SUBSURFACE ANALYSIS AND CORRELATION OF CAMBRIAN FORMATIONS BENEATH THE COLVILLE HILLS, NORTHERN MAINLAND, NORTHWEST TERRITORIES

By

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ABSTRACT

The Lower and Middle Cambrian succession in the Colville Hills region, Northwest Territories consists of the Mount Clark, Mount Cap and Saline River Formations, which were deposited in an epicontinental basin. Significant research had been conducted over the last hundred years to better understand the stratigraphy of the region. To further these efforts, a high-resolution facies analysis that included ichnology, in addition to updated lithostratigraphic and sequence stratigraphic frameworks were required. To achieve this object, sedimentological and ichnological data was acquired from 10 drill cores, in conjunction with wireline data and geological reports from 45 wells that were used for correlations within an area approximately 300,000 km^2. Twenty distinct facies were observed and categorized into 4 facies associations: FA1 storm-influenced shoreface, FA2 fairweather shoreface, FA3 offshore and FA4 carbonate ramp. FA1 tended to preserved primary sedimentary structures with absent to minimal bioturbation suggesting ichnologically stressed environments during deposition, while FA2 recorded abundant bioturbation and relatively high ichno-diversity. A lithostratigraphic and sequence stratigraphic framework of the Lower and Middle Cambrian succession was then constructed, consisting of the Mount Clark and lower Mount Cap Formations. At the base of the Cambrian is a regional-scale sequence boundary, the sub-Cambrian unconformity. Up-section, three maximum transgressive surfaces and three maximum regressive surfaces were identified, resulting in three T-R cycles.

PREFACE

This thesis is an original work by Matthew Sommers. No part of this thesis has been previously published.

DEDICATION

To my mother, Heather, my grandmother, Susan, my Uncle, Doug and my girlfriend, Simone, I dedicate this thesis to you as your never-ending love, support and encouragement has been nothing short of incredible! Mom, I am forever indebted to you for your love, generosity, and patience, and am incredibly blessed to have you as my parent and role model. There are no words to express the sacrifices you have made in your life so that I may better my own. You have always pushed me to be a smarter, stronger person and this thesis is but a sliver of a lifetime's worth of encouragement you have so courageously provided. Simone, your love, understanding, care and support helped me immensely. I'm incredibly proud and honoured to be by your side.

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Of course there are so many to thank from the Ichnology Research Group. First a big thanks to David Herbers for getting me up and running on everything he knew about the Mount Clark. Thanks to Carolyn Furlong for many discussions on how to pretty-up figures and providing so much feedback on my thesis. Thanks to Alina Schepetkina for answering my elementary ichnology questions and taking us for coffee and cookies. Thanks to Eric Timmer, Donald Prenoslo and Derek Hayes for encouraging Friday beers and crib time. Thanks to Brette Harris and Maya LaGrange for helping organize our incredible trip to France and always willing to chat about what amazing things there are to be eaten. Thanks to Reed Myers for educating me on all things fish and aquarium related. Thanks to Aimee Gegolick for your patience and guidance while teaching Illustrator.

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LIST OF SYMBOLS AND ABBREVIATIONS

ICHNOFOSSILS

At	*Altichnus*
Ar	*Arenicolites*
As	*Asterosoma*
Ch	*Chondrites*
Cy	*Cylindrichnus*
Di	*Diplocraterion*
Eq	Equilibrichnia
fu	fugichnia
Li	*Lingulichnus*
Pa	*Palaeophycus*
Pl	*Planolites*
Rh	*Rhizocorallium*
Sk	*Skolithos*
Te	*Teichichnus*

FACIES/SEDIMENTOLOGY

FA1	Facies Association 1
FA2	Facies Association 2
FA3	Facies Association 3
FA4	Facies Association 4
HCS	Hummocky Cross-Stratification
SYN	Synaeresis Cracks
PYR	Pyrite

SEQUENCE STRATIGRAPHY

SB	Sequence Boundary
BSFR	Basal Surface of Forced Regression
CC	Correlative Conformity
MRS	Maximum Regressive Surface
MFS	Maximum Flooding Surface
WRS	Wave Ravinement Surface
FS	Flooding Surface
HST	High Stand Systems Tract
LST	Low Stand Systems Tract
TST	Transgressive Systems Tract
FSST	Falling-Stage Systems Tract
NR	Normal Regression
FR	Forced Regression

