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Article

Microbial, tidal, and storm activity in a macrotidal to shallow marine shelf environment during the Paleoproterozoic era

Carolyn M. Hill-Svehla[a] and **Patricia L. Corcoran**[b]

[a]Surface Science Western, The University of Western Ontario, London, ON, Canada; [b]Department of Earth Sciences, The University of Western Ontario, London, ON, Canada

Corresponding author: **Carolyn M. Hill-Svehla** (email: chill59@uwo.ca)

Abstract

The Gordon Lake Formation (GLF) of the Paleoproterozoic Huronian Supergroup is a siliciclastic-dominated succession ranging from 300 to 1100 m in thickness. Lithostratigraphic and sedimentological analyses of the formation in the Bruce Mines and Flack Lake areas, and Killarney and Lady Evelyn-Smoothwater provincial parks, Ontario, Canada, revealed seven lithofacies, which comprise three distinct lithofacies associations. The lithofacies associations are subtidal nearshore, subtidal to shallow shelf, and mixed intertidal flat. A variety of structures interpreted to be biogenic in nature, including microbially induced sedimentary structures (MISSs) and stromatolites, are preserved, which support local microbial colonization in a tidally influenced marine environment. Wave, current, and tide-generated sedimentary structures, including symmetrical ripples, trough cross-beds, flaser and lenticular bedding, and mudstone drapes, are abundant in all study areas. Storm influence is suggested by normally graded deposits, mudstone rip-up clasts, and soft-sediment deformation structures (SSDSs), including load casts, ball-and-pillow structures, convolute bedding, and pseudonodules. Interbedding and interlamination of sandstone and mudstone units are present throughout the GLF and represent fluctuations in water level and energy, related to tidal and storm processes. A lowermost carbonate-rich unit may represent a period of low clastic influx. The contacts with the underlying Lorrain and overlying Bar River formations appear gradational. The depositional environment can be visualized as an open coast, shallow marine shelf that was influenced by microbial mats, tides, and storms.

Key words: Huronian Supergroup, Paleoproterozoic, siliciclastic, shallow marine, tides, microbial mats

Introduction

Precambrian sedimentary systems are notoriously difficult to interpret due to the absence of pronounced biological activity, especially bioturbation (Schopf 1975; Eriksson et al. 2004 and references therein; Flannery et al. 2018). In addition, the paucity of chronological markers, combined with the lack of modern analogues unaffected by biological activity, poses a significant challenge in developing ancient depositional models. As a result, considerable dependence is placed on sedimentary structures as environmental indicators, even though many depositional environments share similar sedimentary characteristics, including "diagnostic" structures, and therefore care must be taken when reconstructing Precambrian paleoenvironments.

Previous studies of the Gordon Lake Formation (GLF) have tended to base environment analysis on individual structures, such as nodules (Chandler 1988), and typically do not consider regional trends. Much of the existing literature proposes that the GLF was deposited in shallow coastal water (Wood 1973; Frarey 1977), and that it may have formed part of a back–barrier system, although this has never been proven. Studies of barrier systems older than the Holocene are uncommon as they are inherently transient systems with poor preservation potential (Hoyt and Vernon 1967; Riggs 2010). Barrier islands and associated features are also thought to have generally been absent on tidally influenced Precambrian shelves, but this may be a result of poor preservation or difficulty distinguishing these environments from fluvial and offshore deposits (Eriksson et al. 1998, 2004, and references therein; Donaldson et al. 2002).

Building on the work of Hill et al. (2016), Hill and Corcoran (2018), and Hill et al. (2018), this paper aims to (1) define the major lithofacies of the GLF, (2) determine the depositional processes responsible for lithofacies development, and (3) propose a viable depositional model for the formation. Understanding the depositional environment of a well-preserved succession exposed over an area roughly 280 × 125 km, provides critical information about sedimentary processes that took place on nonvegetated surfaces, with only local development of microbial mats. The present study also attempts to explain the depositional transition between the fine-grained sandstone and mudstone of the GLF, and the underlying and overlying extensive quartz arenite successions.

Geological setting

Several global developments occurred during the Proterozoic eon, including the rise of atmospheric oxygen, evolution of eukaryotes, and multiple extreme climate shifts (Eriksson et al. 2001, 2004; Javaux and Lepot 2018). Evidence of rising atmospheric oxygen levels and glacial periods is well preserved in rocks of the Huronian Supergroup which is exposed north of Lake Huron, Canada (Fig. 1). This primarily siliciclastic succession forms part of the Southern Geological Province and unconformably overlies Archean basement of the Superior Province. Basal volcanic units are present locally. Uranium–lead zircon dating of volcanic rocks near the base of the Huronian succession yielded a lower age limit of ca. 2450 Ma (Krogh et al. 1984; Ketchum et al. 2013; Bleeker et al. 2013), whereas an upper age limit of ca. 2220 Ma (Corfu and Andrews 1986; Bleeker et al. 2015) was determined from U–Pb dating of zircons and baddeleyite from a gabbro intrusion. A maximum depositional age of 2315 ± 5 Ma was determined for the GLF and Bar River Formation from detrital zircon in a sandstone and claystone bed, respectively (Hill et al. 2018); this date constrains the time of deposition of the upper Huronian Supergroup to between 2315 ± 5 Ma and emplacement of the gabbro intrusions at ca. 2215 Ma (Bleeker et al. 2015). Depositional ages of 2308 ± 8 and 2311 ± 1 Ma were reported by Rasmussen et al. (2013) from purported tuff beds in the GLF. Although the youngest ages of the detrital zircons analyzed by Hill et al. (2018) coincide with those of Rasmussen et al. (2013), it is impossible to prove a volcanic origin for the grains. In general, the rounded nature of the zircon grains and the high-energy setting of the upper Huronian Supergroup suggest a decreased likelihood of preserving a tuff. In addition, the period from 2450 to ca. 2100 Ma is interpreted to have been quiet in terms of magmatic activity in continental areas (Condie 1998).

The Huronian Supergroup comprises four official groups: the Elliot Lake, Hough Lake, Quirke Lake, and Cobalt groups, from oldest to youngest. Some workers, including Wood (1973) and Long (2009), divided the succession into five groups by including the unofficial Flack Lake Group at the top of the succession. The maximum thickness of the Huronian succession is approximately 12 km in the southern part of the Huronian belt (Young et al. 2001), and sandstone, mudstone, and paraconglomerate are the dominant lithologies. The Hough Lake Group (Ramsay Lake, Pecors, and Mississagi formations), Quirke Lake Group (Bruce, Espanola, and Serpent formations), and Cobalt Group (Gowganda and Lorrain formations) are allocyclic in nature and consist of a lower paraconglomerate unit overlain by mudstone–carbonate and sandstone units, interpreted respectively as glacial deposits, deeper water deltaic deposits, and fluvial–marine deposits (Card et al. 1977; Rice 1986; Robertson and Card 1988; Young et al. 2001; Long 2004*a*, 2009). Huronian strata were folded during at least one event known as the ca. 1875–1825 Ma Penokean orogeny (Van Schmus 1976; Schulz and Cannon 2007), and have been regionally subjected to low greenschist grade metamorphism (Card 1978*b*; Young et al. 2001). In contrast, Huronian strata south of the Murray Fault in the Killarney area, have been subjected to middle to upper greenschist and low amphibolite-grade metamorphism (Card 1978*b*). The prefix “meta” has been omitted in the present study for simplicity.

The Huronian Supergroup is interpreted to reflect the transition from a transform-rift to passive margin during the breakup of the Archean Supercontinent Kenorland (Aspler and Chiarenzelli 1998; Long 2004*a*). The two major influences on the evolution of the Huronian basin were tectonism and paleoclimate cyclicity (Eriksson et al. 2001). The presence of a reducing atmosphere during deposition of the lower Huronian formations is supported by detrital uranium-bearing minerals in the Matinenda Formation (Elliot Lake Group) and sulphur isotope data from the Mississagi Formation (Zhou et al. 2017). The establishment of a partially oxygenated atmosphere midway through the succession is supported by red beds, which first appear in the Gowganda Formation (Cobalt Group), and are present throughout stratigraphically higher formations, as are local evaporite minerals (Wood 1973), microbial mat fragments (Hill et al. 2016; Hill and Corcoran 2018) in the GLF (Flack Lake Group), microbially induced sedimentary structure (MISS) in the GLF and Bar River Formation (Hill et al. 2016), and stromatolites in the Espanola Formation (Hofmann et al. 1980).

Gordon Lake Formation

Strata now assigned to the GLF were originally recorded as fine-grained sandstone and minor limestone (Murray 1858, 76 p.), or “banded cherty quartzite” (Collins 1925, 111 p.), in the upper part of the Huronian succession. The formation was formally defined by Frarey (1967), and has received relatively little attention compared to the older formations of the Huronian Supergroup. The formation was re-examined because it (1) records the final stages of transition from an anoxic to oxic early Earth atmosphere (Great Oxidation Event), (2) contains significant and convincing evidence of fossilized microbial life in the Huronian Supergroup, (3) contains the only carbonates in the upper Huronian Supergroup, (4) represents complex deposition of a significant quantity of fine-grained material on a passive margin lacking evidence of burrowing organisms and marine plants, and (5) is part of an economic and historically significant succession that spans the Siderian and early Rhyacian periods.

In the preserved Huronian basin, the GLF thickens southward, from approximately 300 m near Flack Lake, to approximately 1100 m in the Killarney area (Fig. 2). It is composed primarily of very fine- to fine-grained sandstone, mudstone, and intraformational conglomerate. Three units have previously been suggested for the GLF and are described as upper and lower sandy red members and a middle, fine-grained, green member (Eisbacher and Bielenstein 1969; Card et al. 1977; Card 1978*a*). The lower upward-fining unit was described as containing interbedded rippled white and red sandstone and siltstone, intraformational breccia, and nodular anhydrite. The middle unit was considered a mixture of dark green argillite, chert, and fine-grained grey sandstone,

