Microbe- and metazoan-dominated, tidally influenced environments of the Lower Cambrian Hawke Bay Formation, western Newfoundland

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Abstract

Field and laboratory studies of the Hawke Bay Formation, western Newfoundland reveal that trace fossil diversity, ichnofabric, bioturbation intensity and microbial matground distribution are controlled by depositional environment and relative sea level. A number of distinct depositional environments are recognized and can be placed within a sequence stratigraphic framework, consisting of 2-8 m thick, shallowing-upward parasequences. Palaeoenvironments include lower to upper shoreface sand sheets and subtidal bars, tidal inlet channels, tidal flats and intertidal drainage creeks. Lower and mid-shoreface sandstones contain the highest recorded bioturbation intensities, often associated with concentrations of glauconite and phosphate at flooding surfaces. Vertical trace fossils (*Diplocraterion*, *Arenicolites* and *Skolithos*) form characteristic Lower Palaeozoic "pipe rock" ichnofabrics in lower-upper shoreface environments, often alongside other deposit feeding and grazing trace fossils (e.g. *Cruziana* and *Teichichnus*). At higher stratigraphic positions within parasequences, in mid-upper shoreface environments the bioturbation intensities are lower and ichnofabrics are less complex but dominated by vertical ichnotaxa (i.e. *Diplocraterion*). Parasequences are typically capped by thick (1-3 m) intervals of planar laminated, occasionally ripple-topped, unbioturbated sandstones that are interpreted as tidal flats. The presence of an array of microbially induced sedimentary structures indicates that the tidal flats appear to have been microbially bound. The tidal flats are incised by intertidal drainage creeks. The microbially bound tidal flats appear to represent a Precambrian-style lithofacies that remains in certain environments in the Lower Palaeozoic, but during the Phanerozoic becomes confined to settings where bioturbation is suppressed due to physical or chemical stresses.

1. Introduction

Shallow marine, quartz-rich sandstones are common in Lower Palaeozoic strata around the world. Some units have long been the focus of geological research (e.g. the famous "pipe rock" of northwest Scotland; Peach et al., 1907; McIlroy and Garton, 2010), while others constitute important hydrocarbon reservoirs (e.g. North Africa; Crossley and McDougall, 1998). The c. 150 m thick Lower Cambrian (*Bonnia-Olenellus* Zone) Hawke Bay Formation consists of white, beige or pink, quartz-rich, mature sandstones that are exposed on the coast and in road cuts in western Newfoundland from the Port au Port Peninsula northwards (Fig. 1). The sandstones are highly bioturbated and are, in places, interbedded with siltstones and mudstones (see Knight, 1991).

Despite being identified as a possible reservoir unit in western Newfoundland (Cooper et al., 2001), the Hawke Bay Formation has received limited attention from geologists and explorationists alike. Knight (1991) documented the sedimentology and stratigraphy of the Hawke Bay Formation, described a number of lithofacies, and provided constraints on the depositional environments. The formation was considered to have been deposited on a shallow, tidally influenced shelf and identified depositional environments include sub-wavebase settings, subtidal and intertidal bars, tidal channels, deltas and intertidal sand flats (Knight, 1991). Parasequence development was also recognized in the form of prograding shoreface successions (Knight, 1991).

What have not been recognized until now, however, are the full diversity of the trace fossil assemblage and the abundance of sedimentary structures that indicate the presence of ancient microbial mats. Fieldwork on the Port au Port and Northern Peninsulas has indentified a suite of sedimentary structures that are comparable with microbially induced sedimentary structures (MISS; *sensu* Noffke et al., 2001). The Lower Cambrian Hawke Bay Formation was deposited shortly following the emergence of widespread infaunal bioturbation (Seilacher and Pflüger, 1994; McIlroy and Logan, 1999; Bottjer et al., 2000). This succession therefore provides an ideal case study to examine the emergence of infaunal bioturbation, and the demise of microbial mats across the Precambrian-Cambrian transition (Seilacher and Pflüger, 1994; Seilacher, 1999; Bottjer et al., 2000; Mata and Bottjer, 2009).

As far as we are aware, the Hawke Bay Formation has yet to be directly targeted in exploratory drilling programs. The scarcity of publically available and published data on this unit is surprising, and detailed stratigraphic and sedimentological study is overdue. Here we provide the results of an investigation into the sedimentary facies, sequence stratigraphy and ichnology of the Hawke Bay Formation on the Port au Port Peninsula, and expect that this will help stimulate further research into this potential reservoir unit.

2. Geological Setting

2.1. Tectonic Framework

The Hawke Bay Formation forms part of the Labrador Group, which outcrops in the Humber Zone of western Newfoundland - part of the northeast Canadian Appalachians (Williams, 1979). The Humber Zone has been divided into a number of tectono-stratigraphic megasequences, of which the Hawke Bay Formation comprises part of the second megasequence – Cambro-Ordovician sediments of the Iapetus passive margin – which conformably overlie Ediacaran to earliest Cambrian siliciclastic rift sediments (Bradore Formation) in western Newfoundland (see Cooper et al., 2001).

2.2. Stratigraphic Framework

The Hawke Bay Formation outcrops extensively on the Northern Peninsula of Newfoundland, where it is up to 150 m thick (Fig. 1) and where the contact of the Hawke Bay with the underlying Forteau Formation can be observed. On the Port au Port Peninsular, the lowest two (Bradore and Forteau) formations of the Labrador Group occur only in the subsurface (Cooper et al., 2001) where they are known from the numerous well penetrations and cores from this potentially significant hydrocarbon province (Cooper et al., 2001). Subsurface data shows that the Hawke Bay Formation in the Port au Port area is over 200 m thick, the upper parts of which is exposed in the core of a broad, gently dipping anticline along the southern shore of the Port au Port peninsula. The contact between the Hawke Bay Formation and the overlying carbonate-rich March Point Formation (Port au Port Group) is well exposed in coastal outcrops which provide excellent localities to study the depositional environments, sedimentary structures, sequence stratigraphic relationships and ichnology.

