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Abstract

The Paleoproterozoic Gordon Lake and Bar River formations, Huronian Supergroup, contain a variety of sedimentary structures in the Flack Lake area of Ontario, Canada, that have been considered of debatable origin. We identify these structures as microbially induced sedimentary structures (MISS). The preserved MISS are related to microbial mat destruction and decay, and include sand cracks, mat chips, remnant gas domes, pyrite patches, and iron laminae. A biological origin for the fossil structures is supported by their similarities to modern and ancient documented examples of MISS, the sand-dominated nature of the substrate in which they are preserved, and key microtextures identified in thin section. Microtextures include curled, frayed and layered mat chips, carbonaceous laminae, oriented grains, and concentrated heavy minerals. On outcrop scale, the presence of desiccation cracks, flaser and lenticular bedding, and ripples in association with the types of MISS identified in the Gordon Lake Formation support the interpretation of a tidal flat depositional environment. The Gordon Lake Formation contains a greater number and diversity of MISS than the overlying Bar River Formation, as a result of lower energy deposition in the former. The quartz arenite of the Bar River Formation contains fine-grained to pebbly granulestone characterized mainly by tangential and planar cross beds, which is consistent with a tidal channel or sand shoal setting. Although fossil evidence of life is rare in the rocks of the Huronian Supergroup, identification of MISS in the Flack Lake area provides a significant and convincing indication of microbial colonization at the time of deposition.

1. Introduction

Microbially induced sedimentary structures (MISS; Noffke et al., 1996) develop during growth, metabolism, destruction and decay of microbial mats in siliciclastic-dominated environments (Schieber, 2004; Noffke, 2010). These microbial mats, or biofilms, encrust siliciclastic substrates in diverse natural environments (Gerdes, 2007; Noffke and Chafetz, 2012 and references therein). Although biofilms have existed for billions of years, their preservation in the rock record is highly dependent on the presence of more complex life forms. The majority of Earth's Proterozoic eon was devoid of eukaryotic organisms. This would have enabled microbial mats to readily colonize clastic sedimentary deposits without the interference of grazers, thereby improving the cohesiveness of sand grains and decreasing erodibility of the sediment (Schieber et al., 2007a; Sarkar et al., 2008; Eriksson et al., 2012). Microbially induced sedimentary structures are therefore an invaluable trace fossil when working with Precambrian sedimentary rocks. Numerous structures interpreted as having been related to microbial activity have been described in the literature (e.g. Hagadorn and Bottjer, 1997; Gehling, 1999; Schieber et al., 2007b, and references therein; Noffke, 2010 and references therein), with several examples of Paleoproterozoic MISS (e.g. Parizot et al., 2005; Banerjee and Jeevankumar, 2005; Chakrabarti and Shome, 2010; Eriksson et al., 2012; Simpson et al., 2013). However, we are unaware of any scientific publications reporting the preservation of MISS in rocks of the Paleoproterozoic Huronian Supergroup.

Here we describe possible microbially induced sedimentary structures from the Gordon Lake and Bar River formations, Huronian Supergroup. Identification of these structures is based on comparisons with modern and other ancient analogues, as well as the six criteria for MISS biogenicity as outlined in Noffke (2009). Recognizing different types of MISS in these rocks can provide critical information regarding sedimentary processes, hydraulic energy, and paleoenvironmental settings (Noffke, 2010; Bose and Chafetz, 2012).

2. Geological Setting

The Paleoproterozoic Huronian Supergroup forms part of the Southern Geological Province, and is well exposed along the north shore of Lake Huron, Canada (Fig. 1). The siliciclastic-dominated, up to 12 km thick succession contains volcanic formations at the base of the stratigraphy (Fig. 2). Zircon from a lower rhyolite unit yielded a U-Pb date of ca. 2.45 Ga (Krogh et al., 1984; Ketchum et al., 2013), whereas an upper age limit of ca. 2.22 Ga was determined from primary baddeleyite in diabase intrusions that cut the stratigraphy (Corfu and Andrews, 1986). An alternative upper age limit of ca. 2.31 Ga was proposed by Rasmussen et al. (2013), as determined from zircon in purported tuff beds in the Gordon Lake Formation. However, Young (2014) argues that these zircons may be of detrital origin.

The Huronian Supergroup unconformably overlies Archean rocks of the Superior Province to the northwest (Card et al., 1977; Card, 1978; Young et al., 2001; Rousell and Card, 2009) and is overlain in the south by a Paleozoic succession with a depositional hiatus of 1.7 b.y. (Corcoran, 2008). The Grenville Front Tectonic Zone separates the Southern and Grenville provinces to the southeast (Card, 1978; Rousell and Card, 2009). Rocks of the Huronian Supergroup in the study area have undergone subgreenschist to greenschist grade metamorphism, but the prefix “meta” is herein omitted for simplicity.

Insert Figure 1 and 2 here

Young and Nesbitt (1985) suggested that the Huronian Supergroup formed in a tectonic setting that evolved from rift basin to passive margin. Long (2004) later interpreted the succession as lower pull-apart basin to upper passive margin deposits. In contrast, Hoffman (2013) suggested that the entire Huronian succession was deposited along a passive margin. However, Young (2014) argued that the lower units have limited areal extent, show minor marine influence, display thickness changes across major faults, and contain seismic-related deposits, all of which suggest deposition in restricted fault-bound basins.

The Huronian Supergroup is composed of five groups, which include in ascending order, the Elliot Lake, Hough Lake, Quirke Lake, Cobalt and Flack Lake groups (Fig. 2). The cyclical nature of the Hough Lake, Quirke Lake and Cobalt groups form the basis for tripartite divisions consisting of lower diamictite, overlain by siltstone-mudstone-carbonate, and capped by sandstone (Roscoe, 1957; Wood, 1973; Card et al., 1977; Young et al., 2001; Long, 2004). The diamictite units are of glacial origin, whereas the overlying fine-grained formations are interpreted as deeper water deltaic deposits that formed following post-glacial sea level rise (Card et al., 1977; Robertson and Card, 1988; Long, 2009). The sandstone units in each division are mainly interpreted as fluvial deposits (McDowell, 1957; Long, 1978; Chandler, 1988a), although Rice (1986) suggested that the top of the Lorrain Formation (Cobalt Group) may be marine in origin. Young et al. (1991) suggested that the initiation of the Huronian glaciations was related to the formation of the supercontinent Kenorland. Increased exposure of the buoyant supercontinent enabled enhanced rates of continental weathering to occur, drawing down significant amounts of atmospheric CO_2. The resultant drop in temperature would have initiated the process of glaciation. Alternatively, a decrease in the greenhouse effect during each cycle may have occurred through elimination of atmospheric CH_4 during the rise of O_2 (Pavlov et al., 2000; Tang and Chen, 2013). It has also been suggested that the two lower glaciogenic formations, the Ramsay Lake and Bruce, represent early deposition of detritus at the front edge of a mountain ice sheet, which later grew into a continental ice sheet that deposited the thick and laterally extensive Gowganda Formation (Eyles, 1993; Eyles and Januszczak, 2004; Young, 2014).

The Huronian Supergroup contains a record of the transition from an oxygen-deficient to oxygen-rich Earth atmosphere, as recorded in the presence of detrital uranium-bearing minerals in the Matinenda Formation (Elliot Lake Group), followed up-section by the first appearance of red beds in the Gowganda Formation (Cobalt Group), red beds in the Lorrain Formation (Cobalt Group), and red beds and evaporite minerals in the Gordon Lake Formation (Flack Lake Group) (Wood, 1973). The MISS described in this study are preserved in the formations of the Flack Lake Group.

