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Processes responsible for the development of soft-sediment deformation structures (SSDS) in the Paleoproterozoic Gordon Lake Formation, Huronian Supergroup, Canada

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ABSTRACT

An exposure of the Paleoproterozoic Gordon Lake Formation in the Bruce Mines area, Ontario, Canada, contains abundant soft-sediment deformation structures (SSDS), including load casts, convolute bedding, pseudonodules, ball-and-pillow structures, flame structures and one dewatering pipe. These features are developed in siltstone to fine-grained sandstone beds and are between 1 and 120 cm in width and 3–78 cm high. The primary trigger mechanism is interpreted to be storm or tsunami activity, however seismic shock, overloading brought about by density inversions, or a combination of these processes, may have influenced the formation of SSDS to a lesser degree. Several beds also contain flat to wavy carbonaceous laminae, locally with a botryoidal texture and concentrations of heavy minerals, which are interpreted as relicts of microbial mats. Microbial mats may have played a minor role in the formation of SSDS, but do not appear to have been a prominent driving mechanism. Soft-sediment deformation structures observed in the Baie Fine, Flack Lake, and Cobalt plains regions of Ontario, are smaller and not as abundant as in the study area, suggesting that the deposits in the study area were either affected by local events or different magnitudes of sedimentary processes. In contrast to the tidal flat paleoenvironment interpreted for the Gordon Lake Formation in the Flack Lake area, the stratigraphically lower beds at the studied outcrop more closely resemble shallow shelf deposits.

1. Introduction

Soft-sediment deformation structures form when unconsolidated sediment is destabilized by any mechanism that reduces sediment strength, followed by a force that induces deformation (Owen, 1987; van Loon, 2009). These structures have been reported from a variety of modern and ancient sedimentary deposits (e.g. Davenport and Ringrose, 1987; Molina et al., 1998; Chen and Lee, 2013; Sarkar et al., 2014; Stárková et al., 2015; Roy and Banerjee, 2016). Liquefaction and fluidization are common mechanisms that reduce sediment strength and are the results of pore-fluid overpressuring. Fluidization requires a continuous flow of fluid in order to support and transport particles in suspension, whereas during liquefaction, the internal friction of sediment is reduced to nearly zero, causing the material to temporarily act as a fluid (Owen, 1987; Maltman, 1994; Owen and Moretti, 2011). Liquefaction and fluidization of near surface sediment may be triggered by a number of processes, such as rapid sedimentation, seismic waves, groundwater movement, breaking waves, and storm action (Maltman, 1994; van Loon, 2009). In general, identification of the trigger mechanism(s) of SSDS is important in understanding conditions at the time of, and shortly following deposition, in addition to evaluating their use as possible indicators of basin tectonism. Combinations of multiple processes and mechanisms are often responsible for the formation of SSDS, resulting in a range of complex bedforms (van Loon, 2009).

This paper describes a variety of SSDS and associated biogenic structures that are exposed in a large outcrop of the Paleoproterozoic Gordon Lake Formation of the Huronian Supergroup in the vicinity of Bruce Mines, Ontario, Canada. The objective of this project was to evaluate the origin and possible trigger mechanisms that produced the SSDS and to determine the role of microbial mats in their formation. The abundance and variety of SSDS in the study area provides further clues regarding the paleodepositional environment and local basin conditions during and shortly after deposition.

2. Geological setting

The SSDS described here are found in the Gordon Lake Formation of the Huronian Supergroup. The Huronian Supergroup is a Paleoproterozoic succession of primarily siliciclastic rocks that forms part of the Southern Geological Province of Ontario, Canada (Fig. 1). It