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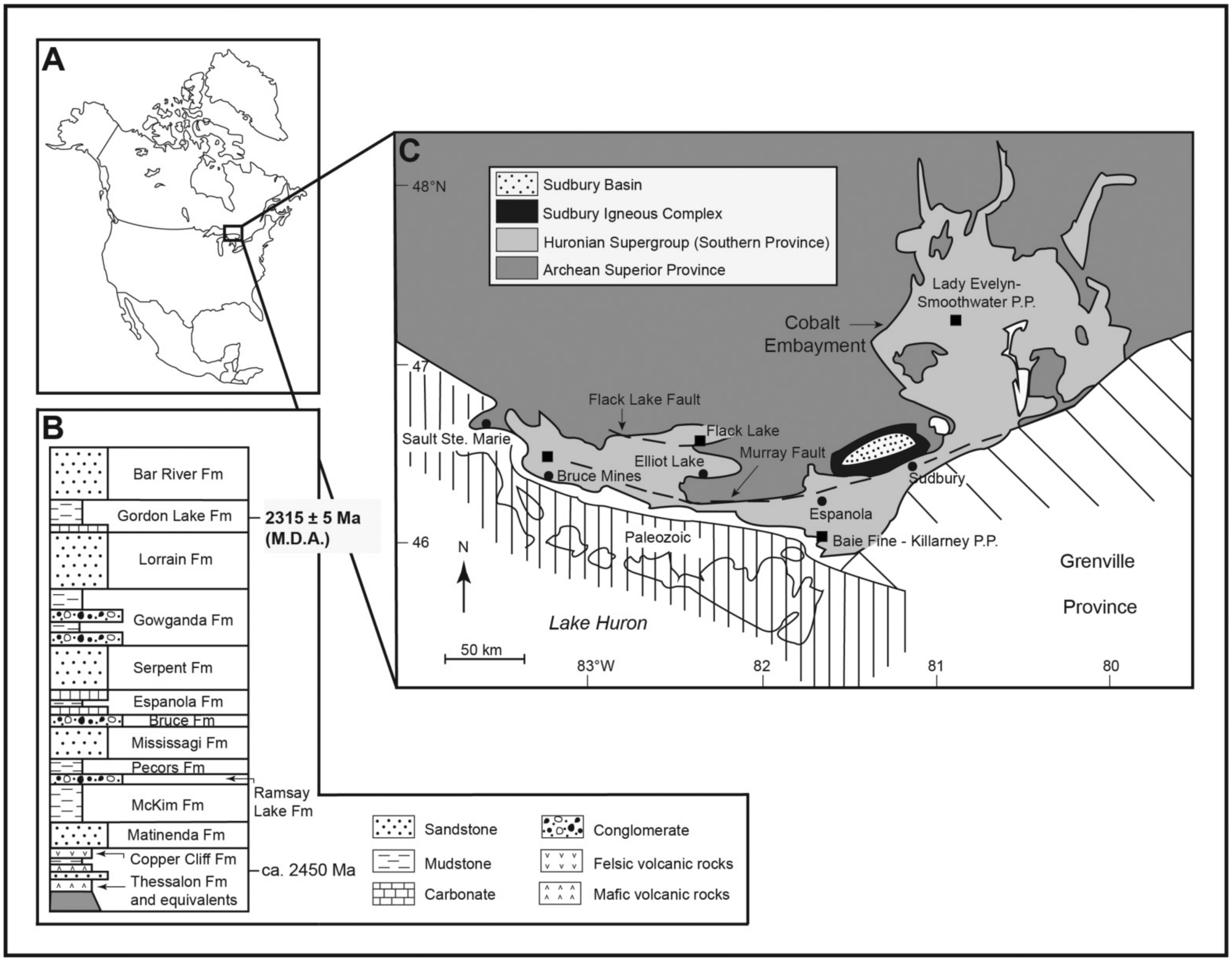
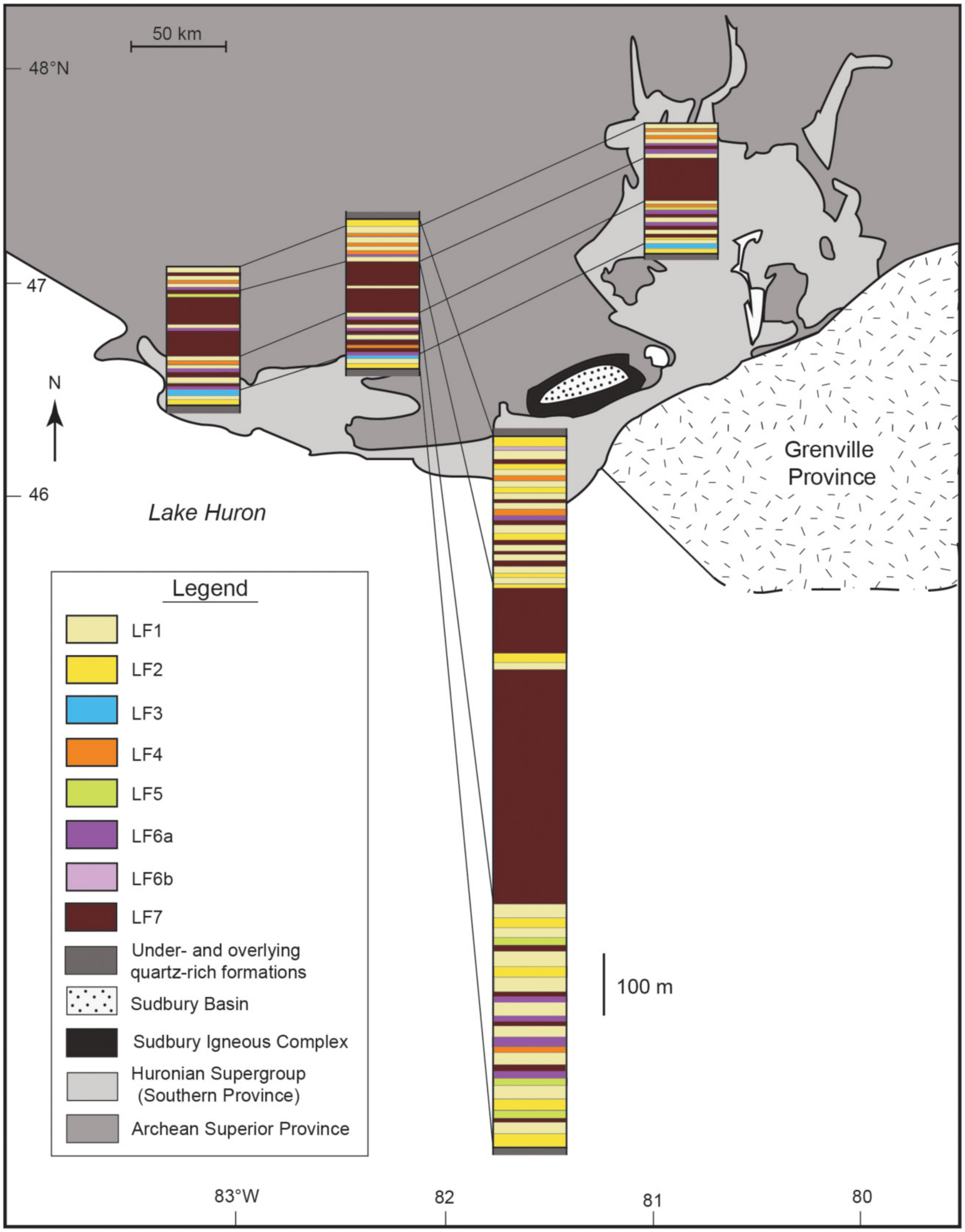
Fig. 1. Simplified geological map showing the distribution of the Huronian Supergroup and locations of the study areas. (A) Location of mapping areas in Ontario, Canada; base map modified from (Jones 2009). (B) General stratigraphy of the Huronian Supergroup. Maximum depositional age (M.D.A.) of the Gordon Lake Formation from Hill et al. (2018) and lower age from Krogh et al. (1984) and Ketchum et al. (2013). (C) Simplified geological map of the distribution of the Huronian Supergroup, modified from Young et al. (2001). General locations of the study areas are shown with black squares. Provincial Park is abbreviated to P.P.



with a variety of sedimentary structures, including cross-laminae, ripples, graded beds, and soft-sediment deformation structure (SSDS). The upward-coarsening top unit was described as containing red, mud cracked siltstone, argillite, and sandstone. The contacts with the underlying Lorrain Formation and overlying Bar River Formation are conformable. Environmental interpretations of the GLF include lagoon (Rust and Shields 1987), tidal flat (Wood 1973; Card 1976; Siemiatkowska 1978), storm-influenced shallow marine (Chandler 1984), and deep-water turbidite settings (Card 1978*a*). Casshyap (1966) suggested a deeper water equivalent to the Lorrain Formation. Wood (1973) identified hematite ooliths and anhydrite-gypsum nodules in the Flack Lake area, and interpreted silt grains to be glacial loess, transported by wind. This led to his interpretation of deposition in a tidal flat setting in a relatively arid, subarctic climate. Alternatively, Chandler (1988) proposed a hot, generally dry coastal sabkha environment for the lower GLF, based on the evaporite nodules near the base, and suggested a storm-dominated shelf setting for overlying strata. Wood (1973) and Chandler (1986) observed minor strata-bound copper mineralization at the base of the GLF at Welcome Lake and concluded that this was sabkha-related. Chandler (1986) also observed possible chamosite oolites and "glauconite-like" peloids in the middle of the formation.

Hofmann et al. (1980) observed fenestral dolostone in the Bruce Mines area, which they interpreted as primary voids possibly indicating localized microbial mat activity. An approximately 30 m thick dolostone unit with wavy, irregular laminae "suggestive of algal mats" was also identified in the Goulais Bay area of Ontario, approximately 60 km north of Gordon Lake (Bennett et al. 1989). Hill et al. (2016) and

Fig. 2. General regional geological correlation of the Gordon Lake Formation. Base map modified from Young et al. (2001).



Hill and Corcoran (2018) recognized MISS and microbial mat fragments in the GLF in the Flack Lake and Bruce Mines areas, significantly increasing the known occurrences of biosignatures in the Huronian Supergroup.

Methods

Four field areas were selected for lithostratigraphic and sedimentological analyses, based on the availability and accessibility of exposure of the GLF. The study areas are located north-northwest of Bruce Mines, around Flack Lake, in Lady Evelyn-Smoothwater Provincial Park around McGiffin and Smoothwater Lakes, and between Baie Fine and Killarney Lake in Killarney Provincial Park, Ontario, Canada (Fig. 1C). Coordinates for the examined outcrops are presented in Supplementary Table S1. Diamond drill core from the Flack Lake area, now stored at the Ontario Geological Survey Core Library in Sault Ste. Marie, Ontario, was also logged.

Can. J. Earth Sci. 00: 1–26 (2023) | dx.doi.org/10.1139/cjes-2022-0042

This included hole 68-1 from Canadian Johns Manville Ltd., and holes 063-83-1, 063-83-2, 063-83-3, and 063-83-9 from Canamax Resources Ltd.

Detailed stratigraphic sections were established in all four study areas (see Hill 2019). At each location, lithology, grain size, and sedimentary and potential biogenic structures were documented. Representative rock samples were collected for petrographic analysis and analyzed in thin sections. The process of lithofacies analysis entailed describing rock samples and units, interpreting sedimentary processes that occurred at the time of deposition, and grouping the lithofacies into associations, which reflect a paleodepositional environment. In this paper, each depositional process is represented by a distinct package of rock types called lithofacies.

Lithofacies descriptions and interpretations

Seven distinct lithofacies were identified in the GLF. These are (1) very fine- to fine-grained sandstone, (2) fine- to medium-grained sandstone, (3) carbonate, (4) interlaminated to interbedded mudstone and fine-grained sandstone, (5) coarse-grained sandstone, (6) intraformational granule- to pebbly sandstone and conglomerate, and (7) mudstone. The strata can be broadly correlated between different areas based on observed units and details of the stratigraphy. Specific marker beds (event beds) were not identified, however distinctive marker "intervals" were identified. Lateral interfingering of GLF facies with strata of the Lorrain and Bar River formations was not observed, and although the formation contacts in places appear gradational, uninterrupted coeval deposition is not proven. A summary of lithofacies and accompanying descriptions and interpretations is presented in Table 1.

Lithofacies 1: very fine- to fine-grained sandstone

Lithofacies 1 (LF1) consists of varicoloured thin to medium bedded, very fine- to fine-grained sandstone (Figs. 3 and 4). Beds are 1–45 cm thick, mainly tabular, and have sharp or scoured basal surfaces, and sharp, rippled, or erosional upper surfaces. Bedsets are up to 110 cm thick. Lithofacies 1 is characterized by massive bedded units (Fig. 3), with lesser planar and trough cross-bedding (Fig. 4A), and plane-parallel (Fig. 4B), wavy, and ripple cross-laminae. Rounded to elongate mudstone intraclasts are present at the base of some beds. Hummocky cross-stratification (HCS), mudstone drapes (Figs. 4C and 4D), alignment of mudstone clasts along laminae and foresets, synaeresis cracks, climbing and flat-topped ripples (Fig. 4E), and iron- and heavy mineral-defined laminae are present locally. In general, beds are laterally continuous, but locally pinch out. Sand-rich clastic dikes and small-scale syn-sedimentary faults were observed in association with LF1 in Baie Fine and Lady Evelyn-Smoothwater Provincial Park (Fig. 4F). Lithofacies 1 is frequently associated with fine- to medium-grained sandstone (LF2), carbonate (LF3), interlaminated to interbedded mudstone, and fine-grained sandstone (LF4), intraformational granular to pebbly sandstone and conglomerate (LF6), and mudstone (LF7).

Interpretation

Lithofacies 1 is interpreted to have formed by processes including migration of sinuous-crested (trough cross-bedding) and straight-crested (planar cross-bedding) subaqueous dunes, as well as by plane-bed transport under upper flow regime conditions (plane-parallel and wavy laminae). Uni- and bidirectional-opposed currents are indicated by ripple cross-laminae. Local combined flow bedload transport is indicated by the presence of HCS. Scoured bases, wavy and cross stratification, along with mudstone rip-up clasts, indicate deposition typically from strong currents (Ricci Lucchi 1995; Nichols 2009). Local flat-topped ripples indicate periods of very shallow water conditions during deposition (Tanner 1962). Mudstone drapes indicate alternation between high- and low-energy conditions that allowed mud to settle out of suspension. Plane-parallel laminae are typically associated with the upper flow regime, but are known to form in the lower flow regime. However, the latter typically develop when grains are larger than 0.6 mm (Harms et al. 1982), which excludes this as a possible depositional trigger for these structures. Lateral continuity is typically high, generally exceeding outcrop width, and suggests uniform depositional conditions.

The overall sheet-like nature of the sandstone beds may have developed as a result of storms and tidal influence on a shallow open shelf (Anderton 1976; Raaf et al. 1977), or by poorly confined drainage on a tidal flat (Donaldson et al. 2002). Beds containing a transition from planar laminae to ripples, or vice versa, indicate a shift between unidirectional and oscillatory flow. Clastic dikes and small-scale syn-sedimentary faults indicate episodes of sediment instability shortly following initial deposition. Periods of current inactivity were characterized by the oscillatory movement of waves, which produced symmetrical ripples. Minor planar cross-bedding containing mudstone rip-up clasts may have formed by either tidal scour or storm activity (Brenchley 1989; Shaw et al. 2012). Synaeresis cracks may have formed by dewatering during compaction, resulting in volume change of mudstone layers, which are subsequently infilled by coarser grained sediment (McMahon et al. 2017). Heavy mineral accumulations are typical of exposed nearshore or shoreline environments and suggest shallow water conditions where winnowing by marine currents and waves can take place (Levson 1995). However, the lack of associated aeolian deposits points to a subaqueous environment. This lithofacies is interpreted as having been deposited in a nearshore, subtidal setting.

Lithofacies 2: fine- to medium-grained sandstone

Lithofacies 2 consists of varicoloured medium to thick bedded, fine- to medium-grained sandstone (Figs. 5 and 6A–6C). Beds are typically tabular and laterally continuous within individual outcrops. They may be planar or trough

Table 1. Summary, description, and interpretation of lithofacies in the Gordon Lake Formation.