2.1 Flack Lake Group

The Flack Lake Group consists of the Gordon Lake and Bar River formations (Fig. 2). The 300-760 m thick Gordon Lake Formation is composed of varicoloured siltstone, argillite, chert, minor sandstone, and anhydrite and gypsum nodules (Card et al., 1977; Card, 1978, 1984; Robertson, 1986; Chandler, 1986, 1988b). The presence of extensive red beds, evaporites and hematite ooliths suggests that a significant amount of oxygen was present in the atmosphere during deposition of these units (Wood, 1973; Chandler, 1988b; Baumann et al., 2011). Reported sedimentary structures within siltstone and argillite units include planar laminations, graded beds, convolute bedding, ball and pillow structures, desiccation cracks and synaeresis cracks, whereas cross laminations and graded beds are common in the sandstone units (Wood, 1973; Robertson, 1976; Card et al., 1977; Card, 1978, 1984; Chandler, 1986; Rust and Shields, 1987; Bennett et al., 1991). Local dolostone containing fenestral cavities was identified near the base of the formation (Hofmann et al., 1980). The sedimentary structures, combined with evaporite minerals and fenestral fabrics, indicate deposition in a low-energy, tidal-flat, lagoonal or sabkha environment (Wood, 1973; Card et al., 1977; Card, 1978, 1984; Chandler, 1986; Rust and Shields, 1987).

The conformably overlying, 100-900 m thick Bar River Formation is predominantly a quartz arenite succession with minor siltstone interbeds (Wood, 1973; Card et al., 1977, Card, 1978; Chandler, 1984; Rust and Shields, 1987; Bennett et al., 1991). Sandstone units contain massive beds, trough, tangential and planar cross-beds, ripple marks, herringbone cross-stratification, and granule-pebble lags, whereas desiccation cracks and synaeresis cracks are common in the siltstone units (Wright and Rust, 1985; Rust and Shields, 1987; Bennett et al., 1991). Roscoe and Frarey (1970) suggested that the Bar River Formation was deposited in a fluvial environment with mature quartz grains being derived from a regolith source. In contrast, Wood (1973) proposed that the Bar River Formation represents a beach deposit that was subjected to aeolian influence. However, the sedimentary structures, polymodal and bimodal paleocurrent patterns, and textural and compositional maturity are more consistent with deposition in a near-shore, shallow marine environment (Pettijohn, 1970; Robertson, 1976; Card, 1978; Chandler, 1984; Rust and Shields, 1987; Bynoe, 2011). More specifically, Rust and Shields (1987) suggested that the Bar River Formation in the Flack Lake area may have been deposited in a tidal channel environment.

To date, there is no consensus on the depositional settings represented by the Gordon Lake and Bar River formations, although most authors agree that the succession reflects deposition along a continental shelf. We postulate that the predominance of certain types of MISS may help in recognizing the physical sedimentary dynamics and associated depositional setting(s) of the top-most formations of the Huronian Supergroup.

We studied the deposits of the Gordon Lake and Bar River formations in the Flack Lake area, near Elliot Lake, Ontario (Fig. 1). The rocks were mapped in detail along Highway 639 and along the shoreline of Flack Lake. In this area, the contact between the Bar River Formation and the underlying Gordon Lake Formation is obscured by a diabase sill. Exposed sections are predominantly flat-lying to gently dipping.

3. Upper Huronian Supergroup MISS

Young (1967) proposed that the Gordon Lake and Bar River formations near Flack Lake contained organic vermiform casts, but he later discounted that finding by attributing the elliptical, spindle-shaped and overlapping structures to infilling of shrinkage cracks both from above and below (Young, 1969). Donaldson (1967) suggested that the spindle-shaped structures described from the Flack Lake area in addition to similar structures described from Michigan (e.g. Faul, 1949; Frarey and McLaren, 1963; Hofmann, 1967; Young, 1967) may have formed from desiccation of algal mats. Since that time, the sedimentology of the Gordon Lake and Bar River formations in the Flack Lake area has been investigated by several workers (e.g. Wood, 1973; Card et al., 1977; Wright and Rust, 1985; Chandler, 1986, 1988a, 1988b; Rust and Shields, 1987; Robertson and Card, 1988). However, these authors indicated that the abundant polygonal, linear and elliptical structures in the rocks were desiccation or synaeresis cracks. Although our present detailed investigation affirms that the polygonal structures are desiccation cracks, the spindle-shaped, overlapping linear structures are consistent with microbially induced sedimentation. These structures are herein described according to Schieber's (2004) process-related classification scheme, which includes development during mat growth, metabolism, physical destruction, and decay. Only the latter two categories of structures were identified in the Flack Lake area.

3.1 Mat-Destruction Structures

In the study area, the physical destruction of microbial mats is indicated by various types of sand cracks, microbial mat chips, and microbial sand and silt chips (Table 1). Sand cracks result from rupturing of an overlying microbial mat that has been placed under stress from wind or water, or desiccation (Gerdes, 2007; Eriksson et al., 2007b). Impressions of the tears in the mat may be preserved in the underlying sand or silt. Cracks representing single incipient tears were identified in quartz arenite of the Bar River Formation and siltstone of the Gordon Lake Formation, and range from 0.5-1.5 cm in size (Fig. 3a). Sand-filled, 0.5-9.5 cm triradiate cracks are common in sandstones of both formations, and are inferred to have formed when sand was transported to the mat surface and filled the open ruptures from above (Fig. 3b). Fine-grained sandstones and siltstones of the Gordon Lake Formation preserve abundant, up to 30 cm long, lenticular, curved, sinuous, and spindle-shaped cracks (Fig. 3c, d). These irregular structures, unlike polygonal mud cracks that form through desiccation, reflect the elasticity of microbial mats, in which tearing results in curved or upturned margins (Gerdes, 2007). Although less common in the Bar River Formation, curved cracks at one locality were clearly infilled with sand from above (Fig. 3e). Locally, cm-size cracks characterize the crests of interference ripples (Fig. 3f). These cracks are interpreted to have formed when fluid was expelled from microbial mats that colonized the ripple crests. Desiccation of the mat may have also led to the formation of these cracks.

Insert Table 1 here

Insert Figure 3 here

Microbial mat chips develop from high-energy erosion of desiccated, mat-adhered sand, forming curved, irregular fragments (Schieber, 2004; Erikssen et al., 2007a). Small mat chips, 2-3.5 cm long, were identified in iron-stained Bar River quartz arenite at one locality (Fig. 4a). Microbial sand and silt chips are 0.25-9 cm long, and were identified mainly in the Gordon Lake Formation (Fig. 4b-d). These structures develop from abrasion of flipped-over mat margins by water or wind, and are normally preserved as rounded or elongated fragments (Erikssen et al., 2007a). Large mat chips were identified only in the siltstone and fine-grained sandstone of the Gordon Lake Formation, and range from 7-150 cm long and 3-30 cm wide (Fig. 4d-f). The edges of the large mat chips are sharp, frayed or irregular. Small chips appear to have been curled (Fig. 4e), which is consistent with erosion of a dried out mat in an environment that is proximal to the site of deposition (Schieber, 2007). Larger, uncurled mat chips contain biolamination and smaller microbial mat chips (Fig. 4d), which suggest that the mat was wet during erosion (Schieber, 2007). One mat chip appears to have a mottled texture (Fig. 4f), which probably reflects mat growth prior to erosion.

