The North African Journal of Scientific Publishing (NAJSP)
مجلة شمال إفريقيا للنشر العلمي (NAJSP)
E-ISSN: 2959-4820
Volume 3, Issue 1, January - March 2025
Page No: 22-35
Website: https://najsp.com/index.php/home/index
SJIFactor 2024: 5.49 معامل التأثير العربي (AIF) 2023: 0.63 ISI 2024: 0.696

Sedimentology and Depositional Context Structural Characteristics of a Shallow Homoclinal Ramp During the Middle Ordovician Period in the Lake Simcoe Region, Ontario

Muftah Saleh El Gadi[1*]
[1]Department of Geology, Faculty of Science, Gharyan University, Gharyan, Libya

البنية الرسوبية وبيئة الترسيب لمنحدر متجانس ضحل في عصر الاردوفيشي المتوسط منطقة بحيرة سيمكو، أونتاريو

مفتاح صالح محمد الجدى[1*]
[1]قسم الجيولوجيا، كلية العلوم، جامعة غريان، غريان، ليبيا

*Corresponding author: melgadi4@hotmail.com

Received: October 28, 2024	Accepted: December 30, 2024	Published: January 30, 2025

Abstract:
During the Middle Ordovician, the southern Ontario region was primarily defined by an extensive shallow-water carbonate platform, where a carbonate ramp system developed in the Lake Simcoe vicinity. Sixteen outcrops and quarry sections of the Middle Ordovician Black River-Trenton Group were analyzed to clarify the origins of meter-scale cycles and depositional sequences, thereby improving the comprehension of platform history. The Middle Ordovician marine transgression features a clear stratigraphic sequence that progresses from supratidal and tidal-flat carbonates to lagoonal and shoal carbonates, ultimately leading to offshore and deep-shelf carbonates. Fifteen microfacies have been identified and categorized into six depositional facies (associations): (1) supratidal regolith and supratidal pond, (2) shallow intertidal and supratidal sabkah, (3) lower supratidal to upper intertidal of low to moderate energy, (4) shallow subtidal low energy and shallow intertidal environment, (5) shallow lagoonal to lower intertidal flats, and (6) high energy marine environment in the photic zone. The lithofacies are arranged in vertically stacked, meter-scale cycles that transition from subtidal to shallowing-upward peritidal habitats. Ramp stratigraphy, facies correlations, and bounding surfaces indicate the presence of four third-order depositional sequences within the Black River-Trenton Group. Furthermore, it can be classified into five fourth-order cycles. Their representation illustrates the shift from a clastic-dominated ramp during the Chazyan-Blackriverian to a carbonate-dominated ramp in the Blackriverian-Trentonian period. The nearest contemporary counterparts of these Ordovician habitats are found on the Arabian shelf of the Persian Gulf for the Black River Group and the Recent West Florida Shelf for the Trenton.

Keywords: Sedimentology, Sedimentary Cycle, Ordovician, Black River, Trenton Groups, Lake Simcoe.

الملخص
خلال العصر الأوردوفيشي الأوسط، كانت منطقة جنوب أونتاريو محددة بشكل أساسي بمنصة كربونات واسعة النطاق في المياه الضحلة، حيث تطور نظام منحدر كربونات في محيط بحيرة سيمكو. تم تحليل ستة عشر مقطع من التكشفات والمحجر لمجموعة بلاك ريفر- ترنتون في العصر الأوردوفيشي الأوسط لتوضيح أصول الدورات على النطاق المترى وتسلسلات الترسيب، وبالتالي تحسين فهم تاريخ المنصة. يتميز التجاوز البحري في العصر الأوردوفيشي الأوسط بتسلسل طبقي

واضح يتقدم من كربونات فوق المد والجزر إلى كربونات البحيرة والضحلة، مما يؤدي في النهاية إلى كربونات بحرية وعميقة. تم تحديد خمسة عشرمن السحنات الدقيقة والتى دمجت إلى ستة سحنات ترسيبية: (1) تربة فوق المد والجزر وبرك فوق المد والجزر، (2) صبخة ضحلة بين المد والجزر وفوق المد والجزر، (3) فوق المد والجزر السفلي إلى المد والجزر العلوي من طاقة منخفضة إلى متوسطة، (4) بيئة مد وجزر ضحلة منخفضة الطاقة وبين المد والجزر الضحل، (5) مسطحات بحيرة ضحلة إلى المد والجزر السفلي، و(6) بيئة بحرية عالية الطاقة في المنطقة الضوئية. يتم ترتيب الواجهات الصخرية في دورات مترية مكدسة رأسياً تنتقل من بيئات تحت المد والجزر إلى بيئات مدية ضحلة. تشير طبقات المنحدر ومطاهات السحنات والأسطح الحدودية إلى وجود أربع تسلسلات ترسيبية من الدرجة الثالثة داخل مجموعة بلاك ريفر-ترنتون. علاوة على ذلك، يمكن تصنيفها إلى خمس دورات من الدرجة الرابعة. يوضح تمثيلهم التحول من منحدر تهيمن عليه الصخور الحتاتية خلال فترة تشازيان- بلاك رفريان إلى منحدر تهيمن عليه صخور الكربونات في فترة بلاك رفريان - ترنتونيان. أقرب انماط مناطرة لهذة البيئات في الاردوفيشي تقع على الجرف العربي للخليج الفارسي لمجموعة بلاك رفر وجرف غرب فلوريدا لمجموعة ترينتون.

الكلمات المفتاحية: علم الرواسب، الدورة الرسوبية، الأوردوفيشي، مجموعة ترنتون للحجر الجيري، بحيرة سيمكو.

Introduction

Meter-scale, shallowing-upward sedimentary cycles are generally considered essential elements in ancient shallow-water carbonate formations [1-2]. These cycles are generally consolidated into prolonged depositional intervals (3rd-order), demonstrating hierarchies of stratigraphic cyclicity [1-5]. In this context, cycle stacking patterns might clarify the differences in accommodation space among various orders, thereby linking meter-scale cycles with larger-scale depositional sequences and aiding in the identification of these sequences [6-8]. Thus, analyzing meter-scale cycles and their stacking patterns can effectively identify depositional sequences in significantly thick, often distorted carbonate successions that are difficult to trace laterally (e.g., Elrick, 1995, Bosence et al., 2009). The stratal cyclicity of different orders is a significant characteristic of shallow-water carbonate successions, including the Middle Ordovician carbonate strata analyzed in this study [9]. The depositional cycles and sequences of coeval carbonates in North America have been extensively documented [9-13]. Research on the origin of meter-scale cycles and sequence identification, based on the internal components defined by intricate vertical stacking patterns of facies and meter-scale cycles within the Middle Ordovician Black River – Trenton Limestone in the Lake Simcoe region, is limited. This study aims to (1) examine the characteristics, scope, and interpretation of different cycle types within the Black River-lower Trenton succession; (2) clarify the origin of meter-scale, shallowing-upward cycles; (3) explore the factors (e.g., eustatic sea-level changes, tectonic subsidence, sedimentation rates, etc.) affecting the development of depositional sequences and platform evolution; (4) provide an analogue for the identification and correlation of cycles.