3. Facies Associations and Stratigraphic Framework

Detailed sedimentological and ichnological logging of 5 stratigraphic sections at Grand Jardin (GJ1, GJ2) and Red Brook (RB1, RB2, RB3) on the Port au Port peninsular enabled construction of a sequence stratigraphic model, in which 2-8 m thick parasequences form components of transgressive and highstand systems tracts (Fig. 2-3). Both coarsening upward and fining upward parasequences are recognized, with flooding surfaces marked by abundances of phosphate, glauconite and high bioturbation intensities. Depositional environments range from sub-wavebase lower shoreface settings to shallow subtital-intertidal flats (Fig. 4). There is little overall variation in grainsize, with the studied sections dominated by fine-medium-grained sandstone. Siltstone and mudstone content is low throughout the succession. Carbonate has been observed in rare concretions and in one oncolitic horizon, which is interpreted here as a possible sequence boundary.

3.1. Facies Association 1 - Sand Sheets and Subtidal Bars (Fig. 5A, 5C)

Fine- to coarse-grained, mature, quartz-rich sandstones consisting of sharp-based, fining upwards beds 5-50 cm in thickness, which form coarsening-upwards packages 1-3 m thick. Sedimentary structures include massive (burrow homogenized), planar, wavy, hummocky cross-stratified, or planar or trough cross-stratified beds with ripple cross-sets up to 10 cm in thickness (Fig. 5A, D). Bed geometries appear sheet-like and beds are laterally continuous over 10s to 100s metres. Upward coarsening packages are interpreted as subtidal, submarine sand bars. Bioturbation intensities range from low to complete bioturbation, the latter resulting in the destruction of all primary sedimentary structures (BI 0-6). Rare phosphatic brachiopods occur in this facies. This facies association is interpreted as sand sheets and bars deposited in settings above and below fair-weather wavebase.

3.2. Facies Association 2 – Glauconite- and phosphate-rich intervals (Fig. 5B, 5D)

This facies is characterized by centimetre-scale alternations of glauconite-rich, fine-grained sandstone and highly bioturbated siltstone. Other features include planar to wavy-bedded (2-10 cm), fine-grained sandstone to siltstone deposition, and by increased abundances of authigenic glauconite and phosphate. Sandy starved ripples and thinly bedded (2 cm) ripple cross-laminated fine-grained sandstones are also components of this facies association. Beds are typically less than 10 cm in thickness. This facies is interpreted as a deposit formed in a sediment starved palaeoenvironment in lower-mid shoreface settings. Bioturbation intensity is variable but some beds can be highly bioturbated (BI 1-5). This lithofacies is associated with the most diverse trace fossil assemblages, including traces produced by what are conventionally interpreted as deposit (e.g. *Teichichnus*) and suspension feeding (e.g. *Skolithos*) organisms. Most commonly this facies association is found in <1 m thick intervals, however, thicker (>1 m) packages of this facies have been used to indicate the presence of a maximum flooding surface somewhere within a flooding zone (e.g. GJ2).

3.3. Facies Association 3 - Tidal Channels and tidal deltas (Fig. 6A-C)

Conspicuous, 0.5-1 m thick, ripple cross-laminated or herringbone cross-stratified, fine- to medium-grained sandstone are interpreted as tidal channel-fill deposits (Fig. 6A-C). These packages typically coarsen upwards into massive to planar stratified sandstones (1-2 m thick), interpreted here as tidal deltas. Reactivation surfaces occur within ripple cross stratified tidal channel facies (Fig. 6B), indicating reworking or the seafloor by tidal and/or wave processes. Tidal inlet channels are sparsely bioturbated (BI 0-3) by ichnofaunas of *Diplocraterion* ispp., with rare *Skolithos* and *Arenicolites*. The overall ichnofabric is dominated by vertical trace fossils, perhaps as a response to suspension feeding in tidal channels. The tidal deltas consist of coarsening upward packages, lacking rippled cross stratification and are more sparsely bioturbated, perhaps due to the difficulties of colonising an unstable or highly mobile substrate (BI 0-1).

3.4.   Facies Association 4 - Tidal flats and creeks (Fig. 7)

Thick (1-3 m) packages of thinly planar or wrinkly stratified (<1 cm), fine- to medium-grained sandstones represent ancient, siliciclastic tidal flats (Fig. 7A-B). Rare thin beds of ripple cross-stratified sandstone occur within the planar stratified facies (Fig. 7D). The facies consists of distinctive alternations of more- and less-well cemented sandstones. In some cases the laminae are seen to be deflected upwards into small domal structures. Short wavelength (<5 cm), straight-crested ripples, and flat topped wind ripples may be present in this facies, and bedding planes are commonly marked by a variety of wrinkle structures, interpreted here as microbially induced sedimentary structures (MISS, *sensu* Noffke et al., 2001). No direct evidence for subaerial exposure has been observed, and these units are interpreted as predominantly shallow subtidal, microbially bound sand flats. In places, the sand flats are incised by scours (< 10 m across), which are filled with ripple cross-stratified and planar laminated sandstones (Fig. 7C). These scours are interpreted as intertidal-supratidal creeks. Neither the creeks nor tidal flats are associated with infaunal or epifaunal bioturbation (BI 0) and no ichnofabrics are visible.