3.2 Mat-Decay Structures

Microbial mat decay in the Flack Lake area is indicated by remnant gas domes, pyrite patches, and iron laminae. Remnant gas domes were identified in fine-grained sandstone of the Gordon Lake Formation, where they are characteristically associated with iron staining (Fig. 5a). The domes are 1-2 cm across and are surrounded by curved sand cracks. The domes appear to be ruptured locally, resembling radial gas escape structures (c.f. Dornbos et al., 2007; Fig. 5b), but these characteristics may also be the results of dome erosion during Pleistocene glaciation.

Pyrite patches were identified in the troughs of interference ripples in Bar River quartz arenite at one locality (Fig. 5c). The pyrite patches are inferred to represent the locations of former microbial mats. The lower portions of a microbial mat are typically anoxic due to the decay of organic matter; this environment is conducive to the formation of reduced minerals, such as pyrite (Berner, 1984; Gerdes et al., 1985). Microbial mats were presumably the dominant source of organic matter during the Paleoproterozoic and would have provided the necessary organic debris within sand of the Bar River Formation at the time of deposition. Iron laminae were identified in quartz arenite of the Bar River Formation at two localities, where they are wavy (Fig. 5d) and cross-laminated. In general, purple, iron-rich laminae are thinner than pink, quartz-rich laminae. The darker laminae may represent periods of calm hydrological conditions during which microbial mats were able to grow, whereas the pink laminae may represent periods of higher energy conditions during which growth of microbial mats was limited (Noffke et al., 2002; Druschke et al., 2009). The permeability of sandstones causes organic matter to be removed fairly early in burial history, therefore the stratiform iron laminae represent residual layers of mat-decay minerals (Schieber et al., 2007b).

Insert Figure 4 here

Insert Figure 5 here

4. Criteria for the biogenicity of MISS in the upper Huronian Supergroup

Fossil sedimentary structures of the Gordon Lake and Bar River formations in the Flack Lake area fulfill the six criteria for biogenicity, as outlined by Noffke (2009), and are therefore defined as MISS. The first criterion is that the sedimentary rocks must not have been subjected to metamorphism greater than greenschist grade. The studied rocks in the Flack Lake area are of subgreenschist metamorphic grade (Card, 1978). The second criterion states that the sedimentary structures are found at stratigraphic transgression-regression points. Deposition of the Flack Lake Group has been interpreted to have occurred along a continental shelf. Detailed geological mapping of the Gordon Lake Formation in the Flack Lake area supports deposition on a tidal flat, whereas the overlying Bar River Formation in the study area contains structures consistent with a tidal channel or estuarine sand shoal environment. The stratigraphic relationship is therefore consistent with a transgression. However, the occurrence of a regression is not preserved unless the transition from the Lorrain Formation to the overlying Gordon Lake Formation supports a falling water level. The majority of the Lorrain Formation is inferred to have been deposited in a fluvial environment, which does not fit a regressive sequence. However, a regression may have taken place following deposition of the Bar River Formation, although any overlying units have been eroded away.

The third criterion of Noffke (2009) is that the structures are part of the “microbial mat facies”, which involves preferential microbial mat development on quartz-rich, fine-grained sand that is frequently associated with small-scale ripples. The ideal environment for establishment of a microbial colony is one of moderate energy in which currents and waves are not strong enough to damage or destroy the microbial mat. However, depositional energy must be strong enough that mud and other fine grains remain in suspension, thereby reducing the likelihood of sunlight obstruction (Noffke, 2009). In the Flack Lake area, MISS of the upper Huronian Supergroup are preserved on quartz-rich, fine-grained sandstone and siltstone beds, repeatedly on and in the stratigraphic vicinity of rippled bedding planes.

Criterion 4 states that the distribution of the structures reflects the hydrodynamic conditions of the depositional environment. The types of MISS identified in the Gordon Lake Formation are consistent with distribution in an intertidal to supratidal setting. These environments experience a complex array of hydrodynamic conditions and are therefore generally colonized by more robust organisms, such as microbial mats. These mats influence the erosion and deposition of sediment, thereby resulting in MISS (Noffke and Krumbein, 1999). Models of both ancient and modern MISS distribution in siliciclastic tidal environments illustrate that small mat chips are found in the lower intertidal zone, sand cracks in the upper intertidal to lower supratidal zones, and gas domes in the upper intertidal to supratidal zones (Noffke et al., 2001; Dornbos et al., 2007; Bose and Chafetz, 2009; Noffke, 2009; Tang et al., 2012). Large mat chips may also be found in the intertidal zone (Noffke et al., 2013). The sedimentary structures of both formations reflect deposition in a shallow marine, tidally-influenced environment, and the identified MISS (Table 1) are consistent with this interpretation. Criterion 5 of Noffke (2009) states that the structures resemble and compare geometrically to modern MISS. Microbially induced sedimentary structures appear to have remained largely unchanged throughout Earth's history, thus the comparison of ancient MISS to modern analogues is not only appropriate, but is integral for determination of a biogenic origin (Noffke, 2009). Examples of modern and ancient MISS (e.g. Dornbos et al., 2007; Eriksson et al., 2007b; Bose and Chafetz, 2012; Tang et al., 2012; Lan et al., 2013; Noffke et al., 2013; Cuadrado et al., 2014) are comparable to the various forms of MISS identified in the Gordon Lake and Bar River formations presented herein.

The final criterion for biogenicity of MISS requires that microtextures identified in thin section denote a relationship to biofilms or microbial mats. In addition to the mesoscopic structures identified in the Flack Lake outcrops, thin sections from the Gordon Lake Formation reveal a variety of microtextures that are characteristic of microbial mat activities, such as growth and trapping. Wavy crinkled laminae, 0.55-3.25 mm torn mat chips and 0.2-1.8 mm mat chips are interpreted as portions of ancient microbial mat layers (Fig. 6a-e). Mat chips formed during erosion and transportation of microbial mats. Locally, the mat chips are layered, which reflects successive periods of mat growth prior to erosion (Fig. 6d), whereas folded mat chips are consistent with transport of eroded material (Fig. 6d). Bands of concentrated heavy minerals may represent the edge of a once-present mat layer (Noffke, 2009). Heavy minerals accumulate on mat surfaces where they are trapped and bound to the sticky mat exterior (Gerdes, 2007; Noffke, 2009). Oriented grains, 0.1-0.2 mm in size, are also identified in thin section (Fig. 6f). These structures develop when gas production in submerged microbial mats, or desiccation of a subaerial mat causes the mat to break into fragments, which then float and are deposited on muddy sediment (Eriksson et al., 2007b; Schieber, 2007). The positive identification of microbial mat chips on a microscopic scale, as illustrated in Figure 6a-f, meets the final criterion for biogenicity of MISS in the sedimentary deposits of the Flack Lake Group.

Insert Figure 6 here

5. Discussion

Previous reports of biosignatures in the Paleoproterozoic Huronian Supergroup include stromatolites in the carbonate-rich Espanola Formation (Hofmann et al., 1980; Bekker et al., 2005; Long, 2009; Al-Hashim, 2015) and laminated fenestral dolostone in the Gordon Lake

Formation at one locality (Hofmann et al., 1980). The identification of MISS in this study has significantly increased the quantity of biosignatures reported from the Huronian Supergroup, and contributes to the relatively small group of reported Paleoproterozoic examples.

