Ichnology, depositional environments and stratigraphy of the Upper Ordovician Stony Mountain Formation in the Williston Basin, Canada

A thesis Submitted to the College of Graduate and Postdoctoral

Studies in Partial Fulfillment of the Requirements for the Degree of

Master of Science in the Department of Geological Sciences University

of Saskatchewan Saskatoon

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ACKNOWLEDGEMENTS

I thank my grandparents for the financial support. I could not have survived in Canada without their help. I thank my wife for accompanying and always being supportive to my goals, no matter what they are. I appreciate all my friends in Canada, local and international, especially the ichnology group, for the happy memories and spending precious time together. Same amounts of appreciations are given to my Taiwanese friends that scattered around the world for walking me through the past two difficult years. Last but not least, I sincerely appreciate Gaby and Luis for providing the opportunity for this graduate study. Regardless the tough funding circumstance, they still found a way to support me. My academic path would have been way shorter without them. I appreciate every single revision process and enjoy seeing my sentences underlined with rewriting requests. They demonstrated rigorous standards in sciences and taught me the way of scientific communication. If there is any achievement in my master degree, it is attributed to them. They are not only the best advisors in academy but also the witnesses in my wedding. They are not going to miss any life course of their students (especially one of them). They are "second parents" in Canada to all the ichno-kids.

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CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW

The Williston Basin is one of the intracratonic basins of North America, together with the Hudson Bay, Michigan, and Illinois Basins. These basins are independent of the development of megasutures, situated on continental lithosphere in between Appalachian-Ouachita, Cordilleran, Innuitian and East Greenland orogens (Quinlan, 1987). Traditionally, the basin was regarded as an elliptical structural depression of 345,000 km^2 bordered by tectonic boundaries, namely the Churchill Superior Province to the East, the Transcontinental arch and the Sweetgrass-Battle River arch to the South and the Meadow Lake Escarpment to the Northwest (Gerhard et al., 1991). However, the Ordovician epeiric sea carbonates deposited beyond this area, and their present distribution is constrained by later erosion. In the specific case of the Williston Basin, erosion on the Trans-Continental Arch, Severn Arch, Peace River Arch, and Sweetgrass-North Battlefield Arch removed some of the underlying deposits in the East, Northeast, Northwest, and West of the basin respectively (Fig. 2.1A) (Norford et al., 1994).

Although the Ordovician stratigraphy in the basin has long been investigated due to petroleum potential, especially the Red River Formation in the USA (Derby and Kilpatrick, 1985; Ruzyla and Friedman, 1985; Husinec, 2016), arguments arose while attempting detailed stratigraphic correlation regarding the complicated facies distribution and stacking pattern in the sequence. For instance, common tripartite carbonate-evaporite cycles in the Ordovician were interpreted as shallowing-upward (Roehl, 1967; Clement, 1985; Derby and Kilpatrick, 1985; Ruzyla and Friedman, 1985) or brining-upward sequences (Kendall, 1976; Longman et al., 1983, 1984; Longman and Haidl, 1996). The former model argues that the boundaries between members are diachronous, and cycles were produced by progradation. On the contrary, the latter model proposes that the boundaries between members are isochronous because of layer-cake stratigraphy and basin-wide environmental changes. Still, an alternative model suggests a stable sea-level accompanying an increase in temperature, due to lacking sedimentary features that are indicative of shallowing in the basin (Pratt and Haidl, 2008). Discrepant interpretations of the depositional environments to the epeiric sea carbonates are central to this debate.

Epeiric sea carbonates in deep-geological time remain enigmatic since the carbonate factory and oceanic conditions, such as chemistry and hydrodynamic, lack modern analogs despite the considerable amount of detailed research performed to date

(Pratt and Holmden, 2008; James and Jones, 2016). During the Ordovician, the Laurentia intracratonic basins were submerged by the vastly extended epeiric sea (Munnecke et al., 2010). These intracratonic basins may be over a thousand km across, with very gentle depositional gradients and shallow basinal water depths (Burchette and Wright, 1992). Distinctively different depositional settings of the epeiric sea result in energy zonation which is remarkably different to that of self-edge setting (Heckle, 1972; Immenhauser, 2009). Therefore, the depositional model of epeiric seas traditionally referred to the epeiric platform model (Shaw, 1964; Irwin, 1965. More recently, Lukasik et al. (2000) proposed an epeiric ramp model in which the proximal epeiric ramp mimics the epeiric platform setting, and the distal epeiric ramp is storm-dominated (Aigner, 1985). Reappraisal of the existing depositional models and calibration based on detailed facies analysis are essential to enhance our understanding of Ordovician carbonates in the Williston Basin.

The Stony Mountain Formation is ideal for refining subenvironments of Ordovician epeiric sea carbonate since it composed of one depositional cycle (Elias et al., 2013b). Regardless the arguable duration of the sequence, a similar depositional pattern was shown in comparable units, such as the Horseshoe Mountain Member of the Big Horn Dolomite, in Wyoming, USA (Holland and Patzkowsky, 2009; Holland and Patzkowsky, 2012). Whereas previous studies focused on the body-fossil record in the Williston Basin, in particular, corals (Elias, 1983; Young and Elias, 1999), bryozoans (Lobdell, 1992) and brachiopods (Jin and Zhan, 2001; Young et al., 2007), the trace-fossil record has been commonly overlooked. The application of ichnology in carbonate systems is still in its infancy (Knaust et al., 2012; Savrda, 2012; Tapanila and Hutchings, 2012), in contrast to the much more refined ichnologic models currently used to delineate sedimentary environments and to identify sequence stratigraphic surfaces in siliciclastic systems (Pemberton et al., 1992; Buatois and Mángano, 2011). The excellent trace fossil preservation in the Stony Mountain Formation makes this unit ideal to test the utility of ichnology in the Ordovician epeiric sea carbonates.

Different subdivisions of the Stony Mountain Formation have been adopted not only between Saskatchewan and Manitoba, but also between outcrop and subsurface. For instance, the Stony Mountain Formation was divided, from base to top, into the Hartaven, Gunn and Gunton members in Saskatchewan (Kendall, 1976). In Manitoba, the formation was divided into the Gunn, Penitentiary, Gunton and Williams members based on type sections in the outcrop belt (Elias et al., 2013b), whereas the formation was divided into the Hartaven, Gunn/Penitentiary and Gunton members in the subsurface of southwestern Manitoba (Nicolas and Barchyn, 2008). The placement of the Williams Member is under debate, whether at the last stage of the Stony Mountain Formation (Elias et al., 2013b) or the base of the Stonewall Formation (Martiniuk, 1992; Norford et al., 1998). This confusion most likely results from marked sedimentary facies variability across the basin. A more precise correlation and member subdivision are expected based on detailed sedimentary facies analysis.

The primary objectives of this research project are to collect sedimentologic and ichnologic data in the study area in order to characterize each subenvironment in the Upper Ordovician epeiric sea deposits, leading to a more precise stratigraphic delineation. This study combines outcrop and subsurface information (Table 1.1), and is the first of its kind to evaluate the dynamic of epeiric seas through the integration of ichnologic and sedimentologic analysis. Chapter 2 integrates both ichnofacies and ichnofabric approaches to refine the depositional environments and establish a facies model of the Stony Mountain Formation. Chapter 3 discusses the definition and distribution of the Williams Member, further evaluating its distribution and correlation at a basin scale. The results of this study are not only expected to be applied to the Ordovician strata in the Williston Basin but also Ordovician epeiric sea deposits in other intracratonic basins in North America.

Drillhole	Location	Core interval	Province
Choiceland no. 1	13-03-050-18W2	545.6–558.7 m	SK
Imperial Hartaven	02-11-010-09W2	2260.4–2282.3 m	SK
Superior Bata no. 2	06-34-042-28W3	1295.4–1310.6 m	SK
Tappit et al Kisbey	04-02-008-06W2	2324.5–2343 m	SK
LSM-11	11-02-035-07W1	11–51.8 m	MB
M-01-82	07-18-011-02E1	6.3–34.4 m	MB
M-01-83	04-09-011-02E1	4.7–31 m	MB
M-01-84	04-15-019-01W1	17–64 m	MB
M-02-69	02-14-013-02E1	0–21.1 m	MB
M-02-88	04-11-018-01W1	40–80.1 m	MB
M-02-96	03-28-044-11W1	11–63.1 m	MB
M-03-74	01-21-011-01E1	2.0–54.9 m	MB
M-03-78	12-07-040-10W1	73.6–116.9 m	MB
M-04-80	10-03-029-10W1	136.7–172 m	MB
Gulf Minerals Minitonas	03-29-036-25W1	381–423.1 m	MB
Tudale Neepawa	15-29-14-14W1	534–586.4 m	MB

Table 1.1. Details of well locations and cored intervals for the cores studied in the Williston Basin, Canada.

CHAPTER 2: ICHNOLOGY AND DEPOSITIONAL ENVIRONMENTS OF THE UPPER ORDOVICIAN STONY MOUNTAIN FORMATION IN THE WILLISTON BASIN, CANADA

Charlie Y.C. Zheng, M. Gabriela Mángano, Luis A. Buatois, Ichnology and depositional environments of the Upper Ordovician Stony Mountain Formation in the Williston basin, Canada: Refining ichnofacies and ichnofabric models for epeiric sea carbonates: *Palaeogeography, Palaeoclimatology, Palaeoecology*, submitted on December 29, 2017.

ABSTRACT

Ordovician epeiric sea carbonates in intracratonic basins of Laurentia are enigmatic due to their unique depositional settings in the absence of modern analogs. The origin of carbonate-evaporite cycles in the Williston Basin is still under debate; some studies interpreted them as "shallowing-upward" sequences, others as "brining-upward" sequences. Since existing models of epeiric seas cannot apparently satisfy the interpretation of facies variation in the Upper Ordovician Stony Mountain Formation, reappraisal of its depositional environments is crucial. Six subenvironments, neritic marine, nearshore marine, open lagoon, restricted lagoon, peritidal sand shoal and peritidal flat, are interpreted along the depositional profile. The *Cruziana* ichnofacies occurs in storm beds and fair-weather deposits formed in neritic (between fair-weather and storm wave bases) and nearshore (around fair-weather wave base) marine environments. The depauperate *Cruziana* ichnofacies is present in open- and restricted-lagoon environments, indicating a shift from fully marine to stressed conditions. In the open lagoon, composite ichnofabrics related to omission surfaces illustrate the low rates of background sedimentation interrupted by event deposition and early cementation. The decreased size of discrete burrows in the restricted lagoon is attributed to reduced oxygenation under stagnation rather than hypersalinity. The peritidal complex includes high-energy sand shoals and low-energy tidal flats. Sporadic bioturbation characterizes these environments. Whereas rapid sedimentation in sand shoals may have prevented bioturbation, the hostile condition of periodically exposed tidal flats may have also been detrimental for organisms. Monospecific colonization took place only in associated subtidal environments. Overall, ichnofacies analysis records changes from open to

restricted conditions along the epeiric ramp, whereas ichnofabrics yield insights into depositional dynamics within subenvironments. These results are expected to be of use for the study of other ancient Paleozoic epeiric sea carbonates.

2.1 Introduction

During the Ordovician, the low-relief Laurentia (North America) was situated across the Equator. A greenhouse climate at the time allowed for the highest sea-level during the Paleozoic, and continental submergence was extensive (Munnecke et al., 2010). The vastly extended shallow sea water (epeiric seas) were characterized by pervasive carbonate deposits in North America, and biostratigraphic correlations of these carbonate sections span intracratonic basins (Webby et al., 2004; Cocks and Torsvik, 2011). For instance, the same brachiopod communities occurred in both the east and west margin of Laurentia during the Middle and Late Ordovician (Potter and Boucot, 1992). Likewise, the representative Richmondian brachiopod faunas of the Cincinnati area of Ohio and New York states were also recorded in Manitoba (Jin and Zhan, 2001). Maximum expansion of the epeiric sea occurred with the acme of sea-level highstands during the early Late Ordovician (Miller et al., 2005; Haq and Schutter, 2008), which is marked by the Red River-Stony Mountain Solitary Rugose Coral Province (Elias, 1981). This province originated by a major transgression in the early Cincinnatian and had a duration of nine million years (Elias, 1991; Elias et al., 2013a), spanning across central and western USA and most of Canada, and extended from Greenland to northern Mexico (Fig. 2.1A).

These epeiric sea deposits are enigmatic since the depositional settings of the ancient carbonates are fundamentally different from typical shelf margin settings. Unlike relatively narrow shelf margin settings, intracratonic basins may be over a thousand kilometer across, with very gentle depositional gradients and shallow basinal water depths (Burchette and Wright, 1992). Furthermore, the absence of modern analogs for oceanic conditions and hydrodynamic modeling in that period leave their depositional setting equivocal, despite the considerable amount of detailed research performed to date (Pratt and Holmden, 2008; James and Jones, 2016).

Multiple approaches, including the study of both lithofacies and biofacies, as well as trace-fossil analysis, are essential to better understand the depositional setting of epeiric seas. Whereas ichnology has already proved to be a powerful tool in delineating sedimentary environments in siliciclastic systems (Pemberton et al., 1992; Buatois and Mángano, 2011), it is recently burgeoning within the field of carbonate systems (Knaust et al., 2012; Savrda, 2012; Tapanila and Hutchings, 2012). With most studies dealing with the ichnologic characterization of modern and Quaternary Bahamian-type carbonates (Curran, 2007), ancient examples, in the early Paleozoic in particular, are scarce (Osgood, 1970; Pickerill et al., 1984, 1987; Pak and Pemberton, 2003; Pak et al., 2010; Mángano et al., 2016; Zhang et al., 2017).

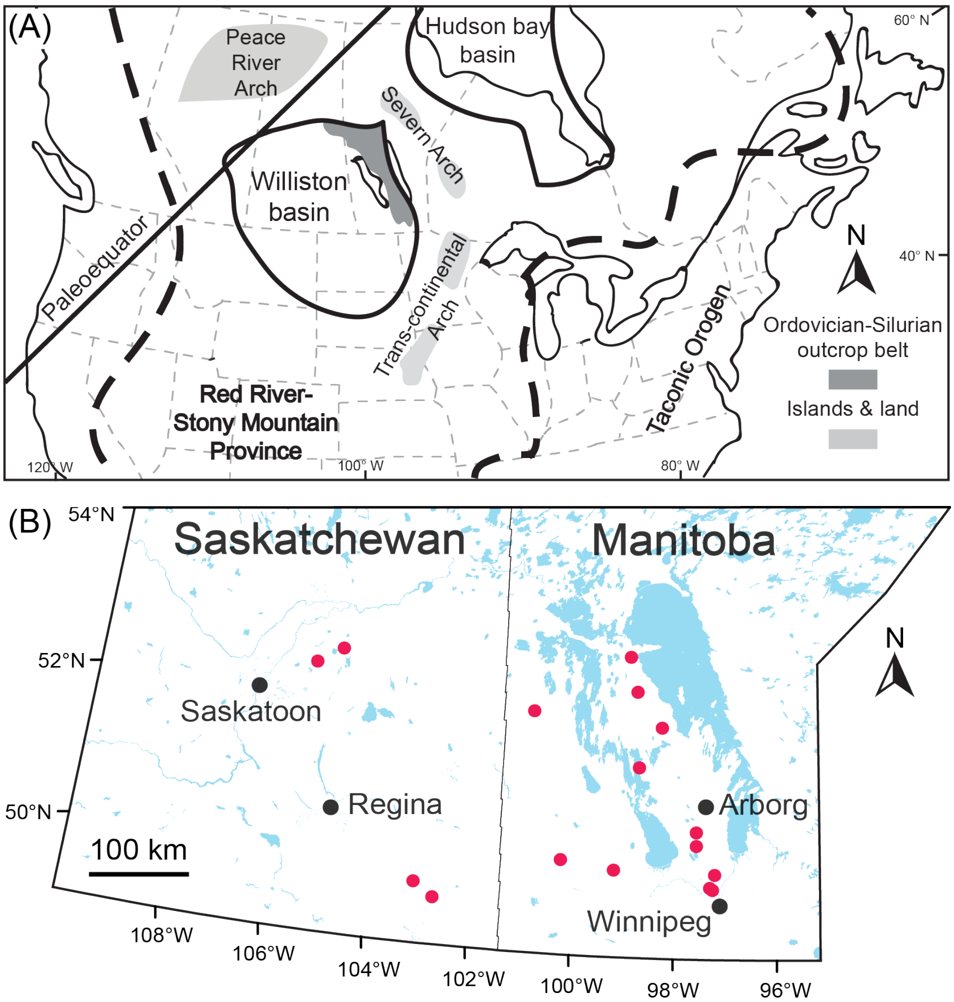

Fig. 2.1. A: Paleogeographical map showing the maximum distribution of the Late Ordovician epeiric sea in North America outlined by the Red River-Stony Mountain Province (modified from Elias *et al.*, 2013a with paleogeographical information from Pratt and Haidl, 2008). B: Location map of the cores and outcrops in this study.

The Stony Mountain Formation in the Williston Basin records deposits of the Late Ordovician (Richmondian) epeiric sea. The purpose of this study is to document trace fossils and apply ichnologic concepts to the study of this formation, aiming to refine the depositional setting of epeiric seas in the Ordovician. Whereas previous research focused on ichnology is limited, the abundance of well-preserved trace fossils makes ichnology an ideal tool for this study. The results demonstrate the utility of ichnology for delineating sedimentary subenvironments and for elaborating on sedimentary dynamics in carbonate systems.

2.2 Geological Background

2.2.1 Paleogeography and stratigraphy of the Williston Basin in the Ordovician

The Williston Basin is one of the largest cratonic-interior basins in the Ordovician. It was situated south of the Equator, bordered by the Trans-Continental Arch to the east, and separated from the Hudson Bay Basin by a series of islands to the north which composes the Severn Arch. The western limit was the result of an upland area which later became Peace River Arch (Fig. 2.1A) (Osadetz and Haidl, 1989; Kent, 1994; Pratt and Haidl, 2008). The Transcontinental Arch is proposed to be the source area of siliciclastic materials introduced into the basin (Porter and Fuller, 1959; Fuller, 1961; Witzke, 1980). Besides the greatest subsidence locus located in northwestern North Dakota, some intrabasinal structures were suggested to affect the depositional patterns as well (Norford et al., 1994; Kreis and Kent, 2000). The Ordovician carbonates deposited way beyond the range of the Williston Basin. Tectonically driven supersequences bounded by major unconformities were introduced to correlate these shallow-sea deposits in North America (Sloss, 1963). For instance, within the carbonate succession of the Tippecanoe Sequence (a 2nd-order sequence), the Big Horn Group, was correlated with the Montoya Group of west Texas and New Mexico, the Fremont Dolomite in Colorado, the Fish Haven Dolomite and Ely Springs Dolomite of Nevada, the Whitewood Dolomite of South Dakota, and the Big Horn Dolomite of Wyoming (Ross et al., 1982). In the Williston Basin, the Tippecanoe Sequence, which spanned from the Late Ordovician to the early Silurian, unconformably overlies the upper Cambrian-Lower Ordovician Deadwood Formation. Beyond the eastern erosional limit of the Deadwood Formation, however, the Tippecanoe Sequence rests directly on Precambrian rocks (Kent and Christopher, 1994; Norford et al., 1994). The sequence begins with a marine transgression from the southeast, leading to deposition of the Winnipeg Formation, comprising shale and glauconitic siltstone to sandstone, followed by an unconformity. The overlying Big Horn Group was formed as a result of another major transgression and is characterized by cyclic sedimentation, comprising burrow-mottled carbonates in the Lower Red River Formation and two carbonate-evaporite cycles in the Upper Red River Formation. Separated by argillaceous carbonates of the lower Stony Mountain Formation, the next two carbonate-evaporite cycles consist of the upper Stony Mountain and the overlying lower Stonewall Formation (Kendall, 1976). The Ordovician-Silurian boundary was considered disconformable, and placed at the top of the Stonewall Formation (Fig. 2.2A) (Demski et al., 2015). Finally, the overlying Silurian Interlake Group was truncated by Devonian erosion, terminating the Tippecanoe Sequence.

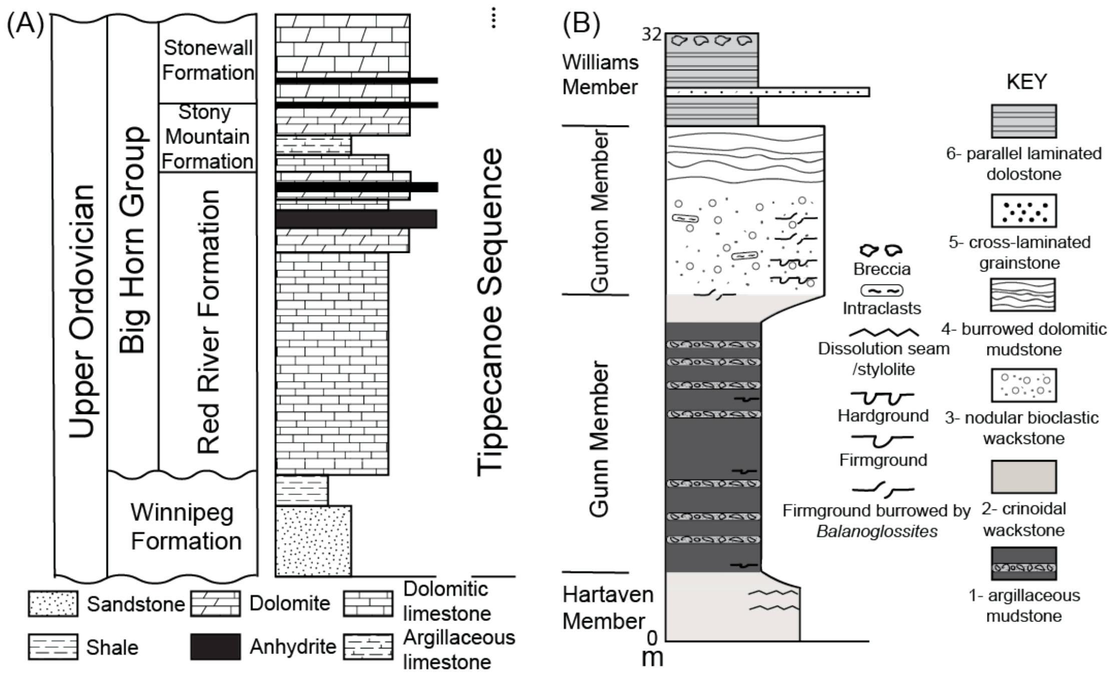

Fig. 2.2. A: Lithostratigraphy of the Upper Ordovician Tippecanoe sequence in the Williston Basin, illustrating repetitive tripartite cycles in the Big Horn Group (modified from Kendall, 1976). B: Composite geological column of the Stony Mountain Formation, illustrating the distribution of facies within the sequence.

