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Original article

Shoaling Upward Cycles (Parasequences) and their Significance in the *Black River - Trenton Carbonates (Ordovician) of Southern Ontario,* Canada

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ABSTRACT

The Black River and Trenton Groups form a thin (average 150 metres) transgressive systems tract of a Middle to Upper Ordovician carbonate depositional sequence. Within this tract, various upward shoaling cycles bounded by flooding surfaces (parasequences) can be used for local correlation. The Black River contains symmetrical and asymmetrical low energy 'lagoonal' - supratidal cycles within a generally deepening (backstepping) succession. Flooding surfaces are marked by various condensed 'glauconitic' horizons with a marine, though somewhat low-diversity, fauna. The facies can be directly compared with those of the modern Persian Gulf. The Black River- Trenton boundary is a major flooding surface separating a 'lagoonal'-tidal flat succession (Black River) from an open marine succession (Trenton Group). This change is practically synchronous from Lake Simcoe to Kingston and marks either a relatively rapid and significant rise in relative sea-level, or an erosion surface caused by shelf reworking between depositional shoreline and deep shelf facies. Interpretations of this open shelf succession are difficult due to major biological changes since the Ordovician; though the 'shaved shelf' depositional model may be more appropriate than current conventional models. The Trenton Group also contains asymmetrical and symmetrical cycles (like the Jurassic Klupfel cycles of western Europe), whose resistant capping grainstones form persistent and mappable units over much of southern Ontario. Like Klupfel cycles, the Trenton cycles become more symmetrical and complete from shelf to basin (from western Ontario to central New York). Furthermore, each cycle contains distinctive biofacies and nektonic/pelagic faunas related to extinction and recolonization. The focus of this paper is on the small-scale cyclicity, its probable control by Milankovitch-forced sea-level oscillations, and how stacking patterns of meter-scale cycles can be used to define internal components of larger-scale sequences and estimate variations in relative sea level.

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INTRODUCTION

Sequence stratigraphy is now routinely used to interpret the cyclicity and architecture of sedimentary basins, in both subsurface and outcrop studies [1]. However, sequence stratigraphy is a genetic procedure, in that the bodies and surfaces defined imply a mode of origination. For this reason, (as noted earlier), it must follow description of the sediments, their geometric relationships, and any apparent cyclicity. As Liro noted, it is particularly important to first identify the relative cycles and their hierarchy, then correlate the significant surfaces defining this hierarchy through the data grid, and then (and only then) apply an interpretation of the relevant sequence stratigraphic nomenclature [2]. The vertical arrangement of facies in the Lake Simcoe area form repetitive cycles which can then be traced laterally into adjacent areas, complicated by the effects of sea-floor topography and possibly synsedimentary faulting. These cycles may repeat through time because carbonate and evaporite sedimentation in shallow water is dependent on changes in subsidence rate, local tectonics, relative sea-level changes, and climate, which may shut down or change the system. Carbonate sediments thus frequently occur in packages bounded by discontinuities. The type and distribution of such cycles provides much information about the nature of, and controls on the depositional at ancient carbonate rocks [3]. These vertical cycles are analogous to those described from other ancient successions, and also inferred from cores of comparable modern ramps, like the Persian Gulf [4-6], and South Australia [7-9]. The mechanisms controlling the development of upward-shallowing cycles in carbonate rocks are reviewed by [10-13], and are of two types: a) Autocyclic mechanisms are those intrinsic to the sedimentary system and the result of processes within the sedimentary basin [10-14]. b) Allocyclic mechanisms are those external to the sedimentary system, such as climatic change, tectonic movements, and eustatic sea level. The objective of this paper are to 1) considers the nature, extent and interpretation of various types of cycles in the Black River- lower Trenton succession; 2) infers the possible mechanisms of cycle development; 3) interprets the outcrop sections in terms of sequence stratigraphy

