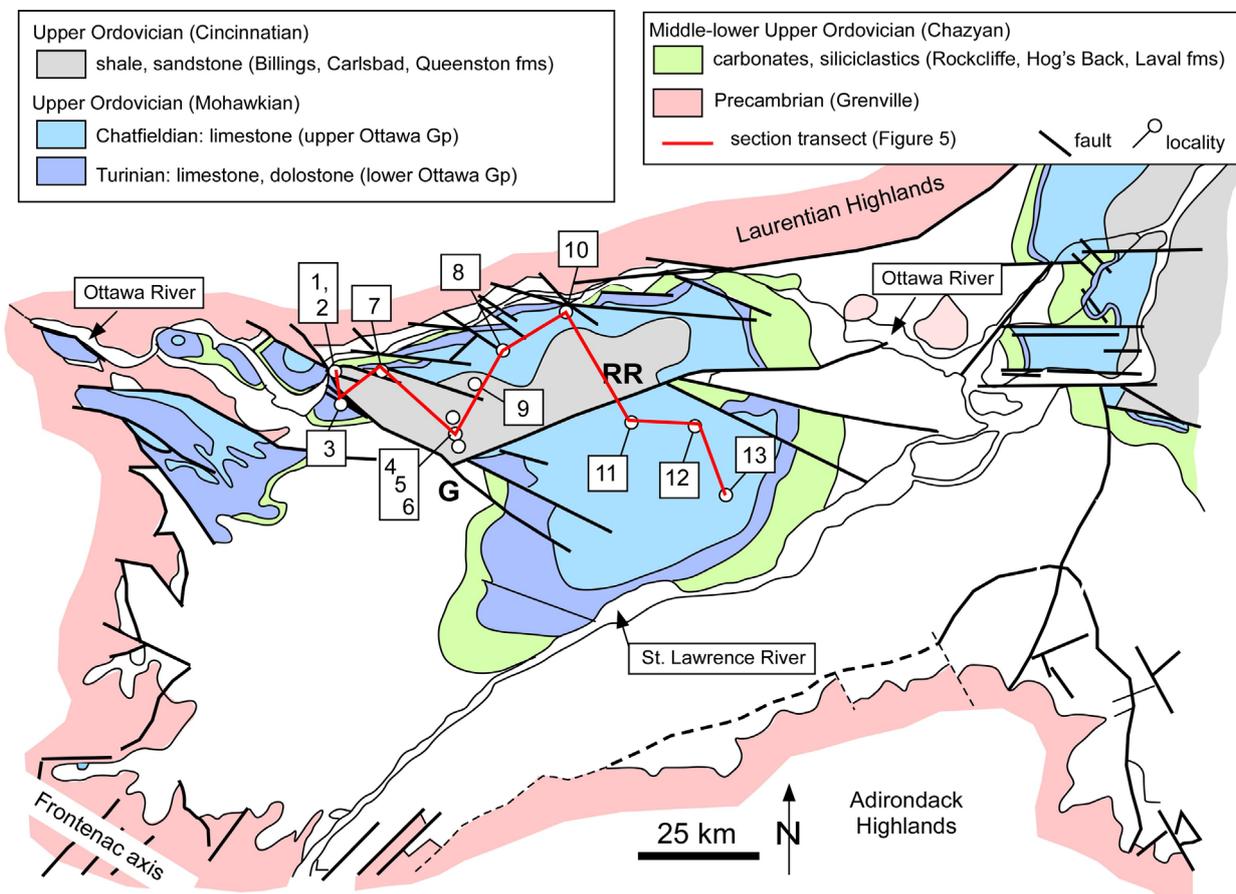
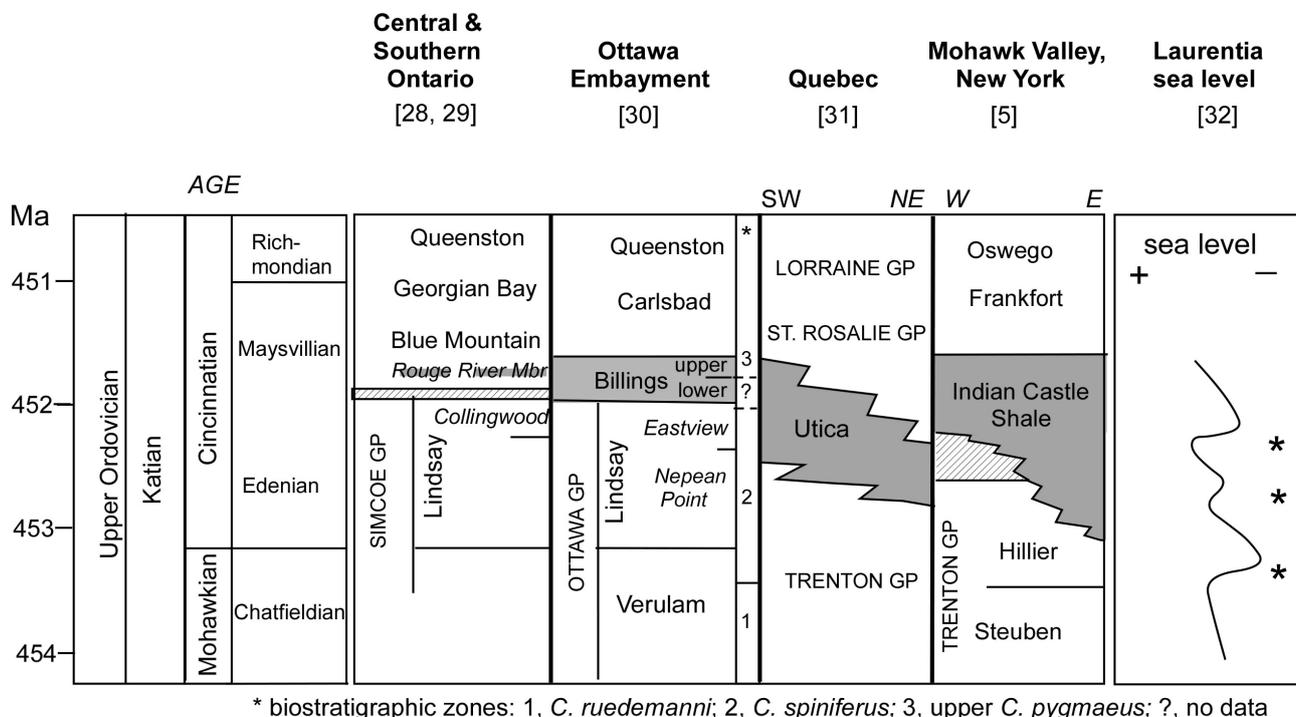


Figure 3. Upper Ordovician stratigraphy of the Ottawa Embayment and adjacent regions [28–31] shown relative to North American sea level curve [32], with large astrices illustrating periods of sea level highstands in the Baltoscandia record [32]. Existing and proposed stratigraphic members of the Lindsay Formation are indicated.



The Ottawa Group is equivalent to the combined Blackriveran and Trentonian successions of New York State (Figure 3) [33,34]. The Blackriveran succession in the Ottawa Embayment has a stronger affinity with New York State stratigraphy [35] whereas the Trentonian section is more similar to the northern Appalachian Basin [36]. Along the outcrop belt of the northern Appalachian Basin in central Ontario (Figure 1), the uppermost Trentonian unit, the Lindsay Formation, contains two stratigraphic members: an unnamed lower carbonate-rich succession overlain by interbedded organic shale and carbonate of the Collingwood Member [28,29]. This latter unit extends into the Michigan Basin, often displaying an associated phosphate-rich cap facies [12]. In the Ottawa Embayment, a similar shale-rich unit is referred to as the Eastview Member [36], and it conformably overlies an equivalent skeletal-rich lower limestone succession. This lower interval is correlated with the Tetreauville Formation of southern Quebec [37] and the Hillier Formation in New York State [38].

3. Results

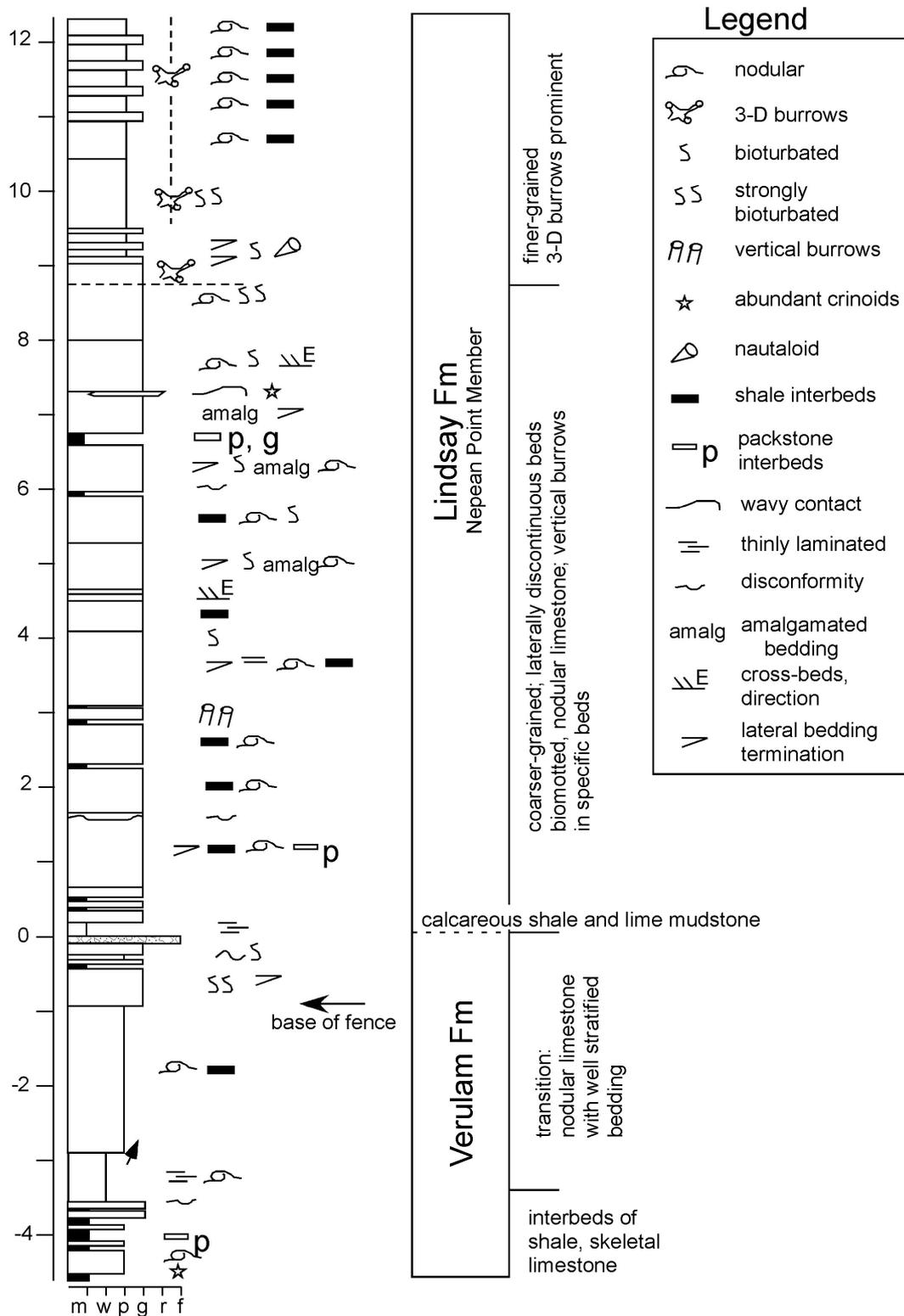
Available outcrop, core, and quarry sections (Table 1) are restricted largely to the central Ottawa Embayment (Figure 2).