Lithofacies and percentage	Lithology, thickness, and geometry	Sedimentary structures and other characteristics	Depositional processes	Associated lithofacies	Interpretation
LF1: Very fine- to fine-grained sandstone (26%)	Very fine- to fine-grained sandstone; thin to medium bedded; tabular overall and locally pinch out; beds are up to 45 cm thick	Sharp or scoured basal surface; rippled, planar, or erosional top surface; massive bedding; plane-parallel, wavy, and ripple cross-laminae, planar and trough cross-beds, local mudstone rip-up clasts, HCS, mudstone drapes, heavy mineral and iron-stained laminae; local SSDS	Migration of sinuous- and straight-crested subaqueous dunes; plane-bed transport in upper flow regime; uni- or bidirectional ripple migration; bedload transport; influenced by tides and storms	LF2, LF3, LF4, LF6a, LF7	Subtidal, nearshore, possible lower shoreface zone; storm deposits
LF2: Fine- to medium-grained sandstone (8%)	Fine- to medium-grained sandstone; medium to thick bedded; tabular and laterally continuous; beds are up to 90 cm thick	Wavy or scoured base; bidirectional planar and trough cross-beds, massive to planar laminae (predominantly faint), rare mudstone rip-up clasts	Migration of sinuous- and straight-crested subaqueous dunes, influenced by tidal currents, storm currents and waves; plane-bed transport in upper flow regime	LF1, LF7, LF4	Subtidal sand bodies; tidal channel; storm deposits
LF3: Carbonate (3%)	Lenticular and medium to thick bedded fenestral and sandy dolostone; beds are up to 20 cm thick	Irregular to laminoid fenestrae, normal grading of dolomicrite rip-up clasts, thin rippled sandstone interbeds and laminae, stratiform and small-scale domal stromatolites	Deposition in relatively shallow water with low clastic influx; minor influence from storms	LF1, LF7	Deposition in inter- to subtidal environment
LF4: Interlaminated to interbedded mudstone and fine-grained sandstone (20%)	Fine-grained sandstone and mudstone; local quartz granules; beds vary laterally and pinch out locally; beds are up to 25 cm thick	Rippled or sharp upper and lower surfaces; sandstone with locally erosive base; lenticular and flaser bedding, wavy to ripple cross-laminae, shrinkage cracks, wave, interference, and combined flow ripples, local normally graded beds, reactivation surfaces, MISS, mudstone rip-up clasts and drapes	Alternating suspension settling and traction deposition under the influence of tides, waves, and storms; possible episodes of subaerial exposure; frequent fluctuations in depositional conditions	LF1, LF7	Intermittently subaerially exposed mixed intertidal flats that were occasionally influenced by storms; possibly shallow subtidal
LF5: Coarse-grained sandstone (4%)	Coarse-grained sandstone; lenses and thin to medium bedded; contains local pyrite fragments; beds up to 20 cm thick	Mudstone drapes, mudstone rip-up clasts, bidirectional trough cross-beds and local normal grading	Traction deposition from high-energy currents; migration of sinuous-crested subaqueous dunes influenced by tidal currents	LF1, LF7, LF4	Subtidal to shallow shelf deposits by storms or tsunamis; subtidal dunes

Table 1. (*concluded*).

Lithofacies and percentage	Lithology, thickness, and geometry	Sedimentary structures and other characteristics	Depositional processes	Associated lithofacies	Interpretation
LF6a: Intraformational granule to pebbly sandstone and conglomerate (9%)	Intraformational granule to pebbly sandstone and conglomerate; lenses and thin to medium bedded; beds are up to 15 cm thick	Erosive basal surface; well-rounded clasts that align parallel to bedding or along foresets; local nodules, normal grading and gradational transition to overlying beds	Traction deposition in the upper flow regime	LF1, LF4 locally, LF7	Subtidal storm deposits; possible influence from tidal currents
LF6b: Matrix-supported intraformational conglomerate (<1%)	Pebble to cobble size, well-rounded, typically elongate quartzite clasts; sandstone matrix	Structureless	Traction deposition in the upper flow regime by strong currents or oscillatory waves	None observed	Nearshore setting
LF7: Mudstone (30%)	Thin to thick bedded fine- to coarse-grained mudstone; coarse-grained mudstone and very fine-grained sandstone streaks, laminae, and lenses	Local normal grading, shrinkage cracks, large- and small-scale SSDS, minor mudstone rip-up clasts, microbial mat fragments	Primarily suspension settling from standing water; influenced by storms; periodic fluctuations in depositional conditions	LF1, LF3, LF4, LF6a	Subtidal-shallow shelf, storm deposits

Note: Abbreviations: HCS, Hummocky cross-stratification; LF1, Lithofacies 1.

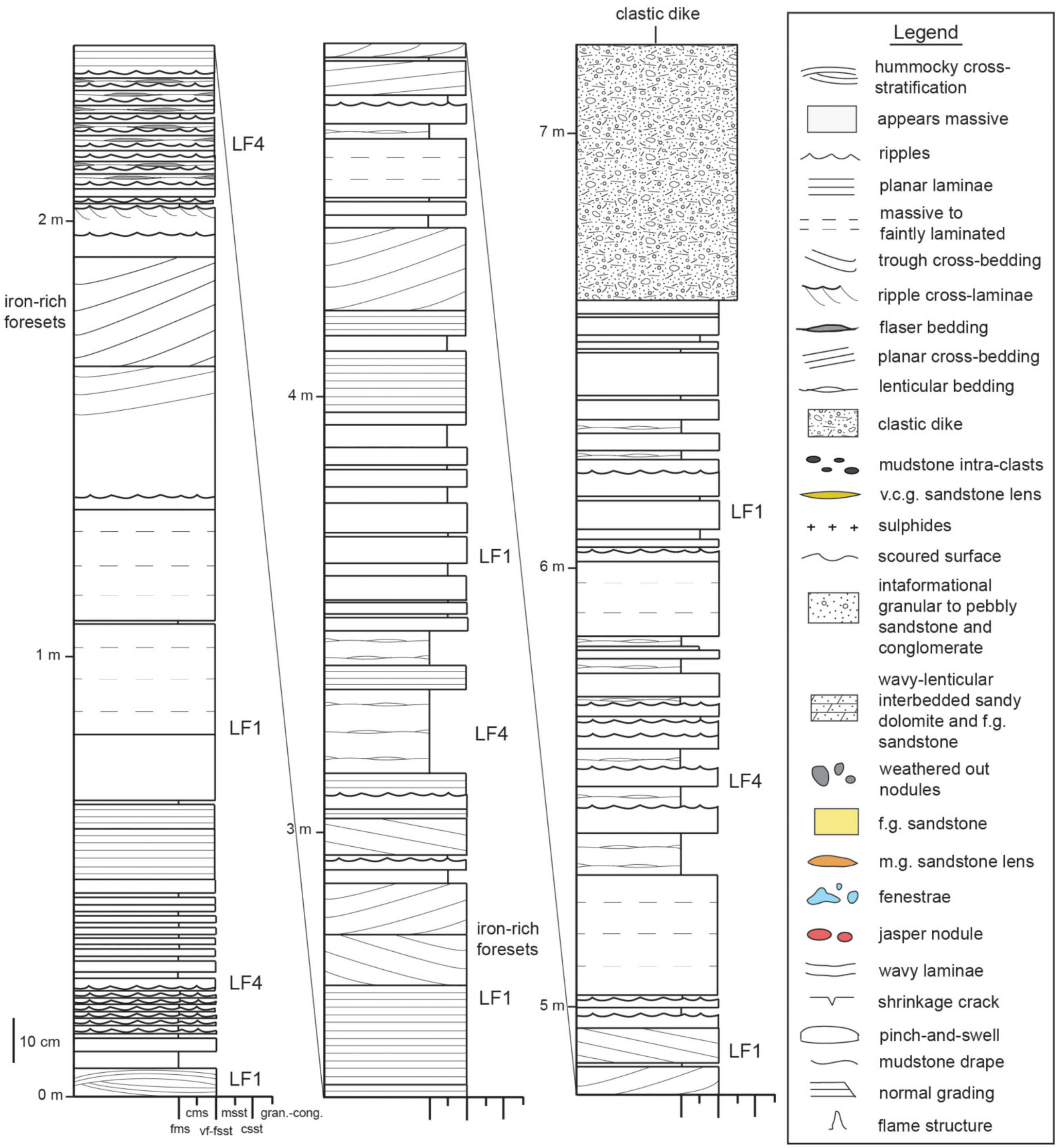
cross-bedded (Fig. 6A), or massive to planar laminated (Fig. 6B), and can have a wavy or scoured base (Fig. 6C). Planar laminae are often faint (0.1–2 mm thick), but where visible are generally continuous and parallel. Rippled surfaces are uncommon, and rounded mudstone intraclasts are subordinate or absent. The paleoflow direction of cross-beds indicate that flow operated locally in both unidirectional and opposing directions. Individual beds are approximately 2–90 cm thick. Massive mudstone cosets up to 20 cm thick are preserved locally. Lithofacies 2 is frequently found in association with LF1, and is present locally near the base, middle, and top of the GLF.

Interpretation

Lithofacies 2 is interpreted to have formed by the migration of sinuous-crested (trough cross-bedding) and straight-crested (planar cross-bedding) subaqueous dunes, alternating with plane-bed transport (planar laminae) in the upper flow regime, and deposition of material with a uniform grain size, such that internal structures are not visible (massive bedding). Original stratification may have also been obscured by post-depositional fluidization (de Souza et al. 2019). Planar laminae often appear faint, however the thickness of LF2 beds indicates a greater volume of sediment than would be expected of deposition in the lower flow regime (Eriksson et al. 1995). Scoured bases and cross-bedding also indicate deposition under a strong current. This lithofacies is interpreted to primarily represent deposition in the subtidal zone. The most common sedimentary structures are planar laminae and trough cross-beds. Foreset dip directions are bipolar, which indicate tidal current action. Simple and compound dunes created by tides form in littoral and shelf environments (Longhitano et al. 2012), and no compound dunes were identified. The horizontally laminated beds may have been deposited within tidal channels (McKee et al. 1967; Tirsgaard 1993) as storm beds (Kreisa 1981), or in the lower shoreface zone (Nichols 2009).

Fluctuating energy levels and transition between the upper and lower flow regimes are inferred from the presence of horizontal laminae, characteristic of upper flow regime conditions, and trough cross-bedding and ripples indicative of lower flow regime conditions. Convolute laminae were not observed in LF2, which supports sediment deposition in tidal channels, as opposed to a braid-delta where deposition occurs at a higher rate (Eriksson et al. 1995). The lack of sigmoidal foresets, mudstone drapes, abrupt channel margins, and beds that are thick centrally and thin laterally in LF2 suggests that intertidal channels may not have been present. One thick, laterally pinching, erosive sandstone bed in Baie Fine is interpreted as a tidal channel (Fig. 6C). In general, it is difficult to differentiate Precambrian tidal channels from that of Precambrian rivers and offshore beds due to their sheet-like nature (Eriksson et al. 1998), although Long (2019) has identified Archean tidal channels based on inclined mudstone laminae. The thick, faintly laminated to massive LF2 beds at the top of the formation may have been deposited as subtidal sand bodies, with the mudstone interbeds representing deposition either between the sand bodies or during slack water conditions.

Fig. 3. Representative stratigraphic section for lithofacies 1 from Smoothwater Lake, Lady Evelyn-Smoothwater Provincial Park. Coordinates for the outcrop are 47°23′39.30″N, 80°41′11.58″W.



In Baie Fine, a general fining-upwards shift from interpreted basal nearshore strata, to subtidal storm deposits, to thick bedded subtidal sandstones suggests that a regression may have occurred following transgression that established shallower water conditions for deposition of LF2 in the middle of the GLF.

Lithofacies 3: carbonate

Lithofacies 3 consists of varicoloured, fenestral, and sandy dolostone (Figs. 6D–6G and 7). In the Flack Lake area, thin, wavy to lenticular interbeds of fenestral and sandy dolostone, and sandstone were observed. Irregular to laminoid voids, interpreted as fenestrae, are up to 20 cm long and

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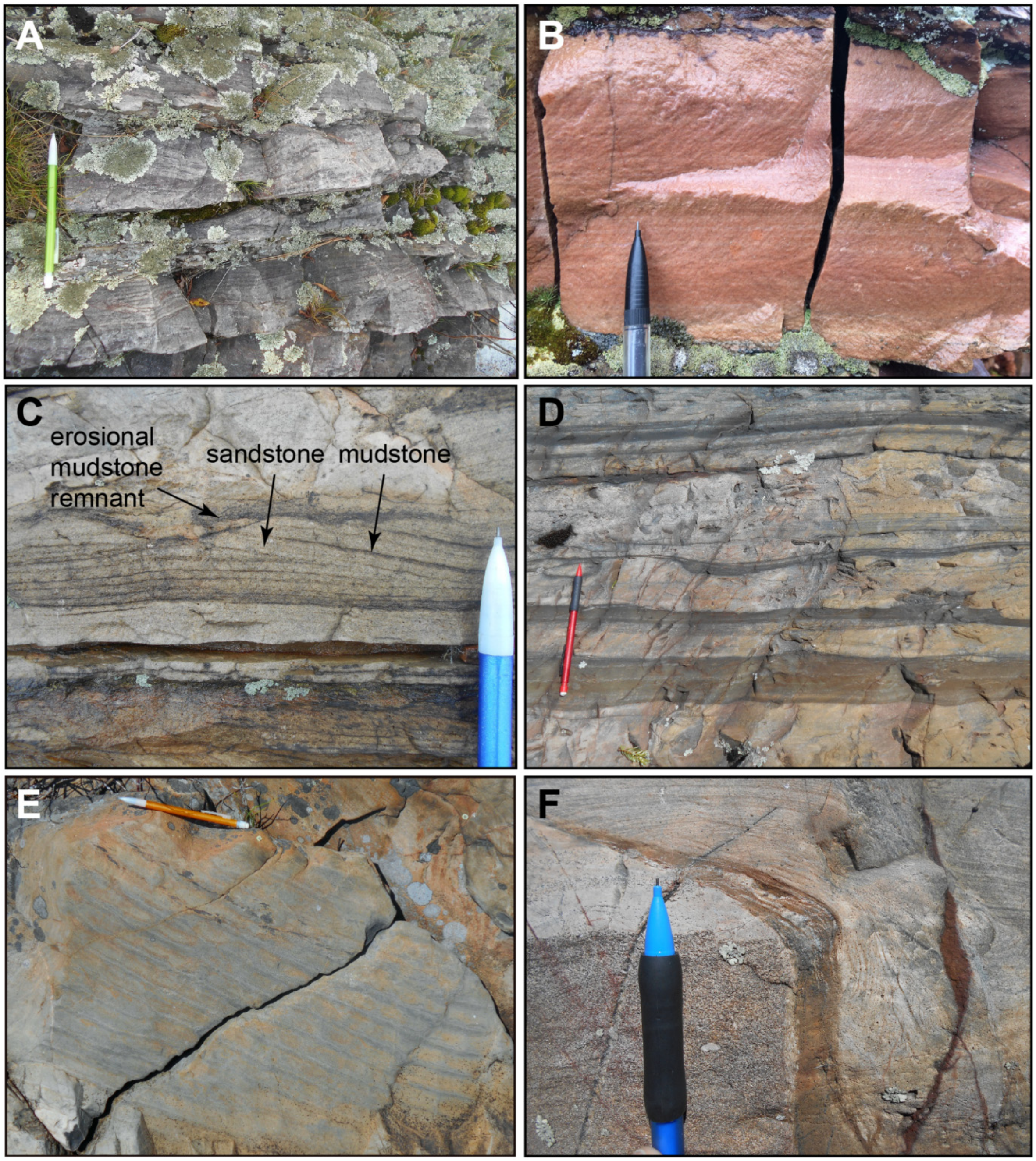
Fig. 4. Representative photos of lithofacies 1, very fine- to fine-grained sandstone. (A) Trough cross-bedded and rippled sandstone with iron-stained laminae from Smoothwater Lake. (B) Planar laminated sandstone from Flack Lake area. (C) Mudstone drapes between wavy to low angle cross-bedded sandstone from Baie Fine. (D) Sandstone beds with scoured bases capped by mudstone drapes (interbeds), and local rippled sandstones from Baie Fine. (E) Flat-topped ripples with local bifurcations from Baie Fine. (F) Small-scale synsedimentary fault with iron staining from Baie Fine. Pencils are 14.5 cm long and 8 mm wide.



