Sedimentological and Ichnological Dynamics of the Early Cambrian Mount Clark Formation, Northwest Territories, Canada

by

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ABSTRACT

The early Cambrian Mount Clark Formation of the Northwest Territories comprises marginal marine to marine siliciclastic sediments deposited in an incipient rift basin on the margin of Laurentia. Within core and outcrop datasets the preserved record of sedimentation represents complex and highly variable lateral to vertical architecture. As a result of recording early Cambrian (Series 2, Stage 3: *Bonnia-Olenellus* trilobites) the Mount Clark Formation represents a rare opportunity to study marine biological interactions at the very onset of the Cambrian Explosion. To achieve this objective, high resolution sedimentological ichnological data was recorded from a six core database within the Colville Hills in addition to the field description of 8 outcrops in the Mackenzie Mountains over the course of two field seasons. Eight distinct lithofacies (F1-F8) were identified in the Colville Hills recording offshore to continental deposition along a strongly storm-influence shoreface succession. Three distinct facies associations (FA1-3) were identified within the Mackenzie Mountains recording shoreface (FA1), deltaic (FA2), and tidal embayment (FA3) sedimentation. Shoreface sedimentation (FA1) ranged from strongly storm-influenced to storm-affected lower shoreface to foreshore environments and were identified on the presence of robust and diverse trace fossil assemblages. Deltaic sedimentation (FA2) ranged from strongly storm-influenced to storm-affected prodelta to upper delta-front environments and were identified on the basis of stressed trace fossil assemblages recording decreasing ichnofossil size, diversity, and abundance in collaboration with more immature lithologies. Tidal compound dune sedimentation (FA3) ranged from embayment margin to the core of a compound dune field. Shoreface trace fossil assemblages within both study areas were found to have higher degrees of diversity, abundance, and complexity than previously identified early Cambrian trace fossil assemblages. It is interpreted that the Mount Clark Formation represents the earliest known radiation into these characteristic ethologies predating the famous and complex body fossils within the Burgess Shale. This body of work seeks to highlight a poorly understood region of Canada’s north, recording deposition at a time when complex life was first inhabiting Earth’s primordial oceans.

PREFACE

This thesis represents the original work of David Herbers. Chapter 2 of this thesis has been submitted for publication as: David Herbers, Robert MacNaughton, Eric Timmer, and Murray Gingras, “Sedimentology and Ichnology of an Early-Middle Cambrian Storm-Influenced Barred Shoreface Succession, Colville Hills, Northwest Territories, Canada” in the Bulletin of Canadian Petroleum Geology (CSPG). This manuscript has been accepted for publication. Chapter 3 will be submitted to the Canadian Journal of Earth Sciences as David Herbers, Eric Timmer, and Murray Gingras, “Mixed Deltaic, Shoreface, and Tidal Embayment Sedimentation Along a Storm-Influenced Early Cambrian Shoreline”. Chapter 4 has been submitted to GEOLOGY for review as David Herbers, Matthew Sommers, Kurt Konhauser, and Murray Gingras, “An Early Cambrian Radiation into Characteristic Ethological Niches”. These manuscripts are part of a larger Northwest Territories northern initiative organized by Dr. Murray Gingras and myself. I performed the data collection, interpretations and manuscript composition with the supervision and guidance of Dr. Murray Gingras. Chapter 1 (literature review) and 5 (conclusions) are my own work.

“*Oh, Andy loved geology. I imagine it appealed to his meticulous nature. An ice age here, million years of mountain building there. Geology is the study of pressure and time. That's all it takes really, pressure, and time*.”

- Red

DEDICATION

This thesis is dedicated to several people. First, James and Dorothy Herbers. Their patience and support cannot be overstated. For my undergraduate studies they left me well enough alone allowing me to bump my way through University and find what I enjoyed on my own. Today's endlessly annoying helicopter parent generation could learn a thing or two. I made mistakes on my own, learned from them, and am better off for it. Second, to Dr. George Pemberton for first giving me the opportunity to work in the Ichnology Research Group. Dr. Murray Gingras for instilling a sense of geological adventure and curiosity within me. Without his support and guidance I would have never had the opportunity to explore Canada's north to the degree that I have. Those fly camp excursions and adventures will live with me forever. My uncle Dave Herbers. It is with great sadness that you are gone but I dedicate this body of work to your memory and family. Finally, my grandparents Jim and Katie McCluskey along with Dorothy Herbers for providing assistance during my undergraduate years. Your help will not be forgotten.

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My time has graduate school has given some of the best memories of my young career thus far and is owed to a great deal of people. First, I would like to thank Dr. George Pemberton for first allowing me the opportunity to work part time in the Ichnology Research Group, even if you didn't tell anyone else of my existence. Rares Bistran, Jesse Schoengut, Greg Baniak, Luke McHugh, Chelsea Rommens, Jenna Phillips, Camillo Polo, and Ryan Lemiski are thanked for making me feel welcome in the lab and passing on sage wisdom. I would first like to thank my AAPG IBA team-mates Eric Timmer, Tariq Mohammed, Levi Knapp, and Micah Morin of Foreshore Drilling and Acquisition Limited for the wicked and wild ride to the final competition down in Houston, Texas. Winning the Canadian Regionals was the highlight of my graduate studies and I couldn't have asked for a better team. All of you are some of the smartest people I have ever had the privilege of working with, I hope someday we may be reunited in a similar fashion. Dr. Murray Gingras provided wisdom during my undergraduate tribulations and thankfully kicked me in the ass when my grades were insufficient for graduate school admittance. Dr. Andrew Locock provided expertise on mineralogical and analytical techniques far above my simple mind. Mark Labbe was of the utmost help and always had time to talk about logistics. My crate and field equipment would have never made it up the Mackenzie River without him. Dr. Brian Jones provided a great deal of expertise when it came to dealing with the Mount Clark Fm carbonates, it is a shame I was unable to include them in this thesis. Joel Pumple, Scott Botterill, Eric Timmer, Gord Campbell, Donald Prenoslo, Derek Hayes, and Aimee Gegolick provided a great deal of laughter and entertainment throughout my graduate degree from the office to the train wrecks that were the Christmas parties and PS Warren keggers. Ryan King is one of the most helpful people I have ever met, with a geological intuition far exceeding my own. Carolyn Furlong provided a great deal of support when it came to writing and wrapping up my thesis, cracking the whip if you will. Her help in figure drafting was immense. Boneless Thursdays with Ben Pedersen at Hudsons on Campus (NOT Devaney's) will always hold a special place in my heart.

My field assistants and fellow NWT workers deserve special recognition for their help conducting 6 weeks of fly camps in the remote Mackenzie Mountains. Brad Bobey, Grayson Bilak, Steve Kolenosky, Maya LaGrange Rao, and Brette Harris; you guys and gals made the those camps an unforgettable experience. Your company was second to none and your patience and dedication unrivalled. From the continual downpours, mosquitos, to blazing sun you stuck through it all while carrying a stuffed backpack due to my voracious appetite for large hand samples. Sahtu and Canadian Helicopters are thanked for providing safe and efficient transport to our fly camp sites.

Finally, I would like to thank Eric Hanson, ConocoPhillips Canada, the Government of Canada, University of Alberta, UALBERTA NORTH, the NTGS, and the Department of Earth and Atmospheric Sciences for supporting and funding this research.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

The early Cambrian Mount Clark Formation of the Northwest Territories is the primary host of significant and conventional gas, condensate, and oil discoveries within the mainland of the Canadian Arctic. Reserves have been postulated to represent as much as one billion barrels of oil and 10.7 TCF of gas within the interior plains of the Northwest Territories (Hannigan *et al*., 2011). Despite this obvious economic importance, the stratigraphic architecture is poorly understood with no detailed sedimentary and ichnological work published. Previous studies have focused on the Mount Clark Formation within a regional mapping context through Geological Survey of Canada (GSC) (Hamblin, 1990; Dixon and Stasiuk, 1998; MacLean, 2011; MacNaughton *et al*., 2013). This is a result of the study area being located in a remote part of Canada along with the demise of the Mackenzie Valley Pipeline project that would have served to access to massive stranded gas reserves in Canada's north. The first published research on the Mount Clark Formation was done by Williams (1922, 1923) that first defined the formation at the type section located at Mount Clark. He defined the Mount Clark as Cambrian quartz dominated bioturbated sandstone. This definition is broadly applicable but was initiated in a lithostratigraphic framework that leaves little room for an interpretative framework taking into account distal to proximal deposition. Subsequent work ramped up in the late 1960s as a result of the GSC's historic Operation Norman that sought to map out the Mackenzie Mountains. This was summarized in Aitken *et al* (1973) that published several maps and measured sections of Cambrian strata. Subsequent work followed up with trilobite work and lithostratigraphic mapping (Serie *et al.,* 2009; MacNaughton *et al*., 2013).

Accurately identifying and charactering ancient environments is greatly enhanced through the integrated approach of using physical sedimentology (grain size, sorting, sedimentary structures) and ichnology (trace fossil assemblages, size, and diversity) (MacEachern *et al*, 2010). Ichnology has been shown to be an invaluable tool in interpretation through illuminating physical and chemical stresses during deposition. This allows for high resolution paleoenvironmental reconstruction (Seilacher, 1978; Pemberton *et al.,* 1982; Frey, 1990; Bann *et al.,* 2004; Gingras *et al*., 2011).

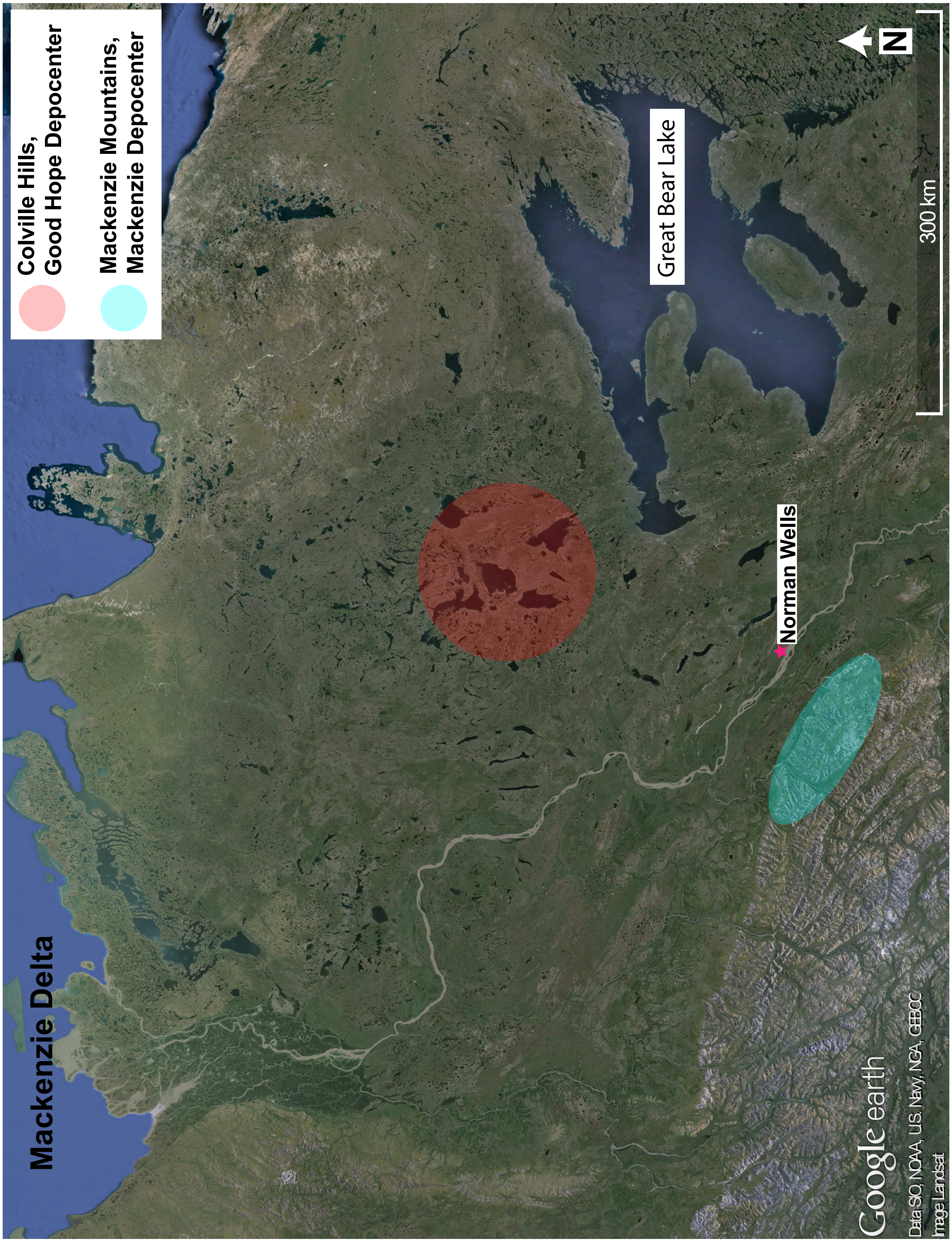
Data collection comes from two main Cambrian depocenters in the Northwest Territories Mainland; 1) Good Hope Depocenter containing the subsurface drill core of the Colville Hills, and 2) the Mackenzie Depocenter in which outcrop belts were described (**Fig. 1**). These depocenters are a result of late Proterozoic and early Cambrian rifting dividing the region into low-relief uplift (domes and arches) and depocenters (Dixon and Stasiuk, 1998).

This study was undertaken in order to enhance the understanding of the architecture, sedimentology, and paleo-ecology of the Mount Clark Formation. Detailed analyses of four subsurface drill cores with complimentary petrophysical wireline logs within the Colville Hills region were completed. Lithology, sedimentology, and ichnological characteristics were documented. This work led to the identification of 8 discrete facies (F1-11) representing a storm-influenced barred shoreface succession (F1-F7) and continental deposition (F8).

Chapter 2 focuses on the outcrop dataset that represents a more complex shoreline environment punctuated by storm-dominated deltaic and shoreface environments in conjunction with protected tidal embayments. Due to the variety and complexity of deposition facies associations were developed instead of individual facies. Three unique facies associations were identified and include shoreface (FA1), wave dominated deltaic complexes (FA2), and protected tidal embayments (FA3). Storm influence was visible in all three environments in ranging from slight to dominated. Outcrops are represented by Carcajou Canyon, Two Lakes, and Waterfall Ridge. Deltaic influence was found to have a strong influence on trace fossil assemblages with a reduction in trace fossil size and suspension feeding forms.

Chapter 3 consists of a paleoecology study of trace fossil assemblages present within the core and outcrop datasets. In addition to economic considerations the Mount Clark Formation contains well-preserved trace fossil assemblages that allow an insight into early Cambrian seas in which complex metazoan life was just evolving and colonizing shallow marine environments. Trace fossil assemblages show that predictable ichnofacies existed 20 million years before the existential Burgess Shale fauna. Animal behaviors within shoreface environments have changed very little over the last 520 m.y., a remarkable feat to animal evolution.

In summary, this thesis seeks to address three issues; 1) identifying the stratigraphic architecture and sedimentary systems in place; 2) presenting the Mount Clark Formation within an allostratigraphic framework; and 3) characterizing the biota of early Cambrian shallow seas and how animal behaviors have evolved through time.


Mackenzie Delta
Colville Hills,
Good Hope Depocenter
Mackenzie Mountains,
Mackenzie Depocenter
Great Bear Lake
Norman Wells
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300 km
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Image Landsat

Figure 1.1: Map showing the study areas within the mainland Northwest Territories, Canada. Modified from Google Earth Pro.

CHAPTER 2: SEDIMENTOLOGY AND ICHNOLOGY OF AN EARLY CAMBRIAN STORM-INFLUENCED BARRED SHOREFACE SUCCESSION, COLVILLE HILLS, NORTHWEST TERRITORIES, CANADA

INTRODUCTION

The Cambrian-aged Mount Clark Formation (Williams, 1922, 1923) is a known reservoir containing oil, natural gas, and condensate in the Colville Hills area of the Northwest Territories [NWT] (Hamblin, 1990; Dixon and Stasiuk, 1998; Janicki, 2004; Price and Enachescu, 2009). A recent resource assessment by Hannigan *et al*. (2011) calculated that the "Cambrian clastics play", which incorporates the Mount Clark Formation beneath the interior plains of the NWT, potentially contains as much as one billion barrels of oil and 10.7 TCF of natural gas. The Mount Clark Formation extends in the subsurface from outcrops in the eastern Mackenzie Mountains (Serie *et al.,* 2009; MacNaughton *et al.,* 2013), eastward beneath the Interior Plains (Dixon and Stasiuk, 1998), and outcrops again along the eastern limit of the northern mainland sedimentary basin. Oil and gas have been found in the Mount Clark Formation exclusively beneath the Colville Hills to date, although the unit may be an exploration target in other parts of the basin (Hannigan *et al*., 2011; MacLean, 2011). As noted by MacLean (2011), clear understanding of the depositional environments of Cambrian reservoir strata will be crucial to hydrocarbon exploration success in the region.

Despite numerous significant hydrocarbon discoveries and subsequent Significant Discovery Licences (SDLs) given out for the Colville Hills area, no literature exists on the detailed sedimentary and ichnological character of reservoir units from the area. Drill cores from four exploration wells in the Colville Hills (Tweed Lake A-67, Tweed Lake M-47, Tweed Lake C-12, and Bele O-35) provide an opportunity to document the lithofacies, ichnology, and depositional environments of the Mount Clark Formation. Details on the four wells are provided in Appendix 1. All wells are within the northwest part of the Good Hope depocentre (Fig. 1), as defined by Dixon and Stasiuk (1998) and refined by MacLean (2011). This report is the first detailed and integrated account of the subsurface lithofacies, sedimentology, and ichnology of the Mount Clark Formation.

Our work suggests that the Mount Clark Formation of the Colville Hills subsurface is characterized by predictable shoreface stacking patterns from offshore to upper shoreface. This should aid the in the identification of undiscovered sand bodies in potential undiscovered stratigraphic traps. These shoreface successions are punctuated by repeated progradation and transgression resulting in porous and permeable sandstone bodies encased in mudstone seals underlying the Mount Cap Fm source shales.

GEOLOGICAL SETTING

Cambrian strata of the Interior Plains lie unconformably upon Proterozoic strata of the Mackenzie Mountains Supergroup and Shaler Supergroup (the "M/S Assemblage" of Cook and MacLean, 2004). The eroded Proterozoic surface was divided into regions of low-relief uplift (domes and arches) and depocentres (Dixon and Stasiuk, 1998) that formed in response to latest Proterozoic and early Cambrian tectonic extension (Williams, 1987; MacLean, 2011) (Fig. 2). The basal Cambrian sandstone of Mount Clark Formation is patchily preserved throughout the region and is best developed in the depocentres (Pugh, 1983; Dixon and Stasiuk, 1998; MacLean, 2011), particularly adjacent to the paleohighs (MacLean, 2011; MacNaughton *et al*., 2013). In the Good Hope depocentre, the preserved Mount Clark Formation thickness reaches at least 88 m (Dixon and Stasiuk, 1998). The Mount Clark Formation is now considered to also include Cambrian sandstone units formerly assigned to the Old Fort Island Formation defined by Norris (1965); see Dixon and Stasiuk (1998) for discussion. Mount Clark Formation strata thus record the initial (Sauk) transgression of the latest Proterozoic peneplain, and contain sand-rich facies deposited in a range of shallow- to marginal-marine environments (Hamblin, 1990; Dixon and Stasiuk, 1998; this work). Subsequent transgression established deeper-marine environmental conditions that led to the deposition of the regionally extensive Mount Cap Formation, a shale-dominated succession with lesser carbonate and sandstone (Aitken *et al*., 1973; Dixon and Stasiuk, 1998). The Mount Cap Formation is overlain unconformably by the Saline River

Formation, a thick package of shale, evaporites, and lesser carbonates that records deposition in a restricted basin (Aitken *et al*., 1973; Dixon and Stasiuk, 1998). The Mount Clark Formation and the Mount Cap Formation thus jointly comprise an unconformity-bounded sequence at the base of the Sauk Supersequence (Sloss, 1963).

Age constraints for the Mount Clark Formation are limited. The presence of intense bioturbation throughout the unit is consistent with its inferred Early Cambrian age. Mount Cap Formation strata are better age-constrained with trilobite faunas, which place the unit in the *Bonnia-Olenellus* to *Glossopleura* zones (Kobayashi, 1936; Fritz, 1970, 1971, 1977; Aitken *et al*., 1973; Serié *et al*., 2009). The Mount Clark Formation and the Mount Cap Formation are in facies contact and the suggestion of Dixon and Stasiuk (1998) that the contact is diachronous has been confirmed based on faunal evidence from outcrops. Depending on locality, the basal beds of the Mount Cap Formation may contain a *Bonnia-Olenellus* Zone or a (younger) *Albertella* Zone trilobite fauna (MacNaughton *et al*., 2013). In the subsurface, the basal part of the Mount Cap Formation in the British Petroleum *et al*. Losh Lake G-22 well (latitude 65° 51’ 29”; longitude 123° 19’ 45”; NAD27) has yielded trilobites that belong to the upper part of the *Bonnia-Olenellus* Zone (Fritz, 1977).

PREVIOUS WORK

Following an initial description by Williams (1922, 1923), the Mount Clark Formation received little attention until the late 1960s. Since then, it has been included in several regional stratigraphic studies, focused both on outcrop belts (Aitken *et al*., 1973; Serie *et al*., 2009; Pyle and Gal, 2009) and the subsurface (Tassonyi, 1969; Pugh, 1983; Dixon, 1997; Dixon and Stasiuk, 1998; MacLean, 2011). The Mount Clark Formation has also been discussed from the perspective of its petroleum potential (Snowdon and Williams, 1986; Hamblin, 1990; Dixon and Stasiuk, 1998; Hannigan *et al*., 2011). Published sedimentological interpretations on the Mount Clark Formation are sparse, and are limited to preliminary studies based on selected drill cores (Hamblin, 1990; Dixon and Stasiuk, 1998) or outcrop data (Aitken *et al*., 1973; MacNaughton *et al*., 2013). MacNaughton and Fallas (2014) identified a new Cambrian map unit named the Nainlin Formation that conformably overlies the Mount Cap Formation and is interpreted to represent the more proximal expression of Saline River Formation deposition. To date this unit has only been identified within the Mackenzie Mountains but may also be found within the Colville Hills.

Early hydrocarbon discoveries were centered on the Tedji Lake K-24 well recovering 124,000m^3 of gas in a thin Mount Clark sandstone sheet covering Proterozoic basement. Exploration activities were most active in the mid-1980s, in which exploration licenses were held by Chevron, Petro-Canada, Dome, and Esso (now

Imperial). Significant discovery licences (SDLs) include Tweed Lake A-67 (gas), Tweed Lake M-47 (gas and condensate), and Bele O-35 (Gas and Condensate) (Hamblin, 1990; Janicki, 2004). Drilling and exploration saw a resurgence in the early 2000s as a result of the proposed Mackenzie Valley Pipeline that would serve to access massive stranded gas reserves in Canada's North. During this time, Apache's Lac Maunoir C-34 well was given an SDL based on recoverable oil, condensate, and gas reserves present (Hannigan *et al*, 2011).

FACIES DESCRIPTIONS AND INTERPRETATIONS

Facies are described in the order of interpreted distal to proximal environments. Facies 1 and 2 represent a *Glossifungites* firm-ground suite and a transgressive lag respectively. These facies are not controlled by distal or proximal trends and hence are described first. Based on the facies descriptions and interpretations below, facies 3-7 represent a shoreface facies model and Facies 8 represents continental illuviation. Tweed Lake-67 is the only core that contains the entire Mount Clark Fm Succession. Bioturbation intensity is quantified with bioturbation index (BI) *sensu* Reineck (1967), Taylor and Goldring (1993). Grain size was classified according to the International ISO 14699-1:2002 scale. Mineralogy was determined through thin sections provided by the GSC. These thin sections were stained with a blue porosity dye.

FACIES 1: *GLOSSIFUNGITES*-DEMARCATED OMISSION SURFACE

A pervasively penetrative burrow boxwork occurs within three substrate types: 1) green mudstone; 2) red mudstone; or 3) fine grained sandstones (Fig. 4A, B, C). Burrows are large, averaging 1-1.5cm in diameter. Burrow morphologies range from branching to simple vertical traces reaching 10 to 20 cm below the inferred sediment-water interface. Trace fossils observed include *Skolithos* and *Diplocraterion.* Burrow fills comprise lower medium-grained sandstone or highly glauconitic (>90% glauconite) lower medium-grained sandstone. The surfaces from which the burrows descend are sharp, undulatory, and are directly overlain by a pebble lag. The burrow fill lithologies resemble overlying bed lithologies.

INTERPRETATION:

This facies represents the erosional exposure of a sedimentary firmground that was subsequently colonized by burrowing animals (Pemberton and Frey, 1985; MacEachern *et al.,* 1990, 1991, 1992; Savrda, 1991). The sharp, undulatory nature of the contact and the presence of a lag are consistent with erosion due to waves. And, the abrupt upward transition from sandstone to clayey siltstone at the contact suggests that the surface represents a transgressive surface of erosion (MacEachern, 1992). This facies likely represents an early major transgression within the Good Hope Depocentre. The dramatic shift in lithology from argillaceous mudstone into medium-grained sandstone corresponds to an increase in depositional energy, most likely due to wave influence. Sedimentary structures such as flaser bedding, tubular tidalites, and tidal rhythmites, which reflect tidal deposition, were not encountered.

FACIES 2: MODERATELY SORTED MEDIUM- TO COARSE-GRAINED SANDSTONE

Facies 2 comprises poorly sorted medium- and coarse-grained sandstone that is typically observed overlying Facies 1 (*Glossifungites*). Pebble- to granule-sized clasts are common (Fig. 4E, F). Bedding is crudely defined and is often not observable. BI ranges from 0-4. Facies 2 is locally capped by an irregular 4 cm thick bioturbated glauconitic sandstone bed (Fig. 4D). When present, bioturbation consists of a low diversity suite comprising *Palaeophycus* and *Teichichnus*. The stratigraphic context for Facies 2 is best demonstrated with strip logs (i.e. Fig. 3, Tweed Lake A-67 1298.5 m and 1288.4; PCI C-12, 1319.5m).. The thickness of facies 2 averages less than 15 cm.

INTERPRETATION:

Based on the abrupt upward shift in grain size from coarse/pebbly sandstone to silt/clay and a lack of evidence for shallow wave action, this facies is interpreted as a pebbly transgressive lag that was deposited and reworked by waves during transgression. This transgressive lag, which demarcates a flooding surface, lies at the base of coarsening upward parasequences. Pebbles and granules were likely sourced from eroded shoreface sediment and subsequently redistributed across the shoreface during transgression (Riemersma and Chan, 1991; Raychaudhuri *et al.*, 1992; Cattaneo and Steel; 2003).

FACIES 3: INTERBEDDED MUDSTONE, SILTSTONE AND SANDSTONE

Facies 3 consists of interbedded green to grey mudstone and siltstone with interbedded sharp-based sandstone beds that display varying degrees of biogenic reworking (Fig. 4G, I, J). Sharp based sandstone beds are upper fine-grained and are characterized by oscillation-ripple and wavy-parallel lamination. Remnant sandstone beds with sparse (BI 0-1) to intense bioturbation (BI 3-4) grade upwards into siltstone. Bioturbation intensity within beds increases upwards; trace fossils include *Palaeophycus, ?Asterosoma Chondrites, Skolithos, Teichichnus,* and *Planolites*. Sandstone lithologies show alternating horizons of laminated to burrowed fabrics. Equilibrichnia structures, interpreted to be fugichnia, are present in the bioturbated beds or are truncated at intra-stratal scours (Fig. 4I, J). Micro hummocky cross-stratification is well developed within some of the sandstone beds (Fig. 4I). Locally, bioturbation completely destroys the primary fabric of sandstone beds resulting in a homogenized appearance (Fig. 4G). Sharp based decimeter-scale massive mudstone beds are randomly distributed and are entirely composed of laminated grey to black mudstone without any apparent bioturbation or sand content (Fig. 4H). Bed thicknesses range from the centimeter to decimeter scale.

INTERPRETATION:

The trace fossil assemblage of facies 3 comprises carnivorous (eg. *Palaeophycus)* and deposit-feeding ethologies and represents an expression of the *Cruziana* Ichnofacies (Howard and Frey, 1984; MacEachern and Pemberton, 1992; MacEachern and Bann, 2008; Ekdale *et al*., 2012). The thoroughly bioturbated intervals reflect depositional periods dominated by fair-weather processes (Vossler and Pemberton, 1988b). The *Cruzian*a Ichnofacies may further indicate that settling and subsequent embedding of organic matter in the seafloor occurred during fair-weather conditions. Episodic storms increased turbulence and generated erosional features, high-energy depositional (Micro HCS) structures, while redistributing organic detritus (Seilacher, 1982a). This resulted in a tripartite zonation within tempestite sandstone beds: 1) a set of bioturbated interbedded sandstone and siltstone deposited during fair-weather; 2) a sharp based erosional sandstone bed with undulatory to hummocky cross-stratification grading into a burrowed “scrambled” top; and 3) a return to ambient, thoroughly bioturbated, fair-weather shoreface conditions (Seilacher, 1982). Fugichnia are observed within the tempestite beds, illustrating likely unsuccessful organism escapes from rapid sedimentation events. Laminated grey to black mudstone likely indicates fair weather sedimentation in which the sandier intervals are a result of offshore directed storm currents that carried and deposited sediment further offshore. Facies 3 was deposited in the proximal offshore to offshore transition where fair-weather processes cease to influence sedimentation and offshore processes dominate sedimentation (Reinson, 1984) (Fig. 7A).

Facies 4: Interbedded Cross-Stratified to thoroughly bioturbated silty muddy sandstone

Facies 4 is a mixture of intensely to moderately bioturbated sandstone, siltstone, and shale. Intensely bioturbated strata are characterized by *Rosselia*, *Asterosoma*, *Rhizocorallium*, *Cylindrichnus*, *Arenicolites*, *Chondrites*, *Teichichnus*, *Palaeophycus*, and equilibrichnia (Fig. 5A) Punctuated occurrences of green ?glauconitic shale laminae contain *Palaeophycus* and *Chondrites (*Fig. 5C). Sandstone intervals are generally fine to lower medium in grain size and thoroughly bioturbated. Current rippled sharp-based sandstones are commonly intercalated with intensely bioturbated strata (Fig. 5B,C). Alternating horizons of undulatory to planar laminated sandstone are interbedded with bioturbated intervals containing abundant fugichnia. (Fig. 5D). The tops of laminated sandstone beds are sporadically burrowed and contain *Skolithos* and *Cylindrichnus*.

Interpretation:

Thoroughly bioturbated strata containing large robust traces indicate fair-weather shoreface conditions in which both deposit and suspension feeding organisms thrived (MacEachern and Pemberton, 1992; Uchman and Krenmayr, 1995). Trace fossil assemblages of facies 4 are an archetypal example of the Cruziana Ichnofacies, which is characteristic of fully marine water, and oxygen- and benthic-food-rich conditions

(MacEachern and Pemberton 1992). The deposit feeding behaviours of Cruziana Ichnofacies reflect ambient wave energy, strong enough to disperse organic matter into the proximal offshore (MacEachern and Pemberton, 1992). In contrast, storm-weather conditions are preserved as sharp-based, cross-stratified sandstone beds. The “Lam-Scram” pattern of alternating undulatory laminae and bioturbated horizons (*sensu* Howard, 1978; MacEachern and Pemberton, 1992). Undulatory laminae indicate storm onset and burrowed beds indicate storm. During storms, wave base is lowered, which causes reworking of the fair-weather substrate. Fugichnia are present within these tempestite beds, reflecting the rapid and sudden onset of sedimentation. Truncated trace fossils and fugichnia further demonstrate the erosional nature of storm processes. Only the deepest penetrative trace fossils are preserved. Nonbioturbated cross-stratified beds indicate rapid storm deposition; following the storm, tempestite bed recolonization is initiated by opportunistic animals that generated *Skolithos* and *Cylindrichnus* trace fossils (Pemberton and MacEachern, 1997). *Skolithos* and *Cylindrichnus* are commonly associated with r-selected metazoans that are capable of adapting to agitated and rapidly changing environments (Vossler and Pemberton, 1988b). Facies 4 is interpreted to record fair-weather and storm-weather lower shoreface sedimentation over the zone of shoaling where the initial breaking of waves occurred (Reinson, 1984).

FACIES 5: LOW-ANGLE CROSS-STRATIFIED SANDSTONE WITH THIN BIOTURBATED HORIZONS

Facies 5 comprises upper fine- to lower medium-grained well-sorted sandstone characterized by low-angle cross-stratified to hummocky cross-stratified beds (Fig. 5E, G). The amplitude of HCS is generally approximately 15 cm. Hummocky cross-stratification is recognized using the following criteria: 1) erosional lower bounding surfaces that commonly slope at angles less than 15 degrees; 2) laminae above these surfaces are parallel to sub-parallel; 3) laminae can thicken or thin laterally within a set resulting in a fan-like geometry on a vertical surface; 4) the dip directions of the erosional set boundaries and of the overlying laminae are scattered (Harms *et al*., 1975). Bioturbated intervals are thin (3-4cm thick) and contain simple mud-lined traces such as *Skolithos*, *Cylindrichnus,* and *Palaeophycus* (Fig. 5F). Amalgamated sandstone beds with sharp erosional bases are prevalent, and preserve alternating horizons of laminated to burrowed sandstones. Mudstone is limited to thin laminae (Fig. 5F). Intraformational mudstone rip-up clasts are observed within the HCS beds (Fig. 5E). Sandstone bed thickness is on the dm scale on average.

INTERPRETATION:

The paucity of highly bioturbated and diverse trace fossil assemblages and the dominance of high-energy sedimentary structures of oscillatory origin are interpreted to represent persistent storm influence and deposition. Rip-up clasts within HCS beds are interpreted to be the result of strong storm surge currents transporting more proximal material basinward. The rare occurrence of bioturbation within these beds is interpreted to represent either sufficiently pervasive storm activity to preclude bioturbation or the removal of fair-weather bioturbated suites. Preserved trace fossils are interpreted to represent opportunistic post-colonization suites by r-selected metazoans (Vossler and Pemberton, 1988). These trace fossil suites record a departure from the complex deposit feeding traces seen in Facies 3 and 4, to simple suspension feeding forms. This shift in trace fossil ethology in association with larger more pervasive storm-induced bed-forms is interpreted to represent shoaling upward into the middle shoreface (Walker, 1984; Leckie and Krystinik, 1989; Duke, 1990; Duke *et al.*, 1992). Facies 5 is interpreted to have accumulated within the middle shoreface as evident from pervasive and amalgamated HCS storm deposits along with a lack of *Cruziana* deposit feeding behaviors (Buatois *et al*., 1999; MacEachern and Pemberton, 1992) (Fig. 7).