3.1. The Nepean Point Member (Lindsay Formation)

We propose that the previously unnamed lower member of the Lindsay Formation in the Ottawa Embayment [36] be referred to as the Nepean Point Member, after an excellent exposure at Nepean Point (NTS Ottawa 31G, Grid Zone 18T: easting 445430, northing 5030887) in the City of Ottawa.

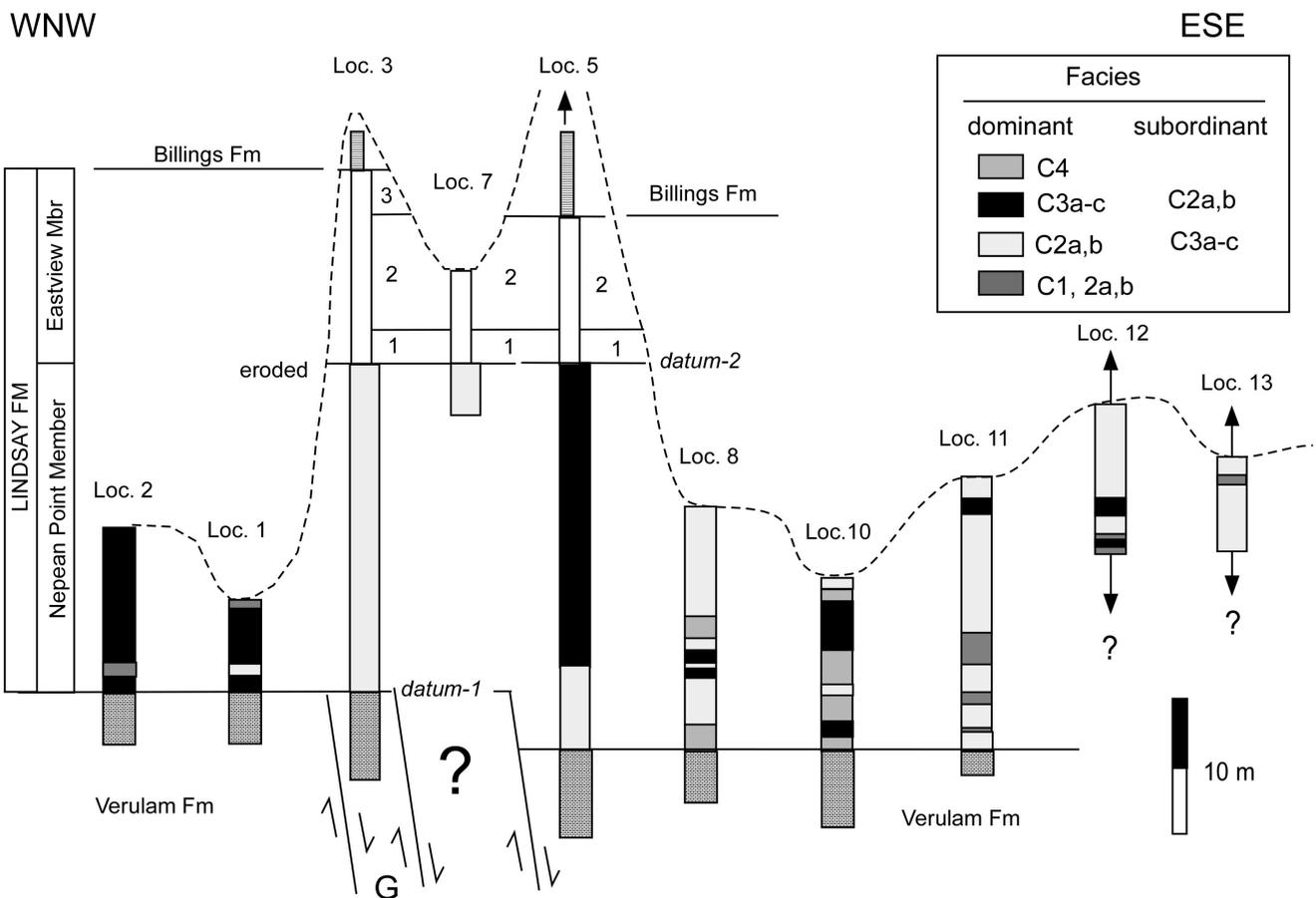
The section (Figure 4) extends along an escarpment below the National Art Gallery of Canada (Locality 2, Table 1, and is ~12.5 m thick. It contains the lower conformable contact with the Verulam Formation, and a capping erosional surface corresponding to a Quaternary glacial surface. Available biostratigraphy (macrofauna and conodonts) establish a Late Ordovician (Edenian) age [36].

Figure 4. A graphic representation of the proposed stratotype (Locality 2) of the Nepean Point Member.



We use outcrop and core sections of the Lindsay Formation to create a regional transect (Figure 2) illustrating the stratigraphic and facies distributions along the axis of the embayment (Figure 5). At the scale drawn only the most abundant facies are illustrated in a given section. The section shows that the lower (Nepean Point) member thickens by ~3 m to the east between Localities 3 and 5, a distance of ~27 km (Figure 5). The change in thickness occurs in a region containing the trace of the Gloucester Fault (Figure 2) and a change in the aeromagnetic signature of the Precambrian basement [39,40], including a possible isolated basement block beneath Locality 5 [41] (Figure 6). Over this same distance, the Eastview Member thins (~13 to ~7 m) to the east such that its uppermost (unit 3) division disappears due to an east-directed increase in depth of erosion across the top of the member (Figures 6 and 7).

Figure 5. Distribution of the dominant carbonate facies (see Table 2) of the Nepean Point Member along the regional transect, and a tripartite (units 1–3) lithic division of the Eastview Member [42,43]. Present-day fault traces are illustrated, their position scaled with respect to section localities: G, splay zone of the Gloucester Fault (see Figure 2) whereas the right-hand fault lies sub-parallel to the Gloucester Fault [39].



In the northern Appalachian Basin, the Lindsay Formation thickens toward the basin centre from ~55–60 m in the outcrop belt [28] to ~92–95 m near Lake Ontario in southern Ontario (Locality 14, Figure 1) [43]. The Lindsay Formation thickens from ~38 m in the Ottawa Embayment to its equivalent succession of ~125 m in southern Quebec [36], but the gradient is about the same. In contrast to this common basin-directed thickening, the succeeding upper unit of the Lindsay Formation in the northern Appalachian Basin, the Collingwood Member, and its equivalent in the northern

Michigan Basin, thin and disappear basinward from a maximum thickness of ~12–14 m [12,44]. This is a similar maximum thickness to the preserved (~13 m, Figure 7) thickness of the equivalent Eastview Member in the Ottawa Embayment.

Initial foreland-basin sediments of the Billings Formation (Figure 2) are exposed only during construction excavations, but a complete section is preserved in continuous core at Locality 5 [42,45]. Gamma-ray well-log correlation, based on a cluster of gas-test wells in the vicinity of this well site, which lies adjacent to the trace of the Gloucester Fault, revealed local synsedimentary faults that offset the Eastview Member and coincide with deposition of the deep-water facies [42].

Figure 6. Intraformational correlation of the Lindsay Formation, shown relative to lithotectonic terrane boundaries of the underlying Grenville orogen [9] and positions of present-day fault traces. Abbreviations: CMB, Central Metasedimentary Belt; terrane names: M, Morin; SL, Sharbot Lake; F, Frontenac; AL, Adirondack Lowlands; AH, Adirondack Highlands. The greyed region of the inset map identifies the subsurface continuation of the Morin-Adirondack Highland beneath sedimentary cover based on aeromagnetic properties [40,41].