Sand cracks in the study area have previously been interpreted as shrinkage or synaeresis cracks (e.g. Young, 1969; Card, 1978; Chandler, 1984, 1986; Wright and Rust, 1985; Rust and Shields, 1987). Synaeresis cracks are narrow, curved to linear, tapering structures that have a non-polygonal pattern in plan view and contorted sides in cross-section (Pratt, 1998; Harazim et al., 2013; Davies et al., 2016). Although there is much debate on the mechanism of formation of synaeresis cracks, many authors agree that the structures form in muddy sediment through the rapid shrinkage of clay under changing salinity conditions in a shallow submarine environment (Jüngst, 1934; White, 1961). Other proposed methods of formation include: desiccation (Allen, 1982), desiccation and infilling of evaporite molds (Astin and Rogers, 1991), seismic deformation (Pratt, 1998), and microbial facilitation (Pflüger, 1999; Harazim et al., 2013). Harazim et al. (2013) determined that cracked mudstones of the Ordovician Beach Formation in Newfoundland, Canada, were colonized by microbial mats, whereas non-cracked mudstones show no indication of microbial mat development. The authors suggest that microbial mats may be a pre-requisite for intra-stratal shrinkage crack formation, however Davies et al. (2016) suggest that synaeresis cracks may be polygenetic in nature and that there is no universal mode of formation. The curved, spindle and lenticular structures in the study area are found primarily on fine-grained sandstone to siltstone beds in the stratigraphic vicinity of other varieties of MISS, thus favouring a mat-induced origin. Associated sedimentary structures, such as desiccation cracks and flaser and lenticular bedding, support deposition in an environment that experienced periods of subaerial exposure, which is contradictory to synaeresis crack formation, which generally occurs in a submerged environment. Many of the cracks are exposed on rippled bedding planes, indicating that the sediment was stabilized, presumably by biofilms. Pyrite grains, horizons and patches are also found in many of the outcrops with sand cracks and may have formed under reducing conditions created by the decay of microbial mats.

A greater diversity and quantity of MISS is preserved in the Gordon Lake Formation compared to the Bar River Formation (Table 1). This discrepancy can be attributed to the different depositional environments of the formations within a tidally-influenced setting. The recurrence of desiccation structures in the Gordon Lake Formation documents numerous periods of subaerial exposure. Desiccation cracks were also identified in the Bar River Formation, but in a comparably minor amount. The main rock types in which MISS of the Gordon Lake Formation are found include thin siltstone and fine-grained sandstone beds. These beds are mainly planar to wavy laminated and bedding planes display oscillation ripples, local interference ripples and abundant desiccation cracks. Our interpretation is that the Gordon Lake Formation was deposited on a tidal flat where microbial mats flourished during relatively calm water conditions (Fig. 7). Large mat chips and microbial sand and silt chips would have developed during periods of strong wind or wave action, which detached and transported mat chips to an adjacent location. Microbial mat tears and chips are common in wet microbial mats in protected inter- and supra-tidal environments due to the effects of wind shear on very shallow tidal ponds or directly on exposed mats (Bouougri and Porada, 2012). Microbial shrinkage and sand cracks analogous to the types observed in the Flack Lake area occur in the intertidal and lower supratidal zones and often display a range of shapes that are linked to the maturity, cohesiveness, and the extent of desiccation of the microbial mat (Eriksson et al., 2007a). In addition, gas domes generally occur only in the intertidal zone (Dornbos et al., 2007). Similar MISS to those herein described are reported from the tidally influenced Proterozoic succession of the southern North China Platform (Tang et al., 2012), the Neoproterozoic peritidal deposits of the West African Craton (Bouougri and Porada, 2002), and the Mediterranean coast of modern southern Tunisia (Eriksson et al., 2007a).

Insert Figure 7 here

The quartz arenite nature of the Bar River Formation and internal sedimentary structures, such as tangential and planar cross-beds and granule-pebble lags suggest relatively higher energy conditions at the time of deposition compared with those during deposition of the Gordon Lake Formation. Sand cracks identified in fine- to medium-grained sandstone beds are a reflection of microbial influence, as microbial filaments increase the cohesiveness between sand- and silt-sized sediment grains that would otherwise remain unaltered during desiccation (Gerdes et al., 2000). Microbial mats cannot form in a high-energy environment as they will be eroded before they have sufficient time to establish. However, once established, a microbial mat is robust enough to tolerate high-energy conditions (Noffke, 2010). This may account in part for the lower diversity and the reduced number of MISS in the Bar River Formation relative to the Gordon Lake Formation. The coarser grained, more porous and permeable nature of the Bar River Formation may have also contributed to poorer preservation of microbial mats.

Many examples of ancient MISS are found in coastal, passive margin settings (Schieber et al., 2007a), thus the inferred deposition of the upper Huronian Supergroup along a continental margin would be conducive to the development of MISS. The types of MISS identified in the Gordon Lake and Bar River formations are valuable indicators of depositional environment and support the interpretation of deposition in a transgressive, tide-influenced setting.

6. Conclusions

Paleoproterozoic microbial mats developed, decayed and were destroyed in shallow marine environments where they influenced sedimentation patterns. The structures described from the Gordon Lake and Bar River formations contribute substantial evidence for microbial colonization during deposition of the upper Huronian Supergroup. The varieties of sand cracks, mat chips, pyrite patches, iron laminae, microbial sand and silt chips and remnant gas domes identified in the Flack Lake area satisfy the criteria for biogenicity as outlined by Noffke (2009). The differences between the MISS identified in the two formations are a function of varying composition and grain size, which are the direct results of water energy and depth in each depositional environment.

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Tables and Figures

Table 1: Summary of the microbially induced sedimentary structures (MISS) identified in the Gordon Lake and Bar River formations in the Flack Lake area.

Figure 1: Simplified geologic map of the distribution of the Huronian Supergroup north of Lake Huron. The study area is located 29 km north of Elliot Lake. Modified from Young et al. (2001) and Long (2009).

Figure 2: General stratigraphy of the Huronian Supergroup. Modified from Long (2004) and Young (2013). Date for Nipissing Diabase from Corfu and Andrews (1986). Date for Copper Cliff Formation from Krogh et al. (1984) and Ketchum et al. (2013).

Figure 3: Mat-destruction structures identified in the Flack Lake area. Scales include pencil (14.5 cm) and camera lens cap (5.8 cm). (A) Single incipient tears preserved in fine-grained sandstone of the Bar River Formation. (B) Triradiate cracks preserved in fine-grained sandstone of the Gordon Lake Formation. (C) Curved, sinuous sand cracks preserved in siltstone of the Gordon Lake Formation. (D) Curved, corrugated sand cracks preserved in siltstone of the Gordon Lake Formation. (E) Curved sand cracks filled from above preserved in fine-grained sandstone of the Bar River Formation. (F) Curved cracks confined to the crests of interference ripples preserved in fine-grained sandstone of the Bar River Formation.

Figure 4: Mat-destruction structures identified in the Flack Lake area. Scales include pencil (14.5 cm) and camera lens cap (5.8 cm). (A) Microbial mat chips preserved in iron stained, fine-grained sandstone of the Bar River Formation. (B) Microbial sand and silt chips preserved in fine-grained sandstone of the Gordon Lake Formation. (C) Microbial sand and silt chips preserved in fine-grained sandstone of the Bar River Formation. (D) Microbial sand and silt chips preserved in fine-grained sandstone of the Gordon Lake Formation.

Note the frayed margins of the large mat chip and the biolaminations below the pencil. (E) Microbial mat chips preserved in fine-grained sandstone of the Gordon Lake Formation. Note the curled appearance of these chips. (F) Large mat chips preserved in the same fine-grained sandstone bed as Figure 4-E. Note the mottled appearance of the mat and distinct torn margins.