aligned parallel to bedding (Fig. 6D). Bedding surfaces are sharp to gradational and the upper surface is rippled locally. In Lady Evelyn-Smoothwater Provincial Park, LF3 is preserved as blocks of interbedded sandy dolostone and sandstone (Fig. 6E), with calcareous, millimeter scale, flat to wavy laminae, and up to 8.5 cm wide and 4.5 cm high laterally linked, laminated domes (Figs. 6*f*–6g). In the Bruce Mines area, dolostone beds are approximately 8–20 cm thick, and alternate with fine-grained sandstone, mudstone, and intraformational conglomerate. Dolostone beds contain irregular to laminoid fenestrae up to 20 cm long, and local, normally graded, intraformational dolomicrite intraclasts. Siliciclastic interbeds are planar to wavy laminated, or faintly rippled, and contain minor small-scale SSDS. Calcareous intraclasts were observed in core. Lithofacies 3 was not exposed in the Baie Fine-Killarney area.

Fig. 5. Representative stratigraphic section for lithofacies 2 from Baie Fine. Legend as in Fig. 3. Coordinates for the outcrop are 46°2′8.77″N, 81°30′22.25″W.

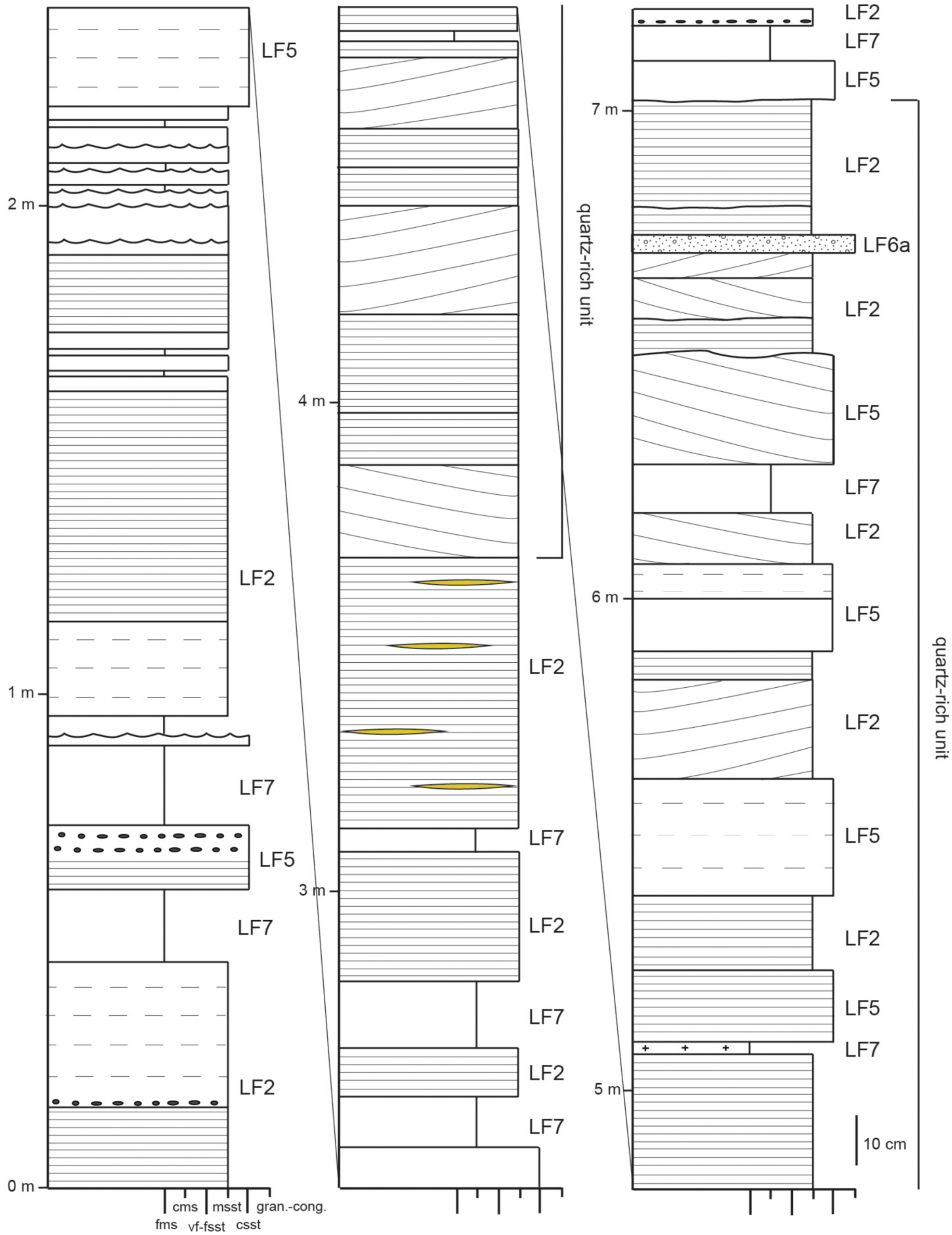
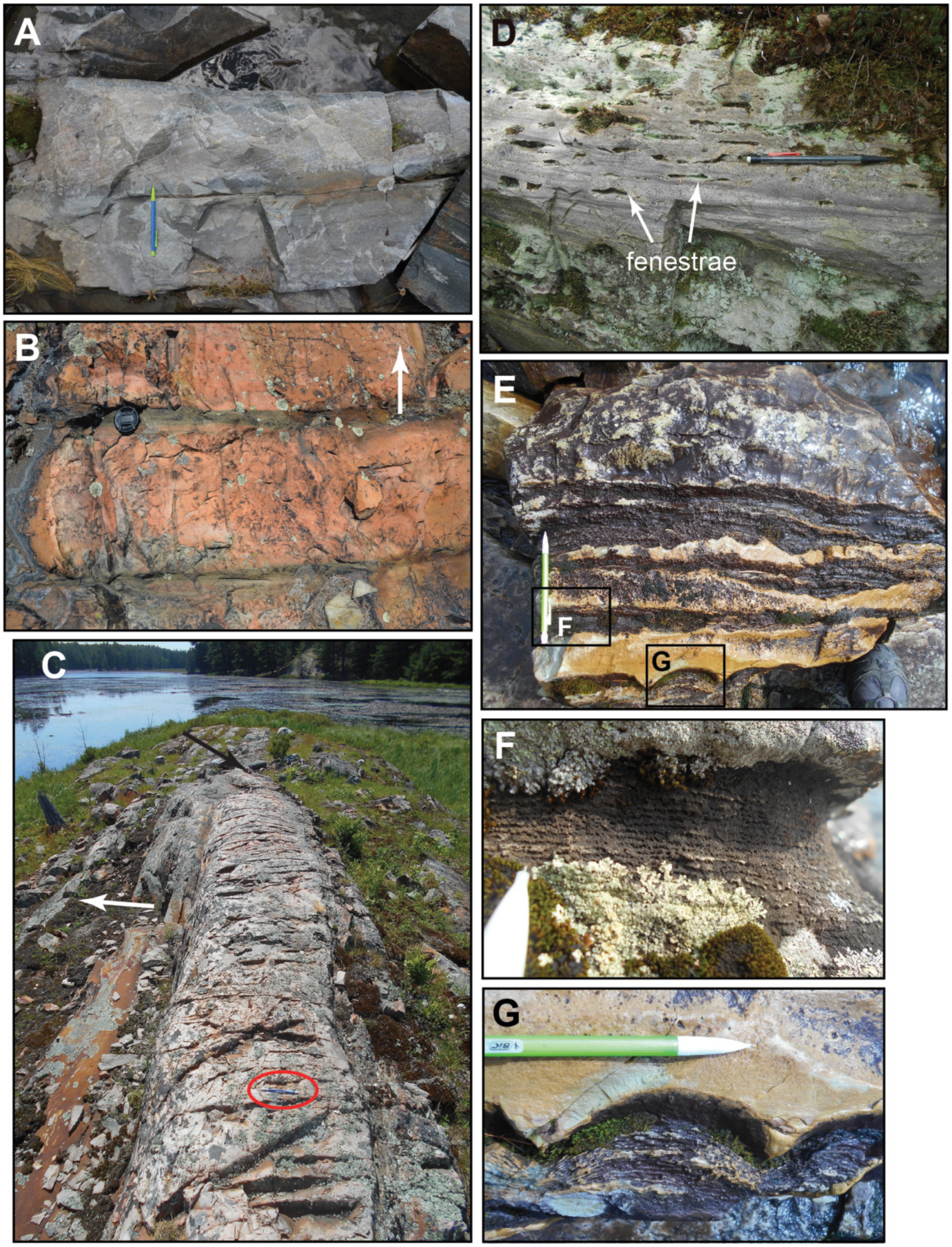


Fig. 6. Representative photos of lithofacies 2 (A–C) and 3 (D–G). (A) Trough cross-beds in the quartz-rich middle section from Baie Fine (refer to Fig. 5). Pencil points to top. (B) Massive bedded sandstone with thin mudstone interbeds from Baie Fine near the upper formational contact. Arrow points to top. (C) Massive to faintly laminated sandstone with scoured base that tapers out laterally on Artist Lake in Killarney Provincial Park. Interpreted as a tidal channel deposit. Thin adjacent beds contain mudstone pebbles, minor cross laminae, ripples, and minor SSDS. One nodule bed was observed above the channel. Beds generally thin-up section. Black arrow points to bed termination and white arrow points to top. (D) Lenticular bedded fenestral dolostone near Flack Lake. (E) Stromatolitic sandy dolostone from Smoothwater Lake. (F) Close-up of stratiform stromatolites from (E). (G) Close-up of laterally linked, domal stromatolites from (E). Pencils are 14.5 cm long and 8 mm wide and camera lens cap is 5.8 cm wide.



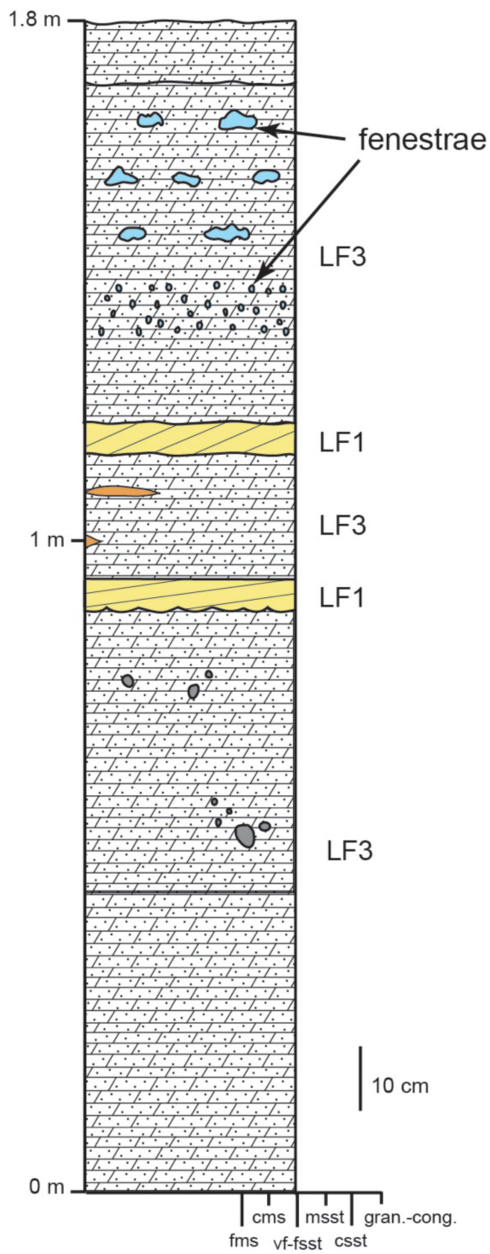


Fig. 7. Representative stratigraphic section for lithofacies 3 from the Flack Lake area. Legend as in Fig. 3. Coordinates for the outcrop are 46°37′30.97″N, 82°50′1.90″W.

