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Original article

Microfacies Analysis and Depositional Model for the Black River - Trenton Carbonates (Ordovician) of Southern Ontario, Canada

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ABSTRACT

This study documents the detailed microfacies depositional environment of the Ordovician Black River and Trenton limestone Groups in Lake Simcoe area of southern Ontario, resting unconformably on Precambrian basement. Local Precambrian 'highs' complicate the overall facies pattern and lithofacies patterns define local shoal, intershoal and basinal environments. Detailed microfacies and facies analysis in large quarries in the Lake Simcoe area are used to infer various carbonate environments by comparison with analogous modern and ancient ramps. Fifteen microfacies are grouped into six microfacies associations based on composition, grain size and texture. Relative energy levels, and depositional environments for these are then inferred. These environments resemble the Recent Arabian Shelf of the Persian Gulf for the Black River Group, and the Recent West Florida Shelf for the Trenton, though other Recent ramps like South Australia are also comparable. The vertical arrangement of facie\s in the Lake Simcoe area forms repetitive cycles, which can then be traced laterally into adjacent areas, complicated by the effects of sea-floor topography and possibly by synsedimentary faulting.

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INTRODUCTION

As in many other regions of the world, one of the most outstanding features of the early Paleozoic rocks exposed in the Lake Simcoe area southern Ontario is the development of a thick succession of shallow water, Ordovician carbonate shelf. These rocks were recognized to have been deposited on carbonate ramp [1]. The study and interpretation of the textures, sedimentary structures, fossils and lithologic associations of this carbonate succession on the scale of an outcrop, quaries, and cores comprise the subject of microfacies analysis. The microfacies associations are recurring groups of interbedded microfacies. These are basically the same as facies in that they are interbedded lithologies with some paleoenvironmental significance. Though it is possible to use a simple descriptive classification of associations, a genetic classification based on the environmental interpretations of individual microfacies leads to a clearer view of how these facies associations compare with modern environments, and the interpretations of [2-4]. The environmental divisions recognized are: supratidal, intertidal, lagoonal, and shoal for the Black River (following [4]), and shallow to deep marine and shoal (with variations) for the lower Trenton (following [5]). The type and stratigraphic distribution of the Black River-lower Trenton environments places constraints on any possible facies model used to explain them. Carbonate facies models use up to nine distinct environments, which fit into three major divisions: basin, outer shelf, and inner shelf [6]. There are two basic variants of carbonate shelf models: rimmed shelves and ramps [7]. Rimmed shelves have areas of shallow water (either reefs or shoals) separating a lagoonal from a basinal area. Ramps ideally deepen gradually towards a shelf edge without an intermediate shallow water area [1]. The vertical succession of the

Black River-Trenton facies in the study area has no major time breaks and, according to Walther's Law, show the nearshore to offshore distribution of facies at any one time. Despite local variation and cyclicity, the consistent vertical change in the facies associations implies a consistent onshore-offshore pattern which shows progressive deepening interrupted by a zone of high-energy shoals (Coboconk Formation). A ramp model best fits the both vertical facies distribution of the Black River and Trenton Groups in the study area as justified below. The main modern analogies chosen for comparison with the Black River-Trenton microfacies are the Arabian Shelf of the Persian Gulf and the West Florida Shelf. The objective of the paper is: 1. To establish the facies and depositional environments; microscale to macroscale and to examine the heterogeneity of the sedimentary sequences of the Black river -trenton limestone; 2. To provide an outcrop analogue model with its evolution.

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 [8]. The Ordovician rocks were deposited on what appears to have been a gently undulatory peneplain [9]. 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 Ordoviciansea level and persisted for a long time during Black River and lower Trenton times [8]. Alternatively, synsedimentary faulting during Ordovician times may have formed these inliers [10]. The Middle Ordovician carbonates in this area are defined as the Simcoe Group though earlier study [11]. though earlier study [11] 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). Tectonic activity in this area is restricted to simple normal faulting. 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 [12]. The faults recognized in the Peterborough-Lake Simcoe area are small in both lateral and vertical extent though earlier study [11]. 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 [13]. The stratigraphy of Paleozoic outliers in Ontario [14-18] and adjacent Quebec [19-21] 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. 1).

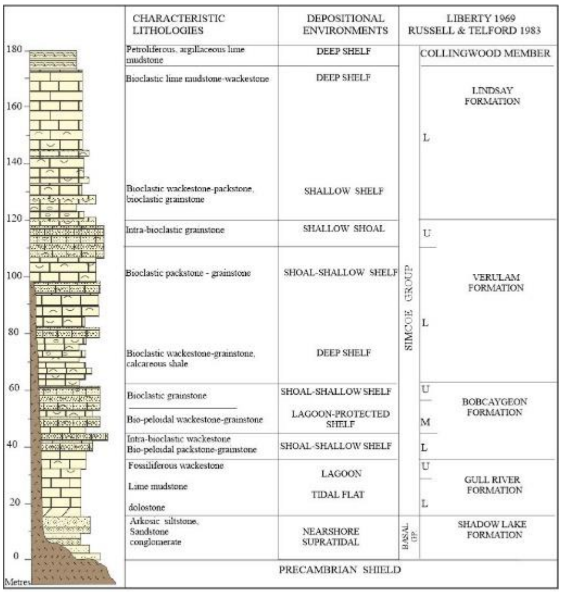

Figure 1. Lithostratigraphy and depositional environments of the Simcoe Group (Black River and Trenton limestones) in southern Ontario. (Modified after [8]).

METHODS

Study area

The study area extends from Coldwater in the west to Bobcaygeon in the east and covers approximately 2030 km' (Fig.2). The principal exposures studied are: Waubaushene Quarry, Medonte Quarry, Uhthoff Quarry, Longford Quarry; Rama Township Quarry, Sebright Quarry, Dalrymple Lake roadcut, Brechin Quarry, Carden Quarry, Dalrymple Quarry, New Kirkfield Quarry, Coboconk Quarry, a roadcut on Highway 35; two nearby roadcuts on Highway 503; Burnt River Quarry.

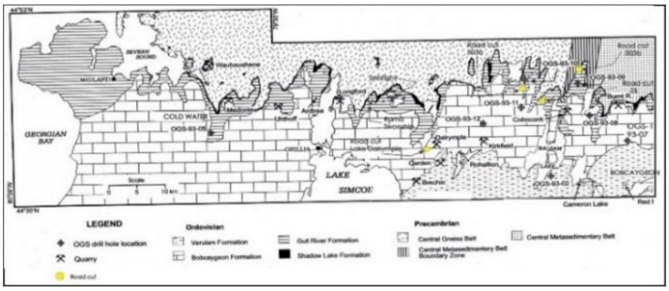

Figure 2. Geology of the northern Lake Simcoe area, showing location of main quarries, natural exposures, and OGS drill holes and Precambrian inliers (Ardtrea, Rohallion, Cameron Lake and Red Rock). Geology after [22]. [23], [24]

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Data collection procedure

These16 sections received detailed bed-by-bed field study (macroscopic description) concentrating on lithology, sedirnentary structures when available, fauna, and diagenetic features. Individual samples frorn these are the basis for the microfacies analysis. Samples were also studied from five cores of the Ontario Geologicai Survey (localities 17 to 21; Fig. 2). A total of 490 samples were collected from 21 sections. The vertical spacing of samples varies according to the lithological change and bed thickness, averaging 0.6 m in natural exposures and quarries, and 1.4 m in drilled cores. The average sampling is about one thin section every 0.8 m. Of the 490 thin sections and peels made, 362 thin sections and peels were from quarries and natural exposures, and 128 thin sections were from drilled cores. Microfacies were studied using the standard methods of [25-26-27-28]. For each peel or thin section, the following were recorded; type and relative abundance of primary constituents, matrix and cement, texture, and structure. Secondary diagenetic minerals, structures and sequences were not initially used to define microfacies (. From these, fifteen microfacies are grouped into six microfacies associations based on composition, grain size and texture (Fig. 3). Relative energy levels and depositional environments for these are then inferred. Genetic associations of Ordovician microfacies were then inferred by comparison with modern associations.