GEOLOGICAL SETTING

The Lake Simcoe area is essentially a lowland plain sloping gently toward the southwest and terminating against the Niagara Escarpment. The Ordovician carbonates in this area lie unconformably on Precambrian basement which is exposed to the north and contain resistant units which form several north-facing escarpments [15]. The Ordovician rocks were deposited on what appears to have been a gently undulatory peneplain [16]. Precambrian shield inliers, for example those west of Sebright and at Rohallion, indicate that paleotopographic highs may have been up to a few tens of meters above the Ordovician sea level and persisted for a long time during Black River and lower Trenton times [15]. Alternatively, synsedimentary faulting during Ordovician times may have formed these inliers [17]. The Middle Ordovician carbonates in this area are defined as the Simcoe Group [18]. Though [18] assigned a basal siliciclastic unit, the Shadow Lake Formation, to a separate Basal Group, most later workers include it in the Simcoe Group together with four overlying carbonate units, the Gull River Formation, the Bobcaygeon Formation (alternatively Coboconk and Kirkfield formations), the Verulam Formation, and the Lindsay Formation (alternatively Coburg Formation). These underlie the black fissile shales of the Whitby Formation of the Upper Ordovician. (Table 1).

Table 1. Middle to Upper Ordovician stratigraphic units used in Ontario (adapted from [21])

Series	Stage		Southwestern Ontario (Subsurface)		South-Central Ontario		Eastern Ontario)	
Upper Ordovician	Maysvillian		Trenton Group	Cobourg Fm.	Simcoe Group	Colling wood Mb.	Ottawa Group	Estview Mb.
	Edenian					Lindsay Fm.		Lindsay Fm.
	Trenton	Edenian		Sherman Fall Fm.		VerulamFm.		VerulamFm.
		Kirk - fieldian		Kirkfield Fm.		Bobcaygeon Fm.		Bobcaygeon Fm.
		Rock - Landian	Black River Group	Coboconk Fm.				
Middle Ordovician	Blackriverian			Gull River Fm.		Gull River Fm.		Gull River Fm.
				Shadow Lake Fm.		Shadow Lake Fm.		Shadow Lake Fm.
	Chazyan							Rockfill Fm.

Tectonic activity in this area is restricted to simple normal faulting [18]. Moderate to steep dips are found only around Precambrian inliers, where such dips are due both to initial inclination around shoal areas in the Ordovician sea and to later compaction around them [19]. The faults recognized in the Peterborough-Lake Simcoe area are small in both lateral and vertical extent [18]. Some faults have moderate stratigraphic displacement of up to 4m: most show only as surface lineaments extending for up to 1 km with topographic relief of < 2 m [20].

REGIONAL GEOLOGY SETTING

Middle Ordovician carbonate rocks are widely distributed in the Great Lakes regions of Canada and the United States. They occur in the subsurface in the Michigan and Appalachian basins, and form an outcrop belt along the periphery of tectonic elements, extending from the Adirondack region of New York State, through south-central Ontario, to the states of Michigan and Wisconsin [22,23] (Fig. 1).

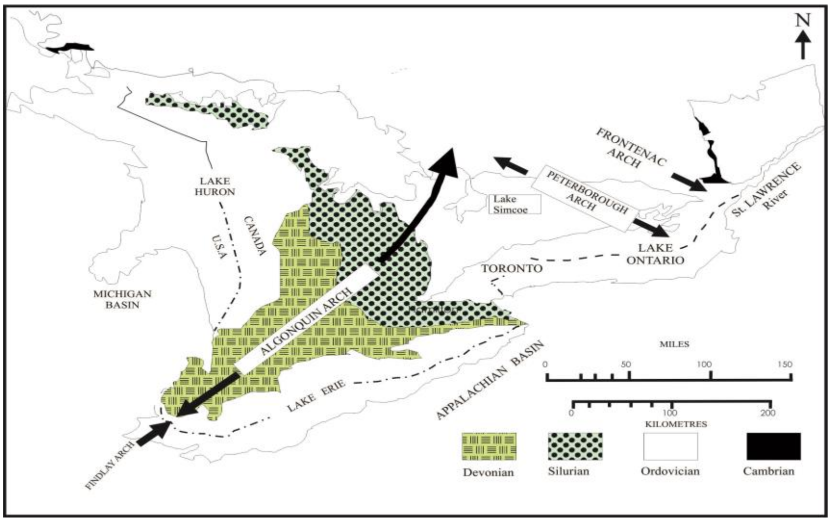

Figure 1. Major structural elements and general Paleozoic bedrock geology of southern Ontario (modified from [24].