FACIES 6: LOW TO HIGH ANGLE CROSS STRATIFIED SANDSTONE

Facies 6 consists of upper medium-grained sandstone characterized by trough cross-stratification (TCS) (Fig. 6A), planar-tabular bedding (Fig. 6B), and HCS (Fig. 6D). Planar-tabular bedding commonly occurs as 8-20 cm thick beds whereas low-angle cross-stratified beds are typically ~75cm thick. Micro-faulting and convolute bedding is present (Fig. 6C). Bioturbation is absent.

INTERPRETATION:

Facies 5 is distinguishable by its multidirectional trough cross-stratification, which occurs in 15-45cm thick sets manifested as low-angle cross stratification (Howard, 1971; Elliot, 1986; MacEachern and Pemberton, 1992) and is interpreted to result from the migration of low-relief 2D and 3D dunes. Hummocky cross-stratification is generated by oscillatory flow that caused by storm-waves (Walker, 1984; Leckie and Krystinik, 1989; Duke, 1990; Duke *et al.*, 1992). The absence of bioturbation is interpreted to reflect environmental conditions dominated by abundant sediment supply and rapidly migrating bedforms (Reineck, 1977). Micro-faulting and convolute bedding resulted from soft-sediment deformation possibly associated with wave-induced liquefaction (Clifton, 1971; Pratt, 2002). The presence of HCS, persistent dune migration, and the absence of bioturbation suggest that Facies 6 was deposited within the upper shoreface of a shoreline (Fig. 7). The upper shoreface environment is situated in the high-energy surf zone landward of the breaker zone (Clifton, 1971; Barwais, 1976; Reineck and Singh, 1980; MacEachern and Pemberton, 1992). This zone is characterized by wave driven currents that flow parallel to the shoreline seaward of the subaqueous bar (*i.e.* longshore drift), and by currents generated by translatory flow associated with plunging waves that generate multidirectional 2-D and 3-D dunes (Clifton, 1971; Davies *et al., 1971;* MacEachern and Pemberton, 1992).

Facies 7: “Piperock” Sandstone

Facies 7 consists of lower to upper medium-grained occasionally glauconitic arenite dominated by a *Skolithos* and *Lingulichnus* “piperock” assemblage (Fig. 6F-I). Bioturbation is intense and sometimes results in the homogenization of the sediment. *Skolithos* and *Lingulichnus* burrow diameters range from 3 to 14 mm and burrow lengths range from 10 to 15 cm. Oil staining is prevalent and concentrated within *Skolithos* and *Lingulichnus* burrows (Fig. 6G). *Lingulichnus* displays well developed equilibrium adjustments (Fig. 6F). Sandstone units are well sorted and comprise the coarsest bed scale (>5 cm) grain sizes observed in this study. One core, Tweed Lake A-67, contains a relatively thin interval of planar-tabular cross bedding at 1279.7m depth (Fig. 6E). This planar tabular bedding is 20cm thick and is observed within an intensely bioturbated piperock succession.

Interpretation:

Based on the presence of large robust *Skolithos* and *Lingulichnus,* a lack of sedimentary structures, and a relative increase in grain size (compared to other facies observed), we place this facies in the proximal upper shoreface and foreshore. The upper shoreface to foreshore environment landward of the sub-aqueous bar is characterized by shifting sandy substrates in shallow waters (Reineck and Singh, 1980) (Fig. 7). Suspension-feeding animals likely depended on food suspended in the water column. The foreshore to proximal upper shoreface is typified by the appearance of the *Skolithos* Ichnofacies of which piperock is archetypal (Droser, 1991; Howard, 1971; MacEachern and Pemberton, 1992). Observed equilibrium traces indicate an environment characterized by sporadic sedimentation events, that were not substantive enough to kill the original tracemakers, allowing them to adjust and move upward (Zonneveld and Pemberton, 2010). These re-equilibrium movements likely indicate post storm re-establishment (MacEachern and Pemberton, 1992; Nara; 1995, 1997). The high bioturbation intensity (BI 4-5) suggests that during fair-weather, biogenic reworking rates exceeded hydraulic reworking rates. As such, the shoreface profile is inferred to have been dissipative to intermediate, shielded by sub-aqueous bars in the upper shoreface (e.g. Hunter *et al*., 1979; Leckie and Walker, 1982) (Fig. 7). These bars act as a barrier against large hydraulic energies, resulting in abundant populations of suspension feeding ichnogenera, forming piperock assemblages within the trough positioned landward of the longshore bar. Large storms are capable of breaching this barrier, depositing the characteristic nonbioturbated washover fan deposits (Fig. 6E) (Reinson, 1984).

FACIES 8: NONBIOTURBATED MASSIVE RED MUDSTONE

Homogeneous massive-appearing, red mudstone that contain no recognizable sedimentary structures, trace fossils, or primary depositional fabric (Fig. 6J). Facies 8 is found at the base of the Tweed Lake A-67 core where it is 1.5m thick. No caliche nodules were observed in the interval.

INTERPRETATION:

The lack of bioturbation and distinctive red colouring is interpreted to reflect continental processes (Basu, 1981). Iron-rich clay minerals were exposed to continental weathering causing the red colouration (Krynine, 1949; Driese *et al*., 1995; Retallack *et al*., 1988). As a result of the lack of bioturbation, red colouration, and fine grained lithology Facies 8 is interpreted to represent a windblown regolith/loess (Fig. 7). This regolith is eventually transgressed, resulting in the formation of a firm-ground substrate that hosts the *Glossifungites* assemblage seen in F1.

FACIES MODEL AND DISCUSSION

DEPOSITIONAL SETTING

The Mount Clark Formation in the Colville Hills area represents a progradational shoreface complex. Constituent parasequences coarsen upwards from offshore mud deposition to shallow-water piperock of the upper shoreface/foreshore (Fig. 7). In this study, large-scale hummocks (Fig. 6E), an absence of bioturbation in the middle shoreface (Fig. 5E, G), and the presence of tempestites into the proximal offshore (Fig. 4 I, J) suggest that storm waves shaped the shoreface. Numerous authors have illustrated the relationship of HCS to storm induced sedimentation (e.g., Walker, 1984; Duke, 1985; Walker and Plint, 1992). Tempestite beds are characterized by the following ichnological and sedimentological characteristics: 1) a fair-weather trace fossil assemblage; 2) a sharp erosional basal contact; 3) subparallel to parallel laminae interpreted to be hummocky or swaley cross-stratification; 4) fugichnia (escape structures); 5) post-storm colonization trace fossil suite emplaced in the newly deposited sand bed; 6) a return to fair-weather trace fossil assemblages (Pemberton and MacEachern, 1997).

Storm influence within the Cambrian was likely due to summer hurricane seasons as Laurentia was situated near the equator (Duke, 1995) (Fig. 8). Hurricanes are particularly effective in generating HCS because of their ineffective coupling of the water column (stratified water column) resulting in powerful oscillatory currents (Duke, 1985).

In the studied strata, wave energy likely erosively stripped fair-weather strata of the middle shoreface as result of storm-induced intensive oscillatory currents (Wetzel and Aigner, 1986). The presence of sub-aqueous longshore bars and the progressive waning of wave energy into an intermediate or dissipative upper shoreface and foreshore enabled suspension-feeding animals to successfully colonize the substrate (Fig. 7). However, within a strongly storm-influenced shoreface succession that records frequent storm influence even in the offshore, the question is raised as to how suspension feeding organisms could thrive in very shallow water in a coastal setting routinely ravaged by storms. The presence of a sub-aqueous longshore bar provided a barrier to intense wave activity, absorbing wave action, which enabled suspension feeders to successfully thrive and colonize the substrate (Fig. 7**)**. A modern analogue for this type of system is provided by the Oregon coastline. This type of bar and trough system is characteristic of an intermediate shoreface profile reflecting a balance between dissipative and reflective shoreface profiles (Short, 1999; Woodruffe, 2003). Suspension-feeding animals are able to thrive in the 2-4m deep, protected trough, where wave action is strong enough to ensure necessary benthic-food supply and shifting sandy substrates, but sufficiently attenuated to spare the burrowing animals from routine exhumation. Bioturbation extends to the foreshore where energy dissipates (Clifton, 1971).

Significance of Piperock

Various workers (McIlroy and Logan, 1999; McIlroy and Garton, 2004; Desjardins *et al.,* 2010 a, b; 2012*)* have studied early to middle Cambrian successions and have ascribed probable piperock depositional environments. These studies interpret piperock to form in shallow-water, proximal sub-tidal tide-dominated sand sheets that are dominated by compound dunes and sand ridges. The Mount Clark, in comparison, lacks evidence for tidal sedimentary features (e.g. bi-directional current structures, grain striping, flaser bedding, double-mud drapes, sigmoidal bedding, or tubular tidalites). In this study, the distributions of trough cross-stratification and hummocky cross-stratification strongly support wave-dominated sedimentary environment interpretations characterized by persistent storm influence, which erosively removed the record of fair-weather sedimentation, resulting in the preservation of far stronger than average storm events (Wetzel and Aigner, 1986).

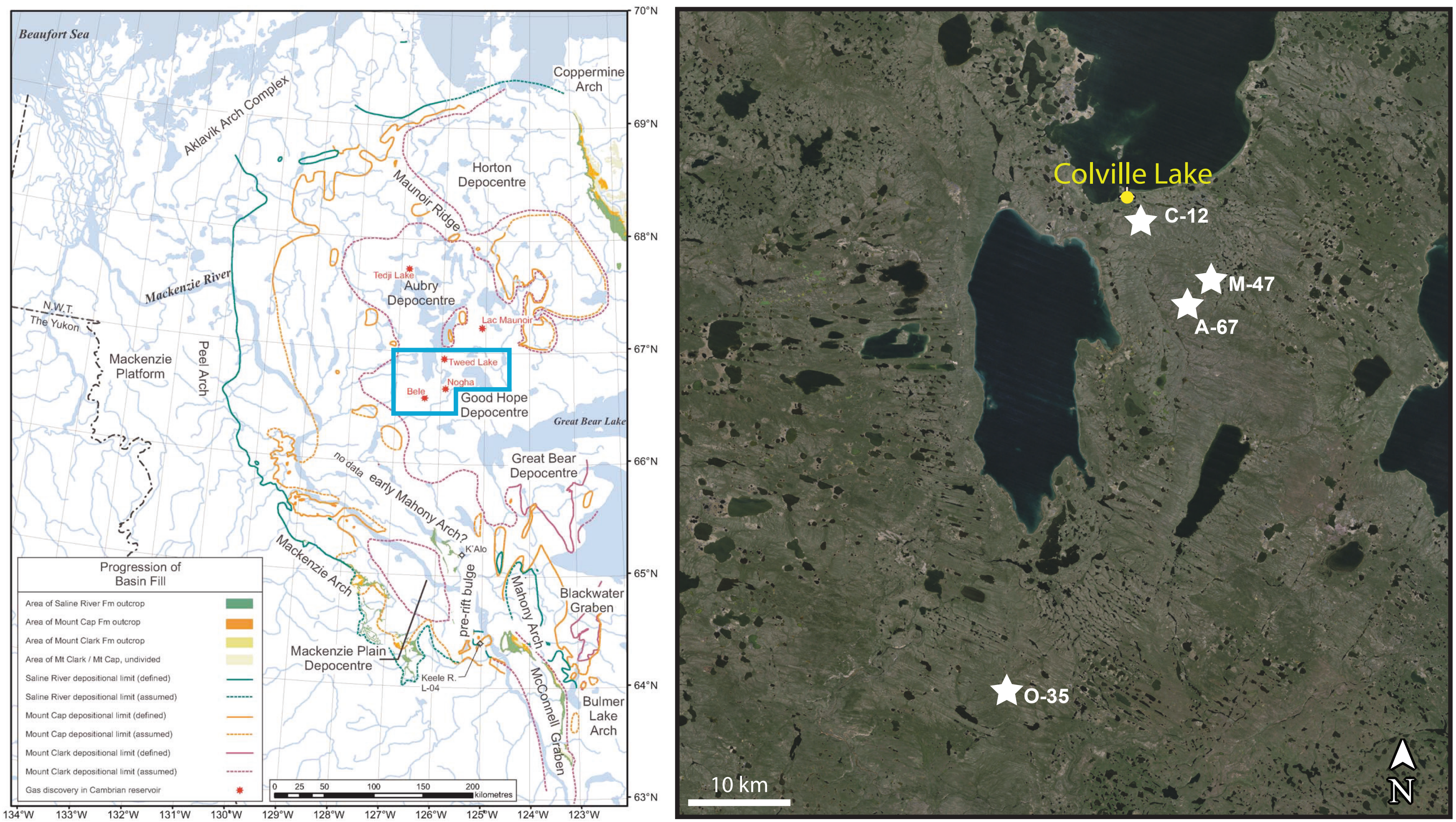
The piperock, documented in the present study contains abundant *Skolithos* and *Lingulichnus* (F7). In contrast, previously documented occurrences of piperock report *Skolithos, Diplocraterion, Monocraterion,* and *Rosselia* as the principle trace fossils (Hallam and Swett, 1966, Häntzschel, 1975, Miller and Byers, 1984; Droser, 1991; McIlroy and Logan, 1999; McIlroy and Garton, 2004; Desjardins *et al.,* 2010; McIlroy *et al.,* 2010). Importantly *Lingulichnus* within the Mount Clark Formation also displays well-developed equilibrium adjustments not seen in other localities (Fig. 6F).

Compared to other studies, piperock within the Mount Clark Formation of the Colville Hills most closely corresponds to *Skolithos* Ichnofabric 2 within the Early Cambrian Gog Group of Western Canada reported by Desjardins *et al.* (2010a). Ichnofabric 2 can be summarized as follows: fine- to medium-grained sandstone; moderate to intense bioturbation; *Skolithos* and *Diplocraterion;* and massive to flaser to TCS bedding. Desjardin *et al*. (2010a) attributed deposition to moderately strong tidal currents coupled with moderate sedimentation rates and minor scouring, thereby allowing multiple colonization events. It is these colonization windows, caused by a drop in current velocity or sediment supply that stall the migration of bedforms that host piperock. In wave-dominated settings, colonization events are limited to areas sheltered from fair-weather wave energy and zones below fair-weather wave base. *Lingulichnus* is an ideal behaviour for surviving in storm-influenced shoreface succession (Zonneveld and Pemberton, 20010; Zonneveld and Greene, 2010). Lingulide brachiopods, the primary tracemaker for *Lingulichnus*, are excellent storm survivors as a result of deep infaunal lifestyles that develop during early growth stages (Zonneveld and Pemberton, 2003). Furthermore, their ability to re-burrow and rapidly equilibrate allows them to survive storm induced erosional exhumation and transport (Zonneveld and Pemberton, 2010).

The piperock reported herein better corresponds to ichnofossil distribution in Mesozoic and Cenozoic shorefaces, as the energy-sheltered uppermost shoreface and foreshore zones likely host substantial infaunal biomass. In Cretaceous to modern examples, this niche is associated with the presence of *Macaronichnus* and more rarely *Thalassinoides* or *Ophiomorpha* (MacEachern and Pemberton, 1992; Pollard *et al*., 1993). However, the upper shoreface and foreshore zones are colonized for similar reasons (1) that the somewhat lower hydraulic energies permit larvae to settle and colonize the substrate; (2) similarly, the dissipative part of the shoreface is where marine organics can accumulate; and (3) more stable (i.e. non-shifting) substrate are amenable to long-term colonization (Pemberton and Frey, 1984). Droser (1991) noted piperock was indicative of shallow water marine sedimentation with planar, trough, and hummocky cross-stratified commonly hosting well-developed piperock assemblages. This is interpreted to represent the availability of multiple or extended colonization periods during which a decrease in sediment supply and/or hydraulic currents allowed metazoans to successfully inhabit and reproduce within the substrate. It is interesting to note that the Mount Clark Fm does not contain this style of piperock, where bedforms such as HCS and TCS are colonized and where piperock is limited geo-spatially to the foreshore.

SUMMARY

A facies model for an early Cambrian wave-dominated storm-influenced shoreface succession is herein presented based on detailed sedimentological and ichnological analyses of subsurface drill core from the Colville Hills region of the Northwest Territories. The facies model presented illustrates a predictable shoreface stacking pattern composed of eight distinct lithofacies representing an overall offshore to upper shoreface succession. Flooding surfaces are demarcated by pebbly poorly sorted transgressive lags separating shallow and distal facies and by *Glossifungites*-demarcated omission firm-ground suites. The presence of a bar shelter is predicated on the presence of large robust suspension feeding traces comprising *Skolithos* and *Lingulichnus* in an otherwise high-energy storm-influenced succession. This work establishes a predictive framework for subsurface Mount Clark Formation reservoirs in the Colville Hills. Future work can apply this framework towards a comprehensive sequence stratigraphic model.


Beaufort Sea
Aklavik Arch Complex
Coppermine Arch
Horton Depocentre
Maunoir Ridge
Mackenzie River
Tedji Lake
Aubry Depocentre
Lac Maunoir
N.W.T.
The Yukon
Mackenzie Platform
Peel Arch
Tweed Lake
Nogha
Bele
Good Hope Depocentre
Great Bear Lake
Great Bear Depocentre
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early Mahony Arch?
K'Alo
Mackenzie Arch
pre-rift bulge
Mahony Arch
Blackwater Graben
Mackenzie Plain Depocentre
Keele R. L-04
McConnell Graben
Bulmer Lake Arch
Progression of Basin Fill
Area of Saline River Fm outcrop
Area of Mount Cap Fm outcrop
Area of Mount Clark Fm outcrop
Area of Mt Clark / Mt Cap, undivided
Saline River depositional limit (defined)
Saline River depositional limit (assumed)
Mount Cap depositional limit (defined)
Mount Cap depositional limit (assumed)
Mount Clark depositional limit (defined)
Mount Clark depositional limit (assumed)
Gas discovery in Cambrian reservoir
0 25 50 100 150 200 kilometres
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Colville Lake
C-12
M-47
A-67
O-35
10 km
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Figure 2.1: Location map showing study area and core locations within the Colville Hills. Modified after MacLean (2011). Air photo provided by Google Earth Pro.

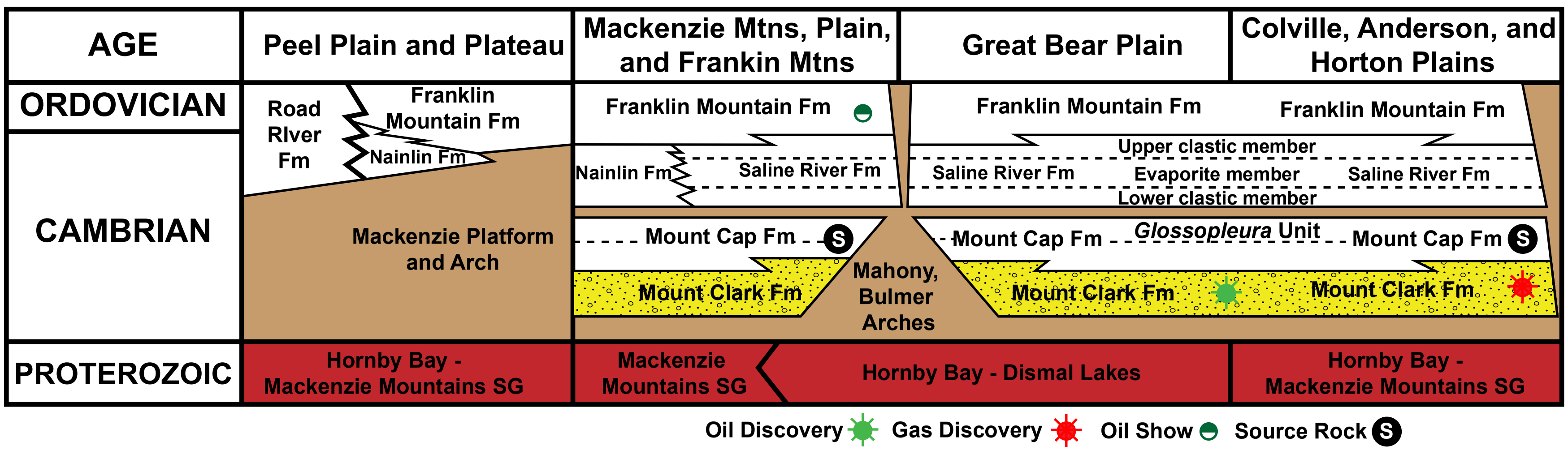
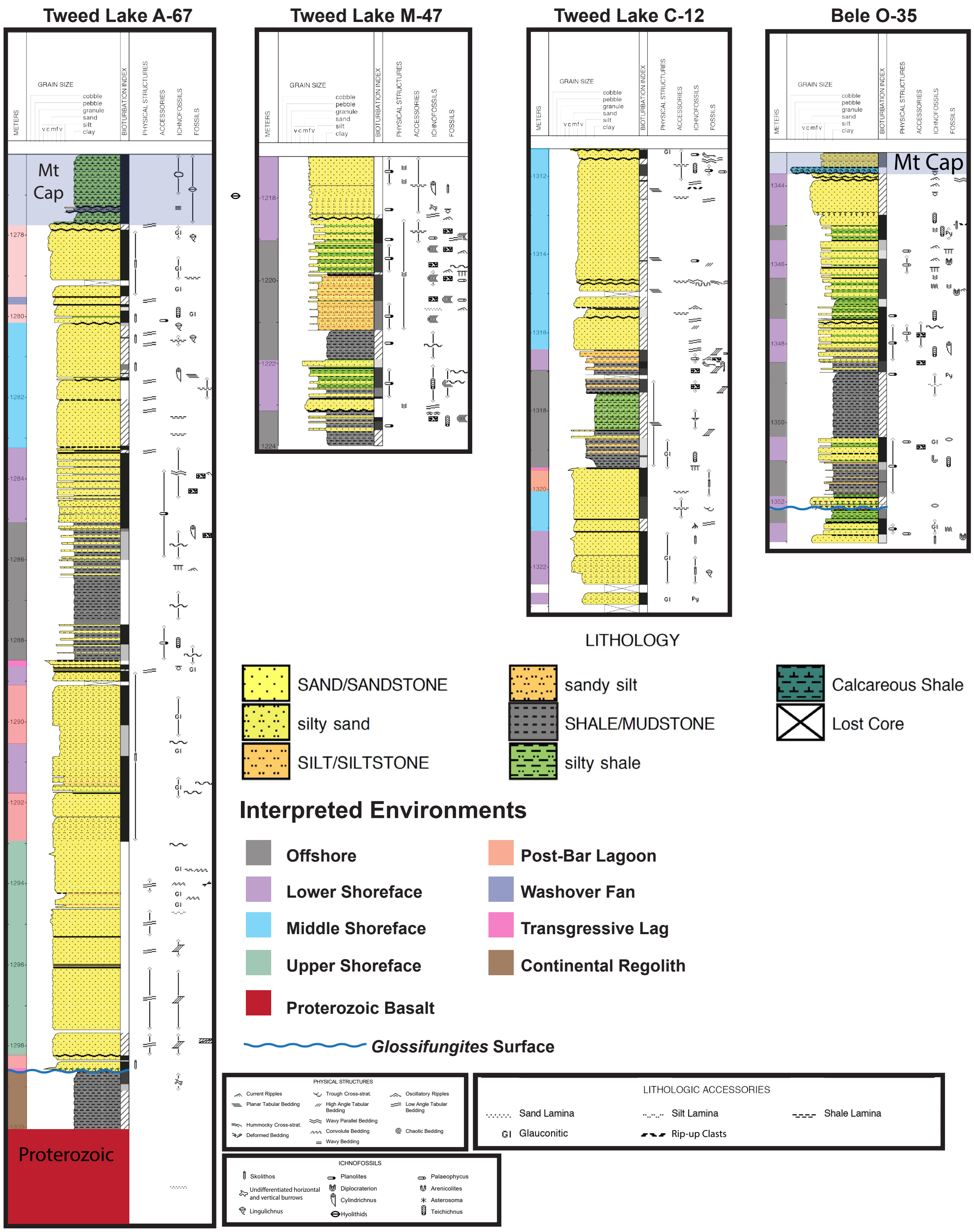

AGE
Peel Plain and Plateau
Mackenzie Mtns, Plain, and Frankin Mtns
Great Bear Plain
Colville, Anderson, and Horton Plains
ORDOVICIAN
CAMBRIAN
PROTEROZOIC
Road RIver Fm
Franklin Mountain Fm
Nainlin Fm
Mackenzie Platform and Arch
Franklin Mountain Fm
Nainlin Fm
Saline River Fm
Mount Cap Fm
Mount Clark Fm
Mahony, Bulmer Arches
Franklin Mountain Fm
Franklin Mountain Fm
Upper clastic member
Saline River Fm
Evaporite member
Saline River Fm
Lower clastic member
Mount Cap Fm
Glossopleura Unit
Mount Cap Fm
Mount Clark Fm
Mount Clark Fm
Hornby Bay - Mackenzie Mountains SG
Mackenzie Mountains SG
Hornby Bay - Dismal Lakes
Hornby Bay - Mackenzie Mountains SG
Oil Discovery
Gas Discovery
Oil Show
Source Rock

Figure 2.2: Stratigraphic column showing the relationship of the Mount Clark, Mount Cap, and Saline River Formations. Chief focus on this study is the Mount Clark Formation within the Colville area. Modified from MacLean (2011) with information from MacNaughton and Fallas (2014).


Tweed Lake A-67
Tweed Lake M-47
Tweed Lake C-12
Bele O-35
METERS
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v c m f v
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FOSSILS
Mt Cap
Proterozoic
LITHOLOGY
SAND/SANDSTONE
silty sand
SILT/SILTSTONE
sandy silt
SHALE/MUDSTONE
silty shale
Calcareous Shale
Lost Core
Interpreted Environments
Offshore
Lower Shoreface
Middle Shoreface
Upper Shoreface
Proterozoic Basalt
Post-Bar Lagoon
Washover Fan
Transgressive Lag
Continental Regolith
Glossifungites Surface
PHYSICAL STRUCTURES
Current Ripples
Planar Tabular Bedding
Hummocky Cross-strat.
Deformed Bedding
Trough Cross-strat.
High Angle Tabular Bedding
Wavy Parallel Bedding
Convolute Bedding
Wavy Bedding
Oscillatory Ripples
Low Angle Tabular Bedding
Chaotic Bedding
LITHOLOGIC ACCESSORIES
Sand Lamina
Silt Lamina
Shale Lamina
Gl Glauconitic
Rip-up Clasts
ICHNOFOSSILS
Skolithos
Undifferentiated horizontal and vertical burrows
Lingulichnus
Planolites
Diplocraterion
Cylindrichnus
Hyolithids
Palaeophycus
Arenicolites
Asterosoma
Teichichnus

Figure 2.3: Logged cores with annotated environments of deposition**.** Four cores were logged with special attention paid towards sedimentologic and ichnologic characteristics. Only one core (A-67) captured the entire Mount Clark succession, from the basal unconformity to the overlying mixed carbonate-clastic Mount Cap Fm. Mount Cap Formation is recognized by the first appearance of carbonate rich lithologies, often hyolithid rich rocks. Core logging was done through AppleCore© software.

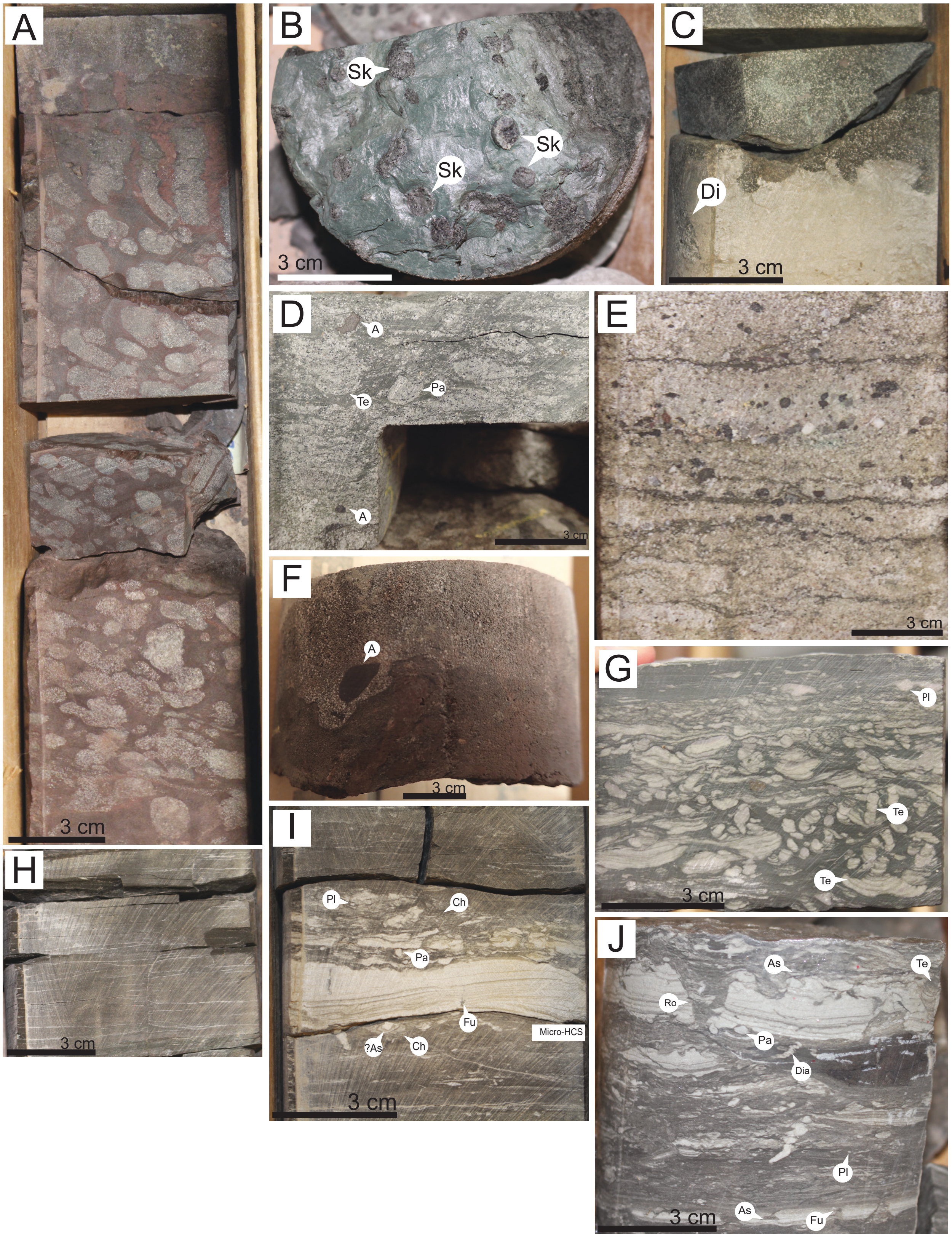
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Figure 2.4: Facies Plate I (Facies 1, 2, and 3)

A) Facies 1; *Glossifungites* demarcated omission surface, sand filled burrows in a red mudstone, Tweed Lake A-67.

B) Facies 1; Bedding plane view of *Skolithos (Sk) Glossifungites* firm-ground suite within a green mudstone substrate. Bele O-35.

C) Facies 1; *Glossifungites* firm-ground suite with a large *Diplocraterion (Di)*, green colour is a result of glauconite. Bele O-35.

D) Facies 2; Bioturbated glauconitic upper fine sandstone with granule to pebble sized clasts (A). *Palaeophycus* (*Pa*), *Teichichnus* (*Te*). Tweed Lake A-67.

E) Facies 2; Transgressive lag manifested as a coarse grained sandstone with pebble to granule sized clasts. Tweed Lake A-67.

F) Facies 2; Transgressive lag overlying a *Glossifungites* surface, large clast (A) within burrow. Tweed Lake A-67.

G) Facies 3; Offshore sandy mudstones intensely bioturbated with *Teichichnus* (Te) *Planolites* (Pl). Tweed Lake A-67.

H) Facies 3; Offshore nonbioturbated massive black mudstones. PCI C-12.

I) Facies 3; Distal biogenically reworked sandy tempestite bed within offshore mudstones. Depositional hydraulic currents great enough to produce Micro Hummock Cross-Stratification (HCS). Note upper portion of tempestite bed has been biogenically reworked from the original bed resulting in bed disintegration; Fugichnia (Fu), ?*Asterosoma* (?As), *Chondrites* (Ch), *Palaeophycus* (Pa). Tweed Lake M-47

J) Facies 3; Multiple intensely biogenically reworked distal sandy tempestite within offshore mudstones. Lamination seen in sand bed that has been disrupted through bioturbation. Trace fossils consist of Fugichnia (Fu), *Asterosoma* (As), *Palaeophycus* (Pa), *Teichichnus* (Te), *Rosselia* (Ro), *Planolites* (Pl). Diastasis cracks also seen (Dia). Tweed Lake A-67

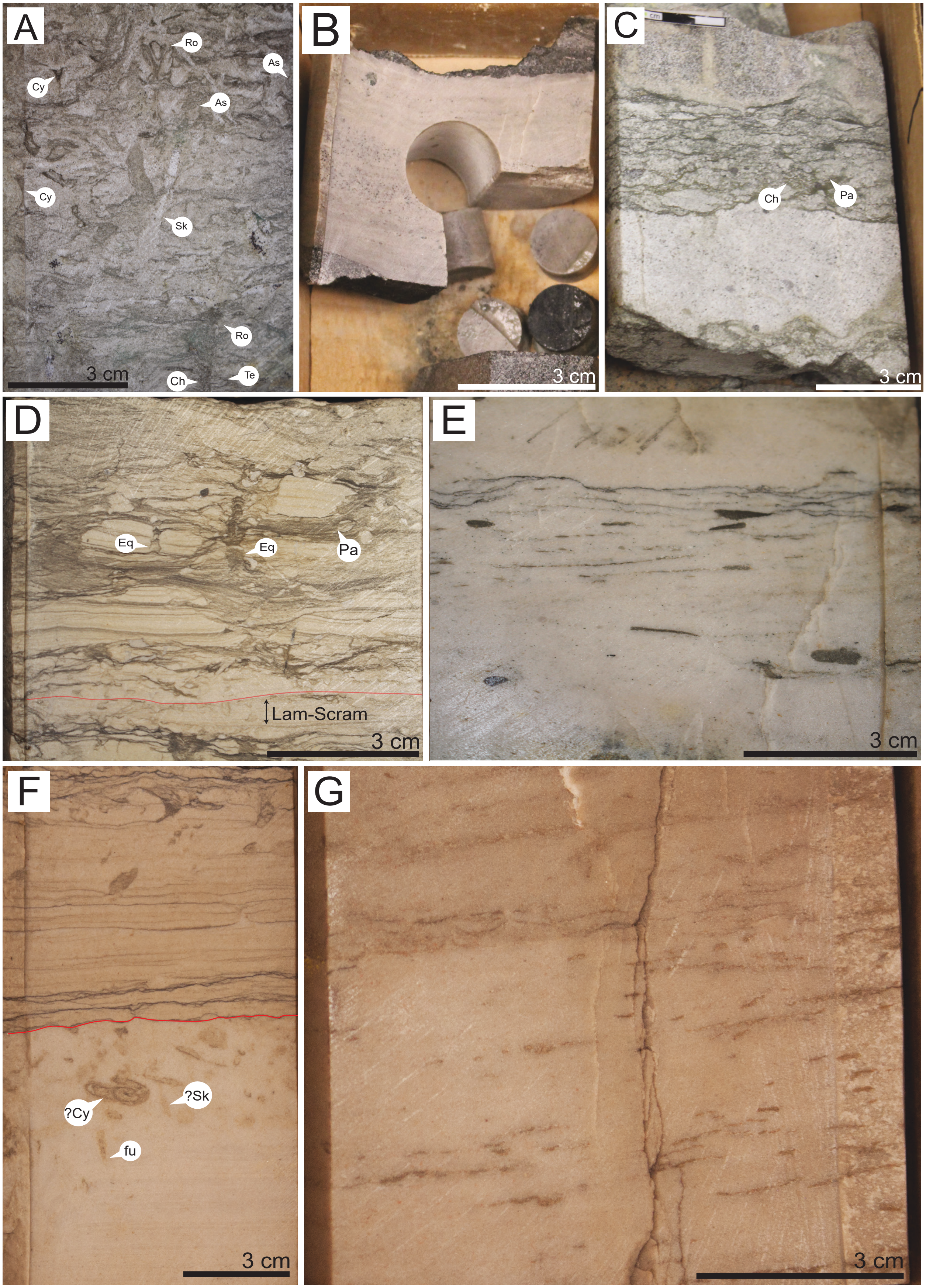
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Figure 2.5: Facies Plate II (Facies 4 and 5)

A) Facies 4; Lower shoreface intensely bioturbated muddy sandstones with a diverse fair-weather trace fossil assemblage. *Rosselia (Ro), Asterosoma (As),, Cylindrichnus (Cy), Skolithos (Sk), Chondrites (Ch, Teichichnus (Te), Palaeophycus (Pa),* Equilibrichnia *(Eq).* Typical of the Cruziana Ichnofacies. PCI C-12.