3.5.   Facies Association 5 – Dolomitized oncolitic grainstone (Fig. 10E)

At one horizon at Grand Jardin two separate beds, bearing spherical, nodular carbonate clasts are observed. The clast-bearing beds are up to 10 cm thick and are separated by 2 cm of siltstone. The clasts themselves are up to 3 cm in diameter and field and laboratory investigation shows that they have a concentric internal structure. Petrographic analysis reveals that these large clasts are composed of microcrystalline dolomite rhombs, interpreted here as secondary dolomite after primary calcite or aragonite. The concentric internal structure and carbonate composition leads us to interpret these clasts as dolomitised oncolites, which formed in high energy depositional environments, presumably in a nearshore environment. The large grain size of these clasts compared with the average grain size of the surrounding strata, coupled with the unusual occurrence of carbonate among beds containing abundant glauconite leads us to suggest that these beds represent decrease in relative sea level, and possibly a sequence boundary. No trace fossils have been observed in association with this facies association.

4. Ichnology

A diverse assemblage of trace fossils has been recorded from the Hawke Bay Formation, including both vertically penetrative ichnofabric-forming ichnotaxa, and predominantly surface or shallow tier ichnotaxa. The most commonly observed trace fossils, their associated ichnofabrics and palaeoenvironmental implications are described below. Some very rare ichnotaxa are not described here, although are still recorded on logs:

Arenicolites isp. – Unlined U (or occasionally J) shaped burrows occur commonly in massive, planar, or ripple cross-laminated sandstone beds (FA 1-3; Fig. 8B-C). These trace fossils occur as monospecific assemblages, and also occur alongside other vertical trace fossils including *Skolithos* and *Diplocraterion*, particularly at flooding surfaces where they appear to be particularly abundant (BI 5-6). Typically the causative burrows are 2 mm in diameter, with the limbs of the "U" 1-2 cm apart and with a maximum vertical penetration of 6 cm. *Arenicolites* is typically interpreted as the burrow of a deposit-feeding, worm-like organism.

Bergaueria sucta – Shallow, bulb like trace fossils, circular in cross section (up to 2 cm diameter) with a convex base and a maximum vertical penetration of 1-2 cm (Fig. 9B). No radial structures or external ornament are visible and the traces occur within grey-green siltstone and are filled by glauconite-rich, fine-grained sandstone (FA 2). The trace fossils are rare in the Hawke Bay Formation and occur in only one studied section (JG2), and are conventionally interpreted as the basal impression of an actinian (cnidarian) organism (e.g. Seilacher, 2007).

Cruziana isp. – Bilobate, elongate trace fossils preserved in positive hypichnial relief on sandstone soles. *Cruziana* from the Hawke Bay Formation may be up to 8 cm in width, forming irregularly meandering trails up to 1 m long. *Cruziana* is interpreted as the locomotion traces of trilobites, although no trilobites have been recorded from the Hawke Bay on the Port au Port (cf. Knight, 1991). Paired limb scratch marks are preserved either wide of a median furrow. Examples can be seen which appear to consist of a combination of locomotion (cruzianaeform) and stationary (rusophyciform) behaviour. Due to the poor preservation of the limb scratch markings and the relatively small number of specimens it has not been possible to accurately designate an ichnospecies.

Diplocraterion – This well known and iconic trace fossil has been defined as vertically oriented, U-shaped trace fossils, possessing a single set of spreiten between the limbs of the U (see Seilacher, 2007; Schlirf, 2011; Fig. 6D. 8D, F). In the Hawke Bay Formation, it is possible to identify two morphotypes of U-shaped, spreiten-bearing trace fossils, which we assign here to two ichnospecies. *Diplocraterion* is typically interpreted as the dwelling and feeding trace of a vermiform organism.

Diplocraterion habichii – This ichnospecies is identified as short (<10 cm) but wide (up to 10 cm) U-shapes, with widely spaced limbs relative to the depth of the burrow. Causative burrow diameters are estimated to have been <5 mm. Only protrusive forms have been identified. This ichnospecies can occur in high abundances, producing high bioturbation intensities, associated with *Arenicolites*, *Skolithos* and *D*. *parallelum. D*. *habichii* is abundant across a variety of marine depositional environments (FA 1-3) but is absent from tidal flats and tends to form monospecific ichnofabrics in tidal inlet channel sandstones (FA 3). It may be abundant at flooding surfaces (FA 1) where due to the high bioturbation intensity, individual traces are difficult to identify without polished slabs or large thin slices (see Garton and McIlroy, 2006). The bases of *D. habichii* are commonly observed covering bedding planes at flooding surfaces.

Diplocraterion parallelum – In addition to the short, squat *D. habichii*, a long (>10 cm) form of *Diplocraterion* with narrowly spaced limbs (c. 2 cm) can also be recognized. This form is here referred to *D. parallelum* and is less abundant in tidal channels (FA 3) but can occur in high abundances at flooding surfaces, and alongside *Skolithos*, *Arenicolites* and *D. habichii* in lower shoreface sheet sandstones (FA 1). The aspect ratio of this ichnospecies, and its long, parallel limbs clearly distinguish it from *D. habichii*.

Gordia marina – Small (2-3 mm diameter), irregularly meandering burrows, with characteristic overlapping loops preserved on the top surfaces of bedding planes. *G. marina* occurs rarely in lower to mid shoreface environments (FA 1-2) in planar laminated or massive siltstones and fine-grained sandstones.

Gyrolithes – Helically coiled trace fossils, with a maximum vertical penetration of 5 cm and an original burrow diameter of 3-4 mm. The burrows are unlined and the fill differs from the host sediment. *Gyrolithes* has been observed in only one studied section in the Hawke Bay Formation in glauconite-rich fine-grained sandstones and siltstones (FA 2). In post-Palaeozoic sediments *Gyrolithes* is commonly interpreted as an arthropod dwelling burrow, but in these Early Cambrian strata it is more likely to represent the feeding trace of a vermiform organism.