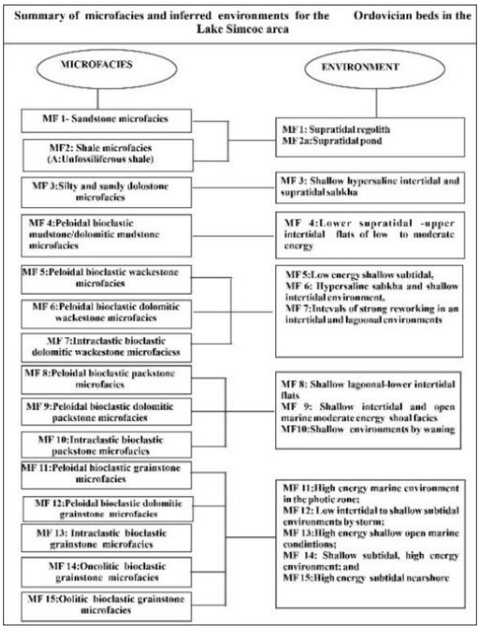


Figure 3. Summary of microfacies and inferred environments for the Ordovicianbeds in the Lake Simcoe area.

RESULTS AND DISCUSSION

Microfacies analysis

Fifteen microfacies are distinguished in the study area based on the bed -by-bed study and microscopic analysis of all major natural exposures, quarries and drilled cores when available. Each microfacies is described in the following order: outcrop and petrographic description of microfacies (Fig. 4); equivalents in other local studies; interpretation of depositional process; equivalent modern microfacies; and environmental comparisons. Individual microfacies are grouped into sex microfacies associations. These are basically the same as facies in that they are interbedded lithologies with some paleoenvironmental significance. Though it is possible to use a simple descriptive classification of associations, a genetic classification based on the environmental interpretations of individual microfacies leads to a clearer view of how these microfacies associations compare with modern environments.

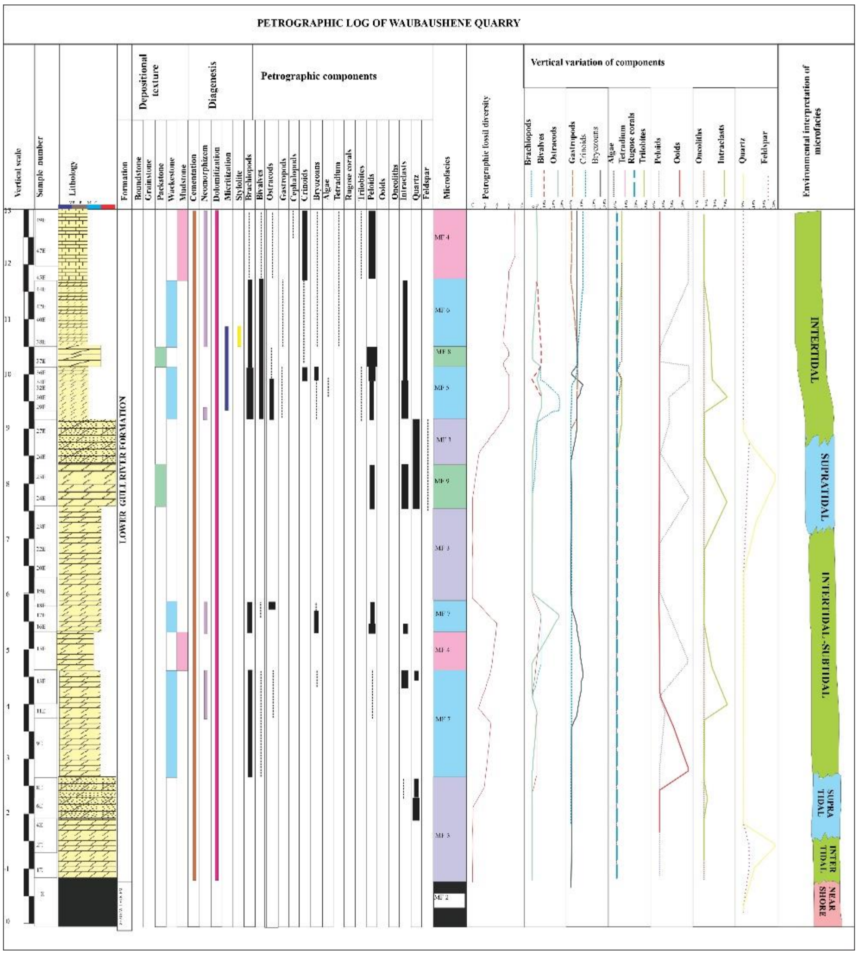


***Figure 4:** Distribution and identification of microfacies plotted in petrographic log based on type and relative abundance of primary constituents, matrix and cement, texture, diagenetic mineral, and structure.*

Siliciclastic Microfacies

Sandstone microfacies (MF1)

Description: This microfacies occurs in the basal Shadow Lake Formation underlying the shale microfacies. In outcrop, its thickness varies from zero (where the overlying carbonates rest directly on the Precambrian surface) to a few meters in paleo-topographic lows in the underlying Precambrian basement. The sandstone microfacies consists of red to green, often mottled, often granular and pebbly, poorly to moderately sorted and sometimes clayey sandstones (Fig. 5). Normally, very coarse-grained sandstones pass upward into course to fine grained sandstones. The beds of this microfacies are typically massive and thick and separated by thin silt and shale layers. Thin sandstone beds are rare; as are sedimentary structures, which, however, include wavy and cross lamination, graded bedding, mud cracks, occasional Skoliths-type vertical burrow, Cruziana burrows, and general bioturbation. Sand grains are subrounded to subangular quartz, with rare feldspar. Rare quartz grains (<5%) have pre-depositional overgrowths. Grains show cubic packing and

loose-tangential contacts: rare concavo-convex sutured contacts formed by compaction reduce the porosity (Figure 5). Cementation is by ferroan calcite, ferroan and non-ferroan dolomite, iron oxide, and clay mineral which fill voids.
Interpretation**:** Most researchers agree that all these features indicate a generally low-energy regolith subject to reworking by water. Sedimentation was controlled by the irregular Precambrian paleotopography and extremely low overall slope, resulting in low energy conditions in a tidal or supratidal environment [29, 11. 2, 30]. There are no comparable modern facies in the Persian Gulf where the underlying bedrock is carbonate. Mature, wind-blown quartz sands and muddy quartz sands accumulate in dunes and sabkhas.

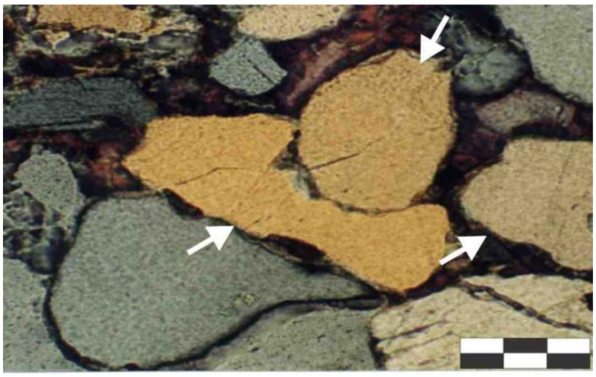


Figure 5. Photomicrograph of sandstone microfacies (Shadow Lake Formation). Note quartz overgrowths (white arrows) probably these quartz grains are derived from Cambrian. Interallochem voids filled by ferroan calcite. Scale bar is 240 Fm. Sample 49.30 m depth in OGS 93-1.