Geological Context

The lower Paleozoic formations of south-central Ontario are visible at the surface in east-west oriented outcrop belts that stretch for several hundred kilometers, influenced by a little (<0.5°) southern dip as illustrated in Figure 1(a). The undeformed strata are bordered to the north by the metamorphic and granitic shield rocks of the Proterozoic Grenville Province. The Upper Ordovician strata, comprising the Basal, Simcoe, and Nottawasaga groups, onlap exposed crystalline Grenville-age rocks, which likely provided coarse siliciclastic sediments to the basal transgressive Paleozoic strata and, in some areas, to younger carbonate strata, originating from paleotopographic basement highs that would have constituted islands. Silurian carbonate formations constitute the Niagara Escarpment to the south and west. The Ordovician strata form a relatively continuous outcrop strip northeast of the escarpment, linked in the subsurface to analogous rocks of the Michigan Basin and Appalachian Basin, and are somewhat displaced from the Ottawa Embayment by a narrow belt of exposed crystalline foundation. The Upper Ordovician formations found in southern Ontario document shallow, potentially cool-water settings of the Trenton carbonate platform [15]. This platform, located on the southeastern edge of Laurentia, was positioned next to the cratonic margin of the Taconic peripheral foreland basin and experienced influxes of muddy sediments from the Taconic Highlands, along with intermittent volcanic ash deposition as the Taconic volcanic island arc collided with Laurentia during the Late Ordovician. The Trenton carbonate platform was situated in the southern subtropics at around 20° south latitude and supported a diverse invertebrate fauna. The Simcoe Group, as delineated by [14], comprises the Gull River, Bobcaygeon, Verulam, and Lindsay formations. The Simcoe Group is underpinned by the Basal Group (comprising the Jacobsville and Mount Simon formations, which are exclusively found in the subsurface) and is overlain by the Nottawasaga Group, which encompasses the Blue Mountain (formerly the upper Whitby Formation), Georgian Bay, and Queenston formations. The Shadow Lake

Formation, first classified inside the Basal Group, is now designated as the basal component of the Simcoe Group. The Gull River Formation and the lower member of the Bobcaygeon Formation comprise clean-water micrites and grainstones, respectively, of the 'pre-Taconic foreland,' which exhibit minimal signs of tectonic influence; however, the Bobcaygeon Formation contains several bentonitic clays that suggest volcanic activity linked to the impending Taconic magmatic arc. The intermediate and superior strata of the Bobcaygeon Formation, Verulam Formation, and Lindsay Formation comprise a greater proportion of siliciclastic mudstones and shales originating from the advancing clastic wedge, demonstrating a pronounced back-stepping pattern linked to a significant marine transgression intensified by tectonic loading and subsidence of the Laurentian margin due to Taconic allochthons. The Simcoe Group preserves various facies, which and their inferred environments encompass: a) supratidal and intertidal mudstones, b) shallow water shoal grainstones, c) protected shelf and lagoonal micrites, d) subtidal muddy grainstones, and e) deeper-water siliciclastic mudstones as presented in Figure 1(b) [15].

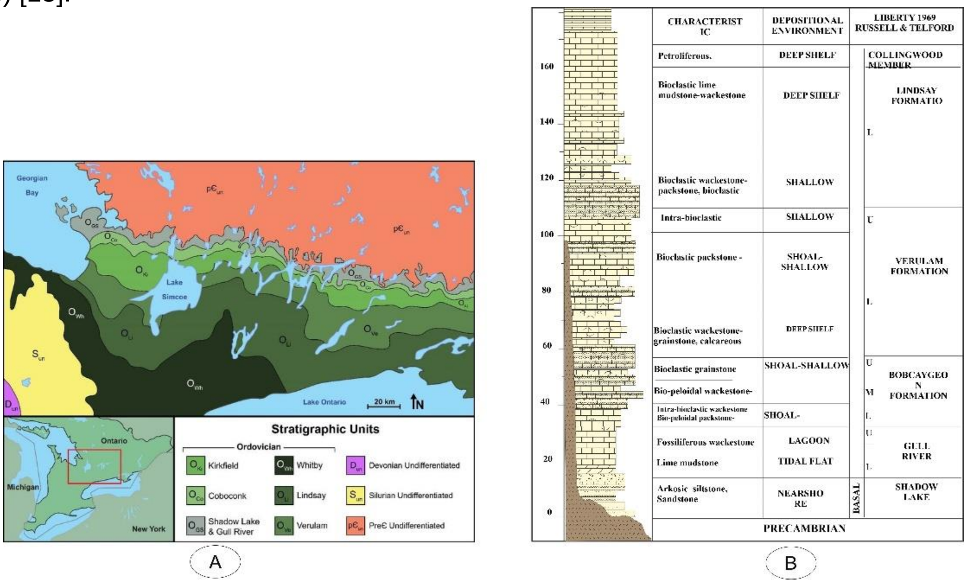

Figure 1. (a) Geologic map of the Simcoe District of Southern Ontario. (b) Ordovician stratigraphic units of the Lake Simcoe area (modified from [19] [22-23].

Materials and Methods

Extensive fieldwork was conducted at outcrops and quarry sections in the Lake Simcoe region to determine depositional facies, meter-scale cycles, and third-order depositional sequences of the Middle Ordovician Black River-Trenton Group, which has a total thickness of approximately 170 meters in southern Ontario. Derived from bed-to-bed facies characterizations. Three hundred fifty thin pieces of the Black River-Trenton series were fabricated. The percentages of limestone in the matrix were approximately determined using a polarized microscope, in accordance with [24]. Additionally, the delineation of sedimentary facies and the formulation of depositional models were executed in accordance with references [25] and [26]. Meter-scale, shallowing-upward cycles (parasequences) were recognized through the recurrence, continuity, and offset of vertically stacked lithofacies successions. Third-order depositional sequences were identified by the vertical arrangement of lithofacies and meter-scale cycles.

Depositional Facies

Fifteen microfacies types were identified in the Black River – Trenton Group within the Lake Simcoe area, based on textures, fabrics, primary constituents, sedimentary structures, and fossil content. These microfacies were subsequently categorized into six major genetically-related depositional facies associations, ranging from supratidal and tidal-flat carbonates to lagoonal and shoal carbonates.

Sandstone microfacies (MF1): comprises red to green, frequently mottled, granular and pebbly, weakly to moderately sorted, and occasionally clayey sandstones. Typically, very coarse-grained sandstones transition upward into coarse to fine-grained sandstones.

Shale microfacies (MF2): It comprises two categories: Subfacies A. Non-fossiliferous shales. Subfacies B: Fossiliferous Shales. The second shale type manifests as slender fossiliferous, unbioturbated black to dark brown strata within the upper Black River and Trenton formations.

Silty and sandy dolostone microfacies (MF3) comprises silty dolostone that may transition into sandy dolostone. Both exhibit analogous features, with the sole distinctions being their clastic particle size and composition.

Peloidal bioclastic mudstone/dolomitic mudstone microfacies (MF4): It comprises thick and medium-bedded light cream to white microcrystalline mudstones that weather to a light cream hue. It is prevalent across the Black River Group and is found in the majority of natural exposures and drilled cores.

Peloidal bioclastic wackestone microfacies (MF5): medium gray to light brown, exhibiting weathering to dark gray. The beds are medium to thick (25-70 cm) with irregular to planar sharp contacts, interspersed with thin shale films (1-2 cm). Textures range from medium to coarse, infrequently fine to extremely coarse; sorting is moderate to poor, and grains are subrounded to rounded.

Bioclastic dolomitic wackestone microfacies (MF6): It bears resemblance to the peloidal bioclastic wackestone microfacies, although is uncommon. It comprises light to medium grey, light brown to pink dolomitic wackestones, exhibiting weathering to dark grey.

Intraclastic bioclastic wackestone microfacies (MF7): medium-light grey wackestones, exhibiting weathering from dark grey to light grey to tan. Beds range from thin to medium thickness (10-25 cm), exhibiting mottled patterns with irregular to sharp contacts and thin shale films. The composition varies from medium to coarse, with uncommon occurrences of fine to very coarse grains, and the sorting is moderate to poor; grains are subrounded to subangular. Allochems are commonly seen micritic intraclasts, peloids, and infrequently ooids, with varying quantities of quartz.