Figure 5: Mat-decay structures identified in the Flack Lake area. Pencil for scale (14.5 cm). (A) Remnant gas domes preserved in fine-grained sandstone of the Gordon Lake Formation. Note the iron staining concentrated around the domes and the shrinkage cracks in the upper left portion of the figure. (B) Close-up of ruptured gas dome preserved in fine-grained sandstone of the Gordon Lake Formation. Note the radial nature of the dome center. (C) Pyrite patches preserved in the troughs of interference ripples in fine- to medium-grained sandstone of the Bar River Formation. (D) Wavy iron laminae preserved in fine- to medium-grained sandstone of the Bar River Formation.

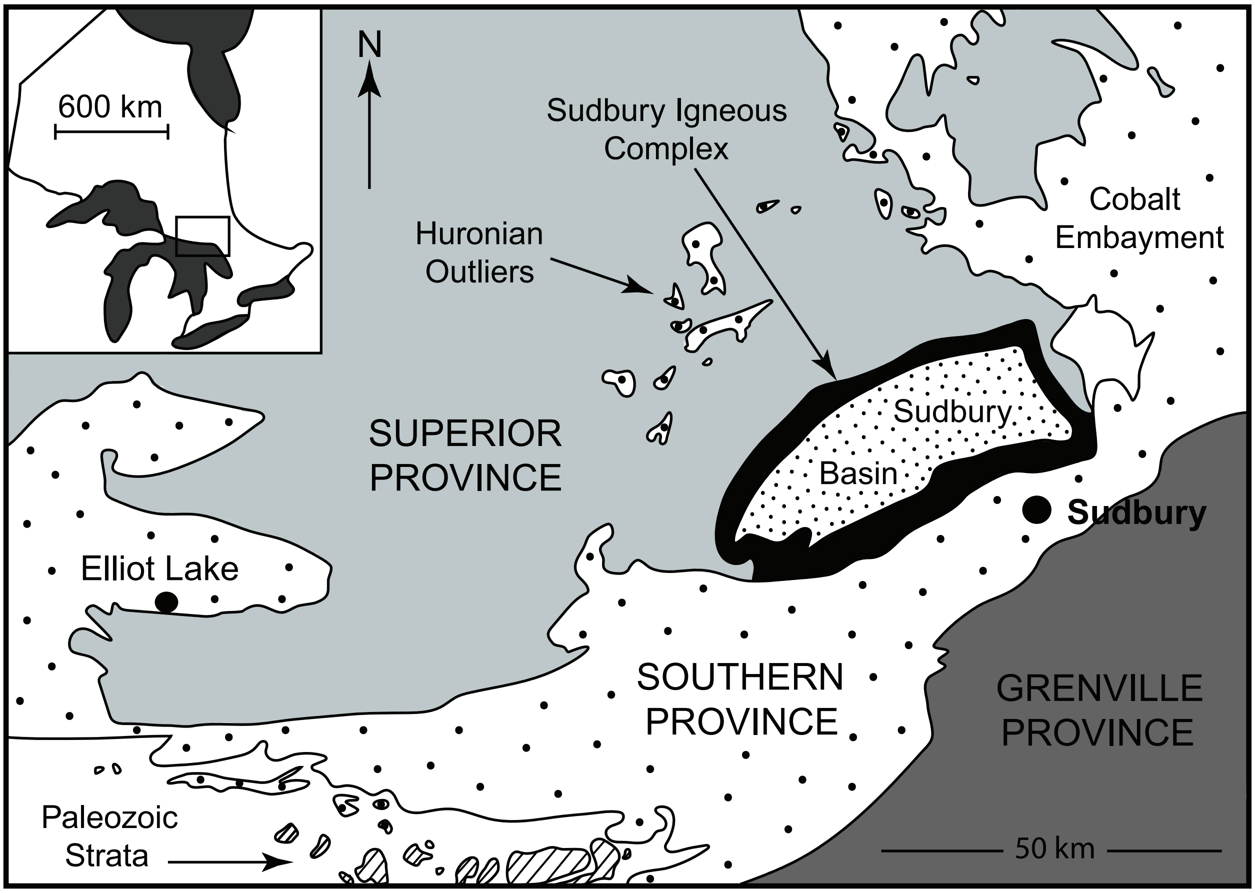
Figure 6: Mat microtextures identified in thin sections from the Gordon Lake Formation. (A) Frayed mat chip preserved in fine-grained sandstone. Note the internal layering and torn margin on the right side of the mat chip. (B) Mat chip preserved in siltstone. Note the iron cement concentrated around the wavy carbonaceous laminae. (C) Mat chips preserved in a granule- to pebble-conglomerate with a siltstone to fine-grained sandstone matrix. (D) Close-up of the center of Figure 6-C showing a layered mat chip (L) and curled mat chip (C). (E) Carbonaceous laminae preserved in siltstone. (F) Oriented quartz grains preserved in mudstone.

Figure 7. Schematic model showing the distribution of different MISS on a Paleoproterozoic barrier island-tidal flat system. The Gordon Lake Formation is represented by the sediments in the intertidal and lower supratidal settings. The Bar River Formation is represented by the sand ridges and barrier island.

Table 1

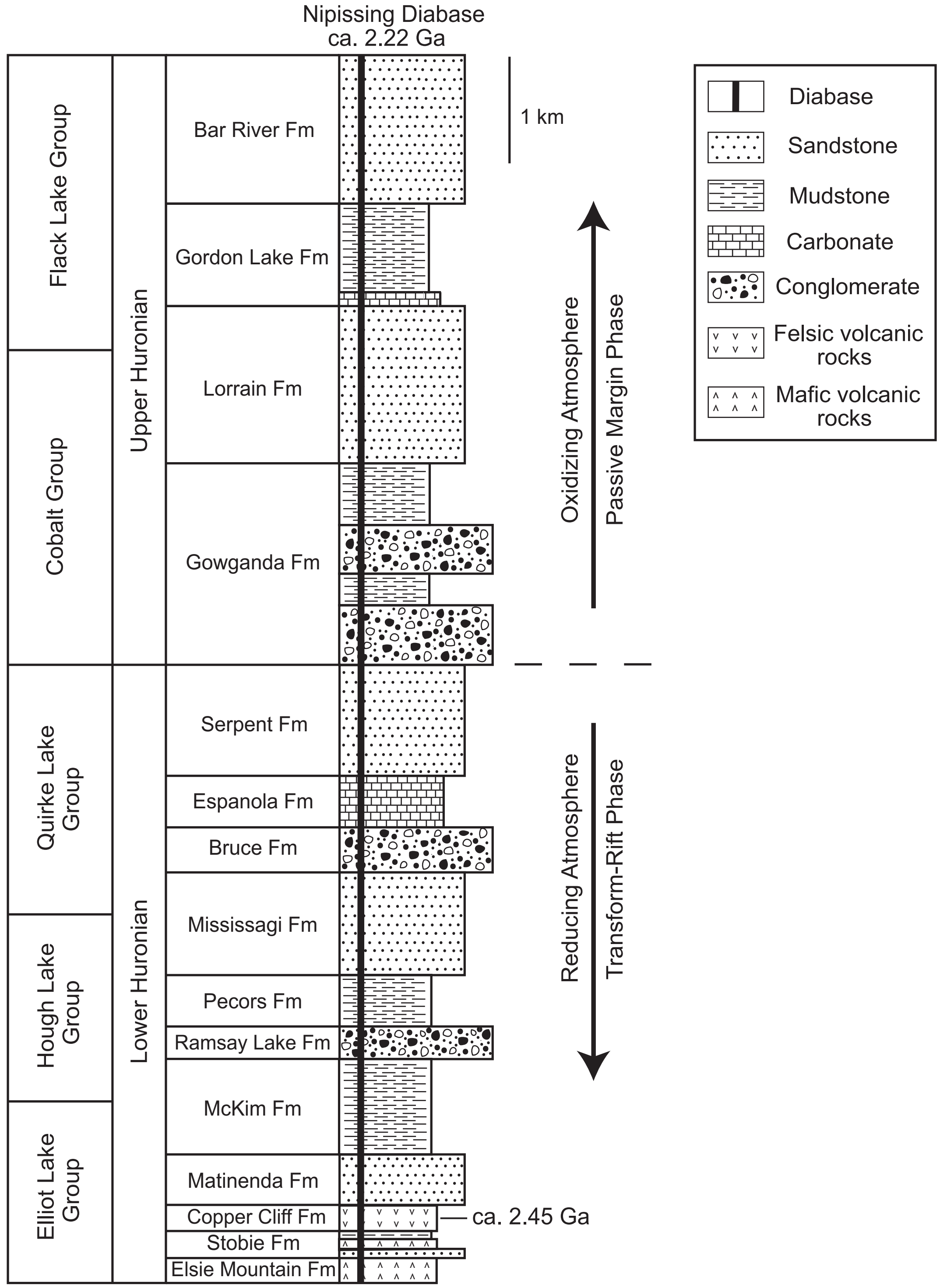
Mat-related Feature	Gordon Lake Formation	Bar River Formation
Sandcracks		
single incipient tears	—	—
triradiate	—	—
curved	—	—
lenticular	—	
spindle	—	
sinuous	—	
Microbial sand and silt chips	—	
Large mat chips	—	
Small mat chips		—
Remnant gas domes	—	
Iron patches		—
Iron laminae		—