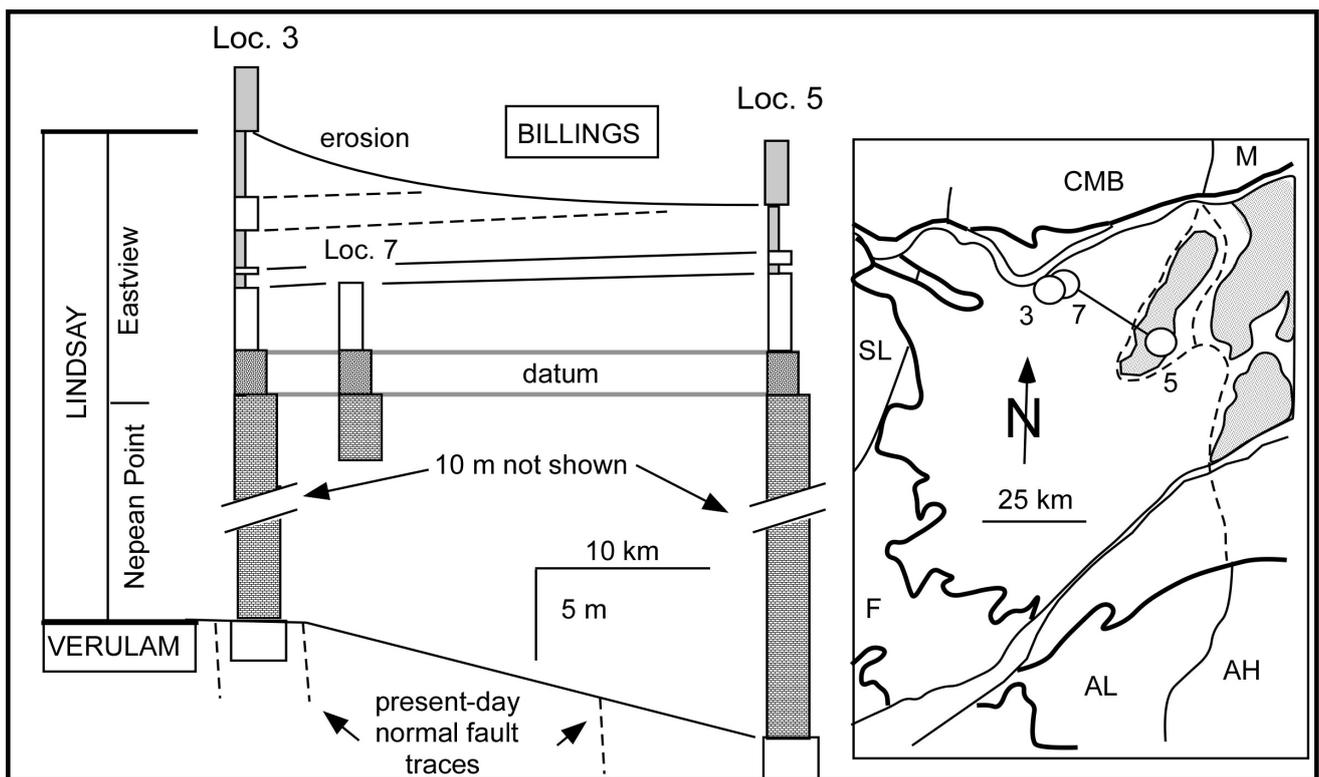
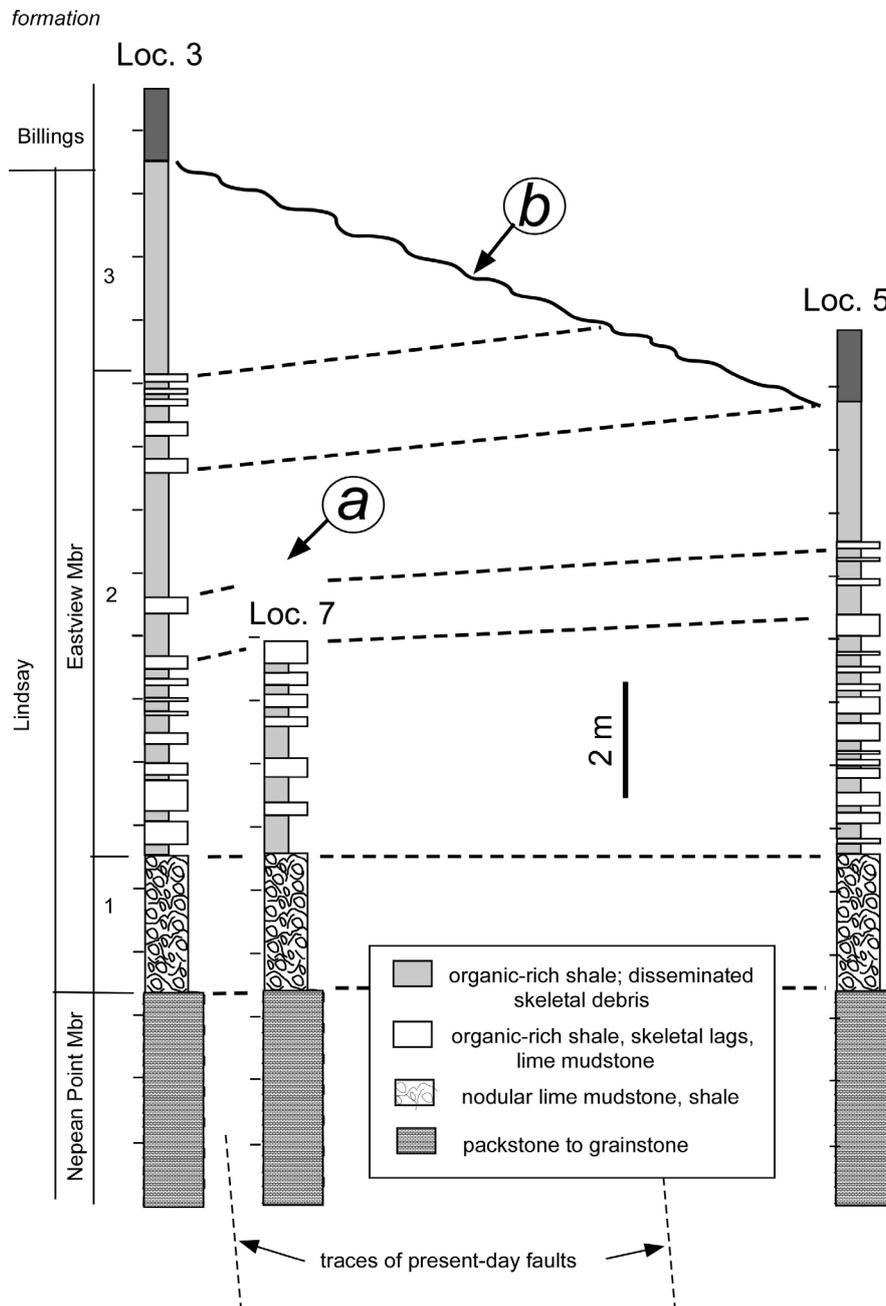


Figure 7. Detailed stratigraphy of the Eastview Member showing vertical succession of a changing carbonate-shale partitioning; a possible thickening between Localities 3 and 7 (a); and a disconformity (b) with an east-directed increase (~6 m) in stratigraphic omission.



3.2. Lithofacies Succession of the Nepean Point Member (Lindsay Formation)

In the Ottawa Embayment, there is a conformable transition from the underlying Verulam Formation (Figure 2) that is quite distinctive, characterized by finely interstratified, and often graded, grainstone, calcisiltite, and shale [46]. The base of the Nepean Point Member is a relatively thick (<10 cm) shale (Figure 4; datum-1 in Figure 5) that overlies a coarse skeletal and lithoclastic rudstone.

Three prominent characteristics of the member are its apparent metre-scale stratification (Figure 8A), with bedding breaks highlighted by increased siliciclastic content, a prominent nodular (bioturbation) fabric (Figure 8B), and a relatively uniform facies assemblage (Table 2).

Figure 8. Facies character of the Nepean Point Member stratotype (Locality 2). **(A)** View of the middle part of the section highlighting the apparent metre-scale stratification. Vertical view is about 10 m. **(B)** Nodular facies C3a with intervening thin bed (arrow) of facies C3c that is about 10 cm thick. **(C)** Thin laminated skeletal-rich beds (facies C3c) terminating laterally within the nodular facies, C3. Some burrows extend down from the tops of the thin beds. Scale card is marked in centimetres. **(D)** Well-developed vertical burrows in packstone; measuring rod is 1.2 m long. **(E)** 3-dimensional burrow networks in wackstone (facies 2) highlighted (yellowish brown) by presence of weathered dolomite and silt-size siliciclastics. Scale card is marked in centimetres.

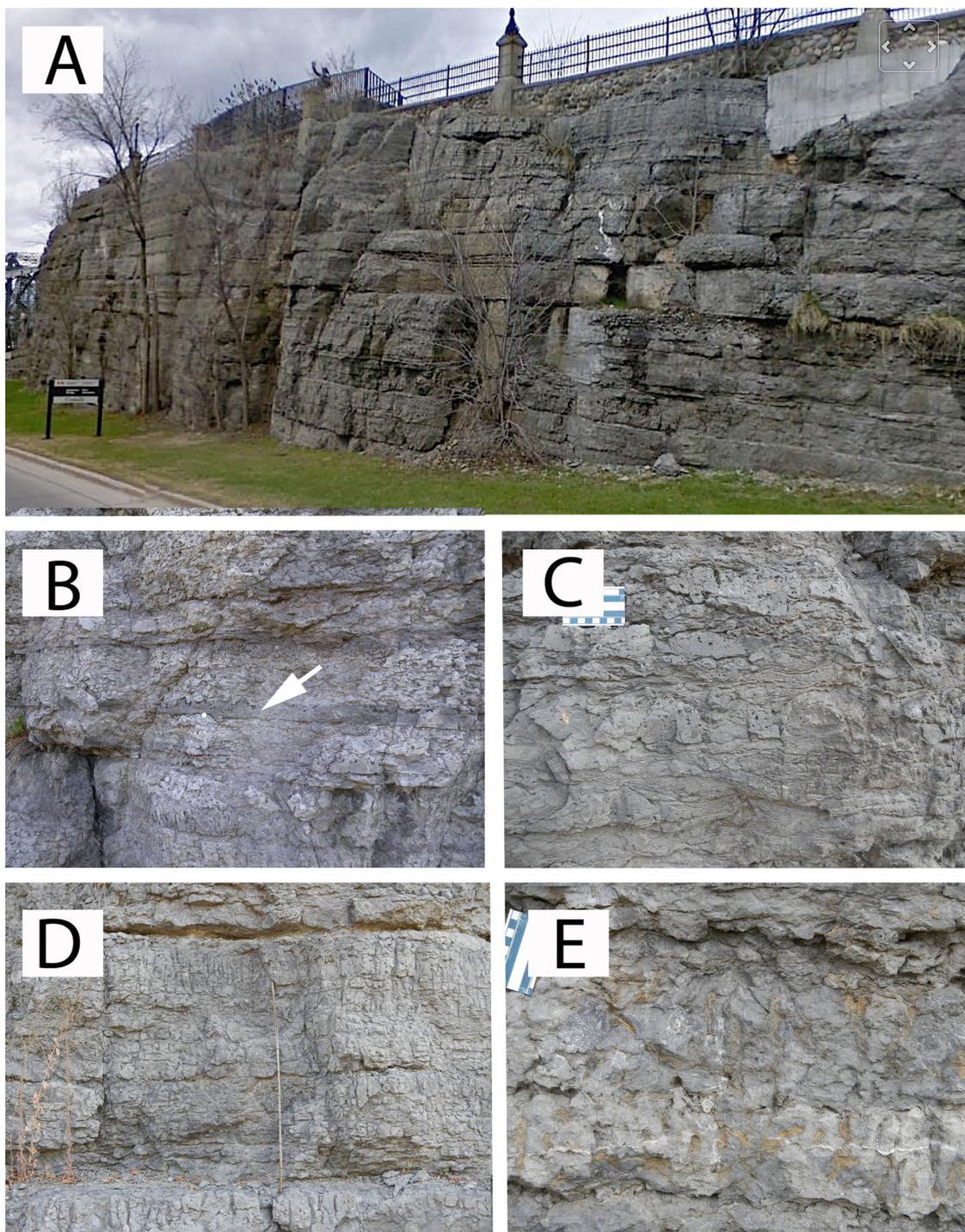


Table 2. Carbonate facies characteristics, Lindsay Formation.