Shale microfacies (MF2)
Description:The shale microfacies occurs as relatively thick units within the basal clastics, and as thin layers and interbeds from 2 to 20 cm thick at different levels throughout the succession. I use one lithofacies with two types here for convenience because the microfacies is relatively rare, and for easy comparison with the schemes of other researchers. But, in fact the shales differ greatly in character, biofacies and environmental significance (Fig. 6). Subfacies A. Unfossiliferous shales. The first shale type occurs in, and especially toward the top of, the basal Black River clastics. It consists of unfossiliferous, bioturbated, fissile dark-grey to black often-calcareous shale, interbedded with clayey and calcareous dolosiltite (Fig 6a). Subfacies B. Fossiliferous shales. The second shale type occurs as thin fossiliferous, unbioturbated black to dark brown layers within the higher Black River and Trenton beds. The upper and lower contacts are sharp. It contains a variety of crinoids, bryozoans, brachiopods, bivalves, and gastropods, whose composition varies considerably (Fig. 6b). Some shales are crowded with a restricted brachiopod fauna (Sowerbyella, Dalmanella, or Orbiculoidea). Others contain more diverse open marine fauna with crinoids which indicate an open-marine and entirely subtidal environment. Some even contain graptolites and the trilobite Triarthrus, characteristic of the basinal muds of the Whitby Formation. Some hardgrounds are exquisitely preserved below thin dark shales; for example, the famous edrioasteroid-bearing Kirkfield Quarry hardground in the lower Trenton Limestone Group is blanketed by this microfacies [31].
Interpretation: The subfacies “A” interpreted to represent local fluctuations in clastic input in a peritidal setting. It has no modern Arabian Shelf equivalent except in some sabkha ponds.The interpretation of subfacies “B” depends on the associated biota. However, the subfacies “B” represents relatively short-lived clastic inputs, or complete cessation of carbonate-producing conditions. This microfacies resembles the clayey bivalve packstones, wackestones and mudstones found in open marine environments more than 10 metres deep in the Persian Gulf [32].

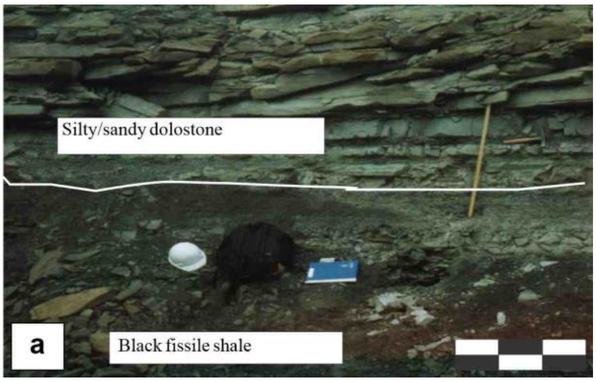


Figure 6a. Photograph showing Unfossiliferous shale (subfacies A) at the top of Shadow Lake Formation (below white line) interbedded with silty/sandy dolostone microfacies at the basal part of Lower Gull River (above white line). Scale bar is 100 cm, Waubaushene quarry.

Figure 6b. Photograph of fossiliferous shales (subfacies B) inVerulam Formation containing trilobites (black arrow), and worm tubes (white arrow). Scale bar is 20 cm, Gamebridge quarry.

Carbonate microfacies

Silty and sandy dolostone microfacies (MF3)

Description: This consists of silty dolostone which may grade up into sandy dolostone. Both have similar characteristics, the only differences being their clastic grain size and content. This microfacies is easy to recognize by its green color and forms two useful and widespread stratigraphic markers ('green marker beds' of Armstrong 1999a) within the Black River Group. The sandy dolostone variety weathers light green to tan, and is medium-coarse in the lower level and coarse to medium in the upper level. The detrital components are quartz (50-90 µm and some 500-800 µm), and rare feldspar (100-200 µm.) (Fig. 7). The silty dolostone variety consists of olive-green to greenish tan, medium to thick dolostone beds characterized by sharp to irregular contacts, thin shale partings, and styolites. The beds consist of fine-grained highly variable usually disrupted dolostone with scattered subrounded to subangular, coarse silt to fine sand quartz and rare feldspar grains, intraclasts, and rare brachiopods and bivalves. Evaporites are sporadically present and include crystals and nodules of gypsum, anhydrite and celestite. Pyrite occurs as both euhedral crystals and irregular grains. Sedimentary structures are parallel lamination, cross-lamination, wavy to nodular disrupted layering, moderate bioturbation (type 2a), and desiccation cracks.

Interpretation: The silty and sandy dolostone microfacies has the pervasive fine-grained early dolomitization, evaporite minerals, and layering disruption characteristics of recent hypersaline intertidal and supratidal sabkhas [33-35]. In the Persian Gulf, a very similar microfacies occurs where quartz sand is blown into the adjacent intertidal to subtidal areas along lee coasts in the SE Qatar Peninsula [32].

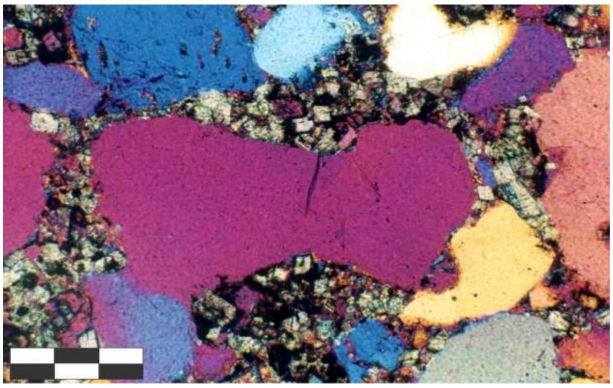


Figure 7. Photomicrograph of sandy dolostone (Lower Gull River Formation). Dominant quartz grains with tangential-longitudinal contacts, cemented by ferroan calcite and idiotopic dolomite crystals. Scale bar is 240 Fm. Sample 47.70 m depth in OGS 93-12.

Peloidal bioclastic mudstone/dolomitic mudstone microfacies (MF4)

Description: This microfacies consists of thick and medium-bedded light cream to white, microcrystalline mudstones which weather light cream. It is common throughout the Black River Group and occurs in most of the natural exposures and drilled cores. Beds vary from medium (20-60 cm) to thick (160-180 cm), with sharp-irregular stylolitic contacts and shale partings. Grains include common peloids, rare intraclasts, and traces of quartz ranging in size from silt to very fine sand. Clay occurs as irregular laminae and lining stylolites. Bioclasts include bivalves, ostracods, brachiopods, trilobites, and scarce calcareous algae (Hedstroemia). Grains are subangular to subrounded: textures are mostly very fine to fine grained, and rarely medium-coarse grained. Sorting is poor to moderate (Fig. 8). Sedimentary structures include desiccation cracks, parallel and wavy lamination, micro cross-bedding, moderate bioturbation (type 2a), fenestrae (cavities filled by small drusy mosaic calcite (Fig 8). Neomorphism includes original lime mud neomorphized into microcrystalline calcite to produce microspar (10-20 mm) normally formed by coalescive enlargement. Diagenetic features are euhedral and anhedral dolomite crystals of idiotopic and rarely xenotopic mosaics (30-130 µm) with scarce large crystals (300 µm).

Interpretation: There is no exact analogy with the Persian Gulf microfacies of [32]: the closest is the bioclastic gastropod mudstone, typical of restricted, low energy, shallow water environments less than 5 meters deep.