2.2.2 Tripartite cycles in the basin

The carbonate-evaporite cycles are common in the Williston Basin, and typically contain bioclastic wackestone or mudstone biomicrite at the base, which grade upwards into thinly bedded to thickly laminated, slightly argillaceous dolomite and are capped by bedded to nodular anhydrite (Kendall, 1976; Kent and Christopher, 1994). The tripartite stratigraphy reflects periodically open-restricted basin conditions. The Late

Ordovician cycles (lower Big Horn Group) are well documented because of petroleum exploration, but their origins are still under debate. While some studies interpreted them as "shallowing-upward" sequences (Roehl, 1967; Clement, 1985; Derby and Kilpatrick, 1985; Ruzyla and Friedman, 1985; Husinec, 2016), others explained them as "brining-upward" sequences (Kendall, 1976; Longman et al., 1983, 1984; Longman and Haidl, 1996). The former model argues that the boundaries between members are diachronous, and cycles were produced by progradation. On the contrary, the latter model proposes that the boundaries between members are isochronous because of layer-cake stratigraphy and basin-wide environmental changes. Hence, the cycles resulted from increasing basin hypersalinity accompanied by shallowing, as a consequence of evaporative down-draw and basin edge emergence (Kendall, 1976). Moreover, an alternative model challenged both scenarios, indicating that a lack of sedimentary features demonstrating significant shallowing suggests a stable sea-level. In this scenario, the cycles were formed as a result of an increase in temperature (Pratt and Haidl, 2008). Conflicting interpretations of the sedimentary environments are at the core of this controversy.

2.2.3 Stony Mountain Formation Cycle

The Stony Mountain Formation comprises one of the carbonate-evaporite cycles, although the capping anhydrites are commonly missing and are only preserved at the basin center (Bezys and McCabe, 1996). Paleontological evidence from this formation, in particular, corals (Elias, 1983; Young and Elias, 1999), bryozoans (Lobdell, 1992) and brachiopods (Jin and Zhan, 2001; Young et al., 2007), suggests that the cycle is made up of one 3rd-order depositional sequence (Stewart, 2012; Elias et al., 2013b). The Stony Mountain Formation cycle records a shallowing-upward trend leading to a more restricted environmental condition, which resulted in a decrease of the abundance and diversity of fossils. A similar conclusion was drawn for comparable units in the Horseshoe Mountain Member of the Big Horn Dolomite, in Wyoming, USA (Holland and Patzkowsky, 2009; Holland and Patzkowsky, 2012). However, different scales of sequences were proposed. The cyclicity through the succession was considered to be the stacking of parasequences (4th-5th-order sequences), and the three cycles of the Red River and Stony Mountain formations in the Williston Basin were interpreted as an analog to three parasequences. Further, an increase in amplitude and duration of eustatic fluctuations, driven by greenhouse-icehouse climate change during the late

Katian, was suggested (Holland and Patzkowsky, 2012).

Different stratigraphic subdivisions have been adopted in Saskatchewan and Manitoba. The Stony Mountain Formation is divided into the Hartaven, Gunn and Gunton members in Saskatchewan (Kendall, 1976), whereas in Manitoba this formation was subdivided into the Gunn, Penitentiary, Gunton and Williams members based on the type sections in the outcrop belt (Elias et al., 2013b; Zheng et al., 2017) (Fig. 2.3).

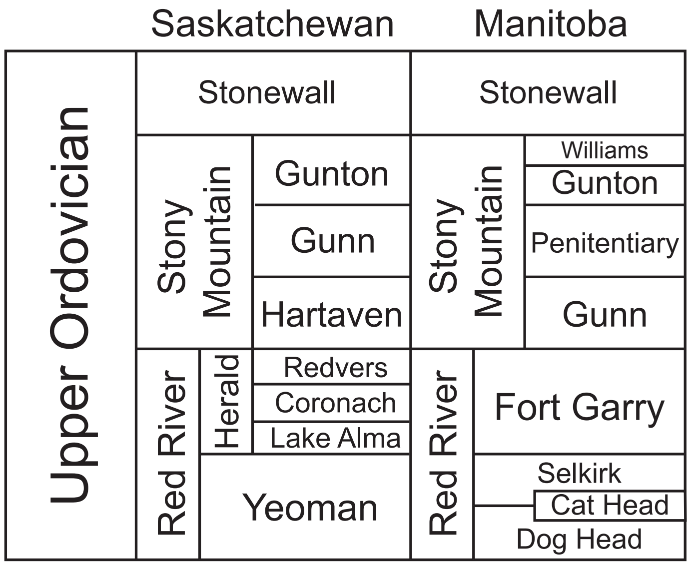

Fig. 2.3. Upper Ordovician stratigraphy in the Williston Basin illustrating different subdivisions between Saskatchewan and Manitoba (Saskatchewan subdivisions are taken from Kendall, 1976; Manitoba subdivisions are taken from Elias et al., 2013b).

2.3 Methods

Stratigraphic sections were measured at the Stony Mountain Quarry and the Sylvian Quarry in Manitoba. In addition, four cores from southeastern Saskatchewan and fifteen cores from Manitoba have been logged (Fig. 2.1B, Table 1.1). Twenty-eight thin sections representative of the facies identified were taken from samples of outcrops and cores in order to refine the lithologic description. Simplified geologic columns were made by integrating outcrop and core information. Dolomitization is common in all studied sections, with the degree varying at different locations. Therefore, applying detailed microfacies analysis is difficult. On the contrary, visibility of ichnofabrics was enhanced by dolomitization in many cases. Therefore, emphasis is put on the ichnologic analysis rather than microfacies analysis in this study.

2.4. Results

2.4.1 Depositional cycle

Through the analysis of various trace-fossil assemblages preserved in the succession of the Stony Mountain Formation, changes of hydrodynamic energy along the depositional profile are inferred and a transgressive to regressive- upward trend is apparent. Regardless of the arguable order of the sequence, the depositional cycle is similar to equivalent units in the Rock Creek beds of the Horseshoe Mountain Member, Wyoming (Kolata, 1976; Holland and Patzkowsky, 2009, 2012). It is suggested herein that the Stony Mountain Formation, which is bounded by two possibly subaerially exposed sequence boundaries, records a transgressive-regressive succession. The transgressive and regressive intervals are separated by a greenish lime mud containing a maximum flooding surface. Different sequence architectures at various locations within the basin are interpreted as reflecting proximal to distal expressions. Detailed analysis of the sequence-stratigraphic architecture is beyond the scope of this study and will be addressed elsewhere.

2.4.2 Facies

Six facies (F1-6) have been defined and interpreted to represent neritic marine, nearshore marine, open lagoon, restricted lagoon, peritidal sand shoal and peritidal flat. Facies change along basinal trend aside; a typical distribution of the facies within the Stony Mountain Formation is illustrated in the simplified column (Fig. 2.2B). Facies 1 constitutes most of the Gunn Member with the most distal part preserved in southeast Manitoba. Facies 2 is the predominant facies in the Hartaven Member and usually topped Facies 1 at the uppermost part of the Gunn Member before grading into the Gunton Member. The Gunton Member is widespread in the Williston Basin, making up by Facies 3 and 4. Typically, Facies 3 grades into Facies 4 upward. Finally, the uppermost part of the cycle is recorded in the Williams Member, which consists of Facies 5 and 6. A single thin bed of dolomitic lime mud containing angular clasts of the same lithology of the underlying facies and overlain by dolomitic mudstone occurs at the top of the Williams Member towards the North of Manitoba and terminates the Stony Mountain Formation sequence. Most contacts between facies are gradual, with the exception of Facies 6 which is sharp based and Facies 5 which displays scoured bases. On the other hand, the contact between the Gunn and Gunton members is commonly marked by a firmground with a distinctive bioturbation pattern. In order to assess degree of bioturbation, the bioturbation index (BI) of Taylor and Goldring (1993) has been adopted to evaluate the extent to which the primary sedimentary fabric has been reworked.

2.4.2.1 Facies 1. Skeletal argillaceous mudstone and sharp-based packstone and grainstone

Description

Facies 1 consists of up to 2 m thick, fully bioturbated (BI 5-6) mudstone and wackestone, punctuated by 5-20 cm thick, wavy, lenticular bedded, sharp-based, skeletal packstone and grainstone (Fig. 2.4A). This facies interval is up to 20 m thick, being thickest in southeast Manitoba and pinching out toward the northwest. A high diversity of brachiopods, solitary rugose corals, bryozoans, gastropods, bivalves, trilobites and echinoderms was recorded (Fig. 2.4B) (Elias, 1982; Young and Elias, 1999; Holland and Patzkowsky, 2009). Skeletal packstone beds are not bioturbated to sparsely bioturbated (BI 0-1), containing stacked, concave-up oriented disarticulated shells or normally graded, sorted bioclasts (Fig. 2.4C, D). Intercalated, lenticular, up to 10 cm thick, sharp-based grainstone beds tend to be unfossiliferous and display low-angle stratification, which may represent hummocky cross stratification (Fig. 2.4H). Some loosely packed, complete and non-abraded fossils, commonly brachiopods, are 3-5 centimeter wide and encased within carbonate-mudstone (Fig. 2.4G). Deep-tier *Chondrites* (both large and small) is the dominant trace fossil in the mudstone (Fig. 2.4E), whereas some intervals preserved abundant shallow-tier trace fossils, such as *Palaeophycus tubularis*, *Planolites annularis*, *Teichichnus rectus*, *Rhizocorallium* isp., *Nereites missouriensis*, *Phycosiphon incertum* and some undetermined horizontal structures. Up to 7 cm thick, mudstone layers lacking bioclasts and characterized by undetermined burrows (BI 1-2) infilled by the overlying lime-muds are common in several intervals (Fig. 2.4F).

Fig. 2.4. Selected photographs of Facies 1, documenting the neritic marine environment. A: Bioturbated mudstone punctuated by packstone in the outcrop, Stony Mountain quarry, Manitoba. B: A lenticular layer of bioclastic packstone. C: Fossiliferous packstone made up of stacked, disarticulated shells, representing a high diversity biota. D: Sharp-based, normally graded packstone overlain by a firmground, representing proximal tempestites. E: Fully bioturbated mudstone dominated by *Chondrites* isp. F: Undetermined burrows in an early-cemented layer. G: Well-preserved, non-abraded fossils encased within lime-muds, representing parautochthonous concentration. H: A wavy bed of grainstone (up to 10 cm thick) with possible low angle cross-lamination and scoured base illustrating a distal tempestite. A, B, G, and H are from the Stony Mountain quarry, Manitoba. C and E are from M-3-74 and M-2-88, subsurface Manitoba, respectively. D is from Tappit et al. Kisbey 5, subsurface Saskatchewan. F is from M-4-80, subsurface Manitoba. ***Ch***: *Chondrites* isp.

Interpretation

The abundant and diverse skeletal fauna, including brachiopods, corals, bryozoans and trilobites, suggests fully marine environments (Elias, 1982; Young et al., 2008; Elias et al., 2013b). The presence of the archetypal Cruziana Ichnofacies points to neritic, fully marine conditions. Further, alternation of fully bioturbated mudstone and non-bioturbated to sparsely bioturbated grainstone indicates alternation of slow background sedimentation and rapid event deposition, respectively. Similar facies have been documented in storm-dominated ramp systems elsewhere, occurring between fair-weather wave base and storm-wave base (Aigner, 1985; Seilacher and Aigner, 1991). Normally graded, erosively based, wavy to lenticular packstone with sorted bioclasts or concave-up orientation of disarticulated shells is interpreted as proximal tempestites. Other stacked-out, erosively based lenticular beds with basal lags and possible hummocky cross stratification and lacking bioclasts are interpreted as distal tempestites (Kidwell et al., 1986; Kidwell, 1991; Fürsich, 1995). Firmgrounds commonly occur under shelly event deposits, because early diagenesis tends to selectively cement erosional mud surfaces (Seilacher, 1982). The early-cemented mudstone layers that overly shell beds or occur elsewhere within Facies 1 units can also be interpreted as event deposits since their higher cementation potential is associated with greater carbonate content influx derived by storms (Fig. 2.4D, F) (Fürsich, 1982). The style of passive fill in the undetermined burrows from the stiff mudstone layers is also suggestive of firmgrounds since the lime mud infill was piped down from overlying sediments, contrasting with the surrounding early-cemented mudstone. Locally well-preserved and non-abraded shells “floating” in lime mudstone indicate time-averaging (Kidwell and Bosence, 1991), suggesting a low rate of net sedimentation that leads to autochthonous or parautochthonous shell concentrations adjacent to the habitat of these animals. This is consistent with the fact that brachiopods were most abundant in mid-ramp settings in the early Paleozoic.

2.4.2.2 Facies 2. Crinoidal Packstone

Description

Facies 2 consists of sharp-based, crinoidal packstone and skeletal wackestone. Mud content decreases in this facies with respect to Facies 1 and gradually mixed with peloidal grains. In outcrop, this facies is characterized by the amalgamation of two 50 cm thick wavy beds (Fig. 2.5A). In core, up to 1 m thick packstone beds composed dominantly of fine to silt sand-size peloids together with distinct crinoid bioclasts, forming up to 5 m thick intervals, represent this facies. Intercalated, 10-20 cm thick wackestone commonly contains wavy, irregular mud laminae. Layered bioclasts (BI 0-1) display elements of a highly diverse biota having a similar composition to that of Facies 1, but non-abraded fossils are absent (Fig. 2.5B). The packstone portions are commonly moderately bioturbated (BI 2-3), whereas muddy intervals are more intensely bioturbated (BI 4-5) with dominant *Chondrites* isp. and rare *Palaeophycus tubularis*. Partially bioturbated (BI 3), current-ripple cross-laminated packstone is locally preserved. Dissolution seams and stylolite are common throughout the section.

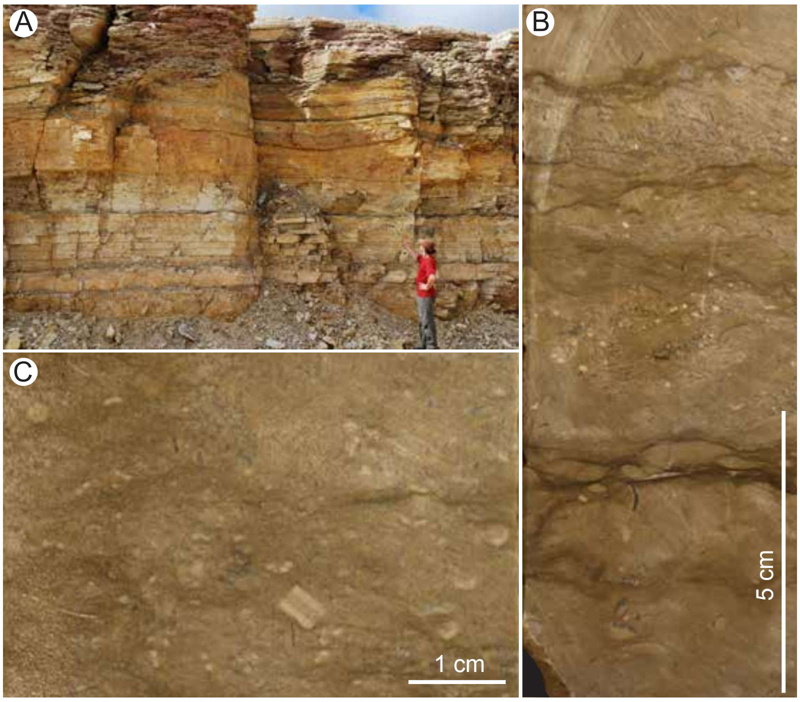

Fig. 2.5. Selected photographs of Facies 2, documenting the nearshore marine environment. A: Stacking of two wavy beds in the outcrop, Sylvian quarry, Manitoba. B: Layered hydro-bioclasts with dissolution seams, from Imperial Hartaven, subsurface Saskatchewan. C: Characteristic crinoid fossils of nearshore marine deposits, from Imperial Hartaven, subsurface Saskatchewan.

Interpretation

Facies 2 is interpreted as formed in a nearshore marine environment, around fair-weather wave base. The highly diverse biota comparable to Facies 1 is indicative of fully marine conditions, but the increased peloid content and grain size suggest a shallower-water environment near the carbonate factory. Bedded hydro-bioclasts together with the absence of non-abraded fossils indicate that the bioclasts were transported. In addition, the characteristic crinoids suggest shallow-water, wave agitation around fair-weather wave base (Fig. 2.5C) (Flügel, 2010; Botting et al., 2013). The primary sedimentary fabric was altered due to compaction, particularly the intervals of mixed peloidal sands and carbonate muds. However, stacked wavy beds and preferential preservation of deeper-tier burrows imply amalgamation of episodic beds (see section 2.4.3.2). Locally preserved current-ripple cross-lamination (<10 cm thick beds) is also indicative of relatively high hydrodynamic energy, although the limited preservation in cores prevents differentiation if this is due to currents or waves.

2.4.2.3 Facies 3. Nodular dolomitic wackstone

Description

Facies 3 consists of 1-2 m thick, sharp-based, heterolithic nodular wackestone and packstone (Fig. 2.6A), containing mixed peloidal sands and calcareous algae. This facies dominates the Stony Mountain Formation section toward the northwest, forming intervals up to 26 m thick. Scarce, fragmented bioclasts evidence a low faunal diversity. The most abundant and diverse bioclasts are preserved at the lower part of facies 3 intervals. This is particularly illustrated by solitary rugose corals, which are relatively abundant in the lower part of these facies intervals, becoming sparse up section (Stewart, 2012). Intraclasts of bored cobbles are present (Fig. 2.6B) (Roehl, 1967). The dominant ichnotaxon is *Balanoglossites* isp., which in places is reworked by small *Chondrites* isp.; *Palaeophycus tubularis* is rarely present. Firmgrounds penetrated by *Balanoglossites* isp. are ubiquitous throughout section, but they tend to be particularly abundant towards the base of facies 3 intervals delineating their lower contacts (Fig. 2.6C). In places, such firmgrounds are expressed by an enrichment in pyrite content, resulting in dark surfaces. Hardgrounds bored by *Trypanites weisei* and undeterminate plug-shaped bioerosion structures are also more common in the lower part of the facies interval (Fig. 2.6D). Bioturbation is generally intense (BI 4-5) in the section, particularly close to basal contacts of this facies, resulting in the massive appearance of these deposits.

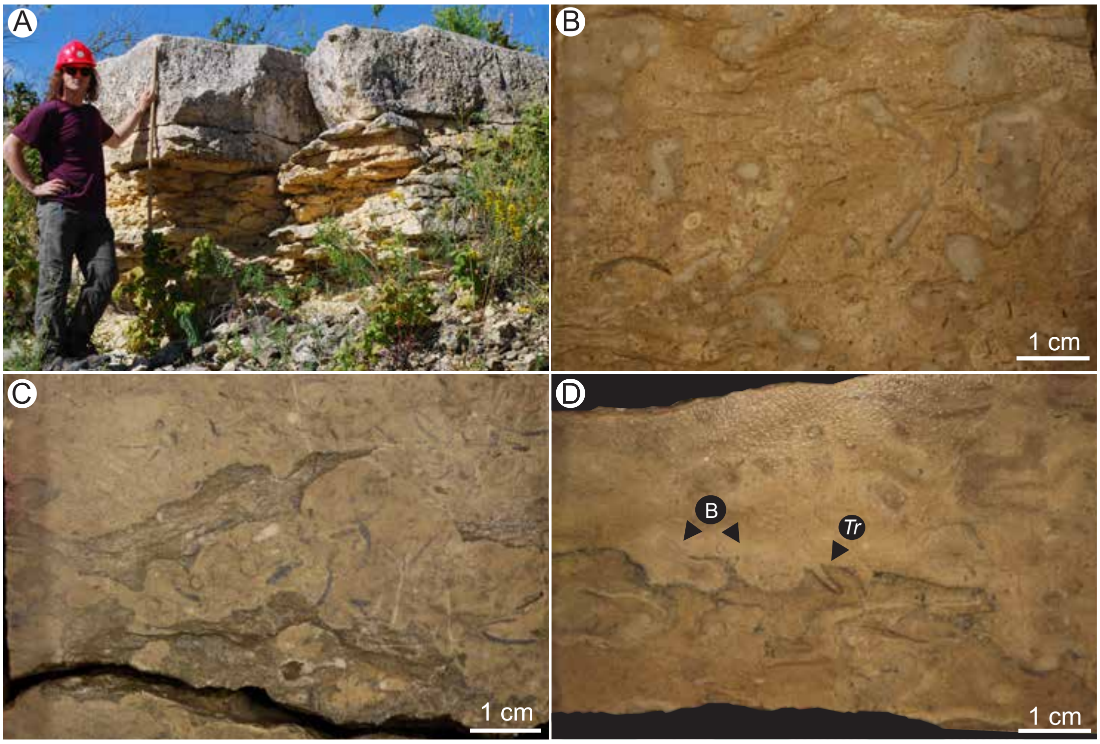

Fig. 2.6. Selected photographs of Facies 3, documenting the open lagoon environment. A: Massive nodular dolomitic wackestone in the outcrop, Stony Mountain quarry, Manitoba. B: Bored cobbles mixed with fragmented bioclasts in wackstone. C: Lower contact of the Gunton Member with a specific burrowing pattern produced by *Balanoglossites* isp. D: Hardground bored by *Trypanites weisei* and undeterminate plug-shaped bioeriosions. B, C, D are from Tappit et al. Kisbey 5, subsurface Saskatchewan. **B:** Undeterminate plug-shaped bioerosion structure, ***Tr:*** *Trypanites weisei.*

Interpretation

Although nodular limestones can be of diagenetic origin in a deep-water environment (Möller and Kvingan, 1988), the nodular bedding in this facies has been genetically related to *Thalassinoides*-like burrowing (i.e., *Balanoglossites* isp.) in shallow subtidal settings (Kendall, 1977; Myrow, 1995; Zenger, 1996; Jin et al., 2012). The presence of peloidal grains and calcareous algae is suggestive of protected, shallow-water conditions. In addition, the local presence of small corals may originate from adjacent patch reefs, suggesting relatively shallow waters. In a seaward direction, skeletal remains occur in open burrows representing tubular tempestites, indicating that the environment was affected by high-energy events (Wanless et al., 1988a; Tedesco and Wanless, 1991; Beavington-Penney *et al*., 2006). Semi-lithified and lithified surfaces commonly result from early carbonate cementation on shallow seafloors due to rapid synsedimentary carbonate precipitation, related to aragonite fossil dissolution of saturated calcite seas in the Ordovician, instead of prolonged hiatus driven by major sea-level change (Brett and Brookfield, 1984; Wilson et al., 1992; Palmer and Wilson, 2004). Development of short-lived hardgrounds in a seaward direction is related to sustained periods of non-deposition or low net sedimentation rate caused by constant wave reworking. This fair-weather wave reworking is also responsible for producing abrasion and fragmentation of skeletal grains and winnowing of muds that are transported into deeper-water environments (Lukasik et al., 2000; Flügel, 2010). The presence of bored intraclasts in this facies also demonstrates the role of early lithification and erosion (Taylor and Wilson, 2003). In a landward direction, the drastic decrease of bioclasts and hardgrounds and the higher sedimentation rate are the results of increased protection from highly energetic and erosive oceanic processes. Also, the presence of pyrite in some firmgrounds located inland suggests periods of anoxic condition within the sediment (Bertling, 1999), which may be related to more limited water circulation in lagoonal environments. The composite ichnofabric in this facies indicates a complicated relationship of depositional events and omission periods (see section 2.4.3.2). In short, the facies is interpreted as formed in a shallow, open-lagoon environment which is affected by sporadic high-energy events.