| Facies | Features | Fossils/Clasts | Environment |
|---|--|---|---|
| C1: Bioclastic argillaceous mudstone | massive beds, 5–30 cm thick; gradational boundaries | crinoids, skeletal hash | subtidal, above storm wave base (SWB); normal marine; mid ramp |
| C2A: Bioclastic mudstone to wackestone | massive beds, 10–40 cm thick; sharp to gradational boundaries | crinoids, bivalve molds, brachiopods, skeletal hash | subtidal, above SWB; normal marine; moderate energy; mid ramp |
| C2B: Nodular bioclastic mudstone to wackestone | 5–100 cm thick beds; nodular, with shale partings; bioturbated; sharp to gradational boundaries; local dolomite | crinoids, bivalve and gastropod molds, trilobites, intraclasts, skeletal hash | subtidal, fair weather wave base (FWWB) to SWB; normal marine; moderate energy; mid ramp |
| C3A: Nodular bioclastic packstone to grainstone | beds are 10–90 cm thick; nodular biomottling locally overprints primary cm-scale stratification; erosional surfaces; sharp to gradational boundaries | similar to C2B; with bryozoans, clasts of indeterminate microbial calcite; rare <i>Vermiporella</i> sp.; <i>Girvanella</i> ; <i>Skolithos</i> isp, and 3-D burrow networks; | subtidal, above FWFB; normal marine; moderate to high energy, shoal environment?; inner ramp |
| C3B: Nodular crinoid-rich packstone to grainstone | beds are 10–70 cm thick; nodular biomottling with shale partings; overprints primary stratification | As in C3A, but very abundant crinoids | subtidal, above FWFB, normal marine; moderate to high energy; shoal environment; inner ramp |
| C3C: Bioclastic packstone to grainstone | beds are < 15 cm thick; often laminated; local dune cross-beds | as in C3A | subtidal, above FWFB; normal marine, high energy; inner ramp |
| C4: Bioclastic floatstone | beds are 10–30 cm thick; fine to coarse-grained wackestone to packstone; gradational boundaries | as in C3A | subtidal, normal marine; rip-up clasts of lithified seafloor, rapid deposition; storm deposit |
| C5: Bivalve/brachiopod rudstone | dark grey to black; beds are < 5 cm thick; densely packed skeletal grains; sharp base, gradational to abrupt top | bivalve molds; brachiopods; trilobites (<i>Triarthrus</i> sp.; <i>Pseudogygites</i> sp.) | skeletal condensation in shale and capping facies C1; low accumulation rates; below SWB; outer ramp |

Facies distribution along the stratigraphic transect (Figure 5) suggests two areas dominated by coarser textured (packstone, grainstone) facies (C3, Table 2), including Locality 5 which lies adjacent to the trace of the Gloucester Fault and its splays (Figure 5). Although metre-scale breaks are visually dominant, closer inspection reveals an often cm-scale stratification locally obliterated by bioturbation along beds. Nodular intervals of packstone to wackestone are abruptly interbedded with thin-bedded grainstone to packstone that are often also well laminated (Figure 8B). Beds without nodules extend over meters to tens of meters, either pinching out laterally or truncated by bioturbation (Figure 8C). They usually display abrupt bases and bioturbated tops. Low-angle cross beds oriented both to the east

and northwest are rarely developed, but large ($H = 10$ cm, $\lambda = 1$ m) poorly exposed megaripples with ENE-WSW oriented crests occur in facies C3C at Locality 2B. This locality is structurally juxtaposed to the stratotype (Locality 2A), but its relative stratigraphic position remains uncertain. Wackstone and mudstone facies of the Nepean Point Member illustrate lesser fragmentation of allochems, and a greater amount of bioturbation. To the east, there is a general increase in abundance of silt-size carbonate and micrite, more shaley partings to thin beds of shale, a greater amount of disseminated silt-size siliciclastics in carbonate, and less crinoidal debris [43].

Nodularity is a function of bioturbation, and three forms are present. Biomottling is most typical, but packstone and grainstone beds often exhibit densely distributed vertical (*Skolithos*-like) burrows (Figure 8D), often overlain by a thin shale parting. Three-dimensional burrow networks (Figure 8E) predominate in muddier wackestone to packstone intervals, and often weather yellowish due to crystals and crystal mosaics of anhedral to subhedral ferroan dolomite [43]. All burrows usually contain an elevated amount of micrite, skeletal debris, and silt- to sand-size siliciclastics relative to adjacent non-bioturbated sediment.

Grain types in the Nepean Point Member include strongly fragmented skeletal material, microcrystalline peloids, and grainstone lithoclasts (Figure 9A–C). Skeletal material includes crinoidal debris; calcitized bivalve fragments of with micritized margins (Figure 9D); molds of gastropods filled with two generations (non-ferroan, then ferroan) of burial calcite cement [43]; brachiopods, bryozoans, and trilobites; rare nautiloids and rare fragments of the dasycladacean alga *Vermiporella* sp. with micritic fill (Figure 9E). Syntaxial overgrowth cement on crinoid fragments (Figure 9A) provided a rigid framework for development of gastropod molds. There are irregular to spherical bodies of micritic carbonate that occur individually, and others that form short chains (Figure 9C,F). The latter are similar to the alga *Halysis* sp. [47,48], which is widespread in the Ordovician succession of the St. Lawrence Platform [48]. However, these chains, and especially individual bodies, may be *Rauserina*, as they are similar to forms described previously from the equivalent platform succession in eastern Canada [48]. Fragments of the cyanobacteria *Girvanella* form lithoclasts, and indeterminate microbial carbonate consisting of small cellular (coccooid) to tubule geometries occur as thin (6 to 60 μm) discontinuous microlaminae on skeletal grains [49].

3.3. Lithofacies Succession of the Eastview Member (Lindsay Formation)

The unit marks an abrupt appearance of dark-brown to brownish-grey shale, with total organic carbonate (TOC) percentages ranging up to 4% [42,45]. The shale contains a similar mineralogy as siltstone in the Nepean Point Member [43], but with an increased Ni/Cr ratio that suggests influence of sediment derived from a volcanic-arc source positioned along the plate boundary [45]. Shale abundance increases upsection coincident with a change in fabric partitioning relative to carbonate. This produces a vertical tripartite succession (Figures 5–7) [42]: Unit 1 consists of a nodular fossiliferous lime mudstone with shale differentially compacted around the nodules (Figure 10A); Unit 2 consists of interstratified calcareous to non-calcareous shale and limestone (Figure 10B), with beds of each being 10–40 cm thick; and, Unit 3 consists of mostly massive non-calcareous to calcareous shale, with layers of disseminated skeletal detritus.

Carbonate beds are mostly poorly fossiliferous lime mudstone, but some of these are capped disconformably by thin (<2 cm) beds of densely compacted skeletal rudstone (facies C5, Table 2, Figure 9C). This latter stratigraphic position suggests development of a shelly pavement subsequently buried by shale.

Crinoids, brachiopods, and trilobites (*Triarthrus* sp., and *Pseudogygites* sp.) [45,50] are present in mudstone, and trilobite fragments (mostly pygidia) contribute to the shelly rudstone facies. Rare fragments of the dasycladean *Vermiporella* sp. along with lithoclasts of *Girvanella* sp. are also present.

Figure 9. Petrographic characteristics of the Nepean Point Member. (A) Crinoid-rich microfacies with abundant intergranular iron-poor (pink) syntaxial calcite on echinoderm fragments. Scale bar = 50 microns. (B) Skeletal packstone with fragment possibly of *Halysis* sp. (arrow), shown in detail in (F); scale bar = 50 microns. (C) Abundant micritic lithoclasts in a skeletal-crinoidal grainstone. The lithoclasts are likely reworked from lower energy carbonate mudstone. Scale bar = 50 microns. (D) Micrite border of a now calcitized bivalve fragment; scale bar = 500 mm. (E) Fragment of the dasycladacean *Vermiporella* (based on comparison with Upper Ordovician algae [48]; scale bar = 125 mm. (F) Fragment of a microfossil that may be *Halysis* or *Rauserina* [48]; scale bar = 10 microns.