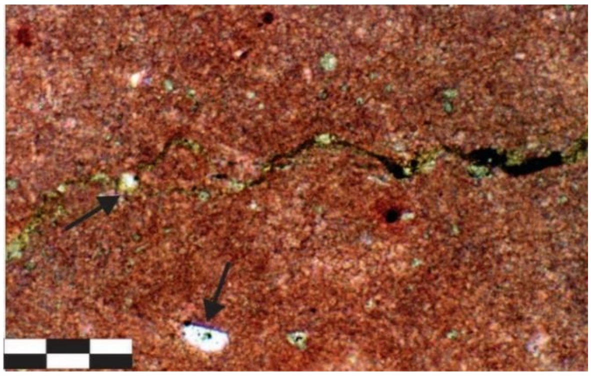


Figure 8. Photomicrograph of peloidal bioclastic mudstone and dolomitic mudstone (Lower-Upper Gull River Formation). Note most of micrite is neomorphized to microspar; common stylolites; chert around stylolites, and filling small cavities; rare quartz grains (black arrows). Scale bar is 120 Fm, sample 27a, Uhthoff quarry.

Peloidal bioclastic wackestone microfacies (MF5)

Description: This microfacies consists of medium grey to light brown wackestones, weathering dark grey. The beds are medium to thick bedded (25-70 cm) with irregular to planar sharp contacts separated by thin films of shale (1-2 cm). Textures are medium to coarse, rarely fine to very coarse; sorting is moderate to poor and grains are subrounded to rounded. Allochems are frequent to common peloids (60-250 µm) and rare quartz and feldspar grains (Fig. 9). Bioclastic grains are common to rare and include bivalves, ostracods, brachiopods, trilobites, and bryozoans. Sedimentary structures include thin lamination, rare micro- cross-lamination and graded bedding, medium bioturbation (type 2a), and

hardgrounds. Neomorphism of micrite into ferroan and non-ferroan calcite microspar is common. Shallow subtidal peloidal carbonate muds occur in the most protected part of the Bahama platform, at depths normally less than 4m.
Interpretation**:** They occur in areas where tidal currents and waves are very weak, and where there are no cross-bank currents, so that the sediments are only reworked during major storms [36]. Similar sediments occur in Persian Gulf subtidal lagoonal sediments behind barrier islands [37]. Microfacies 5 resembles the bioclastic gastropod mudstone of [32].

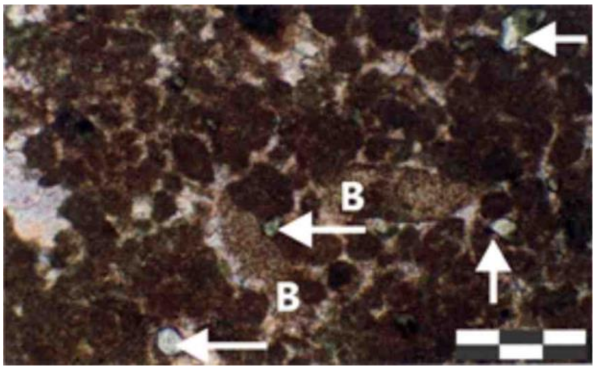


Figure 9. Photomicrograph of peloidal bioclastic wackestone (Upper Gull River Formation). Frequent peloids (100-150 Fm), brachiopods (B), note drusy mosaic of ferroan calcite filling interallochem voids, rare quartz grains (white arrows). Scale bar is 240 Fm, sample 11Z, Dalrymple Lake roadcut.

Bioclastic dolomitic wackestone microfacies (MF6)

This microfacies resembles the peloidal bioclastic wackestone microfacies, but is rarer. It consists of light to medium grey, light brown to pink dolomitic wackestones, weathering dark grey. Beds are medium to thick-bedded (20-55 cm), frequently mottled and include thin layers of shale. Textures are medium to fine grained, rarely very coarse to fine grained; sorting is poor to moderate, and grains are subrounded to subangular. Allochems include common to rare peloids, quartz, feldspar, and scarce intraclasts. Bioclastic grains are rare to common bivalves, ostracods, trilobites, brachiopods, and bryozoans. Sedimentary structures include thin parallel lamination, fenestrae, and extensive bioturbation (type 3a) has destroyed most sedimentary structures. Cementation is by syntaxial overgrowths of ferroan and non-ferroan calcite. Drusy mosaics consist of ferroan and non-ferroan calcite growing toward the centre, and there are scarce poikilotopic crystal mosaics. Neomorphism of micrite into microspar is rare to common. Replacement occurs by idiotopic and xenotopic, euhedral and anhedral ferroan dolomite crystals (40-70 µm) (Fig. 10). Gypsum occurs in places, and pyrite and stylolites are common to frequent. The bioclastic dolomitic wackestone microfacies occurs as discontinuous layers alternating with the argillaceous/calcareous dolostone microfacies in the Lower Gull River Formation.
Interpretation**:** The presence of evaporites (gypsum), fenestrae, dolomite, and the restricted biota indicate that the microfacies was deposited in a hypersaline sabkha and shallow intertidal environment. Modern equivalents of this microfacies occur in the hypersaline, supratidal and shallow intertidal environments of the Bahamas [35], [38] and Persian Gulf [39]. There is no equivalent in [32].

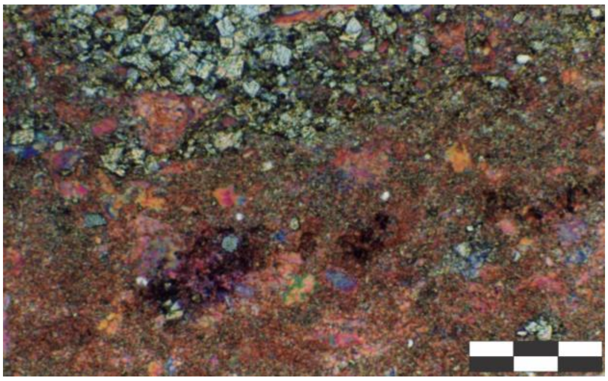


Figure 10. Photomicrograph of bioclastic dolomitic wackestone (Lower member of Gull River Formation). Micrite neomorphized into microspar. Common to frequent idiotopic-xenotopic dolomite crystals 30-60 Fm. Ferroan calcite cement fills pore spaces. Scale bar is 240 Fm, sample 4a, Uhthoff quarry.

Intraclastic bioclastic wackestone microfacies (MF7)

*D*escription: This microfacies consists of medium-light grey (weathering dark to light grey to tan) wackestones. Beds are thin to medium (10-25 cm), mottled and with irregular to sharp contacts and thin films of shale. Erosion surfaces are common. Textures are medium to coarse, rarely fine to very coarse and sorting is moderate to poor; grains are subrounded to subangular. Allochems are frequent to common micritic intraclasts, peloids and rare ooids, with variable amounts of quartz and feldspar grains (Fig. 11). Bioclasts are rare to common and include ostracods, brachiopods, bivalves, bryozoans, trilobites, and gastropods. Calcareous algae and the colonial? Tabulate coral Tetradium are present in this microfacies in the Moore Hill Formation. Sedimentary structures include cross bedding, micro-wavy lamination, graded bedding, and moderate bioturbation of type 2a. The intraclastic bioclastic wackestone microfacies occurs in the Gull River Formation as thin beds (2-10 cm) representing intervals of periodic strong reworking in an intertidal environment of low energy.

Interpretation: The presence of intraclasts indicates that the mudstone and wackestone have been reworked by storm action. Modern equivalents occur in intertidal, lagoonal, and barrier environments in the Persian Gulf, including the gastropod grainstone/packstone microfacies [32].