Three major structures control Paleozoic rock distribution across southern Ontario (Fig.1). The north-east trending Algonquin Arch was probably tectonically active periodically throughout the Paleozoic in response to flexural subsidence in the Appalachian basin [25]. This Arch is a prominent feature which separates the intracratonic Michigan basin from the foreland Appalachian Basin. However, its effect on Ordovician sedimentation was limited and it does not affect the thickness of Ordovician formations [26]. The Frontenac Arch is a Precambrian high that isolates strata in eastern Ontario from the rest of the province, and connects the Grenville outcrop belt of southern Ontario to that of the Adirondack mountains in northern New York [24]. Like the Algonquin Arch, it had little effect on Ordovician sedimentation. The Peterborough Arch is less pronounced and broader, and identifiable only from variation in Ordovician sedimentation [18]. In fact, it is the only major tectonic feature which affected Ordovician sedimentation. The Middle Ordovician rocks of Ontario form the lower part of Sloss's Middle Ordovician to Early Devonian Tippecanoe sequence which is underlain (mostly in the subsurface) by the Cambrian to Lower Ordovician Sauk sequence. The Sauk sequence (Cambrian-Lower Ordovician) is bounded by a basal unconformity on the underlying Precambrian shield and an upper erosional surface related to the onset of the Taconic orogeny. It consists of nonmarine, craton-derived sandstones passing gradually upwards into dolostones that progressively onlapped and ultimately overlapped the Algonquin and Findlay arches [27,23]. In Ontario it is known only in easternmost areas and in the subsurface [28,29]. In most areas, the Sauk sequence was eroded prior to the transgression marking the base of the Tippecanoe.The Tippecanoe sequence (Middle Ordovician to Early Devonian) is bounded by a basal erosional contact resulting from a post Lower Ordovician regression and upper boundary that is locally erosional and marked by a significant influx of younger Devonian orogen-derived clastic sediments. It also includes the carbonate rocks studied in this thesis. The stratigraphy of Paleozoic outliers in Ontario [30-33] and adjacent Quebec [34-36], indicates progressive overlap of the Precambrian shield, Sauk, and older Tippecanoe sequence rocks during the Tippecanoe marine transgression. The transgression is marked by a generally simple stratigraphic sequence from supratidal, tidal flat clastics and carbonate, through lagoon and shoal carbonates into offshore carbonates (Fig. 2). This inundation produced a succession of shallow-water marine carbonate rocks with minor clastic rocks collectively known as the Black River and Trenton Groups in south-western Ontario, the Simcoe Group in south-central Ontario, the Ottawa

Group in eastern Ontario, and the lower part of the Liskeard Group in the Lake Temiscaming outlier [37, 26, 18, 34, 38]. Table 1 shows the approximate correlation of the various lithostratigraphic units of the three main regions of southern Ontario. The terms Black River and Trenton groups are used instead of the composite term Simcoe Group to emphasize their distinct lithological and faunal characteristics. An unsolved problem is to what extent the various formations and facies succeed each other through time,and to what extent they are lateral equivalents of one another. At least for the major Black River - Trenton Group boundary, bentonite correlation indicates an almost isochronous contact from eastern Ontario to south-central Ontario [39]. Though a major faunal turnover occurs at the Black River-Trenton boundary [40], this might simply be due to the overall major facies change from lagoonal to open marine conditions at this boundary. The biofacies-based stages (unfortunately still in use) simply perpetuate a discredited idea that formations and their benthonic faunas mark isochronous horizons [41].

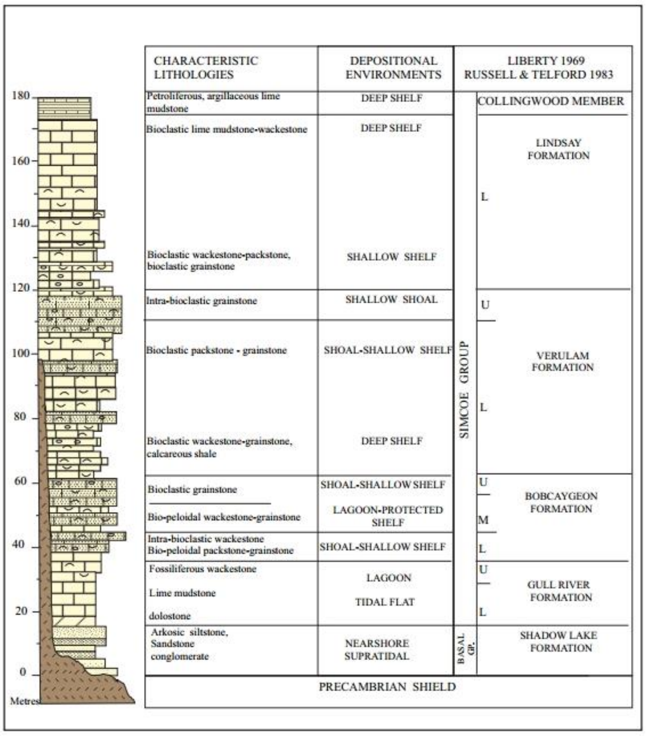

Figure 2. Lithostratigraphy and depositional environments of the Simcoe Group (Black River and Trenton limestones) in ***southern Ontario. lithostratigraphic column modified after [8].***