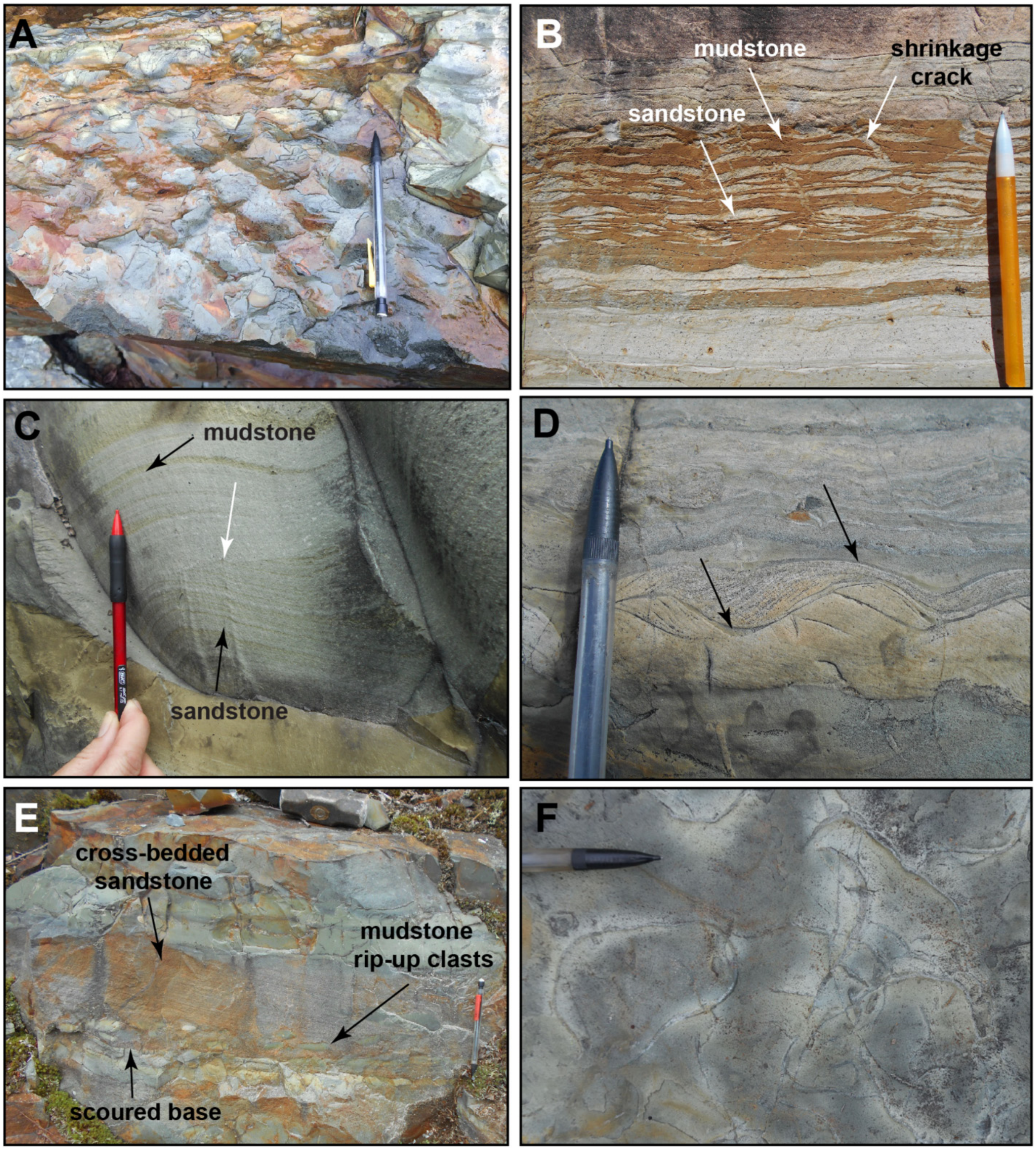
Interpretation

Lithofacies 3 is interpreted to have formed in a shallow marine setting during periods of low clastic influx. The flat to wavy and domal calcareous structures observed at Smoothwater Lake (Figs. 6E–6G) are interpreted as stratiform and domal stromatolites, respectively. The presence of dolostone implies that by the end of deposition of the Lorrain Formation there was a return to locally stable marine conditions suitable for establishment of microbial communities. Alternating laminae in the sandy dolostone likely formed by fluctuating rates of sediment deposition wherein the sandy laminae represent a higher rate of detrital influx and the dolomitic and stromatolitic laminae represent periods of low detrital influx. The disrupted laminae are here interpreted as primary features, and may have formed by desiccation of the stromatolite surfaces at the time of deposition (Riding 1991). The overall paucity of ripples suggests low wave activity, however, primary sedimentary structures may have been destroyed during dolomitization (Einsele 2000). Fenestrae are likewise interpreted to have a microbial origin. These structures have multiple modes of formation, including infill of gas bubbles produced by decaying organic matter (Flügel 2010), repeat flooding and exposure of carbonate sediment (Shinn 1968), and desiccation of microbial mats, leading to separation from surrounding sediment (Logan et al. 1974). Fenestrae are often associated with microbially induced or precipitated sediment that form in carbonate facies on intertidal and supratidal flats (Logan et al. 1974; Mazzullo 2004), and support carbonate precipitation at least in part influenced by microbial mats (Grotzinger and Knoll 1999; Reid et al. 2000; Altermann 2004; Schopf et al. 2007). Due to the abundance of tidal sedimentary structures and recognition of microbial mat structures in the Flack Lake and Bruce Mines areas, an explanation involving the decay or shrinkage of microbial mats in an inter- to subtidal environment is appropriate for the formation of fenestrae in LF3. Graded beds containing rounded intraformational dolomicritic rip-up clasts likely formed during storm events.

Lithofacies 4: interlaminated to interbedded mudstone and fine-grained sandstone

Lithofacies 4 consists of interlaminated to interbedded mudstone with fine-grained sandstone (Figs. 8 and 10A). The beds are varicoloured. Bedsets can be tens of centimetres thick and individual beds are 0.5–15 cm thick; on average, mudstone and sandstone beds have equal thickness. Upper and lower contacts are generally sharp and predominantly rippled. The sandstone beds locally have erosive bases. Beds frequently pinch out laterally over 5–10 m. Lenticular and flaser bedding, wavy to ripple-cross laminae, shrinkage cracks, and wave, interference, and combined flow ripples are the dominant sedimentary structures preserved in LF4 (Figs. 8A and 8B). Ripples commonly have low, rounded, symmetrical tops, but internally contain different types of laminae, including unidirectional and microcross varieties; asymmetrical ripples are rare and where observed have reworked, rounded crests. Reactivation surfaces (Fig. 8C), single or double mudstone drapes (Fig. 8D), minor small-scale SSDS, thin normally graded beds, cross-beds (Fig. 8E), and mudstone clasts are present locally. MISSs (Fig. 8F) are also preserved in LF4 in the Flack Lake area (see Hill et al. 2016). Identified varieties of MISS include sand cracks, microbial sand and silt chips, large mat chips, remnant gas domes, and iron patches. Evidence for biogenicity includes microtextures identified in thin section that denote a relationship to microbial mats and their activities, including growth and sediment trapping (e.g., wavy crinkled laminae and trapped sand grains, Fig. 9; see also Hill et al. 2016 and Hill and Corcoran 2018). In Lady Evelyn-Smoothwater Provincial

Fig. 8. Representative photos of lithofacies 4. (A) Interference ripples near Flack Lake. (B) Lenticular bedding, desiccation cracks, rippled sandstone, and mudstone drapes from Killarney Provincial Park. (C) Oblique view of a reactivation surface from Lady Evelyn-Smoothwater Provincial Park. White arrow points to the erosion surface. (D) Complete tidal cycle deposit from Baie Fine. Arrows point to mudstone drapes that were deposited in slack water between both ebb and flood current reversals. Ripple cross laminae support bipolar-opposed tidal currents. (E) Interpreted small tidal channel deposit from Flack Lake area. (F) Microbially induced curved and sinuous sand cracks near Flack Lake. Pencils are 14.5 cm long and 8 mm wide.

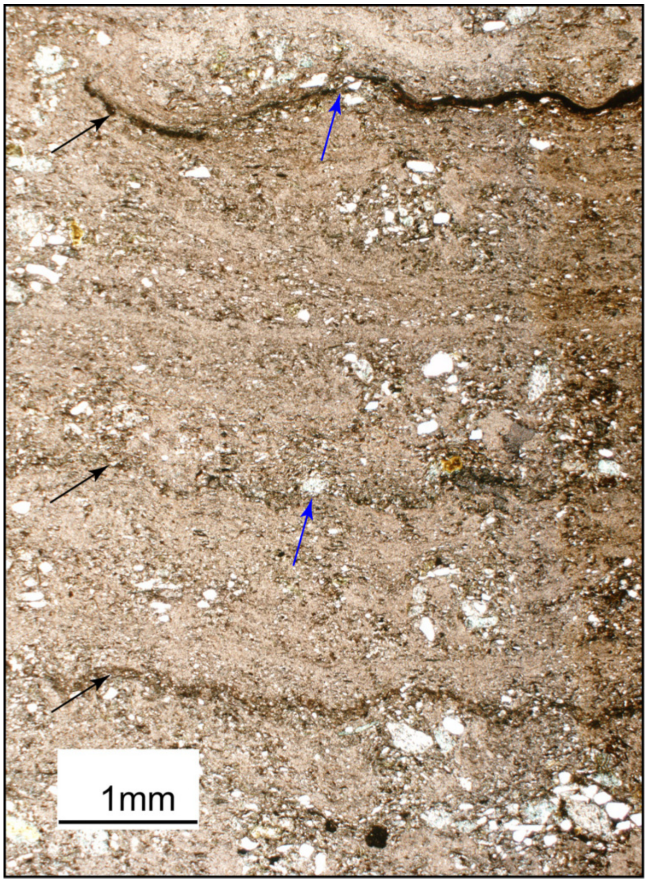


Park, local quartz granules are present in sandstone of LF4. This lithofacies is commonly associated with LF1 and LF7.

Interpretation

Lithofacies 4 is interpreted to have formed by alternating suspension (mudstone) and traction (sandstone) deposition under the influence of tides and waves (ripples, flaser, and lenticular bedding), with minor influence from storms. Desiccation cracks and microbially induced sand cracks formed during periods of subaerial exposure on tidal flats, whereas microbial mat chips formed through erosion of biofilms by wind or waves (Schieber 2004; Eriksson et al. 2007; Hill et al. 2016). Mudstone drapes formed through suspension

Fig. 9. Example of microbial mat microtextures identified in thin section. The photomicrograph shows irregular, wavy carbonaceous laminae (black arrows). Note the sand grains bound to and within the laminae (blue arrows).



settling during slack water periods of tidal cycles (Reineck and Singh 1980; Dalrymple 2010; de Souza et al. 2019). Reactivation surfaces are formed when ripples advancing during one tidal phase were eroded by the reversing ebb tidal current (Dalrymple 2010). Thin, normally graded beds indicate deposition from waning currents, which might be associated with storms, turbidity currents, or fluvial overbank floods (Kuenen and Menard 1952; Figueiredo et al. 1982; Nichols 2009). The frequent association of graded beds with sedimentary structures possibly indicative of subaerial exposure and deposition by tides and waves points to a shallow marine setting. In addition, the observation that storms were one of the main trigger mechanisms for the formation of SSDS in the GLF (Hill and Corcoran 2018), lends support to a waning storm origin for the graded beds. This lithofacies is typical of mixed intertidal flats and shallow marine settings.

Lithofacies 5: coarse-grained sandstone

Lithofacies 5 consists of white to grey, coarse-grained quartz arenite, that locally contains pyrite grains. In the Bruce Mines area, LF5 was observed as a sandstone lens in one outcrop where it is approximately 4 cm thick at its thickest point and pinches out laterally (Fig. 10A). The lens contains generally rounded, circular to elongate pyrite grains (Fig. 10B), and one load structure. Faint cross-laminae are preserved; however sulphide weathering covers much of the lens' surface, obscuring any structures. In Baie Fine and Lady Evelyn-Smoothwater Provincial Park, LF5 is massive to planar laminated and trough cross-bedded with heavy minerals defining laminae locally (Fig. 10C). Mudstone drapes and rippled bedding planes are preserved locally, and mudstone clasts were observed at the bases and tops of some beds.

Interpretation

Lithofacies 5 is interpreted to have formed by traction deposition from high-energy currents. In the Bruce Mines area, LF5 has a scoured base, pinches out laterally, is quartz-rich, and distinct from the overall fine-grained over- and underlying strata, suggesting that the sediment originated in a foreshore environment and was transported offshore by storm- or tsunami-generated flows (Dawson and Stewart 2007). A number of the rounded and elongate grains are interpreted as pyritized chips representing eroded microbial mats that were mineralized selectively. The pyrite likely formed under favourable anoxic conditions provided by decaying microbial mat chips (Berner 1984; Schieber 2004). The regular overlapping relationship with adjacent siliciclastic grains and cement indicate a diagenetic origin. In general, LF5 is associated with LF1 and LF7, indicating deposition from strong currents. This lithofacies is interpreted as representing subtidal to shallow shelf deposits. Coarse-grained sediment would have been transported to the coast by fluvial channels or reworked from adjacent coastal areas or older deposits (Sha and De Boer 1991). Winnowing by storms or tidal currents may have also contributed to the concentration of coarse-grained sediment (Nichols 2009; Reynaud and Dalrymple 2012).