B) Facies 4; An nonbioturbated tempestite bed (white quartz rich sands) of the lower shoreface deposited within extremely glauconitic (>90%) sandstone. Bele O-35.3

C) Facies 4; Lower shoreface interbedded bioturbated and cross-stratified strata. Bioturbated intervals contain *Palaeophycus* and *Chondrites.* Non-bioturbated strata interpreted to be tempestite deposits. Tweed Lake A-67.

D) Facies 4; Lower shoreface deposits featuring biogenically reworked amalgamated tempestite beds featuring Lam-Scram indicating frequent storm activity. Frequent fugichnia (*Fu*) indicate rapid sedimentation rates in which a burrowing organism moved upward through the substrate. Tweed Lake M-47.

E) Facies 5; Hummocky Cross-Stratification of the middle shoreface with rip up clasts. PCI C-12.

F) Facies 5; Amalgamated tempestite beds of the middle shoreface, nicely developed lam scram fabric seen in the bottom half. Post-storm colonization suite consists of a multitude of lined burrows, ?*Cylindrichnus* (?Cy), and ?*Skolithos (?Sk).* Red line denotes the erosional truncation and emplacement of second storm event. Tweed Lake A-67.

G) Facies 5; Low angle Cross-Stratification with shifting dip angle that is consistent with HCS of the middle shoreface. Tweed Lake A-67.

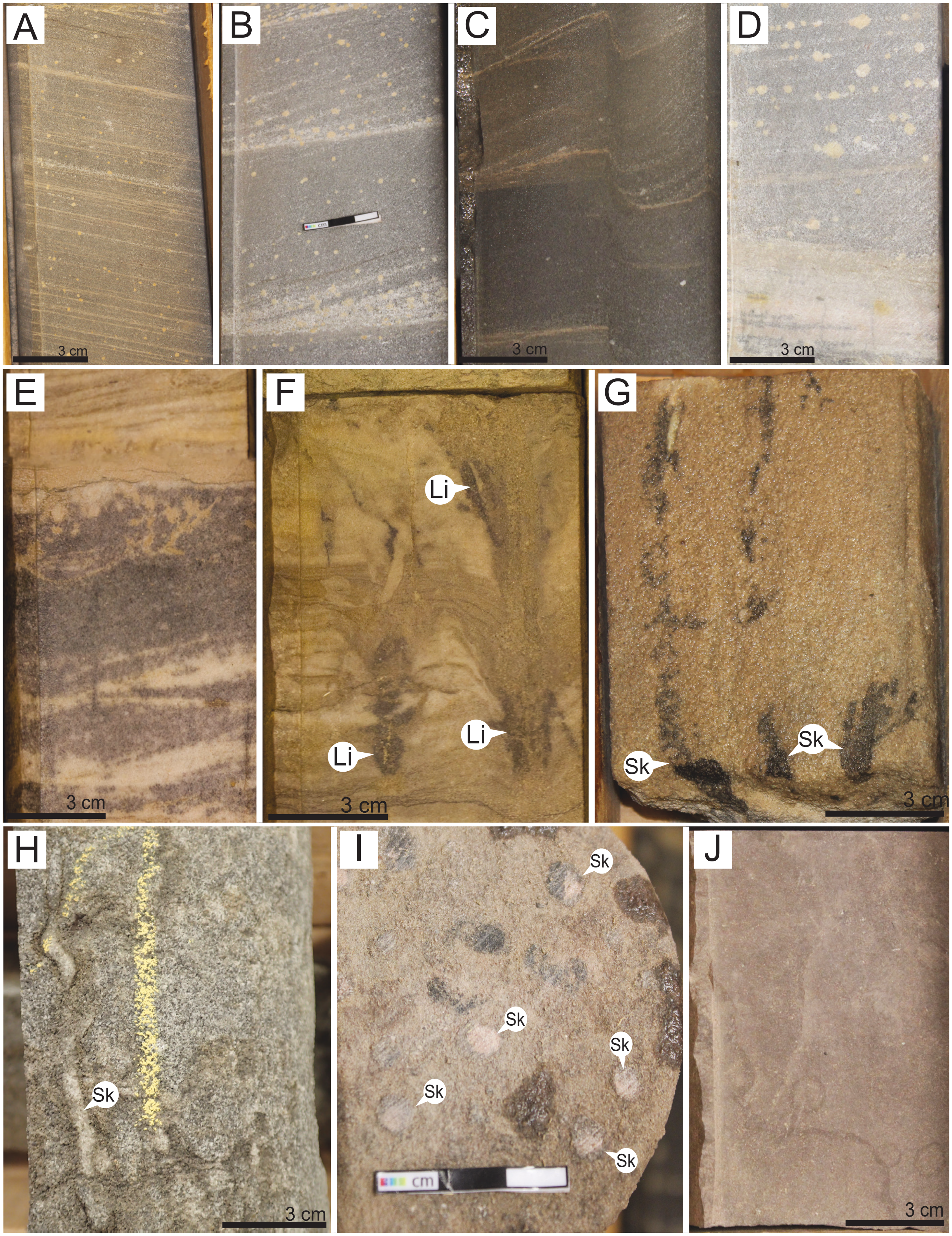
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Figure 2.6: Facies Plate III Facies (6 and 7).

A) Facies 6; High angle cross-stratified upper medium grained sandstone. Tweed Lake A-67.

B) Facies 6; Decimeter scale bed sets of trough cross-stratified sands interpreted to be the result of large sub-aqueous dune migration. Tweed Lake A-67.

C) Facies 6; Soft sediment deformation in the form of micro-faulting within trough cross stratified sandstone. Tweed Lake A-67.

D) Facies 6; Hummocky cross-stratified sandstones.

E) Facies 6; Trough cross-stratified sandstones of a washover fan deposit. Tweed Lake A-67.

F) Facies 7; *Lingulichnus (Li)* traces showing equilibrium adjustments. Tweed Lake A-67.

G) Facies 7; Large oil stained *Skolithos* (*Sk*) in upper medium sandstone. Tweed Lake A-67.

H) Facies 7: 12 cm long *Skolithos* (*Sk*). PCI C-12

I) Facies 7; Bedding plane view of *Skolithos* piperock assemblage. Tweed Lake A-67.

J) Facies 6: Core view of the massive homogenous red regolith mudstone. Tweed Lake A-67.

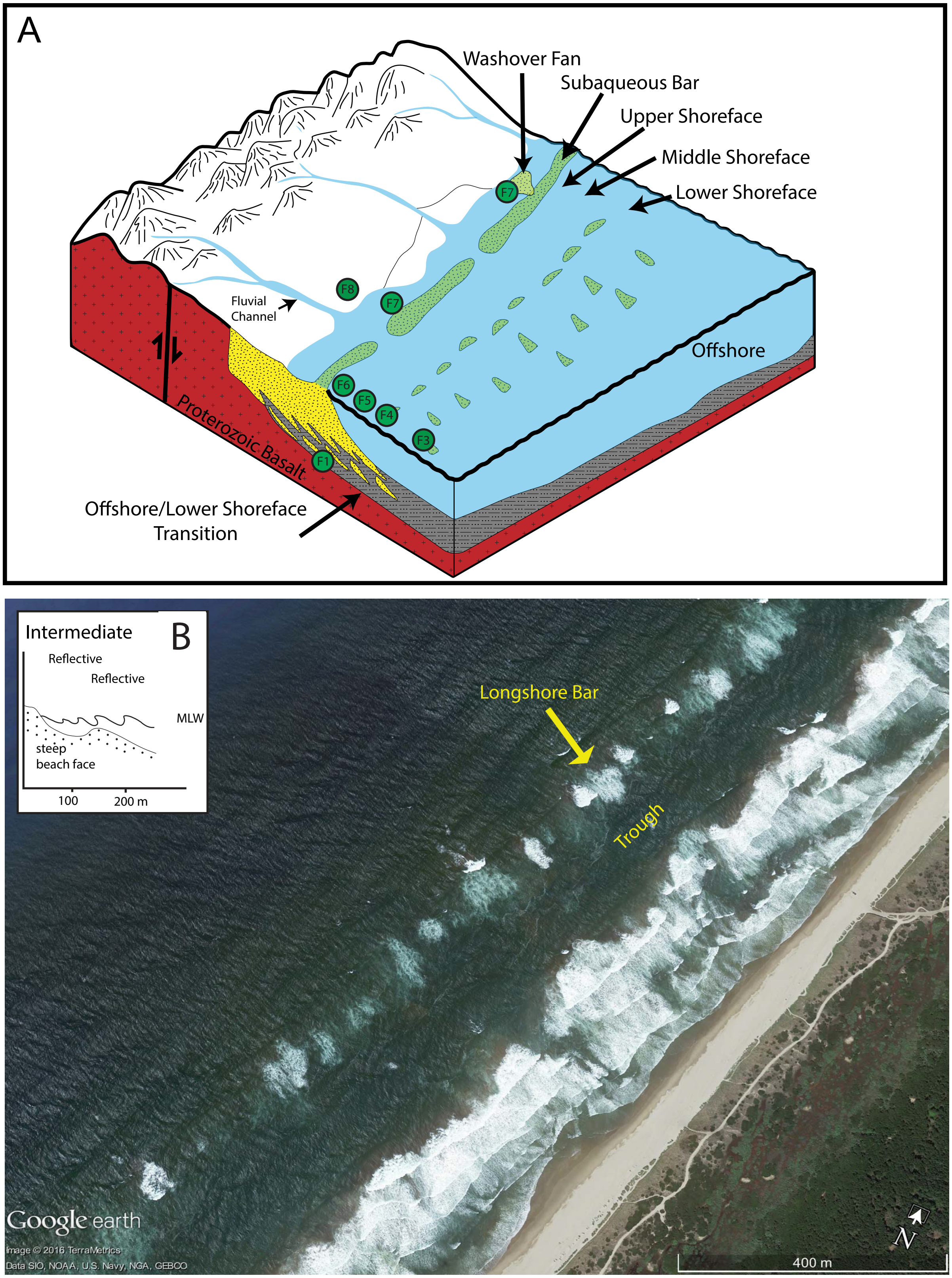

A
Washover Fan
Subaqueous Bar
Upper Shoreface
Middle Shoreface
Lower Shoreface
Offshore
Fluvial Channel
F1
F3
F4
F5
F6
F7
F8
Proterozoic Basalt
Offshore/Lower Shoreface Transition
Intermediate
B
Reflective
Reflective
MLW
steep beach face
100
200 m
Longshore Bar
Trough
Google earth
Image © 2016 TerraMetrics
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
400 m
N

Figure 2.7: Depositional model for the Colville Hills Cambrian Mount Clark Formation. Modified from Short (1999) and Deutsch (1992).

A) Facies are placed on the upper block diagram in green filled circles.

B) Lower figure a modern example of an intermediate barred shoreface profile; a shore parallel longshore bar separated by a wide deep longshore trough, Oregon Coast, United States. Air photo from Google Earth Pro.

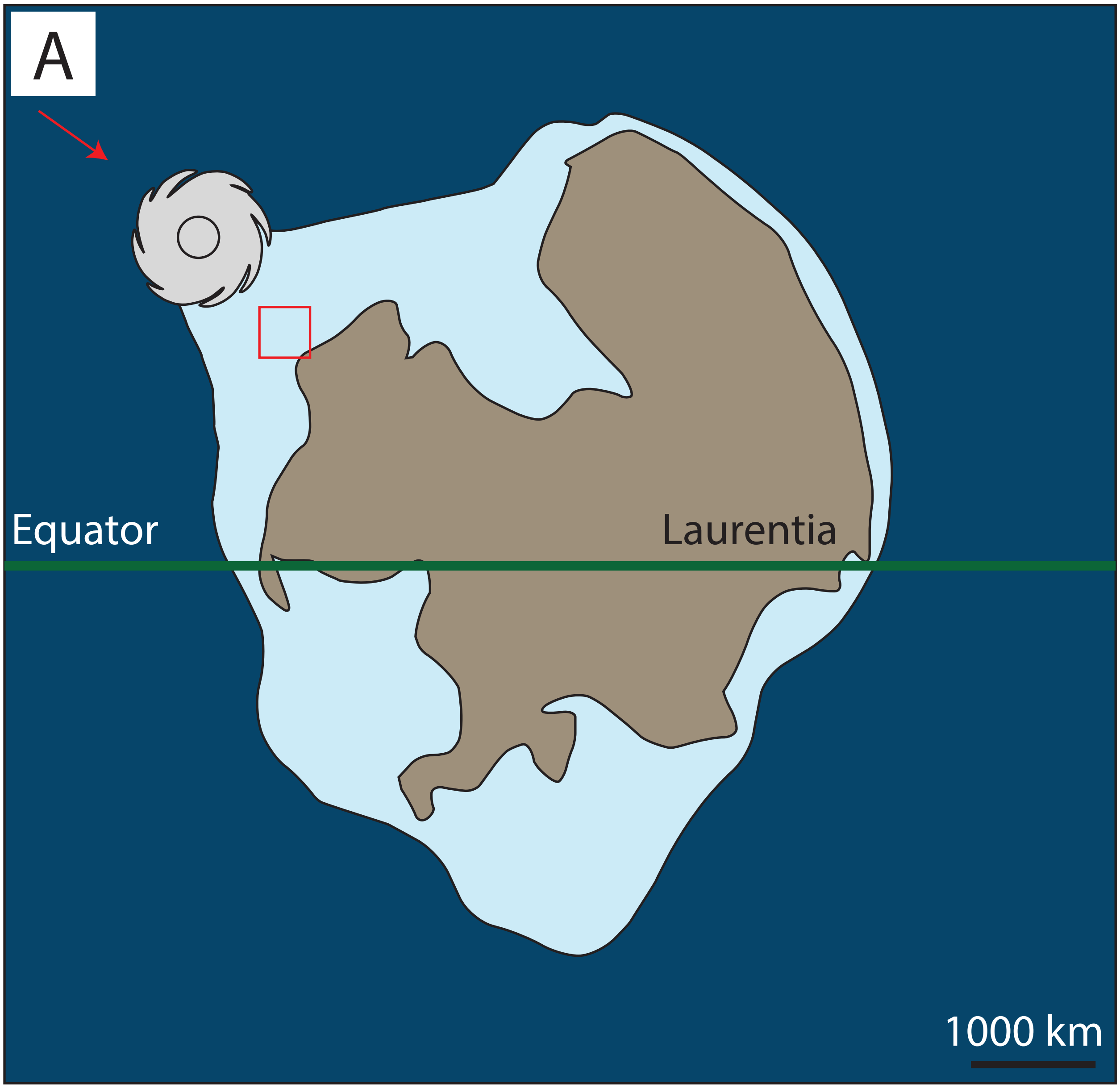

A
Equator
Laurentia
1000 km

Figure 2.8: Simplified palaeogeographic map recording hurricane influence on Cambrian deposition within Laurentia. Modified from Scotese *et al*. (1979).

CHAPTER 3: MIXED DELTAIC, SHOREFACE, AND TIDAL EMBAYMENT SEDIMENTATION ALONG A STORM-INFLUENCED EARLY CAMBRIAN SHORELINE; OUTCROPS WITHIN THE EASTERN MACKENZIE MOUNTAINS, NORTHWEST TERRITORIES, CANADA

INTRODUCTION

During the Lower Cambrian, the absence of land plants resulted in the development of extensive aeolian dune fields and braided fluvial systems (Rainbird *et al.,* 1997*;* Long and Yip., 2009). These braided fluvial systems delivered large amount of sediment to the shoreline which was subsequently reworked by wave and storm action. Early Cambrian paralic environments have been ascribed to transgressive environments wherein large volumes of these compositionally mature sands accumulated (Dalrymple and Rhodes*.,* 1995; Cant and Hein, 1986; Simpson and Eriksson, 1990; MacNaughton *et al.,* 1997; Desjardins *et al.,* 2010, 2012a,b). These environments were commonly manifested as widespread, tidally reworked sand shelves on passive margins (Bond *et al.,* 1984; Dalrymple and Rhodes*.,* 1995; Cant and Hein, 1986; Simpson and Eriksson, 1990; MacNaughton *et al.,* 1997; Desjardins *et al.,* 2010, 2012a,b).

Here we present a detailed study of the sedimentology and ichnology of the Mount Clark Formation exposed within the Mackenzie Mountains of the Northwest Territories. This paper provides detailed sedimentological and ichnological data and interpretations meant to complement earlier regional work that was focused on the Mount Clark Fm (Aitken *et al.,* 1973; MacLean, 2011; Fallas and MacNaughton, 2012). And, this paper has the fundamental aim of expanding our view of Cambrian shoreline associated facies models for comparison and application elsewhere. In comparison to previous Cambrian work within Western Canada and Arctic Canada that identified tidally dominated environments (Hein, 1987, Pemberton and Magwood, 1990; Desjardins *et al*., 2010, 2012; Durbano *et al.,* 2015) we report strongly storm influenced shoreface deposition with wave-dominated deltaic intervals. Tidal influence on sedimentation is interpreted to be minimal outside of one outcrop locality.

PREVIOUS WORK

The Mount Clark Formation (Fig. 1) was defined by Williams (1922; 1923). In the subsurface and in outcrop belts of the Mackenzie Mountains the Mount Clark Formation is dominated by cross-bedded or bioturbated quartz-rich sandstone. The overlying Mount Cap Formation was also defined by Williams (1922; 1923) as an interbedded black shale and carbonate unit. The Mount Clark Formation is now considered to include strata of the Old Fort Island of Norris (1965).

Previous geologic research on the Mackenzie Mountains were broad regional studies operated by Geological Survey of Canada (GSC) mapping programs. Aitkens *et al.* (1973) initially delineated and described the Cambrian strata of the Mackenzie Mountains during the course of Project Norman in the late 1960s and early 1970s. Since then, work has focused on refining the trilobite stratigraphy of the Cambrian interval and on higher resolution mapping (Fallas and MacNaughton, 2012; MacNaughton *et al.,* 2013). MacLean (2011) conducted an in depth study of the regional extent of Cambrian strata throughout the Northwest Territories Mainland using available seismic data. His work helped to delineate the depocentres and arches present during Cambrian deposition. In the 2000's the GSC and industrial stakeholders sought after potential reservoir extensions of the proven reserves found in the Colville Hills. This work was summarized in the Serie *et al.* (2009) open file report that contained descriptions of Cambrian successions within the Mackenzie Mountains.

GEOLOGIC SETTING

Cambrian strata of the Northwest Territories Interior Mainland lies unconformably on Proterozoic strata of the Katherine and Little Dal Group (Aitken *et al.,* 1973). This unconformity translates into an angular unconformity in some areas. Cambrian strata are punctuated by several depocentres and arches (Dixon and Stasiuk, 1998). The outcrops that form the basis of this study are flanked by the Mackenzie and Mahony arches to the West and East respectively (Dixon and Stasiuk, 1998) (Fig. 2). Hamblin

(1990) and Dixon and Stasiuk (1998) suggested that the Mount Clark and Cap formations represented the sedimentological response to the marine transgression of the Sauk sequence (Hamblin, 1990; Dixon and Stasiuk, 1998).. The overall trend of transgression finally resulted in a shift to the carbonate/shale dominated Mount Cap Formation.

There are several inconsistencies regarding the nomenclature of the Mount Clark-Mount Cap transition. Previous work focused on the lithostratigraphic framework of these units, which presents difficulties with basin wide depositional systems and sequence stratigraphic correlations. The Mount Cap Formation was defined on the basis of a heterolithic, shale-dominated succession at the type locality of Mount Cap by Williams (1922). The type section is approximately 250 km from the outcrops presented in this study, and lie within a different depocenter. For the purposes of this study, we identify the Mount Clark-Cap Fm transition as the shift from siliciclastic sandstone dominated to interbedded shale and carbonate intervals.

Biostratigraphic age constraints of the Mount Clark Formation are based on trilobite zones. However, many of the sandstone dominated parts of the Clark Formation are devoid of trilobites. The Dodo Canyon section is an important locality because the entire Cambrian Succession along with the Proterozoic unconformity is persevered (Aitken *et al.,* 1973). In the area: three trilobite zonations have been established and are (from oldest to youngest): 1) *Bonnia-Olenellus;* 2) *Albertella*; and 3) *Glossopleura (*Fig. 3a). *Albertella* zone trilobites were recorded from the base of the Mount Cap Fm interval at Carcajou Canyon (Fallas and MacNaughton, 2012) (Fig. 3b). At the Dodo Canyon section, *Albertella* and *Glossopleura* trilobites were found in the organic-rich shale in the upper half of the section along with *Bonnia-Olenellus* specimens in the lower sandier heterolithic interval (Fritz, 1970; Aitken *et al.,* 1973; MacNaughton *et al.,* 2013). This suggests that the lower heterolithic, mixed carbonate-clastics of Dodo Canyon are coeval with the quartz dominated Mount Clark Fm at Carcajou Canyon. The Mount Clark Fm is assigned an approximate age of 520-514 m.y. based on presence of the *Bonnia-Olenellus* zone trilobites. For this study the allostratigraphic Mount Clark Fm is assigned as lying below *Albertella* containing interbedded carbonates and shales of the

Mount Cap Fm. This surface is sharp and is interpreted to record a flooding surface separating the *Bonnia-Olenellus* Mount Clark Fm from the *Albertella* to *Glossopleura* Mount Cap Fm.

METHODS

Three outcrop localities were studied (Fig. 2). Carcajou Canyon, Waterfall Ridge, and Two Lakes were chosen due to the quality of outcrop exposure, proximity to fresh water sources, and helicopter accessibility. Outcrops were measured using a 1.5 m Jacobs Staff. Lithology, mineralogy, the nature of bedding contacts, body and trace fossils, and overall bioturbation intensity were recorded. For select outcrops (Carcajou Canyon, Dodo Canyon), high resolution 3-D photo mosaics with a 4K Camera equipped Unmanned Aerial Vehicle (UAV or "drone") were compiled. Photos taken from the drone were merged together using Agisoft PhotoScan©. Using outcrop, hand sample, and thin section observations, detailed lithologs were generated in AppleCore©. Sedimentological and ichnological features of selected sections are illustrated in Fig. 4. Ichnological data in the form of trace fossil size, diversity, and intensity was plotted against these logs (Fig. 5).

FACIES ASSOCIATIONS

Three facies associations are reported based on field observations (Table 1): 1) shoreface; 2) wave-dominated deltas; and, 3) tidal compound dune fields. Outcrop mosaics are presented in Fig. 6. Due to the great number and high degree of variability, facies associations have been summarized in Table 1 to keep prose succinct.

FACIES OVERVIEW

Lower shoreface deposits (FA1a,b) were characterized by a high trace fossil diversity, large trace fossils and intense bioturbation. Paleo-storm conditions ranged from strongly storm-influenced (Fa1a) to storm-affected (FA1b) deposition. Strong storm-influence was evidenced by the presence of amalgamated HCS beds interpreted to record powerful oscillatory currents. More quiescent storm-affected conditions were identified on the presence of thinly laminated sharp based sandstone beds interpreted to record storm-derived sediment suspension settling. Upper shoreface environments (FA1c) were associated to pervasive intervals of nonbioturbated TCS sandstone interpreted to record rapidly migrating subaqueous dunes in a unidirectional current. Foreshore deposits (FA1d) contained low angle bedding and herringbone cross-stratification, which was interpreted to record bi-directional currents.

Wave-dominated deltaic deposits were composed of strata associated with lower delta front to prodelta settings. Delta front deposits were displayed moderate to intense bioturbation corresponding to a stressed *Cruziana* Ichnofacies. Trace fossil size and diversity was reduced in comparison to fully marine lower shoreface assemblages. Suspension feeding behaviors were also significantly suppressed. Storm influence varied from strongly storm-influenced (FA2a) recording amalgamated HCS beds to storm-affected (FA2b) recording interference ripples. Prodeltaic intervals (FA2c) comprised immature, silty very-fine grained sandstone, containing an impoverished *Cruziana* Ichnofacies assemblage. Biogenically reworked sandier laminae were interpreted to record tempestite deposition.

Tidal compound dune field deposits were identified recording core (FA3a), front (FA3b), and margin (FA3c) environments. The core of the dune field (FA3a) was identified by low angle bedsets of TCS with varying foreset directions. Bioturbation was limited with rare only *Diplocraterion* and *Arenicolites* observed. The front of the dune field (FA3b) was identified by sigmoidal TCS beds with sharp erosive bed boundaries truncating bioturbated lithosomes. Reactivation surfaces and herringbone cross-stratification are common and interpreted to record tidal currents. Bioturbated lithosomes are interpreted to represent an ecological niche in between migrating dune bedforms that are erosively truncated. The margin of the dune field (FA3c) was identified on the presence of intensely bioturbated sandstone lithologies with thin sharp cross-stratified horizons. Bioturbated horizons recorded the *Cruziana* Ichnofacies with *Rusophycus* and *Cruziana* observed. Sharp based cross-stratified horizons are interpreted to record an increase in sediment supply and/or hydraulic energy. The dominance of ichnofossils linked to deposit feeding suggests that FA3c was deposited at the margin of the compound dune field due to its relative isolation from actively migrating dune forms.

OUTCROP SUMMARY AND DESCRIPTION

Regionally, the Mount Clark Formation represents progradational and retrogradational paralic deposits that include storm-influenced shorefaces, wave-dominated deltas, tidally-dominated subtidal dune fields, and proximal offshore sediments. Integrated sedimentological and ichnological striplogs of wave-dominated deltas and shorefaces are presented in Figure 15.

WATERFALL RIDGE OUTCROP

The most notable observations at Waterfall Ridge are a paucity of HCS bedding, and the presence of 2D and 3D sparsely burrowed compound dunes intercalated with intensely bioturbated media (Fig.4; Fig. 6c). The absence of HCS indicates that powerful storm generated long-wavelength sea-waves did not influence sedimentation at this locale (Dumas and Arnott, 2006; Plint, 2010). Storm influence is, however, manifested by thin (~5cm) crudely cross-bedded pebbly intervals that are interpreted to represent storm surges that transported shoreline-associated clastics seawards (i.e. FA3b Table 1; Fig. 11h).

The 3D and 2D compound dunes that locally contain sparse *Skolithos*, *Arenicolites* and fugichnia are ascribed to tidal sedimentation. This is based on the observation of abundant herringbone cross-stratification and reactivation surfaces observed within dunes (Fig. 11c,e). These features share similarities with the Cambrian (Gog Group) (Desjardins *et al.*, 2010, 2012). Intensely bioturbated horizons characterized by the Cruziana Ichnofacies represent inter-dune deposition in an embayment setting (Fig. 14). Intense bioturbation within tidally dominated coastal settings is indicative of abundant food resources and overall low sedimentation rates (Gingras *et al.,* 2012). The bioturbated beds are erosionally truncated by overlaying 2D and 3D dunes. Previous work within tide dominated Cambrian siliciclastic intervals identified sediment supply and bedform migration as the main controls on trace fossil distributions (Desjardins *et al*., 2010, 2012). We interpret these relationships to represent a compound dune field and not a subtidal sand-sheet complex. Due to their slower rates of migration and prolonged abandonment phases, sub-tidal sand sheet fronts are characterized by abundant piperock (Desjardins *et al.,* 2010).

In summary, Waterfall Ridge is interpreted to have been situated within a shallow marine embayment protected from open marine storm influences. Embayment morphology is interpreted to promote tidal currents, which were the dominant sedimentary transport mechanism in the wave-sheltered bay. These conditions allow a greater chance of preservation for tidal deposits than elsewhere on an exposed coastline (Davis and Hayes, 1984; Dalrymple, 2010). Overall, Waterfall Ridge likely contains one transgressive sequence marked by a shift from dune field front to dune field margin This is interpreted on the strong decrease in physical sedimentary structures and increase in bioturbation intensity when moving up section. Overlying the Proterozoic unconformity we see sparsely bioturbated compound dune deposits (FA3a) that grade into interbedded compound dunes and intensely bioturbated horizons (FA3b). The succession is capped off by the gradational shift into intensely bioturbated horizons with thin episodic planar to trough-cross-stratified biogenically reworked sharp based sandstone beds (FA3c). The transition from FA3a-FA3c could be interpreted as one large transgressive cycle, however autogenic factors such as sediment supply and budget could also explain the transition. Waterfall Ridge may represent sediment supply changes oriented along depositional strike. Bathymetrically FA3a-c may be deposited along strike within a similar water depth with FA3a recording deposition associated with a large sediment budget while FA3c may be sediment starved with FA3b recording deposition somewhere in between.

CARCAJOU CANYON OUTCROP

Carcajou Canyon records highly variable sedimentation in which shoreface, deltaic, and tidal environments are preserved (Fig. 4; Fig. 6a). Storm influence is variable with strong to weak storm conditions observed.

Highly storm-influenced lower shoreface (LSF) deposits (FA1a) are seen within the lower half of the section (~6m). These deposits are characterized by interbedded sharp-based HCS and bioturbated horizons (Table 1; Fig. 7a). Bioturbated intervals record robust, diverse, and intense (BI 5) trace fossil assemblages with pervasive deeply tiered deposit feeding behaviours such as *Asterosoma* (Fig. 7f). Thoroughly bioturbated strata containing large robust traces correspond to fully marine fair-weather shoreface conditions in which both deposit and suspension feeding organisms thrived (MacEachern and Pemberton, 1992; Uchman and Krenmayr, 1995). Large HCS beds with accompanied graded rhythmites record storm-weather conditions (Fig. 7e) (Aigner and Reineck, 1982). Stronger storm conditions are recorded through amalgamated HCS intervals interpreted to represent more sustained storm activity. Bioturbation within HCS beds is rare apart from occasional burrow mottling at bed tops (Fig. 7e). This is interpreted to reflect storm-waning and subsequent colonization resulting in a "Lam-Scram" pattern (*sensu* Howard, 1978; MacEachern and Pemberton, 1992).

Sharply overlying FA1a of Carcajou Canyon lie intensely bioturbated (BI 4-5) silty muddy very fine grained prodeltaic sandstone of FA2c (Table 1; Fig. 9f). In contrast to the robust deposit and suspension feeding trace fossil assemblages observed in the underlying LSF deposits of FA1a, FA2c comprises trace fossil assemblages limited to diminutive *Teichichnus, Rhizocorallium*, and *Asterosoma* (Fig. 9g). These trace fossils correspond to a stressed Cruziana Ichnofacies with a paucity of suspension feeding forms (McIlroy, 2008). Trace fossils are diminutive in comparison to the fully marine shoreface strata of FA1a interpreted to record salinity stresses (Pemberton and Wightman, 1992). The absence of suspension feeding behaviors is interpreted to record turbidity stress (MacEachern *et al*., 2005). Mineralogies within FA2c are more immature when compared with the quartz rich lithologies of FA1a as lithics, chert, micas, clays, feldspars are common (Fig. 9h). MacNaughton *et al* (1997) noted offshore deposits of

Cambrian shorelines contained greater amounts of silt than later Palaeozoic successions and attributed this to the aeolian transport of fines offshore. The presence of salinity and turbidity stressed trace fossil assemblages and more immature mineralogy is interpreted to reflect deltaic sedimentation on a wave-dominated prodelta (Bann and Fielding, 2004). Wave energy attenuated deltaic stresses such as hypopycnal plumes and freshwater salinities. This is contrasted with fluvially dominated river systems typically record sparse to nonbioturbated prodeltaic deposits (MacEachern *et al*., 2005).

Storm influenced lower delta front deposits (FA2b) sharply overlie prodeltaic deposits of FA2c (Table 1). These delta front deposit comprise interbedded heavily bioturbated (BI 4-5) horizons with nonbioturbated planar-tabular cross stratified 2-D dunes (Fig. 9b&e). Boundaries between the lithosomes are sharp and with trace fossils erosively truncated (Fig. 9d). Bedding plane exposures depict interference ripples overlying 2-D dune horizons (Fig. 9a). Slabbed hand samples contain mm scale mud drapes (Fig. 9c). Erosive planar tabular sandstone beds are interpreted to reflect periodic storm influence. Storm-generated currents mobilize sediment and allow for bedform migration that truncates fair-weather bioturbated horizons (Swift *et al*., 1979; Li and King, 2007). Asymmetrical interference ripples are formed through oscillatory currents that is common in nearshore settings (Clifton, 1971; Li and King, 2007). Deformed trace fossil assemblages within bioturbated horizons comprise *Teichichnus, Asterosoma, Chondrites, Rhizocorallium, Cylindrichnus, Gyrolithes*, and *Palaeophycus* (Fig. 9c). *Chondrites* is concentrated within mud laminae. These trace fossil assemblages correspond to the Cruziana Ichnofacies indicating sufficient food stored in the substrate (MacEachern *et al.,* 2007). The paucity of suspension feeding forms is interpreted to record turbidity induced stress (Moslow and Pemberton, 1988) while the deformed burrow morphologies are interpreted to represent heightened sedimentation rates (Gingras *et al*., 2011). Facies association 2b at Carcajou Canyon records storm-influence within the lower wave-dominated front. Fair-weather sedimentation is recorded by thoroughly bioturbated lithosomes dominated by the Cruziana Ichnofacies. Deltaic influence is interpreted on the paucity of suspension feeding forms and deformed burrow morphologies resulting from increased water turbidity and sediment supply.

Storm-influence is visible *via* erosionally based interference ripples and 2-D dunes that truncate bioturbated fair-weather horizons.