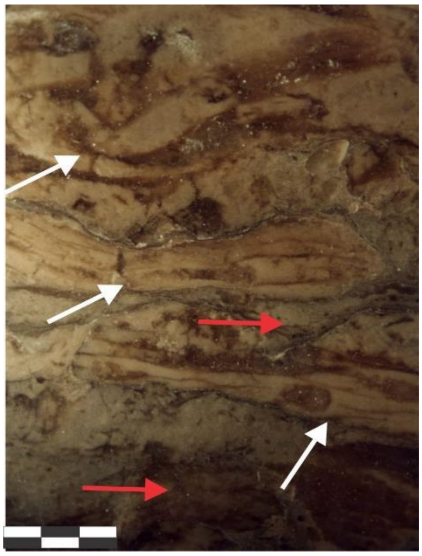


Figure 11. Core photomicrograph of intraclastic bioclastic wackestone microfacies (Lower Gull River Formation). Note intraclasts (white arrows) interbedded with calcareous dolostone beds (red arrows). Scale bar is 3mm, sample 10-11-73.

Peloidal bioclastic packstone microfacies (MF8)

Description:This microfacies consists of light-dark grey (weathering dark grey, brown, and tan) packstones. Beds are thick bedded (100-200 cm) and split into thin to medium beds (10-25 cm) are moderately to highly bioturbated (types 2 and 3) with sharp - planar to irregular stylolitic contacts. Textures are coarse to very coarse, less commonly medium or fine grained; sorting is moderate to poor, and grains are rounded, subrounded and subangular. Bioclasts are frequent to common bivalves, ostracods, crinoids, brachiopods, gastropods, bryozoans, trilobites, calcareous algae (Solenopora, Hedstroemia, Kazakhstanelia, Parachaetetes), and Tetradium. Allochems include frequent to common peloids, rare intraclasts with poorly preserved internal structures (Fig. 12). Sedimentary structures are rare because of the heavy bioturbation; however, wavy to parallel lamination, a small-scale cross-bedding survive in places. The peloidal bioclastic packstone microfacies occurs throughout the Gull River Formation and Moore Hill Formation, but is vertically and laterally discontinuous. It dominates the Coboconk Formation, but is scarcer in the Kirkfield and Verulam Formations.

Interpretation: It corresponds with lithofacies LF 6 of [2] "wackestone-packstone with interbeds of amalgamated pelletal grainstones", deposited by storm in high energy conditions in an intertidal flat to a shallow subtidal environment, LF 4.5.2 of [3] "skeletal peloidal wackestone-packstone", interpreted as generally low energy, stenohaline shallow subtidal deposit, and LF 5 [4] "peloidal bioclastic wackestone and packstone", deposited in lower intertidal to lagoonal environments. Modern equivalents of this microfacies occur in the outer shelf of Florida Bay, as well as in the marine, unrestricted low energy environment of the Persian Gulf, where bivalve packstones/wackestones occur [32].

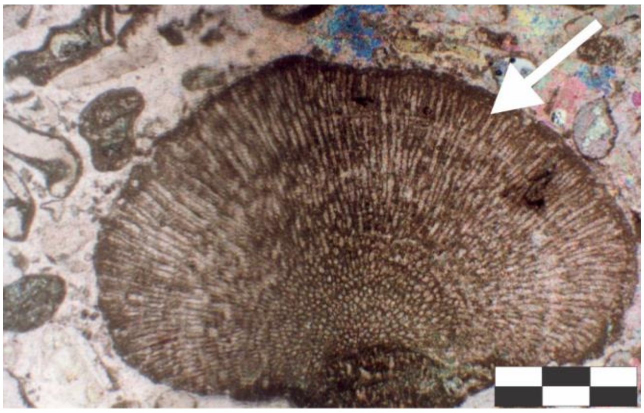


Figure 12. Photomicrograph of bioclastic peloidal packstone (Coboconk Formation). Note calcareous algae (white arrow) interpreted as Solenopora. Scale bar is 940 Fm, sample 4G, Coboconk quarry.

Bioclastic dolomitic packstone microfacies (MF9)

Description: This microfacies consists of medium to dark grey and light brown (weathering dark grey) packstones. Beds are medium to thick (20-55 cm) with sharp, gradational, and irregular stylolitic contacts lined with thin films of shale (2-5cm) and are moderately to heavily bioturbated (types 2 and 3). Textures are medium to fine grained (rarely coarse grained in the Upper Gull River and Kirkfield formations, and medium to coarse grained in the Kirkfield and Verulam formations). Bioclasts are frequent to rare crinoids, ostracods, bivalves, brachiopods, bryozoans, gastropods, trilobites, calcareous algae, and scarce corals. Allochems are common peloids and rare intraclasts. The moderate to heavy bioturbation has destroyed most sedimentary structures, but parallel lamination, wavy lamination, and cross bedding occur at the tops of the Kirkfield and Verulam Formations. Cementation is by ferroan and non-ferroan drusy calcite mosaics filling cavities (Fig.13). Dolomitization is common with anhedral to euhedral dolomite crystals (200-400µm) forming idiotopic but rarely xenotopic mosaics (Fig. 13). Chert commonly replaces both bioclasts and cement in the Kirkfield and Verulam Formations.

Interpretation: The presence of algae (Hedstroemia) and corals, as well as ostracods, bivalves, and bryozoans indicate the microfacies was deposited in shallow intertidal and open marine moderate energy shoal facies. Modern equivalents of this microfacies occur in shallow intertidal and open lagoon environments of low energy in the Persian Gulf [32] and in the outer shelf of Florida bay [40].

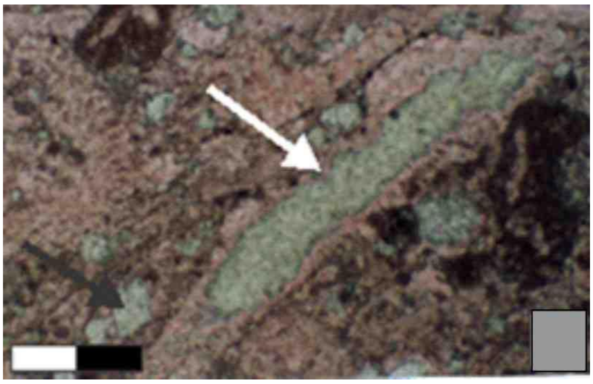


Figure 13. Photomicrograph of bioclastic dolomitic packstone (Verulam Formation). Note presence of chert replacing brachiopods (white arrow), and calcite cement, dolomite crystals of idiotopic type (black arrows). Scale bar is 240 Fm, sample 36m, Brechin quarry.

Intraclastic bioclastic packstone microfacies (MF 10)

Description: This microfacies is scarcer than the bioclastic dolomitic packstone microfacies; it consists of medium to dark grey and brown (weathering dark grey) packstones. Beds are thin-bedded (5-15 cm) with sharp, planar, and erosional contacts. Hardgrounds also occur. Textures are coarse to medium, rarely very coarse grained, and sorting is moderate: grains are subrounded to subangular. Bioclasts are frequent to rare crinoids, bivalves, brachiopods, bryozoans, and ostracods. Calcareous algae (Parachaetetes, Hedstroemia, and Solenopora) occur in the Coboconk Formation (Fig. 14), and there are rare gastropods and Tetradium in the Moore Hill Formation. Allochems include common intraclasts, with rare quartz and feldspar in the Lower Gull River Formation. The intraclastic bioclastic packstone microfacies occurs sporadically throughout the Lower and Upper Gull River Formation, the Moore Hill Formation, and the Coboconk and Kirkfield Formations. Sedimentary structures include thin lamination, graded bedding, and fenestrae. Cementation is by ferroan and non-ferroan calcite drusy mosaics (Fig.14) and rare poikilotopic mosaic filling cavities and interallochem Chert replaces calcite cement and crinoid bioclasts and chert-filled voids are common to frequent.