Peloidal bioclastic packstone microfacies (MF8): light to dark grey packstones, exhibiting weathering in dark grey, brown, and tan hues. Beds are thick (100-200 cm) and divided into thin to medium beds (10-25 cm), exhibiting moderate to high bioturbation (types 2 and 3) with sharp-planar to irregular stylolitic connections. Textures range from coarse to very coarse, with medium or fine grains being less common; sorting is moderate to poor, and the grains are rounded, subrounded, and subangular. Bioclasts commonly consist of bivalves, ostracods, crinoids, brachiopods, gastropods, bryozoans, trilobites, and calcareous algae such as Solenopora, Hedstroemia, Kazakhstanelia, Parachaetetes, and Tetradium.

Bioclastic dolomitic packstone microfacies (MF9): medium to dark grey and light brown (weathered dark grey) packstones. Beds are of medium to thick thickness (20-55 cm) featuring acute, gradational, and irregular stylolitic contacts, accompanied by thin shale films (2-5 cm) and exhibit moderate to heavy bioturbation (types 2 and 3).

Intraclastic bioclastic packstone microfacies (MF 10) is less prevalent than the bioclastic dolomitic packstone microfacies and comprises medium to dark grey and brown (weathering dark grey) packstones. Beds are characterized by a thin thickness (5-15 cm) with abrupt, flat, and erosional boundaries. Hardgrounds also manifest. The textures range from coarse to medium, seldom exhibiting very coarse grains, with moderate sorting; the grains are subrounded to subangular. Bioclasts include crinoids, bivalves, brachiopods, bryozoans, and ostracods, ranging from regular to rare occurrences.

Peloidal bioclastic grainstone microfacies (MF 11): grey, brown-grey, and tan grainstones. Textures range from coarse to extremely coarse, transitioning to medium and fine-grained textures; sorting varies from fair to moderate to bad; grains are rounded to subrounded. Bioclasts commonly include crinoids, brachiopods, ostracods, bivalves, bryozoans, gastropods, calcareous algae (Solenopora, Kazakhstanelia, Parachaetetes, Hedstroemia), solitary rugose corals, colony tabulate corals, and trilobites.

Intraclastic bioclastic grainstone microfacies (MF 12): medium to dark grey, light brown (weathering from dark to light grey) grainstones. Beds range from thin (2-10 cm) to medium (5-25 cm) thickness, characterized by sharp and irregular stylolitic contacts with erosional bases. Textures are categorized as very coarse, coarse, and medium. The sorting is moderate, infrequently good: the grains are subrounded to rounded with concavo-convex contacts. Bioclasts predominate over prevalent crinoids, brachiopods, bryozoans, bivalves, ostracods, gastropods, calcareous algae (Hedstroemia, Parachaetetes, Solenopora, Vermiporella, Ortonella, Kazakhstanelia), as well as rugose and tabulate corals.

Bioclastic dolomitic grainstone microfacies (MF 13): light grey and pink grainstones that alternate with peloidal bioclastic dolomitic packstones (microfacies 4.3.9). Textures range from very coarse to coarse, progressing to medium and fine. Sorting is moderate to poor; grains are subrounded to subangular. Bioclasts are predominantly frequent to common among crinoids, brachiopods, bivalves, ostracods, bryozoans, and gastropods.

Peloidal bioclastic oncolitic grainstone microfacies (MF14): light brown and medium to dark grey, extremely coarse to coarse to medium-grained, exhibiting poor sorting, with grains that are subangular to subrounded to rounded. Bioclasts are prevalent among crinoids, brachiopods, bivalves, calcareous algae, bryozoans, gastropods, rugose corals, and big stromatoporoids. Allochems are commonly to rarely found oncolites formed around bioclasts (brachiopods, bryozoans) and intraclasts.

Oolitic bioclastic grainstone/packstone microfacies (MF 15). Grainstones and packstones in shades of brown, light brown, and tan exhibit coarse, medium, and fine granulation, with very coarse granules being uncommon. The sorting ranges from poor to moderate, and the grains are predominantly rounded to subrounded. Bioclasts are commonly found in brachiopods, ostracods, crinoids, bryozoans, bivalves, gastropods, and occasionally in corals and calcareous algae.

Depositional model

The Black River-lower Trenton ramp can be categorized into the inner ramp (Gull River and Moore Hill formations) and mid ramp sections (Kirkfield and Verulam formations), delineated by bioclastic bars (Coboconk Formation) that indicate the fair weather wave base (Figure 2). The middle Ordovician of the Black River-Trenton Group predominantly consists of MF 4-8, representing peritidal to restricted facies (Gull River and Moore Hill Formations), and MF 10, MF 11, MF 13, MF 14, indicative of open marine subtidal facies (Kirk Field and Verulam Formations), interspersed with shoal facies of MF 8, MF 9, MF 12, and MF 15 (Coboconk Formation), delineating the fair weather wave base. The vertical facies changes indicate a gradual shift from peritidal facies to restricted shallow subtidal and then to open-marine shallow subtidal facies. The presence of MF 3, MF 4, MF 5, MF 6, and MF 7 in the Gull River Formation signifies deposits from supratidal sabkha and upper intertidal environments. The presence of MF8, MF12, and minor MF5 within the Moore Hill Formation indicates a deepening trend, characterized by relatively restricted intermediate to deep subtidal (lagoon) environments, influenced by sea-floor topography and potentially accelerated subsidence due to synsedimentary faulting. The Seaward to Coboconk Formation is primarily characterized by MF 12, MF 14, and MF 15 open-marine subtidal facies, with minimal occurrences of MF 8, MF 9, and MF 5 suggesting a shoal environment. The Kirkfield and Verulam Formations are predominantly composed of MF 10, MF 11, and MF 13, with low representations of MF 8 and MF 14, indicating a fore shoal environment.

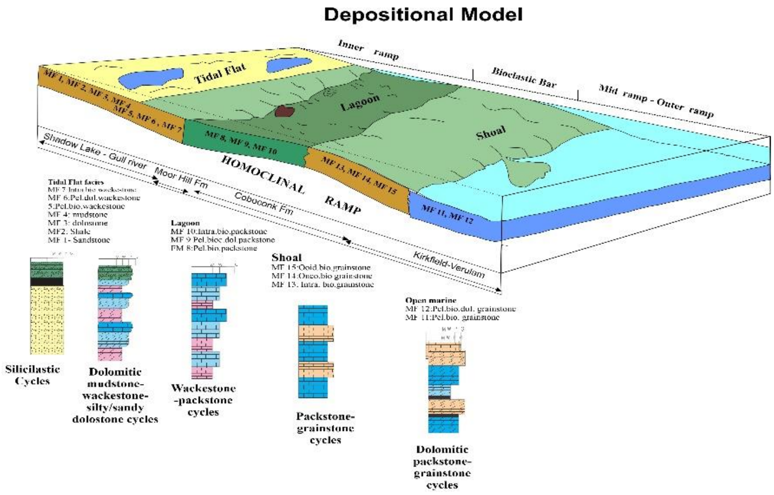

Figure 2. Depositional model of a carbonate ramp system proposed for the Black River – Trenton Group, Southern Ontario.

Meter-Scale, Shallowing-Upward Cycles and Depositional Sequences

The Black River – Trentron Group in the research area consists of recurrent meter-scale, shallowing-upward cycles. The average cycle thickness varies among all analyzed sections, and the number of cycles demonstrates a decreasing tendency from Shadow Lake-Gull River through Coboconk to Kirkfield and Verulam formations. Two primary cycle types are identified based on lithofacies constituents and their vertical arrangements: (1) peritidal cycles, characterized by peritidal facies at the top (Figure 3(a), (b), and (c)); and (2) subtidal cycles, characterized by shallow subtidal facies at the top (Fig. 3d and e). The meter-scale cycles have average thicknesses of 5 m, 2.5 m, 4 m, 2.5 m, and 1 m in Shadow Lake, Gull River, and Mooree Hill Formations, respectively.