Lying further upstream lying coeval with FA2b are tidal compound dune deposits of FA3a. These deposits were only observed using a UAV allowed a high resolution aerial photomosaic of the interval (Fig. 10a; Fig. 16). This observation is noted due to distinctive LSF deposits of FA1b that erosionally overlie the two. A change in thickness in FA1b when walking from the falls up section and river towards the compound dune interval seen at river's edge was recorded. FA1b decreases in thickness from 1.90m to 1.30m (Fig. 19). This is interpreted to represent a shift in overall accommodation due to either shoreline profile or fault blocks dropping out. The compound dune facies are more proximal than the delta front deposits of FA2b. This is aided by their sedimentologic and ichnologic characteristics: 1) abundant high energy bi-directional sedimentary structures; and 2) suspension feeding *Skolithos* traces (Fig. 10b,c). The transgressive surface directly above is also an indicator of paleo water depth as the compound dune has been erosively transgressed resulting in large scour marks (Fig. 9a). FA1d has no such scour marks and the only indication of transgression is the vertical disparity in interpreted environments with FA2b being shallower.

A flooding surface (MRS) overlies FA2b corresponding to transgression and subsequent deposition of storm-affected lower shoreface deposits of FA1b. These lower shoreface deposits comprise intensely bioturbated (BI 6) lower fine sandstones with thinly laminated quartzose interbeds (Fig. 7j). Quartzose interbeds are sharply based with *Glossifungites* firm-ground suites observed (Fig. 7k). These thin quartzose interbeds are interpreted as thin tempestites recording storm deposition. *Glossifungites* surfaces underlying tempestites ascribed to low sedimentation rates (Hubbard and Shultz, 2008). In comparison to the strongly oscillatory HCS bedforms observed in FA1a these thin tempestite beds likely represent deposition from suspension fall out (Aigner and Reineck, 1982). Storm influence is interpreted to be significantly reduced in comparison to the amalgamated HCS beds observed in FA1a. Trace fossil assemblages are robust and diverse with *Rhizocorallium, Asterosoma, Teichichnus, Rosselia, Palaeophycus, Chondrites, Planolites, Skolithos, Diplocraterion*, and

Rusophycus (Fig 7l&m). These trace fossil assemblages correspond to the Cruziana Ichnofacies with a combination of suspension and deposit feeding behaviors within fully marine physico-chemical conditions (MacEachern and Pemberton, 1992). Due to the presence of diverse and robust trace fossil assemblages comprising deposit and suspension feeding behaviors in conjunction with thinly bedded tempestites FA1b is interpreted to record deposition within a storm-affected lower shoreface.

Directly overlying lower shoreface deposits of FA1b lies a well-developed *Glossifungites* demarcated omission surface (Fig. 13). *Taenidium* burrows contain a celadonite, a brilliant blue-green mineral in association with large manganese cemented lithoclasts (Fig. 13b-d). This surface is interpreted to represent a regressive surface of erosion as a result of FA1d that lies above the *Glossifungites* surface (explained below).

Mount Clark Fm deposition terminates at Carcajou Canyon with FA1d recording foreshore deposition. Lithologies comprise lower medium grained celadonitic sandstones with alternating horizons of cross-stratified and bioturbated horizons (Fig. 8d&e). Cross-stratified horizons are represented by herringbone cross-stratification and current ripples. These cross-stratified horizons impart sharp and erosive contacts on bioturbated intervals comprising of robust and intense (BI 4-5) assemblages of *Chondrites.* The large size of these traces is interpreted to record well-oxygenated sediment with healthy amounts of nutrients within the substrate (Bromley and Ekdale, 1984). Herringbone cross-stratification is interpreted to record bi-directional currents through tidal currents and/or wave swash (Reineck and Singh, 1980). Facies association 1b is interpreted to record deposition within the foreshore environment due to the presence of bi-directional current sedimentary structures and robust *Chondrites* assemblages indicating well-oxygenated sediment. Subsequent transgression continued into the Mount Cap Formation resulting in deposition of interbedded carbonate and black shale lithologies (Fig. 13a).

In summary, Carcajou Canyon is interpreted to have been situated within open marine to embayed shoreline. Open marine lower shoreface conditions are represented by FA1a&b consisting of robust marine trace fossil assemblages. Storm influence is interpreted on the presence of tempestite beds ranging from amalgamated HCS (FA1a) to thinly laminated beds (FA1b). This shift in storm influence may have resulted from a shift in shoreline orientation in which FA records more shielded sedimentation away from the brunt of storm influence. FA1a likely records more open conditions facing the brunt of storm activity resulting in amalgamated HCS deposition. Wave-dominated deltaic sedimentation is recorded in delta front (FA2b) and prodelta (FA2c) deposits. These deposits depict a marked decrease in trace fossil diversity and suspension feeding behaviors interpreted to record fluvially induced turbidity and salinity stresses (Fig. 5) (MacEachern *et al*., 2005). Storm influence is visible in thin biogenically reworked very fine sand intervals and storm-activated 2-D dunes. Coeval to the delta front deposits are tidal compound dune deposits observed by the river's edge. This shift to tidal sedimentation may record shallow water deposition in which tidal forces control sedimentation. This scenario would require protection from open marine waves that overwhelm tidal currents (Davis and Hayes, 1984). Shoreline orientation may have shifted resulting in the creation of a protective embayment promoting tidal sedimentation.

TWO LAKES OUTCROP

Two Lakes records strongly storm-influenced shoreface and wave dominated deltaic sedimentation represented by the resistant sandstone cliffs seen in Figure 6b.

The most notable observations at Two Lakes are an abundance of HCS bedding interbedded with impoverished (FA2a; Fig. 8f-h)) to diverse bioturbated (FA1a; Fig. 7g-i) horizons. Nonbioturbated lithologies are characterized by trough to planar cross-stratified sandstones (FA1c; Fig. 8a-c). The presence of HCS indicates that Two Lakes was situated within an open marine environment subjected to storm activity (Walker and Plint, 1992). The presence of two opposing trace fossil assemblages is interpreted to represent varying physico-chemical conditions (Pemberton *et al.,* 1982; Gingras *et al*., 2011). Bioturbated are interpreted to record fair-weather sedimentation while HCS is interpreted to record storm-weather sedimentation.

Sparsely to bioturbated lithologies interbedded with sharp based HCS beds are ascribed to storm-influenced wave-dominated delta front sedimentation. This is based on impoverished trace fossil assemblages comprising *Chondrites, Palaeophycus, Cylindrichnus,* and *Asterosoma.* with diminished suspension feeding behaviors (Gingras *et al.,* 1998; Coates and MacEachern, 2007). These impoverished trace fossil assemblages are starkly contrasted with the robust, diverse, and intense bioturbate fabrics of FA1a,b within the lower shoreface (Fig. 7g-i). Deltaic-induced salinity and turbidity stresses in the form of mud flumes and freshwater influx are interpreted to be the cause of these impoverished trace fossil assemblages (MacEachern *et al*., 2005). Although these physico-chemical stresses had an appreciable effect on trace fossil assemblages it should be noted that wave energy attenuated these stresses resulting more hospitable conditions than a fluvially dominated delta (Bann and Fielding 2004).

Sharply overlying delta front deposits of FA2a lie nonbioturbated multi-directional TCS and planar-tabular lithologies of FA1c. The nonbioturbated nature of these units is interpreted to reflect rapidly migrating bedforms under strong unidirectional currents (Reineck, 1977). We interpret this interval to record deposition on the upper shoreface or upper delta-front. Distinguishing between the two is difficult as both environments show identical sedimentologic and ichnologic characteristics. The erosive surface that separates lower delta-front (FA2a) and upper shoreface/delta front (FA1c) deposits is interpreted to represent a surface of forced regression (Fig. 6b). We interpret that FA1c was deposited during a relative sea-level fall creating a surface of forced regression (Hart and Plint, 1995).

Directly overlying the upper shoreface/delta front deposits of FA1c lies strongly storm-influenced lower shoreface deposits of FA1a separated by a flooding surface (MRS; Fig. 6b). In stark contrast to the underlying deltaic deposits of FA2a, FA1a records diverse, robust, and intensive trace fossil assemblages. Whereas FA2a displayed a paucity of suspension feeders FA1a contains robust *Diplocraterion* and *Skolithos* in association with deeply tiered deposit feeding traces such as *Asterosoma*. Hummocky cross-stratification is pervasive throughout with well developed post-storm colonization suites of *Diplocraterion* and *Cylindrichnus* (Fig. 7c). These suites are interpreted to be the result of r-selected organisms rapidly inhabiting the newly deposited sandy substrate (Vossler and Pemberton, 1988). Transgression of FA1c and subsequent deposition of FA1a is interpreted to be the result of an auto-cyclic deltaic lobe switch in which sediment supply can no longer keep pace with sea level and transgression occurs (Bhattacharya and Walker, 1991). This explains the contrasting trace fossil assemblages seen in the lower delta front and overlying lower shoreface deposits. Alternatively, this flooding event could also represent an allo-cyclic sea level rise and the contrasting trace fossil assemblages could be a result of along strike variation in physico-chemical water conditions in relationship to proximity to a delta distributary channel. Distinguishing between the two scenarios would require greater outcrop control that was unavailable.

In summary, Two Lakes is interpreted to have been situated within open marine shoreline. Open marine lower shoreface conditions are represented by FA1a comprising robust marine trace fossil assemblages. Strong storm influence is interpreted on the presence of amalgamated HCS tempestite beds (FA1a, FA2a). Wave-dominated deltaic sedimentation is recorded in delta front (FA2a) deposits. These deposits depict a marked decrease in trace fossil diversity and suspension feeding behaviors interpreted to record fluvially induced turbidity and salinity stresses (MacEachern *et al*., 2005). Delta front/upper shoreface deposits are characterized by nonbioturbated multidirectional trough and planar-tabular cross-stratification (FA1c) formed through unidirectional currents. The transgression (MRS) following deposition of FA1c is interpreted to record a delta lobe switch in which sediment supply was unable to keep up with sea level rise (Bhattacharya and Walker, 1991). Evidence for this is observed in the overlying lower shoreface deposits of FA1a that comprise diverse and robust trace fossil assemblages.

ICHNOLOGY OF CAMBRIAN WAVE-DOMINATED DELTAS

The ichnological and sedimentological expressions of Cambrian tidally dominated sand sheets have been well studied (Desjardins *et al*., 2010, 2012; Durbano *et al*., 2015; Mangano and Buatois; 1999, 2004a,b; Schafer, 1972). This discussion will therefore focus on the comparison of Cambrian shoreface and wave dominated deltaic complexes.

Early Cambrian shoreface deposits from the Mount Clark Formation in the Northwest Territories contain ichnological signatures marked by moderate to intense bioturbation, high diversity (12 ichnospecies), and a remarkable number of specialized feeding behaviours (Table 2). The relative decrease in diversity when compared with well-studied Cretaceous shorelines is an evolutionary phenomenon as decapod crustaceans and bloodworms responsible for *Ophiomorpha*/*Thalassinoides* and *Macaronichnus* did not radiate until the Mesozoic (Carmona *et al*., 2005). Diverse assemblages are composed of the robust burrows of deposit and detritus feeders mixed in with a well-developed array of vertical traces that represent the burrowing activities of carnivores, scavengers, and suspension feeders. These complex assemblages are interpreted to represent a diverse proximal expression of the Cruziana Ichnofacies mixed with major elements of the Skolithos Ichnofacies. This suite reflects a fully marine well-oxygenated environment with abundant suspended and buried nutrients in which mature metazoan communities were able to thrive. Ichnological responses to storm sedimentation were observed in impoverished *Skolithos* style colonization suites within HCS beds composed of *Diplocraterion*, *Skolithos*, and *Cylindrichnus*. These suites were developed as result of a storm induced shift in nutrient distribution favoring r-selected organisms (Pemberton and MacEachern, 1997).

In contrast, the ichnological signature of early Cambrian deltaic deposits is characterized by a significant reduction in trace fossil size and diversity along with the absence of robust suspension feeding forms. Bioturbation is comprised of 3-4 ichnospecies and is sporadically distributed with reduced intensity. These assemblages correspond to a stressed expression of the Cruziana Ichnofacies. Rare examples of *Cylindrichnus* and *Skolithos* were observed within the delta front lithologies of FA2a,b indicating a suppressed element of the Skolithos Ichnofacies.

Integrated ichnological and sedimentological logs are illustrated in Figure 17 contrasting the differences between Cambrian shoreface and deltaic deposits**.** In prodeltaic intervals primary lamination has been disrupted by intense bioturbation consisting of abundant *Teichichnus* and *Asterosoma* with rare *Rhizocorallium.* The size of trace fossils is significantly smaller in comparison to the fully marine assemblages (**Fig. 17)**. Thin, lighter coloured and coarser grained laminae (tempestites) have been largely reworked (BI 5) by biogenic activity. Facies association 2C has been completely homogenized during fair-weather conditions through deposit feeding organisms.

Cambrian shoreface and delta front deposits differ in significant ways from an ichnological perspective (Fig. 17). Lower shoreface deposits comprise a diverse fair-weather assemblage that represents a proximal expression of the *Cruziana* ichnofacies reflecting sustained periods of abundant nutrients and healthy marine conditions. Tempestites occasionally contain a relatively impoverished distal expression of the *Skolithos* ichnofacies in the uppermost 10cm of HCS beds. This suggests that r-selected organisms were able to colonize the substrate after storm deposition. In contrast, the delta front is characterized by stressed infaunal community marked by diminutive, opportunistic deposit feeding organisms. Vertical suspension feeding forms such as *Skolithos* and *Diplocraterion* are very rare.

The overall paucity of robust suspension feeders in deltaic deposits may reflect elevated water turbidity. High levels of suspended sediment within the water column render colonization and survival difficult for suspension feeding organisms by plugging filter-feeding apparati and reducing the efficiency of feeding (Moslow and Pemberton, 1988; Gingras *et al*., 1998; Bann and Fielding, 2004; MacEachern *et al.,* 2005). Large increases in suspended fine-grained sediment are typically associated with heightened precipitation and subsequent increased fluvial discharge into the basin (Coates and MacEachern, 2007). A large fluvial sediment supply can be inferred based on the presence of large braided river systems that avulsed regularly due to the lack of any stabilizing land vegetation in the Cambrian (MacNaughton *et al.,* 1997). In the absence of land plants aeolian transport of fine sediment may have been prolific resulting in windblown sediment blown offshore (Dalrymple *et al.,* 1985). Braided rivers were likely bedload dominated with unstable banks and high width:depth ratios bringing large amounts of sediment to the shoreline (Schumm, 1968; Cotter, 1978). As a result, suspended sediment load may have been greater than what may have occurred in well studied Permian and Mesozoic deltaic successions (Bann and Fielding, 2004; McIlroy, 2004; Coates and MacEachern, 2007).

Organic rich mudstone drapes covering tempestite beds are a relatively common observation in late Paleozoic and Mesozoic deltaic successions (Saunders *et al*., 1994; Coates and MacEachern, 1999; Bann and Fielding, 2004). These mud drapes have been interpreted to cause rapid oxidation and oxygen depletion inhibiting opportunistic storm suites colonizing the storm bed (Coates and MacEachern, 2007) However, these organic rich mud drapes are absent in the Cambrian Mount Clark Fm and a likely result from having no land plants in the Cambrian. Cambrian transport of silt and clay sized fractions is thought to be dominantly aeolian resulting in a tradewind dominated fine-grained sedimentation (Dalrymple *et al*., 1985). This dominantly aeolian transport of fines results in clay and silt poor Cambrian marine successions. Internal erosion surfaces and rip-up clasts provide evidence that storm activity was pervasive and frequent enough to remove previously established colonization communities.

Broadly speaking, stressed, low-diversity, diminutive trace fossil assemblages recorded from the Early Cambrian deltaic deposits of the Mount Clark Fm reflect less hospitable living conditions than those in fully marine shoreface environments. Most inhabitants are opportunistic species that flourish in unpredictable conditions with respect to water salinity and turbidity. The highly variable and interfingering nature of these deltaic and shoreface deposits is a testament to the highly variable braided fluvial drainage patterns on barren Cambrian cratons (MacNaughton *et al*., 1997).

CONCLUSIONS

The early Cambrian Mount Clark Fm at the outcrop localities of Waterfall Ridge, Carcajou Canyon, and Two Lakes records deposition of inter-fingered shoreface, deltaic, and tidal dune field deposits. The highly variably nature of these deposits is attributed to large braided river systems delivering large amounts of sediment to the shoreline on a barren Cambrian craton. Due to no stabilizing land vegetation, these rivers are inferred to have frequently avulsed creating mixed shoreface and deltaic successions seen at Two Lakes and Carcajou Canyon. Tidal forces are interpreted to be minimal outside of shielded marine embayments that amplified tidal activity while shielding sedimentation from storm and wave influence resulting in the deposition of tidal dune fields. Integrated sedimentological and trace fossil analysis through bioturbation intensity, trace fossil size, and diversity has shown to be a robust methodology for delineating tidal and wave/storm influences through identifying physico-chemical stresses. These ichnological responses are very similar to well-studied late Paleozoic and Mesozoic deltaic successions.

1) The Mount Clark Formation represents a complex depositional environment punctuated by wave, storm, and tidal influences in shoreface, deltaic, and tidal settings.
2) Outcrops listed in order of increasing wave/storm influence are as follows: 1) Waterfall Ridge; 2) Carcajou Canyon; and 3) Two Lakes.
3) Wave-dominated deltaic deposition is marked by strong decrease in trace fossil size and diversity along with a reduction in suspension feeding behaviours. This is interpreted to represent salinity and turbidity stresses from fluvial influx.
4) More immature mineralogies consisting of an increase in feldspar, lithics, chert, and mica fragments accompany these deltaic ichnological suites.
5) Deltaic influence punctuates the basin and is a likely cause for base-level falls, due to lobe abandonment and subsequent switching. Cambrian river systems may have shifted more rapidly due to no stabilizing vegetation.
6) Fair-weather shoreface deposits show the most diverse and intense bioturbate fabrics with uniformly high bioturbation intensities (averaging BI 5).
7) Storm-weather HCS deposition punctuates shoreface and deltaic sedimentation with rare post-storm *Skolithos* style colonization suites.
8) Tidally-dominated dune deposits show the most ichnologically variable conditions. Compound dune forms are characterized by highly stressed conditions with limited and sparse bioturbation trends (BI 0-2). This stress is a

likely result of high sediment supply, continuously shifting substrates, and salinity fluctuations associated with tidal periodicities. In turn the heavily bioturbated (BI 6) horizons are representative of a quiescent stable niche that occupies the trough in between migrating compound dunes (Fig. 14).

Facies Associations: Description and Occurrence	Sedimentological Characteristics	Ichnological Characteristics	Depositional Environment
FA1a: Interbedded HCS and thoroughly bioturbated sandstone Occurrence: Two Lakes and Carcajou Canyon	**Observations**: · Upper- to lower fine-grained sandstone. · Interbedded HCS and thoroughly bioturbated sandstone. · Low angle (Fig. 7a,b) to nearly parallel laminated beds (Fig. 7e) with sharp erosive bases. · Soft sediment deformation shown by ball and pillow structures (Fig. 7d). **Interpretations**: · Low angle laminated sharp based sandstones interpreted as HCS beds with both the hummock and swale preserved (Walker, 1984). · Nearly parallel laminated sharp based beds interpreted to be graded rhythmites, the distal expression of HCS (Aigner and Reineck, 1982). · Sharp based and erosive HCS beds interpreted to represent storm activity and tempestite deposition (Walker, 1984; Plint, 2010). · Amalgamated HCS beds are interpreted to represent prolonged storm conditions and/or pervasive erosional truncation of previously deposited fair-weather accumulations (Kumar and Sanders, 1976; Leckie and Walker, 1982). · Ball and pillow structures evidence for rapid HCS sedimentation (Dott and Bourgeois, 1982).	**Observations:** · Thoroughly bioturbated lithologies characterize non-HCS horizons (BI 5). · Trace fossils observed: *Rhizocorallium, Diplocraterion, Asterosoma, Phoebichnus, Teichichnus, Rosselia, Palaeophycus, Chondrites, Planolites*, and unidentified arthropod tunnels (Fig 7f-i). · Rare impoverished trace fossil suites (*Cylindrichnus, Skolithos*, and *Diplocraterion*) observed in the uppermost 10 cm of HCS beds (Fig. 7c). · HCS associated bioturbation characterized by a gradational transition from laminated to burrow mottled sandstone (Fig. 7e). **Interpretations:** · *Cruziana* Ichnofacies, combination of suspension and deposit feeding behaviors (MacEachern and Pemberton, 1992). · Diverse and robust trace fossil assemblage ascribed to fully marine shoreface physico-chemical conditions (MacEachern and Pemberton, 1992). · HCS associated bioturbation consistent with pot-storm colonization suites (Vossler and Pemberton, 1988). · R-selected organisms capable of rapidly colonizing tempestite HCS bed tops forming the laminated to burrow mottled appearance known as "lam-scram" (Howard, 1978; MacEachern and Pemberton, 1992).	· Two distinct environments preserved: 1) fair-weather; and 2) storm-weather. · Fair-weather conditions represented by intensely bioturbated horizons with no sedimentary structures. · Storm-weather conditions represented by the rapidly emplaced HCS tempestite beds as evidenced by sharp erosive bed contacts and soft sediment deformation (Walker, 1984; Plint, 2010). **· Interpreted to represent deposition in a storm-influenced to dominated lower shoreface.**
FA 1b: Thoroughly bioturbated sandstones with thin laminated quartzose interbeds. Occurrence: Carcajou Canyon	**Observations:** · Lower fine-grained sandstone. · Thoroughly bioturbated sandstones with thin laminated quartzose interbeds (Fig. 7j). · Episodic low to parallel laminated thin (<5 cm) quartzose beds with sharp bases and a lateral continuity of 10s of meters (Fig. 7j,k). **Interpretations:** · Sharp based erosive laminated quartzose beds interpreted to represent tempestite deposition due to storm influence. · In comparison to the strongly oscillatory HCS beds forms observed in FA1a, these thin tempestite beds likely represent deposition from suspension fall out (Aigner and Reineck, 1982). · Storm influence significantly reduced in comparison to the large amalgamated HCS beds observed in FA1a.	**Observations**: · Similar to FA1a except for a higher degree of bioturbation, BI 6 vs BI 5. · Thin tempestites biogenically reworked with a BI of 2-3 (Fig. 7k). · Trace fossils observed: *Rhizocorallium, Asterosoma, Teichichnus, Rosselia, Palaeophycus, Chondrites, Planolites, Skolithos, Diplocraterion*, and *Rusophycus* (Fig 7l,m). · *Glossifungites* firm-ground suites (Skolithos) observed at the bases of thin quartzose tempestites (Fig. 7k). **Interpretations**: · *Cruziana* Ichnofacies, combination of suspension and deposit feeding behaviors (MacEachern and Pemberton, 1992). · Diverse and robust trace fossil assemblage ascribed to fully marine shoreface physico-chemical conditions (MacEachern and Pemberton, 1992). · *Glossifungites* suites underlying tempestites ascribed to low sedimentation rates (MacEachern and Pemberton, 1992; Hubbard and Shultz, 2008). · Biogenic reworking of tempestite beds interpreted to represent more sustained fair weather conditions following tempestite deposition (Pemberton et al., 1992).	· Similar to FA1a with the exception of fair-weather conditions dominated deposition. · Storm influence less pervasive than FA1a noted through thinner tempestite beds. **· Interpreted to represent deposition in a storm-affected lower shoreface.**

FA 1c: Unbioturbated high angle cross-stratified sandstone. Occurrence: Two Lakes	**Observations**: · Upper fine to lower medium sandstone. · Unbioturbated high angle cross-stratified sandstone (Fig. 8a-c). · Trough Cross-Stratification (10-15cm bed thickness) (Fig. 8b). · Planar Tabular Cross-Stratification (10-15cm bed thickness) (Fig. 8c). **Interpretations**: · Strong unidirectional currents forming two and three dimensional dunes (Clifton *et al*, 1971).	**Observations**: · No trace fossils observed. **Interpretations**: · Bioturbation inhibited by strong hydraulic currents, high turbidity, and rapidly shifting substrates (MacEachern et al., 2007).	· Wave dominated sedimentation. **· Interpreted to represent deposition in the upper shoreface or upper delta front.**
FA 1d: Interbedded Bioturbated and cross-stratified celadonitic sandstone Occurrence: Carcajou Canyon	**Observations:** · Lower to upper medium-grained sandstone. · Interbedded bioturbated and cross-stratified celadonitic sandstone. · Contacts between the two lithosomes are sharp and erosive. · Herringbone cross-stratification (Fig. 8e). · Current ripples (Fig 8e). **Interpretations:** · Herringbone cross-stratification is interpreted to represent bidirectional currents through either tidal currents or wave swash.	**Observations**: · Robust monospecific *Chondrites* assemblages, BI 4 (Fig. 8d). **Interpretations** · Pervasive deposit feeding traces indicating healthy amounts of nutrients within the substrate. · Large size indicates well oxygenated sediment.	· Bi-directional currents interpreted to represent wave swash or tidal activity. **· Interpreted to represent deposition within the foreshore environment.**
FA 2a: Interbedded HCS and thoroughly bioturbated sandstone Occurrence: Two Lakes	**Observations**: · Upper to lower fine-grained sandstone. · Interbedded HCS and thoroughly bioturbated sandstone (Fig. 8f). · Low angle to nearly parallel laminated beds with sharp erosive bases observed (Fig 8f). · Mm scale mud drapes (Fig. 8g,h). **Interpretations**: · Low angle laminated sharp based sandstones interpreted as Hummocky Cross-Stratification (HCS) beds with both the hummock and swale preserved (Walker, 1984). · Nearly parallel laminated sharp based beds interpreted to be graded rhythmites, the distal expression of HCS (Aigner and Reineck, 1982). · Sharp based and erosive HCS beds interpreted to represent storm activity and tempestite deposition (Walker, 1984; Plint, 2010). · Amalgamated HCS beds are interpreted to represent prolonged storm conditions and/or pervasive erosional truncation of previously deposited fair-weather accumulations (Kumar and Sanders, 1976; Leckie and Walker, 1982). · Mud drapes interpreted to be fine grained material sourced through hypopycnal mud plumes from a nearby deltaic source (Bhattacharya, 1989; Leithold, 1989). · Such discharge events could be the result of large fluvial runoff during storm events (Coates and MacEachern, 1999).	**Observations:** · Moderately bioturbated lithologies (BI 2-3) characterize non-HCS horizons. · Reduced size and diversity when compared with FA1a,b (Fig. 5). · Impoverished trace fossil assemblages of *Cylindrichnus, Planolites, Palaeophycus, Chondrites*, and *Asterosoma* (Fig. 8g,h). · Dominantly deposit feeding forms, robust suspension feeding forms not observed. · Rare Arenicolites in HCS. **Interpretations**: · Stressed *Cruziana* Ichnofacies (Coates and MacEachern, 2009). · Diminutive nature and paucity of trace fossils interpreted to reflect significant physico-chemical stresses on the burrowing organisms (MacEachern et al., 2005; Gingras et al., 2011). · Suspended sediment increases turbidity resulting in clogged filter feeding apparati (Moslow and Pemberton, 1988). · Reduction in size attributed to brackish water influence (Howard and Frey, 1973; Pemberton et al., 1982). · Absence of robust suspension feeding structures and reduced diversity/size of trace fossil assemblages is attributed to fluvial influence in the form of deltaic sedimentation (Gingras et al., 1998; Coates and MacEachern, 1999; Bann and Fielding, 2004).	· Reduction of suspension feeding forms along with overall size interpreted to represent salinity and turbidity stresses associated with a wave-dominated delta (Moslow and Pemberton, 1988; Bann and Fielding, 2004 MacEachern et al., 2005). · Pervasive HCS deposition interpreted to represent intensive storm activity. **· Deposition in storm influenced wave dominated lower delta front.**

FA2b: Interbedded planar-tabular and intensely bioturbated sandstone. Occurrence: Carcajou Canyon	**Observations**: · Upper fine to lower medium-grained muddy sandstone. · Interbedded planar-tabular and intensely bioturbated sandstone (Fig. 9b). · Planar tabular cross-bedding (2-D dunes, 10cm amplitude) with sharp erosional bases cutting into bioturbated lithologies (Fig. 9d). · Interference ripples (Fig.9a). · Mm scale mud drapes (Fig. 9c). **Interpretation**: · Erosive planar tabular sandstone beds interpreted to represent episodic storm influence. · Storm currents mobilize sediment and allow for bedform migration that truncates far-weather bioturbated deposits (Swift et al., 1979; Li and King, 2007). · Asymmetrical interference ripples evidence for oscillatory flow, common in near shore settings (Clifton, 1971; Li and King, 2007). · Muddy drapes are consistent with rapid and episodic mud deposition related to deltaic hypopycnal flows (Bann and Fielding, 2004; Bhattacharya and MacEachern, 2009).	**Observations**: · Moderate to intensely bioturbated (BI 3-5) lithologies characterize non cross-stratified horizons (Fig. 9c,e. · No bioturbation observed in cross-stratified horizons. · Bioturbated lithosomes contain *Teichichnus, Asterosoma, Chondrites, Rhizocorallium, Cylindrichnus, Gyrolithes*, and *Palaeophycus* (Fig. 9c,e) · *Chondrites* concentrated in mud drapes (Fig. 9c,e). · Burrows frequently deformed (Fig. 9c). **Interpretation**: · *Cruziana* Ichnofacies. · Suspension feeding forms rare, inferred turbidity. · Deformed burrows are interpreted to represent heightened sedimentation rates and bioturbation near the sediment-water interface (Gingras et al, 2011). · Well oxygenated marine conditions with rapid sedimentation interpreted to represent deposition on a wave dominated delta.	· Two distinct environments preserved; 1) fair-weather, and 2) storm-weather. · Fair-weather conditions represented by intensely bioturbated horizons with no sedimentary structures. · Storm-weather conditions represented by the rapidly emplaced planar tabular beds as evidenced by sharp erosive bed contacts (Swift et al., 1979; Li and King, 2007). · Deltaic influence visible through muddy drapes, heightened sedimentation rates, and diminished suspension feeding activity. · **Interpreted to represent deposition on a mildly storm-influenced wave-dominated lower delta front.**
FA2c: Highly bioturbated silty very fine sandstone Occurrence: Carcajou Canyon	**Observations:** · Black silty very fine-grained sandstone (Fig. 9f). · Highly bioturbated silty very fine sandstone (Fig. 9g). · Lighter coloured laminae coarser grained (Very fine sand). · Relatively immature mineralogy in comparison to other lithologies within the Mount Clark Fm. · Abundant micas, lithics, and clays (Fig.9h). · No sedimentary structures observed, complete biogenic homogenization (Fig. 9g). **Interpretation**: · Relatively immature mineralogy is interpreted to reflect proximity to fluvial input in the form of deltaic sedimentation (Dott, 1966). · Silt sized factions may have been derived from windblown aeolian sources as a result of extensive aeolian dune fields developed in the absence of stabilizing land plants (Dalrymple et al., 1985). · Lighter coloured very fine and horizons interpreted to be distal tempestites that have been biogenically reworked (Bann and Fielding, 2004).	**Observations**: · Intensely bioturbated with BI 5 (Fig. 9g). · Diminutive deposit feeding traces in *Teichichnus, Asterosoma*, and *Rhizocorallium* (Fig. 9g). · Suspension feeding behaviors absent. **Interpretation**: · Stressed Cruziana Ichnofacies. · Trace fossil diminution interpreted to reflect salinity derived stress (Pemberton et al., 1982; Pemberton and Wightman, 1992). · Fair-weather conditions coupled with sufficient oxygen and nutrients allowed organisms to homogenize the sediment (MacEachern et al., 2007). · Absence of suspension feeding behaviors interpreted to reflect increased water turbidity (Gingras et al., 1998; Coates and MacEachern, 1999). · Deltaic influence interpreted as the source of turbidity and salinity changes.	· Deltaic influence predicated on the presence of a more immature mineralogy and an impoverished, diminutive trace fossil assemblage (summarized in MacEachern et al., 2005). · **Interpreted to represent deposition in a wave dominated prodelta.**

FA3a: Sporadically bioturbated Trough Cross-Stratified sandstone. Occurrence: Carcajou Canyon, Waterfall Ridge	**Observations:** · Lower medium- to lower coarse-grained sandstone. · Sporadically bioturbated Trough Cross-Stratified sandstone (Fig. 10a,b). · Low-angle compound bedsets of Trough Cross-Stratification (TCS) with varying foreset directions (Fig. 10a, c,f). · Overall lenticular geometries (Fig. 10d). · Sharp erosive TCS bed contacts (Fig. 10c). · Mudstone rip up clasts common (Fig. 10g). **Interpretations:** · Uni- or bi- directionally stacked Trough and/or planar cross strata interpreted to be the result of tidally generated 2D and 3D dunes (Olariu et al., 2012). · Thick successions of stacked cross strata are considered to be characteristic of tidal environments (Kreisa and Moila., 1986; Dalrymple and Rhodes, 1995). · Mudstone rip up clasts may be sourced from interior mud flats. · Wave-generated sedimentary structures such as HCS and combined flow ripples are absent.	**Observations:** · Generally unbioturbated. · Rare horizons of *Diplocraterion, Arenicolites* (Fig. 10b). **Interpretations**: · Opportunistic Skolithos Ichnofacies. · Abundant sediment supply and intensive tidal currents result in consistently migrating bedforms impeding bioturbation. · Limited bioturbated horizons interpreted to represent brief colonization events possibly resulting from a reduced sediment budget causing a pause in bedform migration.	· Tidally dominated sedimentation interpreted on stacked assemblages of cross-stratified strata with common reactivation surfaces. **· Interpreted to represent deposition within the core of a tidally dominated compound dune field.**
FA3b: Interbedded Trough-Cross Stratified and intensely bioturbated sandstone. Occurrence: Waterfall Ridge	**Observations:** · Upper medium-grained sandstone with rare thin (<10cm) pebbly/granular intervals (Fig. 11h). · Sigmoidal trough cross-stratified beds with sharp erosive bed boundaries truncating bioturbated lithosomes (Fig. 11a, b,d). · Flame structures common at the sharp erosive contacts. separating TCS and bioturbated strata (Fig. 11b). · Reactivation surfaces and herringbone cross-stratification common (Fig. 11c,e). · Common convolute bedding within cross-stratified horizons (Fig. 11f). **Interpretations**: · Abundant herringbone cross-stratification and reactivation surfaces interpreted to represent frequent current reversals in a tidally dominated succession (Dalrymple, 2010). · Abundant soft sediment deformation features interpreted to represent liquefaction caused by water saturated substrates moving rapidly and becoming unstable (Mills, 1983). · Flame-structures interpreted to represent the soft soupy substrates that dunes migrate over (Mills, 1983). · Sharp erosive contacts separating bioturbated from TCS horizons interpreted to represent rapid sedimentation rates and subsequent dune migration (Desjardins et al., 2010; 2012). · Pebbly to granular, crudely cross-bedded intervals are likely a result of stronger wave energies, possibly storm derived, transporting more proximal point source material distally (Hiscott, 1982).	**Observations** · Bioturbated intervals have a BI of 6, "biogenically deformed" fabric (Buatois and Mangano, 2011) (Fig. 11b, d). · TCS units unbioturbated except for occasional fugichnia (Fig. 11g). **Interpretations:** · High intensity of bioturbation and complete homogenization of the sediment indicates trace makers had sufficient time to colonize and bioturbated the sediment (MacEachern et al., 2007). · Bioturbated horizons interpreted to represent an ecological niche in between migrating dune bedforms, a "bioturbated trough". · As dunes migrated these "bioturbated troughs" were erosionally truncated (Desjardins et al., 2010; Olariu et al., 2012). · Fugichnia interpreted to represent rapid sedimentation rates in which the tracemaker attempted to equilibrate.	· Abundance of herringbone cross-stratification and reactivation surfaces interpreted to represent tidally dominated sedimentation. **· Interpreted to represent the front of an active compound dune field punctuated by inter-dune bioturbated troughs.**