Interpretation: The variation in bioclast composition- from restricted to algal to open marine- intertidal to subtidal suggests deposition in a variety of low energy environments: supratidal in the Lower Gull Formation; in the Upper Gull Formation, Moore Hill, and the Kirkfield Formations. Modern equivalents of this microfacies are the lamellibranch muddy sands deposited in shallow marine, low-energy environment microfacies in the Persian Gulf; and the muddy sands of the outer shelf in the northern portion of the West Florida ramp.

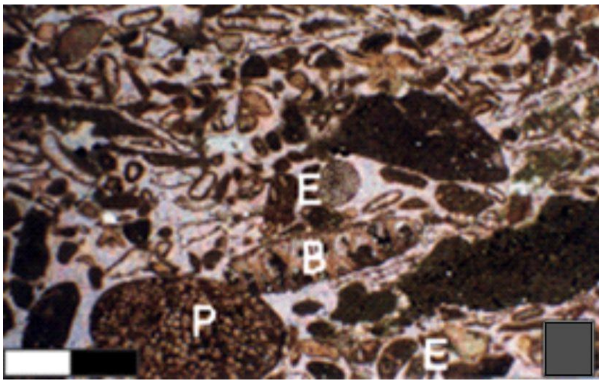


Figure 14. Photomicrograph of intraclastic bioclastic packstone (Moore Hill Formation). Note micritized bryozoans (B), calcareous algae interpreted as Parachaetetes (P), brachiopods, echinoderms (E), intraclasts and peloids. Scale bar is 320 Fm, sample 21G, Coboconk Quarry.

Peloidal bioclastic grainstone microfacies (MF 11)

Description: This microfacies consists of grey (weathering dark grey, brown-grey, and tan) grainstones. Beds are medium to thick (15-65 cm) with sharp, irregular contacts lined with millimeter thin shale partings, alternating with the previous packstone microfacies. Textures are coarse to very coarse, grading up to medium and fine-grained texture: sorting is good to moderate to poor; grains are rounded to subrounded. Bioclasts are frequent to common crinoids, brachiopods, ostracods, bivalves, bryozoans, gastropods, calcareous algae (Solenopora, Kazakhstanelia, Parachaetetes, Hedstroemia), solitary rugose and colonial tabulate corals, and trilobites. Tetradium is abundant in this microfacies in the Moore Hill Formation. Allochems are dominant to frequent peloids, and rare to sporadic intraclasts (400-800 µm) and ooids (Fig. 15). Bioturbation is only moderate (type 2a), so preserved sedimentary structures are common and consist of parallel lamination, cross lamination, cross bedding and graded bedding. Hardgrounds are present. Micritization forms microenvelopes on brachiopod and crinoid bioclasts. Chert replaces calcite cement and bioclastic grains (Fig. 15). Stylolites are common.

Interpretation: The petrographic components and sedimentary structures indicate this microfacies was deposited in a high-energy marine environment in the photic zone. The common cross-lamination indicates that peloids and clastic silt were transported as bed load. The peloids may have formed by erosion of adjacent subtidal mudstones, wackestones and packstones; or, they may have been transported supratidal and intertidal intraclasts. [41], [42], [2] and [4] interpreted similar bioclastic-peloidal grainstone facies as deposits of subtidal sand shoals on a shallow-water, high energy open marine carbonate platform. Modern equivalents of this facies are peloidal bioclastic grainstones deposited on wide, moderate energy, tidal flats in the Persian Gulf, where the grains are derived locally from the shallow lagoonal environments adjacent to the tidal flats [32].

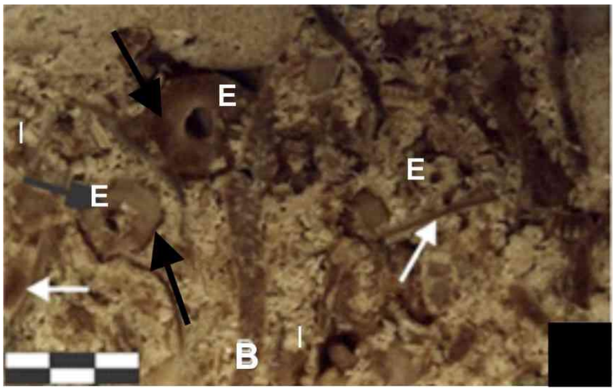


Figure 15. Core photomicrograph of peloidal bioclastic grainstone (Coboconk Formation). Dominant bioclasts of brachiopods (black arrow), echinoderms (E), bryozoans (white arrows), intraclasts (I). Scale bar is 3 mm. Core 11/depth 8.10 m.

Intraclastic bioclastic grainstone microfacies (MF 12)

Description: This microfacies is the second most common grainstone microfacies. It consists of medium to dark grey, light brown (weathering dark to light grey) grainstones. Beds are thin (2-10 cm) to medium (5-25 cm), with sharp and irregular stylolitic contacts, and with erosional bases. Textures are very coarse, coarse and medium. Sorting is moderate, rarely good: grains are subrounded to rounded with concavo-convex contacts. Bioclasts are dominant to common crinoids, brachiopods, bryozoans, bivalves, ostracods, gastropods, calcareous algae (Hedstroemia, Parachaetetes, Solenopora, Vermiporella, Ortonella, Kazakhstanelia), and rugose and tabulate corals (Fig. 16). Large stromatoporoids (3-50cm) occur in this microfacies in the upper beds of the Coboconk Formation and can be used for local stratigraphic correlation. Allochems are frequent to common intraclasts and peloids with rare quartz sand grains. Moderate to heavy bioturbation (types 3a) has destroyed most sedimentary structures: those that survive include graded bedding, wavy lamination, and thin parallel lamination. Micrititization is rare and occurs as microenvelopes around bioclasts of crinoids and brachiopods (Fig.15). Cementation is by ferroan and non-ferroan calcite drusy mosaics with crystals increasing in size toward the center, syntaxial overgrowths, and poikilotopic mosaics filling interallochem voids.

Interpretation: The sedimentary structures and petrographic components indicate that this microfacies was deposited in low intertidal to shallow subtidal environments by storms. The comparable intraclastic/bivalve grainstone microfacies of the Persian Gulf accumulates in shallow open marine environments of moderate energy and with slow deposition [32].

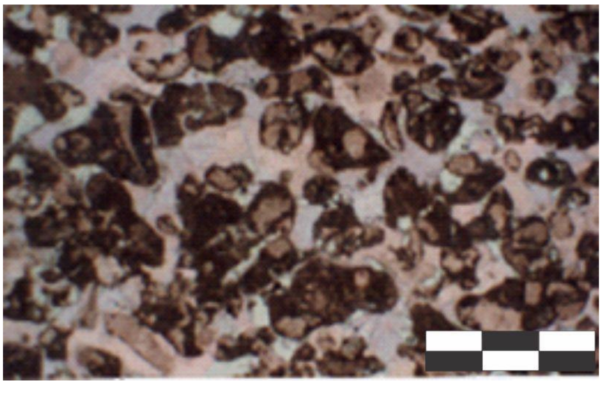


Figure 16. Photomicrograph of intraclastic bioclastic grainstone (Upper part of Cobconk Formation). Intraclasts, bioclasts of echinoderms, brachiopods, poikilotopic calcite filling pore spaces, chert replacing crinoids (white arrows). Scale bar is 240 Fm, sample 16G, Coboconk quarry.