Fig 1



600 km
N
Sudbury Igneous Complex
Huronian Outliers
Cobalt Embayment
SUPERIOR PROVINCE
Sudbury Basin
Sudbury
Elliot Lake
SOUTHERN PROVINCE
GRENVILLE PROVINCE
Paleozoic Strata
50 km

Fig 2



Nipissing Diabase
ca. 2.22 Ga
1 km
Flack Lake Group
Cobalt Group
Quirke Lake Group
Hough Lake Group
Elliot Lake Group
Upper Huronian
Lower Huronian
Bar River Fm
Gordon Lake Fm
Lorrain Fm
Gowganda Fm
Serpent Fm
Espanola Fm
Bruce Fm
Mississagi Fm
Pecors Fm
Ramsay Lake Fm
McKim Fm
Matinenda Fm
Copper Cliff Fm
Stobie Fm
Elsie Mountain Fm
ca. 2.45 Ga
Oxidizing Atmosphere
Passive Margin Phase
Reducing Atmosphere
Transform-Rift Phase
Diabase
Sandstone
Mudstone
Carbonate
Conglomerate
Felsic volcanic rocks
Mafic volcanic rocks

Fig 3
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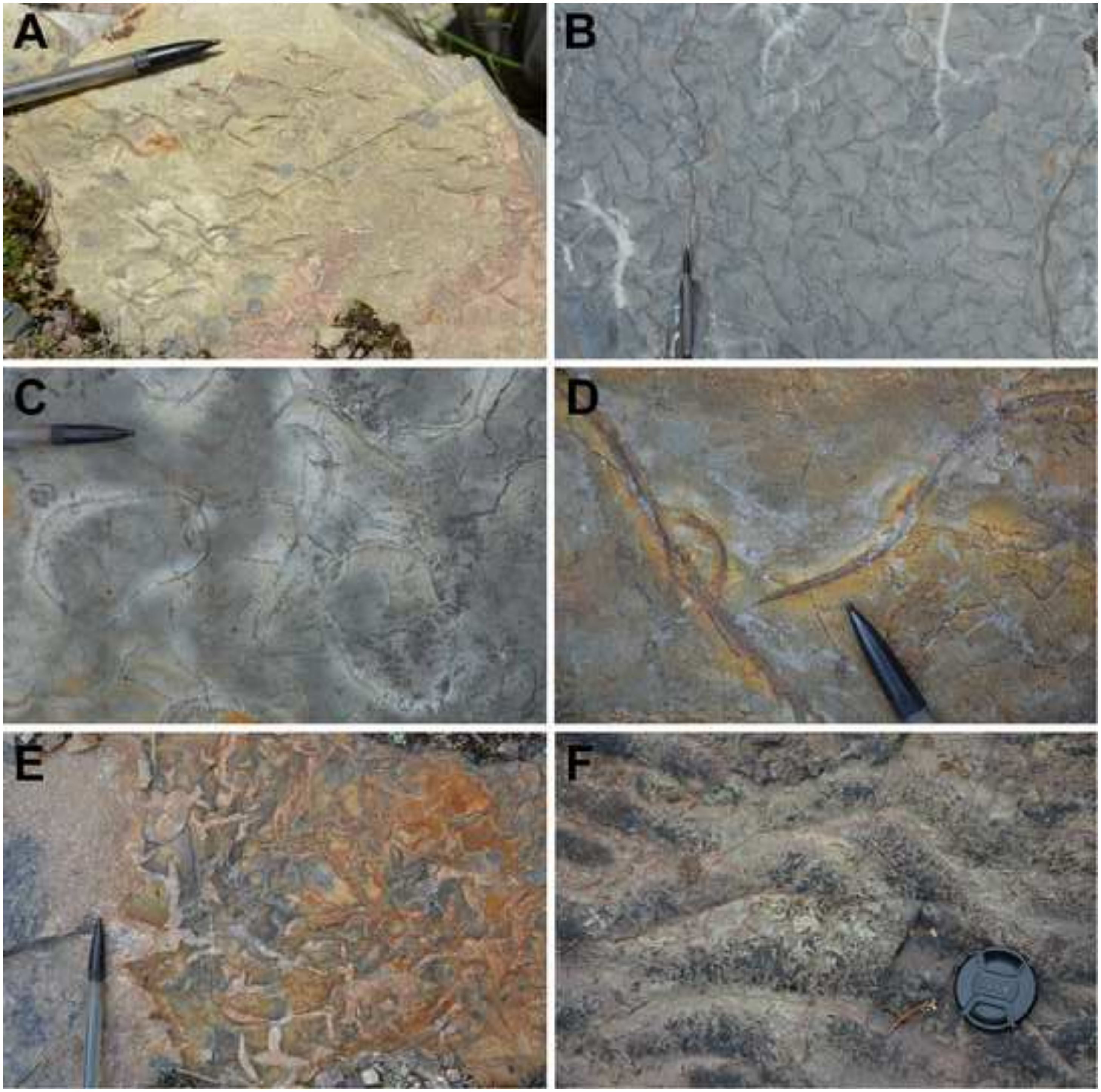