FA3c: Interbedded intensely bioturbated and thin cross-stratified sandstone. Occurrence: Waterfall Ridge	**Observations**: · Lower medium- to upper fine-grained sandstone. · Interbedded intensely bioturbated and thin cross-stratified sandstone (Fig. 12a-c). · Thinly bedded planar-tabular units (<10 cm thick) (Fig. 12b,c). · Sharp erosive contacts separating bioturbated strata and planar-tabular beds (Fig. 12b,c). **Interpretations**: · Erosive thin TCS beds interpreted to represent rapid deposition across the substrate under strong currents. · Relative paucity of cross bedded lithosomes in comparison to FA3a,b interpreted to represent a relative decrease in overall sediment supply and increase in water depth. (Desjardins et al., 2010, 2012). · Relatively quiescent conditions in comparison to FA3a,b.	**Observations**: · Bioturbated horizons characterized by a BI of 6 (Fig. 12f). · *Rusophycus, Cruziana* (Fig. 12d,e) · 2-D show various degrees of biogenic reworking from nearly intact to completely homogenized (Fig 12b). **Interpretations**: · Intensely bioturbated lithologies dominate deposition indicating more hospitable conditions through reduced sediment supply and hydraulic energy. · Biogenic reworking of 2D dunes indicates considerable time between event bed deposition allowing bioturbators to rework event sedimentation (Pemberton and MacEachern., 1997)	· Intensely bioturbated horizons dominate deposition in comparison to FA3a,b. indicating more hospitable conditions., reduced sediment budget and hydraulic energy. **· Interpreted to represent deposition on the margins of a compound dune field.**
Stratigraphic Surface Occurrence: Carcajou Canyon	Not Applicable	· *Glossifungites* firm-ground suite, (BI 3-4) *Taenidium* observed (Fig. 13c). · Infilled by large irregular and poorly sorted clasts of ?manganese cemented sandstones and celadonite (brilliant blue/green mineral (Fig 13b-d). · Substrate lithology is FA1b.	· *Glossifungites* demarcated omission surface (MacEachern *et al*., 1992)

Table 3.1: Summary of facies associations and depositional environments of the Mount Clark Formation within the Mackenzie Mountains**.**

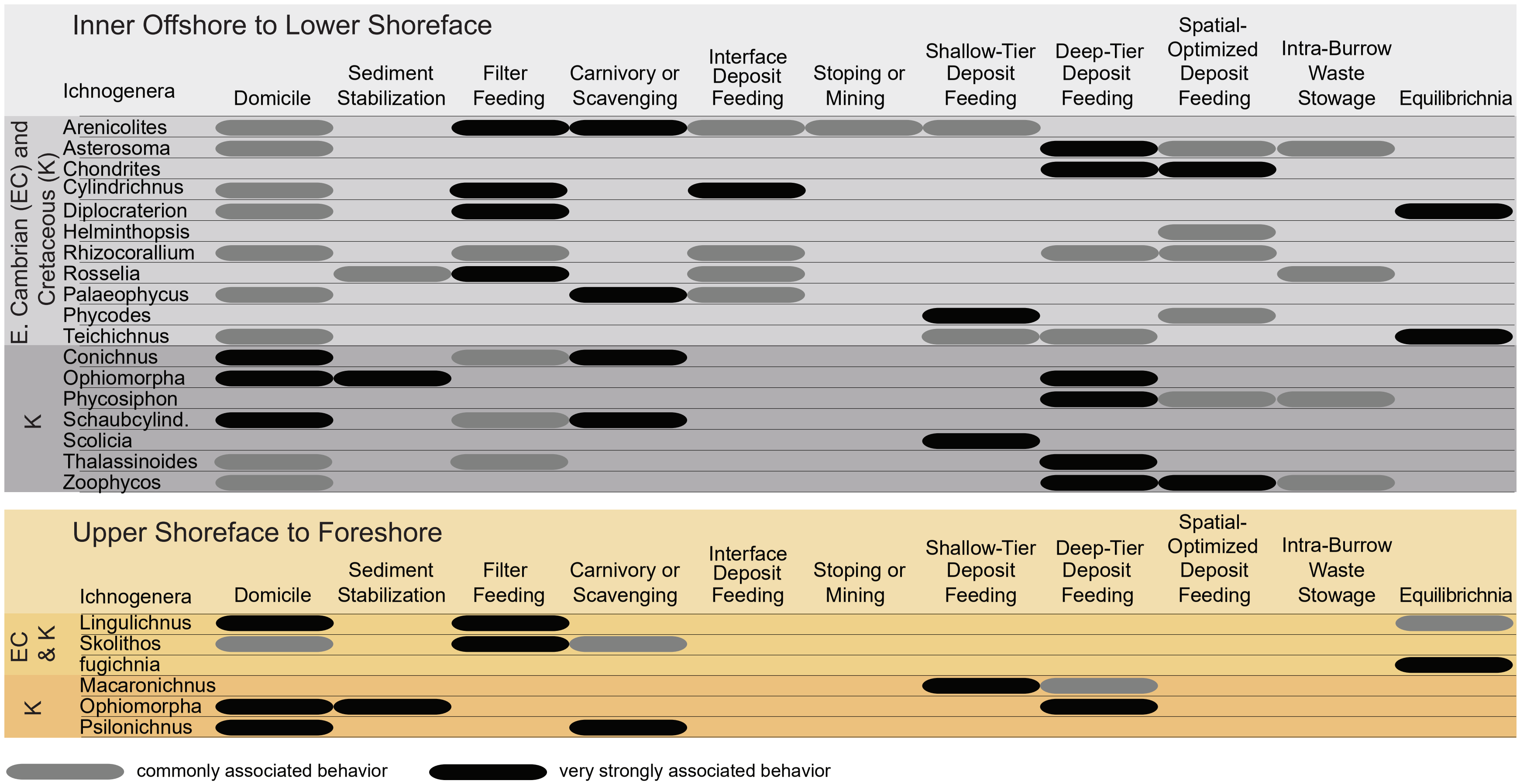

Inner Offshore to Lower Shoreface
Ichnogenera
Domicile
Sediment Stabilization
Filter Feeding
Carnivory or Scavenging
Interface Deposit Feeding
Stoping or Mining
Shallow-Tier Deposit Feeding
Deep-Tier Deposit Feeding
Spatial-Optimized Deposit Feeding
Intra-Burrow Waste Stowage
Equilibrichnia
E. Cambrian (EC) and Cretaceous (K)
Arenicolites
Asterosoma
Chondrites
Cylindrichnus
Diplocraterion
Helminthopsis
Rhizocorallium
Rosselia
Palaeophycus
Phycodes
Teichichnus
K
Conichnus
Ophiomorpha
Phycosiphon
Schaubcylind.
Scolicia
Thalassinoides
Zoophycos
Upper Shoreface to Foreshore
Ichnogenera
Domicile
Sediment Stabilization
Filter Feeding
Carnivory or Scavenging
Interface Deposit Feeding
Stoping or Mining
Shallow-Tier Deposit Feeding
Deep-Tier Deposit Feeding
Spatial-Optimized Deposit Feeding
Intra-Burrow Waste Stowage
Equilibrichnia
EC & K
Lingulichnus
Skolithos
fugichnia
K
Macaronichnus
Ophiomorpha
Psilonichnus
commonly associated behavior
very strongly associated behavior

Table 3.2: Shoreface Associated Ethologies of Mesozoic and Cambrian Shorefaces. Trace fossil behaviours documented from the Early Cambrian (EC) Mount Clark Formation and a range Cretaceous (K) strata (Leckie and Walker, 1982; Saunders and Pemberton, 1990; MacEachern and Pemberton, 1992;). Behaviours are adapted from MacEachern *et al*. (2007).

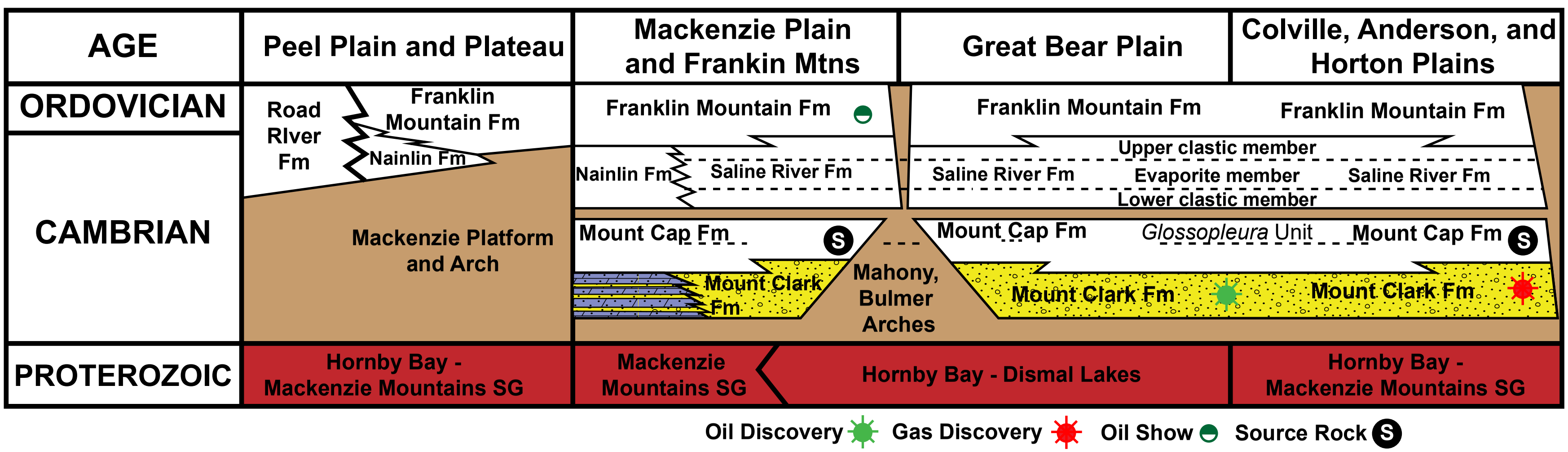
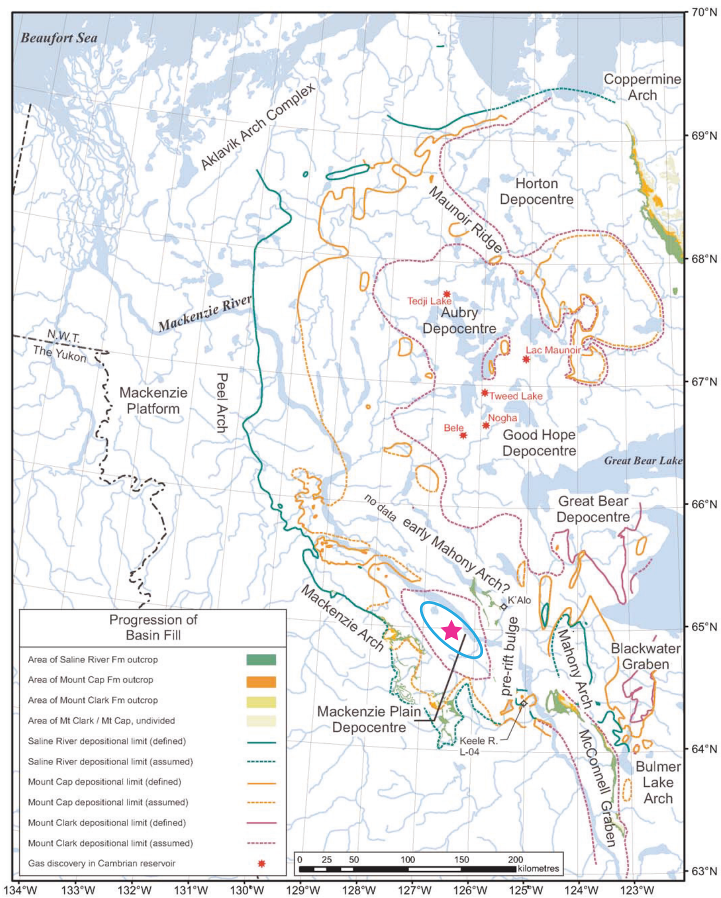
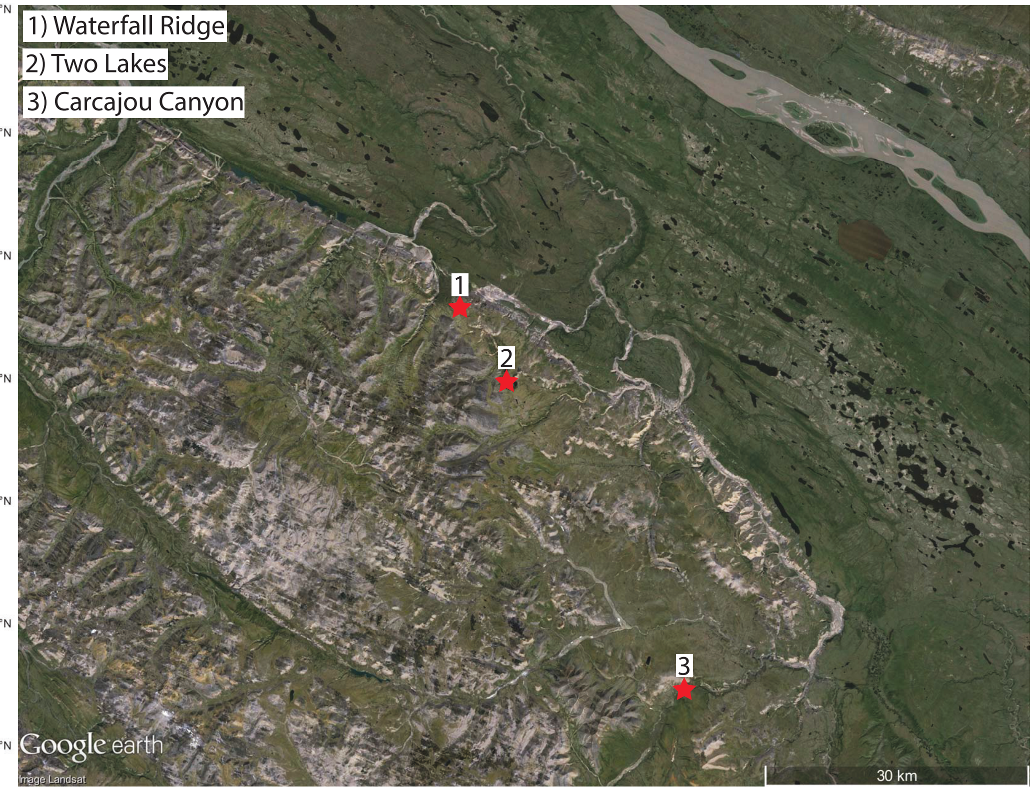

AGE
Peel Plain and Plateau
Mackenzie Plain and Frankin Mtns
Great Bear Plain
Colville, Anderson, and Horton Plains
ORDOVICIAN
CAMBRIAN
PROTEROZOIC
Road River Fm
Franklin Mountain Fm
Nainlin Fm
Mackenzie Platform and Arch
Franklin Mountain Fm
Nainlin Fm
Saline River Fm
Mount Cap Fm
Mount Clark Fm
Mahony, Bulmer Arches
Franklin Mountain Fm
Upper clastic member
Saline River Fm
Evaporite member
Saline River Fm
Lower clastic member
Mount Cap Fm
Glossopleura Unit
Mount Cap Fm
Mount Clark Fm
Mount Clark Fm
Franklin Mountain Fm
Hornby Bay - Mackenzie Mountains SG
Mackenzie Mountains SG
Hornby Bay - Dismal Lakes
Hornby Bay - Mackenzie Mountains SG
Oil Discovery
Gas Discovery
Oil Show
Source Rock

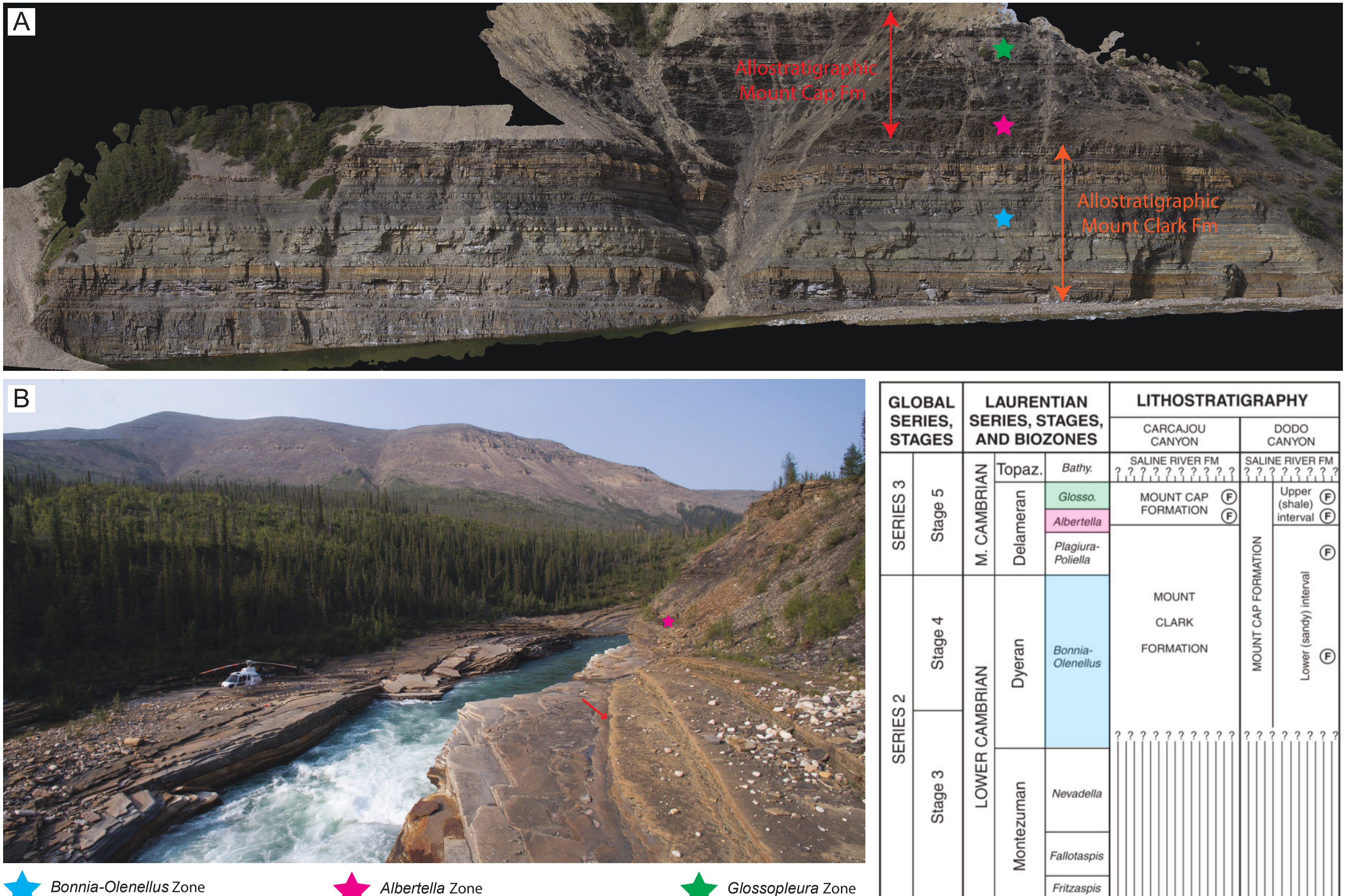
Figure 3.1: Stratigraphic column for the Cambrian System within the Northwest Territories, Canada. The chief focus of this study is the Mount Clark Formation within the Mackenzie Plain area. Modified from MacLean (2011).





Waterfall Ridge: 65° 3'16.92"N 127°45'6.12"W
Two Lakes: 64°58'34.00"N 127°36'22.90"W
Carcajou Canyon: 64°40'16.90"N 127° 9'40.82"W

Figure 3.2: Basemap of the study area showing the outcrop locations within the Mackenzie Depocenter**.** Map modified from MacLean (2011). Air photo from Google Earth.



Bonnia-Olenellus Zone   Albertella Zone   Glossopleura Zone

Figure 3.3: Biostratigraphic framework of the Mount Clark Formation using trilobite zonations.

A) Photomosaic of the Dodo Canyon section of the Mount Clark Formation. Allostratigraphic Mount Clark and Cap Formations are indicated by the orange and red arrows respectively. Trilobite faunas represented by the blue, pink, and green stars.

B) UAV acquired overview photograph of the Carcajou Canyon locality illustrating the typical Mount Clark quartz dominated sandstones overlain by the dolostone and black shale of the Mount Cap Formation. The blue arrow indicates the Mount Clark/Cap Fm boundary. Note the pink star indicating *Albertella* zone trilobites placing the quartz dominated sandstones as older than *Albertella*.

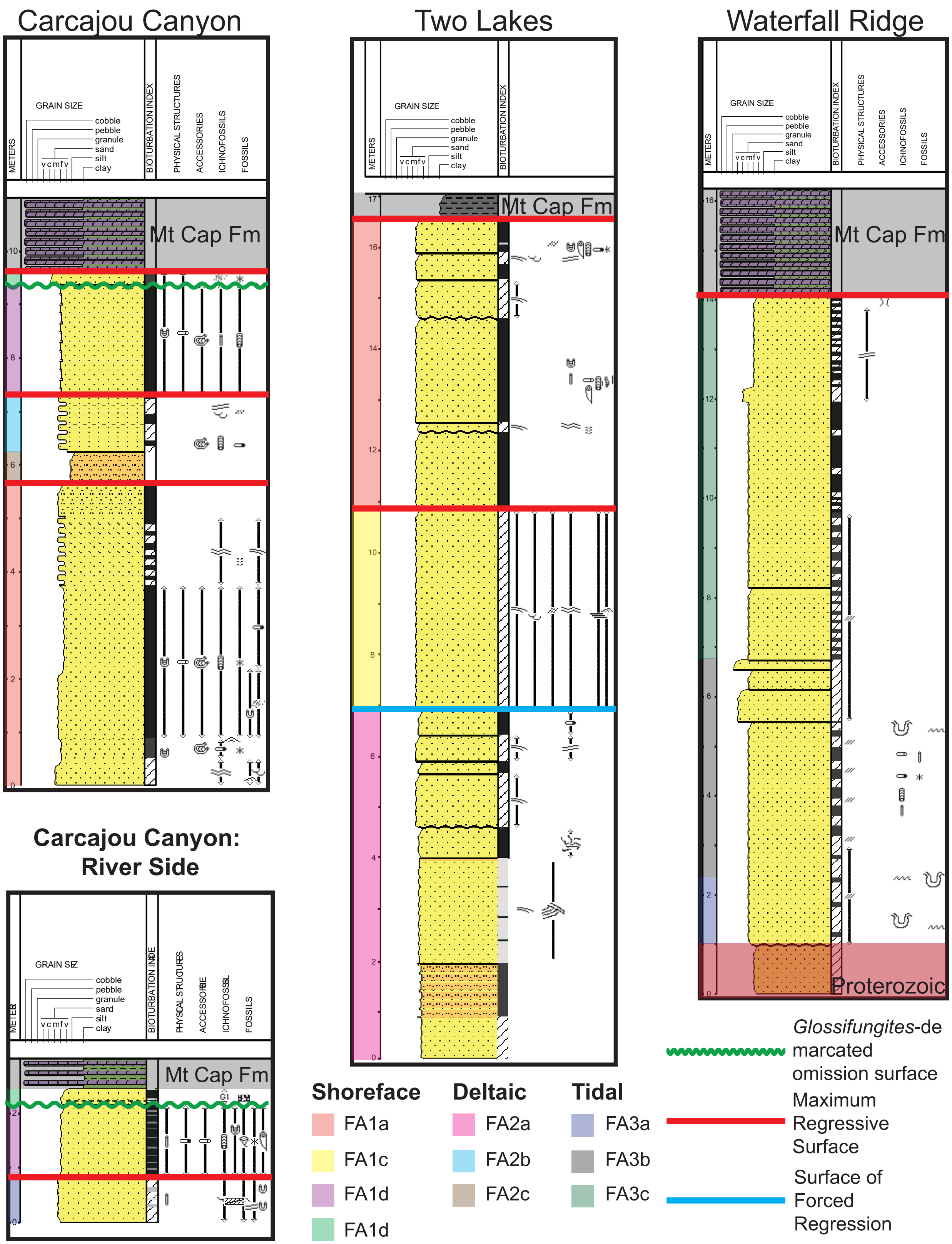

Carcajou Canyon
Two Lakes
Waterfall Ridge
METERS
GRAIN SIZE
cobble
pebble
granule
sand
silt
clay
v c m f v
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FOSSILS
Mt Cap Fm
Proterozoic
Carcajou Canyon: River Side
Shoreface
FA1a
FA1c
FA1d
FA1d
Deltaic
FA2a
FA2b
FA2c
Tidal
FA3a
FA3b
FA3c
Glossifungites-demarcated omission surface
Maximum Regressive Surface
Surface of Forced Regression

Figure 3.4: Striplogs of the outcrop sections logged.

Red lines indicate flooding surfaces (maximum regressive surfaces) while green squiggly lines represent a *Glossifungites* surface. Surface of forced regression outlined in blue at Two Lakes. The depositional environments are indicated by coloured shading in the left margin of each log. Digitized logs were done through AppleCore© software.

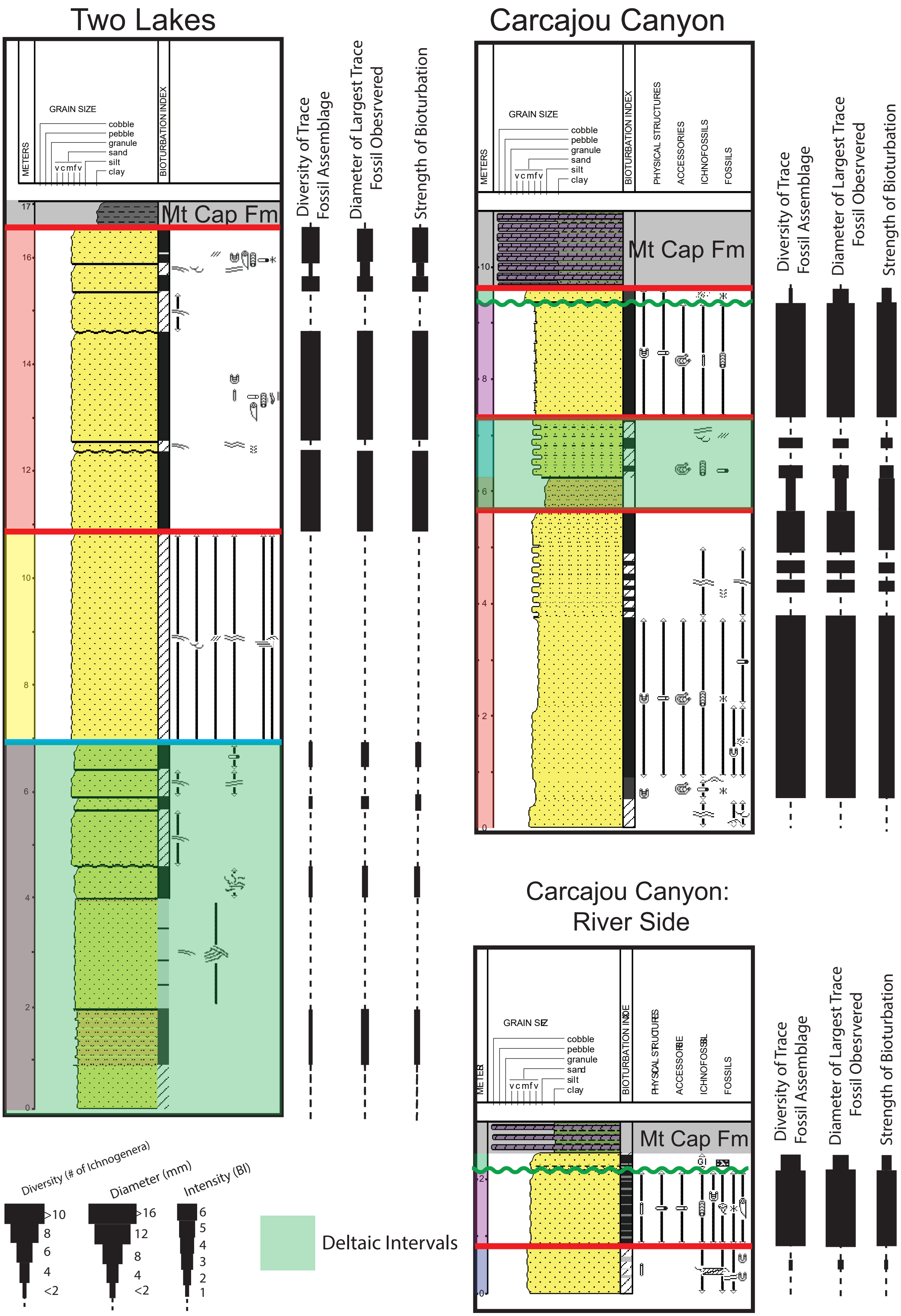

Two Lakes
METERS
GRAIN SIZE
cobble
pebble
granule
sand
silt
clay
v c m f v
BIOTURBATION INDEX
Mt Cap Fm
Diversity of Trace Fossil Assemblage
Diameter of Largest Trace Fossil Obesrvered
Strength of Bioturbation
Carcajou Canyon
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FOSSILS
Carcajou Canyon: River Side
Diversity (# of Ichnogenera)
Diameter (mm)
Intensity (BI)
>10
8
6
4
<2
>16
12
8
4
<2
6
5
4
3
2
1
Deltaic Intervals

Figure 3.5: Carcajou Canyon and Two Lakes striplogs with trace fossil size, diversity, and intensity plotted. Deltaic signatures (translucent green) become manifested through trace fossil size and diversity reductions.

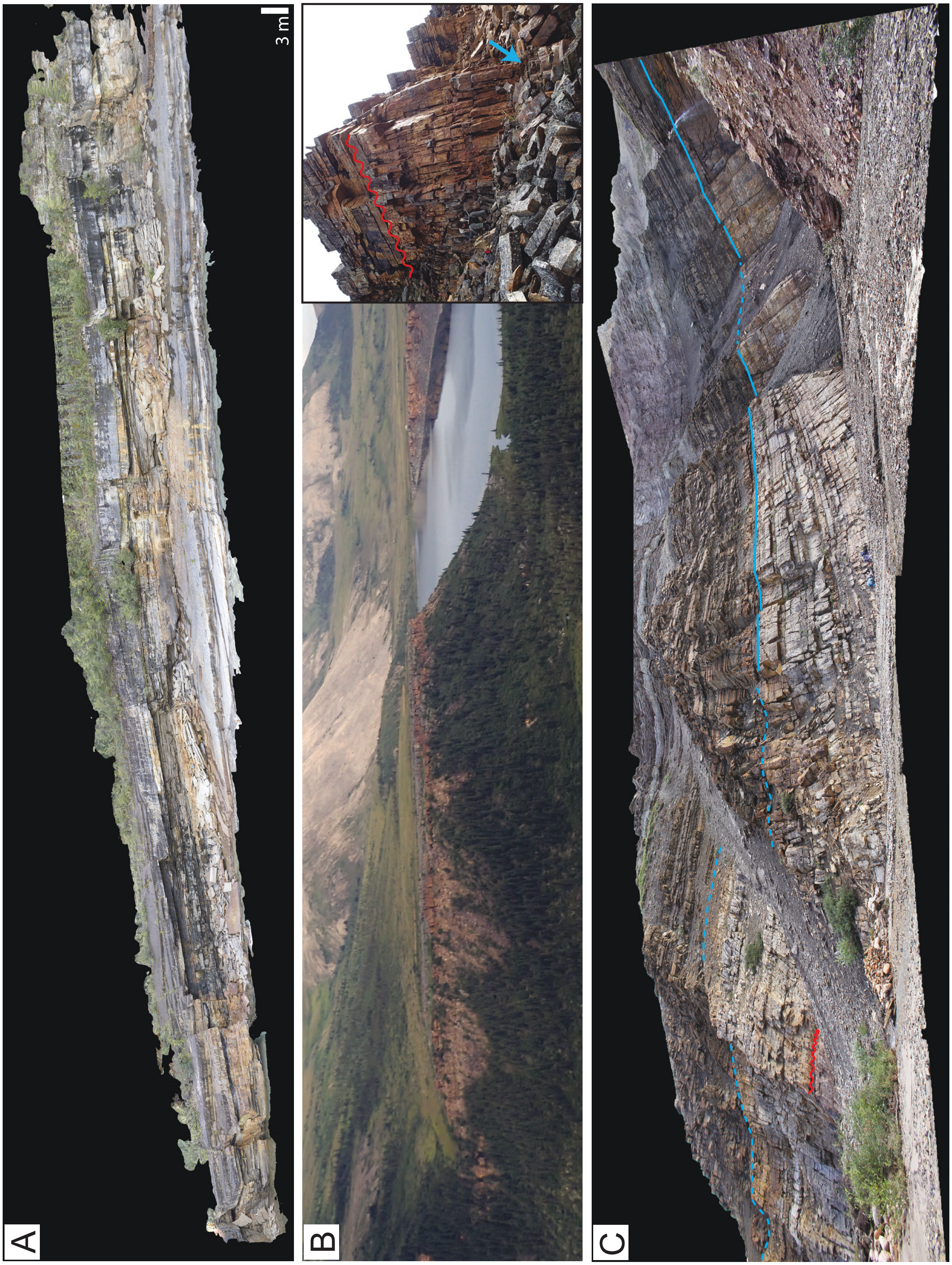
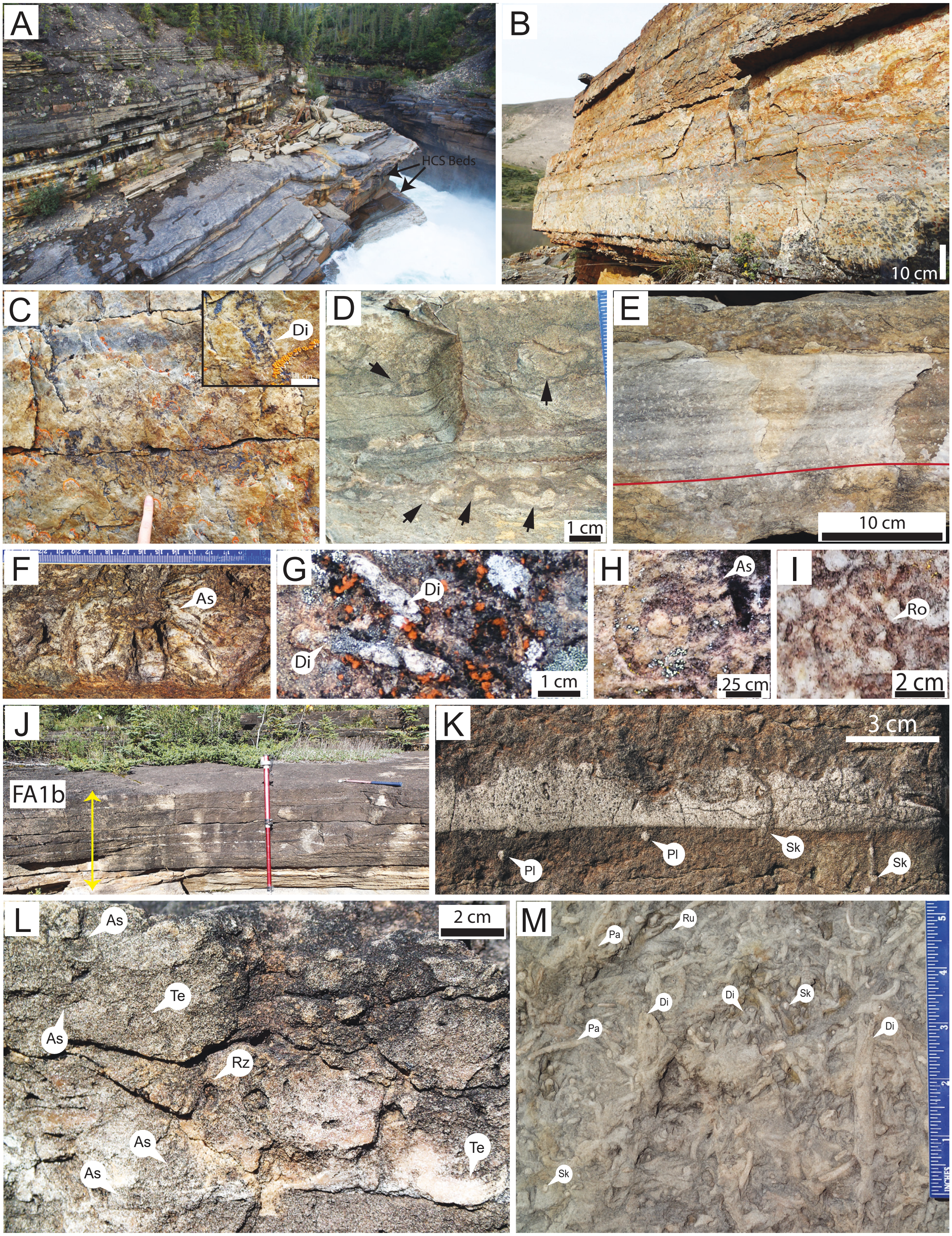

A
3 m
B
C

Figure 3.6: Overview photomosaics of the three outcrop localities studied.