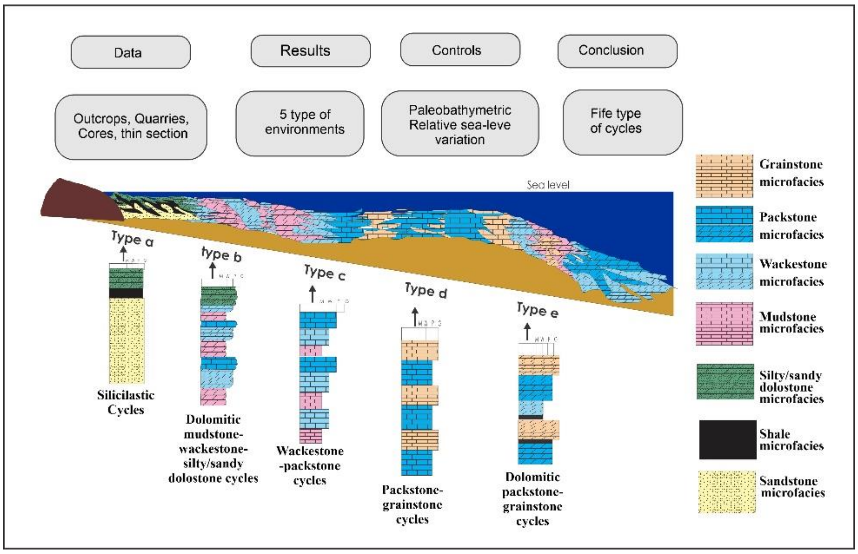

Figure 3. Schematic cross section showing the distribution of peritidal cycle (a, b, and c), and subtidal cycle (d, and e) in the Lake Simcoe area.

Peritidal cycles

This cycle is characterized by peritidal facies capping and is predominantly found in the Shadow Lake, Gull River, and Moor Hill Formations. Five subtypes of peritidal cycles are further recognized based on facies alterations over the bounding surface. Siliciclastic cycles, dolomitic mudstone-wackestone and silty/sandy dolostone cycles, wackestone-packstone/grainstone cycles, packstone-grainstone cycles Cycles of dolomitic packstone and grainstone.

Siliciclastic cycles: are restricted to the lower Shadow Lake Formation and consist of fining upward sequences of breccia/sandstone, siltstone, and claystone, attaining thicknesses of up to 5 meters (figure 3a). In the Lake Simcoe region, the cycle measures 4 meters in thickness, and the underlying breccias and sandstones also appear substantial; however, this evaluation is based on drilled cores, as natural exposures only display fragmentary sections of the Shadow Lake Formation. These siliciclastic cycles are generally regarded as indicative of transgressive continental and supratidal deposits.

Dolomitic mudstone-wackestone - silty/sandy dolostone cycle: comprise the predominant composition of the Lower Gull River Formation and are also found in the Upper Gull River Formation (figure 5b). They consist of asymmetrical coarsening upward sequences of dolomitic mudstone (MF 4), peloidal wackestone/-packstone (MF 5, 6), and sandy/silty dolostone (MF 3) (Figure 3 (b)). Modern equivalents of these microfacies are located in the hypersaline, supratidal, and shallow intertidal environments of the Bahamas [28] (Figure 4) [29-30], Persian Gulf [31], and Florida Bay [32] (Figure 5). This cycle is generated by the migration of tidal flats.

Figure 4. Peritidal environments comprising hypersaline, supratidal and intertidal of the Bahama.

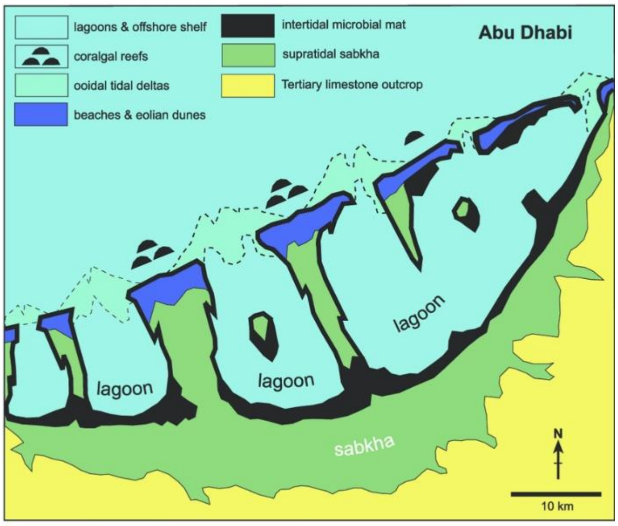

Figure 5. Photograph from space showing the area of the Florida Keys. The platform interior behind the cays is a muddy, restricted environment with well-developed lime-mud banks. In front of the cays are the open platform interior and a platform-margin barrier reef.

Wackestone-packstone/grainstone cycles: consist of peloidal bioclastic wackestones, which are succeeded by peloidal bioclastic packstones and grainstones, predominantly located in the Upper Gull River and Moore Hill formations (figure 3 (c)). Modern equivalents of these microfacies are located in the most protected areas of the Bahamas platform at depths generally exceeding 4 meters, in environments marked by negligible tidal currents and wave action, lacking cross-bank currents, leading to sediment reworking solely during major storms [33]. Similar sediments are present in the subtidal lagoonal sediments of the Persian Gulf (Figure (6)), located behind barrier islands, where the movement of low-relief tidal bars over tranquil water muds produces analogous vertical configurations of microfacies [34].

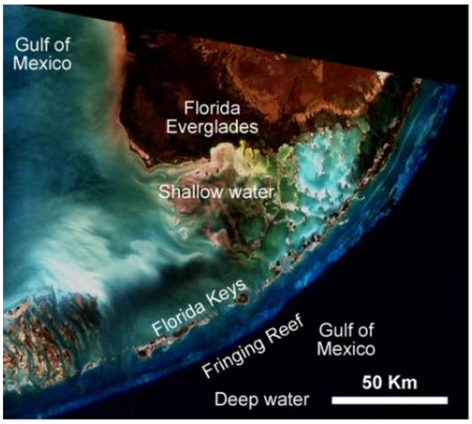

Figure 6. Simplified map of modern tidal flat near Abu Dhabi, Arabian/Persian Gulf. Coastal lagoons are floored with peloidal and bioclastic sands and muds, and are drained by subtidal channels

Subtidal Cycles

Subtidal cycles are volumetrically predominant and dispersed throughout the Coboconk. Kirkfield and Verulem formations from all measured sections. These cycles begin with relatively deep subtidal facies, succeeded by shallower subtidal facies, lacking indications of extended subaerial exposure, while frequently exhibiting internal erosive surfaces. Two subtypes of subtidal cycles are further identified: Packstone-grainstone cycles and dolomitic packstone-grainstone cycles (Figure 3).

Packstone-grainstone sequences: These cycles generally measure under 2.5 m in thickness, demonstrate asymmetry, and exhibit a shallowing upward tendency. They are common in the Coboconk Formation, but are also found in the Kirkfield Formation (figure 3 d). They arise from the movement of several bioclastic and oolitic bars across interbar depressions [32]. Numerous varieties are present. Analogous to the Persian Gulf, these phenomena can be interpreted as shallow-water cycles arising from the seaward displacement of bedforms beyond the principal Coboconk bar. A possibility entails the relocation of deeper water facies similar to the 40-to-100-meter deep grainstones of the West Florida Shelf (Fig. 7). The crinoidal grainstone cycles of the Verulam resemble the cross-bedded grainstone cycles of the South Australian ramp, which were formed under conditions of storm wave reworking and superimposed oceanic currents, as well as specific deep-water banks of the West Florida Shelf.