Bioclastic dolomitic grainstone microfacies (MF 13)

Description: This microfacies consists of light grey and pink (weathering medium to dark grey) grainstones which alternate with peloidal bioclastic dolomitic packstones microfacies. Beds are thin to medium (10-25 cm) with sharp to irregular contacts and with thin interbedded shales (5-7 cm). Textures are very coarse to coarse, grading upwards to medium to fine. Sorting is moderate to poor: grains are subrounded to subangular. Bioclasts are dominant to frequent to common crinoids, brachiopods, bivalves, ostracods, bryozoans, gastropods, and trilobites, which frequently have micritized edges. Allochems are frequent to rare peloids and intraclasts (Fig. 17). Moderate to heavy bioturbation (type 2 and 3) usually disturbs the original sedimentary structures, including wavy lamination, graded bedding, and cross

lamination. Rare poikilotopic calcite mosaics fill interallochem voids and cavities, and iron oxide is present. Chert replaces brachiopod and crinoid bioclasts and calcite cement (Fig 17).
Interpretation: This peloidal bioclastic dolomitic grainstone microfacies is restricted to the Kirkfield and Verulam Formations. Modern equivalents of this microfacies have been described from outer shelf of South Florida where hardgrounds are overlain by grainstones, which grade into fine sediments of slope [40]. It resembles the bivalve grainstone of the Persian Gulf, deposited in shallow, high energy, open marine environments [32].

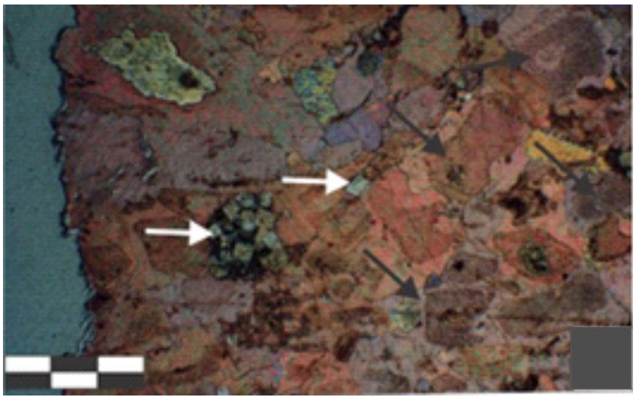


Figure 17. Photomicrograph of bioclastic dolomitic grainstone (Verulam Formation). Note dolomite of idiotopic type (white arrows), dominant echinoderms (black arrows). Scale bar is 240 Fm, sample 34 m, Brechin quarry.

Peloidal bioclastic oncolitic grainstone microfacies (MF14)
Description: This microfacies consists of light brown and medium to dark grey. Beds are thin to thick bedded (10-45 cm) with sharp to irregular contacts and rest on basal erosion surfaces. Textures are very course-to-course to medium grained, sorting is poor, and grains are subangular to subrounded to rounded. Bioclasts are dominant to frequent to common crinoids, brachiopods, bivalves, calcareous algae (Vermiporella, Parachaetetes, Solenopora, Hedstroemia, and Kazakhstanelia), bryozoans, gastropods, rugose corals and large stromatoporoids (30-50cm diameter) (Fig.18). Allochems are frequent to rare oncolites developed around bioclasts (brachiopods, bryozoans), intraclasts, and calcareous algae: their edges are often micritized. Sedimentary structures include graded bedding, parallel lamination, and cross lamination. Bioturbation is less pervasive in this microfacies, but large dwelling burrows are common, as are hardgrounds and other erosional surfaces. Neomorphic microspar is of coalescive type with rare irregular pseudospar. Chert commonly replaces bioclasts of crinoids, brachiopods and calcareous algae, and also cement (Fig.18). Dolomite replacement is by euhedral and anhedral crystals of idiotopic type.
Interpretation: The sedimentary structures, coated bioclasts and other petrographic components indicate that this microfacies was deposited in a shallow subtidal, open marine, high-energy environment. [41] interpreted analogous facies as a skeletal-sand shoal deposited in an environment of persistently high energy. Modern equivalents of this microfacies occur in the Persian Gulf, where oncoidal bioclastic grainstones form on unrestricted offshore highs between 30 and 60 metres depth [32].

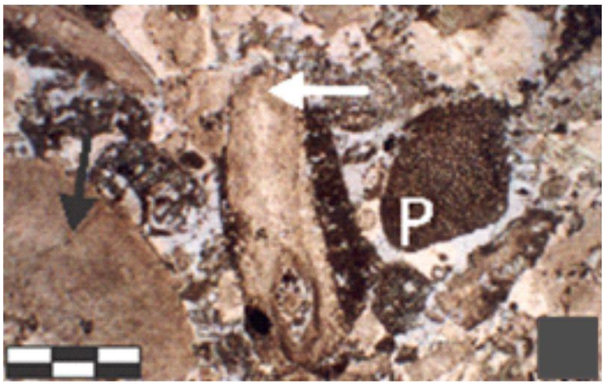


Figure 18. Photomicrograph of bioclastic oncolitic grainstone (Coboconk Formation). Coated grains of brachiopods form oncolites (white arrow); echinoderms (black arrow), calcareous algae interpreted as Parachaetetes (P), interallochem voids filled by ferroan calcite of poikilotopic type. Scale bar is 960 Fm.

Oolitic bioclastic grainstone/packstone microfacies (MF 15)

Description: This microfacies consists of brown, light brown and tan (weathering light medium-grey) grainstones and packstones. Beds are usually medium to thin (5-25 cm) but occasionally thick in the Lower Gull Formation. Textures are coarse, medium and fine grained, rarely very coarse: sorting is poor to moderate; grains are rounded to subrounded. Bioclasts are frequent to common brachiopods, ostracods, crinoids, bryozoans, bivalves, gastropods, bryozoans, rare corals, calcareous algae (Hedstromia), and trilobites. These are often micritized. Allochems are frequent and includes ooids varying in size from 400-800 µm with the average of 600µm (Fig.19), peloids (100-150 µm) and common intraclasts (300-1200 µm). Sedimentary structures are rare but include thin lamination and weak to moderate bioturbation (type 2a). Cementation is by ferroan and non-ferroan syntaxial overgrowths, and poikilotopic and drusy mosaics filling interallochem voids and cavities. Neomorphism of micrite produced coalescive microspar. Rare dolomite is of anhedral and euhedral idiotopic type (50-120µm). Hardgrounds and lenticular and nodular chert are present.
Interpretation: Oolitic grainstones/packstones are usually interpreted as deposits of high-energy tidal shoal and barrier bar channels [28]. Modern equivalents of this microfacies occur in recent Bahama ooidal sands and are deposited in high-energy shoal environments [43]. In the Persian Gulf, oolitic grainstones form in areas of active tidal currents in shallow waters less than 3 m deep and within a few kilometres of the coast [32].

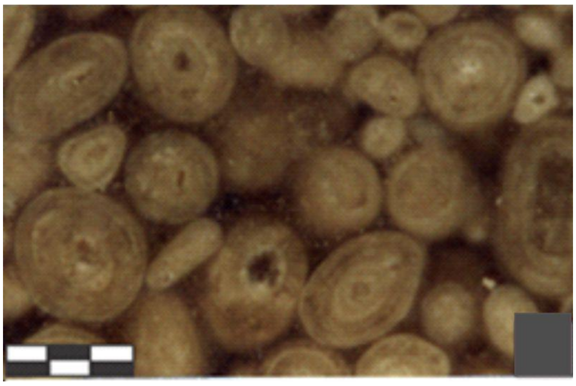
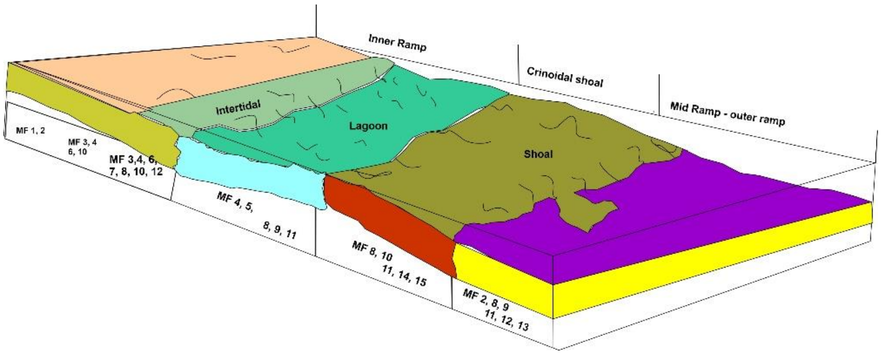


Figure 19. Core photomicrograph of oolitic grainstone (Lower member of Gull River Formation). Note ooids (0.40-0.50 mm) concentric layers well preserved, the pore spaces are filled by calcite. Scale bar is 0.52 mm. Core 5/depth 36.04 m.