A) Carcajou Canyon
B) Two Lakes. Resistant sandstone cliffs mark the Mount Clark Formation. Inset photo of two significant surfaces. Blue arrow indicates surface of forced regression. Red squiggly line indicates maximum regressive surface (MRS) separating upper shoreface/delta front deposits from lower shoreface deposited above.
C) Waterfall Ridge. Red squiggly line marks the Proterozoic-Cambrian unconformity. Blue line marks the top of the Mount Clark Formation, base of the Mount Cap Formation.



A
HCS Beds
B
10 cm
C
Di
D
1 cm
E
10 cm
F
As
G
Di
Di
1 cm
H
As
.25 cm
I
Ro
2 cm
J
FA1b
K
3 cm
Pl
Pl
Sk
Sk
L
2 cm
As
Te
As
Rz
As
As
Te
M
Pa
Ru
Di
Di
Sk
Pa
Di
Sk

Figure 3.7: FA1a (Storm-Influenced Lower Shoreface) and FA1b (Storm-Affected Lower Shoreface) Photo Plate.

A) UAV acquired aerial shot of river washed HCS beds. FA1a, represents storm-weather conditions. Carcajou Canyon.
B) Amalgamated HCS beds indicating pervasive and intense storm weather conditions and deposition, note sharp lower erosive boundary cutting unto heavily bioturbated fair-weather conditions. Two Lakes, FA1a.
C) HCS storm bed colonization suite with abundant mud-lined burrows and *Diplocraterion* (Di). Two Lakes, FA1a.
D) Ball and pillow structures or “pseudo-nodules” indicated by black arrows underlying HCS bed. Carcajou Canyon, FA1a.
E) Distal expression of HCS, graded rhythmite. Carcajou Canyon, FA1a.
F) Robust *Asterosoma* (As). Carcajou Canyon, FA1a.
G) Robust bedding plane expressions of *Diplocraterion* (Di). Two Lakes, FA1a.
H) Cross-sectional view of *Asterosoma* (As). Two Lakes, FA1a.
I) Bedding plane expressions of *Rosselia* (Ro). Two Lakes, FA1a.
J) Overview photo of FA1b, intensely bioturbated lower shoreface fair-weather deposits with thin white quartzose tempestites. Carcajou Canyon, Fa1b.
K) Biogenically reworked quartzose tempestite with auto-cyclic *Glossifungites* firm-ground developed underneath, *Planolites (*Pl) and *Skolithos* (Sk). Carcajou Canyon, FA1b. Red Jacobs staff is 1.5 m in length.
L) Intensely bioturbated fair-weather deposits of the lower shoreface containing cross-sectional views of *Asterosoma (As), Teichichnus (Te),* and *Rhizocorallium (Rz)*. Carcajou Canyon, FA1b.
M) Bedding plane expressions of Intensely bioturbated (BI 6) fair-weather trace fossil assemblages of FA1d; *Palaeophycus (Pa), Cylindrichnus (Cy), Diplocraterion (Di), Skolithos (Sk),* and *Rusophycus (Ru).*


A
B
C
5 cm
D
Ch
Ch
Ch
Ch
20 cm
E
1 cm
F
G
Ch
Pa
Ch
1 cm
H
1 cm
Pa
As
Cy

Figure 3.8: FA1c (Upper Shoreface/Upper Delta Front), FA1d (Foreshore), and FA2a (Storm-Influenced Lower Delta Front) Photo Plate.

A) Planar-tabular bedding of FA1c. Two Lakes, 10cm increments on red pogo staff.
B) Trough cross-stratification of FA1c. Two Lakes.
C) Planar-tabular bedding of FA1c. Two Lakes.
D) Mono-specific assemblages of *Chondrites* (Ch) within celadonitic sands of FA1d. Carcajou Canyon.
E) Herringbone cross-stratification of FA1d. Carcajou Canyon.
F) Large scale HCS bedding (storm-weather) and intensely bioturbated (fair-weather) horizons. 1.5 m red Jacobs staff for scale. Two Lakes, FA2a.

G-H) Slabbed and polished hand samples from fair-weather bioturbated horizons of FA2a. Diminutive and impoverished *Cruziana* ichnofacies consisting of *Asterosoma (As), Cylindrichnus (Cy), Chondrites (Ch),* and *Palaeophycus (Pa)*. Two Lakes.

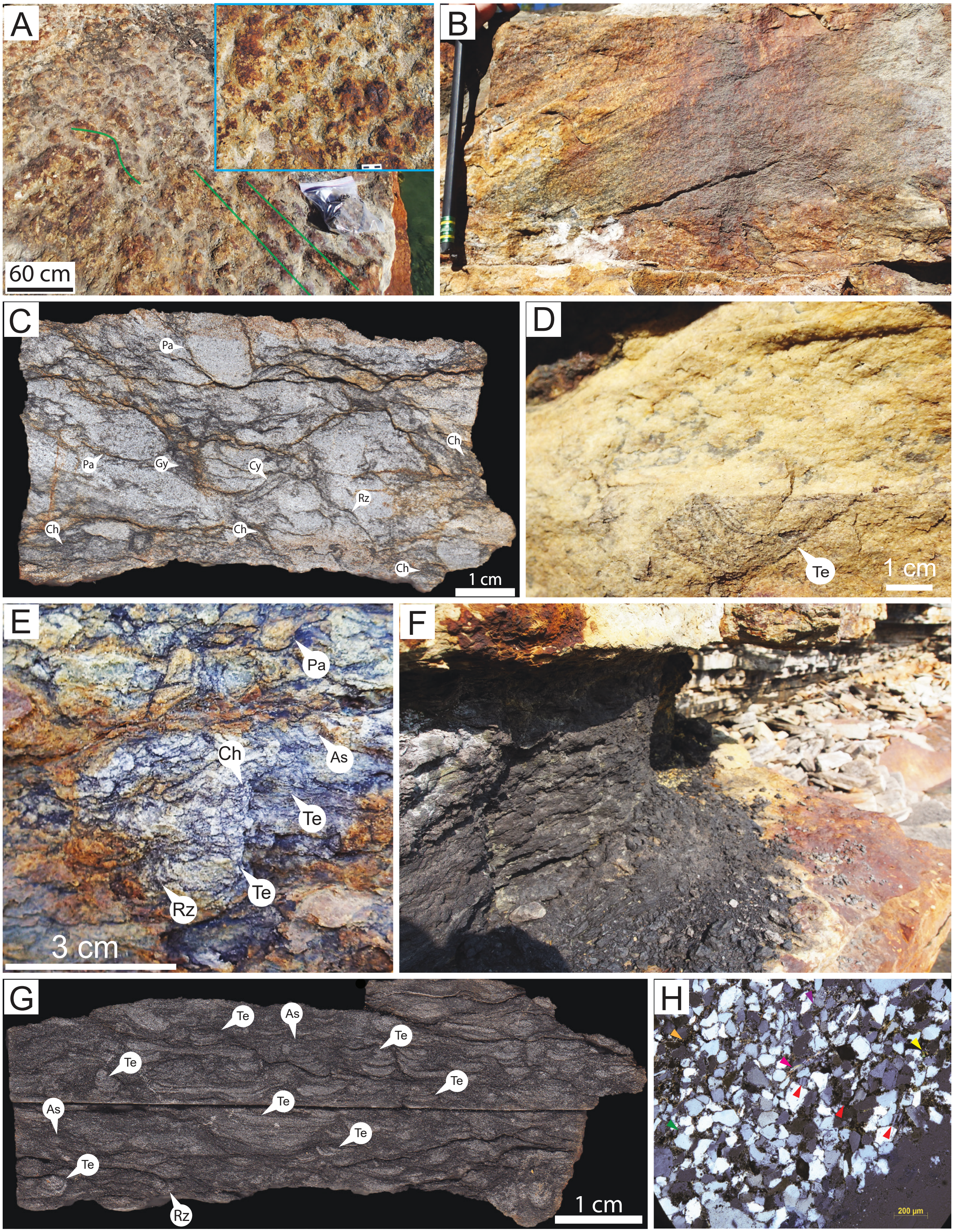

A
60 cm
B
C
Pa
Pa
Gy
Cy
Ch
Rz
Ch
Ch
Ch
1 cm
D
Te
1 cm
E
Pa
Ch
As
Te
Te
Rz
3 cm
F
G
Te
As
Te
Te
Te
Te
As
Te
Te
Rz
1 cm
H
200 µm

Figure 3.9: FA2b (Storm-Influenced Wave-Dominated Lower Delta Front) and FA2c (Wave-Dominated Prodelta) Photo Plate.

A) Oscillatory interference ripples observed on the bedding plane of FA2b, rough orientation provided by green lines. Blue box provides a more detailed inset image. Carcajou Canyon.

B) 2-D dune manifested as planar-tabular cross-stratification. Pencil approximately 12 cm in length. Carcajou Canyon, FA2b.

C) Cross-sectional view of a slabbed hand sample of FA2b showing muddy sandstone with *Gyrolithes* (Gy), *Cylindrichnus* (Cy), *Palaeophycus* (Pa), *Chondrites* (Ch), and *Rhizocorallium* (Rz). Carcajou Canyon, FA2b.

D) *Teichichnus* (Te) erosionally truncated by 2-D dune. Carcajou Canyon, FA2b.

E) Outcrop cross-sectional close-up of FA2b showing an intensely (BI 5) bioturbated muddy sandstone fabric with *Palaeophycus* (Pa), *Chondrites* (Ch), *Asterosoma* (As), *Teichichnus* (Te), and *Rhizocorallium* (Rz). Carcajou Canyon, FA2b.

F) Shaley black appearance and recessive weathering of FA2c at Carcajou Canyon.

G) Slabbed hand sample of FA2c showing an impoverished *Cruziana* Ichnofacies containing *Teichichnus (Te), Asterosoma (As),* and *Rhizocorallium (Rh).*

H) Thin-section photograph of FA2c indicating plagioclase and potassium feldspars (red arrows), muscovite (pink arrow), zircon (yellow arrow), clay minerals (orange arrow), lithics (purple arrow), and chert (green arrow).

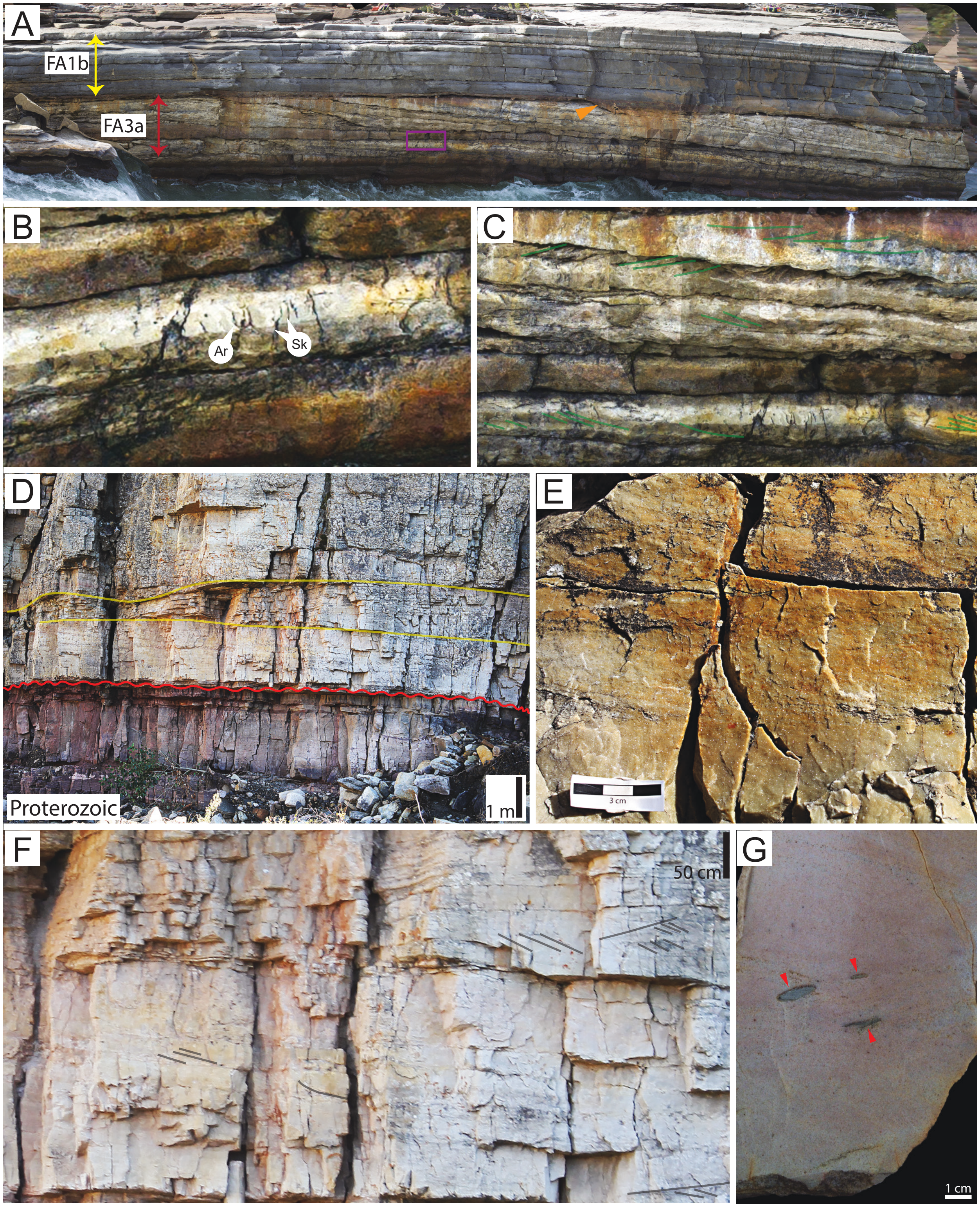

A
FA1b
FA3a
B
Ar
Sk
C
D
Proterozoic
1 m
E
3 cm
F
50 cm
G
1 cm

Figure 3.10: FA3a (Compound Dune Field Core) Photo Plate.

A) UAV acquired photomosaic of section near the rivers' edge showing FA1d (fair-weather lower shoreface) and FA4a (compound dune field core) in the yellow and red arrows. Orange arrow shows erosive scouring cutting into FA4a. The purple box provides the inset for B. Carcajou Canyon.
B) Colonization suite consisting of *Skolithos* and *Arenicolites* burrows within FA3a. Diagnostic of the *Skolithos* ichnofacies with BI of 3. Carcajou Canyon.
C) Trough cross-stratification indicated by the translucent green lines. Note opposing foreset dip angles. Carcajou Canyon, FA3a.
D) Compound dunes overlying the Proterozoic unconformity (red squiggly line). Yellow lines are interpreted to represent compound dune geometries. Waterfall Ridge, FA3a.
E) Sigmoidal trough cross-stratification of FA3a. Waterfall Ridge.
F) Zoomed image of (D) showing high to low angle cross bedding of trough cross-stratification. Translucent black lines show cross-bedding. Waterfall Ridge, FA3a.
G) Slabbed and polished hand sample containing mudstone rip up clasts (red arrows. Waterfall Ridge, FA3a.

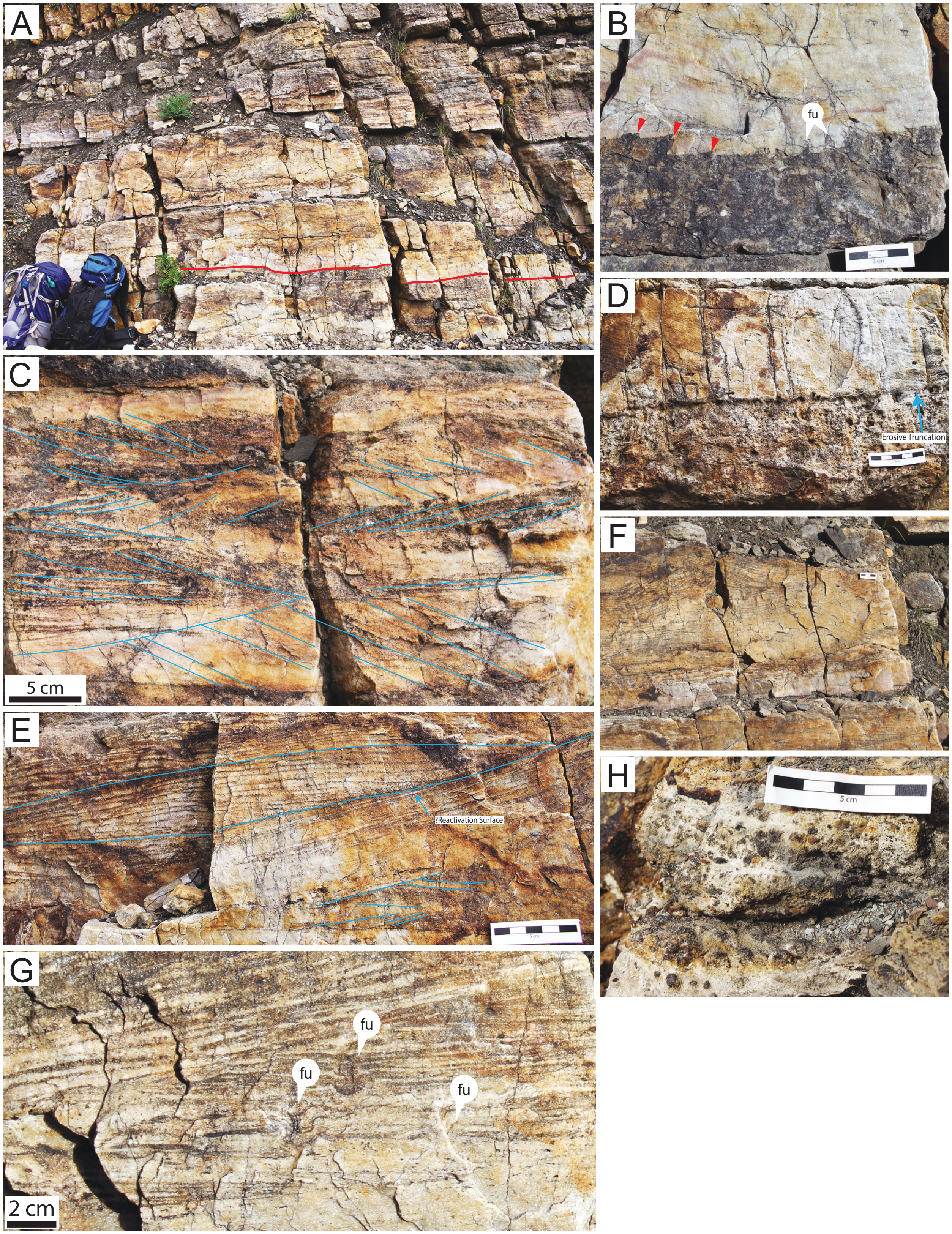

A
B
fu
3 cm
C
5 cm
D
Erosive Truncation
E
?Reactivation Surface
F
G
fu
fu
fu
2 cm
H
5 cm

Figure 3.11: FA3b (Compound Dune Field) Photo Plate.

A) Overview photo of FA3b depicting sigmoidal dune forms and sharp erosional contacts with underlying bioturbated horizons (red line). Waterfall Ridge.
B) Flame structures riding up into overlying 3-D dune indicated by red arrows showing a soupy soft unconsolidated bioturbated substrate from FA3b. Waterfall Ridge.
C) Herringbone cross-stratification interpreted to represent bi-directional tidal currents. Waterfall Ridge, FA3b.
D) 3-D dune erosionally truncating heavily bioturbated (BI 5-6) horizons. Waterfall Ridge, FA3b.
E) Sigmoidal dune migrating up a previously deposited dune creating a reactivation surface, herringbone cross-stratification in the lower beds traced in translucent blue lines. Waterfall Ridge, FA3b.
F) Large scale convolute bedding, scale bar is 3cm. Waterfall Ridge, FA3b.
G) Fugichnia within 3-D dune. Waterfall Ridge, FA3b.
H) Crudely cross-bedded recessive pebbly interval interpreted to record storm deposition. Waterfall Ridge, FA3b.

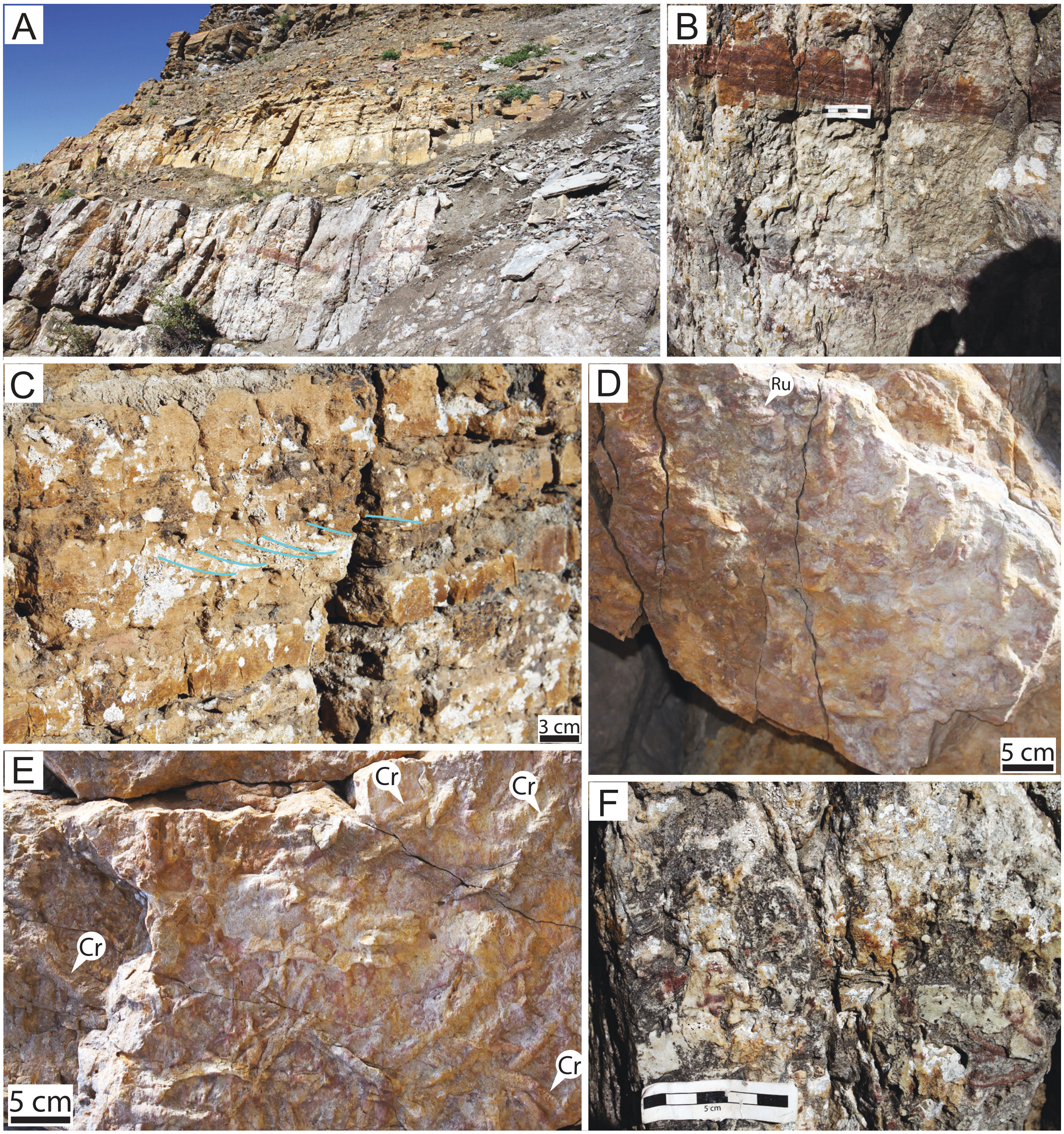

A
B
C
D
Ru
3 cm
5 cm
E
Cr
Cr
Cr
Cr
5 cm
F
5 cm

Figure 3.12: FA3c (Compound Dune Field Margin) Photo Plate.

A) Overview outcrop shot showing FA3c, darker red beds indicate 2-D dunes. Waterfall Ridge.

B) Two examples of 2-D dunes (darker red colour) in FA3c. The lower bed has been nearly obliterated due to biogenic reworking while the upper one shows significantly less biogenic reworking. Waterfall Ridge, FA3c.

C) 2-D dunes with sharp erosional bases migrating overtop of bioturbated intervals. Waterfall Ridge, FA3c.

D-E) Bedding plane traces of *Rusophycus* and *Cruziana*. Waterfall Ridge, FA3c.

F) Biogenic deformation ichnofabric, complete homogenization of the sediment. Waterfall Ridge, FA3c.

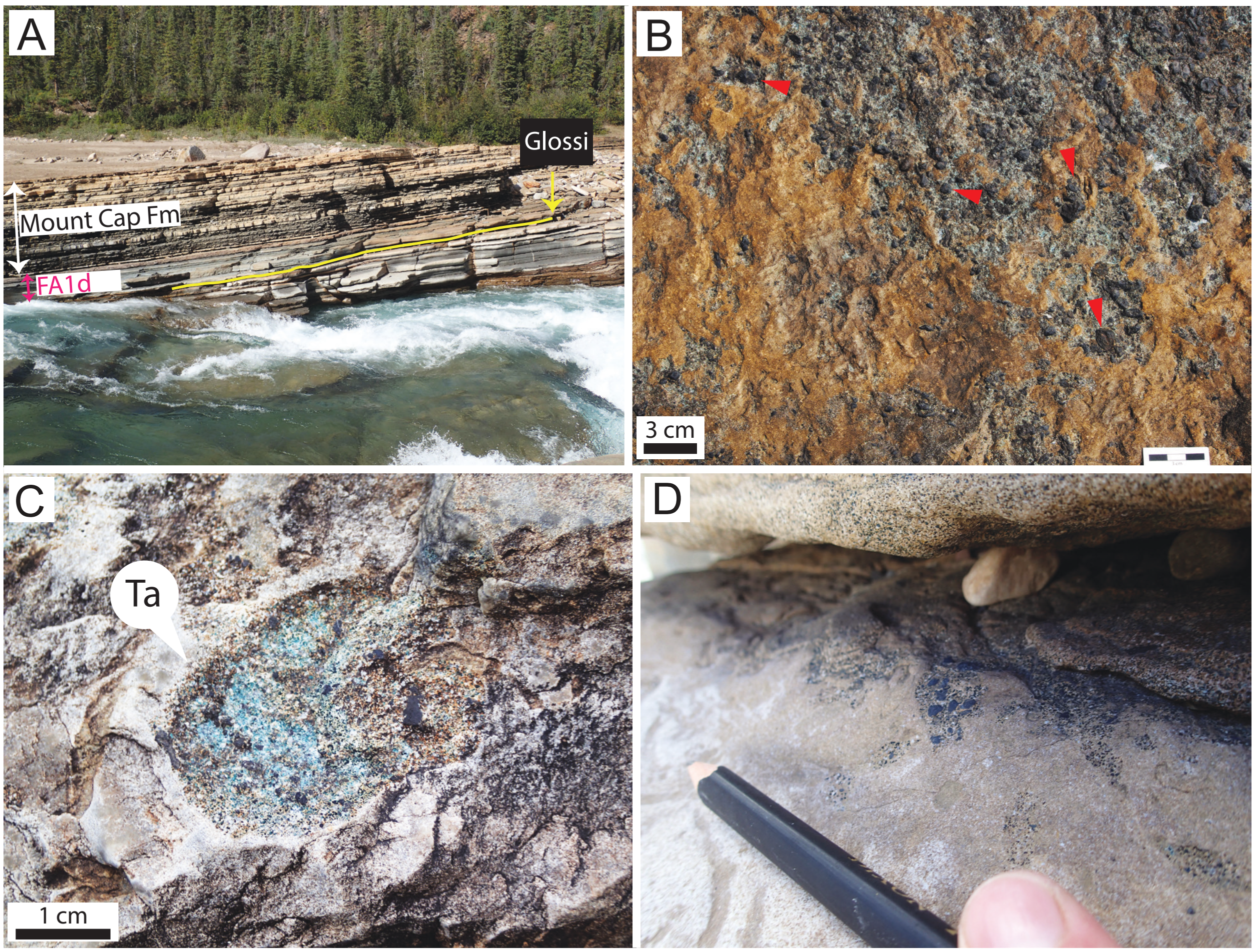

A
Glossi
Mount Cap Fm
FA1d
B
3 cm
C
Ta
1 cm
D

Figure 3.13: *Glossifungites* Demarcated Omission Surface, Carcajou Canyon**.**

A) Overview photo of the Mount Clark to Cap Formation interval. The yellow line indicates the *Glossifungites* surface. The pink arrow represents the relatively thin deposits if FA1d.
B) Transgressive lag of *Glossifungites* surface. Red arrows point to large pebble sized clasts of ?manganese cemented sandstone.
C) *Taenidium* (Ta) with brilliant blue/green celadonite infill.
D) Cross-sectional outcrop expression of the *Glossifungites* surface.

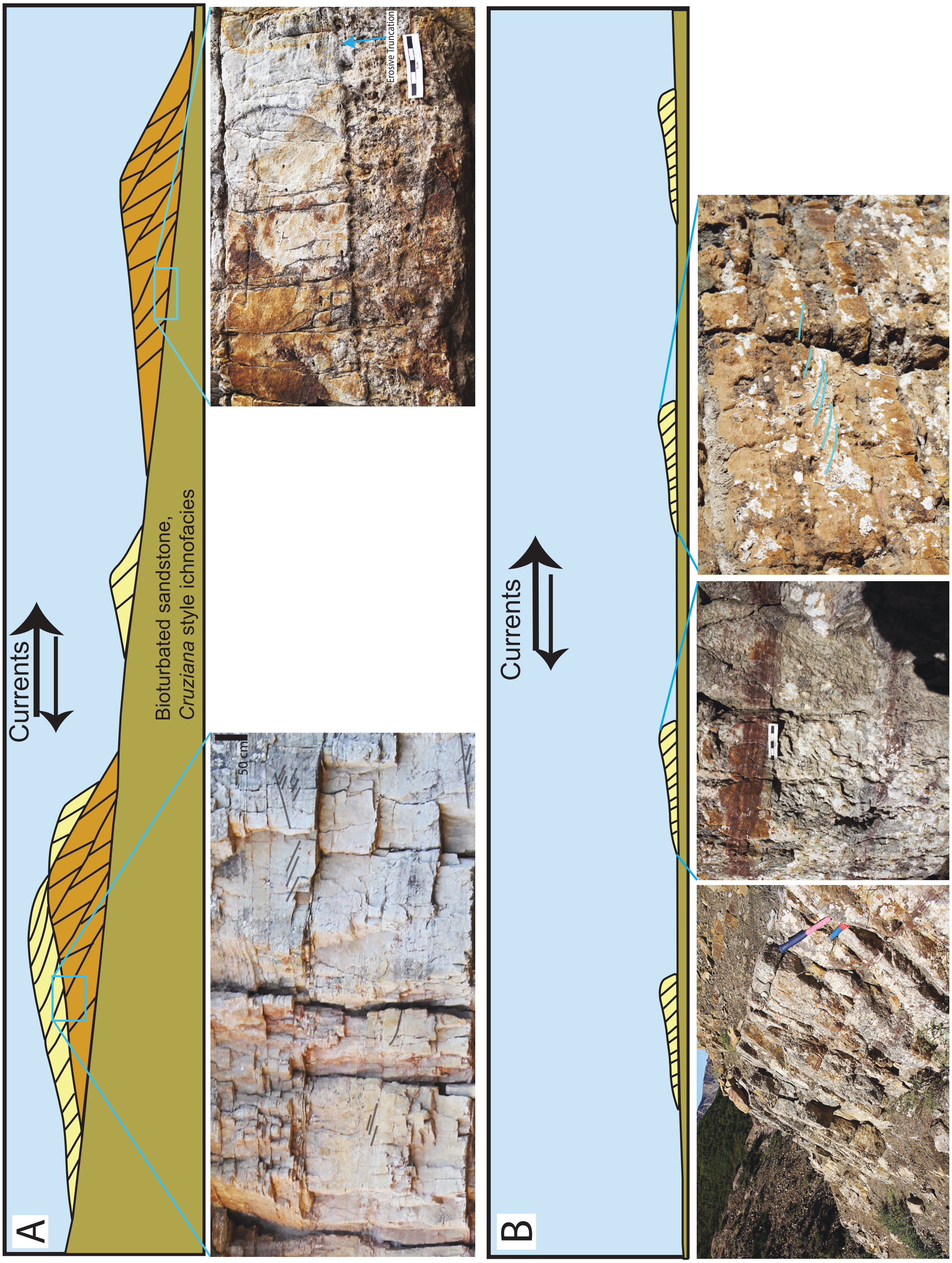

A
Currents
Bioturbated sandstone,
Cruziana style ichnofacies
50 cm
Erosive Truncation
B
Currents

Figure 3.14: Tidal Compound Dune Field of FA3.