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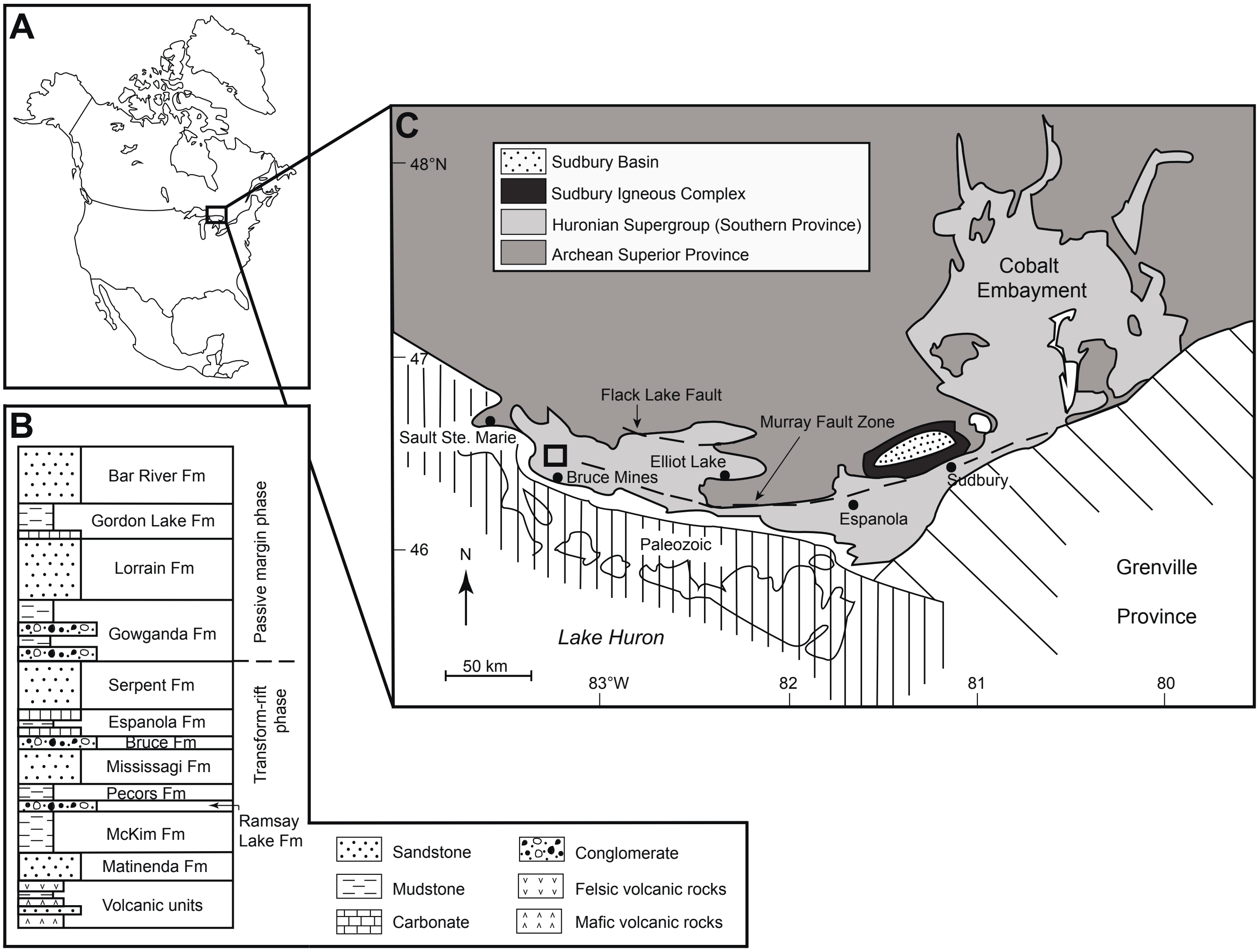

Fig. 1. Simplified geologic map of the distribution of the Huronian Supergroup north of Lake Huron with major fault zones. The study area is located approximately 11.5 km north-northwest of Bruce Mines (small black box). Modified from Young et al. (2001).

is well exposed along the north shore of Lake Huron, and extends northeast into the Cobalt Embayment. Maximum U-Pb ages of 2450 + 25/ − 10 Ma (Krogh et al., 1984) and 2452.5 ± 6.2 Ma (Ketchum et al., 2013) were determined from zircon in a rhyolite unit near the base of the supergroup, whereas primary baddeleyite from gabbro intrusions that cut the stratigraphy provide a minimum age limit of 2219.4 ± 3.5 Ma (Corfu and Andrews, 1986). Rasmussen et al. (2013) proposed an alternative upper age limit of ca. 2.31 Ga, which was determined from zircon in purported tuff beds of the Gordon Lake Formation. These zircons, however, have been interpreted as having a detrital rather than volcanic origin (Young, 2014).

Young and Nesbitt (1985) proposed that the Huronian Supergroup was deposited in a tectonic setting that evolved from rift basin to passive margin. Similarly, Long (2004, 2009) suggested that the succession formed in a pull-apart basin that later transitioned into a passive margin. The Huronian Supergroup is composed of five groups: the Elliot Lake, Hough Lake, Quirke Lake, and Cobalt groups, as well as the informal Flack Lake group. The Hough Lake, Quirke Lake and Cobalt groups contain tripartite divisions (Roscoe, 1957; Wood, 1973; Card et al., 1977; Young et al., 2001; Long, 2004) that are interpreted as having been sequentially deposited by glaciers, deltas and fluvial systems (McDowell, 1957; Card et al., 1977; Long, 1978, 2009; Chandler, 1988a; Robertson and Card, 1988). Soft-sediment deformation structures have been reported throughout the Huronian Supergroup, a stratigraphic summary of which is found in Table 1.

The Huronian Supergroup contains a record of Earth's transition from a reducing to oxygenated atmosphere. Evidence supporting low atmospheric oxygen is provided by sulphur isotopes in pyrite (Zhou et al., 2017), and the presence of detrital uranium-bearing minerals in the Matinenda Formation (Elliot Lake Group). Red beds in the Gowganda and Lorrain formations (Cobalt Group), and in the Gordon Lake and Bar River formations (Flack Lake group) indicate that the atmosphere was oxygenated at the time the upper half of the stratigraphic succession was deposited.

2.1. Gordon Lake Formation

The Gordon Lake Formation is the second youngest formation in the Huronian Supergroup and is part of the Flack Lake group. It is 300–1100 m thick and generally agreed to have been deposited along a continental shelf; a transgressive relationship has been interpreted between the Gordon Lake Formation and overlying Bar River Formation (Hill et al., 2016). Red beds, evaporites, hematite ooliths, and microbially induced sedimentary structures (MISS) have been reported from the formation, suggesting that the atmosphere at the time of deposition contained a significant amount of oxygen (Wood, 1973; Chandler, 1988b; Baumann et al., 2011; Hill et al., 2016). Existing evidence for microbial colonization at the time of deposition includes MISS in the Flack Lake area (Hill et al., 2016) and fenestral fabrics in dolostone in the Bruce Mines area near the base of the formation (Hofmann et al., 1980).

The Gordon Lake Formation is fine-grained overall and is composed