Lithofacies 6: intraformational granule to pebbly sandstone and conglomerate

Lithofacies 6 consists of two subfacies: (a) green to white-grey, intraformational granular to pebbly sandstone and conglomerate (Figs. 10D, 10E, and 11B) and (b) pink, matrix-supported intraformational conglomerate (Fig. 10F). Lithofacies 6a is found in all of the study areas and is composed of mudstone clasts that are <1 mm to 14 cm wide. The clasts are well-rounded and appear circular to elongate in two dimensions, with rare irregular forms; some mudstone clasts contain fine laminae. The elongate clasts are predominantly aligned parallel to bedding or along foresets. Lithofacies 6a is typically overlain by LF1 or LF7. Association of LF6a with lenticular bedding, shrinkage cracks, and mudstone drapes of LF4 was observed locally. Beds are approximately 1–15 cm thick, and massive to faintly laminated. Basal surfaces are erosive, and a gradational transition into the overlying LF1 is common. Normal grading was observed locally. Siliceous and sulphate nodules (Chandler 1988) (Figs. 10G and 10H) were found associated with LF6a in the lower portion of the GLF, however, they were not restricted to this lithofacies. Lithofacies 6b is anomalous in the stratigraphy, and was only observed on one small, isolated outcrop exposure in

Can. J. Earth Sci. 00: 1–26 (2023) | dx.doi.org/10.1139/cjes-2022-0042

Fig. 10. Representative photos of lithofacies 5 and 6. (A) Lens of LF5 that tapers out laterally near Bruce Mines. Loading is evident at the base of the bed. (B) Photomicrograph of pyrite grain morphologies in (A). (C) Trough cross-bedding outlined by heavy mineral laminae from Baie Fine. Arrows point to over- and underlying mudstone drapes. Bipolar flow directions were observed in this interval. (D) Lithofacies 6a from Lady Evelyn-Smoothwater Provincial Park, interpreted as the base of a fining-upwards storm deposit. (E) Lithofacies 6a from Baie Fine. Possible herringbone cross-stratification. Note pebbles aligned along foresets. (F) Lithofacies 6b from Baie Fine. (G) Jasper nodules in thin LF5a bed from Lady Evelyn-Smoothwater Provincial Park. (H) Sugary quartz nodules from Baie Fine. Note how bedding was displaced by nodule growth after deposition. Pencils are 14.5 cm long and 8 mm wide.

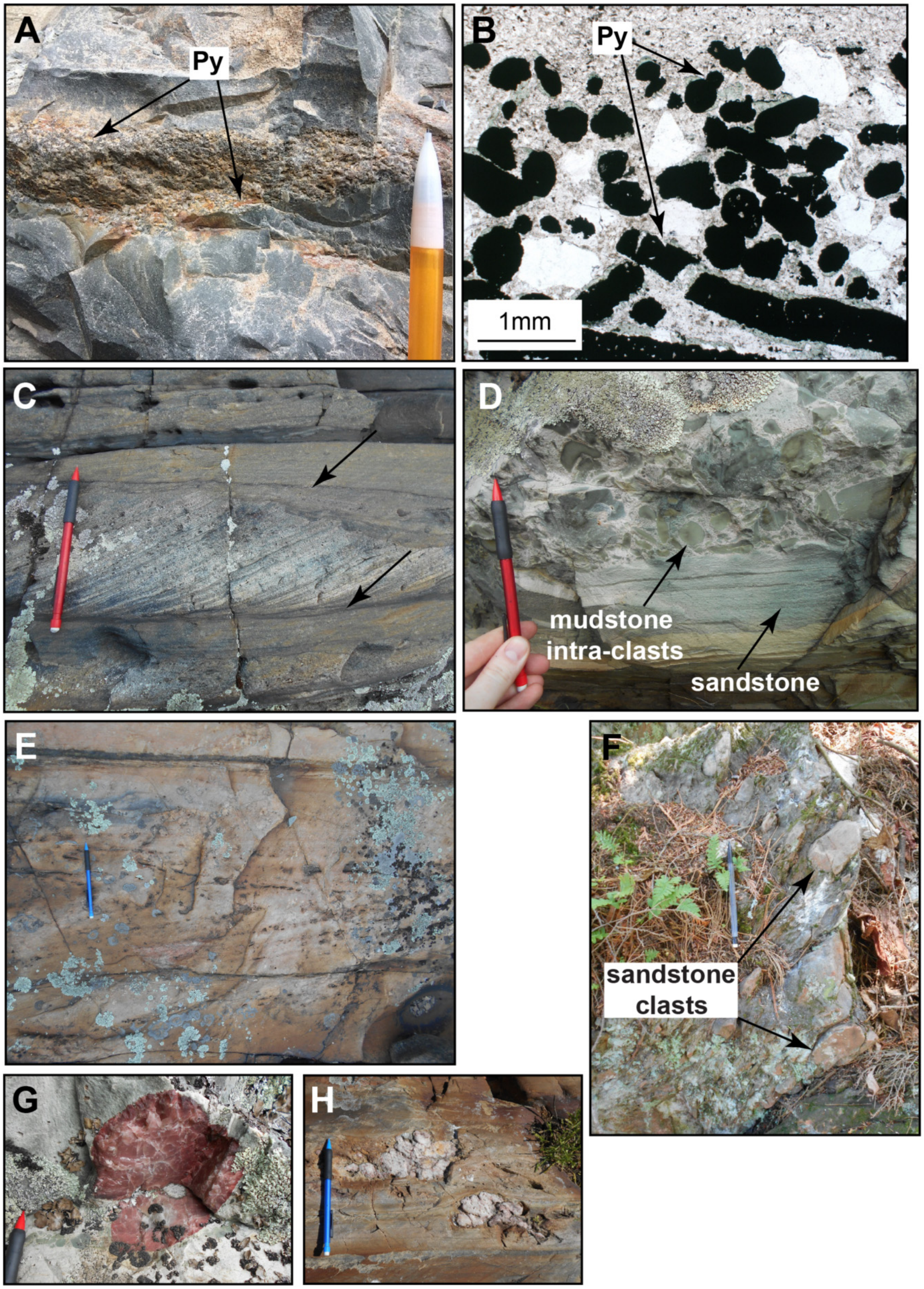
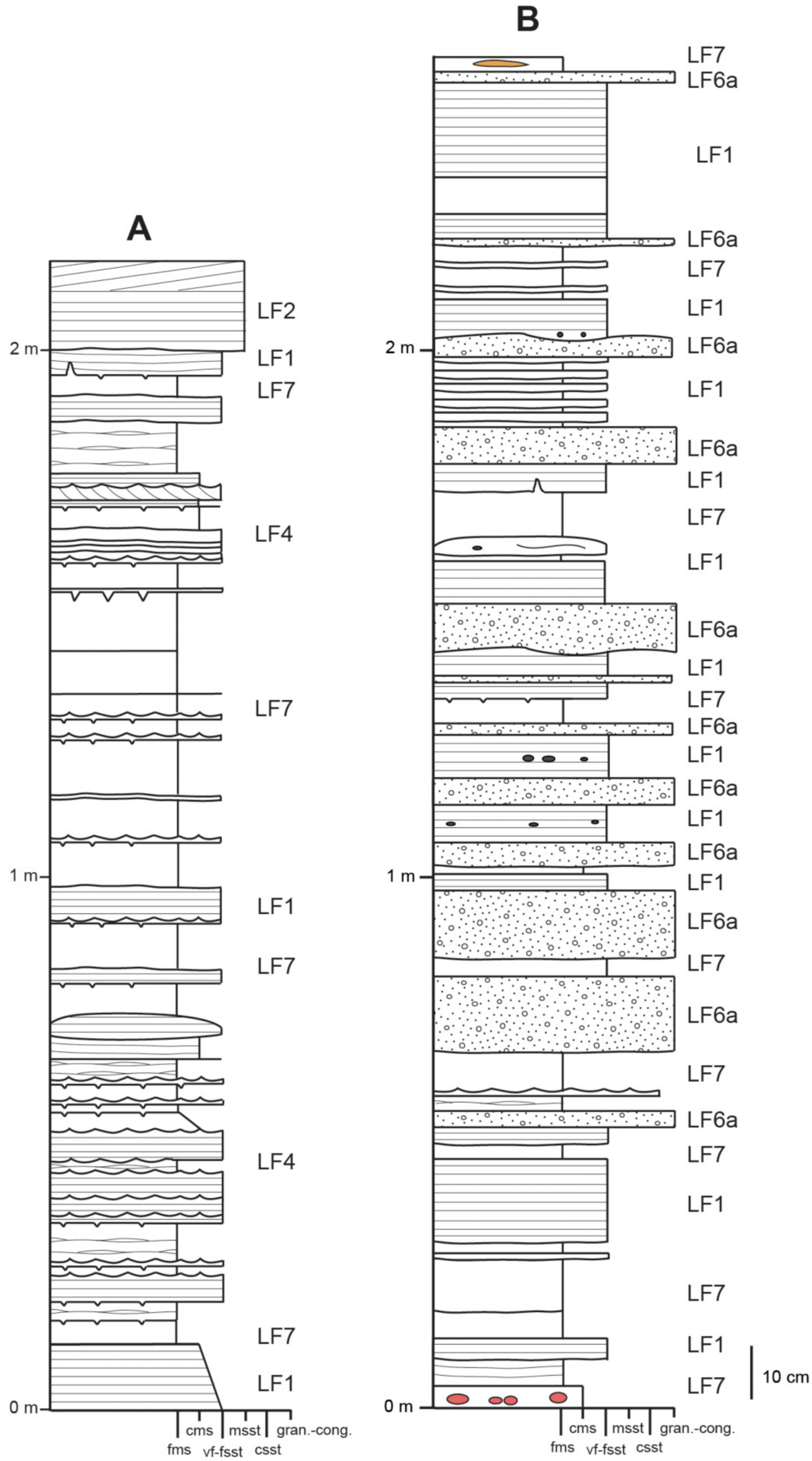


Fig. 11. (A) Representative stratigraphic section for lithofacies 4 and 7 from the Flack Lake area. Coordinates for the outcrop are 46°35′55.00″N, 82°46′27.30″W. (B) Representative stratigraphic section for lithofacies 6a from Lady Evelyn-Smoothwater Provincial Park. Coordinates for the outcrop are 47°21′48.78″N, 80°31′2.06″W. Legend as in Fig. 3.



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Baie Fine that is highly foliated (Fig. 10F). In outcrop, it is structureless and contains 1–20 cm wide quartzite clasts that are sub- to well-rounded and typically elongated.

Interpretation

Lithofacies 6a is interpreted to have formed by traction deposition in the upper flow regime. Mudstone clasts with preserved undeformed laminae indicate a semilithified state of the sediment at the time of erosion. In addition, mudstone beds preserved in the process of being eroded were observed in thin section, which indicates local sourcing of mud (Garzanti 1991; Schieber et al. 2010). Lithofacies 6a forms the base of fining-upward units that are locally overlain by LF1 and LF7. Lithofacies 4 was found substituting for LF7 in some units. These packages are interpreted as storm deposits (Kreisa 1981; Duke et al. 1991; Cheel and Leckie 1992). Lithofacies 7 and 4 are not always preserved at the top of storm cycles, but where present are typically overlain by LF1. The mudstone beds may represent fair-weather deposits or the tailings of a waning storm. Consecutive storm deposits likely formed through erosion of mudstone cap layers by ensuing storms and incorporation of the clasts into the basal lag layer (LF6a) of a new storm package (Kreisa 1981; Chandler 1988; Duke et al. 1991; Cheel and Leckie 1992). This lithofacies is interpreted to have been deposited in the subtidal to lower shoreface zone. Observation of minor lenticular bedding, possible desiccation cracks, and mudstone drapes indicate deposition within the realm of tidal influence and not in a deep offshore setting. However, rippled sand and mud can be deposited in offshore settings during weak storms (Plint 2010; Daidu 2013), and a number of crack structures are interpreted to be subaqueous synaeresis cracks. The association of LF6a with inferred storm beds may, therefore, be consistent with a shallow shelf environment.

Siliceous nodules are interpreted as replacements of syndepositional evaporites as indicated by the presence of anhydrite inclusions and calcite, dolomite, and ankerite core fillings in thin section, in addition to local up- and downwarping of the over- and underlying host material. The common association of LF6a with nodules suggests that porosity may have played a role in formation of the structures or that some of the nodules have a detrital origin. However, nodules preserved in sandstone or mudstone beds may have formed subaqueously (Chandler 1988).

Lithofacies 6b is interpreted to have formed by traction in the upper flow regime. Storms may have played a role in deposition and remobilized clasts as a storm lag, however, the prevalence of sand in the matrix suggests that little winnowing occurred (cf Clifton 2003). Possible depositional environments and deposits include nearshore/beach, tidal channel, subtidal trough/depression, debris flow, or barrier. All but debris flows are affected by waves, tides, or storm currents, in addition to the potential influence from longshore currents. The small size of the exposure and metamorphic overprinting masking sedimentary structures and lateral associations makes interpretation of LF6b very difficult. A shallow marine setting characterized by strong currents or oscillatory waves, such as the nearshore or a subtidal depression or trough, is tentatively proposed due to the high maturity of the matrix, sub- to well-rounded nature of the clasts, and the stratigraphic association with shallow marine and tidally influenced deposits.