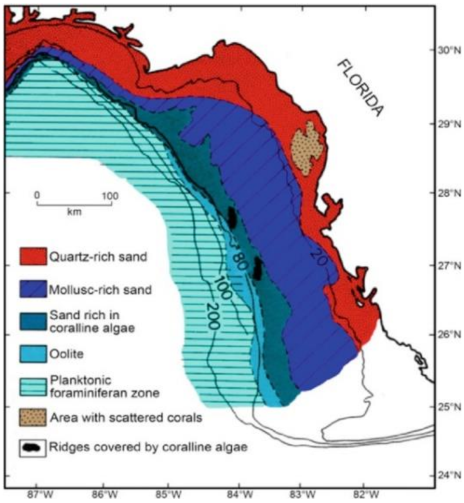

Figure 7. General map of the surface sediment facies on the west Florida shelf.

Dolomitic packstone-grainstone cycles: These cycles often have a thickness of less than 1 meter, have vertical and lateral discontinuities, and are prevalent in the Kirkfield and Verulam Formations. They consist of bioclastic dolomitic packstones and peloidal bioclastic dolomitic grainstones (figure 3 (e)). These cycles were described by [15] as proximal to distal storm cycles. Contemporary counterparts of the microfacies are found in low-energy open lagoon and open marine settings of the Persian Gulf (Figure 8), in the hardground regions of the outer shelf of West Florida (Figure 7), and beneath the usual wave base on the South Australian ramp**.**

Figure 8. Shuttle photo showing open lagoon and open marine environments in Persian Gulf**.**

Meter-Scale Cycle Stacking Patterns and Third-Order Depositional Sequences

Meter-scale fifth-order cycles exhibit regular upward variation within third- and fourth-order sequences, establishing different stacking patterns. Cycle stacking patterns establish the essential connection between meter-scale cycles and larger-scale sequences, together with their constituent systems tracts. Stacks of genetically linked cycles constitute the parasequence sets under sequence stratigraphic nomenclature. In shallow-water carbonate sequences, cycle thickness can be considered indications of variations in accommodation space resulting from high-frequency eustatic fluctuations [1,2],[6], [9], [35]. Additionally, cycle stacking patterns can reflect stratal cyclicity of varying orders and connect the interval between meter-scale cycles and larger-scale (third-order) depositional periods together with their associated systems tracts. [5], [7,8]. This study's comprehensive outcrop, quarry, and sedimentological analyses demonstrated that, aside from the basal and upper limits of the Black River-Trenton Group identified as unconformities, transitional sequence boundary zones rather than a singular surface (e.g., [3,4], [11] define sequence boundaries. Transitional border zones are characterized by cycles that are thinner than average, superimposed by cycles that are thicker than usual, within shallow-water depositional environments (Shadow Lake, Gull River, Moore Hill, and Coboconk formations) (figure 9, 10, and 11).

The boundary zones exhibit thicker-than-average cycles superimposed by thinner-than-average cycles in deeper-water depositional settings (Kirkfield and Vefrulam formations) (figure 12). The cycle boundary zones or surfaces can be traced laterally over considerable distances, without evident subaerial exposure characteristics. Five third-order depositional sequences are identified in the Black River-Trenton Limestone Group based on vertical facies differences and meter-scale cycle stacking patterns. The meter-scale cycle (fourth-order cycle) ranges from 6 to 30 meters in thickness. Four cycles of regional extent are present in the Black River-Lower Trenton Groups (figure 9-12). The depositional model of a carbonate ramp system developed for the Black River-Trenton Group in the study area indicates that the initial type consists of the transgressive basal clastic to supratidal cycle of the Shadow Lake and lower Gull River formations, represented by sequence 1. The second kind consists of supratidal to nearshore shallowing upward cycles within the Gull River, as depicted in sequence 2. The third type consists of two upward-coarsening cycles within the Moore Hill, Coboconk, and Kirkfield-lower Verulam formations, which exhibit no identifiable nearshore facies [38].

Sequence: commences at the base of the Shadow Lake Formation and represents the initial sequence established during the early transgressive-regressive phase.d This sequence , 7 - 32 m thick, corresponds to one huge meter-scale cycle (4th order cycle) consisting of two 5th order cycles. This sequence consists of supratidal sandstone/siltstone and shale microfacies interbedded and overlain by intertidal-supratidal calcareous/argillaceous dolostone, with sandy argillaceous dolostone capping the cycle (figure 9). The initial sequence in the Lake Simcoe region is 7 meters in thickness and correspond to one meter scale cycle, and two minor meter-scale cycles, incorporating the Shadow Lake Formation and Lower Gull River Formation (submember A1 of [14]). The basal transgressive section comprises conglomerate at the base, transitioning to coarse sandstone, siltstone, and shale. Superjacent regressive facies consist of supratidal calcareous/argillaceous dolostone, topped by progressively sandy argillaceous dolostone, ending in the deposition of a 15-25 cm bed of intraformational conglomerate, as witnessed in the Waubaushene and Uhthoff quarries. Sequence 1 emerged during the initial significant transgression period of the Middle Ordovician. Analogous to the Persian Gulf, it signifies the layering of increasingly coastal supratidal facies above a basal regolith. The fluctuation in cycle thickness can be attributed to changes in paleotopography and possibly local tectonics.

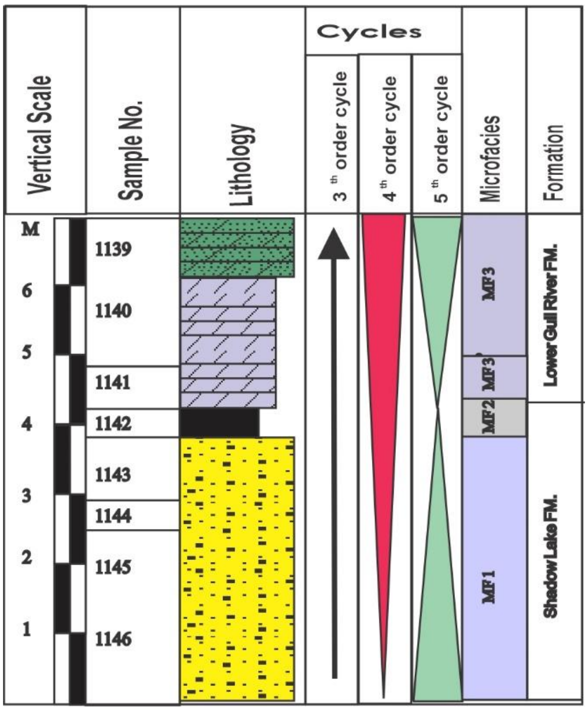

Figure 9. Section of OGS-93-11, showing sequence 1 contains one 4th order cycle (large meter scale cycle) and two 5th order cycle (small scale cycle) deepening and upward-shallowing and their microfacies arrangements (modified from [39]).

Sequence 2: is 5 to 18 meters thick and comprises one fourth-order cycle, which includes three fifth-order cycles, constituting the majority of the lower Gull Formation. The deposits consist of a package of asymmetrical, shallowing-upward units of supratidal calcareous/argillaceous to sandy argillaceous dolostone (Green marker bed). Cycle 2 is an intertidal-supratidal cycle characterized by limited subtidal and intertidal sediments transitioning into silty dolomitic supratidal sediments (figure 10). In the Lake Simcoe region, cycle 2 is merely 5 meters thick and comprises tidal flat carbonates, indicative of shallow hypersaline intertidal to lower supratidal environments with low energy. The formation is mostly composed of calcareous-argillaceous dolostone, interspersed intermittently with shallow subtidal facies of wackestone-mudstone, occasional storm deposits of packstone associations, and rare grainstone associations. It comprises two small asymmetrical cycles exceeding 2 m in thickness (figure 10).