SEQUENCES

A sequence is a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities [42]. A sequence boundary is an unconformity updip, and a correlative conformity downdip: it is generated by a relative fall in sea-level. Thus, the entire Middle to Upper Ordovician succession in Ontario, from basal Shadow Lake to Queenston Formation represents a single transgressive-regressive cycle (a sequence *sensu stricto*) with numerous smaller-scale transgressive-regressive cycles (parasequences) within it. The basal sequence boundary is the unconformity below the Shadow Lake Formation. The upper sequence boundary is the unconformity below the transgressive Silurian Whirlpool Sandstone [43]. The Black River - Trenton succession represents the transgressive systems tract of the Shadow Lake - Queenston sequence. The cycles already described previously are the basic architectural elements of this transgressive systems tract. Such upward-coarsening cycles are given lots of different names: Klupfel cycles [44], upward-shallowing cycles [9], parasequences [45], or depositional sequence [14]. The erosion surface that separates the Lindsay Formation from the Whitby Formation in places is of minor significance. Both are deep-water deposits and the principal difference between them is the relatively abrupt change in carbonate and organic carbon content. There is no evidence for subaerial exposure or significant regression at the boundary between these units, and there is no biostratigraphic or lithologic evidences for a disconformity. Therefore, the contact does not represent a sequence boundary, but a maximum flooding surface.

PARASEQUENCES

Parasequence has defined by [42] as; "a relatively conformable succession of related beds or bedsets bounded by marine flooding surfaces and their correlative surfaces. Parasequences are progradational and therefore beds within parasequences shoal upward. By this definition, the coarsening upward major cycles of the Black River and lower Trenton are parasequences. They are marked by flooding or deepening events at their bases, with fine muds and carbonates overlain by higher energy sandy or grainstone-dominated units. The overall transgressive nature of the succession means that each parasequences backsteps, and is more offshore than the one below, and each parasequence contains a deeper set of facies than the parasequences below (Fig. 4). Though the rapid rises in base-levels (and thus accommodation space) that start parasequences are often attributed to eustatic sea-level rise; in fact, some flooding surfaces can be caused by autocyclic mechanisms, such as reduction in sedimentation, increased tectonic subsidence (perhaps rapidly during an earthquake), migration of tidal channels, and so on. Because shallow water facies within a parasequences will pinch out laterally in a downdip direction, and deeper water facies will pinch out updip, the facies of a single parasequences will change predictably updip and downdip. Because of the generally strike-alignment of the Ontario Black River-Trenton outcrop, this is not apparent from this outcrop-based study.

Black River parasequences

The first two Black River parasequences are relatively uniform and appear to be the result of relative sea-level fluctuations across an extensive, generally flat surface. In each, a complex of variable intertidal-subtidal lagoonal sediments passes up into more uniform supratidal sandy dolomite (Green Marker Beds). The third and fourth parasequences are little different, in that the coarsening upwards is the result of shoal transgression over lagoonal sediments. There is no actual regression at the top. Furthermore, it is possible to consider these third and fourth parasequences as one transgressive lagoonal-shoal unit, with no regression at the top; in which case, neither is a parasequence1.

1). The first predominantly supratidal parasequences consists of the Shadow Lake clastics overlain by the basal part of the lower member of the Gull River Formation (sub member A1of Liberty and corresponds to cycle 1. Arkosic conglomerates fine upwards into sandstones, siltstones and shales, followed by thin supratidal carbonates (calcareous/argillaceous dolostone), and capped by the first Green marker bed [18]. The problem is whether the siliciclastic facies of the Shadow Lake unit at the base of this first parasequence should be classified as an incised valley fill or as a basal transgressive unit. The cap Green Marker Bed (sandy argillaceous dolostone facies) marks regressive superposition of supratidal sabkhas, and at the Uhthoff and Waubashene quarries is accompanied by the deposition of a 15-25 cm bed of intraformational conglomerate. Whether regression was due to sediment build-up or actual sea-level fall is impossible to determine.