Lithofacies 7: mudstone

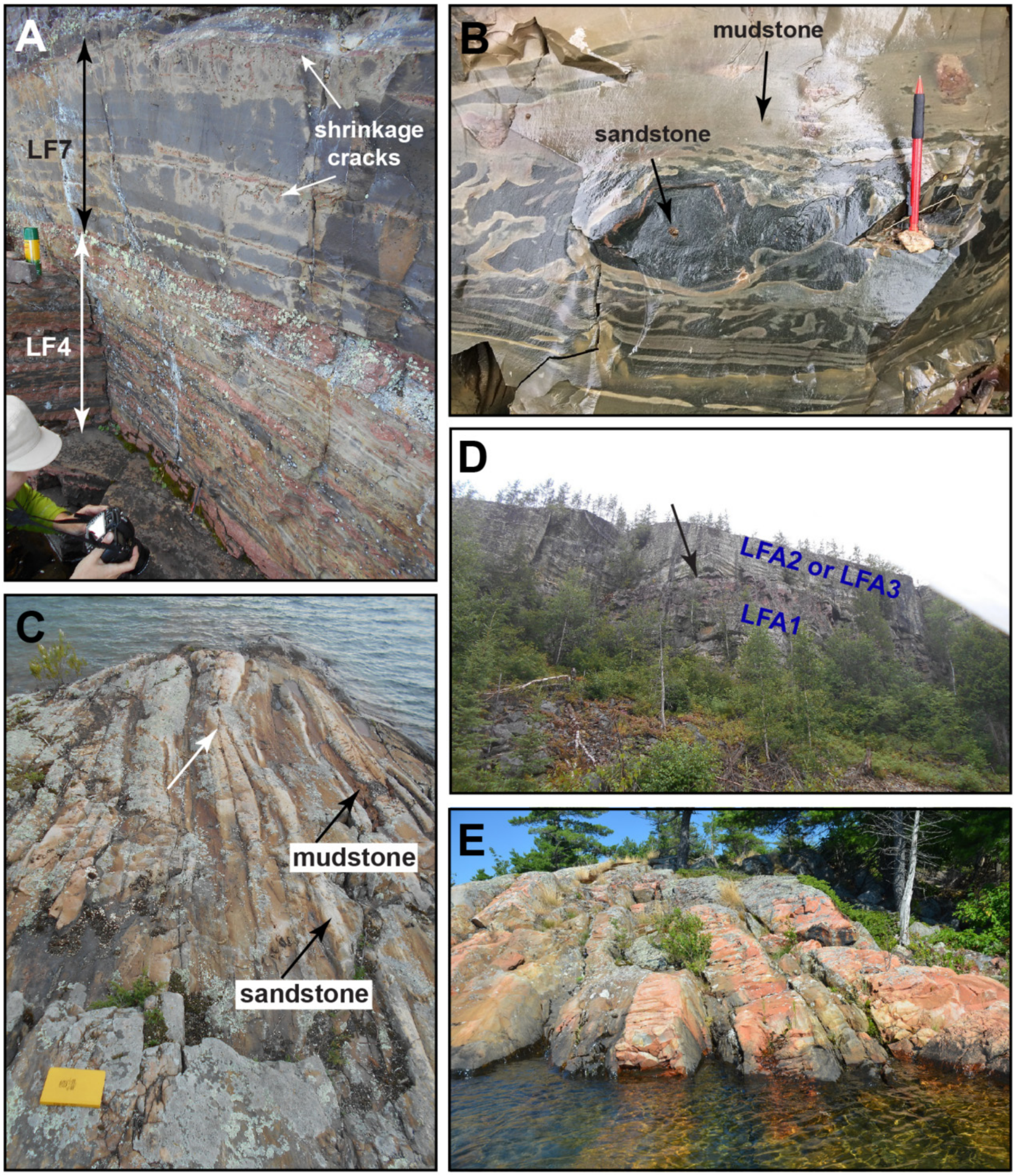
Lithofacies 7 consists of varicoloured, fine- to coarse-grained mudstone (Figs. 11A, 12A, and 12B). Mudstone beds are up to approximately 30 cm thick, and appear massive or finely planar and wavy laminated. Coarse-grained mudstone to very fine-grained sandstone streaks and laminae are common, with local thin, lenticular beds of sandstone and graded beds. Crack structures are also common overall. At Flack Lake, LF7 contains possible synaeresis cracks up to 10 cm long, infilled with fine-grained sandstone, and minor thin lenticular beds of sandstone (Fig. 12A). Thin, normally graded mudstone beds were also observed in the area. In general, LF7 was observed in association with LF1, LF3, LF4, and LF6a throughout the GLF.

In the Bruce Mines and Baie Fine areas and in core, LF7 is interbedded with LF1 beds that are massive to planar laminated with flat to undulatory bases and local rippled surfaces. Several intervals hosting a variety of large- and small-scale SSDS (Fig. 12B), including load casts, pseudonodules and flame structures (see Hill and Corcoran 2018), normal graded beds, and minor intraformational conglomerate are preserved. Lateral variations in thickness are minor. In addition, LF7 in the Bruce Mines area is interbedded with thin to medium bedded, fine- to medium-grained sandstone that is regularly overlain by microbial mats and mat chips. A minor quantity of similar microbial structures was observed in core from the Flack Lake area. Lithofacies 7 also forms a capping mudstone layer on interpreted storm beds across the region. In the Flack Lake area, LF7 can be highly siliceous and resembles chert, however, local sand-sized grains of quartz and muscovite, seen in thin section, indicate a detrital origin for these rocks.

Interpretation

Lithofacies 7 is interpreted to represent suspension settling from standing water and weak bottom currents and (or) tractive flows. The presence of coarse-grained mudstone to very fine-grained sandstone streaks and laminae and the association of LF7 with LF1 and LF6a point to periodic fluctuations in depositional conditions (Pickett 2002). This lithofacies is inferred to have been deposited in the subtidal nearshore to shallow shelf zone. Thick mudstone beds require extended periods of quiet water to form, which can be attained during the tidal slack-water flood phase on mud flats or in intertidal ponds, and under fair-weather conditions in the subtidal to offshore transition zone (Potter et al. 2005; Dalrymple 2010). Preservation of long shrinkage cracks near Flack Lake indicates possible extended periods of subaerial exposure, which would have occurred during the ebb tidal phase. Mud is often the topmost constituent of a storm deposit due to the retention of clay- and silt-sized particles in suspension in high-energy storm currents that get deposited

Fig. 12. Representative photos of lithofacies 7 and bedding types. (A) Top of photo shows medium to thick beds of mudstone overlying LF4 near Flack Lake. Vertical crack fills and thin lenticular pink sandstone define bedding surfaces. (B) Convolute bedding and load structures near Bruce Mines. (C) Possible HCS (white arrow) near the top of the formation in Baie Fine. Top to left. (D) Rapid transition from sandy red beds to fine-grained green mudstone beds in a cliff section (marked by arrow) in Lady Evelyn-Smoothwater Provincial Park. (E) Thick bedded pink sandstone (LF2) near the transition with the overlying Bar River Formation in Baie Fine. Top to right. Pencil is 14.5 cm long and 8 mm wide and field book is 19 cm long.



once fair-weather conditions are re-established (Duke 1985; Prave et al. 1996). Interbedded sandstones with erosive bases point to frequent transitions to bedload transport in currents strong enough to erode muddy layers (Schieber 1999), such as storm and tidal currents. Sandstone with flat or undulatory bedding surfaces may represent episodic storm deposits (Duke 1985); the graded beds, SSDS, and the infrequent shallow water sedimentary structures support this interpretation.

Discussion

Paleoenvironmental interpretation and lithofacies associations

This section presents an interpretation of the main sedimentary processes that controlled the deposition and composition of the GLF, using observations of lithofacies and petrographic analysis. The lithologies and sedimentary structures support deposition in subenvironments developed along an open coast, in mainly siliciclastic, microbe-, tide-, and wave-influenced marginal marine to shallow shelf environments.

The seven lithofacies of the GLF can be arranged into three lithofacies associations: LFA1 (subtidal nearshore), LFA2 (subtidal to shallow shelf), and LFA3 (mixed intertidal flat). Unlike fluvial systems in the Precambrian that experienced episodic discharge and increased rates of runoff due to the absence of vegetation (Long 2004*b*), tidal action was constant during deposition and may account for the prevalence of tidal deposits in the geologic record.

LFA1: subtidal nearshore

The association of very fine- to fine-grained sandstone (LF1), fine- to medium-grained sandstone (LF2), and coarse-grained sandstone (LF5) is interpreted to represent deposition in a nearshore setting, such as in subtidal shoals. This association is present in Baie Fine and in Lady Evelyn-Smoothwater Provincial Park, near the stratigraphic middle and top of the formation (Figs. 2, 3, and 5). Medium to thick bedded, quartz-rich sandstone interbedded with thin- to medium-bedded mudstone characterize this lithofacies association. Recurring sedimentary structures include planar laminae, massive bedding, and planar and trough cross-bedding with minor ripples. Mudstone in LFA1 is preserved in relatively small abundance compared to the other lithofacies associations. Minor clastic dikes and small-scale syn-sedimentary faults were locally observed in association with this lithofacies association.

Planar-laminated and bipolar-opposed trough cross-bedded sandstone stratigraphically overlies interpreted sandy storm beds in Baie Fine (see LFA2), and appears to record a transition in depositional processes from primarily storm-induced oscillatory flows to an increased influence of tidal currents. The absence of rippled bedding planes in the upper portion of the middle LFA3 section in Baie Fine is a result of deposition under higher energy water conditions (Harris and Eriksson 1990). The upward decrease in mudstone may indicate an increase in the frequency of storm events, which remove fine-grained, fair-weather deposits. The trough cross-bedded sandstone of LFA1 has a high maturity, but does not contain truncating sets of cross-bedding, banded sigmoidal foresets, reactivation surfaces, mudstone drapes, lag deposits, or associated inclined heterolithic bedding, which suggests that LFA1 is unlikely to represent deposition in tidal channels (Hamberg 1991; Ehlers and Chan 1999; Dalrymple and Choi 2007). However, at least one bed of fine- to medium-grained sandstone in Baie Fine resembles a channel (Fig. 6C). No clear relationship between grain size and cross-bed set thickness was observed, however, a number of the sandstone beds exhibit marked lateral variability in thickness. Beds have flat to undulatory surfaces and generally exhibit a tabular form, suggesting a possible broadly alternating sequence of storm sheet beds and tidal sand shoals (Goldring and Bridges 1973; Johnson 1977). The lack of wedge-shaped elements containing cross-bedding points to a nonbarrier subenvironment (Kumar and Sanders 1974; Murakoshi and Masuda 1992).

A tidal shelf ridge interpretation may be appropriate for the middle quartz-rich sequence in Baie Fine due to the interpreted under- and overlying offshore storm deposits. In addition, tidal shelf sand ridges are characteristic features of tide-dominated, transgressive shelves, and can form in water as shallow as 30 m (Liu et al. 2007). Approximately 6 km northeast of the middle quartz-rich sequence in Baie Fine (46°2′8.41″N, 81°30′19.69″W) lies a 26 m thick planar-laminated and trough cross-bedded quartz arenite succession interbedded with minor mudstone (located at 46°3′4.46″N, 81°25′48.47″W), and is proposed to be stratigraphically equivalent. The apparent lateral continuity of LFA1 points to a continuous zone of deposition, typified by subtidal deposits and offshore tidal shelf ridges, which can be spaced 1–30 km apart and reach lengths of over 20 km (Posamentier 2002). Overall, LFA1 is thought to represent deposition in the subtidal zone on a storm-influenced continental shelf.

In general, the formational contacts of the GLF are associated with LFA1. Sandstone of LF1 and LF2, with mudstone interbeds, are characteristic of this interval. A transition from planar to ripple cross-laminae, or vice versa, was observed locally at the tops of convex-up and planar surfaced sandstone beds suggesting shallowing water conditions during deposition or a shift from oscillatory to unidirectional flow (cf Aigner and Reineck 1982). The basal contacts of beds are often erosive in these units and many appear hummocky (Fig. 12C). Regular intercalation of mudstone beds with sandstone indicates that flow was intermittent, but the absence of mudstone rip-up clasts indicates that the flows were not significantly erosive (Duke and Prave 1991), or that the muds remained fluid. Variations in stratification also point to fluctuations in flow velocity, from rapid deposition of sand, to slack water deposition of mud. The overall lack of simple wave-influenced structures and high-angle cross-beds suggests deposition in a subtidal shelf environment. Hummocky lower surfaces and ripple cross-lamination may be a result of emplacement by storms.

LFA2: subtidal to shallow shelf

Multiple examples of storm-generated deposits are preserved in the GLF, and specifically in fining-upward intervals of LF6a, LF1, and LF7 or LF4 that are interpreted as representing subtidal to shallow shelf deposits. The mudstone caps suggest waning current or fair-weather deposits. These units are best observed in Lady Evelyn-Smoothwater Provincial Park, Baie Fine, and in core from the Flack Lake area. Tide-related sedimentary structures in these intervals are minor.

Overall tabular, thin- to medium-bedded sandstone and mudstone beds that contain normal grading, planar to wavy laminae, synaeresis cracks, and minor HCS are interpreted as a type of storm deposit. These deposits are best observed in strata at Baie Fine where they are underlain by thin beds and lenses of LF6a, and minor tide-generated deposits. The overlying strata consist of tabular, laminated sandstone with minor mudstone clasts. Small-scale SSDS, including load casts, pseudonodules, and flame structures, were observed throughout the storm beds and indicate local sediment instability.