2.4.2.4 Facies 4. Dolomitic mudstone

Description

Facies 4 consists of 10-30 cm thick dolomitic mudstone locally with very fine-grained, peloidal sands (Fig. 2.7A), forming up to 8 m thick intervals. This facies also occurs forming up to 2 m thick intervals intercalated within Facies 3 packages. The degree of dolomitization is generally high and increases stratigraphically upward. The texture becomes "chalky" where the dolomitization is most severe. Fossils are absent; however, sparse fenestrae may be voids left by dissolved-out centimeter scale fossils. Angular, flat bioclasts (1-2 cm) occur locally within grainy intervals. Generally, this facies is sparsely bioturbated (BI 1-2) and dominated by small *Balanoglossites* isp. The more argillaceous intervals are highly bioturbated (BI 4-5), with small *Balanoglossites* isp., *Phycosiphon incertum* and small *Chondrites* isp. being present at some horizons.

Interpretation

Facies 4 is ascribed to a restricted-lagoon environment. Overall the muddy intervals and the absence of fossils are indicative of a protected and restricted environment, whereas the local presence of intraclast breccia and grinded, grainy sediment represents rare high-energy events. In the restricted lagoon, carbonate productivity was most likely hampered due to the poor water circulation. Consequently, sediments were supplied from the active carbonate factory nearby (Facies 3) (Demico and Hardie, 2002). As a result, the more bioturbated muddier intervals may reflect condensation due to a low rate of sedimentation. The vertical transition from Facies 3 to 4 suggests that these facies were adjacent to each other along a depositional gradient, with an open-lagoon environment situated at a more seaward direction and the restricted lagoon positioned landward. Lower degrees of cementation in a landward direction probably resulted from deprived subsurface water circulation (James and Jones, 2016) and absence of cementation materials, in this case, aragonitic fossils (Palmer and Wilson, 2004).

Fig. 2.7. Selected photographs of Facies 4 (A) and Facies 5 (B), documenting the restricted lagoon and peritidal sand shoal environments, respectively. A: Balanoglossites isp. in dolomitic mudstone, containing small, fragmental bioclasts, from M-4-80, subsurface Manitoba. B: Low angle cross-laminated grainstone with erosive base and lags of flat pebbles or brecciated intraclasts, from M-2-88, subsurface Manitoba. ***Ba:*** *Balanoglossites* isp.

2.4.2.5 Facies 5. Cross-laminated dolomitic grainstone

Description

Facies 5 consists of 8-15 cm thick, sharp-based, cross-laminated to cross-bedded grainstone (Fig. 2.7B), forming up to 1 m thick intervals. The grainstone is composed of well-sorted, medium sand-sized peloids. Mudstone drapes are locally mantling the foresets. Scoured bases are draped by a basal lag containing angular to flattened intraclasts, which invariably passes upward into the low-angle cross laminated to bedded interval. Bioclasts are absent, as well as bioturbation (BI 0). This facies is intercalated with Facies 6. Despite its general limited thickness, this facies can be traced over tens of kilometers in the subsurface.

Interpretation

This facies is interpreted as recording high-energy sand shoals at very shallow water depth. Scour bases and basal lags resulted from erosion of adjacent tidal-flat deposits. The mudstone drapes suggest tidal influence. Analog to the tidal inlet at Lee Stocking Island, Bahamas, currents induced by storms are ascribed to these erosive, high-energy deposits, whereas secondary bedforms in these sand bodies were controlled by tidal currents (Gonzalez and Eberli, 1997). Cross lamination record ripple migration and larger scale cross stratification may represent small composite dunes (Gonzalez and Eberli, 1997; Rankey and Reedar, 2012). The lack of skeletal debris further supports emplacement of these sand bodies in a restricted environment. Pristine preservation of the primary sedimentary fabric suggests that the colonizing window for bioturbation was insufficient because of rapid deposition.

2.4.2.6 Facies 6. Parallel-laminated dolostone

Description

Facies 6 is dominated by 10-20 cm thick, sharp-based, parallel-laminated dolostone, forming 3-5 m thick intervals (Fig. 2.8A). Body fossils are absent within the laminated intervals, while remnants of dissolved out shells forming 3-5 cm thick sheets are intercalated within the intervals (Fig. 2.8B). These thin sheets are sharp based, containing vugs or molds of dissolved out shells. Sheets, molds and fragmented bioclasts become more abundant towards southeast Manitoba. Parallel-laminated intervals are unbioturbated (BI 0), but thin sparsely bioturbated, 3-7 cm thick, mudstone layers containing monospecific suites of *Phycosiphon incertum* or small *Chondrites* isp. are preserved in-between parallel-laminated intervals. The bioturbation intensity of these burrowed intervals varies from low to high (BI 2-5). This facies is intercalated with Facies 5. In addition to the uppermost part of the Stony Mountain Formation, similar facies also occurs in the upper part of the Fort Garry Member in the Red River Formation.

Fig. 2.8. Selected photographs of Facies 6, documenting the peritidal flat environment. A: Parallel-laminated dolostone, from M-1-84, subsurface Manitoba. B: Sharp based thin layers (less than 5 cm) of molds and vugs, representing remnants of dissolved out bioclasts, from M-3-74, subsurface Manitoba.

Interpretation

While some authors have indicated deposition in intertidal to supratidal settings for the parallel-laminated dolostone (Roehl, 1967; Kendall, 1976; Clement, 1985; Derby and Kilpatrick, 1985; Ruzyla and Friedman, 1985; Husinec, 2016), others have estimated a water depth of 20-30 m, below fair-weather wave base, indicating that a critical increase in temperature has impeded benthic activity (Pratt and Haidl, 2008). The crinkly lamination formed by microbial mats, suggestive of upper intertidal to supratidal environments in the Paleozoic (James and Jones, 2016), is uncommon in the Stony Mountain Formation. In addition, structures that are indicative of subaerial exposure are probably absent, suggesting that the bulk of this facies was formed subaqueously. However, intercalations with the associated lagoon deposits (Facies 5) and overall stratal stacking pattern (indicative of overall shallowing for the whole formation) argue in favor of shallow-water deposition rather than sedimentation below storm wave base. In this scheme, the unbioturbated parallel-laminated intervals are envisaged as being situated in the lower intertidal zone (Ginsburg et al., 1977), whereas the bioturbated intervals are thought to record improved environmental conditions that allowed colonization by an opportunistic infauna under subtidal conditions. Thin layers of dissolved out small fossils intercalated within the succession are interpreted as storm events. The parallel-laminated intervals may have also resulted from reduced faunal activity under hypersaline conditions in the shallow subtidal zone, whereas the sporadic presence of bioturbated intervals suggests periods of refreshment (Hardie and Ginsburg, 1977; Wanless et al., 1988b). Accordingly, this is consistent with shallowing due to tidal-flat progradation, instead of local changes in salinity conditions. Comparable environmental shift in the Red River Formation was ascribed to tidal-flat progradation toward the basin center related to the reduction of accommodation space (Husinec, 2016). Therefore, this facies is best interpreted as shallowing-upward successions of tidal-flat progradation.

2.4.3 Ichnology of the Stony Mountain Formation

2.4.3.1 Ichnofacies distribution along the depositional gradient

The six environments interpreted are characterized by various trace-fossil assemblages, which in turn illustrate different ichnofacies. The neritic marine environment (Facies 1 and 2) is dominated by the *Cruziana* Ichnofacies, containing large and small *Chondrites* isp., *Planolites annularis*, *Teichichnus rectus*, *Rhizocorallium* isp., *Palaeophycus tubularis*, *Nereites missouriensis*, *Phycosiphon incertum,* and horizontal structures (Fig. 2.9, 2.10A). This trace-fossil assemblage occurs in moderate to low-energy marine settings characterized by the accumulation of organic detritus in the associated heterolithic sediment under relatively stable conditions (Pemberton et al., 1992; Buatois and Mángano, 2011). Deposit feeders prevail in this benthic community with secondary contribution by detritus feeders at the water-sediment interface. Abundance of food was indicated by intermittent dark-colored intervals completely burrowed by an abundant shallow-tier infauna in addition to deep-tier *Chondrites* isp. (Fig. 2.9F) (Wetzel and Uchman, 1998). The most distal facies (Facies 1), containing the maximum flooding surface and characterized by *Phycosiphon incertum* and *Nereites missouriensis,* sits within this neritic marine environment. The low ichnodiversity and high bioturbation intensity that characterize maximum flooding surfaces is consistent with slow rates of sedimentation and possible limited oxygen content.

Balanoglossites isp. dominates in the open-lagoon deposits (Facies 3), together with small *Chondrites* isp. and rare *Palaeophycus tubularis* (Fig. 2.10B). The depauperate nature of this assemblage indicates conditions that depart from fully marine conditions. The *Glossifungites* Ichnofacies indicated by *Balanoglossites* isp. in firmgrounds and the *Trypanites* Ichnofacies characterized by *Trypanites weisei* and undeterminate plug-shaped borings in hardgrounds are suggestive of rapid early cementation (Wilson and Palmer, 2006).

Balanoglossites isp. is also the dominant ichnotaxon in the restricted-lagoon deposits (Facies 4), followed by small *Chondrites* isp. and *Phycosiphon incertum* (Fig. 2.10C). A decrease in burrow size is apparent in these deposits with respect to the ichnofauna that characterizes more open-marine environments. Size decrease may be a strategy to cope with harsh conditions related to salinity changes or oxygen availability (Buatois and Mángano, 2011). In brackish-water environments, faunas are less diverse than their marine equivalents and usually opportunistic, resulting in simple, non-specialized burrows. These small burrows form monospecific suites, displaying sparse or intense bioturbation in specific intervals (Pemberton and Wightman, 1992; Buatois et al., 1997; Mángano and Buatois, 2004; MacEachern and Gingras, 2007). However, freshwater input may not effectively dilute waters in these large-scale lagoon environments, especially in areas situated distant from the coast. Dilution may only play a role if climate was sufficiently humid, providing significant discharge from the continent. Similarly, stressed benthic communities in restricted, hypersaline settings also result in low-diversity ichnoassemblages dominated by small and poorly specialized trace fossils (Gibert and Ekdale, 1999; Jaglarz and Uchman, 2010). Still, another controlling factor, depletion of oxygen, may drive the decrease in burrow sizes (Savrda and Bottjer, 1991), and can be associated to restricted hypersaline marine environments (Gibert and Ekdale, 1999; Jaglarz and Uchman, 2010). Under a greenhouse climate, discriminating these two factors is difficult since they both may have played a role under the stagnated water circulation that typifies these restricted environments. However, the absence of evaporites may indicate that salinity was perhaps only slightly above normal marine levels, suggesting that the main control on burrow size may have been oxygen deficiency.

In the most proximal deposits (Facies 6), bioturbation is absent in intertidal settings, where periodical subaerial exposure and perhaps higher salinity conditions may have been highly detrimental to animal activity. Only monospecific colonization of small *Phycosiphon incertum* or small *Chondrites* isp. are recorded during subtidal conditions (Fig. 2.10D). This assemblage reflects stressful conditions, most likely low-oxygen content in bottom and interstitial waters, which is consistent with shallow penetration by the infauna.

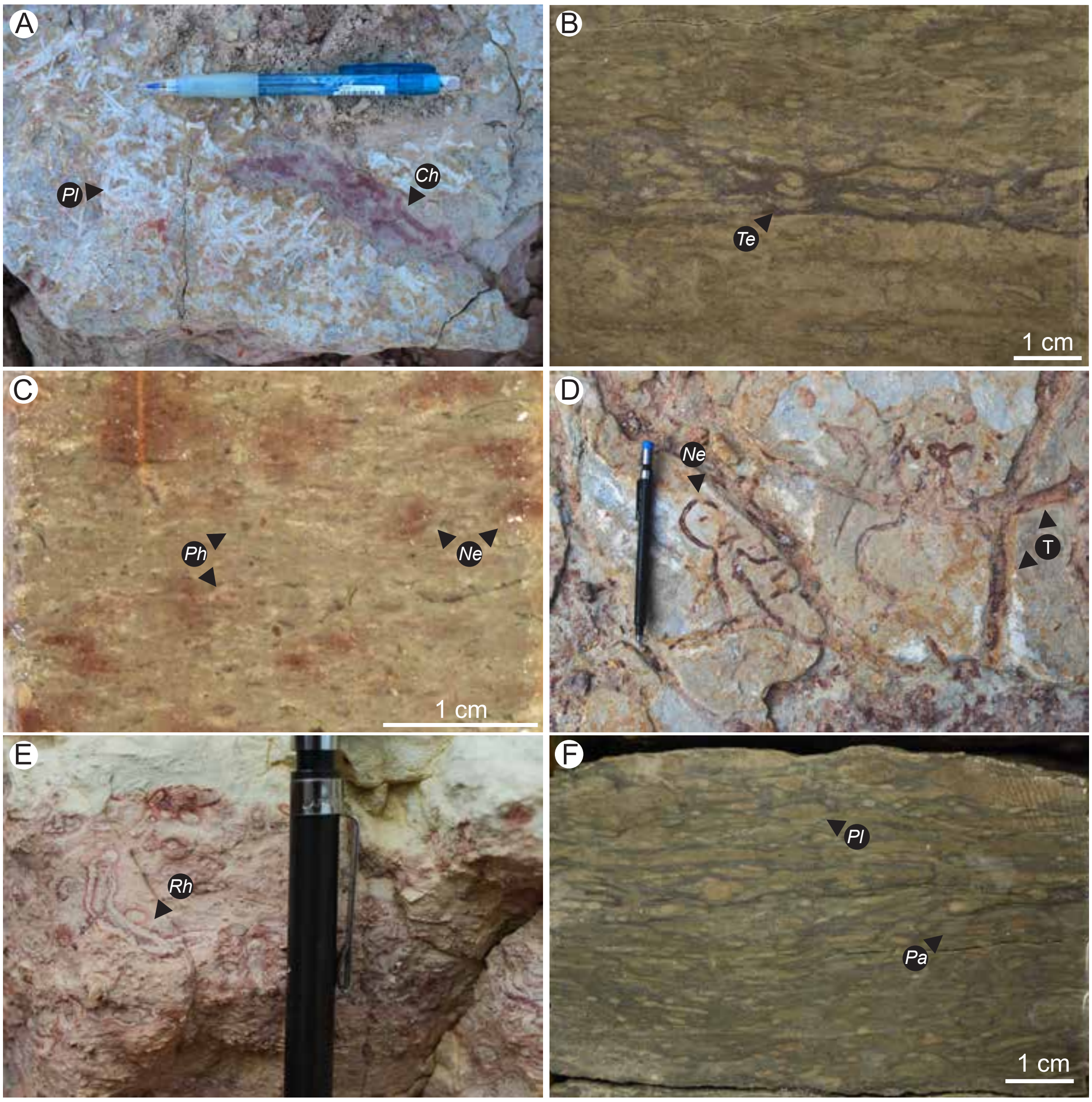

Fig. 2.9. Trace fossils of the *Cruziana* Ichnofacies in the Stony Mountain Formation. A: Cross-cutting relationship of burrows exhibiting the tiering structure. A layer of *Planolites montanus* truncated by a trial reworked by deep tier *Chondrites* isp. B, C, D, E: Examples of trace fossils of the *Cruziana* ichnofacies. F: Fully bioturbated, dark-color interval, dominated by horizontally developed burrows. A, D and E are from Stony Mountain quarry. B and F are from Tappit et al. Kisbey 5, subsurface Saskatchewan. C is from M-3-74, subsurface Manitoba. ***Ch:*** *Chondrites* isp., ***Ne:*** *Nereites missouriensis,* ***Pa:*** *Palaeophycus tubularis,* ***Ph:*** *Phycosiphon incertum,* ***Pl:*** *Planolites annularis,* ***Rh:*** *Rhizocorallium* isp. and ***Te:*** *Teichichnus rectus*.

Unlike lower Paleozoic siliciclastic successions in which nearshore facies are characterized by the *Skolithos* Ichnofacies, in places forming pipe rocks (Droser, 1991; Desjardins et al., 2010), this ichnofacies is missing in the Stony Mountain Formation. The *Skolithos* Ichnofacies is commonly preserved together with sedimentary structures indicative of bedform migration in high-energy, shallow-marine environments

(Pemberton et al., 1992; Buatois and Mángano, 2011; Desjardins et al., 2012). In the shallow neritic marine zone, which is typically characterized by more agitated waters, the *Skolithos* Ichnofacies is expected. However, structures indicative of migration of large bedforms are scarce in this succession, only represented to some extent by the high-energy sand shoals recorded in Facies 5. Instead, proximal areas are characterized by very low sedimentation rate that allowed intense bioturbation, non-deposition and formation of omission surfaces. In addition, the stagnant-hydraulic condition of the lagoon environment also inhibits the strategy of suspension feeding in more protected areas. In any case, it should be noted that *Skolithos* piperock is typically restricted to siliciclastic settings elsewhere.

2.4.3.2 Ichnofabrics

An ichnofabric comprises any aspect of the texture and internal structure of a substrate resulting from bioturbation and bioerosion at any scale (Bromley and Ekdale, 1986). Tiering, a central concept of the ichnofabric approach, is the vertical partitioning of the infaunal ecospace (Ausich and Bottjer, 1982), which can be identified through analysis of the cross-cutting relationship of burrows (Fig. 2.9A). By reconstructing the tiering structure of an infaunal community, various ichnofabrics can be characterized. This can then be used for deciphering aspects of taphonomic and depositional histories, such as completeness of the stratigraphic record (Wetzel and Aigner, 1986). The infaunal communities of the Stony Mountain Formation are assigned to particular facies along the depositional profile accordingly (Fig. 2.10). The use of the infaunal ecospace can be summarized into three main tiers: the deepest tier formed by both small and large *Chondrites* isp.; a mid-tier made by *Balanoglossites* isp., *Palaeophycus tubularis* and *Techichnus rectus*; and the shallowest tier characterized by *Planolites annularis, Rhizocorallium* isp., *Nereites missouriensis, Phycosiphon incertum* and other horizontal structures. Notably, *Chondrites* isp. may occupy mid tiers in more proximal settings.

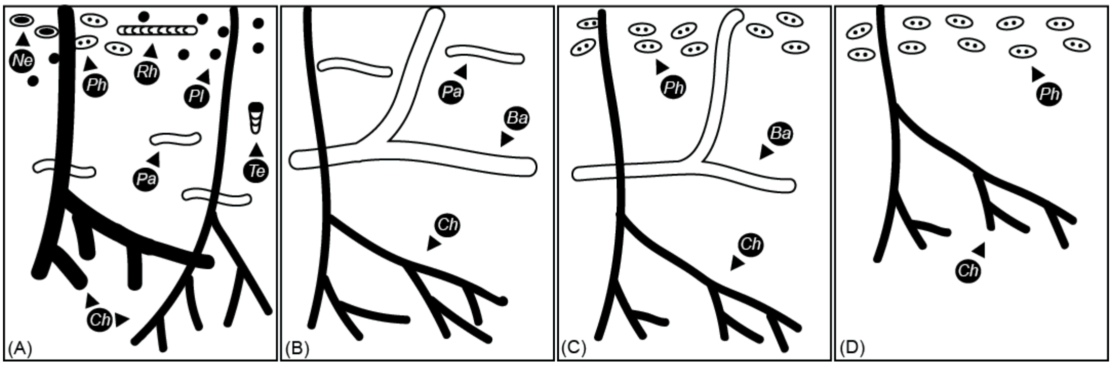

Fig. 2.10. Tiering diagrams of facies along the depositional profile, illustrating neritic marine, open lagoon, restricted lagoon and peritidal flat environments, from A to D accordingly. ***Ba:*** *Balanoglossites* isp.*,* ***Ch:*** *Chondrites* isp.*,* ***Ne:*** *Nereites missouriensis,* ***Pa:*** *Palaeophycus tubularis,* ***Ph:*** *Phycosiphon incertum,* ***Pl:*** *Planolites annularis,* ***Rh:*** *Rhizocorallium* isp. *and* ***Te:*** *Teichichnus rectus.*

Chondrites-Planolites-Nereites ichnofabric

This ichnofabric is dominated by deep-tier *Chondrites* isp., occurring in the mudstone of Facies 1 (Fig. 2.11A). Large and small *Chondrites* isp. commonly reworked shallow-tier burrows, including *Palaeophycus tubularis, Planolites annularis, Teichichnus rectus, Rhizocorallium* isp.*, Nereites missouriensis, Phycosiphon incertum* and some undetermined horizontal trails. Intensity of bioturbation is remarkably high (BI 5-6). The *Chondrites-Planolites-Nereites* ichnofabrics is the most diverse of the whole Stony Mountain Formation. This ichnofabric is the most abundant in Facies 1.