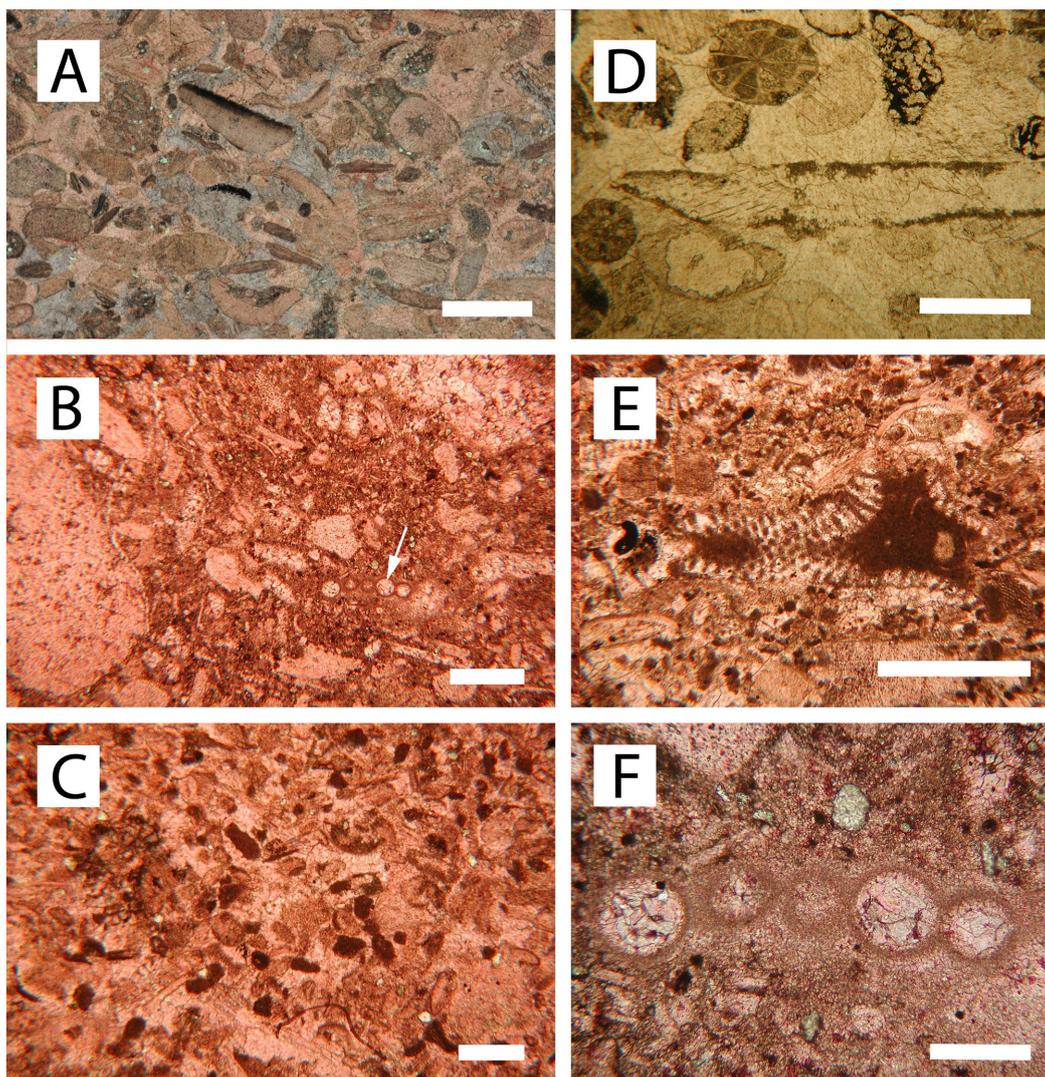
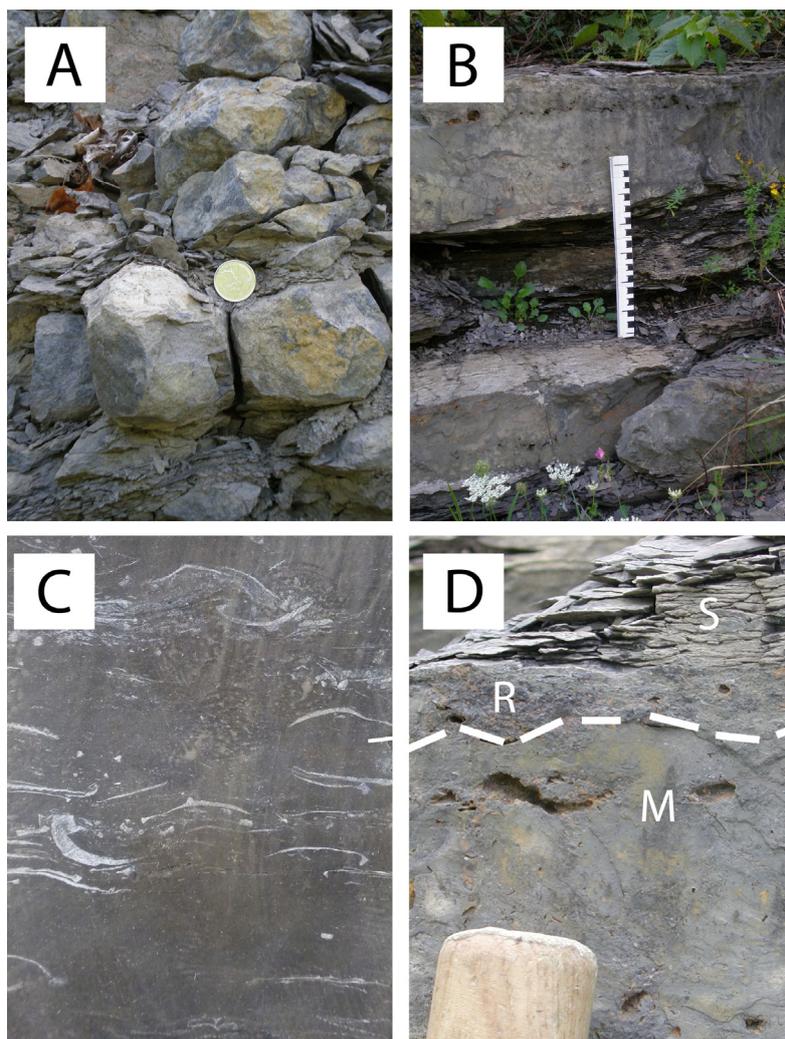


Figure 10. Facies partitioning in the Eastview Member, Lindsay Formation, Locality 7. (A) Unit 1, nodular fossiliferous mudstone with thinly intercalated shale. Coin is 2.4 cm in diameter. (B) Unit 2, planar stratified shale and fossiliferous lime mudstone; vertical scale bar is marked in centimetres. (C) Unit 3, core section of fossiliferous mudrock with disseminated fossil material; width of view is 4 cm. (D) Skeletal rudstone (R) disconformably overlying lime mudstone (M), and overlain by shale (S); hammer handle width is 4 cm.



3.4. Lithofacies of the Billings Formation

The prominently pyritic black to dark grey shale is laminated to thinly bedded, and contains TOC percentages fluctuating between 1 and 6 wt % [42]. A lower division of the formation is mostly claystone, and associated paleoceanographic proxies identify a largely dysoxic environment [45]. An upper division contains lighter (dark grey) mudrock, and its base is defined by the appearance of laminae of siltstone and fine-grained sandstone interbedded with claystone. This vertical transition characterizes the appearance of the distal part of the westerly migrating Taconic clastic wedge [45]. Fossils are few in the lower Billings Formation, but include locally pyritized orthocones, trilobites (*Triarthrus* sp.), graptolites, and bivalves. Paleoceanographic proxies demonstrate a largely dysoxic seafloor environment for initial deep-water sedimentary facies [45].

4. Discussion

The transition from carbonate platform to siliciclastic basin in the Taconic foreland periphery preserved in the Ottawa Embayment records an environmental succession of temporary shallowing bounded by local structural and erosional processes. These attributes are interpreted as a coupled response to changing patterns of uplift and subsidence driven by distal Taconic collisional tectonics.

4.1. Regional Shallowing of a Carbonate Ramp

The consecutive stratigraphic transitions from, first, the upper Verulam to lower Lindsay formations, then Nepean Point to Eastview members of the latter formation document an apparent conformable record of initial shallowing, then deepening. In both the northern Appalachian Basin and Ottawa Embayment, the Verulam Formation forms a storm-dominated, open-marine ramp succession with intercalated thin-bedded tempestites, hardgrounds, and shoal deposits, all with intervening (background) shale [46,51]. In the northern Appalachian Basin, a shift from distal to proximal storm deposits records a shallowing upward succession in the craton interior [52].

Carbonate lithofacies of the Nepean Point Member (Lindsay Formation) in the Ottawa Embayment identifies a relatively sustained energetic normal-marine setting that was punctuated by periods of intense bioturbation associated with finer-grained (lower energy) facies and an increased abundance of fine-grained disseminated siliciclastics. Discrete shale beds are rare. Grainstone lithoclasts identify local cementation possibly related to scouring of the seafloor and exposure of the near-surface cemented by abundant intergranular (echinoderm) syntaxial calcite (Figure 9A). Fragmented bioclasts (Figure 9A,C) in such a high-energy setting may represent mechanical reworking, but they may also reflect some influence of arthropod (e.g., trilobite) predation [53]. In this type of setting, vertical burrows (Figure 8D) may demonstrate relatively unstable depositional surfaces through constant sediment transport and/or erosion of the seafloor [54]. The presence of finely (cm-scale) stratified well-sorted sediment, the fabric of which was locally obliterated by biomottling, suggests that there was an abrupt change in the depositional system from a substrate initially subject to high-frequency sediment mobility to one of intense bioturbation.

Similar biomottled fabric characterizes many contemporary Upper Ordovician platform successions in North America [55]. For the Lindsay Formation in the Ottawa Embayment, an association of fine-grained, silt-sized, siliciclastic material with biomottling suggests that in a setting wherein an overall elevated energy level excluded significant accumulation of siliciclastics, episodic slackening of energy allowed both bioturbation and accumulation of a background level of fine-grained siliciclastics.

The common presence of crinoid debris in all facies illustrates a sustained normal-marine succession. Other attributes, such as the local abundance of micrite (Figure 9B), micritized margins of now calcitized aragonite shells (Figure 9D), and calcareous (dasycladacean) algae (Figure 9E), help to identify a warm-water setting [56] that lay within the photic zone. In modern tropical settings, dasycladaceans are rare in high-energy deposits, and prefer more protected environments known to extend to ~90 m [57–61]. During the Ordovician, however, these algae occupied a greater environmental expanse, including barrier settings [48]. The presence of intraskeletal micrite

(Figure 9E) suggests that these algae were reworked from a lower energy facies, possibly packstone and wackestones interbeds.

The Eastview Member records a shift to lower energy conditions with prominence of carbonate mud and increase in abundance of variably organic-rich shale. Limestone-shale rhythmic deposition is a consistent pattern of offshore marine mixed facies in the Phanerozoic [62–64]. Metre-scale patterns of shale and carbonate interstratification in the equivalent Collingwood Member have been interpreted as evidence of a likely eustatic control superimposed on a net deepening upward succession from the lower Lindsay Formation [13]. Such a control may also explain the stratification of the Eastview Member, but is associated with lateral transport and accumulation of siliciclastics with an apparent volcanic-arc signature [45]. The presence of a disconformity capping the Eastview Member (Figure 7) precludes knowing if there was a phosphatic cap rock as is often present along the top of the equivalent Collingwood Member in the northern Appalachian and Michigan basins [12,13].