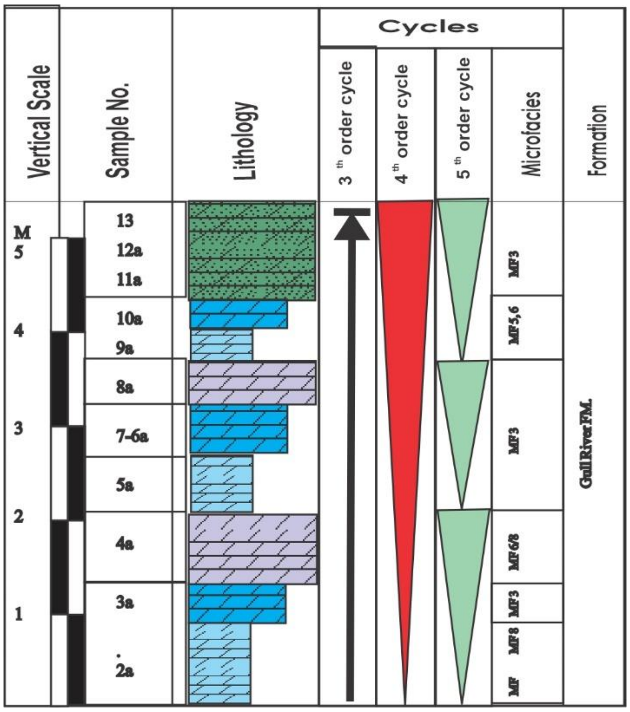

Figure 10. Section of Uhtjoff quarry showing sequence 2 contains one 4th order cycle (large meter scale cycle), and three 5th order cycle (small scale cycle) upward-shallowing cycles of the intertidal-supratidal, and their microfacies arrangement (modified from [39]).

Sequence 3: is 8–22 meters thick and comprises two fourth-order cycles, which consist of eight asymmetrical fifth-order upward-shallowing cycles, each ranging from 2 to 5 meters in thickness. The bottom 4th order cycle, consisting of two 5th order cycles, comprises interbedded intertidal-subtidal lagoonal mudstones and wackestones from the Upper Gull River Formation and Moore Hill Formation. The lower section of sequence 3 resembles the sediments that accumulate in the sheltered lagoons around Abu Abyad and Marrawh on the western region of the Trucial Coast. The upper 4th order cycles consist of sex 5th order cycle, cyclical transitions between shallow subtidal open lagoon and shoal bioclastic peloidal grainstones, which are occasionally interbedded with intraclastic bioclastic grainstones and frequent packstones of the Coboconk Formation (Figure 11). The sediments in the top section are analogous to those found along the Great Pearl Bank, where sediment variation correlates with water depth.

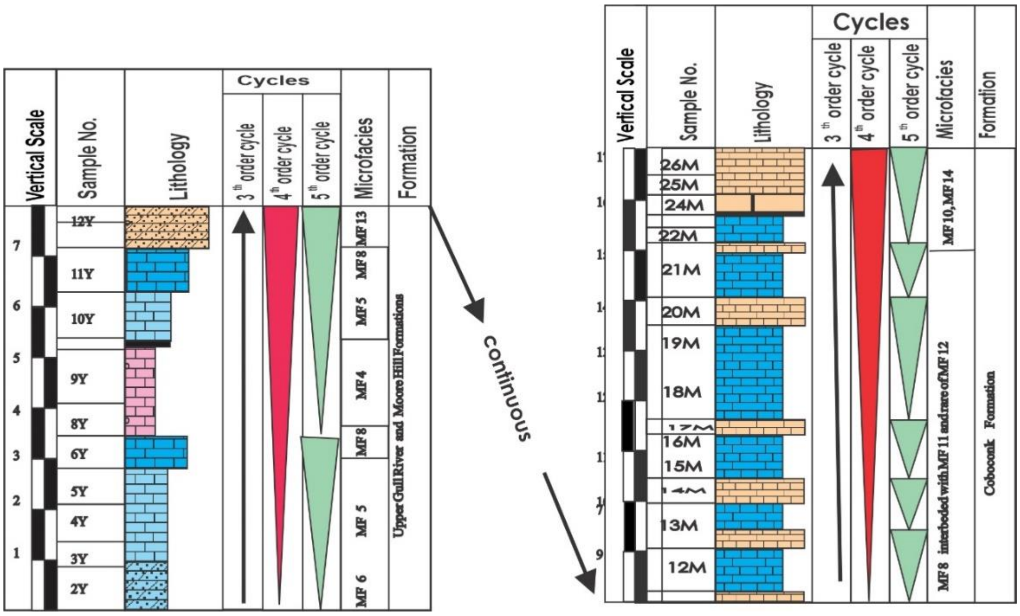

Figure 11. Composite section from Dalrymple & Brechin quarries, showing sequence 3 contains 2-4th order cycle (large meter scale cycle), and eight 5th order cycle (small scale cycle) upward-shallowing cycle of the third transgression phase, and their microfacies arrangement. (Modified from [39]).

Sequence 4: In the Lake Simcoe region, the sequence 4 is 18 meters deep and comprises one fourth-order cycle, which is subdivided into five fifth-order cycles (small-scale cycles) that include the Kirkfield and lower Verulam formations. Shales and interbedded grainstones and packestones, reflecting fluctuating calm and turbulent circumstances, transition into sporadically cross-bedded, bioclastic peloidal and dolomitic packstones and grainstones (including hardgrounds), together with rare oncolithic grainstones that signify more sustained turbulence. Sequence 4 resembles the open marine ecosystems of the Persian Gulf, located seaward of the Great Pearl Bank. The interbedded bioturbated grainstones and packstones, along with shales from the Kirkfield and lower Verulam formations, resemble the shallow water bivalve sands (bioclastic grainstones) and deeper water bivalve muds (packstone/wackestone to mudstone) found in the mid-ramp of the Persian Gulf.

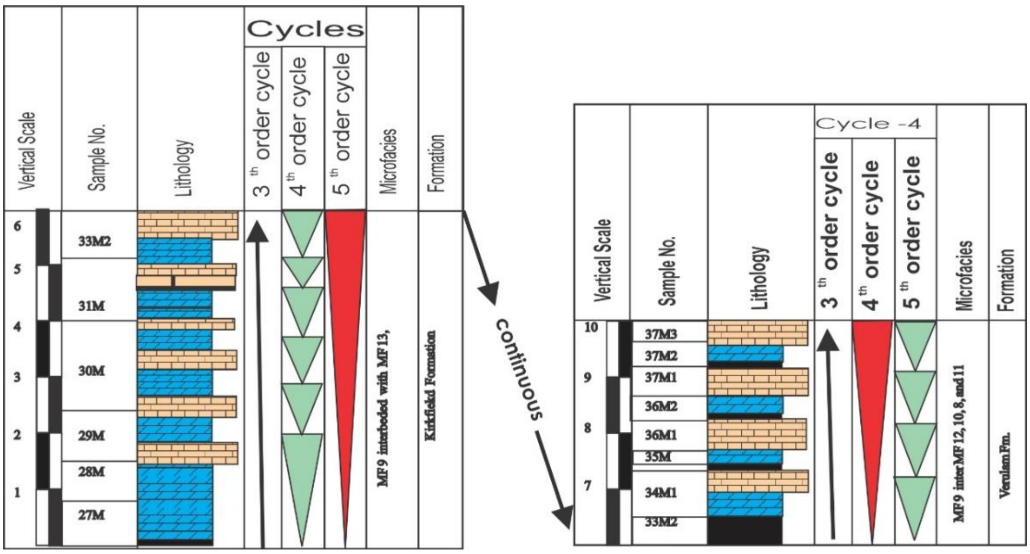

Figure 12. Composite section of Brechin quarry, showing sequence 4 consists of one 4th order cycle (large meter – scale cycles), and Ten 5th order cycles (small meter-scale cycles) upward-shallowing cycles and their microfacies arrangement (from [39]).