The dominance of *Chondrites* isp. in this ichnofabric is due to the vertical upward migration of the deep-tier infauna under slow and steady background sedimentation, therefore representing a composite ichnofabric. This ichnofabric reflects continuous bioturbation under gradual accretion of the sea floor (Bromley and Ekdale, 1986). Shallow tiers are only preserved right below storm beds, illustrating episodic sedimentation involving rapid burial of the resident community in the absence of significant erosion. Such rapid burial ceased bioturbation and preserved all tiers, including those structures emplaced in the mixed layer, forming frozen-tiering profiles (Fig. 2.12A) (Savrda and Ozalas, 1993; Orr, 1994; Taylor *et al*., 2003). Intense bioturbation and high ichnodiversity are consistent with fully marine conditions and sedimentation in distal settings. Specifically, these settings correspond to neritic marine areas situated between fair-weather wave base and storm wave base.

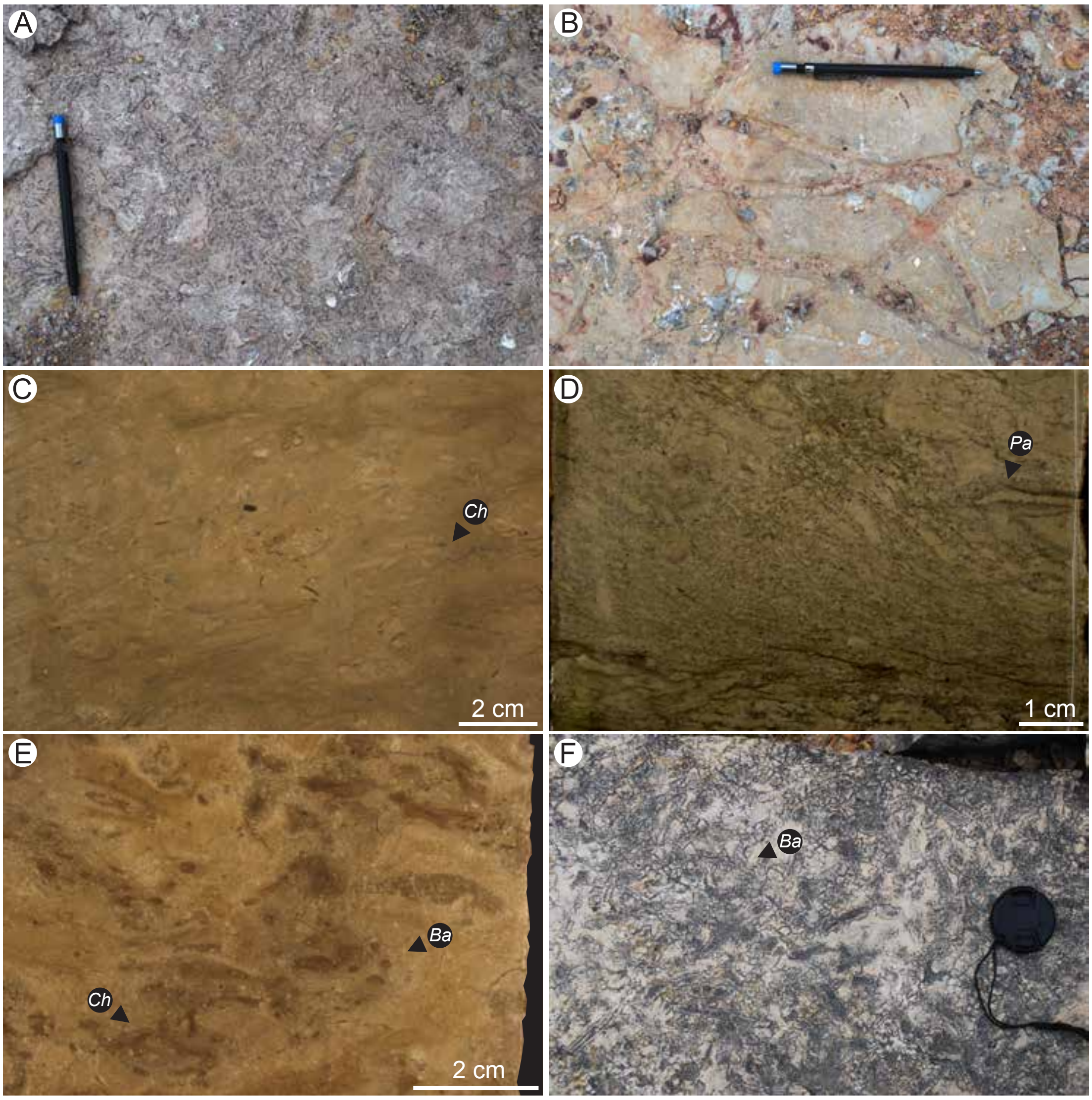

Fig. 2.11. Ichnofabrics in the Stony Mountain Formation. A: Bedding plain view of extensive *Chondrites* isp. bioturbation. B: Bedding plain view of horizontal trails at the top of an event bed. C: Preferential preservation of the deepest tier burrow, *Chondrites* isp., resulted from amalgamation. D: The cross-lamination is partially preserved at the base of the core interval, whereas the upperpart was mottled by bioturbation. E: A shaft of *Balanoglossites* isp. reworked by small *Chondrites* isp. F: Bedding plain view of intensive *Balanoglossites* isp. bioturbation in the lower Gunton Member close to the lower contact. A, B and E are from Stony Mountain quarry. C is from Imperial Hartaven, subsurface Saskatchewan. D and E are from Tappit *et al.* Kisbey 5, subsurface Saskatchewan. ***Ba:*** *Balanoglossites* isp., ***Ch:*** *Chondrites* isp. and ***Pa:*** *Palaeophycus tubularis.*

Nereites ichnofabric

This ichnofabric consists of abundant shallow-tier *Nereites missouriensis* and undetermined horizontal trails (3-5 cm wide) on the top of storm beds in Facies 1. Degree of bioturbation is low (BI 1-2). Tunnels of *Nereites missouriensis* are filled with less dense, finer-grained lime mud that are surrounded by grainier sediments of the host rock (Fig. 2.9D). These tunnels were developed close to the surface on the top of the storm beds without evidence of vertical migration. Some of the unidentified horizontal trails seem to display overcrossing or secondary successive branching and may be misinterpreted as *Thalassinoides* isp. (Fig. 2.11B). This ichnofabric is relatively rare and is intercalated with the *Chondrites-Planolites-Nereites* ichnofabric.

Exceptional preservation of surficial burrows at the top of storm beds is attributed to colonization of opportunistic organisms after storms under relatively low-energy conditions (Fig. 2.12C). Wetzel (2008, 2010) suggested that the *Nereites* producer adopted a double feeding strategy in response to fluctuation of organic matter content, namely detritus feeding during times of abundant food and deposit feeding during times of food scarcity. Further, oxygen content of interstitial waters decreased during food-rich periods, resulting in upward migration. As a result, the predominance of surficial burrows without evidence vertical migration may suggest abundant and constant supply of benthic food (Wetzel, 2010). The *Nereites* ichnofabric of the Stoney Mountain Formation is a simple ichnofabric formed during a single colonization event. As in the case of the *Chondrites-Planolites-Nereites* ichnofabric, the *Nereites* ichnofabric is present in areas located between fair-weather wave base and storm wave base.

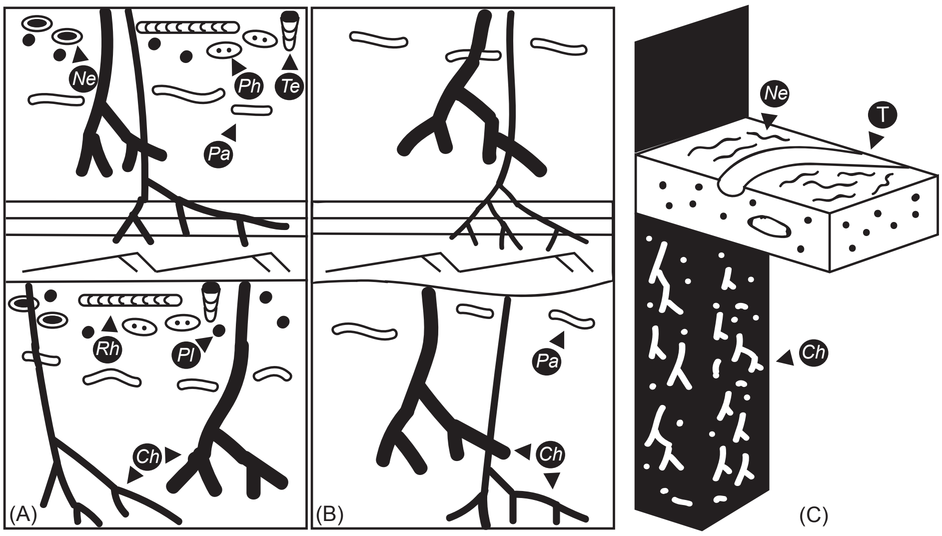

Fig. 2.12. Schematic illustrations of episodic deposition in the neritic marine environment. A: Episodic sedimentation with minor erosion, preserving shallow tiers. B: Episodic sedimentation with erosion, which removed shallow tier, preserving only deep tiers. C: Background sedimentation recording upward migration of deep tier Chondrites isp. seized by occasional events, characterized by exceptionally preserved trails. ***Ch:*** *Chondrites* isp*.,* ***Ne:*** *Nereites missouriensis,* ***Pa:*** *Palaeophycus tubularis,* ***Ph:*** *Phycosiphon incertum,* ***Pl:*** *Planolites annularis,* ***Rh:*** *Rhizocorallium* isp*.,* **T**: Trails *and* ***Te:*** *Teichichnus rectus.*

***Chondrites-Palaeophycus* ichnofabric**

This ichnofabric is dominated by deep-tier *Chondrites* isp. and rare, mid-tier *Palaeophycus tubularis* in wackestone and packstone, making up most of Facies 2 (Fig. 2.11C). Degree of bioturbation is low to moderate (BI 2-3) and exceptionally intense bioturbation (BI 4-5) is only reached in the muddier intervals. Overall, both ichnodiversity and degree of bioturbation are lower than in the ichnofabrics present in Facies 1.

Amalgamation due to repeated erosion resulted in the dominance of deep-tier *Chondrites* isp. Storm events in more proximal settings are usually conducive to the erosion of shallow-tier trace fossils, which commonly correspond to the fair-weather suite, resulting in the preferential preservation of deep tiers (Bromley, 1996; Buatois et al., 2015) (Fig. 2.12B). *Chondrites* is indicative of K-selected strategy and represents climax population (Bromley, 1996). Therefore, various degrees of bioturbation intensity in this composite ichnofabric may have resulted from taphonomic factors that depend on storm intensity and frequency. The *Chondrites-Palaeophycus* ichnofabric suggests strong erosion and amalgamation. It corresponds to shallow neritic marine settings, situated above fair-weather wave base.

***Palaeophycus* ichnofabric**

This ichnofabric contains monospecific suites of mid-tier *Palaeophycus tubularis*. It occurs at the top of current-ripple cross-laminated packstone of Facies 2 (Fig. 2.11D). Bioturbation indexes are typically low to moderate (BI 2-3).

The *Palaeophycus* ichnofabric may reflect the activity of an opportunistic infauna, related to rapid sedimentation. Although physical sedimentary structures are usually absent as a result of combined bioturbation and subsequent diagenesis, cross-lamination is still recognizable in places (Fig. 2.11D). Preservation of the primary fabric tends to be associated with the regressive phase when the degree of bioturbation is less intense due to shorter colonization windows resulting from higher sedimentation rates.

***Balanoglossites-Trypanites* ichnofabric**

This ichnofabric is characterized by two distinctive trace-fossil suites, the *Balanoglossites* firmground suite and the *Trypanites* hardground suite. The former consists of mid-tier *Balanoglossites* isp., in places extensively reworked by deep-tier *Chondrites* isp. The top of beds containing the *Balanoglossites* firmground suite displays a very diagnostic morphology with ridge-shaped or flat, sharp surfaces (Fig.

2.6C, 2.14). The *Trypanites* hardground suite consists of shallow-tier *Trypanites weisei* and undeterminate plug-shaped borings (Fig. 2.6D) and is present in flat surfaces. This ichnofabric occurs in the nodular wackestone of Facies 3. The *Balanoglossites*-*Trypanites* ichnofabric is intercalated with beds containing the *Balanoglossites* ichnofabric 1.

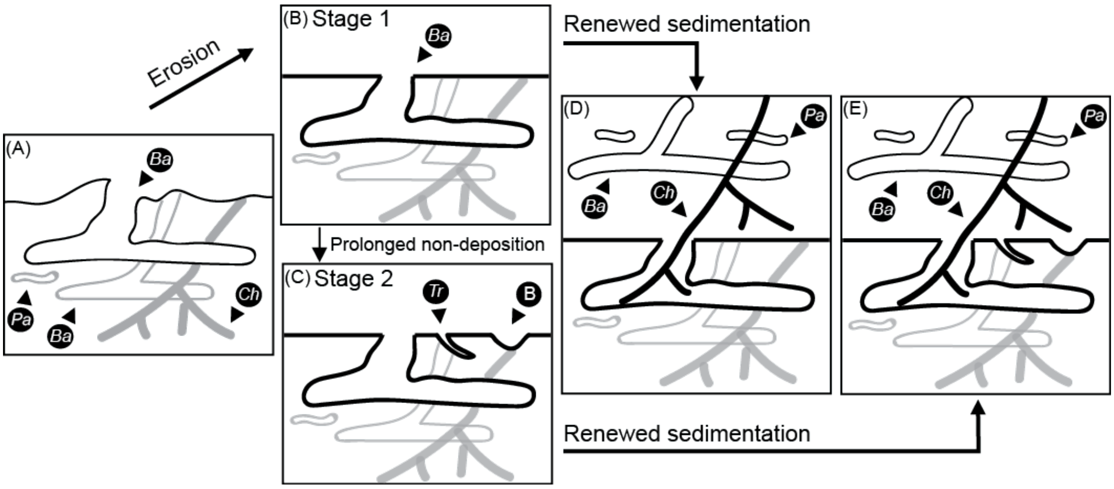

Fig. 2.13. Reconstruction of the ichnofabrics at omission surfaces. A. The cementation took place a few decimeters below the sea floor, whereas the pre-omission suite preserved *Balanoglossites* isp., *Chondrites* isp., and *Palaeophycus tubularis* (in grayish color), the omission suite *Balanoglossites* isp. produced the teepee shape burrow in the firm substrate. B. A slight erosion related to a high energy event exposed the firm layer followed by a period of non-deposition, which further cemented the surface. The pre-lithified omission suite, *Balanoglossites* isp., is still able to burrow into the surface at Stage 1. C. Prolonged non-deposition produced the hard substrate at Stage 2, only the post-lithified omission suite, *Trypanites weisei* and *?Palaeosabella* isp., colonized the lithified substrate. D. Recovery of sedimentation at Stage 1, sediments composed of post-omission suite, *Chondrites* isp., *Balanoglossites* isp. and *Palaeophycus tubularis,* piped into open burrows of *Balanoglossites*, resulting in intensive, confined *Chondrites* isp. burrowing. E. Recovery of sedimentation at Stage 2, a sharp, flat hardground separate the overlying post-omission suite and the underlying pre-omission suite, both contain the same ichnosuites of *Balanoglossites* isp., *Chondrites* isp., and *Palaeophycus tubularis*. Although lithified *Balanoglossites* isp. reworked by borers is expected, it is not observed in the section. ***Ba*****:** *Balanoglossites* isp., ***Ch*****:** *Chondrites* isp., ***Pa:*** *Palaeophycus tubularis*, ***?Pa*****:** *?Palaeosabella* isp. and ***Tr*****:** *Trypanites weisei*.

These substrate-controlled trace-fossil suites (omission suites) record the development of omission surfaces resulting from early lithification during times of negligible deposition, therefore representing a composite ichnofabric. The degree of substrate consolidation is marked by a different infauna in pre-lithification, firm substrates (Stage 1, Fig. 2.13) characterized by the *Balanoglossites* firmground suite and in post-lithification, hard substrates (Stage 2, Fig. 2.13) typified by the *Trypanites* hardground suite. Within this context, the *Balanoglossites* ichnofabric 1 underlying and overlying the omission surfaces may be understood as the pre-omission and post-omission suites, respectively. Whereas the pre-omission and post-omission suites represent colonization under background sedimentation, the omission suite reflects colonization during a hiatus (Goldring and Kazmierczak, 1974; Bromley, 1975; Kennedy, 1975; Mángano and Buatois, 1991).

The omission surfaces can be non-erosive or erosive. Non-erosive, intra-lagoonal omission surfaces are common throughout the section. These surfaces are characterized by convoluted, ridge-shaped surfaces resulting from burrowing by the *Balanoglossites* isp. producers during firmground conditions. Subsequent pyrite crystals associated with continuous cementation tend to outline these aforementioned surfaces. Similar structures were ascribed to "hummocky hardgrounds," indicating progressive, sufficiently rapid lithification to preserve the bioturbated seafloor (Bromley, 1975). Such non-erosive omission surfaces also mark the underlying contact with the Gunton Member (Fig. 2.6C), illustrating a hiatus during the shift from neritic marine to open-lagoon conditions. In particular, the *Balanoglossites* firmground suite was associated with the omission surface, resulting in open networks in the neritic marine mudstone. These open burrows may have enhanced permeability in the underlying sediments. In core, poorly defined *Balanoglossites* isp. display reddish, iron-oxide stained rings around indicating a period of omission and continuous cementation (Fig. 2.17). During renewed deposition, sediments from overlying layers were piped down into these cavities. On the contrary, erosive omission surfaces marked by sharp and flat contacts are most common at a seaward direction. For instance, truncated omission suites formed by open *Balanoglossites* isp. are intensively reworked by small *Chondrites* isp. of the post-omission suite (Fig. 2.14A). In other cases, these truncated open *Balanoglossites* isp. were infilled with subsequent high energy, storm deposits characterized by fragmented bioclasts (Fig. 2.14B). The hardgrounds which are representative of prolonged non-deposition related to continuous fair-weather wave reworking (Fig. 6D; Stage 2, Fig. 2.13) only occur in this type of omission surface. These erosive omission surfaces are indicative of high-energy events, possibly storms (Fig. 2.13). Continuous sea-floor cementation under low sedimentation rates was interrupted by rare episodic erosion and deposition, possibly derived from storms (Palmer and Wilson, 2004).

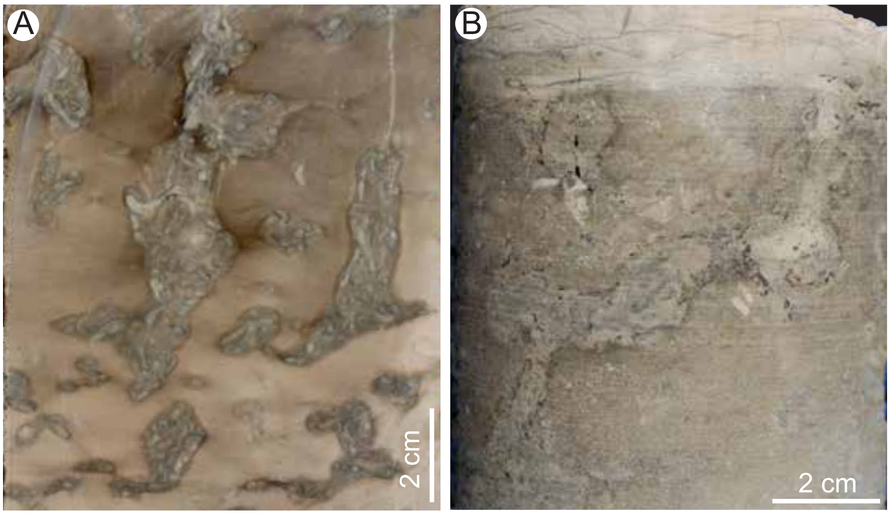

Fig. 2.14. Omission surfaces at Stage 1. A. The omission suite *Balanoglossites* isp. burrows intensively reworked by post-omission suite small *Chondrites* isp., from Superior bata no 2, subsurface Saskatchewan. B. Sharp omission surface at Stage 1, exhibiting omission suite *Balanoglossites* isp. burrows truncated by the erosion, from Choiceland no 1, subsurface Saskatchewan.

Balanoglossites ichnofabric 1

This ichnofabric is dominated by mid-tier *Balanoglossites* isp. (1-3 cm wide), which is commonly reworked by deeper-tier *Chondrites* isp., and by rare mid-tier *Palaeophycus tubularis*. It is preserved in the nodular wackestone of Facies 3 (Fig. 2.10B; 2.11E, F). Degree of bioturbation is intense (BI 4-5). Severe dolomitization and nodular formation tend to modify the primary burrow morphology imprinting a strong diagenetic signature.

Departure from fully marine conditions may have resulted in ichnodiversity reduction. However, the absence of shallow-tier burrows may suggest that erosion may have removed burrows emplaced close to the sediment-water interface. This seems to be particularly the case of *Phycosiphon incertum*, which is ubiquitous through most of the succession, therefore showing a wide environmental range. The massive, nodular appearance of this type of wackstone was attributed to burrowing (Kendall, 1977; Myrow, 1995; Zenger, 1996; Jin et al., 2012). In the specific case of the Stony Mountain Formation, several generations of *Balanoglossites* isp. may have formed composite ichnofabrics under low sedimentation rates with a continuously opened colonization window. In addition to the high density of *Balanoglossites* isp. in thick nodular wackstone, an extended colonization window, under a protected environment or low rates of sedimentation, is further suggested by the common reworking by deep-tier *Chondrites* isp. The *Balanoglossites* ichnofabric 1 is present in shallow, open-lagoon environments punctuated by storms.

***Balanoglossites* ichnofabric 2**

This ichnofabric is composed of mid-tier, small *Balanoglossites* isp. (less than 1 cm wide), representing the bulk of Facies 4 dolomitic mudstone. Rare, fragmented bioclasts present locally together with the burrows (Fig. 2.7A). Intensity of bioturbation is generally low (BI 1-2) within grainer portions of these deposit, although increased disturbance of the primary fabric (BI 4) is observed in thin (5-10 cm thick), more argillaceous intervals that show a significant decrease in *Balanoglossites* isp. size (3-5 mm wide) (the lower intervals in Fig 2.15A, B). These more intensely bioturbated, argillaceous intervals represent the transition from *Balanoglossites* ichnofabric 2 to the *Phycosiphon-Chondrites* ichnofabric.