A) Geomorphic reconstruction of the subtidal compound dune field interpreted as the environment of deposition for FA3. Two inset images are shown distinguishing the different areas of deposition. Left image (FA3a) depicts the core of a compound dune noted by the absence of erosionally truncated bioturbated horizons and pervasive amalgamated dune bedforms. Right image (FA3b) shows the erosional truncation of *Cruziana* style bioturbated muddy sandstones within the “trough” due to compound dune migration across the substrate.
B) Geomorphic reconstruction of the subtidal compound dune field margin interpreted as the environment of deposition for FA3c. Thinly bedded 2-D dunes migrate erosively across the *Cruziana* style bioturbated muddy sandstone substrate as a result of an increase in sediment budget and/or storm influence. Images below show the outcrop depiction.

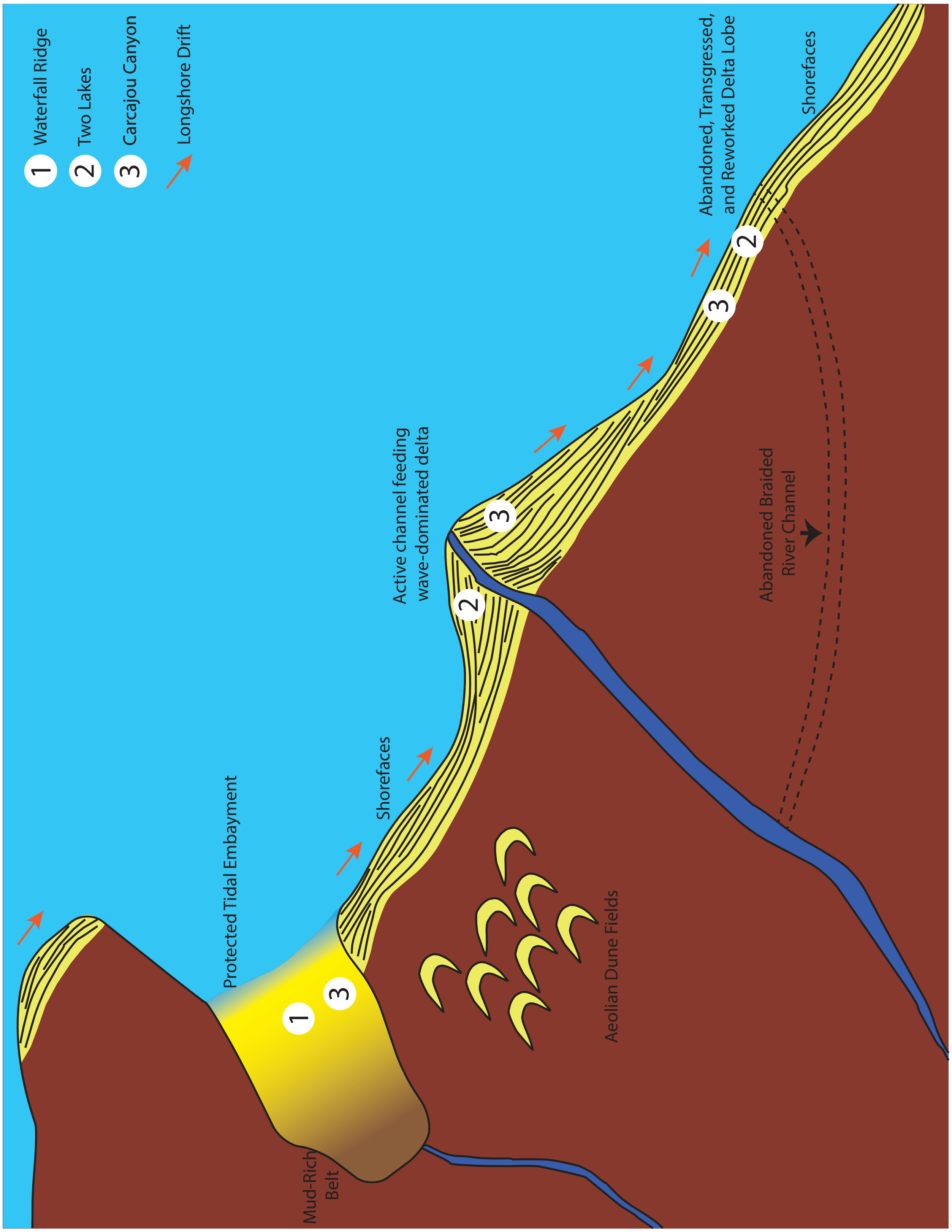
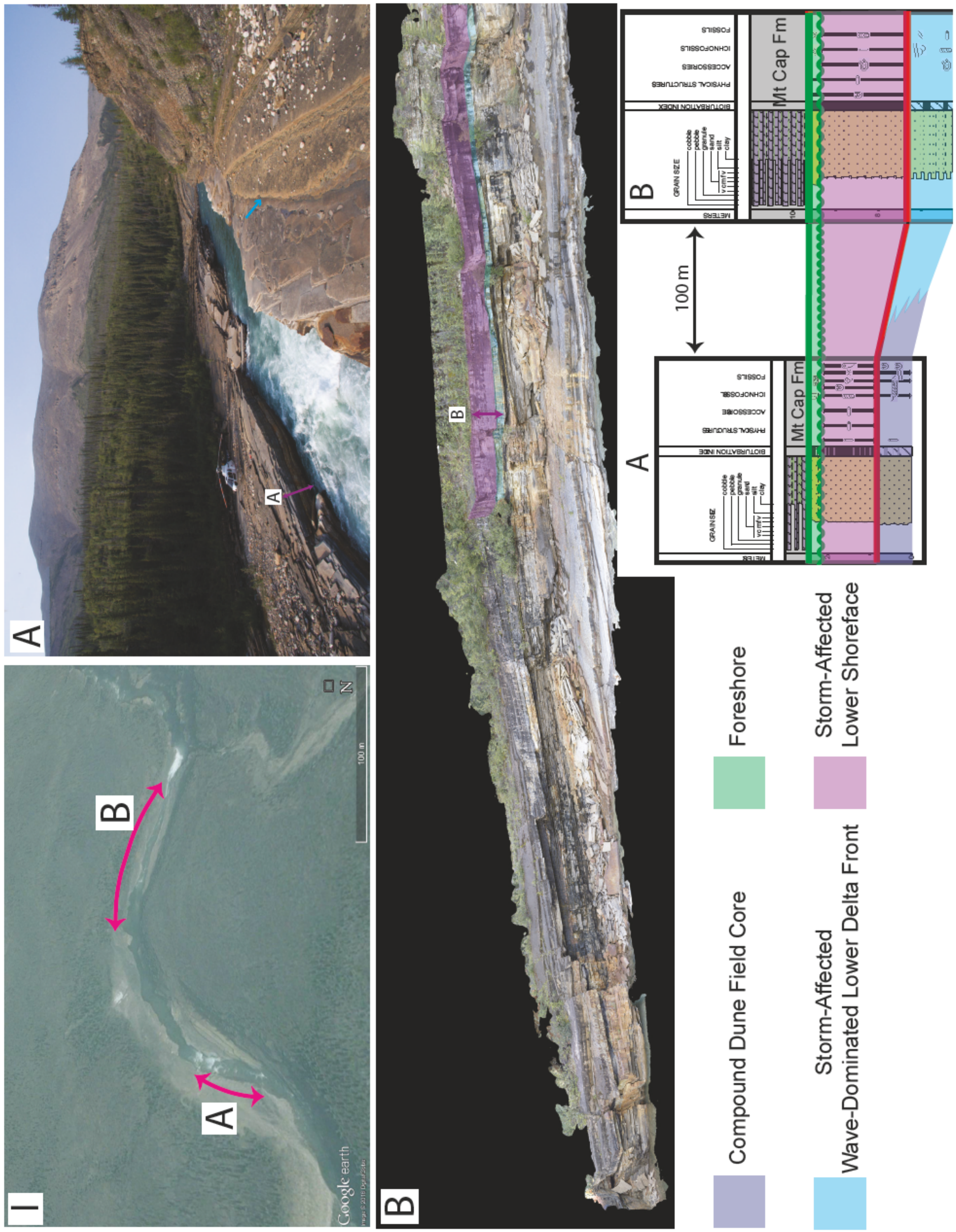

1 Waterfall Ridge
2 Two Lakes
3 Carcajou Canyon
Longshore Drift
Protected Tidal Embayment
Shorefaces
Active channel feeding wave-dominated delta
Abandoned, Transgressed, and Reworked Delta Lobe
Shorefaces
Abandoned Braided River Channel
Aeolian Dune Fields
Mud-Rich Belt

Figure 3.15: Mount Clark Formation Depositional Framework for the Mackenzie Mountains. Numbers indicate outcrop localities where deposition could have occurred.



I
A
B
100 m
Google earth
A
B
A
B
Mt Cap Fm
100 m
Compound Dune Field Core
Foreshore
Storm-Affected Wave-Dominated Lower Delta Front
Storm-Affected Lower Shoreface

Figure 3.16: Carcajou Canyon Paleoenvironmental Juxtaposition.

I) Google Earth image showing the Carcajou Canyon outcrop with the two section of interest noted by the pink arrows A and B.

A) UAV image of the river side section that contains tidally dominated deposits of FA3a in comparison to the storm influenced shoreface and deltaic sections of Carcajou Canyon.

B) UAV mosaic of the lower downstream falls section of Carcajou Canyon consisting of storm-influenced shoreface and deltaic deposits. AppleCore cross section below contrasts the overall rapid change in depositional environments from tidal compound dunes (A) to delta front deposits (B). Also seen is the increase in thickness of FA1d storm-influenced lower shoreface deposits when moving towards the falls.

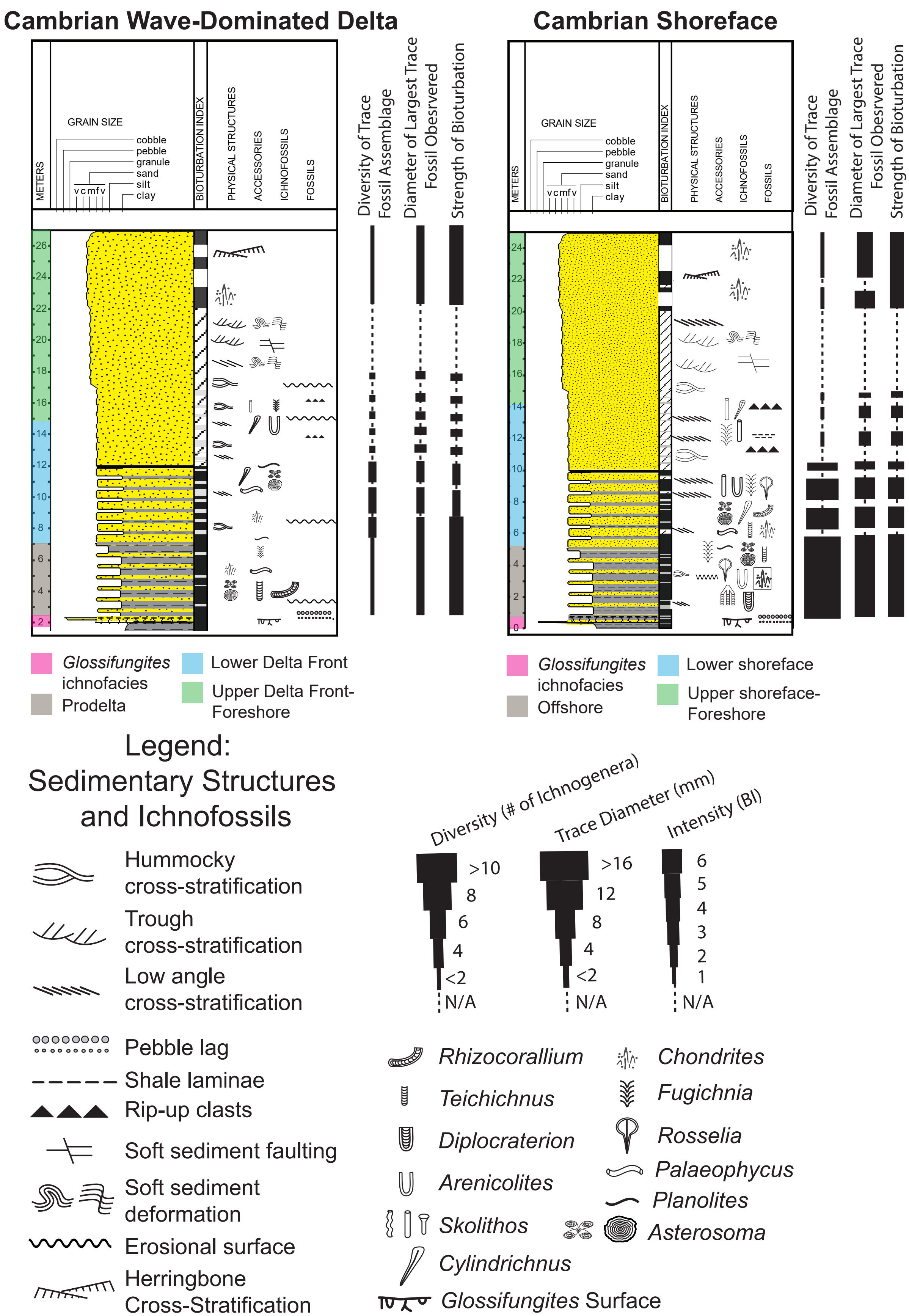

Cambrian Wave-Dominated Delta
METERS
GRAIN SIZE
cobble
pebble
granule
sand
silt
clay
v c m f v
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FOSSILS
Diversity of Trace Fossil Assemblage
Diameter of Largest Trace Fossil Obesrvered
Strength of Bioturbation
Glossifungites ichnofacies
Prodelta
Lower Delta Front
Upper Delta Front-Foreshore
Cambrian Shoreface
Glossifungites ichnofacies
Offshore
Lower shoreface
Upper shoreface-Foreshore
Legend: Sedimentary Structures and Ichnofossils
Hummocky cross-stratification
Trough cross-stratification
Low angle cross-stratification
Pebble lag
Shale laminae
Rip-up clasts
Soft sediment faulting
Soft sediment deformation
Erosional surface
Herringbone Cross-Stratification
Diversity (# of Ichnogenera)
>10
8
6
4
<2
N/A
Trace Diameter (mm)
>16
12
8
4
<2
N/A
Intensity (BI)
6
5
4
3
2
1
N/A
Rhizocorallium
Teichichnus
Diplocraterion
Arenicolites
Skolithos
Cylindrichnus
Glossifungites Surface
Chondrites
Fugichnia
Rosselia
Palaeophycus
Planolites
Asterosoma

Figure 3.17: Sedimentological and ichnological expressions of Cambrian shorefaces and wave-dominated deltas. Idealized composite strip logs based on outcrop data. Note the decreased trace fossil size, diversity, and bioturbation intensity associated with deltaic deposition.

CHAPTER 4: AN EARLY CAMBRIAN RADIATION INTO CHARACTERISTIC ETHOLOGICAL NICHES

INTRODUCTION

The colonization of marine environments by metazoans is one of the most significant events of Earth's history. Trace fossils indicate a dramatic shift from the simple surface grazers of the Proterozoic Ediacaran Period and Fortunian Stage of the Cambrian (Seilacher, 1999; Jensen, 2003; Seilacher *et* al., 2003; 2005; Mangano and Buatois, 2004; Tarhan and Droser, 2014; Tarhan *et al.,* 2015) to more diverse feeding behaviours that characterise younger marine strata (MacEachern and Pemberton, 1992; Bann and Fielding, 2004). As a result of this shift, ichnological aspects of Ediacaran strata are readily discerned from those observed in Cambrian strata.

It has generally been presumed that ichnological diversity and morphological diversity are closely linked (Meysman *et al*., 2006). However, if that is the case, then it is inferred that ethology (behaviour) and animal morphology are related, a premise that is generally not substantiated by ichnological studies. In fact, ichnofacies argue against an ethological dependence on morphology as marine ichnofacies represent a community response to resource distribution and bottom-water conditions that reveal behavioural responses that are influenced by environmental conditions, not animal form.

To better understand the relationship between animal behaviour and morphology, it is important to study Early Cambrian occurrences of then newly established ethological guilds of trace fossils (i.e. ichnofacies), and compare the timing of their establishment to what is known of the timing of the first Cambrian radiations. In this regard, we consider here the ichnological assemblages associated with the Early Cambrian Mt Clark Formation (Series 2, Stage 3), which predates fossil evidence of the Cambrian Explosion. Observed therein are very well developed trace-fossil assemblages that, based on their occurrence in well understood process sedimentological models of shoreface deposits, can be identified with very high certainty as filter-feeding and deposit-feeding centered assemblages.

MOUNT CLARK FORMATION

This study draws from a robust dataset, which includes outcrop of the Mount Clark Fm outcrop in the Mackenzie Mountains, as well as subsurface core from the Colville Hills area of the Northwest Territories, Canada (Fig. 1). Core data includes five wells; Colville D-45, Tweed Lake A-67, Tweed Lake M-47, Bele O-35, and PCI C-12. Outcrops include; Two Lakes (64°58'34.00"N, 127°36'22.90"W) and Carcajou Canyon (64°40'16.90"N, 127° 9'40.82"W), located in the eastern ranges of the Mackenzie Mountains west of Norman Wells, NT, Canada.

Previous studies of the Mount Clark Formation confirm that it was deposited within a shallow-marine shoreface setting (Hamblin, 1990; Dixon and Stasiuk, 1998). Owing to the presence of robust and diverse marine trace fossil assemblages and erosive storm beds manifested as Hummocky Cross-Stratification (HCS), (Fig. 2), the Mount Clark Formation is further interpreted to represent a storm-influenced marine shoreface to wave-dominated delta succession. Both the outcrop and core datasets contain trilobites belonging to the *Bonnia-Olenellus* Zone (Fritz, 1977; MacNaughton *et al*., 2013), which places the Mount Clark Formation within Series 2, Stage 3 of the early Cambrian, ca. 521-514 Ma (*ibid*).

In this study, we focus on the ichnological characteristics of the shoreface deposits summarized in Fig. 1 and Fig. 2. The key facies associations observed include: (1) bioturbated sandy siltstone with rare oscillation ripples and small-scale HCS beds interpreted to represent the proximal offshore (Table 1: A); (2) sandstone containing HCS, low angle cross stratification, and bioturbated silty sandstone interbeds that decrease in thickness and abundance upwards; these are interpreted as the lower shoreface (Table 1: B); and (3) trough cross-stratified and HCS sandstone capped by sporadic occurrences of *Lingulichnus* and *Skolithos* piperock that are interpreted to represent middle and upper shoreface to foreshore settings (Table 1: C).

ICHNOLOGICAL ASSOCIATIONS

Two characteristic ichnological associations are observed: (1) proximal to archetypal expressions of the *Cruziana* Ichnofacies associated with the lower shoreface to offshore, and (2) archetypal *Skolithos* Ichnofacies of the upper shoreface and foreshore (i.e. Piperock). The trace fossil associations documented herein display high degrees of bioturbation intensity, abundant trace fossils, and high ichnogenera diversity (Fig. 3). They also represent feeding ethologies that are emblematic of shoreface niches in younger Paleozoic and Mesozoic strata (Fig. 2 & 3). Importantly, the colonization of these early Cambrian shoreface subenvironments represents a very early establishment of archetypal Ichnofacies that precede geological evidence of the Cambrian Explosion (e.g. Burgess Shale) by 15 to 20 Ma.

OFFSHORE TO LOWER SHOREFACE

Lower shoreface trace fossil assemblages of the Mount Clark Formation are characterized by the proximal expression of the *Cruziana* Ichnofacies (*sensu* MacEachern and Pemberton, 1992; MacEachern and Bann, 2008). Ichnogenera observed include; deposit-feeding and mobile carnivore traces composed of shallowly tiered *Rusophycus, Planolites, Palaeophycus* and *Teichichnus;* intermediately tiered *Cylindrichnus, Rhizocorallium,* and *Chondrites; Asterosoma (*Fig. 3., Fig. 4: A-H). Subordinate numbers of semi-permanent, potentially filter-feeding domiciles are present, including *Skolithos, Diplocraterion*, and *Arenicolites (*Fig. 4: A-H). Trace fossils within the assemblage generally have large causative burrows, commonly exceeding 8 mm diameter. In addition, ichnofabrics extend more than 10 cm below the inferred water-sediment interface and Bioturbation Index (BI) routinely approach 2 to 6 (Fig. 4: D,H). Tempestite beds display erosionally based hummocky or low angle cross-stratified sands with *Skolithos*, *Cylindrichnus,* and *Diplocraterion* occupying the upper portion of the bed (Fig. 4: F): fugichnia are common in the tempestite beds (Fig. 3: E). Storm bed tops are bioturbated (BI 2-3) to a depth of up to 10 cm (Fig. 4: F).

The dominance of deposit-feeding behaviours with significant numbers of permanent dwelling structures and suspension-feeding structures suggests that although food resources were dominantly stored on, and within the sediment, persistent wave agitation above fair-weather wave base suspended food particles into the water column (MacEachern and Pemberton, 1992). This trace-fossil assemblage represents the ambient infaunal community that lived in the seafloor sediments between storm events. Tempestite bed colonization resulted from the settling of opportunistic organisms on storm-bed tops (Ekdale, 1985; Pemberton and MacEachern, 1997). As discussed below, the preserved ichnofabrics and the behaviors that are inferred for them are remarkably similar to shoreface-associated strata in much younger rocks.

UPPER SHOREFACE TO FORESHORE

Within the uppermost shoreface to foreshore, piperock composed of robust *Skolithos* and *Lingulichnus* (expressed by a *Skolithos*-*Lingulichnus* Ichnofabric) is observed (Fig. 4: J,K). These trace fossil assemblages correspond to the archetypal *Skolithos* Ichnofacies which represents dominantly suspension feeding behaviours in sandy shifting substrates (*sensu* MacEachern and Pemberton, 1992). Some *Lingulichnus* show equilibrichnia behaviors, such as spreite, which indicate vertical shifting of the tracemaker. Bioturbated intervals are commonly massive appearing, however, multidirectional trough cross-stratification, convolute bedding, dewatering structures and micro-faulting are also observed (Fig. 4: I).

Based on the presence of large *Skolithos* and *Lingulichnus* and locally complete mixing of the sediment, sedimentation rates are interpreted to have been low. The high degrees of bioturbation are coincident with a small increase in grain size, consistent with sedimentation and colonization of the proximal upper shoreface or foreshore (Fig. 3). The upper shoreface to foreshore environment landward of the sub-aqueous (i.e. breaker) bar is characterized by shifting sandy substrates in shallow waters (Reading and Collinson, 1996). Suspension-feeding animals depended upon food held in the water column (Howard, 1971; MacEachern and Pemberton, 1992). Equilibrium traces observed indicate an environment characterized by sporadic sedimentation events (Fig. 4: J) and subsequent post-storm re-establishment (MacEachern and Pemberton, 1992; Nara; 1995, 1997). The high intensities of bioturbation suggest that during fair-weather, rates of biogenic reworking exceeded rates of hydraulic reworking. As such, the shoreface profile is inferred to have been dissipative to intermediate (e.g. Hunter *et al.*, 1979; Leckie and Walker, 1982).

DISCUSSION

The concept of "Ichnofacies" was introduced decades ago (e.g., Seilacher, 1953, 1964, 1967). All of the original Ichnofacies were based on recurring associations of trace fossils that could be related to different sedimentary environments and bathymetry. Today, it is understood that ethology and their resultant ichnofossils are controlled by factors including, substrate consistency, sediment grain size, energy conditions, food resource type and availability, water salinity, sedimentation rates, oxygenation, and temperature (summarized in MacEachern *et al*., 2012). Ichnofacies are unlike biozones in that they transcend large spans of geologic time. However, archetypal Ichnofacies do not appear until the Phanerozoic (MacEachern *et al*., 2007). Although it has been reasoned that the Cambrian Explosion was accompanied by the Agronomic Revolution (e.g. Seilacher and Pflüger, 1994; Seilacher, 1999; Mangano *et al*., 2013), it is not clear how rapidly characteristic behavioral strategies were deployed in environmental niches, and ultimately expressed as archetypal Ichnofacies.

The Mount Clark Formation is an early example of the new divisions of labor that become prevalent later in the Phanerozoic (Fig. 3). Therein, bioturbate textures that result from characteristic resource exploitation — associated with the *Cruziana* Ichnofacies in the lower shoreface and *Skolithos* Ichnofacies in the foreshore — are observed. That these trace fossil assemblages lie within a shoreface succession is critical to their ethological interpretation. Unlike many other facies models, physical processes are highly inferable in shoreface deposits. As such, the interpreted ethological responses to sedimentary process are comparable to identical niches in younger strata, and in this example present a vertical succession that is ethologically identical to shoreface deposits today.

As with Mesozoic and Cenozoic shoreface deposits, the Cambrian offshore to lower shoreface is characterized by diverse and abundant deposit- and subordinate suspension-feeding strategies within variable substrates. In the proximal offshore to lower shoreface the Lower Cambrian has trace fossils that commonly occur in Mesozoic shorefaces, including *Arenicolites, Asterosoma, Chondrites, Cylindrichnus-Rosselia, Diplocraterion, Helminthopsis, Rhizocorallium, Palaeophycus, Phycodes* and *Teichichnus* (Fig. 3 & 5). These trace fossils represent the range of behaviours observed today in offshore through lower shoreface settings including, domichnia, filter feeding, carnivory, interface deposit feeding, deep-tier deposit feeding and spatially optimized deposit feeding (MacEachern and Pemberton, 1992; MacEachern *et al*., 2007) (Fig. 1 & 5).

Trace fossil occurrences in the upper shoreface are variable as a result of heterogeneous energy distributions and the presence of unidirectional currents. However, the shallow, shifting sands of the uppermost shoreface and foreshore locally contain *Lingulichnus, Skolithos* and fugichnia. The primary uses of *Lingulichnus* and *Skolithos* are filter feeding and as domiciles. Later Mesozoic and Cenozoic (dissipative) foreshore settings can similarly contain *Lingulichnus* (Triassic, Zonneveld and Pemberton, 2003), analogous bivalve-associated *Siphonichnus*, and *Skolithos*. Cenozoic shoreface deposits, in particular, may also contain *Macaronichnus* or *Ophiomorpha*, both of which are normally used for deposit feeding. Although filter-feeding ethologies can be assigned to the Lower Cambrian examples, deposit feeding within the shifting sediments of the foreshore evidently evolved later (Fig. 5).

The ichnological correspondence between this Cambrian shoreface and Cenozoic examples is surprising considering that the Mount Clark Formation was deposited perhaps as little as 25 Ma after the end of the Ediacaran Period. The early establishment of characteristic behavioural niches illustrates that the rise of animals was exceedingly rapid and that their ecological dominance in seafloor sediments perhaps preceded the Cambrian Explosion. Similarly, Buatois and Mangano (2004) showed that Shallow-marine ichnofaunas of the early Cambrian Puncoviscana Formation in northwest Argentina were dominated by moderate- to large-sized, shallow grazing and feeding traces of deposit feeders. Those authors suggested that the Agronomic Revolution occurred at a faster pace in shallow-water settings. Notably, bioturbated textures observed in the Mount Clark Formation mix sediment much deeper than in the Puncoviscana Formation, wherein grazing traces, such as *Multina* and *Nereites,* were emplace on or just below the sediment-water interface and more deeply emplaced deposit-feeding traces, such as *Teichichnus,* were absent. Early Cambrian strata of the Mackenzie Mountains in northwest Canada, as reported by Carbone and Narbonne (2014), show similar ichnological characteristics: an established but very shallowly emplaced deposit- and filter-feeding community generally occupying only the horizontal plane dimensions of ecological space. Interestingly, the shoreface-associated Moraine Lake Member of the St. Piran Formation in Alberta (Desjardin *et al*., 2010) and Brador Formation in Labrador (Hiscott *et al*., 1984) are similarly aged to the Mount Clark Formation, and although putatively filter-feeding assemblages associated with *Skolithos* are present in both, the lower shoreface-offshore assemblage is dominated by *Cruziana*, *Rusophycus* and *Bergauraria.*

From early Cambrian strata, the most similar examples of comparable deposit-feeding assemblages were reported from the Desejosa Formation (Dias Da Silva et al., 2014), and the Mickwitzia sandstone (Jensen, 1997). Dis Da Silva *et al*. (2014) documented *Rosselia* and *Teichichnus* as constituents of the Cruziana Ichnofacies from a shallow-marine depositional environment. Although similar, this occurrence lacks the depth of mixing (generally less than 10 cm), the causative burrows within the trace fossils are smaller than 4 mm diameter, and the overall diversity of grazing animals is lower than in the Mount Clark Formation examples. The maximum depositional age of these measures is 549.6 ± 4.4 MMa (detrital zircons, Pereira *et al*., 2012) but otherwise the age of these strata are difficult to establish: Dias Da Silva *et al*. (2014) suggested Cambrian Age 3 on the basis of the occurrence of *Rosselia*. Jensen (1997) reported a diverse assemblage of trace fossils that represent Pascichnia, Repichnia, Cubichnia and Praedichnia. The ichnodiversity exceeds that of the Mount Clark Formation, but shoreface-associated parts of the Mickwitzia sandstone display far more limited ichnodiversity.

The ichnofabrics presented here provide a stark comparison to the shallowly tiered, two-dimensional bedding plane associated behaviors that typify Lower Cambrian ecosystems. In fact, recent efforts have suggested that deep sediment mixing (e.g. >4 cm), dominated by complex and highly varied feeding and bulldozing behaviors that exemplify upper Paleozoic and Mesozoic Ichnofacies (Tarhan *et al*., 2015), do not become widespread until early Ordovician. The ichnological observations from the Mount Clark Formation, particularly the diversity of ichnofossils and the depth of bioturbation, are clearly at odds with that contention. However, Tarhan *et al* (2015) database focused dominantly on shelfal units where biomat stabilization or perhaps lower dissolved oxygen contents might have played an important role in mitigating animal colonization into the later Paleozoic.

Mangano and Buatois (2014) have recently provided evidence that by Cambrian Stage 1, sediment bulldozing (i.e. rudimentary, shallow-tier grazing) in diffusion-dominated benthic systems gave way to the suspension feeding patterns of advection-dominated benthic systems associated with Cambrian Stage 2 and Stage 3. Subsequently, the suspension-dominated assemblages better irrigated bottom sediments, promoting the evolution of systematic deposit-feeding ethologies. Although some aspects of our research support this contention, we believe that the Mount Clark Formation trace-fossil assemblages show a clear demarcation between ethology and food-resource partitioning, suggesting that the behavioral styles evolved independently.

In general, we disagree that filter feeding prepared Cambrian sedimentary ecosystems for deposit feeding behaviors because of the slow rates of sediment advection ascribed to sessile filter feeding (<1 cm^3 / day) *versus* deposit feeding (<10 cm^3 / day) (Gingras *et al*, 2008). Regarding the general concept of filter feeding resulting in oxygenation of the sediment in preparation for deposit feeding animals, the modern suggests that deposit feeding is a routine occurrence in suboxic sediments so long as animals can sporadically access O_2 resources (Gingras *et al*., 2007).

Earlier efforts (e.g. Butterfield, 2003; Meysman *et al*., 2006; Mangano and Buatois, 2014) also suggest that trace-fossil data is coordinated with the Cambrian explosion, but we view this from another vantage. Based on the later occurrence in the rock record of body fossils and the early occurrence of these very well-established niche-exploiting communities, it is more likely that behavioural diversification was a prerequisite condition for the rapid morphological changes associated with the Cambrian Explosion. In particular, the diversity of deposit-feeding behaviours, their spatial dominance and their size and depth of penetration, collectively point towards rapid ethological diversification resulting from early success in bulldozing and then systematic deposit feeding within rich and hitherto then, unexploited food resources.

CONCLUSIONS

This study provides strong evidence for the establishment of archetypal Ichnofacies / ethological assemblages in well-documented storm-dominated shoreface deposits of the early Cambrian Mount Clark Formation (521 m.y.- 514 m.y.). The reported trace fossil assemblages are ~30 m.y. older than otherwise known. The results show that early Cambrian ichnofaunas have greater potential for ethological adaptation than previously understood and by the early Cambrian behaviors radiated into energy partitioned feeding niches. Early Cambrian ichnofauna described herein were capable of significantly reworking tempestite beds, which leads us to contend with the assertion that early Cambrian deposit feeding behaviors were limited to shallow-tiers and unable to sufficiently mobilize rapidly deposited sediment. Taken as a whole, the Mount Clark Formation trace fossils show derived adaptations within characteristic shoreface niches that are ethologically identical to trace fossil assemblages observed in Upper Paleozoic, Mesozoic and Cenozoic shoreface deposits. This early establishment of two of the archetypal Ichnofacies presents two competing hypothesis: (1) morphological adaptation precedes established ages for the Cambrian explosion and reaches deeper in time than the Chengjiang biota (Zhang *et al*., 2008) and the Burgess Shale; or, (2) ethological diversification preceded morphological adaptation and the partitioning of animals into favoured feeding niches facilitated subsequent morphological radiations, laying the foundation for the Cambrian explosion.