Discussion (Meter cycle Generation)

Two distinct mechanisms have been suggested to elucidate the development of meter-scale, shallowing-upward cycles: (1) autocyclic generation [39-44], (2) Allocyclic mechanisms refer to external factors influencing the sedimentary system, including climate variations, tectonic activity, and eustatic sea level changes. Climatic variations influence carbonate production ([45];[46]) and may be a contributing factor to the transition from the "tropical" Black River to the "temperate" Trenton Group [47]. The autocyclic model claims that tidal flats aggrade and prograde seaward over subtidal deposits, ultimately halting sediment formation and resulting in a meter-scale, shallowing-upward cycle [48- 50]. In this scenario, these cycles must be terminated by tidal-flat facies. This model may elucidate the genesis of peritidal cycles in the Shadow Lake and Gull River formations. The vertical succession of peritidal cycles indicates the reactions of specific tidal flats to fluctuating local sediment accumulation rates surrounding moving islands, rather than to external factors such as eustatic sea level variations. Lateral progradation occurs until adjacent subtidal regions become insufficiently expansive to generate significant sediment and for tidal forces to transport considerable sediment. Peritidal autocycles develop through the accumulation of a localized sediment wedge until it attains or marginally surpasses the high-tide elevation. The significant occurrence of contemporaneous lateral subtidal cycles in the Coboconk, Kirkfield, and Verulam Formations indicates that they cannot be exclusively attributed to an autocyclic origin. These subtidal cycles likely result from a balance between sediment buildup and accommodation gain (e.g., [1]; [6]; [7]). Therefore, the autocyclic model is not the primary mechanism for the formation of meter-scale cycles of the Black River – Trenton Group in the research area. Autocyclic and allocyclic mechanisms have been suggested for numerous shallowing-upward cycles. To ascertain the predominant mechanism in any succession, individual cycles must be meticulously traced laterally and precisely correlated; unfortunately, this is seldom feasible and has not yet been accomplished for the Black River - lower Trenton succession.

Conclusions

A comprehensive examination of microfacies, meter-scale cycles, and depositional sequences of the Middle Ordovician Black River – Trenton Group in Lake Simcoe, southern Ontario, disclosed that:

- A shallow-water carbonate ramp system was established across the Homoclinal ramp in the Lake Simcoe region during the Ordovician, where fifteen microfacies were developed within six depositional facies (associations), comprising peritidal, restricted, and open-marine subtidal facies.
- Four third-order depositional sequences were formed during the deposition of the Black River - Trenton Limestone. They mostly comprise the bottom transgressive and upper regressive components. The depositional sequence of the Black River – Trenton Group evolution and their creation were likely influenced by both autocylic (sedimentary) and allocyclic (sea level, climatic, tectonic) factors. Upward-shallowing cycles occur at two separate scales.
- Small meter-scale cycles (5th order cycles) demonstrate significant unpredictability and inconsistency; they can be interpreted as increasingly marine cycles, evolving from continental to open ramp, and consist of five categories: a) Siliciclastic cycles, b).Dolomitic mudstone-wackestone - silty/sandy dolostone cycles; c) Wackestone-packstone-(grainstone) cycles; d). Packstone-grainstone sequences, and e). Cycles of bioclastic-dolomitic packstone.
- Large meter-scale cycles (fourth-order cycles) extend from 6 to 30 meters in thickness, with three unique forms identified in the Lake Simcoe region. The primary type consists of a single violation, fining upward, regolith-supratidal cycle within the Shadow Lake Formation. The second type consists of two subtidal-supratidal shallowing upward cycles within the Gull River and Moore Hill formations. The third kind is a coarsening and deepening upward lagoonal-shoal cycle within the Coboconk layers. The fourth group includes upward cycles of open marine coarsening (and possibly shallowing) in the Kirkfield and Verulam formations, of which only one was analyzed in this study.
- Autogenic processes may primarily govern the creation of meter-scale cycles in the studied area

References

[1] Goldhammer, R.K., Dunn, P.A., Hardie, L.A. Depositional cycles, composite sealevel changes, cycle stacking patterns, and the hierarchy of stratigraphic forcing: examples from Alpine Triassic platform carbonates. Geol. Soc. Am. Bull. 1990; 102:535–562.

[2] Goldhammer, R.K., Lehmann, P.J., Dunn, P.A.The origin of high-frequency platform carbonate cycles and third-order sequences (Lower Ordovician El Paso Gp, West Texas); constraints from outcrop data and stratigraphic modeling. J. Sediment.nPetrol. 1993; 63:318–359.

[3] Osleger, D., Read, J.F. Relation of eustasy to stacking patterns of meter-scale carbonate cycles, Late Cambrian, USA. J. Sediment. Petrol. 1990; 61:1225–1252

[4] Strasser, A., Pittet, B., Hillgärtner, H., Pasquier, J.-B. Depositional sequences in shallow carbonate-dominated sedimentary systems: concepts for a high-resolution analysis. Sed. Geol. 1999; 128: 201–221.
[5] Chen, D.Z., Tucker, M.E. The Frasnian-Famennian mass extinction: insights from high-resolution sequence stratigraphy and cyclostratigraphy in South China.2003.
[6] Elrick, M. Cyclostratigraphy of middle devonian carbonates of the eastern great basin. J. Sediment. Res.1995; 65:61–79.
[7] Chen, D.Z., Tucker, M.E., Jiang, M.S., Zhu, J.Q. Long-distance correlation between tectonic-controlled, isolated carbonate platforms by cyclostratigraphy and sequence stratigraphy in the Devonian of South China. Sedimentology. 2001; 48:57–78.
[8] Chen, D.Z., Guo, Z.H., Jiang, M.S., Guo, C., Ding, Y. Dynamics of cyclic carbonate deposition and biotic recovery on platforms during the Famennian of Late Devonian in Guangxi, South China: Constraints from high-resolution cycle and sequence stratigraphy. Palaeogeogr. Palaeoclimatol. Palaeoecol. 2016; 448:245–265.
[9] Read, J.F., Goldhammer, R.K. Use of Fischer plots to define third-order sea-level curves in Ordovician peritidal cyclic carbonates, Appalachians. Geology. 1988; 16:895–899.
[10] Pope, M.C., Read, J.F. High-resolution surface and subsurface sequence stratigraphy of late Middle to Late Ordovician (Late Mohawkian-Cincinnatian) foreland basin rocks, Kentucky and Virginia. AAPG Bull. 1997; 81:1866–1893.
[11] Overstreet, R.B., Oboh-Ikuenobe, F.E., Gregg, J.M. Sequence stratigraphy and depositional facies of Lower Ordovician cyclic carbonate rocks, southern Missouri, USA. J. Sediment. Res. 2003; 73:421–433.
[12] Landing, E.D., Westrop, S.R., Keppie, J.D. Terminal Cambrian and lowest Ordovician succession of Mexican West Gondwana: biotas and sequence stratigraphy of the Tiñu Formation. Geol. Mag. 2007; 144:909–936.
[13] Holland, S.M., and Patzkowsky, M.E. Sequence stratigraphy and long-term paleoceanographic changes in the Middle and Upper Ordovician of eastern United States. In Paleozoic Sequence Stratigraphy: Views from the North American Craton. Edited by Witzke, B.J., Ludvigson, G.A., and Day, J. Special Paper - Geological Society of America. 1996; 306: 117–129.\
[14] Liberty, B. A. Paleozoic Geology of the Lake Simcoe Area:Geological Survey of Canada Memoir 355. 1969, 201.
[15] Brookfield, M.E. and Brett, C.E. Paleoenvironments of the Mid-Ordovician (Upper Caradocian) Trenton Limestones of southern Ontario, Canada: storm sedimentation on a shoal-basin shelf model. Sedimentary Geology. 1988; 57:75-105.
[16] Mac Niocaill, C., Van der Pluijm, B. A., and Van der Voo, R. Ordovician paleogeography and the evolution of the Iapetus ocean. Geology. 1997; 25(2): 159–162.
[17] Russell, D.J. and Telford, P.G. Revisions to the stratigraphy of the Upper Ordovician Collingwood Beds of Ontario - A potential oil shale; Canadian Journal of Earth Sciences, 1983; 801 (20): 1780-1790.
[18] Noor, I. Lithostratigraphy, environmental interpretation, and paleogeography of the Middle Ordovician Shadow Lake, Gull River, and Bobcaygeon formation in parts of southern Ontario. Unpublished Ph.D. dissertation, University of Toronto, Toronto, Ontario, 262p.1989.
[19] Melchin, M.J., Brookfield, M.E., Armstrong, D.K., Coniglio, M. Stratigraphy, sedimentology and biostratigraphy of the Ordovician rocks of the Lake Simcoe area, south-central Ontario. Geological Association of Canada B Mineralogical Association of Canada, Joint Annual Meeting, Ottawa 1994, Field Trip A4 Guidebook. University of Waterloo, Waterloo, Ont., pp. 101.
[20] Armstrong, D.K. and Dodge, J.E.P. Paleozoic Geology of Southern Ontario. Ontario Geological Survey, Miscellaneous Release–Data 219. 2007.
[21] Armstrong, D.K. Paleozoic geology of the northern Lake Simcoe area, southcentral Ontario. Ontario Geological Survey, Open File Report. 2000; pp. 43, 6011.
[22] Barnes C.R, Norford B.S, and Skevington D. The Ordovician system in Canada. International Union of Geological Sciences. 1984; Publication No 8, 27p.
[23] Coniglio, M., Melchin, M.J., and Brookfield, M.E. Stratigraphy, sedimentology and biostratigraphy of the Peterborough-Lake Simcoe area of southern Ontario. American Association of Petroleum Geologists, 1990. Eastern Section Meeting, Field Trip Guidebook no.3, 82p. 1990.
[24] Dunham. J. Classification of carbonate rocks according to depositional textures. In: Ham, W.E., (Ed.), Classification of Carbonate Rocks. AAPG Memoir. 1962; l: 108-121
[25] Wilson, J. L., 1975.Carbonate facies in geologic history. New York 30, 471.
[26] Flügel,E. Microfacies of Carbonate Rocks: Analysis, Interpretation and. Application. Springer, Berlin Heidelberg NewYork, 2004; 984.