CHAPTER 1: INTRODUCTION

The Lower and Middle Cambrian succession in the Colville Hills area, Northwest Territories is composed of Mount Clark, Mount Cap and Saline River formations (Figure 1-1) which were described first by Williams (1922, 1923) in outcrop nearly one hundred years ago. Since then, considerable efforts have been put forth to better understand the stratigraphy and evolution of the subsurface Cambrian Basin and to exploit an estimated one billion barrels of oil and 10.8 TCF of gas locked in the subsurface of the Interior Plains Province (Hannigan et al., 2011). Despite these substantial reserves, only regional-scale research had been publicly available, which unfortunately lacked high-resolution facies analysis incorporating ichnology observations and detailed basin reconstruction using sequence stratigraphy modelling (Aitken et al., 1973; MacQueen and Mackenzie, 1973; Meijer Drees, 1974; Williams, 1987; Hamblin; 1990; Pugh, 1993; Dixon, 1997; Dixon and Stasiuk, 1998; Janicki, 2004, MacLean, 2011). Moreover, since the latest publications additional subsurface data had become available thanks to the efforts of an ever-curious petroleum industry.

Cambrian deposits in Colville Basin were formed in a semi-enclosed, epicontinental environment as significant quantities of siliciclastics entered a shallow sea. Laurentia (ancestral North America) was located at the equator (Figure 1-2), rotated 90 degrees clock-wise from present day, and had just rifted from Rodinia resulting in the basal unconformity of the Sauk Sequence and continued subsidence (Sloss, 1963; Dixon and Stasiuk, 1998; Pyle, 2012). Global greenhouse conditions began in the Middle Cambrian causing eustatic sea level to rise, which in conjunction with syndepositional normal faulting, allowed for a large increase in accommodation space in the

Colville Basin (Bond and Kominz, 1984; Scotese and McKerrow, 1990; Levy and Christie-Blick, 1991; MacLean, 2011).

Accurately reconstructing specific paleo-environments is greatly enhanced when taking into account both physical sedimentology (for example, lithology, grain size and sorting, sedimentary structures) and ichnology observations (for example, bioturbation intensity, ichnogenera, ichno-diversity) (Seilacher, 1978; Pemberton et al., 1992a; MacEachern and Bann, 2008; MacEachern, et al., 2010). Additionally, ichnology has become a tool for better understanding physical and chemical variables on an ecosystem at the time of deposition, and post-deposition (Gingras et al., 2011). Using these interpreted paleoenvironments in a sequence stratigraphic model can illustrate the changes of sedimentation rates, base level and tectonism within a basin through time (Catuneanu, 2006; Catuneanu et al., 2009).

This study used prior foundational research in addition to 10 drill cores and 45 wells with a host of petrophysical wireline logs, well reports of cuttings, and striplogs across a study area nearly 300,000 Km^2 in size (Figure 1-3). In core, a total of 20 facies were documented within the Mount Clark, Mount Cap and Saline River formations. Individual facies were based on lithology, grain-size, primary sedimentological character and ichnological character. Facies associations and sequence stratigraphic surfaces were correlated across the study area from cored wells to non-cored wells using wireline.

Chapter 2 focuses on the 10 drill cores that cover formations from the Precambrian to the Saline River. Only the Mobil E-15 core covered this entire interval while the remaining 9 cores generally focused on the reservoir rocks of the Mount Clark. The dataset yielded a complex vertical succession preserving four distinct facies associations: Storm-Influenced Shoreface (FA1), Fairweather Shoreface (FA2), Offshore (FA3) and Carbonate Ramp (FA4).

Chapter 3 uses the high-resolution facies analysis from core and extrapolates those observations across the basin using wireline logs, drill cuttings and striplogs. Applying both lithostratigraphic and T-R Sequence models to the Mount Clark and lower Mount Cap Formations, three major sequences bounded by maximum regressive surfaces (MRS) were interpreted. This further refines the current paleogeography mapping (Figure 1-4) and better illustrates timing of the Mackenzie Trough and small-scale extensional faulting throughout the basin.

Renaming of the Cambrian Basin, herein referred to as the Colville Basin, is proposed to tie in specific geographical context pertaining to Lower and Middle Cambrian strata to the Colville Hills area. The name 'Cambrian Basin' does indicate a geological age but does not provide any context to where that basin is located. Therefore, the name Colville Basin (Figure 1-5) is suggested as the majority of present-day Lower and Middle Cambrian subsurface data is located around the Colville Lake townsite. This name change would unify under a single name all existing depocenters east of the Aklavik Arch Complex, Peel Arch, Mackenzie Arch and Redstone Arch, extending to the craton edge further east delineated by MacLean (2011).