The occurrence of rare fragmented bioclasts and grainer sediments indicates higher-energy event deposition, possibly storms. The discrete, sparse bioturbation in the coarser-grained deposits records a simple ichnofabric associated with event bed colonization. Stressful conditions, most likely due to limited oxygenation, are suggested by the reduced size of *Balanoglossites* isp. in comparison with similar burrows in the *Balanoglossites* ichnofabric 1. In addition, the sparse bioturbation may suggest that the colonization window was not constantly open. Further decrease in size of small *Balanoglossites* isp. in the argillaceous portions may record even more extreme stressful conditions, which eventually prevented bioturbation by the producer of *Balanoglossites* isp. landward. The highly argillaceous content in these more bioturbated intervals suggests lowered rates of sedimentation, most likely representing fair-weather conditions. The *Balanoglossites* ichnofabric 2 records bioturbation in restricted-lagoon environments, regularly affected by storm events.

***Phycosiphon-Chondrites* ichnofabric**

This ichnofabric is characterized by the presence of shallow-tier *Phycosiphon incertum* and mid-tier, small *Chondrites* isp. in mudstone of Facies 4 and 6. In places, only monospecific suites of *Phycosiphon incertum* are present. Associated deposits are characterized by intense (BI 4-5) to moderate bioturbation (BI 2-3). *Phycosiphon incertum* is commonly reworked by small *Chondrites* isp. in the intensely bioturbated intervals (Fig. 2.15A). In the most extreme case, small *Chondrites* isp. fully reworked the argillaceous substrate (Fig. 2.15B). In contrast, less bioturbated intervals are characterized by colonization of *Phycosiphon incertum* with faint, small *Chondrites* isp. penetrating from the top of mudstone intervals (Fig. 2.15C). This ichnofabric forms less than 7 cm thick, bioturbated intervals, sporadically preserved in argillaceous portions of Facies 4, intercalating with the *Balanoglossites* ichnofabric 2 (the lower intervals in Fig. 2.15A, B). This ichnofabric is also sparsely present in Facies 6, forming less than 5 cm thick intervals, intercalated with parallel-laminated intervals, although the degree of bioturbation is commonly lower (Fig. 2.15C, D).

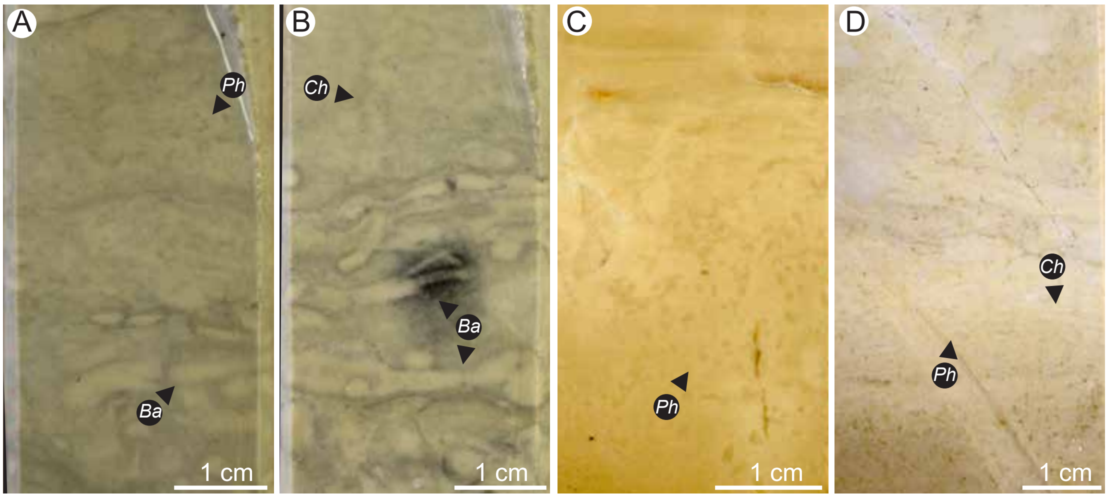

Fig. 2.15. A, B: Ichnofabric of the argillaceous portions of the restricted lagoon environment, contained size decreased burrows, from M-4-80, subsurface Manitoba. C, D: Ichnofabric of the shallow subtidal condition encased between peritidal flat. C shows monospecific *Phycosiphon incertum* colonization, from M-2-88, subsurface Manitoba. D shows *Phycosiphon incertum* colonization with background mottled by small *Chondrites*, from LSM-11, subsurface Manitoba. ***Ba*****:** *Balanoglossites* isp., ***Ch*****:** *Chondrites* isp. and ***Ph*****:** *Phycosiphon incertum.*

Whereas no trace fossils are preserved in the intertidal zone, the *Phycosiphon-Chondrites* ichnofabric is sparsely preserved within Facies 6, recording subtidal conditions related to flooding events. Different expressions of this ichnofabric may reflect extreme stress as a result of fluctuating environmental conditions, which in turn may have controlled the duration of the colonization window. Whereas *Phycosiphon incertum* is an opportunistic trace fossil that requires a short colonization window, the deep-tier small *Chondrites* isp are associated with a prolonged colonization window. Therefore, the less bioturbated intervals indicate a short duration of the colonization window that only allowed bioturbation by the producer of *Phycosiphon incertum*. The less bioturbated intervals containing monospecific suites of *Phycosiphon incertum* indicate that the refreshing events were transient, conceivably autogenic, induced by storm surges. Intense bioturbation is the result of reduced sedimentation rates (i.e., condensed sections) revealed by the extremely argillaceous content together with intense sediment reworking by the small *Chondrites* isp. producer. These intensely bioturbated intervals containing abundant small *Chondrites* isp. indicate long-lasting, allogenic flooding episodes, most likely representing a return to the restricted-lagoonal conditions in the shallowest subtidal zone between tidal-flat progradations. In any case, the overall intensity of bioturbation is lower in these deposits than in fully marine deposits, indicating restricted conditions in these proximal settings. The overall very low ichnodiversity provides further evidence that this ichnofabric records restricted, proximal settings.

Intercalation of *Balanoglossites* ichnofabric 2 and *Phycosiphon-Chondrites* ichnofabric in Facies 4 illustrates the alternation of contrasting environmental conditions. Whereas the storm related suite is dominated by *Balanoglossites* ichnofabric 2, the fair-weather suite is represented by the *Phycosiphon-Chondrites* ichnofabric. Refreshing of the restricted environment possibly happened along with higher-energy depositional events, which brought in sediments under higher-oxygen content and better circulation of sea water, providing sufficient oxygen level for the makers of small *Balanoglossites* isp. to thrive. Under restricted conditions during fair-weather times, only opportunistic *Phycosiphon incertum* and *Chondrites* isp. producers were able to colonize these proximal, stressful settings. In particular, the small *Chondrites* maker burrowed into the anaerobic underlying sediments (Bromley and Ekdale, 1984).

Unlike the fair-weather mudstone dominated by deep-tier, large and small *Chondrites* isp. in the neritic marine environments of the Stoney Mountain Formation, restricted deposits are characterized by, mid-tier, small *Chondrites* isp. Size reduction and decreased burrowing depth is characteristic of *Chondrites* in oxygen-depleted settings (Fig. 2.16) (Bromley and Ekdale, 1984; Savrda and Bottjer, 1991; Taylor et al., 2003).

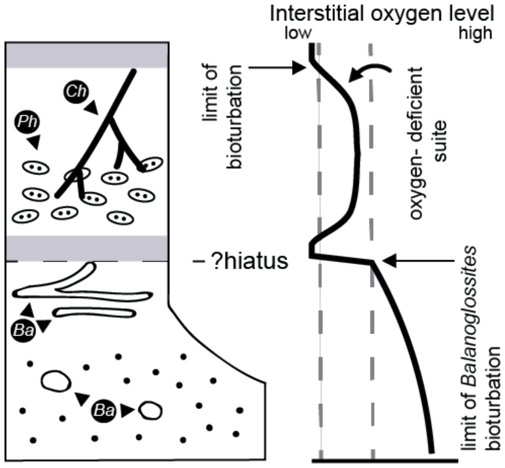

Fig. 2.16. The bioturbation of small *Balanoglossites* isp. was clogged by returning to oxygen depleted condition, perhaps accompanied with a period of non-deposition. Overlying *Phycosiphon incertum* colonization took place during oxygenation event, and small *Chondrites* isp. reworked this interval during the following extended oxygenation stage. The preservation of *Balanoglossites* isp. excluding *Chondrites* and the completeness of *Phycosiphon incertum* are indicative of the decrease in depth of the *Chondrites* isp. tiering. ***Ba*:** *Balanoglossites* isp., ***Ch*:** *Chondrites* isp. and ***Ph*:** *Phycosiphon incertum.*

2.4.3.3 Ichnodiversity vs. bioturbation intensity

The overall ichnodiversity of the Stony Mountain Formation is lower than that of other ichnofaunas recorded in both siliciclastic (Osgood, 1970) and carbonate (Pickerill et al., 1984, 1987) systems of Late Ordovician age. It is possible that this lower ichnodiversity may be partially ascribed to contrasting ichnotaxonomic philosophies (lumping vs splitting). Nevertheless, it is here argued that the main reason of this discrepancy is due to depositional setting. The Williston Basin is a shallow epicontinental basin with environments that fluctuated between neritic to epeiric seas, whereas more open-marine environments, such as peri-continental seas which grade into the open ocean (Heckel, 1972), may have supported higher levels of ichnodiversity. Therefore, the ichnodiversity trends in the Stony Mountain Formation most likely illustrates the open to restricted nature of the Williston Basin, with the highest ichnodiversity of *Cruziana* Ichnofacies in the neritic marine and a subsequent decrease of ichnodiversity in a landward direction. In the most extreme case, in the environment closest to the shoreline, only a few species could withstand the stressful conditions by decreasing their size significantly.

Overall, bioturbation intensity reflects hydrodynamic energy conditions, which typically decreases from settings below fair-weather wave base, characterized by fully bioturbated deposits, to the nearshore which is constantly disturbed by fair-weather waves. Further landward, in the inner protected lagoon, a decrease in hydrodynamic energy is apparent, but restriction of water circulation became a limiting factor, inhibiting colonization by burrowing organisms. As a result, these lagoonal deposits are characterized by lower bioturbation intensities. Sporadic highly bioturbated intervals are attributed to low rates of sedimentation and near normal marine conditions during refreshing events. The peritidal complex developed at the shallowest water depth, closest to coastal region. In this setting, erosion and rapid deposition within sand shoals prevented bioturbation. Only the establishment of subtidal conditions during flooding events provided long enough colonization windows for burrowing. It is in the neritic fully marine settings where intense sediment mixing and tiering is evident, as illustrated by ichnofabrics consisting of discrete, trace fossils emplaced in the transition layer overprinting poorly defined bioturbation mottlings of the mixed layer. These fully marine, regionally extensive deposits are representative of overall sediment mixing intensities at the basin scale, evidencing that the mixed layer was well established (see discussion in Mángano and Buatois, 2017).

2.5 Discussion

2.5.1 Balanoglossites vs. Thalassinoides

The origin of widespread Late Ordovician Tyndall type, *Thalassinoides* ichnofabric, was discussed by Jin et al. (2012), based on examples from the Selkirk Member of the Red River Formation. Several ichnofabric models were proposed, but the producer for Upper Ordovician *Thalassinoides* remains controversial (Kendall, 1977; Sheehan and Schiefelbein, 1984; Myrow, 1995; Ekdale and Bromley, 2003; Pak and Pemberton, 2003; Carmona et al., 2004; Gingras et al., 2004; Young et al., 2008; Pak et al., 2010). Similar ichnofabrics in the Middle Ordovician Volkov Formation of Russia have been assigned to the ichnogenus *Balanoglossites* (Knaust and Dronov, 2013). This ichnogenus comprises branched galleries displaying openings and acorn-, bulb- or lance-shaped side branches. Tunnels are unlined and locally striated, showing elliptical or circular cross sections and remarkable size variability within a single gallery system (Knaust, 2008). Unlike *Thalassinoides*, which is characterized by simultaneous branching with a relatively regular pattern and representing burrows in softgrounds and firmgrounds, *Balanoglossites* is a complex trace fossil representing both burrows and borings, and characterized by highly irregular branching patterns. In addition, it has been suggested that many Ordovician *Balanoglossites* have been misinterpreted as *Thalassinoides* (Knaust and Dronov, 2013).

Several key features diagnostic to *Thalassinoides*, such as anastomosing and enlargement at branching junctions, are missing in the examples from the Stony Mountain Formation. Further, a well-developed boxwork is not observed in this *Thalassinoides*-type ichnofabric. Instead, the burrows are characterized by irregular secondary successive branching. The burrows are unlined, although usually stained and mineralized. Vertical to inclined shafts are envisaged short, up to 15 cm long. Rarer, long, vertical burrows are evident at the contacts of environments switching from the neritic marine to open lagoon. The burrowers excavated up to 80 cm downward into neritic marine mudstone from a firmground contact above and then branched horizontally. This pattern is similar to *T. bacae* described by Bromley and Ekdale (2003). However, the branching of elliptical tunnels seems to reflect reuse of structures (Fig. 2.17). We suggest that the burrow systems traditionally assigned to *Thalassinoides* in the Stony Mountain Formation and related strata are better assigned to *Balanoglossites*. However, we question the boring ability of the *Balanoglossites* maker in the Stony Mountain Formation. The sharp surfaces are products of subsequent erosive events overprinting on the omission suite, *Balanoglossites* burrows, at a firmground stage (Stage 1, Fig. 2.13). The firmness of substrates during burrowing is shown by the ragged outline of *Balanoglossites*. Most important the burrows tend to avoid shells, rather than cut through them. Some authors ascribed the producer of *Balanoglossites* to polychaetes based on their ability to chemically bore into carbonate rocks and the presence of eunicid polychaete body fossils preserved within *Balanoglossites* in the Triassic of Germany (Goldring and Kazmierczak, 1974; Knaust and Dronov, 2013). Nevertheless, as illustrated herein, the boring ability of the *Balanoglossites* producer is unconvincing, at least based on morphologic evidence from the Stony Mountain Formation. On the other hand, enteropneusts are the other candidates to produce the highly variable morphology of *Balanoglossites.* Enteropneusts are deposit feeders that produce U-shaped burrows with open funnels to exploit detritus, commonly resulting in highly complex and variable burrows (Bromley, 1996; Knaust, 2007). They also produce burrow morphologies similar to those that are typical of *Thalassinoides*, consisting of branching subhorizontal networks connected by vertical shafts (Romero-Wetzel, 1989). In the case of the Stony Mountain Formation, the producers of

Balanoglossites lived predominantly in a shallow, open-lagoon environment and were likely linked to the production of peloidal sediments in the shallow, inner epeiric ramp.

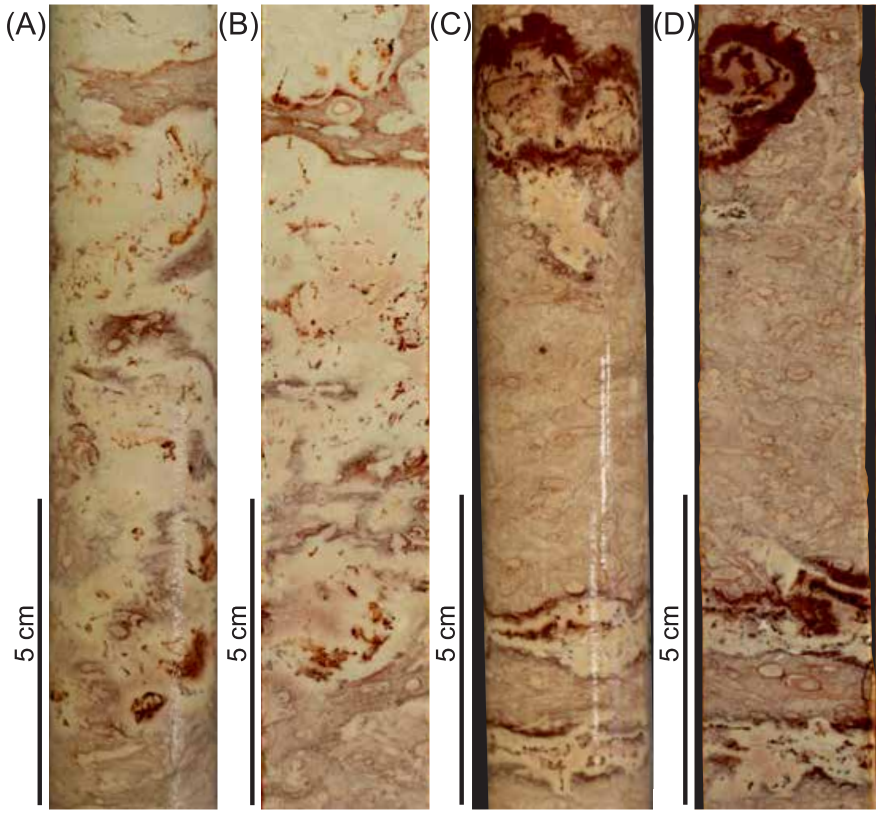

Fig. 2.17. *Balanoglossites* isp., 80 cm in length. A, B: Front and back view of the top of the burrow, which marked the contact of overlying open lagoon and underlying neritic marine environments. C, D: Front and back view of the downward burrowing into the firm mudstone, exhibiting a bifurcation of secondary successive. A, B, C and D are from M-2-88, subsurface Manitoba.

2.5.2 Depositional models of epeiric seas

Energy zonation (controlled by depth of wave base) in open-marine and epeiric-neritic seas are not comparable due to their distinctly different bathymetries (Immenhauser, 2009). Therefore, the depositional model of epeiric seas is usually referred to the classic epeiric platform model, which is without counterpart in modern analogs (Shaw, 1964; Irwin, 1965). The key feature of this model is the shallow basinal water depth (<10 m), accompanying an extremely gentle, usually negligible slope, resulting in waves and tides being dampened before reaching the shoreline. Three energy zones were considered in this model, from seaward to landward, as follows, low-energy Zone X, high-energy Zone Y, and low-energy Zone Z. Zone X and Zone Y, which are separated by the fair-weather wave base, are affected by both oceanic and tidal energy. In zone Z, the oceanic energy is dampened effectively by friction, and only local storms stroke this area, induced epeiric current and waves. Consequently, distribution of lithofacies is mostly dictated by hydrodynamic energy zonation. For instance, bioturbated mudstone with skeletal storm beds characterizes Zone X; amalgamated hydroclastic limestone and sand shoal indicating wave action distinguish Zone Y; and lagoonal-pelleted limestone and chalky dolomite characterize Zone Z (Fig. 2.18). At the innermost region of the epeiric platform, the loss of freshening from tides and waves increases salinities shoreward from the limit of oceanic energy effects. Therefore, evaporitic mudflats or salterns are formed without the need of any physical barrier. Moreover, the gentler the slope, the greater the hypersalinity gradient can be maintained across a broader region. Density flows driven by hypersalinity is the dominated physical process beside local storm events. Hence, a regular pattern of facies from dolomite to anhydrite to halite is typically developed (Shaw, 1964; Irwin, 1965; Heckle, 1972).

The Stony Mountain Formation sequence is not identical to the one proposed in the traditional model because of the absence of well-developed evaporites during the last stage of deposition (Fig. 2.19). Also, the pervasive bioturbation argues against the anticipated hypersalinity conditions of the inner platform. Although the carbonate lithologies of this formation roughly fit the classic model, certain adjustments are required. Two main modifications to the model need to be performed. First, if the weather was sufficiently humid and the inner platform was freshened by enough freshwater, evaporites may not be developed. Instead, the algal, bioclastic, or pelletal facies would extend inland. Another possibility is that the basin was steeper. The steeper the slope, the narrower Zone Y and Zone Z would become. In the extreme case, Zone Z may be missing, wave and tidal effect would extend to the shore, and it would become a modern ramp setting (Irwin, 1965). With a moderate increase of slope, an epeiric ramp would form, which shares sedimentological characteristics with both epeiric platform and carbonate ramps (Fig. 2.18). The difference between epeiric platform and epeiric ramp lies in the width and depth of these settings. Whereas epeiric platforms span hundreds to thousands of kilometers, with maximum depth being shallower than 10 m, epeiric ramps span hundreds of kilometers with a few tens of meters of water depth at their deepest point (Lukasik et al., 2000; Flügel, 2010). Therefore, the most restricted shoreward setting containing evaporites would not be preserved in an epeiric ramp; instead the island model suggests peritidal effects near the strand region (Pratt and James, 1986). It is suggested herein that the Stony Mountain

Formation was deposited either under a more humid, semi-arid climate, the slope was steepper, or a combination of both.

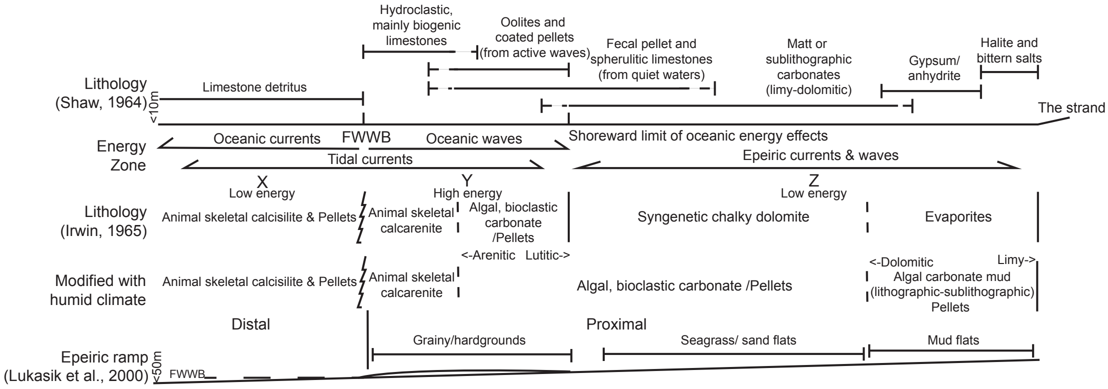

Fig. 2.18. Facies distribution of epeiric platforms and epeiric ramps from strand to sea (epeiric platform complied from Shaw, 1964 and Irwin, 1965; epeiric ramp adopted from Lukasik *et al.*, 2000).

2.6 Conclusions

Paleoenvironmental interpretation of carbonate rocks usually relies on microfacies analysis (Flügel, 2010). However, when dealing with epeiric sea carbonates, severe dolomitization and preferential dissolution pose serious challenges to identify depositional processes and environmental settings. In this regard, trace-fossil analysis, (both ichnofacies and ichnofabrics) provides a valuable approach to enhance high-resolution paleoenvironmental interpretation in these depositional settings. Paleoenvironmental interpretation of the six facies defined in this paper was refined based on ichnofabric characterization. In addition, environmental dynamics is reconstructed based on ichnofabric analysis. Furthermore, environmental changes and the depositional trend from strand to ocean are better elaborated by inspecting trends in ichnodiversity and intensity of bioturbation. Consequently, a refined facies model of the Stony Mountain Formation is proposed. It is expected that this study would encourage further ichnologic examination of other ancient Paleozoic epeiric sea carbonates.