Fig 4
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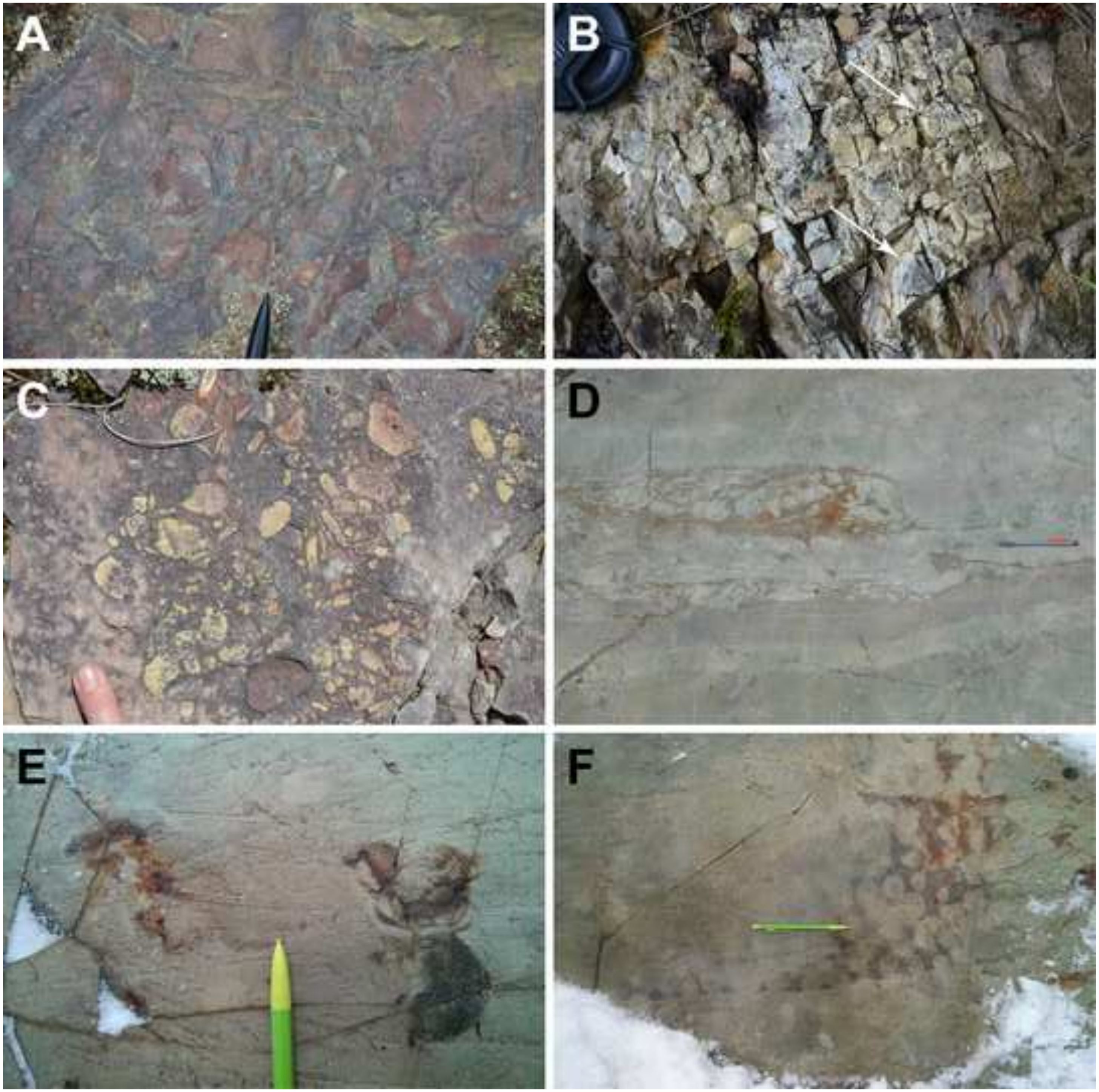

Fig 5
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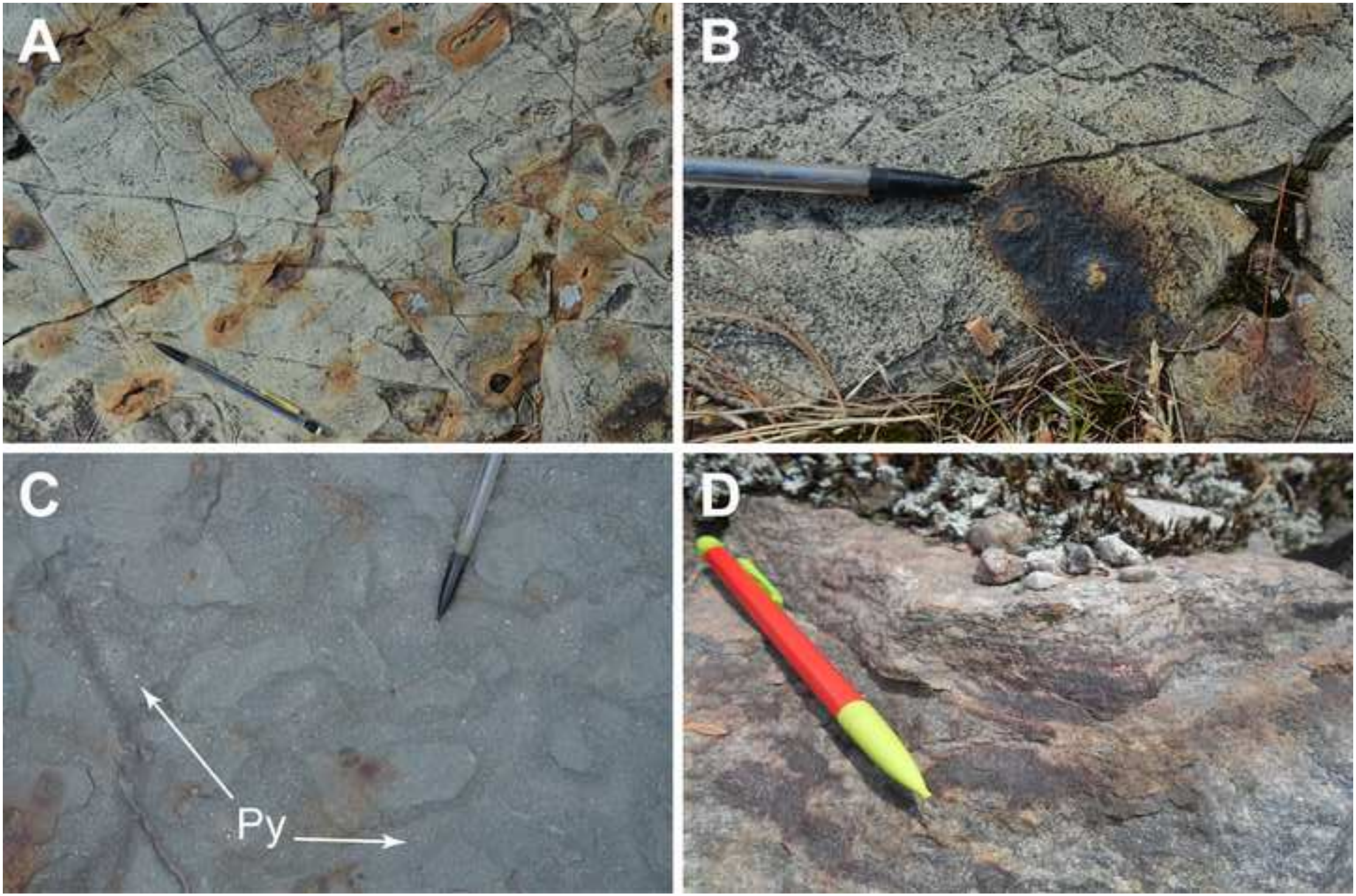