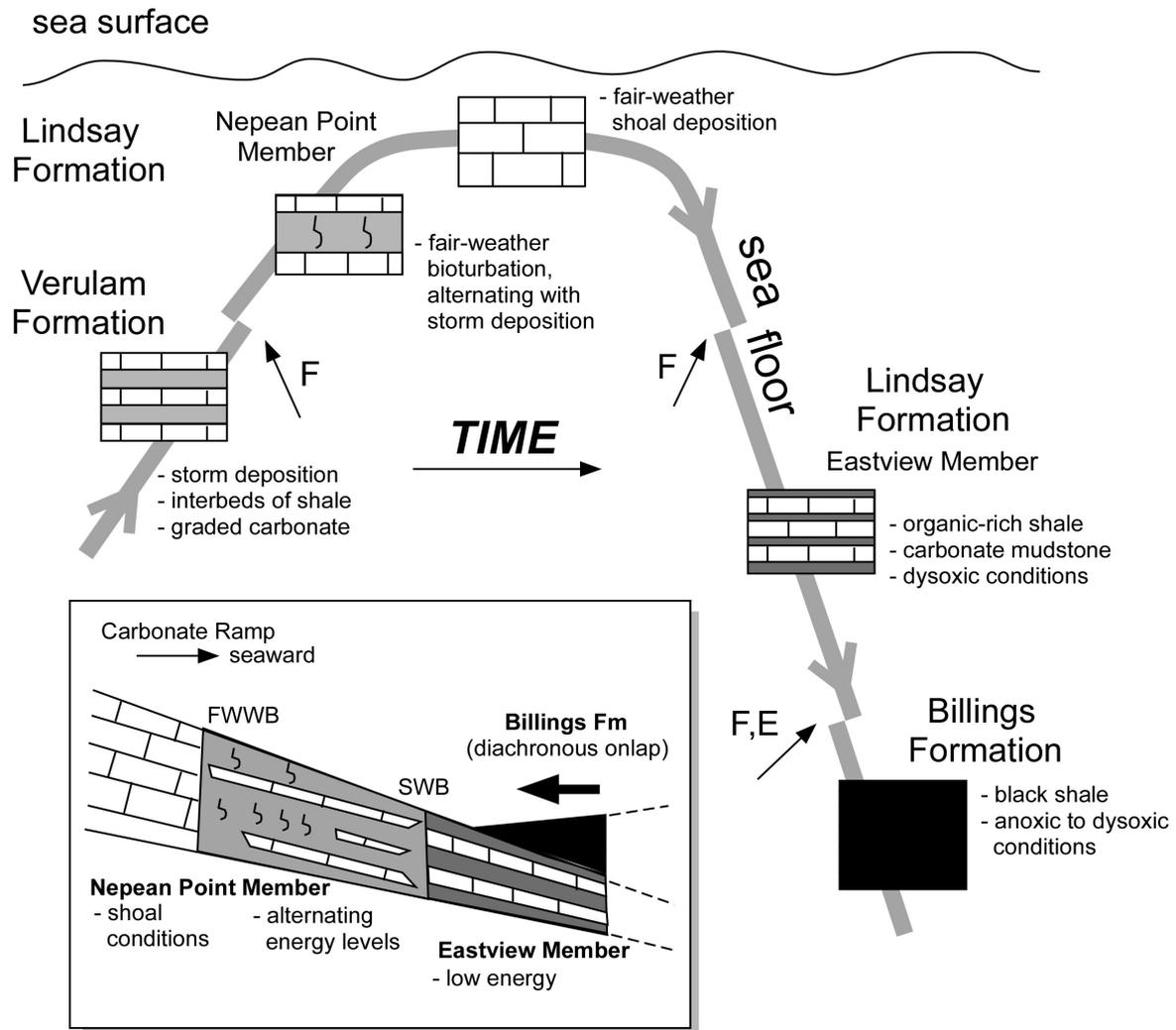
We interpret the distribution of carbonate and siliciclastic facies of the upper Verulam, Lindsay, and lower Billings formations in the context of a regional carbonate ramp [65]. From this emerges a temporal pattern of changing water depths through time (Figure 11). The Verulam Formation represents deposition along a storm-dominated middle to outer ramp [46], and the Nepean Point Member represents shallower water deposition. Its warm-water facies contrasts with an apparent record of cool-water facies spanning most of the Trentonian succession along eastern Laurentia [66–69]. The Eastview Member documents conformable deepening into a lower energy outer-ramp setting. The deeper water Billings Formation disconformably overlies this platform succession.

4.2. Stratigraphic Response to Eustasy or Tectonics?

Ordovician sea level curves for Laurentia and adjacent Baltoscandia [32] identify an abrupt decrease across the Chatfieldian—Edenian boundary, and a progressive increase through the Edenian (Figure 2). This record appears to match the regional stratigraphic succession of the Verulam—Lindsay succession extending across the Ottawa Embayment and northern Appalachian Basin. However, we present evidence for coincidental influence of regional and local (Ottawa Embayment) tectonism that is interpreted to demonstrate that base-level change was strongly influenced by tectonism.

In the Ottawa Embayment, an upper Chatfieldian bentonite in the Verulam Formation is correlated across the Laurentian platform from margin to the interior Michigan Basin [30]. The stratigraphic position of this bentonite correlates shallowing in the upper Verulam Formation in the northern Appalachian Basin with abrupt subsidence and backstepping (~50 km) of the Laurentian margin along the Quebec Embayment [30]. Above this marker unit, the upper Verulam Formation and the Lindsay Formation thicken from the western Ottawa Embayment seaward into southern Quebec [30] where the latter formation is equivalent to the shaley Tetreauville Formation [36,37]. Sustained seaward subsidence was matched by relative interior uplift allowing accumulation of the relatively high-energy facies of the Lindsay Formation in the interior Ottawa Embayment and along the northern Appalachian Basin. This regional difference might identify large-scale tilting of the Laurentian platform, similar to the interpreted record of regional subsidence along eastern Laurentia marking the initial Chatfieldian period [70].

Figure 11. Interpreted change in relative water depth with time during the accumulation of the Verulam, Lindsay, and Billings formations in the Ottawa Embayment. Lateral facies distribution is configured to fit a carbonate ramp model [65]. Faulting (F) and erosional (E) events are indicated by arrows and the offsets along the seafloor path. Other abbreviations: FWWB, fair weather wave base; SWB, storm wave base.



In this structural context, the local east-directed thickening of the Nepean Point Member and erosion capping the Eastview Member can represent stratigraphic accommodation across a structural hinge related to regional differences in subsidence/uplift. The sense of movement (down to the east) of the interpreted normal faults (Figure 5) is compatible with other syndepositional extensional fault systems developed during foreland platform foundering along the Laurentian margin [6]. In absence of a normal fault system, development of an inclined surface between Localities 3 and 5 could illustrate preferred subsidence to the east compared to the western sector of the embayment. Both scenarios would generate the margin of a relative syndepositional paleobathymetric high east of Locality 3 (Figure 5). The high-energy (C3) facies at Locality 5 lies seaward of this structure, and may have established some barrier shoal facies behind which the lower energy C2 facies accumulated at Locality 3 (Figure 5).

Similar bathymetric differences may have influenced the geometry of the post-Eastview disconformity. The erosional surface may define an easterly directed listric surface as illustrated in Figure 6, a planar easterly dipping surface (Figure 7), or a horizontal surface vertically offset across a down-to-the east normal fault. The first and second geometries could lead to development of a slide scar with east-directed mass wasting. This might explain the east-directed increase in stratigraphic omission. Evidence of synsedimentary faults and a small-scale graben centred about Locality 5 [42] demonstrates a likely irregular paleobathymetry across the foundering platform. A slide scar has also been postulated to characterize the equivalent platform-basin transition in part of New York State [7]. The third scenario requires east-directed uplift in order to erode down into the Eastview Member. Whereas such a directed change is counter to the deepening-upward record of the Lindsay Formation (Figure 11), it may be a signature of ongoing differential faulting/uplift across the foundering platform.

From the above discussion, the Verulam-Lindsay stratigraphic succession fits a local tectonic framework governed by, first, regional uplift, and then subsidence related to evolution of the Taconic foreland basin. Shallowing from an outer-ramp position can be explained by peripheral uplift coincident with increased subsidence along the distal active plate boundary driven by structural loading [71–74]. Re-appearance of deeper water facies, as illustrated by the Eastview Member, records initial impact of the westerly migration of the foreland basin and coincides with increased Ni/Cr ratios recording the first evidence of influx of Taconic volcanic-arc sediment [45]. Deposition of the foreland –basin shale of the Billings Formation likely followed a more accelerated subsidence rate coupled with local faulting and erosion. These local structural and erosional features were byproducts of a regional crustal wave, a peripheral bulge, migrating towards the craton interior [1,3,6,7].

4.3. The Significance of Buried Structure

Evidence of the local structural and erosional processes described above occur in a 27-km wide region that contains the present structural traces of the regional Gloucester Fault (Figure 2) and a NNE-SSW-oriented lithotectonic boundary in the Precambrian (Grenville) basement (Figure 6). The Gloucester Fault has a NW-SE strike and forms an apparent structural boundary between NW-SE-oriented basement fabric of the aborted Neoproterozoic rift beneath the western Ottawa Embayment and an E-W-oriented basement fabric extending farther east to the structural limit of the Appalachian orogen [41]. Paleostress analysis of several faults in the Ottawa Embayment, including the Gloucester Fault [75], demonstrated movement during Late Ordovician (Taconic) and Late Devonian (Acadian) periods of orogeneses, as well as during Mesozoic opening of the Atlantic Basin. Recent stratigraphic analysis [41] has revealed movement along the Gloucester Fault, or formation of faults in its vicinity, during the latest Cambrian-earliest Ordovician, Middle Ordovician, and, as noted above, coincident with foundering of the Late Ordovician platform [42].