2). The second intertidal -supratidal parasequence includes the lower member of the Gull River Formation, 5 to 8 meters thick [18]. This parasequence is comparatively simple consisting of shallow hypersaline intertidal to lower supratidal carbonates deposited in quiet water. One problem is the significance of glauconite in the lower units - suggesting relatively deep shelf conditions. However, the parasequence is dominated by calcareous-argillaceous dolostone.

3). The third parasequence- intertidal-lagoonal-shoal- includes the upper Gull River Formation (B1 and B2 of Liberty and the Moore Hill Formation (B3 of Liberty. The basal part is marked by fine-grained intertidal facies overlying the second Green Marker Bed, and it is capped by coarse to very coarse-grained facies. The entire parasequence contains peloidal dolomitic wackestone interbedded with mudstone, and, locally storm deposition of packstone - grainstone associations. As relative sea level rose, subtidal, restricted lagoonal deposits pass upwards into white to cream fenestral limestones and fine-grained peloidal lime mudstone deposited in quieter water. More open lagoonal deposits of the Moore Hill Formation succeed. A number of minor asymmetrical shallowing upward cycles of 3 to 5 m thick occur. This intertidal-lagoonal parasequence corresponds to the lower part of cycle 3.4. The fourth parasequence-lagoonal-shoal- includes the bioclastic shoal deposits of the Coboconk formations, formed as the entire area became open a marine subtidal shallow ramp during a rise in sea level. The complete parasequence can be seen in the Brechin, Carden, Dalrymple, and Kirkfield quarries. It is dominated by high energy, shallow subtidal microfacies consisting of bioclastic peloidal grainstone interbedded with packstones, and locally with low intertidal-shallow subtidal intraclastic bioclastic grainstones deposited by storms. Bioclasts are dominated by crinoids, tabulate corals, stromatoporoids, and calcareous algae. Six minor upward -shallowing cycles, 1.5 to 2.5 m thick, consist of grey to tan, medium-coarse grained, bioclastic peloidal and intraclastic packstone grading upward into coarse-very coarse-grained (grainstone), rare oncolitic bioclastic grainstone, and small scale cross-bedded coarse-very coarse-grained grainstones. This parasequence corresponds to the upper part of the cycle 3.

Trenton parasequences

The Trenton parasequences are much more variable in thickness, and are at least partially controlled by differential subsidence related to the emplacement of the Taconic arc towards the east. Furthermore, they do not show the successively deeper set of facies characteristic of backstepped parasequences. The facies at the tops of the Verulam and Lindsay Formation parasequences show no consistent deepening trend (though the interpretation of these facies is somewhat problematical) [46]. The 5th parasequence includes the Kirkfield and lower Verulam formations, and is a 7 to 9-meter-thick shallowing upward, asymmetrical cycle, with 12 minor upward-shallowing asymmetrical cycles from 1.5 to 2 meters thick (which could themselves be classed as parasequences!). Facies are dominantly bioclastic grainstones interbedded with packstones and common beds of shale, and local and scarce oncolitic grainstones in the Kirkfield Formation. The facies are those of an open marine subtidal ramp with oscillating conditions between high and low energy normally ascribed to storms. Cross bedded and graded coarse-grained facies and hardgrounds throughout the parasequence are normally ascribed to storm reworking [8]. The upper part of the parasequence corresponds to the lower Verulam Formation, where increasing shale content is somewhat at odds with the inferred shallower water conditions.