[27] Lehrmann,D.J. Secular variation in parasequence and facies stacking patterns of platform carbonates: a guide to application of stacking - patterns analysis in strata of diverse ages and settings. In: Harris, P. M., Saller, A. H., Simo, J. A.,(Eds.), Recent Advances in Carbonate Sequence Stratigraphy: Applications to Reservoirs,Outcrops and Models. SEPM, Special Publication. 1999l l(63):187-225.\
[28] Roehl, P. O. Stony Mountain (Ordovician) and Interlake (Silurian) facies analogs of recent low-energy marine and subaerial carbonates, Bahamas: American Association of Petroleum Geologists. 1967; 51: 1979-2032.
[29] Shinn, E.A., Ginsburg, R.N., and Lloyd, R.M. Recent supratial dolomite from Andros Island, Bahamas. Special Publication Society of Economic Paleontologists and Mineralogists. 1965; 13: 112-123
[30] Shinn, E.A. Tidal flat environments. American Association of Petroleum Geologists Memoir. 1983; 33:173-210.
[31] Illing, l. V., and Wells, A.J. Dolomitization in the Persian Gulf (abstract). American Association of Petroleum Geologists Bulletin.1964; 48: p.532.
[32] Ball, M.M., Shinn, E. A. and Stockman, K.W. The geologic effects of Hurricane Donna in South Florida. Geological Journal. 1967; 75:583-397.
[33] Tucker. M.E., and Wright, V.P. Carbonate Sedimentology. Blackwell Scientific Publications, Oxford. 1990; 482pp.
[34] Purser, B.H. Syn-sedimentary marine lithification of Middle Jurassic limestone in the Paris Basin: Sedimentology. 1969; 12: 205-230
[35] Fischer, A. G. The Lofer cyclothems of the alpine Triassic. In: Merriam, D.F., (Ed.), Symposium on Cyclic Sedimentation. Kansas Geological Survey, Bulletin. 1964; l (69):107-148.
[36] Peterson, N. N. Carbonate petrology, structure, and stratigraphy of the Middle Ordovician carbonate rocks near Kingston, Ontario, Canada. Unpublished Ph.D., Queens University, Kingston. 1969: 129p.
[37] McFarlane, R.B. Stratigraphy, paleoenvironmental interpretation, and sequences of the Middle Ordovician Black River Group, Kingston, Ontario, Canada. Unpublished M.Sc.Thesis, Queen's University, Kingston, Ontario. 1992:181p
[38] Brett, C. E. and Brookfield, M.E. Morphology, faunas and genesis of Ordovician hardgrounds from southern Ontario, Canada. Paleogeography, Paleoclimatology, Paleoecology. 1984; 46: 233-290.
[39] El Gadi. Muftah. Sedimentology and sequence stratigraphy of the Ordovician Black River and lower Trenton Groups, Lake Simcoe area, Ontari. Unpublished Ph.D. dissertation, University of Guelph, Guelph, Ontario, 364p. 2001.
[40] Ginsburg, R. N. Landward movement of carbonate mud: new model for regressive cycles in carbonates: Abstract. AAPG Bull. 1971; 55: 340–340
[41] Wilkinson, B.H., 1982. Cyclic cratonic carbonates and phanerozoic calcite seas. J. Geol. Educ. 1982; 30:189–203.
[42] Pratt, B.R., James, N.P. The St George Group (Lower Ordovician) of western Newfoundland: tidal flat island model for carbonate sedimentation in shallow epeiric seas. Sedimentology. 1986; 33:313–343.
[43] Cloyd, K.C., Demicco, R.V., Spencer, R.J. Tidal channel, levee, and crevasse-splay deposits from a Cambrian tidal channel system; a new mechanism to produce shallowing-upward sequences. J. Sediment. Petrol. 1990; 60:73–83.
[44] Satterley, A. The interpretation of cyclic successions of the Middle and Upper Triassic of the Northern and Southern Alps. Earth Sci. Rev. 1996; 40:181–207.
[45] Pitman, W.C. Relationship between eustacy and stratigraphic sequences of passive margins. Geological Society of America Bulletin. 1978; 89: 1389-1403.
[46] Fisher, A.G. The Lofer cyclothems of the Alpine. Bulletin of Geological Survey of Kansas. 1964; 169:107-149.
[47] Patzkowsky, M.E., and Holland, S.M. Biotic response to a Middle Ordovician paleoceanographic event in eastern North America. Geology. 1973; 21: 619-622.
[48] Ginsburg, R.N. Landward movement of carbonate mud: New model for regressive cycles in carbonates [abs.]: American Association of Petroleum. Geologists Bulletin. 1971; 55: 340.
[49] Pratt, B.R., James, N.P.The St George Group (Lower Ordovician) of western Newfoundland: tidal flat island model for carbonate sedimentation in shallow epeiric seas. Sedimentology. 1986; 33: 313–343.
[50] Satterley, A. The interpretation of cyclic successions of the Middle and Upper Triassic of the Northern and Southern Alps. Earth Sci. Rev. 1996; 40:181–207.