Older (Precambrian, Cambro-Ordovician) buried structures, therefore, define a zone of weakness across which the crust may have responded differentially to regional stress patterns associated with younger convergent tectonism along the Laurentian margin. There are many examples of reactivated buried structure influencing sedimentation patterns of younger basins related to change in the character of distal plate-boundaries [14,15]. For the Ottawa Embayment, an apparent local spatial association among Precambrian structure and successive generations of Ordovician faults may demonstrate that

the interpreted local stratigraphic accommodation in the Late Ordovician was a function, in part, of a response of buried and weakened continental crust to changing patterns of younger (Late Ordovician) regional stress; in this case, the Late Ordovician westerly migration of rapid subsidence associated with Taconic orogenesis.

5. Conclusions

The Upper Ordovician (Edenian) Lindsay Formation is the final Taconic foreland platform succession in the Ottawa Embayment. The lower, newly proposed, Nepean Point Member represents a moderate-to high-energy, warm-water, ramp facies that documents shallowing from a preceding outer-ramp facies, and precedes renewed deepening represented by the overlying Eastview Member that contains interbedded carbonate mudstone and shale platform facies. Foreland-basin siliciclastics (Billings Formation) lie with disconformity on this platform succession. An interpreted tectonic control for regional shallowing followed by deepening is migration of foreland-interior uplift associated with westerly diachronous subsidence driven by structural loading along the Laurentian plate boundary. Development of a structural hinge, marked by local structural and erosional anomalies in the central embayment, separates initial cratonward uplift from subsequent seaward subsidence and coincides with the location of inherited buried structure. This latter association suggests that weakened crust may have influenced local stratigraphic accommodation in response to a distal tectonic driver.

Acknowledgements

This paper is based on the senior author's Master's thesis. Funding was provided by an NSERC Discovery grant to G.R. Dix. We thank the Geological Survey of Canada (Ottawa) for access to cores held at their Tunney's Pasture facility; the various quarry owners; and two anonymous journal reviewers for their comments that improved the manuscript.

References

1. Lavoie, D. Diachronous collapse of the Ordovician continental margin, eastern Canada: Comparison between the Quebec Reentrant and the St. Lawrence Promontory. *Can. J. Earth Sci.* **2007**, *31*, 1309–1319.
2. Lavoie, D. Appalachian Foreland Basin of Canada. In *Sedimentary Basins of the World-United States and Canada*; Miall, A.D., Ed.; Elsevier: Amsterdam, the Netherlands, 2008; pp. 64–104.
3. Knight, I.; James, N.P.; Lane, T.E. The Ordovician St. George unconformity, northern Appalachians: The relationship of plate convergence at the St. Lawrence Promontory to the Sauk/Tippecanoe sequence boundary. *Geol. Soc. Am. Bull.* **1991**, *103*, 1200–1225.
4. Ettensohn, F.R. The Appalachian foreland basin in eastern United States. In *The Sedimentary Basins of the United States and Canada*; Miall, A.D., Ed.; Elsevier: Amsterdam, The Netherlands, 2008; pp. 105–162.
5. Brett, C.E.; Baird, G.C. Revised stratigraphy of the Trenton Group in its type area, central New York State: Sedimentology and tectonics of a Middle Ordovician shelf-to-basin succession. *Phys. Chem. Earth* **2002**, *27*, 231–263.

6. Bradley, D.C.; Kidd, W.S.F. Flexural extension of the upper continental crust in collisional foredeeps. *Geol. Soc. Am. Bull.* **1991**, *103*, 1416–1438.
7. Jacobi, R.D.; Mitchell, C.E. Geodynamical interpretation of a major unconformity in the Taconic foredeep: Slide scar or onlap unconformity? *Phys. Chem. Earth* **2002**, *27*, 169–201.
8. Rankin, D.W. Appalachian salients and recesses: Late Precambrian continental break-up and the opening of the Iapetus Ocean. *J. Geophys. Res.* **1997**, *81*, 5605–5619.
9. Bleeker, W.; Dix, G.R.; Davidson, A.; LeCheminant, A. Tectonic Evolution and Sedimentary Record of the Ottawa-Bonnechere Graben: Examining the Precambrian and Phanerozoic History of Magmatic Activity, Faulting and Sedimentation. In Proceedings of Geological Association of Canada–Mineralogical Association of Canada–Society of Economic Geologists (U.S.)–Society for Geology Applied to Mineral Deposits Joint Annual Meeting, Ottawa, Canada, 25–27 May 2011; Guidebook to Field Trip 1A.
10. Lehmann, D.; Brett, C.E.; Cole, R.; Baird, G. Distal sedimentation in a peripheral foreland basin: Ordovician black shales and associated flysch of the western Taconic foreland, New York State and Ontario. *Geol. Soc. Am. Bull.* **1995**, *107*, 708–724.
11. Churcher, P.L.; Johnson, M.D.; Telford, P.G.; Barker, J.F. *Stratigraphy and Oil Shale Resource Potential of the Upper Ordovician Collingwood Member, Lindsay Formation, Southwestern Ontario*; Open File Report 5817; Ontario Geological Survey: Sudbury, Canada, 1991.
12. Wilson, J.L.; Budai, J.M.; Sengupta, A. *Trenton-Black River Formations of Michigan Basin*; Search and Discovery Article #10020; Masera Corporation: Tulsa, OK, USA, 2001.
13. Brett, E.B.; Allison, P.A.; Tsujita, C.J.; Soldani, D.; Moffat, H.A. Sedimentology, taphonomy, and paleoecology of meter-scale cycles from the Upper Ordovician of Ontario. *Palaios* **2006**, *21*, 530–547.
14. Ziegler, P.A.; van Wees, J.; Cloetingh, S. Mechanical controls on collisional related compressional intraplate deformation. *Tectonophysics* **1998**, *300*, 103–129.
15. Marshak, S.; Nelson, W.J.; McBride, J. Strike-slip faulting in the continental interior of North America. In *Intraplate Strike-Slip Deformation Belts*; Storty, F., Holdsworth, R.E., Salvine, F., Eds.; Geological Society: London, UK, 2003; pp. 171–196.
16. Thomas, W.A. Tectonic inheritance at a continental margin. *GSA Today* **2006**, *16*, 4–11.
17. Sanford, B.V.; Arnott, R.W.C. *Stratigraphic and Structural Framework of the Potsdam Group in Eastern Ontario, Western Québec, and Northern New York State*; Geological Survey of Canada Bulletin Volume 597; Geological Survey of Canada: Ottawa, Canada, 2010.
18. Kay, G.M. The Ottawa-Bonnechere graben and Lake Ontario homocline. *Geol. Soc. Am. Bull.* **1942**, *53*, 585–646.
19. Doig, R. An alkaline province linking Europe and North America. *Can. J. Earth Sci.* **1970**, *7*, 22–28.
20. Burke, K.; Dewey, J.F. Plume-generated triple junctions: Key indicators in applying plate tectonics to old rocks. *J. Geol.* **1973**, *81*, 406–433.
21. Kumarapeli, P.S. Vestiges of Iapetan rifting in the craton west of the northern Appalachians. *Geosci. Can.* **1985**, *12*, 54–59.
22. Sanford, B.V. St. Lawrence Platform—Introduction. In *Sedimentary Cover of the Craton in Canada*; Stott, D.F., Aitken, J.D., Eds.; Geological Survey of Canada: Ottawa, ON, Canada, 1993; pp. 709–722.

23. Zagorevski, A.; van Staal, C.R. The record of Ordovician Arc-Arc and Arc-Continent collision in the Canadian Appalachians during the closure of the Iapetus. In *Arc-Continent Collision*; Brown, D., Ryan, P.D., Eds.; Springer: Heidelberg, Germany, 2011; pp. 341–372.
24. Dix, G.R.; Coniglio, M.; Riva, J.F.V.; Achab, A. The Upper Ordovician Dawson Point Formation (Timiskaming outlier, Ontario): New insights into Richmondian-Hirnantian paleogeography within the central Canadian craton. *Can. J. Earth Sci.* **2007**, *44*, 1313–1331.
25. Colton, G.W. The Appalachian Basin—Its depositional sequences and their geologic relationships. In *Studies of Appalachian Geology: Central and Southern*; Fisher, G.W., Ed.; Interscience Publishers: New York, NY, USA, 1970; pp. 5–47.
26. Globensky, Y. *Géologie des Basses-Terres du Saint-Laurent, Québec* [in French]; Report 85-02; Ministère des Richesses Naturelles Québec: Quebec, Canada, 1987.
27. Uyeno, T.T. *Conodonts of the Hull Formation, Ottawa Group (Middle Ordovician), of the Ottawa-Hull Area, Ontario and Quebec*; Geological Survey of Canada Bulletin Volume 248; Geological Survey of Canada: Ottawa, Canada, 1974.
28. Russell, D.J.; Telford, P.G. Revisions to the stratigraphy of the Upper Ordovician Collingwood beds of Ontario—A potential oil shale. *Can. J. Earth Sci.* **1983**, *20*, 1780–1790.
29. Liberty, B.A. *Paleozoic Geology of the Lake Simcoe Area, Ontario*; Geological Survey of Canada Memoir 355; Geological Survey of Canada: Ottawa, Canada, 1969.
30. Dix, G.R.; Al Dulami, M. Late Ordovician (Chatfieldian) catastrophic volcanism and abrupt carbonate platform-interior subsidence: A tectonic link across a Taconian foreland basin (Quebec Embayment) due to inherited crustal weakness. *Geol. Soc. Am. Bull.* **2010**, *123*, 1988–2004.
31. Lavoie, D.; Hamblin, A.P.; Thériault, R.; Beaulieu, J.; Kirkwood, D. *The Upper Ordovician Utica Shales and Lorraine Group Flysch in Southern Quebec: Tectonostratigraphic Setting and Significance for Unconventional Gas*; Geological Survey of Canada Open File Report 5900; Geological Survey of Canada: Ottawa, Canada, 2008.
32. Nielsen, A.T. Ordovician sea level changes: A Baltoscandian perspective. In *The Great Ordovician Biodiversification Event*; Webby, B.D., Paris, F., Droser, M.L., Percival, I.G., Eds.; Columbia University Press: New York, NY, USA, 2002; pp. 84–96.
33. Raymond, P.E. *The Trenton Group in Ontario and Quebec*; Summary Report for 1912; Geological Survey of Canada: Ottawa, Canada, 1914; pp. 342–350.
34. Kay, G.M. Stratigraphy of the Trenton group. *Geol. Soc. Am. Bull.* **1937**, *48*, 223–302.
35. Salad Hersi, O.; Dix, G.R. Blackriveran (lower Mohawkian, Upper Ordovician) lithostratigraphy, rhythmicity, and paleogeography, Ottawa Embayment, eastern Ontario, Canada. *Can. J. Earth Sci.* **1999**, *36*, 2033–2050.
36. Williams, D.A. *Paleozoic Geology of Ottawa-St. Lawrence Lowlands, Southern Ontario*; Open File Report 5770; Ontario Geological Survey: Sudbury, Canada, 1991.
37. Clark, T.H. Stratigraphy and Structure of the St. Lawrence Lowland of Quebec. In Proceedings of 24th International Geology Congress, Montreal, Canada, 1972; Field Excursion C-52.
38. Fisher, D.M. *Correlation of the Hadrynian, Cambrian and Ordovician Rocks of New York State*; Map and Chart Series 25; New York State Museum: Albany, NY, USA, 1977.