Depositional Zone

The distribution of microfacies plotted in the Figure (4) indicate that the Black River and lower Trenton limestone groups were deposited on a shallow homoclinal ramp similar to those described by [44], [45].[6], [46].

The Black River-lower Trenton ramp can be divided into inner ramp (Gull River and Moore Hill formations), and mid ramp areas (Kirkfield and Verulam formations) separated by bioclastic bars (Coboconk Formation) marking fair weather wave base (Fig. 20). The outer ramp, marked by loss of storm-deposited graded beds, begins with the nodular, bioturbated wackestones and packstones of the Lindsay Formation, which was not included in this study.



Fighure 20: Schematic depositional model idealized for the Black River and Trenton Limestone Groups in southern Ontario (MF - microfacies, refer to Figure 3 description).

Inner Ramp

At the base, the siliciclastic association of the Shadow Lake Formation consist of subaerial, lag siliciclastics derived from local reworking of regoliths on the Precambrian shield [47]. This passed seawards into the supratidal and intertidal mudstone and wackestone associations of the Gull River Formation. Periodic build-up of sediment or drop in sea level allowed dolostones (Green marker beds) to accumulate on supratidal areas. Above the second green marker bed, the uppermost Gull River and Moore Hill Formations mark a relative rise in sea-level and include more low-energy, lagoonal sediments.

Shoal Bars

The bioclast-dominated Coboconk Formation forms the subtidal bars separating the inner ramp from the mid ramp. This cross-bedded grainstone unit contains a variety of allochems, peloids, oncoliths, rarely and locally ooids, and a diverse open marine fauna dominated by stromatoporoids, calcareous algae (Solenopora, Hedstromia), crinoids, brachiopods, ostracods, gastropods, trilobites, and bivalves. All this suggests a shallow, relatively high energy, environment within the photic zone [4], and [47].

Mid ramp

The various bioclastic sediments of the Kirkfield and Verulam Formations, interbedded with calcareous clays, and with diverse marine faunas, represent mid ramp facies. The thin bioclastic packstone and grainstone microfacies (interbedded with thin clay layers) of the Kirkfield and Lower Verulam formations pass upwards gradually into the diverse mudstone to grainstone microfacies (with thicker grey shale interbeds) of the middle Verulam Formation, which in turn pass up into the coarse to very coarse grainstone and packstone microfacies of the Upper Verulam Formation. The Verulam coarsening upwards passage is probably a result of shoaling, possibly due to eustatic or tectonic causes".

CONCLUSIONS

The Upper Ordovician carbonate of the Black River and lower Trenton groups in the Lake Simcoe area consists of a basal siliciclastic unit, the Shadow Lake Formation, and five overlying carbonate units (Gull River, Moore Hill, Coboconk, Kitkfield,and Verulam formations). Fifteen microfacies are distinguished in the study area, based on the bed -by-bed macroscopic study of all major natural exposures, quarries and available drilled cores, plus microscopic study of individual beds. The depositional environments for these are then inferred by comparison with analogous microfacies from modern carbonate facies in different settings. Individual formations, with their associations of microfacies-based environments, consist of several, though overlapping larger-scale carbonate environments. The Shadow Lake Formation includes basal regolith and supratidal pond and tidal flat environments. The Gull River Formation is dominated by supratidal to intertidal environments, though with siginficant interbeds of supratidal and subtidal facies reflecting relative sea-level changes. The Moor Hill Formation has mostly subtidal, restricted lagoon environments. The Coboconk Formation consists of open lagoon and shoal environments which, by analogy with the Persian Gulg, are shallow, high-energy environments. An alternative interpretation, based on West Florida, would place them in much deeper water. In view of the gradual change from underlying shallow lagoon of the Moore Hill, the first interpretation is more likely. Similar problems occur with the Kirkfield and Verulam formations. The Persian Gulf model would place both of them on a relatively shallow mid-ramp, while the West Florida model would place them in deeper, outer ramp environments. Further work is required on this.

Lastly, the vertical succession has no major time breaks and, show the nearshore to offshore distribution of facies at any one time. The succession can be interpreted as a ramp, divided into an inner ramp (Gull River and Moore Hill Formations), and a mid-ramp (Kirkfield and Verulam Formations) separated by bioclastic bars (Coboconk Formation) marking fair weather wave base. The outer ramp, marked by loss of storm-deposited graded beds, begins with the nodular, bioturbated wackestones and packstones of the Lindsay Formation which was not included in this study. The modern ramps with the closest analogies to the Black River-Trenton are: the Persian Gulf homoclinal ramp (subtropical to warm temperate); the West Florida homoclinal carbonate ramp (subtropical), the South Australian distally steepened carbonate ramp (temperate); and the Brazilian distally steepened ramp (temperate). The Black River Group appears closest to the Persian Gulf ramp, while the Trenton Group is similar in many respects to the West Florida ramp.

Conflict of Interest

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

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تحليل السحنات الدقيقة ونمط الترسيب لكربونات النهر الأسود – ترينتون (العصر الاردوفيشي) في جنوب أونتاريو ، كندا

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المستخلص

هذه الدراسة توثق البيئة الترسيبية الدقيقة التفصيلية لنهر ألاوردوفيشي الأسود ومجموعات الحجر الجيري ترينتون في منطقة بحيرة سيمكو في جنوب أونتاريو، والتي تقع بشكل غير متوافق علي قبو ما قبل الكمبري. الارتفاعات المحلية في عصر ما قبل الكمبري عقدت نمط السحنات العام وأنماط الصخور الحجرية التي تحدد البيئات الضحلة المحلية، والبيئات بين الضحلة والحوضية. يتم استخدام تحاليل مفصلة للسحنات الدقيقة والسحنات في المحاجر الكبيرة في منطقة بحيرة سيمكو لاستنتاج بيئات الكربونات المختلفة بالمقارنة مع المنحدرات الحديثة والقديمة المماثلة. تم دمج خمسة عشر سحنة دقيقة في ستة مجموعات من السحنات الدقيقة بناء على التركيب وحجم الحبيبات والملمس. ثم الاستدلال على مستويات الطاقة النسبية والبيئات الترسيبية لها. تشبه هذه البيئات الجرف العربي الحديث للخليج الفارسي لمجموعة النهر الأسود ، وجرف غرب فلوريدا لترينتون ، على الرغم من أن المنحدرات الحديثة الأخرى مثل جنوب أستراليا قابلة للمقارنة أيضا. يشكل الترتيب الرأسي للسحنات في منطقة بحيرة سيمكو دورات متكررة يمكن بعد ذلك تتبعها أفقيا في المناطق المجاورة، عقدة بسبب تأثيرات تضاريس قاع البحر وربما بسبب الصدوع الرسوبية.

الكلمات الدالة. علم الصخور، والسمات المجهرية، والمنحدر المتجانس الضحل، والأوردوفيشي، والبيئة القديمة.