Intrites isp. – Small, circular to sub-circular, donut-shaped markings preserved in positive epirelief on siltstone bedding planes. *Intrites* consists of an external raised rim with a central crater-like depression. *Intrites* occurs rarely on the top surfaces of siltstone and mudstone bedding planes in the JG2 section, associated with glauconite and phosphate accumulations and high ichnodiversity assemblages of FA 2. The biological affinities of *Intrites* are currently unknown, although like the co-occurring ichnotaxon *Bergaueria* it may represent the base of a small cnidarian-grade organism.

Monocraterion isp. – Vertically oriented, unlined burrows up to 6 cm in depth. The burrows are broadly conical, and with a narrow base (c. 0.5 cm) and a flaring top (c. 2 cm). On bedding planes these burrows appear to have a concentric fill. *Monocraterion* occurs as a rare component of diverse assemblages in FA 2. It is conventionally interpreted as the burrow of a suspension feeding organism, although the affinities remain unproven.

Monomorphichnus isp. – A single set of parallel scratch marks on mudstone or siltstone bedding planes are here described as *Monomorphichnus*. The scratch marks run for up to 5 cm across the substrate before tapering to a point. Conventionally interpreted as the scratch marks produced by dragging arthropod limbs across the substrate, their preservation requires sufficient cohesiveness of the substrate.

Plagiogmus isp. – At one horizon within a microbially mat-bound, lower shoreface sandstone (FA 1), with synaeresis cracks and glauconite), broad (2 cm diameter), unlined, horizontal grazing or locomotion traces have been identified (Fig. 9E). These burrows appear to have a transversely ridged base, and each burrow has a pronounced rounded termination. The traces are assigned here to

Plagiogmus, which may represent the floor of a backfilled shallow grazing trail of a "snorkel-bearing" mollusc or annelid (McIlroy and Heys, 1997; Seilacher, 2007)

Planolites isp. – Simple, unbranched, unlined horizontal to sub-horizontal, shallow (<5 cm) tier trace fossils are common in the Hawke Bay Formation and are described as *Planolites* isp. (Fig. 9G). The traces may be up to 5 mm in diameter and have a maximum tiering depth of 5 cm. The fill of the trace fossils differs from the surrounding sediment, and in the horizontal plane the traces are straight to meandering. *Planolites* is particularly abundant in sub-wavebase sand sheets (FA 1-2), often alongside other shallow infaunal ichnotaxa including *Treptichnus*.

Polykladichnus isp. – An array of unusual branched, vertical to sub-vertical and oblique trace fossils are referred to as *Polykladichnus* and occur frequently in bioturbated beds of the Hawke Bay Formation (Fig. 9F). Y-shaped branching is a distinctive characteristic of these small (1-2 mm diameter) traces, which occur at the top 10 cm of fine- to medium-grained sandstone beds, often alongside *Arenicolites* and *Skolithos*. The fill of the burrows is the same as the sediment matrix. Trace fossils resembling *Polykladichnus* have been produced in the laboratory by burrowing nereidid annelids (e.g. Herringshaw et al., 2010).

Rusophycus isp. – This trace fossil is recognized as bilobate, oval shaped trace fossils (short axis 1-6 cm) preserved in positive hypichnial relief on the soles of fine-grained sandstones (Fig. 9C-D). Symmetrical scratch marks are present either side of a central depression, and an outer border is sometimes visible. *Rusophycus* is interpreted as the shallow resting depression of a trilobite, and the limb scratch marks reflect this. As mentioned above, it is possible to identify forms that are gradational between cruzianaeform and rusophyciform.

Skolithos isp. – Simple, unbranched, unlined vertical tube-shaped trace fossils are common throughout the Hawke Bay Formation, and represent one of the most abundant trace fossils in all depositional environments (FA 1-4; Fig. 8A, E). These simple burrows range in diameter (1-5 mm) and vertical depth (2-10 cm) but are all referred to as *Skolithos*. The burrows are characterized by an almost constant thickness along the length of the burrow, a tapered apex and an originally circular cross section. *Skolithos* is a common component of many Lower Palaeozoic siliciclastic systems (e.g. Droser, 1991; Garton and McIlroy, 2006; Druschke et al., 2009) but may be significant in terms of its palaeoecological implications. *Skolithos* is particularly abundant at flooding surfaces in lower-mid shoreface sand sheets (FA 1) where it forms high bioturbation intensity (BI 6) ichnofabrics, in which no primary sedimentary structures can be observed. Bioturbation intensities can be so high that even trace fossils can be difficult to observe without the use of large thin slices and thin sections (see McIlroy and Garton, 2004). *Skolithos* is a common component of ichnofabrics dominated by vertical structures including *Diplocraterion* and *Arenicolites* and can also occur as more sparse ichnofabrics (BI 1-2) where short (2-3 cm), narrow (3 mm) forms occur regularly spaced at the top of ripple cross-laminated sandstones in mid shoreface settings. It is also a conspicuous component of ichnofabrics in core from the I-55 well from the Port au Port peninsula where it is highly abundant at flooding surfaces and parasequence boundaries.

Teichichnus isp. – Stacked sets of gutter-shaped, concave-up spreiten can be observed in vertical cross-sections of fine-medium grained sandstones. These trace fossils are interpreted as the repeated vertical repositioning of the burrow over time, each spreiten reflective of previous position of the bottom of the burrow (i.e. protrusive). The burrow diameter may be up to 1 cm and the maximum depth of tiering observed is 10 cm. The presence of *Teichichnus* is interpreted as an indication of intensive deposit feeding activity in lower to mid-shoreface environments.

Treptichnus isp. – In a number of horizons at multiple localities it is possible to see the small (2-3 mm diameter), uniserially branched, upward probing, shallow (<5 cm) tier trace fossils known as *Treptichnus* (Fig. 9A). The contrast between the sediment fill and the host sediment, indicates that this was likely an open burrow system that produced regular upward probes to the sediment surface. *Treptichnus* is locally abundant in lower shoreface sandstones of FA 1 and in glauconite-rich fine-grained sandstones and siltstones of FA 2, but is absent from other depositional environments.