39. Williams, D.A.; Rae, A.M.; Wolf, R.R. *Paleozoic Geology of the Ottawa Area, Southern Ontario*; Geological Series-Preliminary Map P. 2716; Ontario Geological Survey: Toronto, Canada, 1984; 1 sheet, scale 1:50000.
40. Gupta, V.K. *Map 2587-Shaded Image of Total Magnetic Field of Ontario, Southern Sheet*; Ontario Geological Survey: Toronto, Canada, 1991; 1 sheet, scale 1:1000000.
41. Dix, G.R. A Neoproterozoic rift, a Phanerozoic graben: Structural inheritance and influence on ?Ediacaran-Paleozoic basin development (the Ottawa Embayment) interior to the northern Appalachian orogen. *Basin Res.* **2013**, submitted.
42. Dix, G.R.; Jolicoeur, C. Tectonostratigraphy of organic-richness and shale-gas potential of the Upper Ordovician Billings Formation, Ottawa Embayment. *Bull. Can. Petrol. Geol.* **2011**, *59*, 7–26.
43. Gbadeyan, R. Stratigraphy, Sedimentology, and Diagenesis of the Lindsay Formation, Upper Ordovician, Ottawa Embayment, Eastern Ontario. Master's Thesis, Carleton University, Ottawa, Canada, May 2011.
44. Rancourt, C.C. "Collingwood" Strata in South-Central Ontario—A Petrophysical Chemostratigraphic Approach to Comparison and Correlation Using Geophysical Borehole Logs. Master's Thesis, University of Toronto, Toronto, Canada, May 2009.
45. Sharma, S.; Dix, G.R.; Riva, J.F.V. Late Ordovician platform foundering, its paleoceanography and burial, as preserved in separate basins, southern Ontario. *Can. J. Earth Sci.* **2003**, *40*, 135–148.
46. Kiernan, J.P. Lithostratigraphy, Sedimentology and Diagenesis of the Upper Ordovician Hull Beds and Verulam Formation, Upper Ottawa Group, Eastern Ontario. Master's Thesis, Carleton University, Ottawa, Canada, May 1999.
47. Munnecke, A.; Servais, T.; Vachard, D. *Halysis* HØEG, 1932—A problematic Cyanophyceae: New evidence from the Silurian of Gotland (Sweden). *Neues Jahr. Geol. Paläont. Mh.* **2001**, *1*, 21–42.
48. Mamet, B.; Roux, A.; Shalaby, H. Role des algues calcaires dans la sédimentation ordovicienne de la plate-forme du Saint-Laurent [in French]. *Geobios* **1984**, *8*, 261–269.
49. Nehza, O.; Dix, G.R. Stratigraphic restriction of stromatolites in a Middle and Upper Ordovician foreland-platform succession (Ottawa Embayment, eastern Ontario). *Can. J. Earth Sci.* **2012**, *49*, 1177–1199.
50. Ludvigsen, R.; Tuffnell, P.A. The last olenacean trilobite: *Triarthrus* in the Whitby Formation (Upper Ordovician) of southern Ontario. *NY State Mus. Bull.* **1984**, *481*, 183–212.
51. McFarland, S.; Cheel, R.J.; Westrop, S.R. Allogenic versus autogenic processes in the genesis of Middle Ordovician brachiopod-rich beds, Verulam Formation, Ontario. *Palaios* **1999**, *14*, 282–287.
52. Brookfield, M.E.; Brett, C.E. Paleoenvironments of the Mid-Ordovician (Upper Caradocian) Trenton limestones of southern Ontario: Storm sedimentation on a shoal-basin shelf model. *Sediment. Geol.* **1988**, *57*, 75–105.
53. Brett, C.E.; Baird, G.C. Comparative taphonomy: A key to paleoenvironmental interpretation based on fossil preservation. *Palaios* **1986**, *1*, 207–227.
54. MacEachern, J.A.; Pemberton, S.G.; Gingras, J.K.; Bann, K.L. Ichnology and facies models. In *Facies Models 4*; James, N.P., Dalrymple, R.W., Eds.; Geological Association of Canada: St. John's, Canada, 2010; pp. 19–58.

55. Zenger, D.H.; Lemone, D.V. Widespread “Bighorn Facies”, Upper Ordovician, North America. In *Ordovician Odyssey, Seventh International Symposium on the Ordovician System*; Cooper, J.D., Droser, M.L., Finney, S.C., Eds.; Society for Sedimentary Geology, Pacific Section: San Diego, CA, USA, 1995; pp. 389–392.
56. Tucker, M.; Wright, V.P.; Dickson, J.A.D. *Carbonate Sedimentology*; Blackwell Scientific: Brookline Village, MA, USA, 1990.
57. Elliot, G.F. *Permian to Pennsylvanian Calcareous Algae (Dasycladaceae) of the Middle East*; Geology Supplement 4; British Museum of Natural History: London, UK, 1968.
58. Beadle, S.C.; Johnson, M.E. Paleoecology of Silurian cyclocrinid algae. *Paleontology* **1986**, *29*, 585–601.
59. Flügel, E. Diversity and environments of Permian and Triassic Dasycladacean Algae. In *Paleoalgaology*; Toomey, D.F., Nitecki, M.H., Eds.; Springer: Berlin, Germany, 1985; pp. 344–351.
60. Beadle, S.C. Dasyclads, cyclocrinid and receptaculitids: Comparative morphology and paleoecology. *Lethaia* **1988**, *21*, 1–21.
61. Wray, J.L. *Calcareous Algae*; Elsevier: Amsterdam, the Netherlands, 1977.
62. House, M.R. A new approach to an absolute timescale from measurements of orbital cycles and sedimentary microrhythm. *Nature* **1985**, *315*, 721–725.
63. Hallam, A. Origin of minor limestone-shale cycles: Climatically induced or diagenetic. *Geology* **1986**, *14*, 609–612.
64. Holland, S.M.; Miller, A.L.; Dattilo, B.F.; Meyer, D.L.; Diekmeyer, S.L. Cycle anatomy and variability in the storm-dominated type Cincinnati (Upper Ordovician): Coming to grips with cycle delineation and genesis. *J. Geol.* **1997**, *105*, 135–152.
65. Burchette, T.P.; Wright, V.P. Carbonate ramp depositional systems. *Sediment. Geol.* **1992**, *79*, 3–59.
66. Brookfield, M.E. A mid-Ordovician temperate carbonate shelf- the Black River and Trenton Limestone Groups of southern Ontario, Canada. *Sediment. Geol.* **1988**, *60*, 137–154.
67. Lavoie, D. A Late Ordovician high-energy temperate-water carbonate ramp, southern Quebec, Canada: Implications for Late Ordovician oceanography. *Sedimentology* **1995**, *42*, 95–116.
68. Pope, M.C.; Read, J.F. High-resolution stratigraphy of the Lexington Limestone (Late Middle Ordovician), Kentucky, USA: A cool-water carbonate-clastic ramp in a tectonically active foreland basin. In *Cool-Water Carbonates*; SEPM Special Publication 56; James, N.P., Clarke, J.A.D., Eds.; Society for Sedimentary Geology: Tulsa, OK, USA, 1997; pp. 411–430.
69. Holland, S.M.; Patzkowsky, M.E. Sequence stratigraphy and long-term paleoceanographic change in the Middle and Upper Ordovician of the Eastern United States. In *Paleozoic Sequence Stratigraphy: Views from the North American Craton*; Witzke, B.J., Ludvigsen, G.A., Day, J.E., Eds.; Geological Society of America: Boulder, CO, USA, 1996; Special Paper 306; pp. 17–130.
70. Coakley, B.; Gurnis, M. Far-field tilting of Laurentia during the Ordovician and constraints on the evolution of a slab under an ancient continent. *J. Geophys. Res.* **1995**, *100*, 6313–6327.
71. Dorobek, S.L. Synorogenic carbonate platforms and reefs in foreland basins: Controls on stratigraphic evolution and platform/reef morphology. In *Stratigraphic Evolution of Foreland Basins*; Dorobek, S.L., Ross, G.M., Eds.; Society of Sedimentary Geology: Tulsa, OK, USA, 1995; SEPM Special Publication 52; pp. 125–147.

72. Ettensohn, F.R. Tectonic control on the formation and cyclicity of major appalachian unconformities and associated stratigraphic sequences. In *Tectonics and Eustatic Controls on Sedimentary Cycles*; Dennison, J.M., Ettensohn, F.R., Eds.; Society of Sedimentary Geology: Tulsa, OK, USA, 1994; SEPM Concepts in Sedimentology and Paleontology 4; pp. 217–242.
73. Holland, S.M.; Patzkowsky, M.E. Distal orogenic effects on peripheral bulge sedimentation: Middle and Upper Ordovician of the Nashville dome. *J. Sediment. Res.* **1997**, *67*, 250–263.
74. Jacobi, R.D. Peripheral bulge—A causal mechanism for the Lower/Middle Ordovician disconformity along the western margin of the northern Appalachians. *Earth Planet. Sci. Lett.* **1981**, *56*, 245–251.
75. Rimando, R.E.; Benn, K. Evolution of faulting and paleostress field within the Ottawa graben, Canada. *J. Geodyn.* **2005**, *39*, 337–360.

© 2013 by the authors; licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution license (<http://creativecommons.org/licenses/by/3.0/>).