In summary, this thesis aims to better understand the specific paleo-depositional environments, basin fill and evolution of the Colville Basin during the Cambrian to aid small- and large-scale reconstructions for research and exploration opportunities.

FIGURES

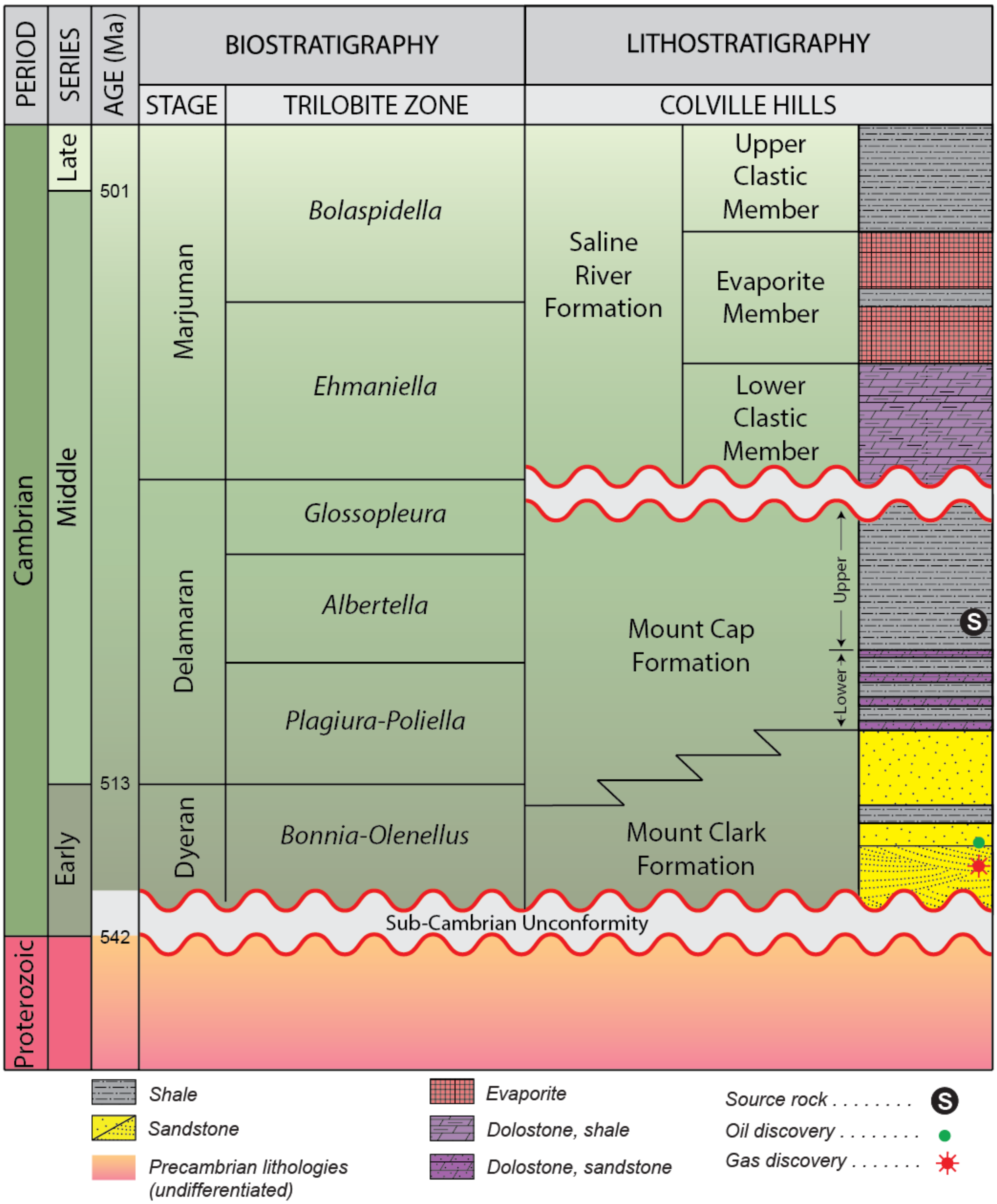

PERIOD
SERIES
AGE (Ma)
BIOSTRATIGRAPHY
STAGE
TRILOBITE ZONE
LITHOSTRATIGRAPHY
COLVILLE HILLS
Cambrian
Proterozoic
Late
Middle
Early
501
513
542
Marjuman
Delamaran
Dyeran
Bolaspidella
Ehmaniella
Glossopleura
Albertella
Plagiura-Poliella
Bonnia-Olenellus
Saline River Formation
Upper Clastic Member
Evaporite Member
Lower Clastic Member
Mount Cap Formation
Upper
Lower
Mount Clark Formation
Sub-Cambrian Unconformity
Shale
Sandstone
Precambrian lithologies (undifferentiated)
Evaporite
Dolostone, shale
Dolostone, sandstone
Source rock
Oil discovery
Gas discovery