5. **Microbially Induced Sedimentary Structures**

Polygonal cracks (cf. Rhysonetron): Reticulate networks of crack-like structures occur on the lower surfaces of fine- to medium-grained, planar stratified or ripple cross-stratified sandstones (Fig. 10A). In some cases a single generation of cracks is present, while in others multiple (up to 3) generations of different sized, intersecting and cross-cutting cracks are present. Cracks range from 0.5-3 cm in width, and polygons range from 3-15 cm in diameter. The subaqueous depositional environment, lack of mudstone and irregular crack margins clearly distinguish these structures from subaerial desiccation cracks. The cracks are here interpreted as sedimentary structures produced during the tearing, disruption or destruction of benthic microbial mats (see Schieber et al., 2007; Noffke, 2010). Similar reticulate structures were once described as trace fossils (e.g. *Rhysonetron*) but have since been described by terms including "mat destruction features" (Schieber et al., 2007), "polygonal petee ridges" (Eriksson et al., 2007) and "polygonal oscillation cracks" (Cuadrado et al., 2011).

Wrinkle micro- and macrostructures: Wrinkle structures (cf. Noffke, 2010) are commonly preserved on bedding planes within the Hawke Bay Formation and are here interpreted as examples of microbially induced sedimentary structures (MISS; *sensu* Noffke et al., 2001; Fig. 10B). These wrinkle structures are closely comparable with wrinkle structures known from modern microbial mats, occur at the top of parasequences in what are interpreted as shallow subtidal to intertidal flats, which contain distinctive planar to crinkly stratification in vertical cross-section. These same sediments contain thin, organic-rich crinkly laminae when viewed in petrographic thin section. As such we are confident in the interpretation of these sedimentary wrinkle structures as primarily microbial in origin (see Noffke, 2009).

Wrinkle structures occur on bedding planes within the thick packages of planar stratified fine-grained sandstone that are interpreted here as microbially bound tidal flats (Fig. 10C; see Drushcke et al., 2007). In vertical section these strata consist of regular alternations of well-cemented, and less-cemented sandstone. These laminae are planar or slightly crinkly, and occasionally show small (cm-scale) upward deflections or domes within the laminae. On a broader scale we have recognized broad (<1 m), low amplitude domal structures within these packages, which appear to be microbially related accumulations (Fig. 10D). These siliciclastic stromatolite-like features presumably result from the trapping and binding effects of benthic microbial matgrounds, and their associated sticky extracellular polymeric substances (see Grotzinger, 1999, Druschke et al., 2007).

Intrastratal shrinkage (cf. Synaeresis) cracks: At a number of horizons in the Hawke Bay Formation it is possible to observe straight to slightly sinuous, spindle-shaped, doubly tapering *en ehelon* cracks within siltstones (Fig. 10F). The cracks are typically compressed when viewed in vertical cross section and their morphology is comparable with the suite of sedimentary structures known as synaeresis cracks (see Pratt, 1998), and their subaqueous depositional environments and lack of polygonality distinguish them from desiccation cracks. Recent work has highlighted the role of microbial binding in the generation of cracks in fine-grained sediments (Harazim et al., in press). We there interpret these cracks (here termed intrastratal shrinkage cracks) as a direct consequence of microbial binding of the upper layers of the sediment during subsequent sediment loading and burial (see Harazim et al., in press).

Oncolites: Dolomitized oncolites are present in a single horizon within the Hawke Bay Formation, where they indicate a possible sequence boundary (Fig. 10E). Despite replacement by microcrystalline dolomite rhombs, it is possible to see the original concentric laminae of the individual oncolite, which is interpreted to have been produced by the trapping, binding and cementation effects of microbes (probably cyanobacteria).

6. Discussion

The Hawke Bay Formation provides an excellent case study to examine the interactions between microbially dominated processes (mat building), physical sedimentary processes and the emergence of infaunal ecosystems at the start of the Phanerozoic. In the shallowest depositional environments (tidal flats), it is clear that microbial processes still dominate, to the exclusion of all burrowing or grazing metazoans. In deeper water environments of the lower-upper shoreface, metazoan communities successfully colonized the sandy, mud-poor substrates of this shallow marine, wave and tide-dominated system. Only rarely is it possible to observe the co-occurrence of microbial mats and

metazoans in the same depositional environments, a good example being *Plagiogmus* within wrinkled and cracked horizons.

There is a clear and predictable relationship between relative sea level, depositional environment, and recorded bioturbation intensity and diversity. The deepest water deposits - sheet-like, lower shoreface sandstones of FA 1 - are typically associated with the highest bioturbation intensities and greatest diversity of trace fossils. At higher stratigraphic positions within parasequences, lower diversity and bioturbation intensities are recorded, and microbial processes appear to dominate. We interpret this in terms of the key ecological requirements of the benthic organisms that produced these trace fossil, i.e. source of food, suitable chemical conditions, stable substrate, low rate of deposition. In lower shoreface environments, the environment was likely to have been relatively stable for long periods, with episodic, rare disruptions due to deposition from large storm or wave events. Chemical conditions are likely to have been suitable in an open marine location and there is likely to be less dilution of organic matter by siliciclastic material, so food availability is predicted to have made this a suitable environment for a wide variety of grazers, deposit feeders and suspension feeders. The trace fossil assemblages of the tidal channels are dominated by vertical burrows of possible suspension feeders (*Diplocraterion*, *Skolithos*, *Arenicolites*), which may situated themselves in tidally influenced settings to benefit from the supply of fine-grained organic material in tidal currents. The ability to shift the burrow vertically through the sediment (e.g. *Diplocraterion*) may have been advantageous in colonising this higher energy environment with relatively mobile substrates.