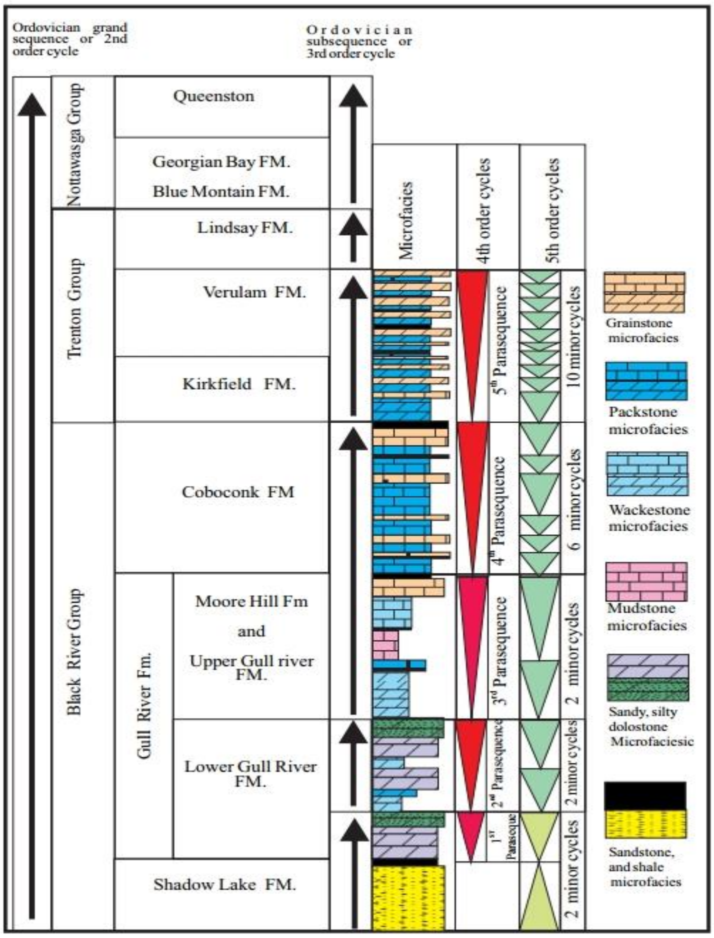

Figure 3. Large scale regional Ordovician sequence in Ontario. The parasequence and small-scale shallowing-upward cycles of this study compare in size with the 4th and 5th order cycles of [47]].

Interpretation

Most of the parasequences are retrogradational shallowing upward cycles, normally bounded by sharp non-depositional surfaces representing small scale marine transgressions. The first three intertidal-lagoonal parasequences are influenced by the paleogeographic high that separated the eastern area (Marmora-Kingston) from the Lake Simcoe area, which was semi-restricted and less influenced by storm deposition, and most of facies are fine-medium grained of less agitated water (lagoon). The fourth shoal parasequences and the succeeding Trenton open ramp parasequences are unaffected by the Marmora-Kingston high, indicating that its inherited topographic, or syndepositional tectonic control no longer operated on sedimentation. This leads to the problem of what did control sedimentation during Black River - Lower Trenton times.

Practical significance

This study has a number of practical uses: 1). Microfacies analyses of this type allow borehole cuttings to be compared with outcrops in which more detail helps in environmental interpretation. This allows better understanding of sediment distributions in the subsurface and can help in delimiting the more porous dolomitized grainstone units which are the main gas and oil bearing units in Ontario. 2). Characterizing the sedimentary nature of individual formations, as well as the variation within them, should help in the planning of cement quarry location and development, though geochemical studies on element composition are also essential

CONCLUSION

Upward-shallowing cycles occur at two scales: Minor cycles are relatively thin, generally less than 5 metres thick, and of five basic types, which tend to be found in specific formations, and consists of five types. Major cycles are between 6 and 30 metres thick, and there are three types of major cycles in the Lake Simcoe area. The generally simple stratigraphic sequence from supratidal, tidal flat clastics and carbonate, through lagoon and shoal carbonates into offshore carbonates can be interpreted as a single transgressive systems tract of a sequence encompassing the entire Middle to Upper Ordovician succession (Shadow Lake to Queenston Formations) in southern Ontario. Within this, the individual major cycles form retrogradational shallowing upward parasequences. The first three intertidal-lagoonal parasequences are influenced by the Peterborough Arch which separated the eastern Marmora-Kingston area from the Lake Simcoe area. The fourth shoal parasequences and the succeeding Trenton open ramp parasequences are unaffected by the Peterborough Arch, indicating that its inherited topographic, or syndepositional tectonic, control no longer operated on sedimentation. Allogenic processes may be the main control on parasequence formation in the study area. The five parasequences are traceable for long distance to the east (Kingston area) as to the west (Manitoulin area), and have systematic change in thickness within stratigraphic section. Within the parasequences, individual cycles are impersistent and are probably the result of autocyclic controls

Disclaimer

The article has not been previously presented or published, and is not part of a thesis project.

Conflict of Interest

There are no financial, personal, or professional conflicts of interest to declare.

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