Figure 1-1. Stratigraphic chart of the Colville Hills area with lithologies and petroleum discoveries. The contact between the Mount Clark and Mount Cap has historically been viewed as a regional diachronous facies change, however within the Colville Basin there lacks evidence to support this and appears as a sharp formational contact. Proterozoic assemblages within the study area are found in Figure 1-6. Compiled from Dixon and Stasiuk, 1998; Janicki, 2004; Serie et al., 2013; Hannigan et al., 2011; MacNaughton and Fallas, 2014.

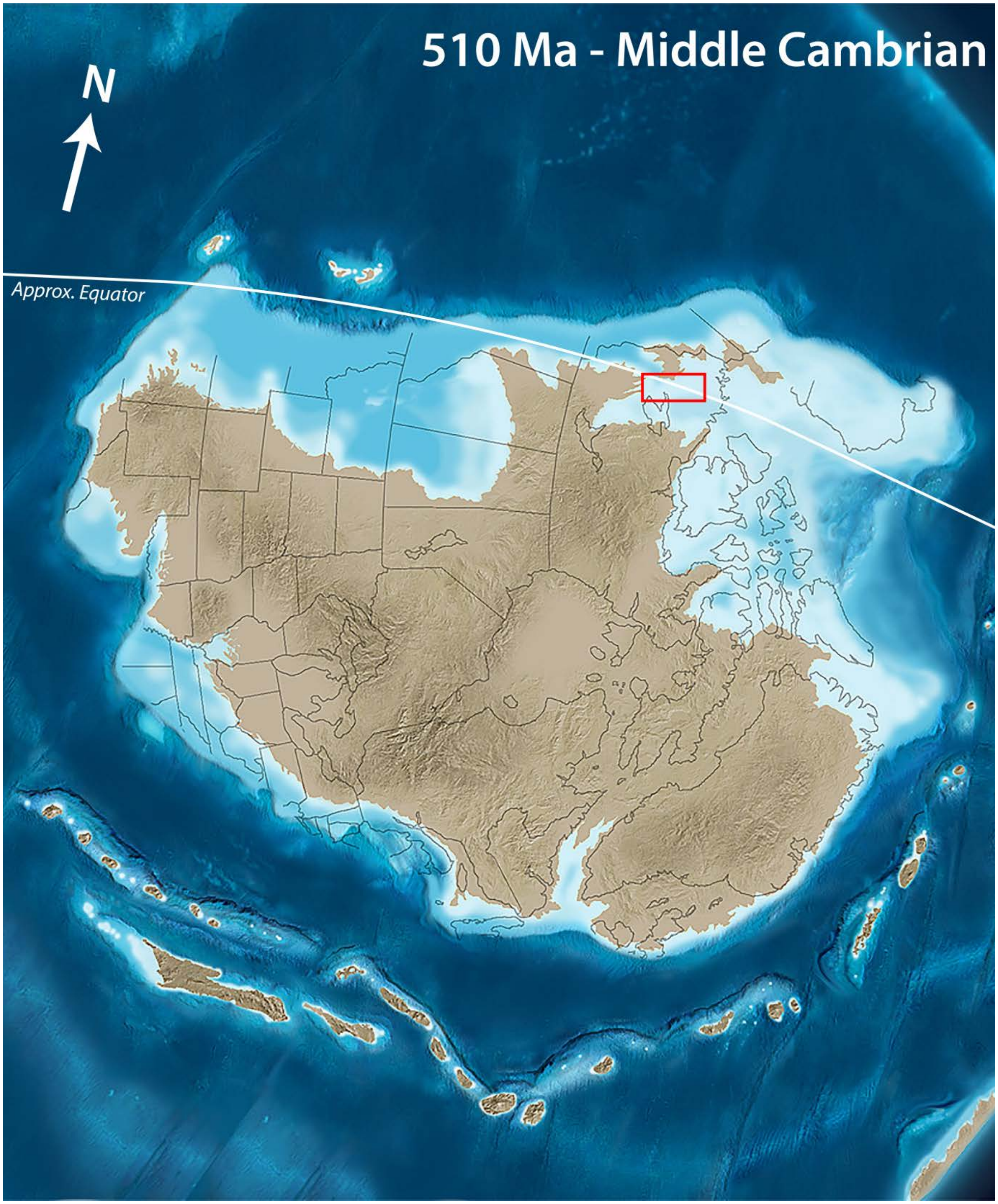


Figure 1-2. Artistic paleogeography sketch of Laurentia (North America) during the Middle Cambrian. Laurentia was rotated approximately 90 degrees clock-wise from present day. The white line indicates the paleo-equator at 510 Ma; red box indicates approximate outline of study area. Modified from Blakey, 2011 © Colorado Plateau Geosystems.

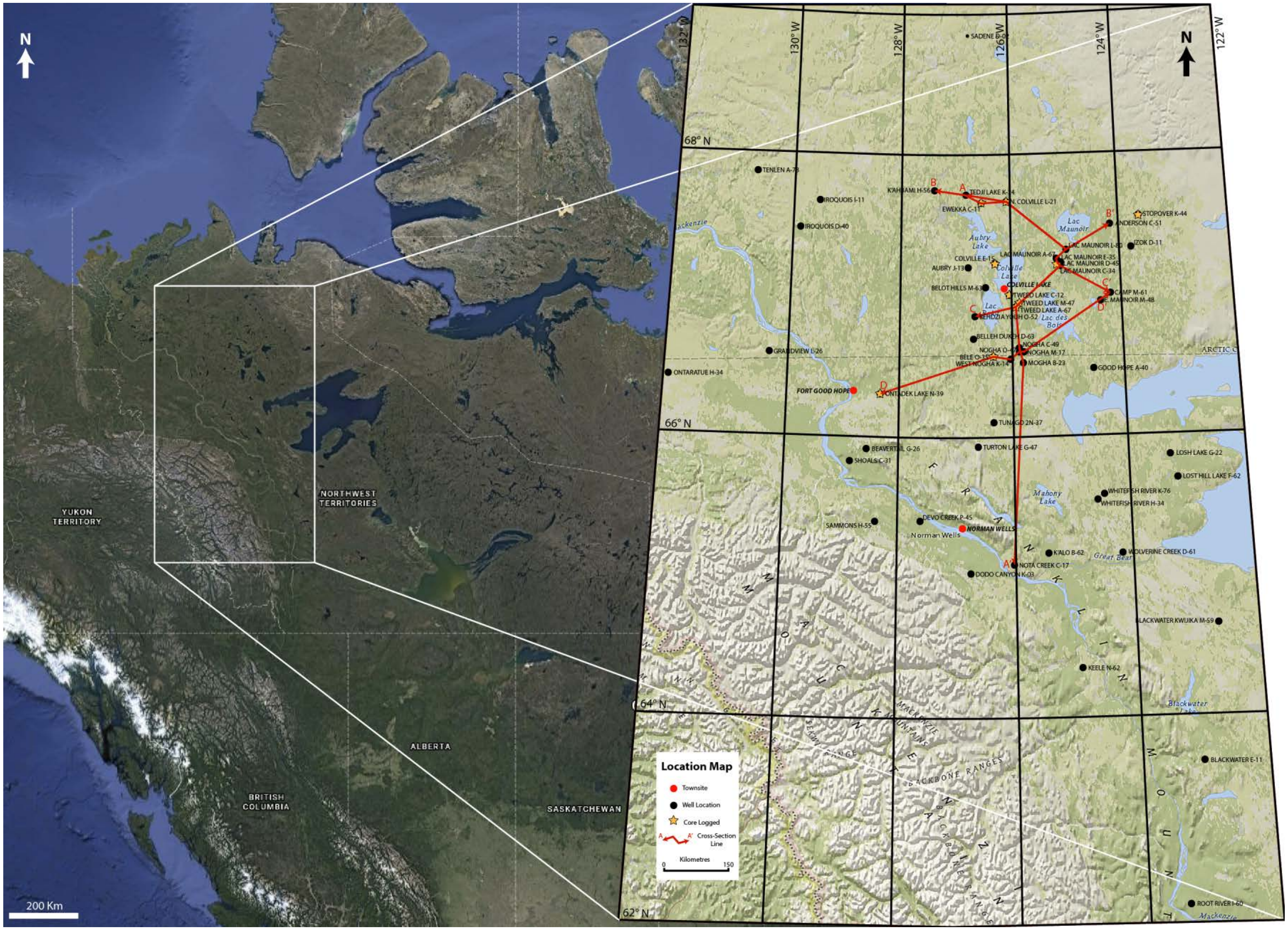


Figure 1-3. Location map outlining study area. Modified from Google Earth.