The unbioturbated planar parallel stratified, microbially bound tidal flats are a relatively unusual and distinctive lithofacies that are not known from most normal marine Phanerozoic successions. In Precambrian shallow marine environments microbially bound facies occur frequently in the geological record (e.g. Hagadorn and Bottjer, 1997; Gehling, 1999; Gehling and Droser, 2009) but in the Phanerozoic, such facies appear restricted to environments where metazoan activity is suppressed by physical or chemical conditions (Druschke et al., 2007). This provides two possible scenarios; 1) that the shallow marine environments of the Hawke Bay Formation were subject to physical or chemical stress; or 2) that microbially influenced environments were more common in Lower Palaeozoic settings, than they appear to be in the later Phanerozoic. Without independent evidence for physical or chemical stress we are unable to eliminate the former hypothesis, but comparable work from other Lower Palaeozoic shallow marine succession suggests that such microbially dominated environments represent Precambrian relicts that remain until the advent of more pervasive, deeper tier bioturbation in the Early Ordovician (e.g. McIlroy and Logan, 1999; Bailey et al., 2006).

7. Conclusion

Depositional environments ranging from the Lower shoreface to intertidal settings have been identified from numerous studied sections of the Hawke Bay Formation on the Port au Port peninsula. These sections all follow a predictable stratigraphic trends with parasequences ranging from lower-mid shoreface to shallow-intertidal zone tidal flats. Unusual depositional environments include microbially dominated tidal flats. Trace fossil assemblages and bioturbation intensity are strongly controlled by the depositional environment and sequence stratigraphic position. The most diverse and abundant trace fossil assemblages are associated with the bases of parasequences, alongside authigenic glauconite and phosphate. Tidal channels and deltas contain a sparse ichnological assemblage, while traces are absent from the shallowest, microbially dominated