A second type of storm-influenced, subtidal to shallow shelf deposit consists of stacked interlaminated and interbedded mudstone (LF7) and sandstone (LF1, with minor LF4). Mudstone-rich intervals are characterized by thin- to thick-bedded mudstone with less common very fine-grained sandstone beds. Normal grading and an abundance of SSDS of varying size and type were observed in LFA2. These deposits are best observed in the Bruce Mines and Baie Fine areas and in core from the Flack Lake area. A few medium-grained sandstone beds containing mudstone pebbles, planar laminae, and low-angle cross-bedding were observed adjacent to interpreted storm deposits in Baie Fine. These sands may have been transported offshore during large storm events, or were reworked from older deposits (Sha and De Boer 1991). Episodes of high-energy reworking can occur when tidal currents, which are strongest in the intertidal and subtidal-offshore zones (Hayes 2005), are enhanced by storm waves (Johnson 1977; Aigner and Reineck 1982). In general, changing water depth produces considerable variability in storm-generated sequences (Kreisa 1981).

The abundance and variety of SSDS in LFA2 led Hill and Corcoran (2018) to propose a primary storm or tsunami trigger mechanism for their formation. Thin sandy event beds observed in the Bruce Mines area are interpreted to represent tsunami deposits that were frequently colonized by microbial mats. Density inversions, overpressuring by microbial mats, and seismic events were interpreted as possible secondary trigger mechanisms. Based on available outcrop exposure and core, the SSDS-rich middle interval is preserved across at least half of the Huronian basin, pointing to large-scale, possibly basin-wide trigger mechanisms, such as storms, tsunamis, or earthquakes.

LFA3: mixed intertidal flat

This lithofacies association includes interlaminated to interbedded mudstone and fine-grained sandstone (LF4), alternating with fine-grained sandstone (LF1) and mudstone (LF7), and is interpreted to represent deposition on mixed intertidal flats. Characteristic sedimentary structures of this subenvironment include flaser and lenticular bedding, wave and interference ripples, ripple cross- and planar laminae, bidirectional-opposed ripples separated by mudstone drapes, desiccation cracks, and MISS. Minor small-scale SSDS are developed locally. Tabular, sheet sandstones of this type may have formed as a result of poorly confined drainage on a tidal flat (Donaldson et al. 2002), and small tidal channels have been recognized locally (Fig. 8E). This lithofacies association was observed mainly in the Flack Lake and Lady-Evelyn Smoothwater Provincial Park study areas, which suggests that overall, tides played an important role in sediment deposition, in addition to waves. Sporadic storm events are indicated by graded bedding.

The alternating association of carbonate (LF3) with very fine- to fine-grained sandstone (LF1) and mudstone (LF7) in the Bruce Mines and Flack Lake areas and in Lady Evelyn-Smoothwater Provincial Park is interpreted to represent deposition on intertidal to subtidal flats. Stratiform stromatolites are known to form in low-energy to intertidal settings and small domal stromatolites in subtidal regions of modern tidal flats (Eriksson 1977; Jahnert and Collins 2012). Precambrian stromatolites may also have been in subtidal settings (Gebelein 1976; Pratt 1982; Grotzinger and Knoll 1999; Cantine et al. 2020), as there were no predators to provide grazing pressure. Dongjie et al. (2013) interpreted stratiform and domal stromatolites in the Mesoproterozoic Wumishan Formation, China, to have formed in upper intertidal and lower intertidal areas, respectively. Similarly, Melezhik et al. (1999) interpreted stratiform stromatolites from the Paleoproterozoic Tulomozerskaya Formation, Russian Karelia, to have formed in the upper tidal zone, ponded tidal flat, lagoon, or playa lake. Laterally linked stromatolites become isolated with increasing water turbulence (McIntyre and Fralick 2017), suggesting that the domal stromatolites in LF3 at Smoothwater Lake formed under relatively low-energy conditions, a theory that is supported by the presence of wave ripples and lack of cross-bedding.

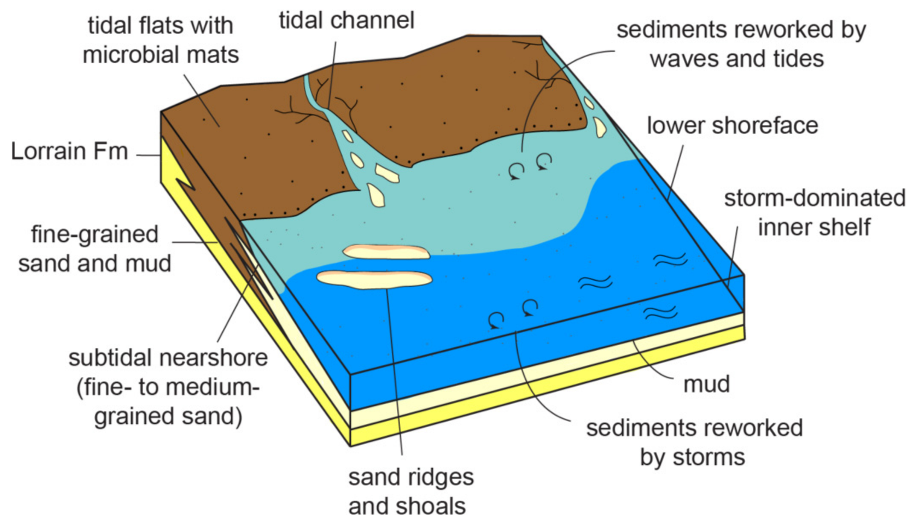
Thin interbeds and interlaminae of sandstone and mudstone in LFA3 represent vertical accretion and shifts in sand and mud placement on mixed intertidal flats (Dalrymple 2010; Daidu 2013). The abundance of tidal signatures in the GLF supports the action of tidal currents throughout the majority of deposition. Although the absence of land plants would have led to increased rates of runoff, the colonization of microbial mats would have enhanced sediment stabilization and led to increased preservation of tidal flat deposits and mud (Eriksson and Simpson 2012). Recognition of MISS and stromatolites in the GLF support the contribution of biofilms to preservation of the succession.

Although the paleoenvironment represented by the upper Lorrain Formation has been disputed, it is generally agreed that a transgression took place (Chandler 1986), which would have resulted in increased accommodation for deposition of the GLF. Upon initiation, the sedimentary processes forming the sandy alluvial and nearshore deposits of the upper Lorrain Formation appear to have changed to tide-dominated processes (Fig. 13). Bimodal-opposed cross stratification is present in both the upper few metres of the underlying Lorrain Formation at Welcome Lake (Long 2004*a*), and overlying Bar River Formation (Rust and Shields 1987; Aranha 2015). The Kona Dolomite of the Marquette Range Supergroup, Michigan, is interpreted to be correlative with the lower GLF (Young 1983; Bekker et al. 2006; Bennett 2006; Vallini et al. 2006), suggesting that a period of overall low sediment influx associated with the onset of transgression may have facilitated carbonate production.

Basin dynamics

The upper Huronian Supergroup is interpreted to have been deposited along a passive margin (Young and Nesbitt 1985; Young et al. 2001; Long 2004*a*, 2009). The characteristics of the GLF support this interpretation, in that it thickens southward towards the proposed paleomargin, does not noticeably change thickness across faults, and contains sedimentary structures indicative of a marginal marine origin (Wood 1973; Chandler 1986, 1988; Hill et al. 2016, 2018). Rifting took place during deposition of the lower Huronian

Fig. 13. Depositional model for the Gordon Lake Formation. Deposition of the lower part of the formation is interpreted to have occurred in the subtidal nearshore to shallow shelf zones along a passive margin. Deposition of the upper part of the formation is interpreted to have occurred in the subtidal nearshore to mixed intertidal flat zones along a passive margin.



Supergroup (Card et al. 1977; Young 1983; Young et al. 2001; Long 2004*a*), and extensional faults could have still been active during deposition of the GLF. Potential evidence of fault movement at the time of deposition includes SSDS, syn-sedimentary faults, and brecciated beds. A primary trigger mechanism of storm or tsunami waves was interpreted for the SSDS due in part to a lack of firm evidence for seismic activity in the associated intervals (Hill and Corcoran 2018). Seismic events, however, cannot be excluded. Clastic dikes and small-scale syn-sedimentary faults may have formed due to local instabilities, or slope failure (Al-Hashim and Corcoran 2021).

The basal, overall fining- and thinning-upward trend in the GLF (Fig. 12D) may signify transgression brought on by regional subsidence of the Huronian passive margin. In general, it is difficult to evaluate the cause of Paleoproterozoic transgressions, and to conclude the relative importance of eustatic over tectonic influence (Eriksson et al. 1998). The top of the formation is characterized by a coarsening- and thickening-upward succession (Fig. 12E), which may be a result of regression or an increase in sediment supply. A combination of sea level rise, subsidence, and microbial mat development may have led to enhanced preservation of strata in the GLF. Bradley et al. (2018) compiled a list of reported pre-vegetation tidal successions and determined that out of 40, 21 contain <2% mudstone and are dominated by quartz-rich sandstone. The muddy nature of the GLF and preservation of lenticular bedding, mudstone drapes, and shrinkage cracks sets it apart from many other Precambrian tide-influenced successions.

Summary of depositional history

The paleoenvironmental model proposed herein is in general agreement with several findings of previous workers, however, the regional approach taken in this study allowed an integrated model to be developed. The vertical association of lithofacies in the GLF supports deposition in the intertidal zone to shallow shelf. Overall, the formation is characterized by tabular bedding, however many basal surfaces are erosive or undulatory in nature, supporting deposition above storm wave base. Both tide and storm processes played a major role in sedimentation during deposition, as indicated by tide- and storm-generated structures throughout much of the formation. An open coast tidal flat environment is envisioned in part due to the relative abundance of sedimentary structures formed by waves or combined flows as opposed to channel-fill deposits, which would be expected in a sheltered tidal flat environment (Dalrymple 2010; Daidu 2013). Coastal barriers are not considered to have been present during deposition of the formation because dominant tidal currents would have disseminated sand offshore (Hayes 2005), and tidal inlet deposits are lacking. The tidal range is estimated to be macrotidal (>4 m) based on (1) the presence of wave-reworked strata in the interpreted mixed intertidal and subtidal zones indicating exposure to open ocean waves at the time of deposition (Hiscott 1982), (2) the lack of barrier deposits, which are commonly found in micro- and mesotidal ranges (Nichols 1989; Shaw et al. 2010), and (3) the closer proximity of the Moon to Earth during the Precambrian, which would have resulted in a larger tidal range (Williams 2000). Similar tidal deposits and associations have been described from the Paleoproterozoic Palms and Pokegama formations, Canada (Ojakangas 1983), early Precambrian Pongola Supergroup, South Africa (Von Brunn and Hobday 1976), Mesoproterozoic Morro do Chapéu Formation, Brazil (de Souza et al. 2019), and Ordovician Graafwater Formation, South Africa (Rust 1977).

Deposition of the GLF is interpreted to have been initiated in response to rising sea levels. This is supported by the gradual shift from an alluvial or nearshore environment of the upper Lorrain Formation to an inferred open coast tidal flat setting of the GLF, where carbonate deposition took place locally, nodular evaporites formed, and alternations of mud and sand were deposited. Increasing sea level and storm activity would have led to the accumulation of stacked fining-upward storm units, characterized by a basal layer of intraformational granular to pebbly sandstone or conglomerate, overlain by fine-grained sandstone and locally capped by mudstone. Fluctuations in sea level would have resulted in deposition of sandy inter- to subtidal deposits overlain by sandy storm beds. A quartz-rich sandstone interval preserved in Baie Fine and Killarney Provincial Park indicates that accommodation fluctuated and experienced at least one reversal, which is considered normal for a transgressive coast (Kraft 1978). Thin, tabular, scoured mudstone and sandstone beds interpreted as subtidal to shallow shelf deposits overlie the quartz-rich unit and indicate a return to deeper marine conditions. A regression, that decreased the available accommodation space, or an increase in sediment supply (coastal progradation) is indicated by an upward-coarsening and -thickening trend, that extends to the top of the GLF. On a small scale, it is possible that some variations in bed thickness may be due to spring and neap tides, or storm influence on sedimentation (Allen 1985; Li et al. 2000; Wang and Cheng 2017). Waning tidal currents can also cause a significant amount of fine-grained material to be deposited from suspension (Dalrymple et al. 1991).

Conclusion

Sedimentary structures formed by tides and storms are common in the GLF, Huronian Supergroup. The combination and distribution of lithologies and physical and biogenic sedimentary structures suggests deposition on a tide- and storm-influenced continental shelf. Seven lithofacies were recognized that comprise three lithofacies associations: subtidal nearshore (LFA1), subtidal to shallow shelf (LFA2), and mixed intertidal flat (LFA3). The overlying Bar River Formation may represent uninterrupted deposition and form the top of a shoaling cycle. The contacts between the GLF and the underlying Lorrain and overlying Bar River formations are typically obscured by gabbro sills. Further work is needed to elucidate the depositional histories of the under- and overlying formations.

The lithofacies analysis and depositional model herein proposed for the GLF provides a valuable addition to the number of mudstone-rich tidal sequences documented in the sedimentary record, particularly those that accumulated in the Precambrian in the absence of complex life. Recognizing tidal-shallow marine shelf deposits in paleoenvironmental interpretations contributes to a better understanding of sedimentation on continental margins and shelf dynamics, tidal influence on coastal deposits and, in the case of this study, the influence of contemporaneous tectonic activity on sediment deposition and preservation on ancient passive margins.

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Data availability

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Author information

Author ORCIDs

Carolyn M. Hill-Svehla https://orcid.org/0000-0002-9544-0732

Author notes

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Author contributions

Conceptualization: CH-S, PLC
Data curation: CH-S
Formal analysis: CH-S, PLC
Funding acquisition: CH-S, PLC
Investigation: CH-S
Methodology: CH-S, PLC
Project administration: CH-S, PLC
Resources: PLC
Supervision: PLC
Validation: PLC
Writing – original draft: CH-S
Writing – review & editing: CH-S, PLC

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Supplementary material

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