Fig 6
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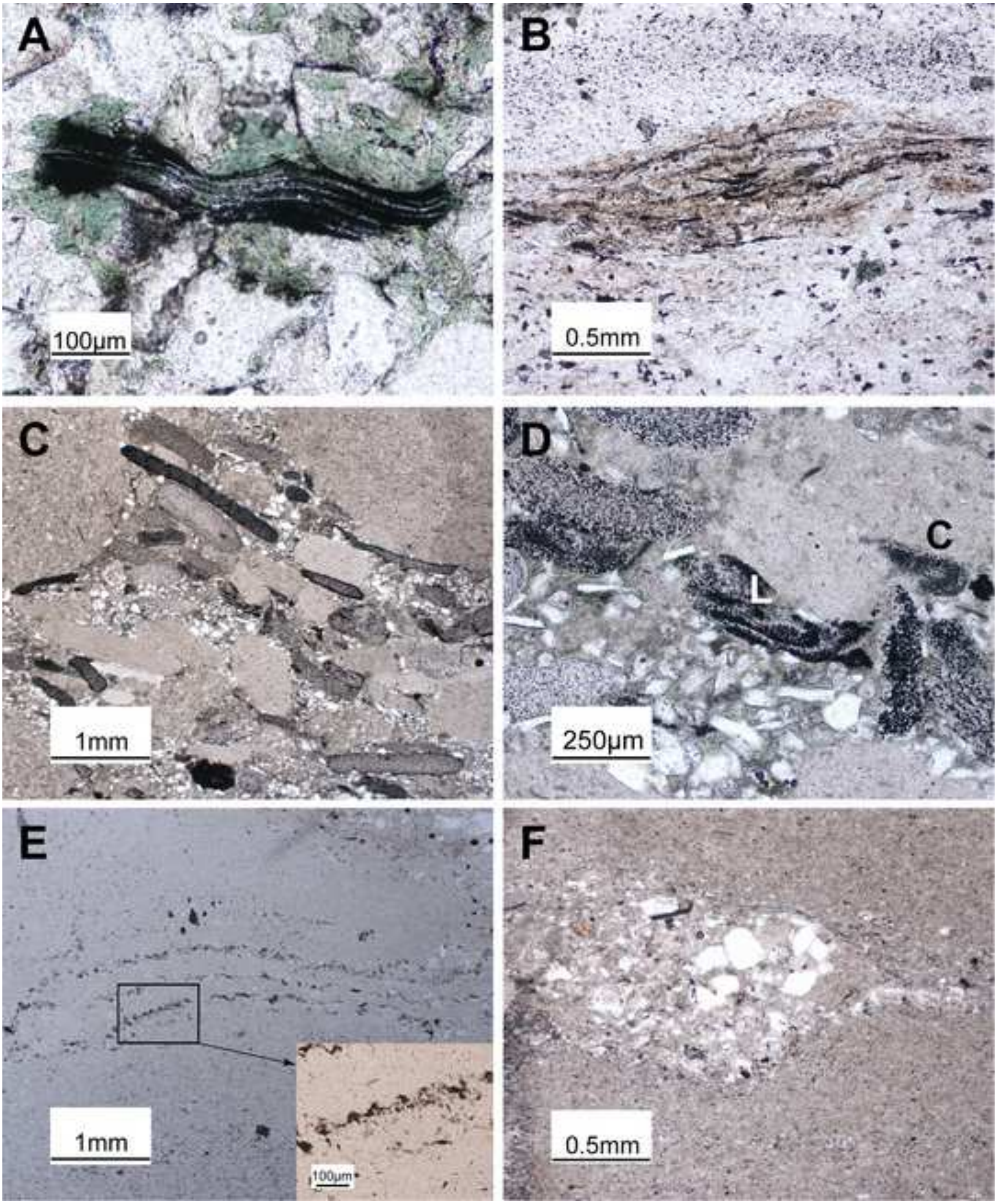
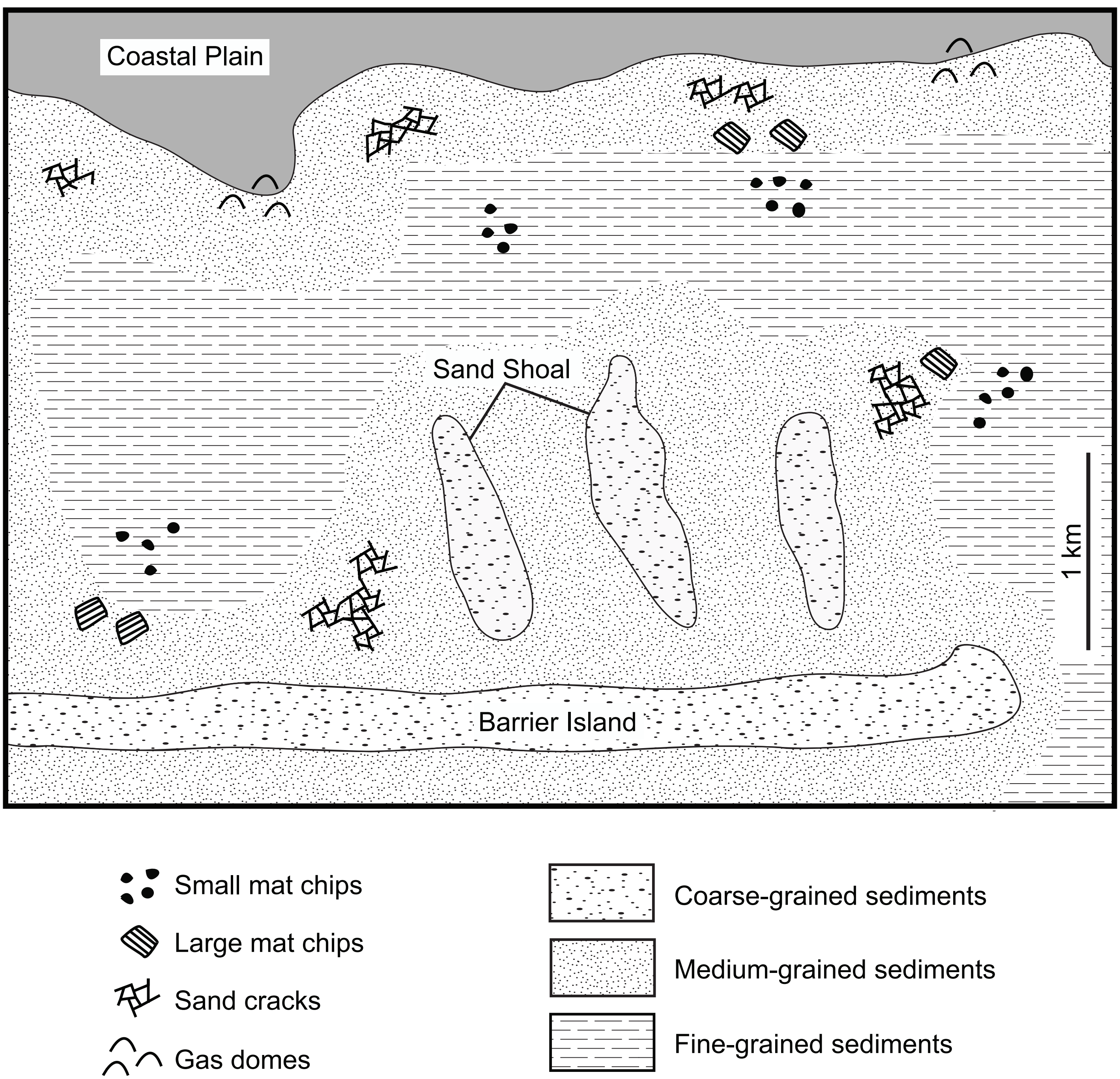


Fig 7



Coastal Plain
Sand Shoal
1 km
Barrier Island
Small mat chips
Large mat chips
Sand cracks
Gas domes
Coarse-grained sediments
Medium-grained sediments
Fine-grained sediments