settings. The dominance of microbial mats in shallow marine environment appears to be a phenomenon that is characteristic of the Lower Palaeozoic, and represents a relic from Precambrian times.
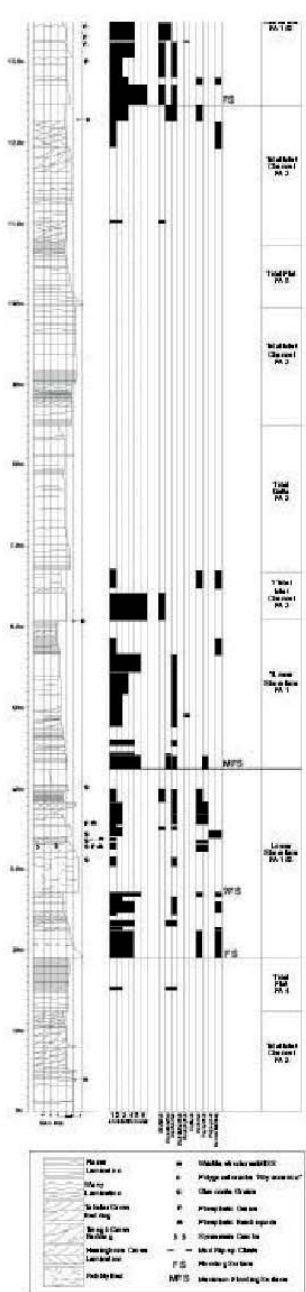
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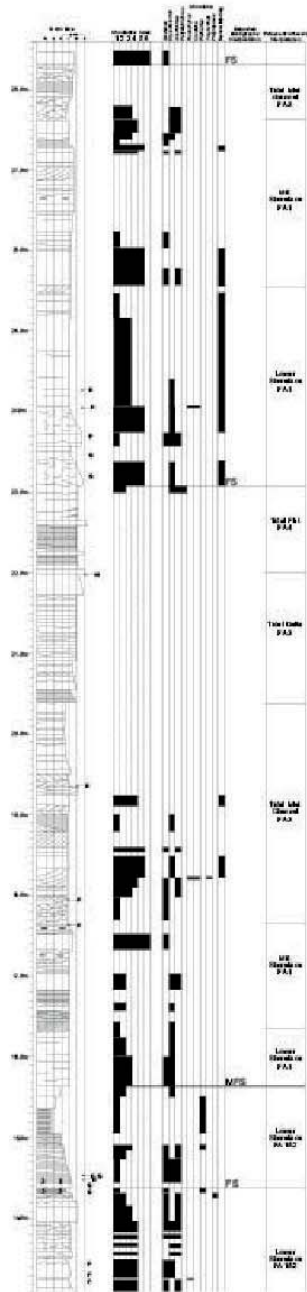
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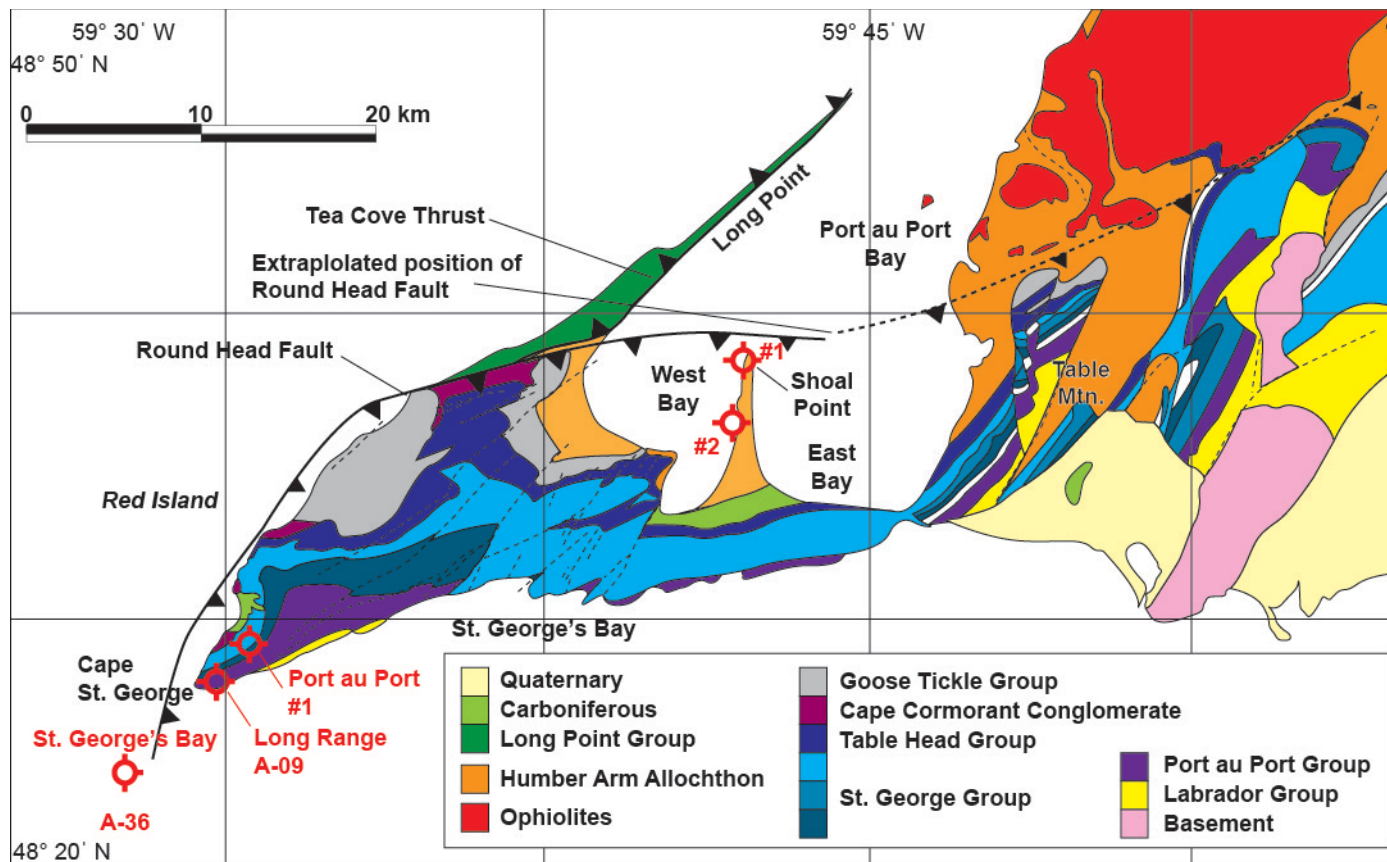
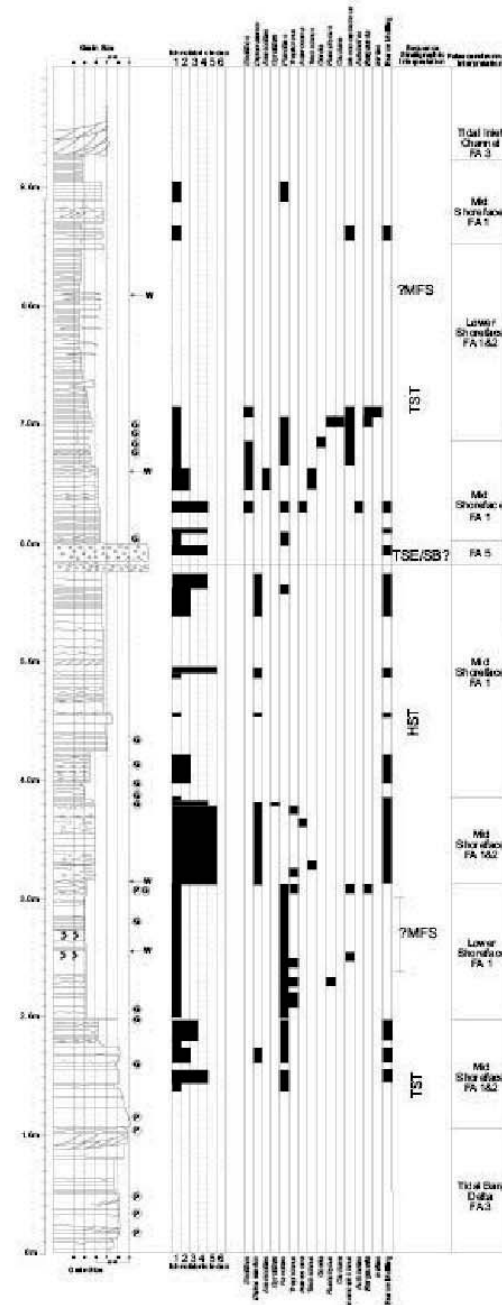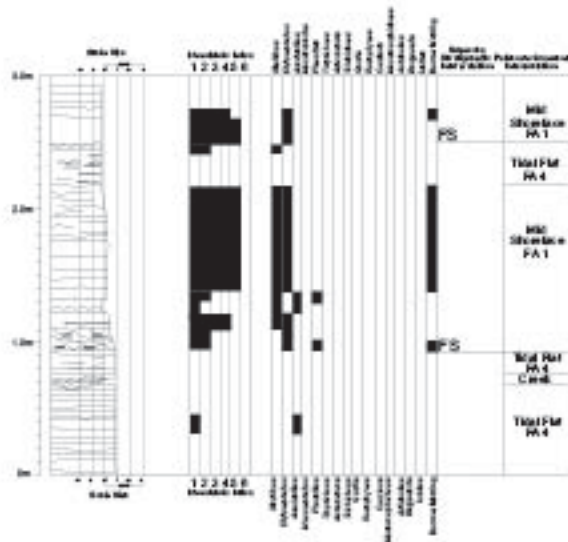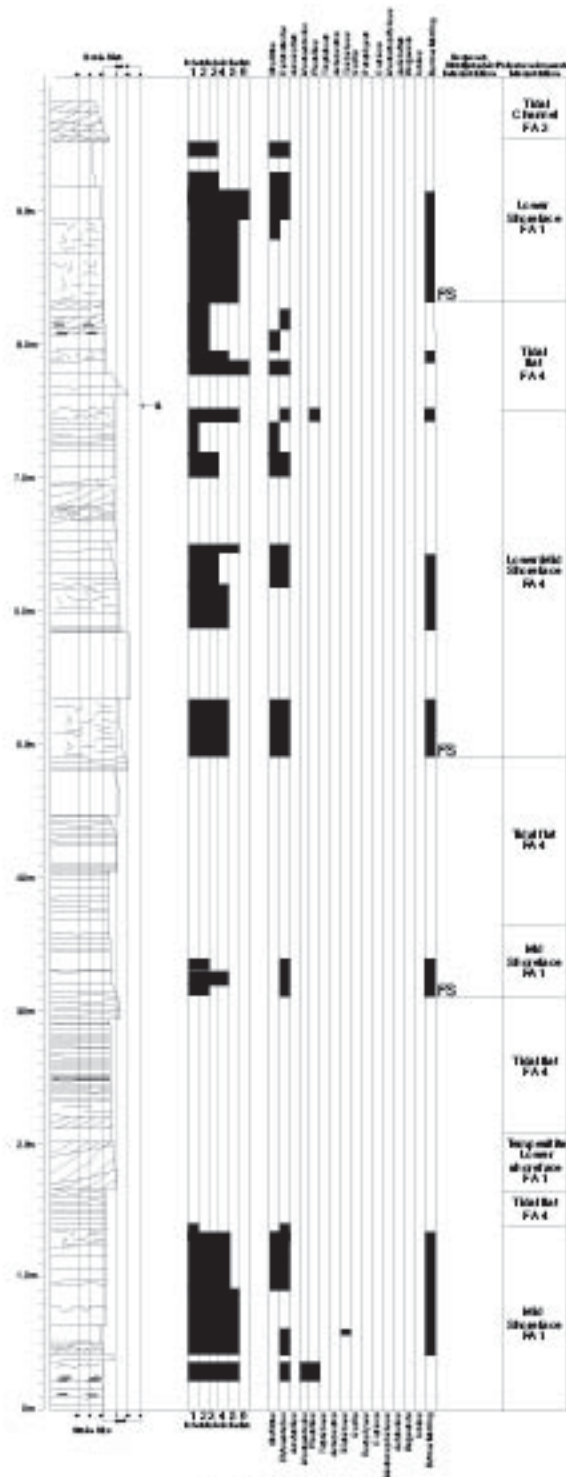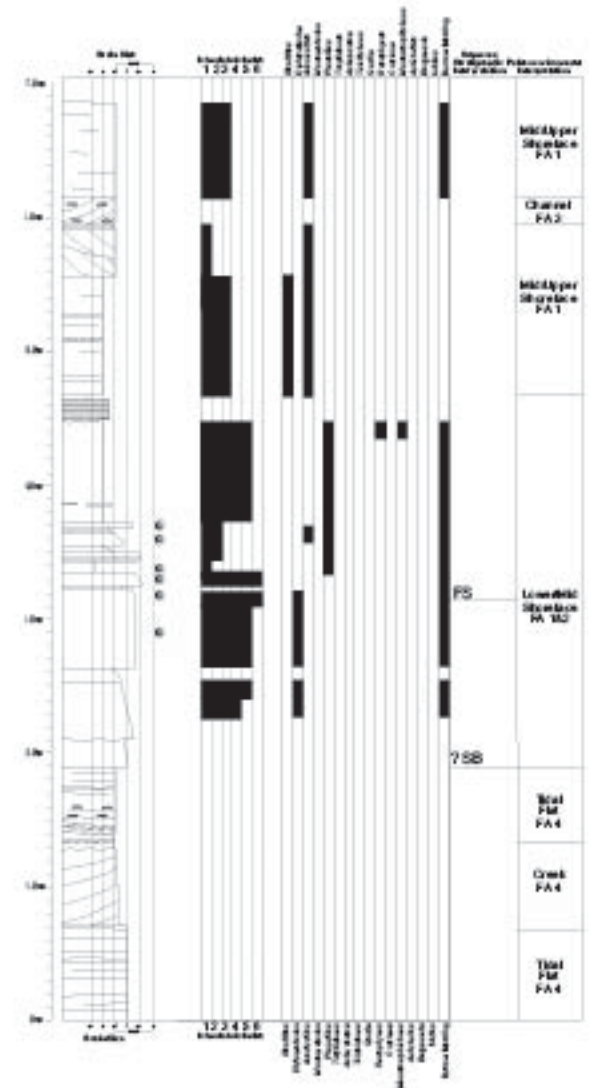| Logged Section	Latitude	Longitude
Grand Jardin 1	48° 28′14.6″ N	59° 13′22.1″ W
Grand Jardin 2	48° 28′16.0″ N	59° 13′14.6″ W
Red Brook 1	48° 29′18.4″ N	59° 9′55.7″ W
Red Brook 2	48° 29′32.2″ N	59° 9′7.4″ W
Red Brook 3	48° 29′28.2″ N	59° 9′19.7″ W

Grand Jardin 1

Grand Jardin 2

Red Brook 1

Red Brook 2

Red Brook 3

LAURENTIA

FA 5

Back Barrier/
Lagoon

Beach Barrier

Shoreface

Flood Tidal
Delta

Shore-parallel Submarine Bar

Inlet Channel

FA 3

FA 1

Ebb Tidal
Delta

FA 2

Offshore