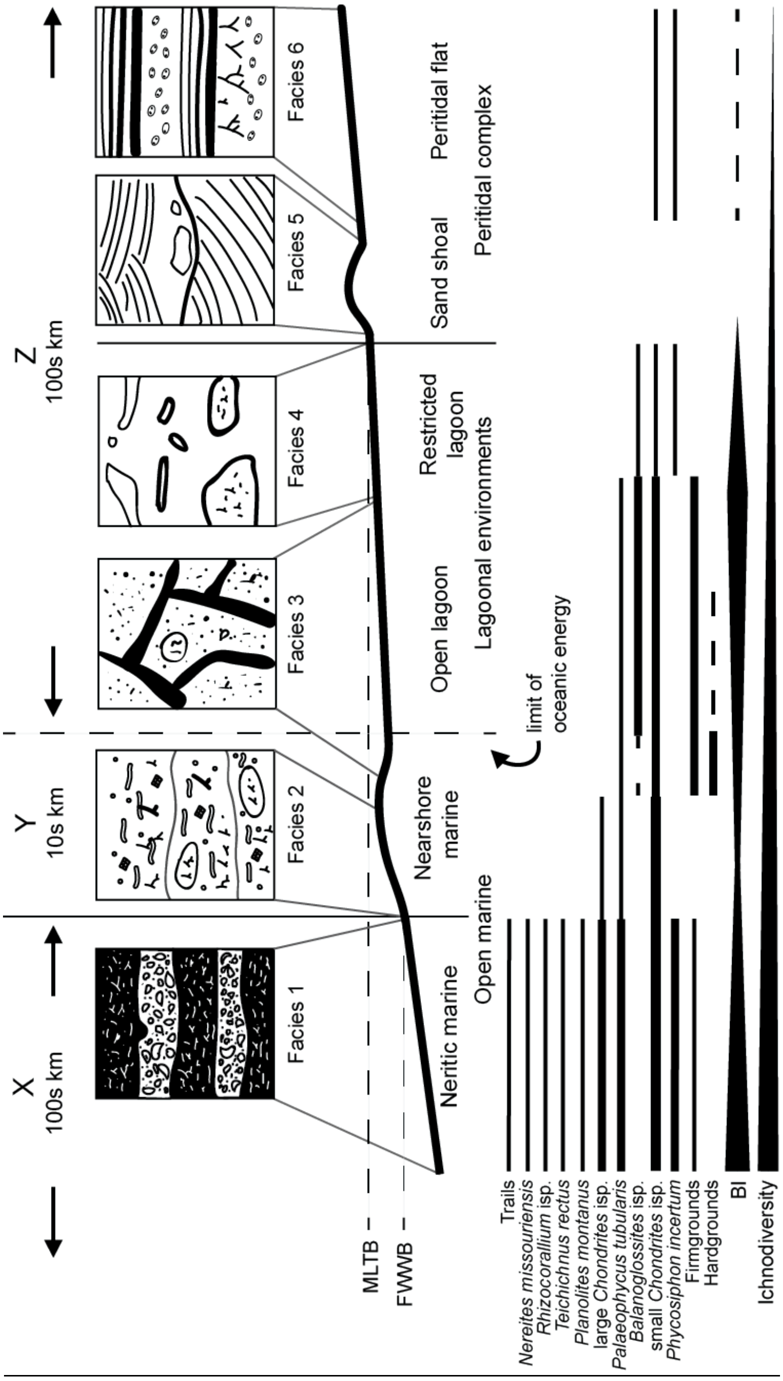

Fig. 2.19. The facies model of the Stony Mountain Formation.

2.7 Acknowledgement

This research was funded by AAPG Grant in Aid program and SEPM student research grant to Zheng, together with Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grants 311727-05/08/13 and 311726-05/08/15 to MGM and LAB, respectively. Special appreciation is given to John Lake, who generously guided core-logging and shared inspiring hypothesis; Colin Ebb, who provided enthusiastic and impeccable assistance in the core lab, Winnipeg; Luc

Chabanole, who assisted during fieldwork; Michelle Nicholas, who arranged and guided the visit to the quarries; Mark Wilson for useful comments on the bioerosion structures, Brian Pratt for valuable criticism; and all the staff in the Regina core lab and Winnipeg core lab, who assisted in core preparation.

CHAPTER 3: SEDIMENTARY FACIES VARIABILITY OF THE UPPER ORDOVICIAN WILLIAMS MEMBER IN THE WILLISTON BASIN, SOUTHERN MANITOBA

Charlie Y.C. Zheng, M. Gabriela Mángano, Luis A. Buatois, Sedimentary facies variability of the Upper Ordovician Williams Member in the Williston basin, southern Manitoba: Lithostratigraphic implications: Report of Activities 2017, Manitoba Growth, Enterprise and Trade, Manitoba Geological Survey, 148–157.

ABSTRACT

The Upper Ordovician Williams Member is analyzed based on the study of seven stratigraphic cores in subsurface Manitoba. Two remarkably different sedimentary facies, representing tidal flat and nearshore complex environments, have been traditionally included in this member. Confusion regarding the use of this member also generates debate on its placement at the top of the Stony Mountain Formation or the base of the lower Stonewall Formation. In this report, the Williams Member is redefined to include only the deposits of the last stage Stony Mountain Formation with two suggested correlations: 1) the member is limited to the nearshore deposits in southwestern Manitoba, or 2) the member includes tidal flat deposits toward the north and nearshore deposits toward the south. In addition, the tidal flat deposits situated above the Stony Mountain Formation should not be assigned to the Williams Member and should be included in the lower interval of the Stonewall Formation.

3.1 Introduction

The Upper Ordovician succession in the Williston Basin is characterized by the basal sandstone unit of the Winnipeg Formation, with overlying epeiric carbonate-anhydrite cycles that compose the Red River, Stony Mountain and Stonewall formations. A disconformity situated at the top of the Stonewall Formation marks a prolonged hiatus separating the Ordovician from the Silurian (Demski et al., 2015). Different subdivisions of these epeiric sea deposits have been adopted not only between Saskatchewan and Manitoba, but also in outcrop and subsurface due to a complex facies pattern. For instance, the Stony Mountain Formation was divided, from base to top, into the Hartaven, Gunn and Gunton members in Saskatchewan (Kendall, 1976). In

Manitoba, the formation was divided into the Gunn, Penitentiary, Gunton and Williams members based on type sections in the outcrop belt (Elias et al., 2013b), whereas the formation was divided into the Hartaven, Gunn/Penitentiary and Gunton members in the subsurface of southwestern Manitoba (Nicolas and Barchyn, 2008). There is disagreement between these subdivisions. Specifically, the Williams Member, in places capped by the basal Stonewall anhydrite, was placed at the base of the lower Stonewall Formation in the subsurface of southwestern Manitoba (Bezys and Bamburak, 2004; Nicolas and Barchyn, 2008). However, the member was first proposed for the uppermost part of the Stony Mountain Formation based on outcrops in the Stonewall quarry (Smith, 1963; Cowan, 1971). The decision to move the Williams Member into the Stonewall Formation was based on detailed stratigraphic investigations conducted jointly by the Manitoba Geological Survey (MGS), Saskatchewan Geological Survey and the Geological Survey of Canada (R. Bezys, pers. comm., 2017), and even though a formal publication of that decision is not available, the stratigraphic reassessment is mentioned in Martiniuk (1992) and Norford et al. (1998). A recent study placed the upper contact of the member at a disconformity in the Stonewall quarry, suggesting its inclusion in the uppermost interval of the Stony Mountain Formation as well (Elias et al., 2013b).

The purpose of this study is to provide a preliminary assessment of the sedimentary facies variability of the Williams Member in the subsurface, aiming to clarify its definition and distribution, based on seven stratigraphic cores in southern Manitoba (Fig. 3.1, Table 3.1).

Drillhole	Location	Core interval
M-3-78	12-07-40-10W1*	73.6–98 m
M-3-74	01-21-11-01E1	2.0–27.7 m (6.6–90.9 ft.)
M-2-96	03-28-44-11W1	11.0–37.0 m
M-2-88	04-11-18-01W1	40.0–56.8 m
M-1-84	04-15-19-01W1	17.00–42.65 m
Tudale Neepawa	15-29-14-14W1	534.0–562.7 m (1752–1846 ft.)
Gulf Minerals Minitonas	03-29-36-25W1	381.0–402.3 m (1250–1320 ft.)

*L.S. 12, Sec. 7, Twp. 40, Rge. 10, W 1st Mer.

Table 3.1. Details of well locations and cored intervals for the seven stratigraphic cores studied in southern Manitoba.

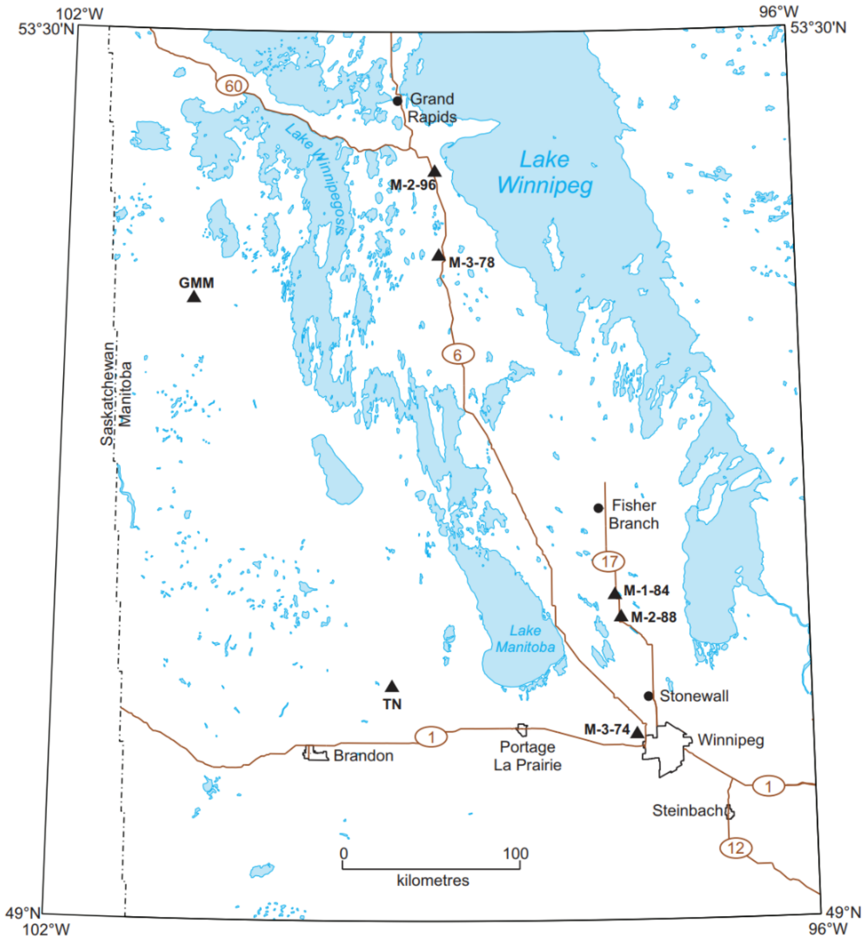

Fig. 3.1. Location map of the seven stratigraphic cores (black triangles) studied in southern Manitoba. Abbreviations: GMM, Gulf Minerals Minitonas; TN, Tudale Neepawa.

3.2 Stratigraphic setting

In the Williston Basin, Late Ordovician sedimentation began with a large-scale marine transgression from the southeast. This punctuated transgression led to the deposition of shoreface sandstone to offshore mudstone of the Winnipeg Formation (Kreis, 2004; Dorador et al., 2014). Detailed lateral facies correlation at this stratigraphic level is complicated due to complex stratal architectures resulting from a series of topographic depressions on the underlying Cambrian Deadwood Formation (Vigrass, 1971; Potter, 2006). Subsequent Late Ordovician sedimentation in the Williston Basin is characterized by carbonate-evaporite tripartite cycles. These cycles typically contain fossiliferous wackestones at the base, grading into parallel-laminated mudstone, and capped by anhydrite beds (Kent and Christopher, 1994; Norford et al., 1994). The Red River Formation records the first two cycles, whereas the Stony Mountain Formation and the lower interval of the Stonewall Formation together record the third cycle (Fig. 3.2) (Kendall, 1976). These cycles are variably preserved across the basin. The complete succession is preserved in a basin-centre position in southeastern Saskatchewan, whereas in Manitoba the capping anhydrites are commonly absent (Nicolas and Barchyn, 2008). Depositional trends in the Red River and Stony Mountain formations show a similar overall pattern in the Williston Basin, exhibiting the thickest strata in southern Manitoba and thinning toward the north (Bezys and Bamburak, 2004; Nicolas and Barchyn, 2008). Furthermore, subsurface correlations in the basin demonstrate continuous southwest-trending strata with minor lithological changes, and indicate depositional and erosional thinning of stratigraphic units from the southeast toward the northwest (Norford et al., 1994). In contrast, although the thickness and lithology of the Stonewall Formation are uniform throughout the outcrop belt (Bezys and McCabe, 1996), subsurface correlations of the formation exhibit a thinning trend toward the outcrop belt in the north and east (Nicolas and Barchyn, 2008). Subsequent erosion highly constrained the present distribution of these Ordovician carbonate successions. In the Williston Basin, erosion on the Transcontinental, Severn, Peace River and Sweetgrass–North Battlefield arches removed parts of the underlying deposits in the east, northeast, northwest and west of the basin, respectively (Norford et al., 1994). The widespread Ordovician epeiric carbonate deposits were correlated from northern Mexico to northern Greenland and from eastern Quebec to eastern Alaska, with the maximum distribution marked by the Red River–Stony Mountain coral province (Ross et al., 1982; Elias, 1991; Elias et al., 2013a).

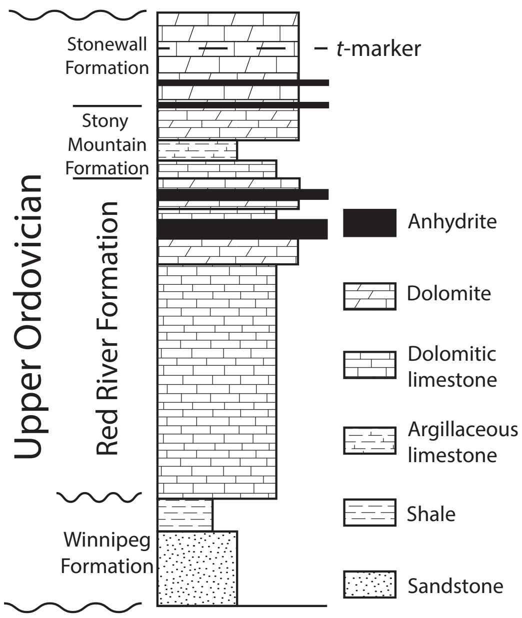

Figure 3.2 The Upper Ordovician succession in the Williston Basin (modified from Kendall, 1976).

In the subsurface of southwestern Manitoba, the Stony Mountain Formation was subdivided, from base to top, into the Hartaven, Gunn/Penitentiary and Gunton members. The Stonewall Formation was subdivided into the lower Stonewall Formation, which contained the basal Williams Member, and the upper Stonewall Formation. In places, the Gunton anhydrite and the basal Stonewall anhydrite capped the Gunton Member and the Williams Member, respectively (Fig. 3.3) (Nicolas and Barchyn, 2008). Although the precise lithostratigraphic position of the Williams Member is still ambiguous, this member serves as a transition between the underlying Gunton Member and the overlying lower Stonewall Formation.

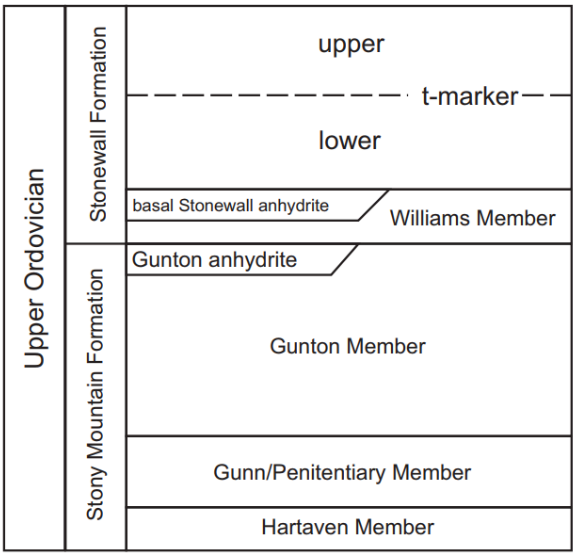

Figure 3.3 Stratigraphy of the Upper Ordovician Williston Basin in the subsurface of Manitoba (modified from Nicolas and Barchyn, 2008).

The Williams Member was first characterized within the standard section at the Winnipeg Supply and Fuel Company quarry (Stonewall quarry) near the town of Stonewall and at that time it was included in the Stony Mountain Formation (Smith, 1963; Cowan, 1978). The member consists of argillaceous, mottled, dense arenaceous dolomite with coarse, well-rounded, frosted and pitted, quartz sand grains abundant toward the base. In places, there is laminated to crossbedded and conglomeratic dolostone. This unit is recessive, pinching out toward the north, with the only other exposure around Fisher Branch (Smith, 1963; Cowan, 1978; Glass, 1990). Recent carbon-isotope profiling of the type section supported placing the formational boundary between the Williams Member of the Stony Mountain Formation and the overlying Stonewall Formation at a sharp, irregular contact (Elias et al., 2013b) located at a stratigraphically higher position than the original contact assigned by Smith (1963).

This contact is indicative of a period of subaerial exposure and significant erosion, occurring after deposition of the bed that contains rounded, sand-size carbonate clasts and frosted quartz grains and before deposition of the overlying dolostone. Furthermore, the Williams Member was suggested to have been deposited during the final regressive stage of the Stony Mountain Formation (Elias et al., 2013b). On the other hand, at outcrops in the Grand Rapids uplands the Williams Member consists of planar-laminated to crossbedded dolostone, in places containing fine, subrounded quartz sand grains, with a subaerially exposed upper contact at the top of a thrombolitic interval. Therefore, the member was suggested to be part of the Stony Mountain Formation, having been formed under a tidal flat to restricted lagoon environment during a regression (Stewart, 2012; Elias et al., 2013b).

Discrepancies also occurred during subsurface investigations. In the subsurface, the Williams Member has an argillaceous marker bed defining the upper contact of the Stony Mountain Formation across southwestern Manitoba and southern Saskatchewan (Cowan, 1971; Kendall, 1976). Kendall (1976) suggested that the equivalent beds of the upper Williams Member in Saskatchewan have a conformable contact with the overlying lower Stonewall Formation, but unconformably rests on the underlying beds of the lower Williams Member. Therefore, Kendall (1976) discarded the Williams Member and put the lower equivalent beds into the Gunton Member and the upper equivalent beds into the overlying lower Stonewall Formation. In the subsurface of southwestern Manitoba, early subsurface investigations placed the member at the top of the Stony Mountain Formation (McCabe, 1978, 1979, 1984, 1988; Bannatyne, 1988). However, later core descriptions and subsurface studies in southwestern Manitoba relocated these strata within the lower Stonewall Formation (Norford et al., 1998; Bezys and Bamburak, 2004; Nicolas and Barchyn, 2008). In addition, the member was assigned to inconsistent positions in the successions.

3.3 Sedimentary facies variability

The sedimentary facies were examined in seven cores (Fig. 3.1) with detailed study of trace fossils to help decipher the depositional environment. Assessing sedimentary facies variability in these strata is crucial to achieving a better correlation. Whereas previous studies focused on body fossils (Young et al., 2007; Stewart, 2012; Elias et al., 2013b), trace fossil analysis has proven useful for facies delineation in overall muddy environmental settings, where body fossils are scarce and severe dolomitization hampers detailed microfacies analysis. Various degrees of bioturbation are assessed following the bioturbation index (BI) scheme established by Taylor and Goldring (1993). Although dolomitization is pervasive in all sections, the lithological description below follows Dunham's (1962) classification of carbonate rocks.

In this study, two remarkably different deposits were included in the Williams Member in the subsurface at various locations in southern Manitoba: 1) the parallel-laminated mudstone predominated toward the northwest (M-3-78 [L.S. 12, Sec. 7, Twp. 40, Rge. 10, W 1st Mer., abbreviated 12-07-40-10W1], M-2-96 [03-28-44-11W1], GMM [Gulf Minerals Minitonas; 03-29-36-25W1]), and 2) arenaceous dolostone, parallel-laminated mudstone and mottled wackestone sharply underlain by parallel-laminated mudstone dominated toward the southeast (M-3-74 [01-21-11-01E1], M-1-84 [04-15-19-01W1], TN [Tudale Neepawa; 15-29-14-14W1]). The dense dolostone in the M-2-88 [04-11-18-01W1] core has an unusually low sand content and the reason for its unusual preservation will be the subject of future study.

3.3.1 Parallel-laminated mudstone

These deposits consist of parallel-laminated carbonate mudstone intercalated with crosslaminated to crossbedded grainstone (Fig. 3.4a). An alternation of very fine sand-size and mud-size carbonate produces the centimetre-scale laminations. Body fossils and trace fossils are absent within the laminated intervals (BI 0). Locally, moulds of dissolved fossils occur, forming thin sheets (3–5 cm) (Fig. 3.4b). Sparsely bioturbated (BI 2), 5–10 cm thick intervals are intercalated within parallel-laminated intervals and contain monospecific suites of *Phycosiphon* (Fig. 3.4c) and *Chondrites*. The grainstone is composed of medium- to fine-grained sand-size peloids and is characterized by scoured bases commonly with a basal lag underlying the low-angle crosslamination. Bioturbation is absent (BI 0) in this interval (Fig. 3.4d).