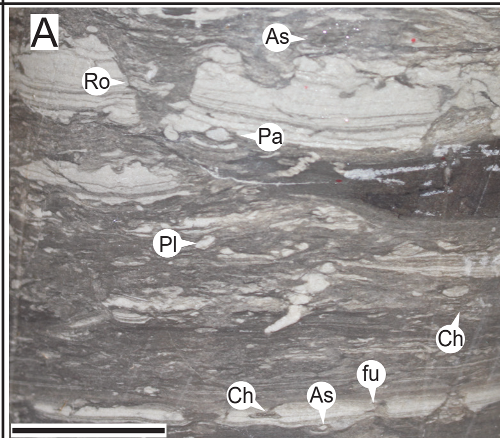
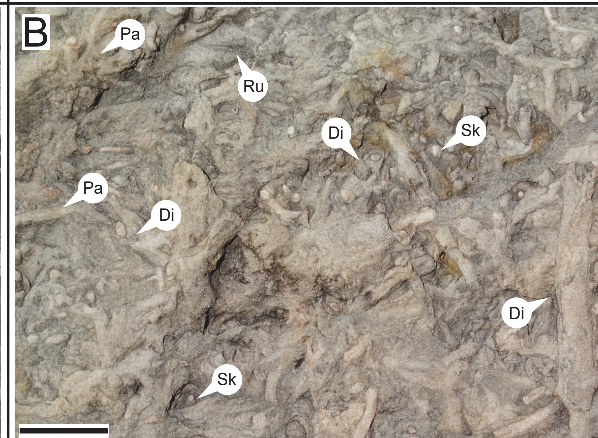
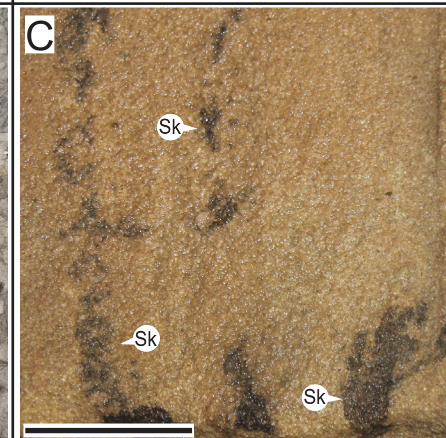
Facies	Offshore	Lower Shoreface	Upper Shoreface-Foreshore
Example Photos			
Trace Fossils	*Planolites (Pl), Palaeophycus (Pa), Asterosoma (As), Chondrites (Ch), Rosselia (Ro), Teichichnus (Te), Phycodes (Py),* fugichnia (fu), equilibrichnia (eq)	*Rhizocorallium (Rh), Diplocraterion (Di), Asterosoma (As), Phoebichnus (Po), Teichichnus (Te), Rosselia (Ro), Arenicolites (Ar), Planolites (Pl), Rusophycus (Ru), Palaeophycus (Pa), Chondrites (Ch)*	*Skolithos (Sk), Lingulichnus (Li)*: "Piperock" Assemblages
Lithology and Sedimentary Structures	Intercalated fine-grained sands and muds with sharp-based micro humocky and low-angle cross-stratification	Fine grained sand with frequent sharp based beds of hummocky and low angle cross-stratification	Medium grained sand with trough cross-stratification, microfaulting, and convolute bedding
Comments	Tempestites common, expressing "lam-scram" fabrics	Fair and storm-weather conditions preserved in bioturbated and cross-stratified horizons respectively	Piperock placed in the protected trough landward of a sub-aqueous longshore bar
Depositional Environment	Storm-Influenced Offshore	Storm-Influenced Lower Shoreface	Upper Shoreface to Foreshore

Table 4.1: Integrated facies association table. Offshore to foreshore environments with characteristic photos, trace fossils, and sedimentary constituents. Scale bar = 3cm in all three photos.

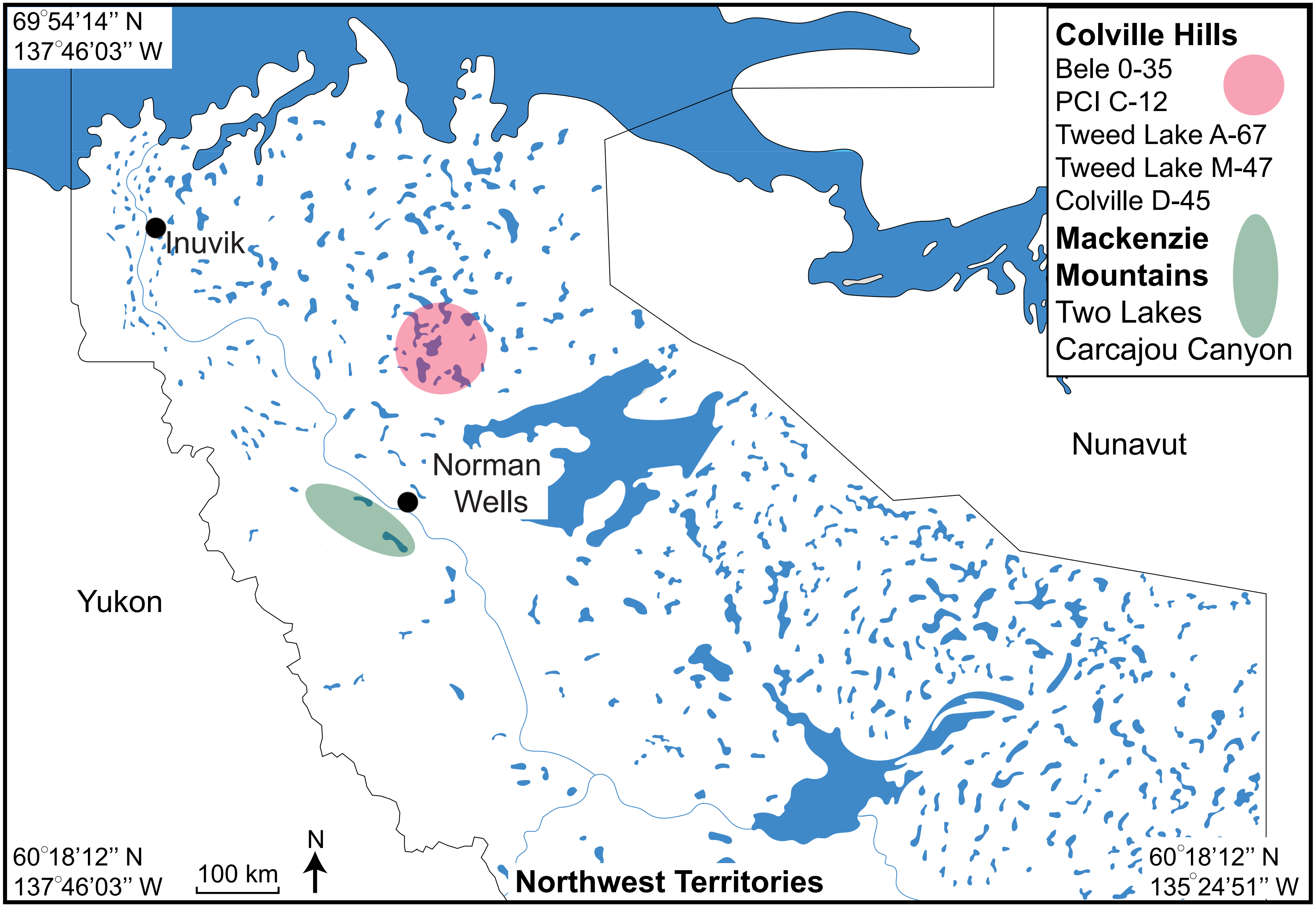
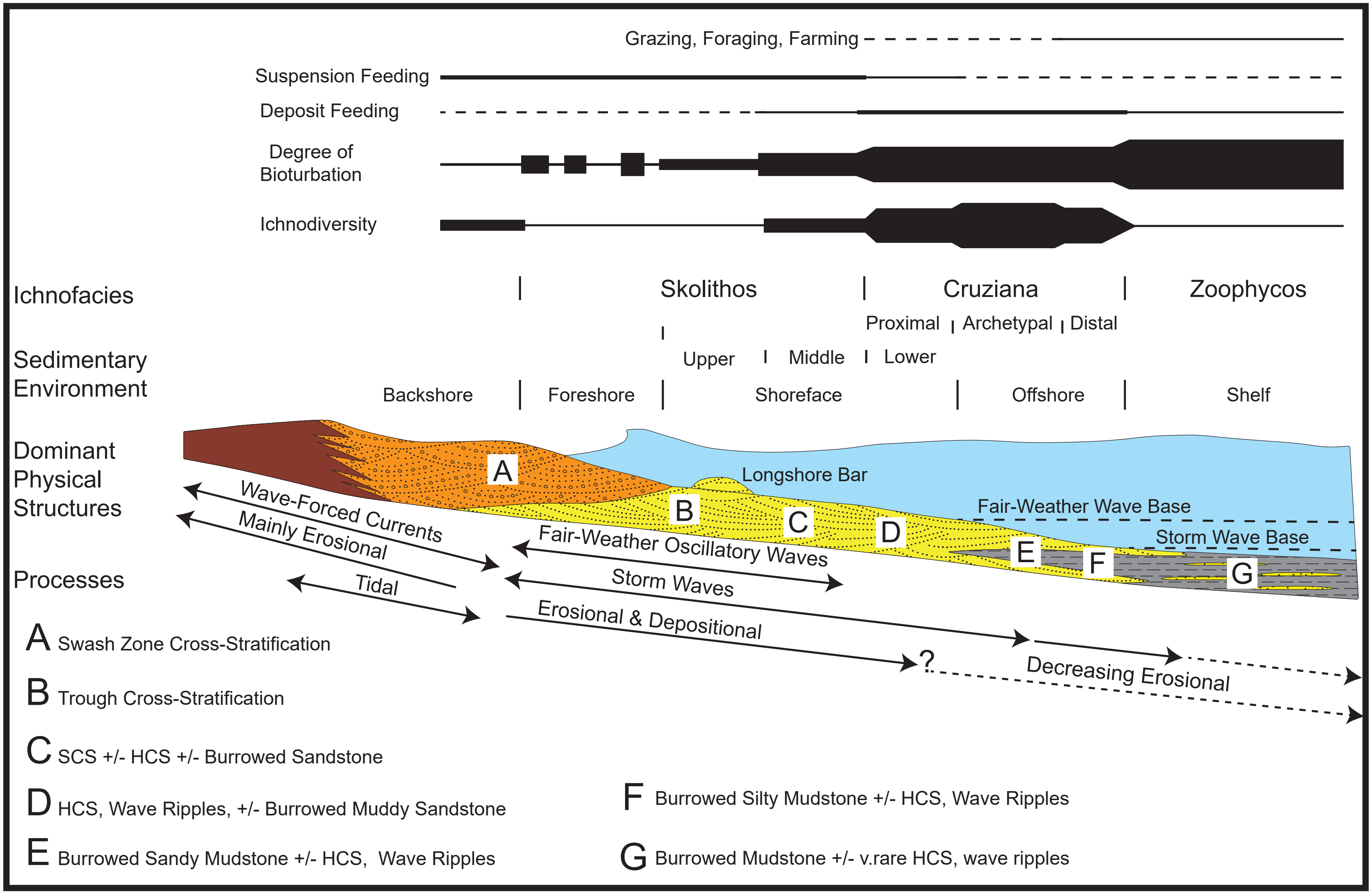

69°54'14'' N
137°46'03'' W
Colville Hills
Bele 0-35
PCI C-12
Tweed Lake A-67
Tweed Lake M-47
Colville D-45
Mackenzie
Mountains
Two Lakes
Carcajou Canyon
Inuvik
Norman
Wells
Nunavut
Yukon
60°18'12'' N
137°46'03'' W
100 km
N
Northwest Territories
60°18'12'' N
135°24'51'' W

Figure 4.1: Location map of the study areas. Location map showing the study area with the two datasets of Colville Hills and Mackenzie Mountains shaded. Latitude and longitude coordinates correspond to the map corners. Modified from Google Earth Pro.



Grazing, Foraging, Farming
Suspension Feeding
Deposit Feeding
Degree of Bioturbation
Ichnodiversity
Ichnofacies
Skolithos
Cruziana
Zoophycos
Proximal
Archetypal
Distal
Sedimentary Environment
Upper
Middle
Lower
Backshore
Foreshore
Shoreface
Offshore
Shelf
Dominant Physical Structures
A
Longshore Bar
B
C
D
Fair-Weather Wave Base
Storm Wave Base
E
F
G
Wave-Forced Currents
Mainly Erosional
Tidal
Fair-Weather Oscillatory Waves
Storm Waves
Erosional & Depositional
?
Decreasing Erosional
Processes
A Swash Zone Cross-Stratification
B Trough Cross-Stratification
C SCS +/- HCS +/- Burrowed Sandstone
D HCS, Wave Ripples, +/- Burrowed Muddy Sandstone
E Burrowed Sandy Mudstone +/- HCS, Wave Ripples
F Burrowed Silty Mudstone +/- HCS, Wave Ripples
G Burrowed Mudstone +/- v.rare HCS, wave ripples

Figure 4.2: Integrated ichnological and sedimentological characteristics of a wave/storm-dominated shoreface. Modified from Buatois and Mangano (2011) based on MacEachern *et al*. (1999).

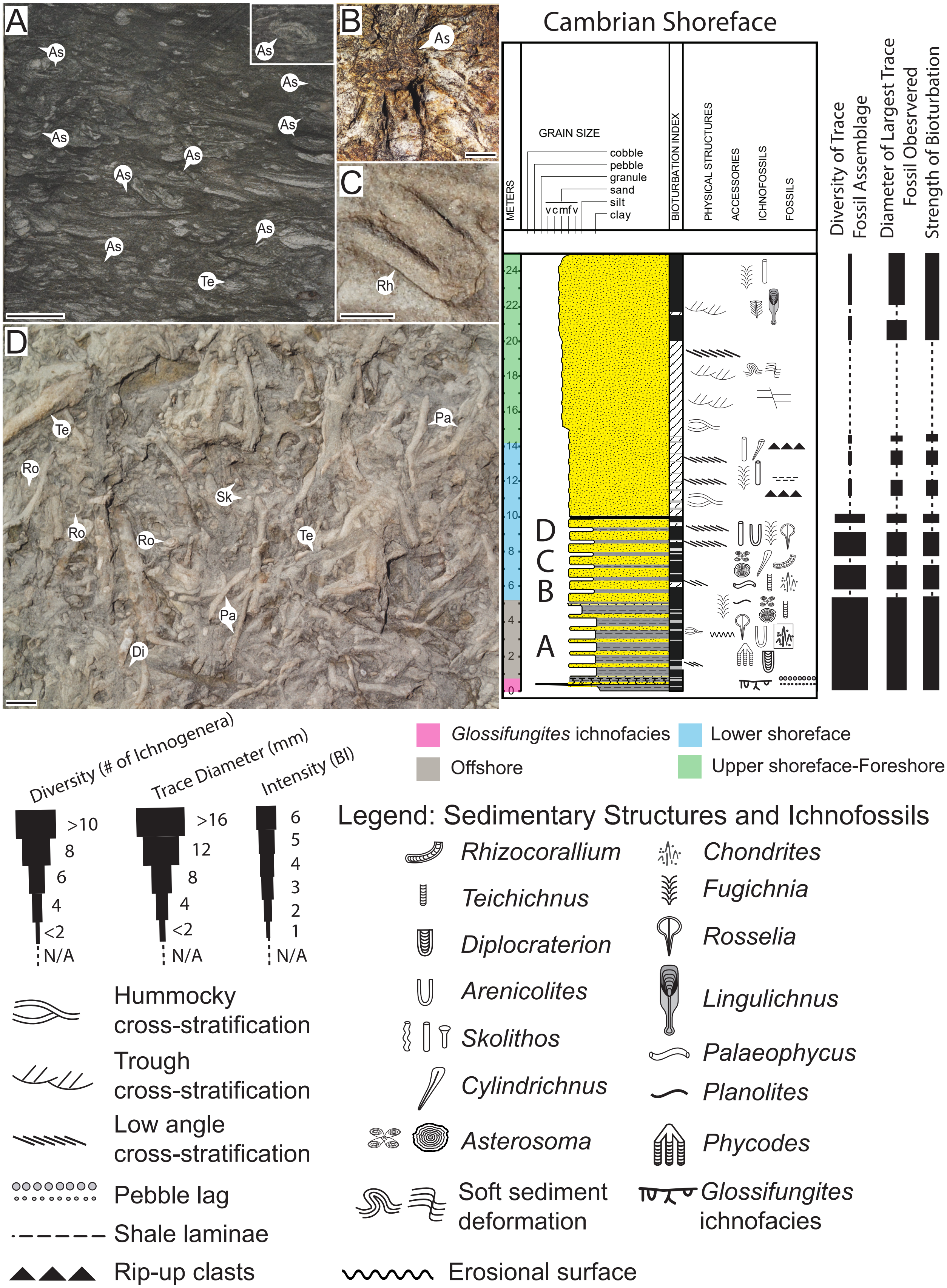

A
B
C
D
As
Te
Rh
Pa
Ro
Sk
Di
Cambrian Shoreface
METERS
GRAIN SIZE
cobble
pebble
granule
sand
silt
clay
v c m f v
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FOSSILS
0
2
4
6
8
10
12
14
16
18
20
22
24
Diversity of Trace Fossil Assemblage
Diameter of Largest Trace Fossil Obesrvered
Strength of Bioturbation
Glossifungites ichnofacies
Lower shoreface
Offshore
Upper shoreface-Foreshore
Diversity (# of Ichnogenera)
>10
8
6
4
<2
N/A
Trace Diameter (mm)
>16
12
8
4
<2
N/A
Intensity (BI)
6
5
4
3
2
1
N/A
Legend: Sedimentary Structures and Ichnofossils
Rhizocorallium
Teichichnus
Diplocraterion
Arenicolites
Skolithos
Cylindrichnus
Asterosoma
Soft sediment deformation
Chondrites
Fugichnia
Rosselia
Lingulichnus
Palaeophycus
Planolites
Phycodes
Glossifungites ichnofacies
Hummocky cross-stratification
Trough cross-stratification
Low angle cross-stratification
Pebble lag
Shale laminae
Rip-up clasts
Erosional surface

Figure 4.3: Early Cambrian Composite Log illustrating ichnological and sedimentological aspects of Mount Clark Shoreface Deposition. Scale bar is 1cm in all photos. Modified AppleCore© logs with annotated depositional environments.

A) Offshore lithologies consisting of heavily bioturbated (BI 5) sandy silty mudstones. *Asterosoma* (As) and *Teichichnus* (Te). Remnant sandstone lamination interpreted to represent distal tempestite deposition. Colville D-45.
B) Bedding plane photograph of ?*Asterosoma* (As) in lower shoreface sandstone deposits at Carcajou Canyon.
C) Bedding plane photograph of *Rhizocorallium* (Rh) in lower shoreface sandstone deposits at Carcajou Canyon.
D) Bedding plane photograph of highly bioturbated (BI 5) lower shoreface deposits at Carcajou Canyon illustrating a high diversity and abundance of ichnofossils. *Teichichnus* (Te), *Rosselia* (Ro), *Skolithos* (Sk), *Palaeophycus* (Pa), and *Diplocraterion* (Di).

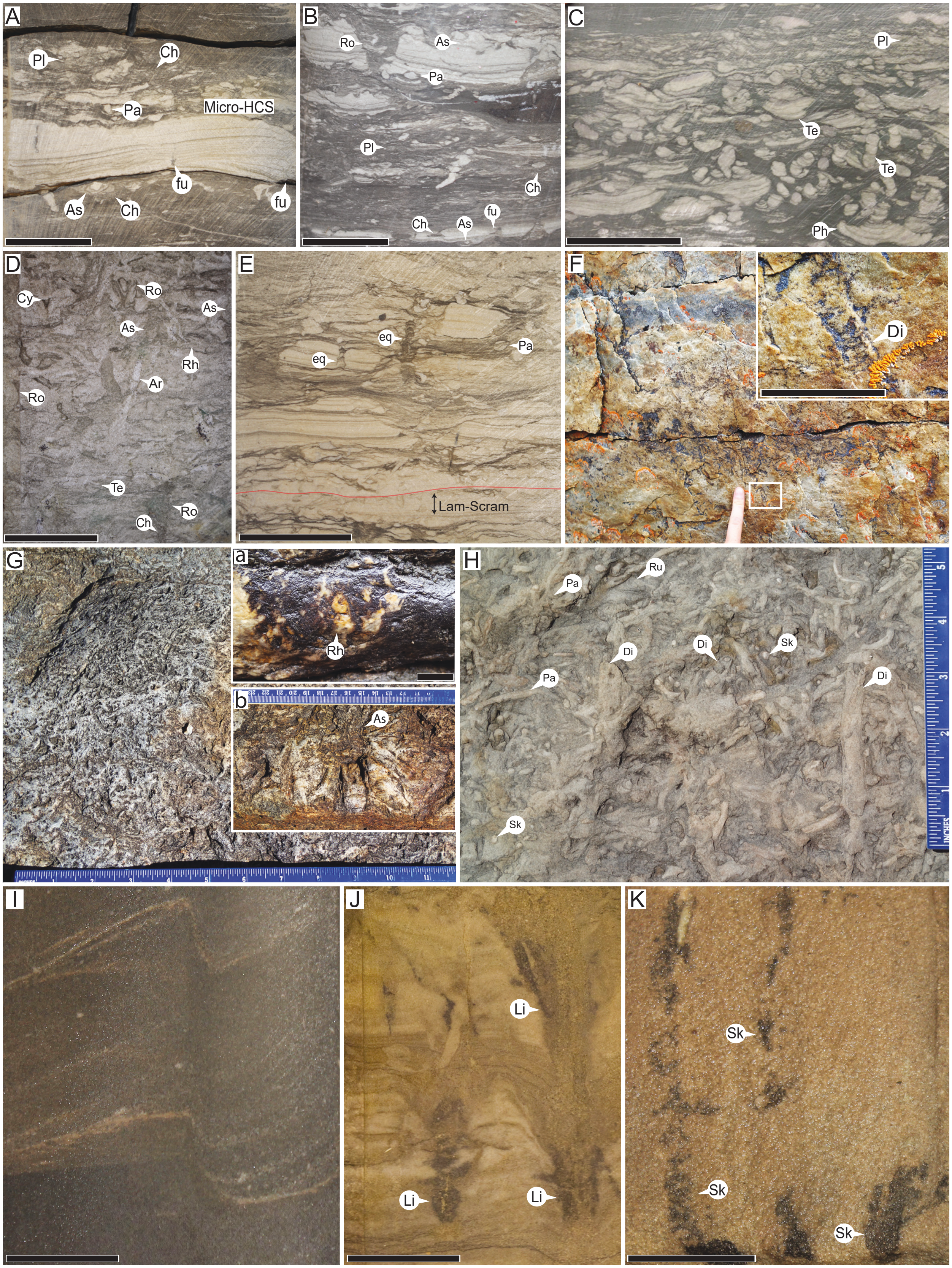

A
Pl
Ch
Pa
Micro-HCS
fu
As
Ch
fu
B
Ro
As
Pa
Pl
Ch
fu
Ch
As
C
Pl
Te
Te
Ph
D
Cy
Ro
As
As
Rh
Ar
Ro
Te
Ro
Ch
E
eq
eq
Pa
Lam-Scram
F
Di
G
a
Rh
b
As
H
Ru
Pa
Di
Di
Sk
Pa
Di
Sk
INCHES
I
J
Li
Li
Li
K
Sk
Sk
Sk

Figure 4.4: Representative facies plate of Cambrian shoreface deposition. Where present scale bars = 3 cm.

A) Distal biogenically reworked sandy tempestite bed within offshore mudstones. Depositional hydraulic currents great enough to produce Micro Hummock Cross-Stratification (HCS). Note upper portion of tempestite bed has been biogenically reworked from the original bed resulting in bed disintegration; fugichnia (fu), *Asterosoma* (As), *Chondrites* (Ch), *Palaeophycus* (Pa). Tweed Lake M-47.

B) Multiple intensely biogenically reworked distal sandy tempestite within offshore mudstones. Lamination seen in sand bed that has been disrupted through bioturbation. Trace fossils consist of fugichnia (fu), *Asterosoma* (As), *Palaeophycus* (Pa), *Teichichnus* (Te), *Rosselia* (Ro), *Planolites* (Pl). Tweed Lake A-67.

C) Offshore sandy mudstones intensely bioturbated with *Teichichnus* (Te) *Palaeophycus* (Pa), and *Phycodes (Py)*. Tweed Lake A-67.

D) Lower shoreface intensely bioturbated muddy sandstones with a diverse fair-weather trace fossil assemblage. *Rosselia (Ro), Asterosoma (As), Rhizocorallium (Rh), Cylindrichnus (Cy), Arenicolites (Ar), Chondrites (Ch), Teichichnus (Te), Palaeophycus (Pa).* Typical of the Cruziana Ichnofacies. PCI C-12.

E) Lower shoreface deposits featuring biogenically reworked amalgamated tempestite beds featuring Lam-Scram indicating frequent storm activity. Frequent equilibrichnia (*eq*) indicate rapid sedimentation rates in which a burrowing organism moved upward through the substrate. Red line illustrates the top of a lam-scram sequence. Tweed Lake M-47.

F) Lower shoreface storm colonization trace fossil suite within an HCS bed. Blue inset looks at a penetrative *Diplocraterion*, an r-selected ichnotaxa. Two Lakes outcrop.

G) Bedding plane photo of the intensely bioturbated (BI 5) lower shoreface fair-weather deposits. Inset images of a) *Phoebichnus* (Po) and b) *Rhizocorallium* (Rh).

H) Intensely bioturbated (BI 6) Fair-weather trace fossil assemblages of FA *Palaeophycus (Pa), Cylindrichnus (Cy), Diplocraterion (Di), Skolithos (Sk), Rusophycus (Ru).*

I) Upper shoreface decimeter scale bed sets of trough cross-stratified sands interpreted to be the result of large sub-aqueous 3-D dune migration. Tweed Lake A-67.

J) Piperock of consisting of large *Lingulichnus (Li)* traces showing equilibrium adjustments. Tweed Lake A-67.

K) Piperock consisting of large oil stained *Skolithos* (*Sk*) in upper medium sandstone. Tweed Lake A-67.

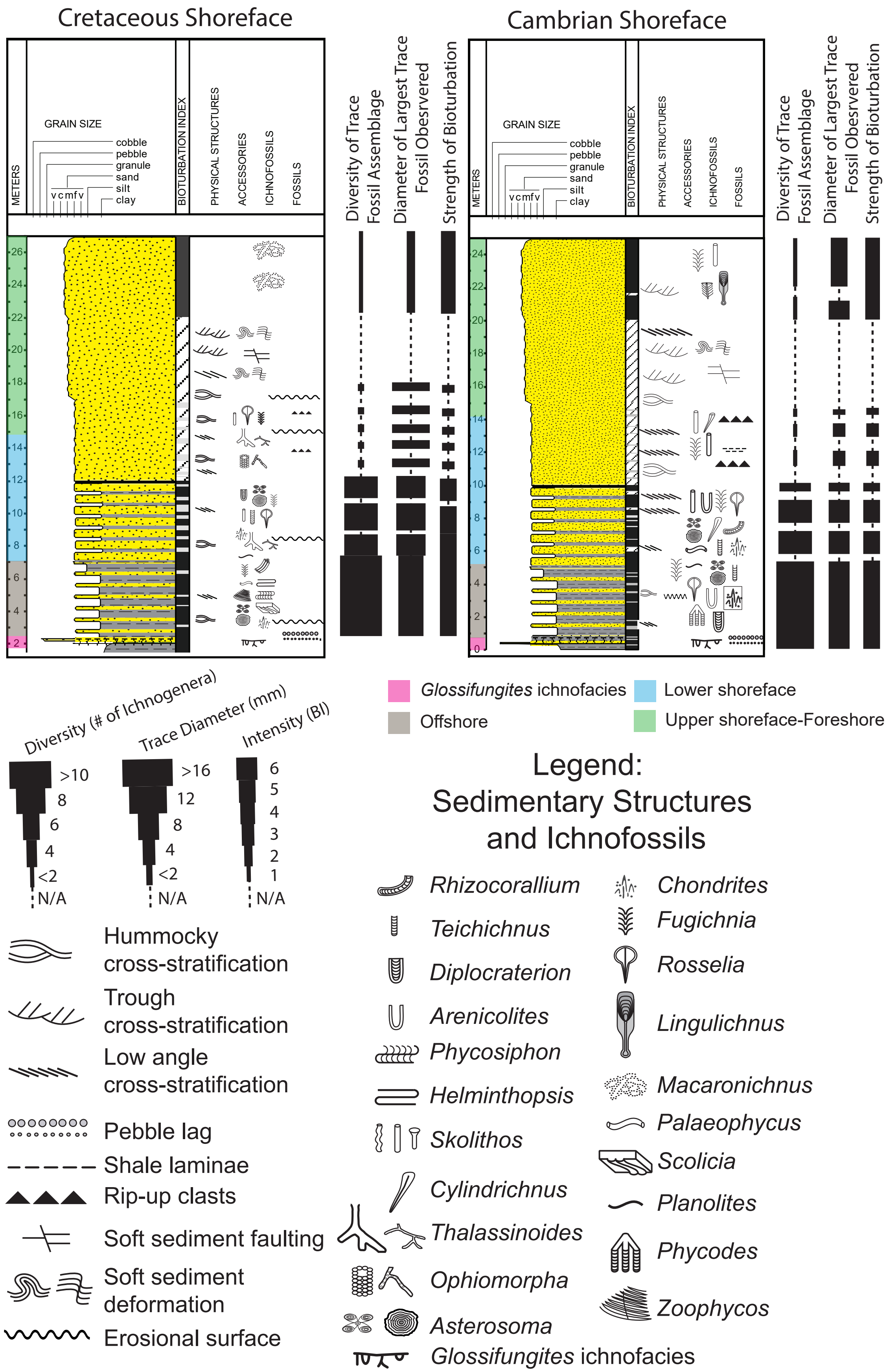

Cretaceous Shoreface
Cambrian Shoreface
METERS
GRAIN SIZE
cobble
pebble
granule
sand
silt
clay
v c m f v
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FOSSILS
Diversity of Trace Fossil Assemblage
Diameter of Largest Trace Fossil Obesrvered
Strength of Bioturbation
Glossifungites ichnofacies
Offshore
Lower shoreface
Upper shoreface-Foreshore
Diversity (# of Ichnogenera)
Trace Diameter (mm)
Intensity (BI)
>10
8
6
4
<2
N/A
>16
12
8
4
<2
N/A
6
5
4
3
2
1
N/A
Legend:
Sedimentary Structures and Ichnofossils
Hummocky cross-stratification
Trough cross-stratification
Low angle cross-stratification
Pebble lag
Shale laminae
Rip-up clasts
Soft sediment faulting
Soft sediment deformation
Erosional surface
Rhizocorallium
Teichichnus
Diplocraterion
Arenicolites
Phycosiphon
Helminthopsis
Skolithos
Cylindrichnus
Thalassinoides
Ophiomorpha
Asterosoma
Glossifungites ichnofacies
Chondrites
Fugichnia
Rosselia
Lingulichnus
Macaronichnus
Palaeophycus
Scolicia
Planolites
Phycodes
Zoophycos

Figure 4.5: Cretaceous and Cambrian type shoreface profiles with typical ichnogenera, sedimentary structures, and annotated environments. Trace fossil size, diversity, and bioturbation intensity plotted alongside each log. Modified AppleCore© logs.

CHAPTER 5: SUMMARY AND CONCLUSIONS

The early Cambrian (*Bonnia-Olenellu*s trilobite zone, 520-514 m.y.) Mount Clark Formation within the Colville Hills and Mackenzie Mountains of the Northwest Territories (NWT) represents a variety of complex depositional systems punctuated by varying degrees of wave, tide, and storm influence. Difficulty in identifying these ancient environments is further compounded by a lack of integrated ichnological and sedimentological models for early Cambrian ecosystems. This thesis identifies the stratigraphic architecture and depositional systems of the poorly understood Mount Clark Formation within the Colville Hills and Mackenzie Depocenter. The paleo-evolutionary aspects of the Cambrian Explosion are explored through exceptionally preserved trace fossil assemblages.

Chapter 2 focuses on a detailed facies analysis of the Mount Clark Fm subsurface core located within the Colville Hills, NWT. Data collected for this study includes four cores (Tweed Lake A-67 & M-47, PCI C-12, and Bele O-35) with supplementary wireline logs. The Mount Clark Fm is a proven hydrocarbon reservoir within the Colville Hills and this study seeks to give a detailed sedimentological analysis of reservoir geo-bodies. Detailed documentation consisted of: lithology, the nature of bed contacts, sedimentary structures, lithologic accessories, body fossils, grain-size, and hydrocarbon staining. Ichnological observations included individual trace fossils, distribution, trace fossil size, diversity, bioturbation intensity, trace fossil deformation, and trace fossil assemblages. In order to visualize bioturbation trends plots were constructed illustrating trace fossil size, diversity, and bioturbation intensity. Observations present a strongly storm-influenced wave dominated barred shoreface succession. Piperock assemblages of *Skolithos* and *Lingulichnus* are interpreted to represent shallow post-bar to foreshore environments, a documentation of piperock outside the tidally dominated sand sheets of previous piperock studies (Hallam and Swett, 1966; Droser, 1991; Desjardins *et al*., 2010).

Chapter 3 contains an outcrop study of the Mount Clark Fm centered within the Mackenzie Mountains on the edge of the Mackenzie Depocenter. Three siliciclastic outcrops (Carcajou Canyon, Two Lakes, and Waterfall Ridge) were chosen along a depositional strike of 65 km. Detailed documentation consisted of: lithology, the nature of bed contacts, sedimentary structures, lithologic accessories, body fossils, grain-size, and hydrocarbon staining. Ichnological observations included individual trace fossils, distribution, trace fossil size, diversity, bioturbation intensity, trace fossil deformation, and trace fossil assemblages. In order to visualize bioturbation trends plots were constructed illustrating trace fossil size, diversity, and bioturbation intensity. UAV acquired images allowed the creation of 3-D outcrop mosaics, allowing a better visualization and understanding of bed scale relationships. This results in a complex lateral distribution of depositional elements on a basin scale with three main depositional hierarchies observed: 1) waves/storm-dominated shorefaces; 2) wave-dominated deltaic complexes; and 3) tidally dominated sand sheet embayments. This work illustrates integrated sedimentological and ichnological facies models for early Cambrian shoreface and deltaic successions illustrating the robustness of ichnofacies even dating back to the early Cambrian.

Chapter 4 characterizes the trace fossil assemblages and subsequent behaviors that were present in the early Cambrian at the onset of the Cambrian Explosion. The early Cambrian represents a crucial and poorly understood time in earth’s history in which complex life was first evolving and colonizing shallow marine niches. This study provides strong evidence for the establishment of archetypal Ichnofacies / ethological assemblages in well-documented storm-dominated shoreface deposits of the early Cambrian Mount Clark Formation (521 m.y.- 514 m.y.). The reported trace fossil assemblages corresponding to archetypal vermiform dominated *Cruziana* and *Skolithos* Ichnofacies are ~30 m.y. older than otherwise known. The results show that early Cambrian ichnofaunas have greater potential for ethological adaptation than previously understood and by the early Cambrian behavioral radiation into energy partitioned feeding niches. Early Cambrian ichnofauna described here were capable of significantly reworking tempestite beds, which leads us to contend with the assertion that early Cambrian deposit feeding behaviors were limited to shallow-tiers and unable to sufficiently mobilize rapidly deposited sediment. Taken as a whole, the Mount Clark Formation trace fossils show derived adaptations within characteristic shoreface niches that are ethologically identical to trace fossil assemblages observed in Upper Paleozoic, Mesozoic and Cenozoic shoreface deposits.

In short this thesis represents an in-depth analysis of the poorly understood Mount Clark Formation of the mainland Northwest Territories, shedding light on an interval of academic and industry interest. The Mount Clark records a variety of depositional systems within the Colville Hills and Mackenzie Depocenter. Trace fossil assemblages comprise of complex, diverse, robust, and multi-tiered behaviors that were previously unknown in the early Cambrian and represent the earliest known occurrence of characteristic shoreface ethological niches.

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