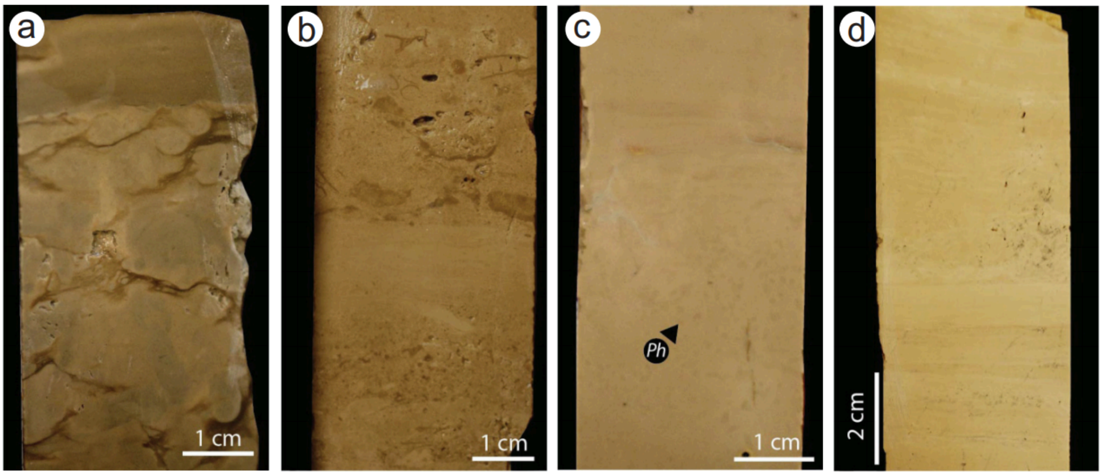

Fig. 3.4 Sedimentary facies of the parallel-laminated mudstone: **a)** sharp, basal contact of the parallel-laminated mudstone resting on top of nodular, mottled wackestone; depth 33.3 m in core M-2-96; **b)** bioclasts forming thin sheets (<5 cm) intercalated within the parallel-laminated mudstone; depth 12.2 m (40 ft.) in core M-3-74; **c)** a thin interval (BI 2–3) containing Phycosiphon (Ph) represents the establishment of short-term subtidal conditions between tidal flat progradations; depth 46 m in core M-2-88; and **d)** the upper part of this core interval contains crosslamination, whereas the bottom of the core interval contains planar-lamination; vugs are possibly remnants of dissolved bioclasts; depth 21.3 m (70 ft.) in core M-3-74. Top direction of the core is at the top of photo.

Similar to the upper Red River Formation, some authors ascribed the parallel-laminated mudstone to intertidal and supratidal settings (Roehl, 1967; Kendall, 1976; Clement, 1985; Derby and Kilpatrick, 1985; Ruzyla and Friedman, 1985). However, the lack of evaporites and structures indicative of subaerial exposure may argue against a supratidal setting (Ginsburg *et al.*, 1977). The scarcity of fossils, together with the presence of monospecific trace fossil suites, suggests restricted conditions. Whereas the producers of *Phycosiphon* and *Chondrites* would have colonized the sediment under subtidal conditions during refreshing events, the laminated intervals represent intertidal deposits formed during restricted conditions that prevented bioturbation. In contrast, the interbedded, crosslaminated grainstone records high energy sand shoals (Gonzalez and Eberli, 1997). In this case, nonbioturbation may have resulted from rapid deposition. Stewart (2012) suggested that the Williams Member in the Grand Rapids uplands was deposited under the shallowest and most restricted conditions in the Stony Mountain Formation, possibly in tidal flat and restricted lagoon environments.

3.3.2 Arenaceous dolostone, parallel-laminated mudstone and mottled wackestone

These deposits consist of a complex array of facies, ranging from arenaceous dolostone, parallel-laminated mudstone to mottled wackestone. In places, where bedding is well developed, the succession consists of basal medium- to fine-grained sandstone (up to tens of centimetres thick) intercalated with argillaceous dolostone, sharply overlain by parallel-laminated mudstone to mottled wackestone with a capping, thin, red-stained, argillaceous dolostone layer. The sandstone interval is rarely bioturbated (Fig. 3.5a). Body fossils are absent. Sedimentary structures are remarkably rare and restricted to a few medium-grained sandstone beds, showing crossbedding and parallel lamination. The mottled wackestone is moderately to intensely bioturbated (BI 3–4), and characterized by *Thalassinoides*-like structures. Some sparse fenestrae in the mottled wackestone may be voids left by dissolved centimetre-scale skeletal remains (Fig. 3.5b). Alternatively, in places where bedding was not well developed, deposits are characterized by arenaceous dolostone locally blackened by pyrite crystals (Fig. 3.5c). Sand content varies at different locations, with visible quartz grains occurring locally. Crosslaminated to planar-laminated, medium-grained sandstone layers intercalate within this interval. Body fossils and trace fossils are usually absent. Certain intervals of arenaceous dolostone were stained by the red argillaceous layers intercalated within the successions.

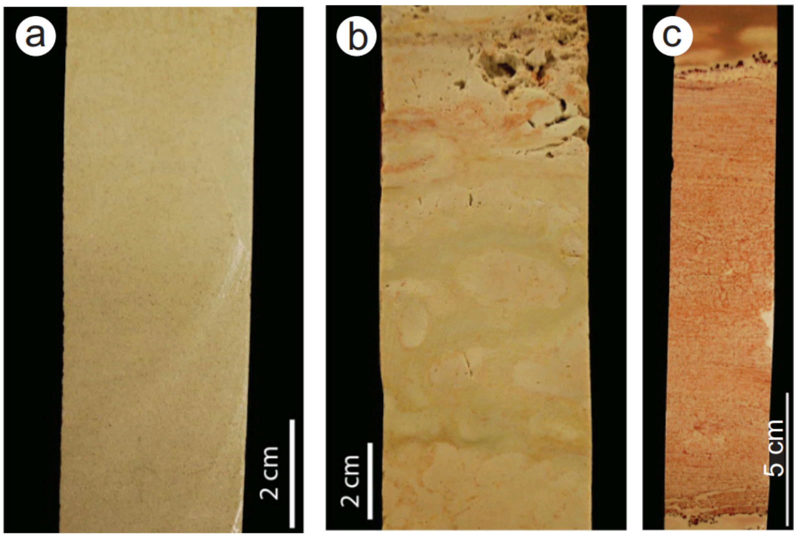

Figure 3.5 Sedimentary facies of the arenaceous dolostone and mottled wackestone: **a)** a medium- to fine-grained sandstone layer (10 cm thick) intercalated within the arenaceous dolostone interval; depth 15.7 m (51.4 ft.) in core M-3-74; **b)** mottled wackestone; the nodular appearance results from the presence of burrows attributed to Thalassinoides; the upper part of the core interval contains vugs of body fossils; depth 10.4 m (34 ft.) in core M-3-74; **c)** planar-laminated to crosslaminated arenaceous dolostone, containing high sand content; black dots are pyrite crystals; depth 16.5 m (54 ft.) in core M-3-74. Top direction of the core is at the top of photo.

As noted above, the parallel-laminated mudstone represents tidal flat deposits. The mottled wackestone with *Thalassinoides*-like structures has been interpreted as recording deposition in shallow subtidal settings (Kendall, 1977; Myrow, 1995; Zenger, 1996; Jin et al., 2012). Generally, shallow-marine, restricted conditions are characterized by the lack of macrofossils (Elias et al., 2013b) together with sparsely preserved bioturbation. Therefore, the *Phycosiphon* producer may have colonized during short-term refreshings likely related to flooding events, whereas the occurrence of *Thalassinoides*-like burrows represents more open marine conditions. The whole succession, recording all the subenvironments interpreted above, is <10 m thick. This significant vertical change in sedimentary facies suggests a highly complex facies mosaic, probably representing a nearshore environment that encompassed a wide variety of subenvironments. Further evidence of a relative sea-level fall is provided by the capping arenaceous dolostone in the type section, which was interpreted to be the result of a period of subaerial exposure (Elias et al., 2013b).

3.4 Discussion

It can be surmised that confusion regarding the precise placement of the Williams Member originates from the application of different definitions. Specifically, in core M-2-96, the parallel-laminated mudstone, representing tidal flat deposits (depth 28.0–33.3 m), was included in the Williams Member and placed within the lowermost Stonewall Formation (R.K. Bezys and K. Horsman, unpublished core description, 1996; Fig. 3.6). On the other hand, very different facies in core M-3-74, comprising vuggy, mottled, argillaceous dolostone intercalated with arenaceous dolostone representing nearshore deposits (depth 6.5–18 m [21.3–59.1 ft.]), were also placed within the lowermost Stonewall Formation (H.R. McCabe, unpublished core description, 1974; Figure 3.6). H.R. McCabe (unpublished core description, 1974) initially assigned the Stonewall Formation–Stony Mountain Formation contact to depth 12.6 m (41.3 ft., Fig. 3.6), but later moved it to depth 18.0 m (59.1 ft., Fig. 3.6).

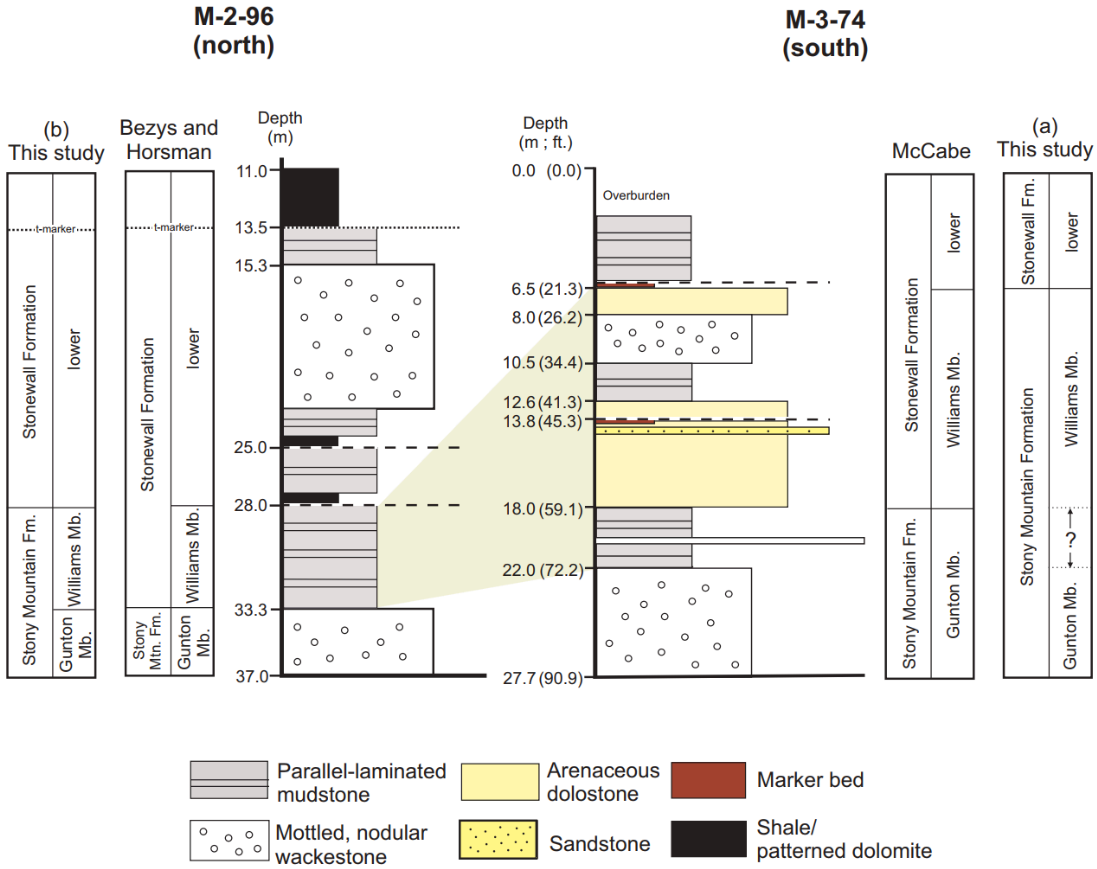

Figure 3.6 Correlation between cores M-2-96 and M-3-74, showing previous subdivisions assigned to the two cores and alongside are the two possible revised subdivisions (labelled a and b) recommended from this study. The beige shaded area marks one revised correlation (b) of the Williams Member of the Stony Mountain Formation. The long dash lines mark shaly marker beds in core M-2-96 and reddish-stained marker beds in core M-3-74. Bezys and Horsman from unpublished core descriptions (1996) and McCabe from unpublished core descriptions (1974). Abbreviation: Mtn, Mountain.

Correlation problems lie not only in the different nature of these deposits, but also in the fact that significant diachronism is involved. A single thin dolomitic mudstone bed containing angular clasts of the same lithology as the underlying facies underlies the Williams Member in core M-3-74. These types of contacts commonly cap the tidal flat deposits toward the northwest, specifically, at depths 388.6 m (1275 ft.) and 79.7 m, in cores GMM and M-3-78, respectively. The underlying successions of the Stony Mountain Formation become dominated by the mottled, nodular wackestone at these places. Also, this contact is believed to mark the fragmental, sharp top of the Williams Member at depth 28.0 m in core M-2-96. Thin, shaly layers invariably mantled these contacts toward the northwest, and are comparable to the marker bed at the top of the Stony Mountain Formation in the subsurface of Saskatchewan (Kendall, 1976). These strata are analogous to equivalent strata in the Big Horn Dolomite in Wyoming, where similar contacts represent subaerial exposure at the termination of the parasequences of the Horseshoe Mountain Member (Holland and Patzkowsky, 2012). It is possible that intervals between three thin shaly marker beds situated higher in the sequence, in places mixed with patterned dolomite, record parasequences overlying the Stony Mountain Formation in southern Manitoba (Fig. 3.7b, c). These possible parasequences could have been formed during a transition from a greenhouse climate to an icehouse climate preceding the Hirnantian glaciation (Holland and Patzkowsky, 2012). Coincidently, three to four informally assigned, reddish-stained marker beds characterize the lower Stonewall Formation in the subsurface of southern Manitoba (Fig. 3.7a). In early investigations, the Williams Member was assigned to the intervals overlying the contacts at places where the Williams Member was considered to be the dolomite with shale interbeds, and overlying the contact, at 73.6–79.7 m in M-3-78, was placed in the Stony Mountain Formation (McCabe, 1978). Later identification of the upper Stony Mountain Formation contact and the capping marker bed is believed to be the reason for moving the Williams Member to within the lower Stonewall Formation (Norford et al., 1998).

The type section of the Williams Member in the Stonewall quarry is representative of the member in southern Manitoba, and Smith (1963) suggested deposition was continuous from the Gunton Member to the Williams Member. However, problems arose correlating the members toward the northwest, where the transitional intervals between the Gunton Member and the lower Stonewall Formation become dominated by parallel-laminated mudstone, representing tidal flat deposits with no sand influx. The authors agree with Elias et al. (2013b) that the Williams Member should be included in the upper part of the Stony Mountain Formation. Therefore, identifying the upper contact or marker bed of the Stony Mountain Formation is crucial. In addition, the parallel-laminated mudstone with shaly interbeds situated above the upper contact of the Stony Mountain Formation should not be assigned to the Williams Member.

The strata in the 6.5–18.0 m (21.3–59.1 ft.) depth interval in M-3-74 is comparable to the Williams Member section in the Stonewall quarry, and the Stonewall Formation–Stony Mountain Formation contact identified in the quarry is suggested to be placed at the top of the interval in M-3-74. In M-2-96, the upper contact of the Stony Mountain Formation is placed at a depth of 28.0 m. The Williams Member should not be assigned to the parallel-laminated mudstone with shaly interbeds situated above depth 28.0 m in M-2-96 (Fig. 3.6). To address these issues, two possible stratigraphic revisions are proposed herein.

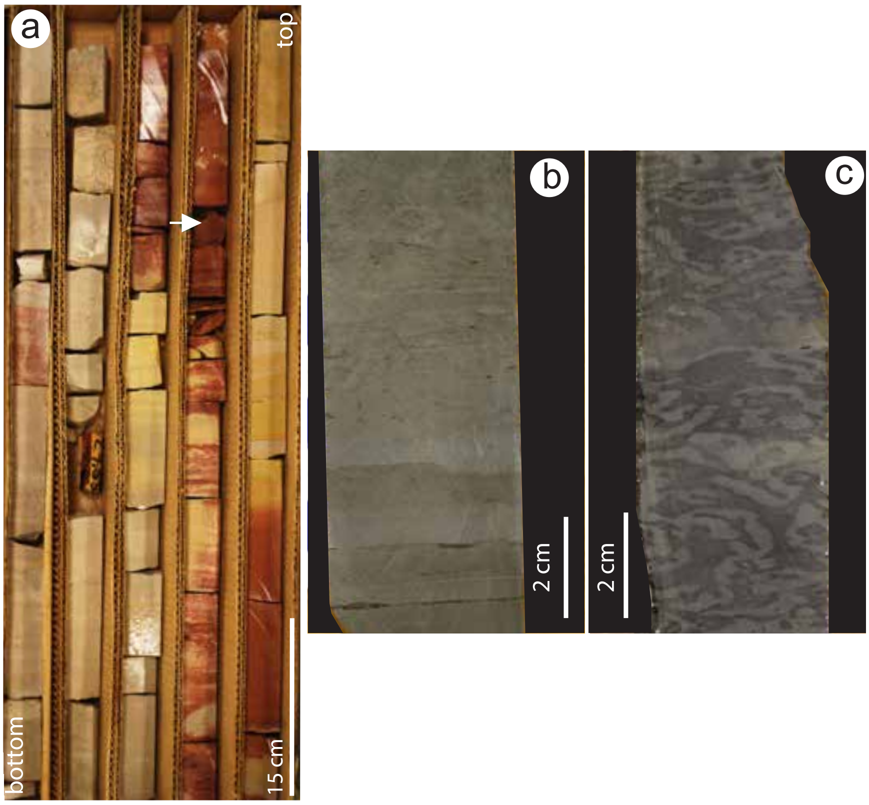

Figure 3.7 Marker beds in subsurface of southern Manitoba: **a)** an argillaceous, red-stained marker bed (indicated by arrow) intercalated within parallel-laminated mudstone and arenaceous dolostone in the Williams Member; depth 27.75–29.15 m in core M-1-84; **b)** a shaly layer punctuated within argillaceous dolostone caps the Stony Mountain Formation; depth 386.5 m (1268 ft.) in core Gulf Minerals Minitonas (GMM); c) a thin patterned dolomite layer marks the lower Stonewall Formation; depth 75.3 m in core M-3-78.

The first revision suggests that based on the characteristic sand content in the type section, the Williams Member in southern Manitoba should be limited to the intervals rich in clastic material and indicative of nearshore deposits. In this scenario, the member occurs in the south and pinches out toward the north, and is comparable to the trend in the outcrop belt. However, the distinct tidal flat deposits of the uppermost part of the Stony Mountain Formation cannot be differentiated from the underlying thick, mottled, nodular wackestone of the Gunton Member. These distinct tidal flat deposits are absent within the Gunton Member. For instance, the Williams Member of the Stony Mountain Formation is assigned to the interval at depth 6.5–18.0 m (21.3–59.1 ft.) in M-3-74and pinches out toward the northwest. Although the 28.0–33.3 m depth interval in M-2-96 correlates to the 18.0–22 m depth interval in M-3-74, the intervals are absent within the Gunton Member (Fig. 3.6, stratigraphic column a).

The second revision suggests that in the Williams Member in the subsurface of southern Manitoba the nearshore deposits in the south correlate to the tidal flat deposits in the north with a northward decrease in arenaceous content. In this case, both the tidal flat deposits and nearshore deposits would be included in the uppermost interval of the Stony Mountain Formation. In this scenario, the Williams Member is assigned to intervals of 28.0–33.3 m (Fig. 3.6, stratigraphic column b) and 6.5–22.0 m (21.3–72.2 ft.; correlation shown in beige in Fig. 3.6) in M-2-96 and M-3-74, respectively, and is included in the uppermost Stony Mountain Formation.

3.5 Depositional trend implications of the Williston Basin

Longman and Haidl (1996) proposed that the boundaries between members in the Willston Basin were isochronous based on a layer-cake stratigraphy and the assumption of basin-wide environmental changes. However, the apparent layer-cake stratigraphy partially originated from the loose definition of members. If the revised definitions of the Williams Member are adopted, then progradational sedimentation with diachronous boundaries between facies is expected since this unit represents the maximum regressive phase of the uppermost part of the Stony Mountain Formation. Allogenic controls, especially eustatic fluctuations, undoubtedly impacted on stratal architecture, highlighting the need for high-resolution sequence stratigraphic studies, which may assist with intrabasinal correlation of key surfaces. Future studies applying sequence stratigraphic concepts to the study of these epeiric deposits may help to provide a more accurate picture of Ordovician facies distribution and depositional history for the Williston Basin.

3.6 Economic considerations

Although only two oil shows have been reported in the Stony Mountain Formation (Nicolas and Barchyn, 2008), the revised schemes proposed in this study may help to refine subsurface stratigraphy and long-range correlations. This is critical in understanding the oil pathways, which in turn help petroleum companies create exploration models they can use to build their wildcat exploration programs.

3.7 Acknowledgments

This research was funded by the American Association Petroleum Geologists

Foundation Grants-in-Aid program and a SEPM student research grant to the first author, together with Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grants 311727-05/08/13 and 311726-05/08/15 to the second author and third author, respectively. Special thanks are given to M. Nicolas (Manitoba Geological Survey), who provided core information, guided the visit to the quarries and helped with this report; C. Epp (Manitoba Geological Survey), who provided enthusiastic and invaluable assistance in the Midland Sample and Core Library; and all the staff of the Midland Sample and Core Library, who assisted in preparing the core for viewing. The authors especially appreciate R. Elias' (University of Manitoba) extensive reviewing and insightful suggestions.

CHAPTER 4 CONCLUSIONS

Six subenvironments are characterized in the Stony Mountain Formation through an integration of ichnologic and sedimentologic datasets, namely neritic marine, nearshore marine, open lagoon, restricted lagoon, peritidal sand shoal and peritidal flat. Whereas ichnofacies analysis records a change from open to restricted conditions along the epeiric ramp, ichnofabrics illustrate dynamics within specific subenvironments. Ichnodiversity is highest in the open-marine environments (archetypal *Cruziana* ichnofacies), decreasing towards lagoonal environments. Under the most stressful, proximal areas, only monospecific trace-fossil suites are recorded. Episodic deposition characterizes the neritic and nearshore marine environments, resulting in various composite ichnofabrics. Reconstruction of omission-related, composite ichnofabrics illustrates the dynamics in the open-lagoon environments, characterized by low sedimentation rates interrupted by episodic erosion and deposition. Intercalation of ichnofabrics in the restricted lagoon shows alternation of event and fair-weather deposition, the latter associated with oxygen-depleted conditions. Assessment of both ichnodiversity and degree of bioturbation also allows more robust characterization of sedimentary facies, especially in a mud-rich, low energy settings, which may represent either very shallow, restricted environments or fully marine, deeper-water environments.

Ichnologic analysis shows its value to enhance the resolution of environmental interpretations in epeiric sea carbonates. A facies model of the Stony Mountain Formation is proposed accordingly (Fig. 2.19). This model shows that the paleo-water depth at the distal portion may have been somewhat deeper than traditionally recognized, and that the depositional setting is keener to an epeiric ramp (Lukasik et al., 2000). Furthermore, fully marine conditions were present within epeiric sea deposits in the Ordovician Williston Basin. Based on the refined facies model, an environmental deepening then shallowing is apparent in the Stony Mountain Formation, leading to a retrograding-prograding stratal pattern. This pattern is supportive of the shallowing upward interpretation in the Stony Mountain Formation (Elias et al., 2013b). Also, this pattern suggests a proximal-distal depositional trend that allows to subdivide the Stony Mountain Formation from a paleoenvironmental standpoint.

Previous studies belittled the effect of sea-level fluctuations based on a layer-cake stratigraphy in the Williston Basin, suggesting the boundaries between members in the

Williston Basin were isochronous and the environmental changes were basin-wide (Longman and Haidl, 1996). However, the layer-cake stratigraphy may have resulted from the extremely gentle gradient of the basin and associated very subtle changes in depositional environments. As a result, it is noticeable now that the controversial subdivisions of the Stony Mountain Formation may have originated by the proximal-distal depositional trend in the basin.

Two suggested correlations of the Williams Member are proposed to characterize deposition during the maximum regressive phase of the Stony Mountain Formation. The first correlation suggests the Williams Member should be confined to sections containing high clastic content, close to the type section in the Southwestern Manitoba, and pinching out towards the northwest. The second correlation suggests that the nearshore deposits in the south correlate with the tidal-flat deposits in the north, displaying a northward decrease in sandy content. However, attention should be made in identifying marker beds (upper boundary of the Stony Mountain Formation) while correlating. Progradational successions with diachronous facies boundaries are visible if the proposed correlations were adopted.

Future research potential lies in applications of the sequence stratigraphy toolbox. This study shows the environmental changes and depositional patterns are evident in the Williston Basin with a higher-resolution depositional model. Such depositional sequence implies an impact of eustatic fluctuations overprinting on the second order, tectonic-driven sequence. It is expected that integrating these sedimentological and ichnologic information with a comprehensive sequence-stratigraphic study will help to understand the sedimentary history and the paleogeography of the Williston Basin.

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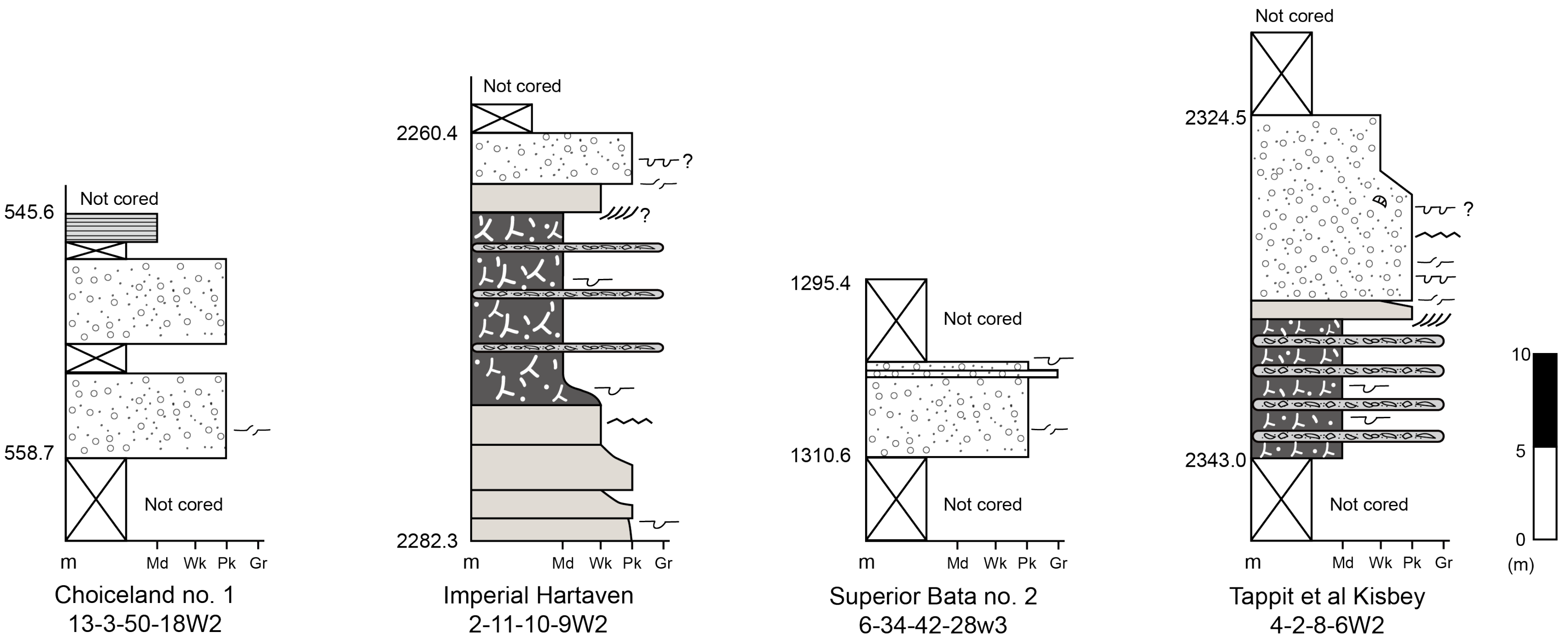
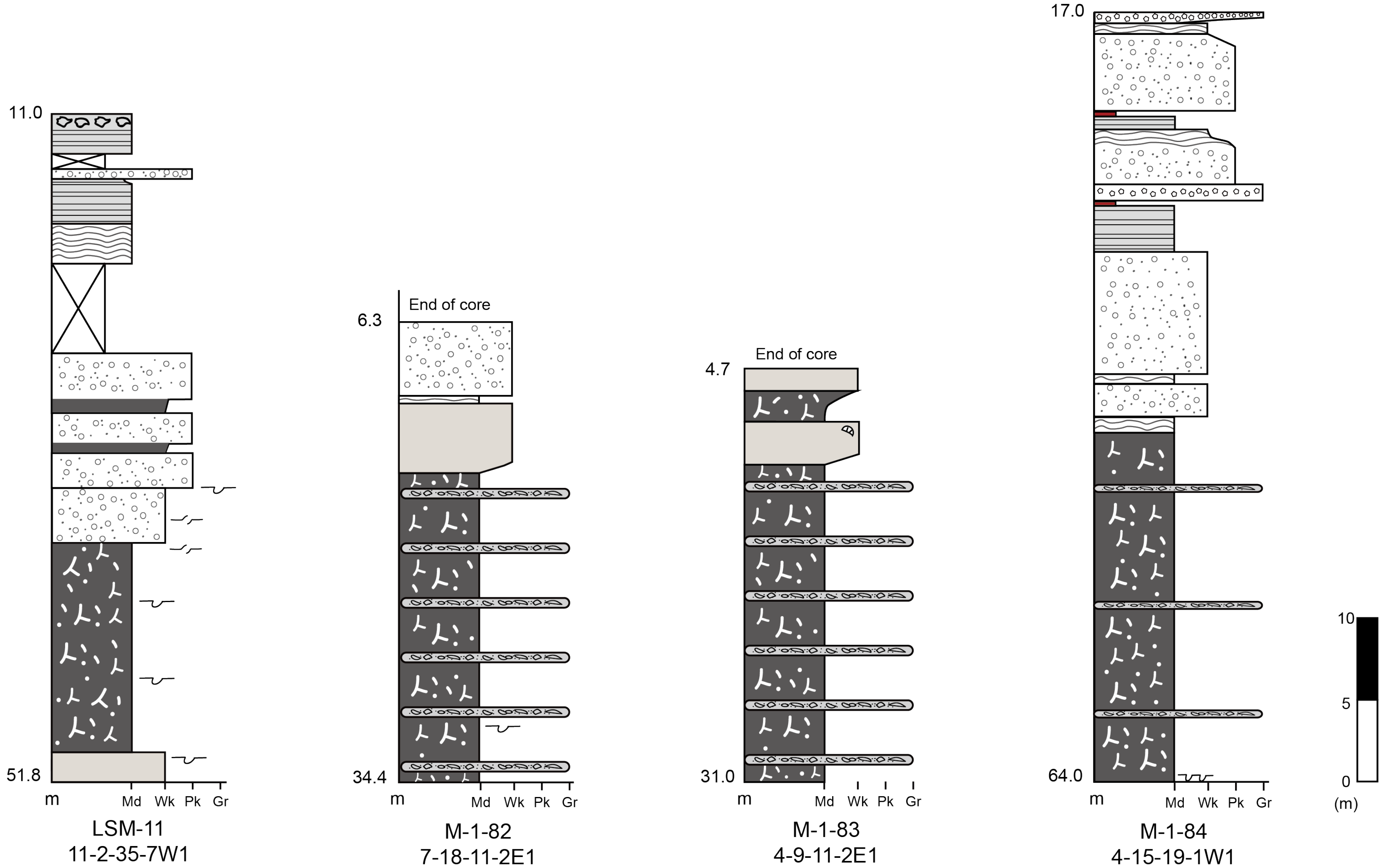
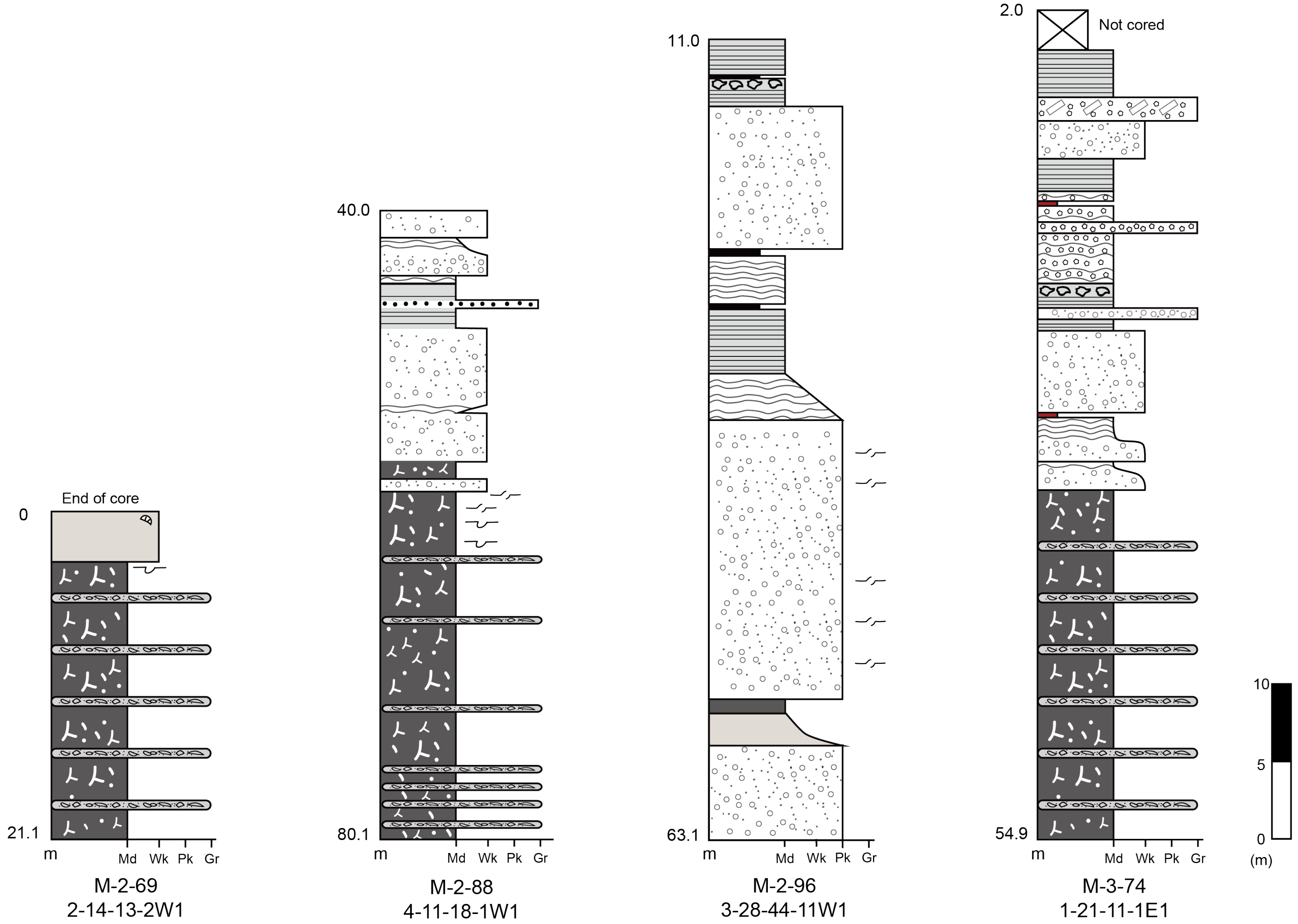
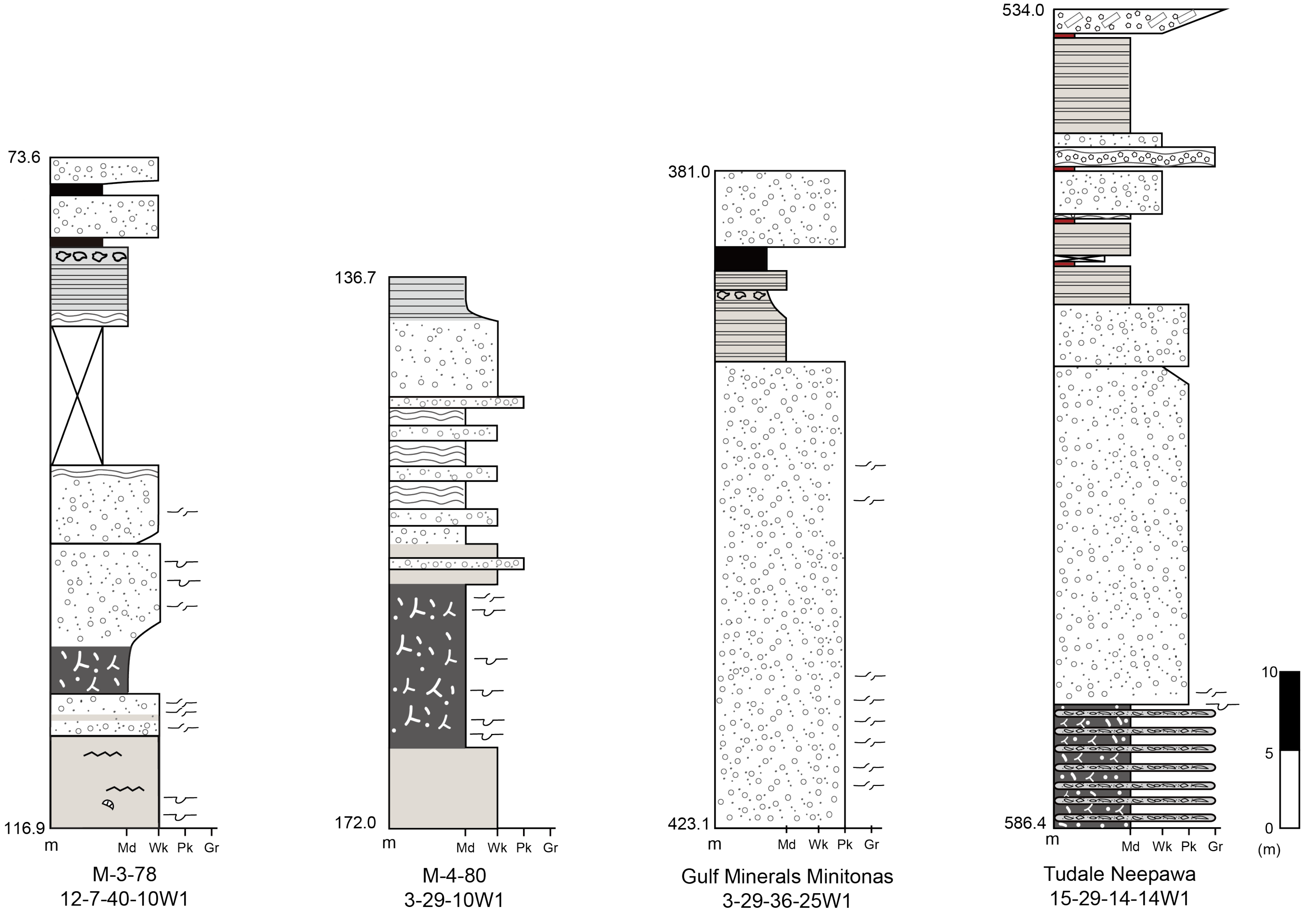
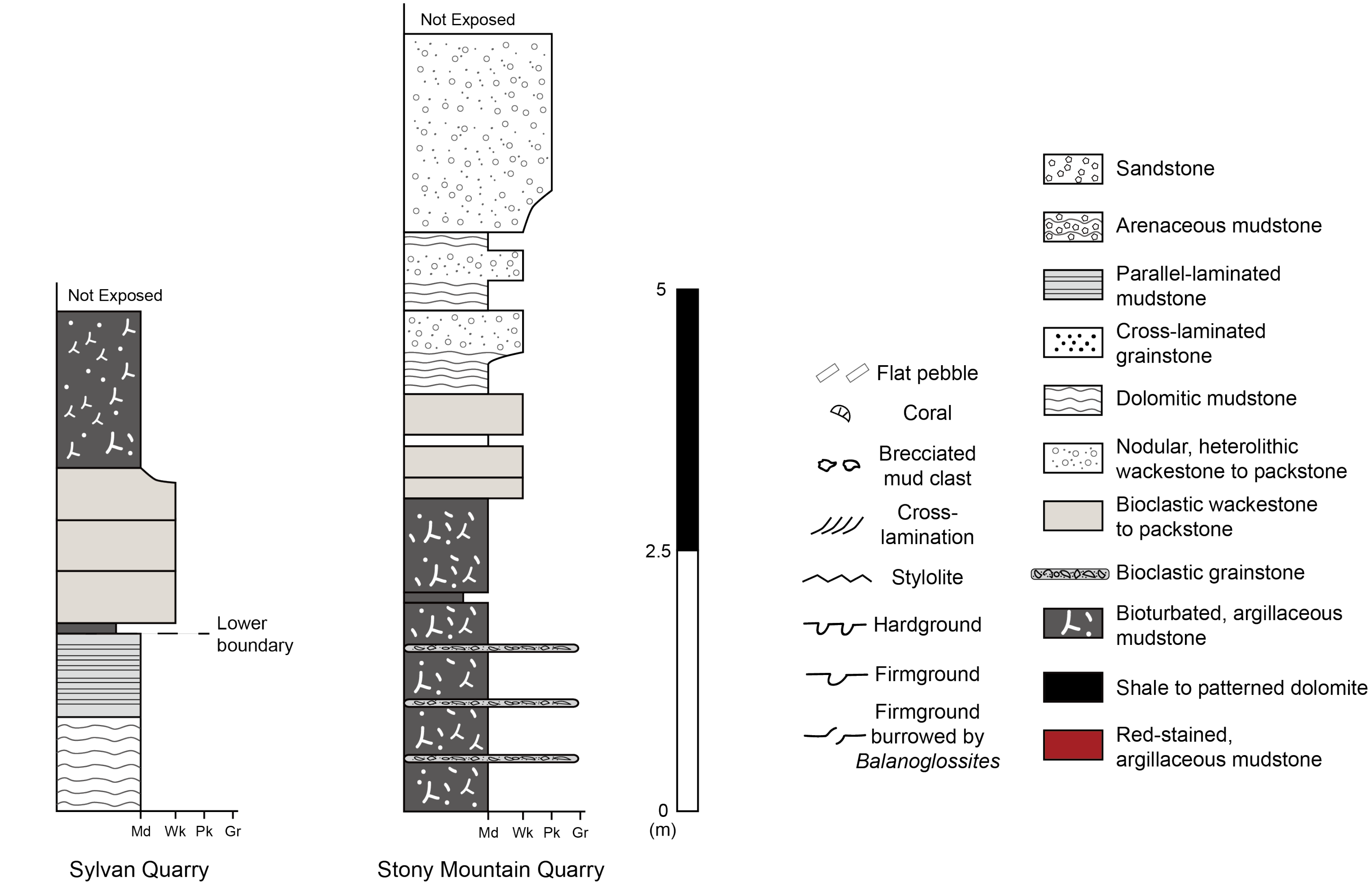
APPENDIX: Stratigraphic sections in this study




11.0
51.8
m
Md
Wk
Pk
Gr
LSM-11
11-2-35-7W1
End of core
6.3
34.4
M-1-82
7-18-11-2E1
End of core
4.7
31.0
M-1-83
4-9-11-2E1
17.0
64.0
M-1-84
4-15-19-1W1
10
5
0
(m)


End of core
0
21.1
m
Md
Wk
Pk
Gr
M-2-69
2-14-13-2W1
40.0
80.1
M-2-88
4-11-18-1W1
11.0
63.1
M-2-96
3-28-44-11W1
2.0
Not cored
54.9
M-3-74
1-21-11-1E1
10
5
0
(m)


73.6
116.9
m
Md
Wk
Pk
Gr
M-3-78
12-7-40-10W1
136.7
172.0
m
Md
Wk
Pk
Gr
M-4-80
3-29-10W1
381.0
423.1
m
Md
Wk
Pk
Gr
Gulf Minerals Minitonas
3-29-36-25W1
534.0
586.4
m
Md
Wk
Pk
Gr
Tudale Neepawa
15-29-14-14W1
10
5
0
(m)



Not Exposed
Lower boundary
Md
Wk
Pk
Gr
Sylvan Quarry
Not Exposed
Md
Wk
Pk
Gr
Stony Mountain Quarry
5
2.5
0
(m)
Flat pebble
Coral
Brecciated mud clast
Cross-lamination
Stylolite
Hardground
Firmground
Firmground burrowed by *Balanoglossites*
Sandstone
Arenaceous mudstone
Parallel-laminated mudstone
Cross-laminated grainstone
Dolomitic mudstone
Nodular, heterolithic wackestone to packstone
Bioclastic wackestone to packstone
Bioclastic grainstone
Bioturbated, argillaceous mudstone
Shale to patterned dolomite
Red-stained, argillaceous mudstone