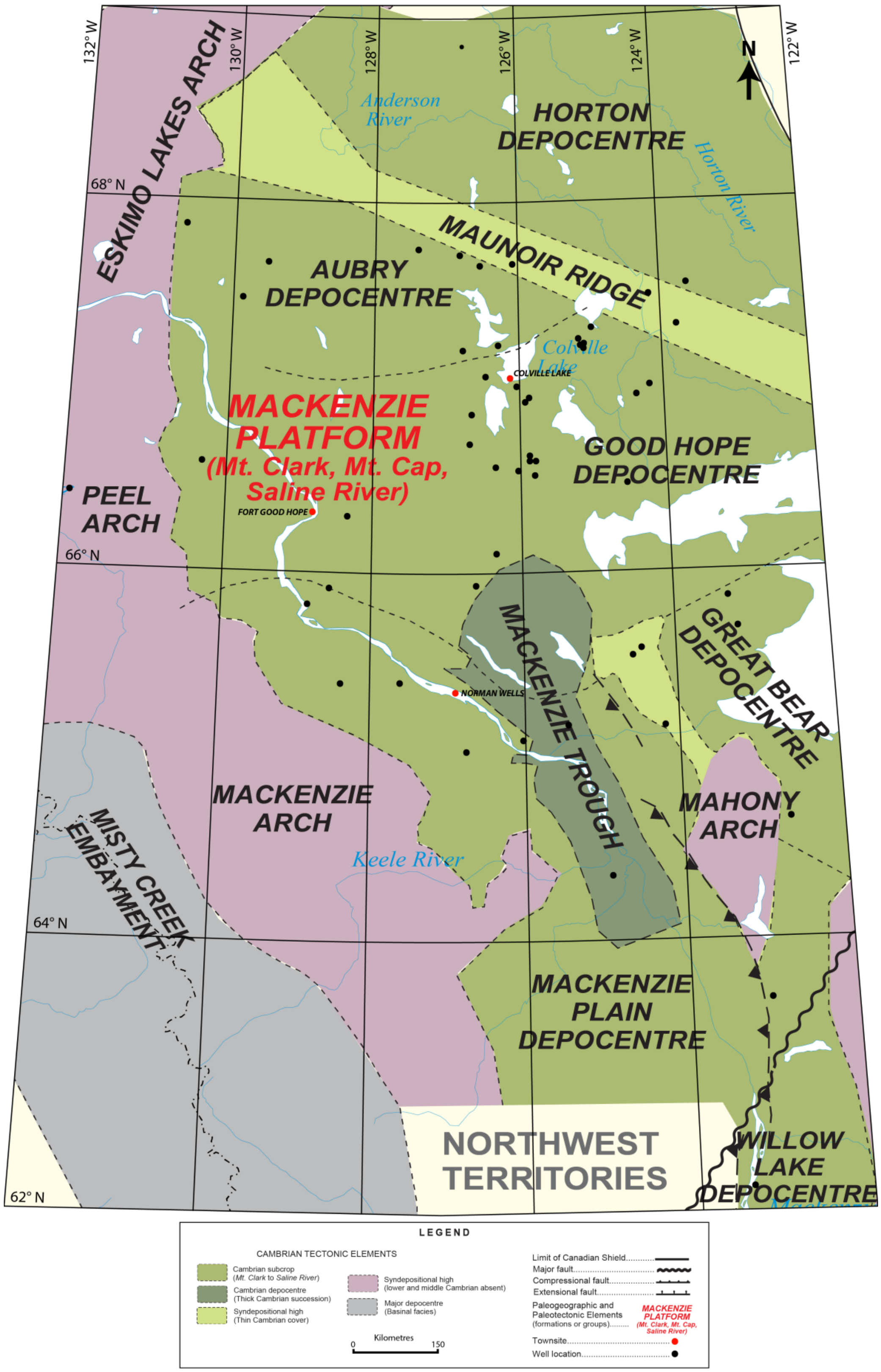


Figure 1-4. Paleogeography map showing tectonic elements and depocentres during the Cambrian. Modified from Hannigan et al. (2011).

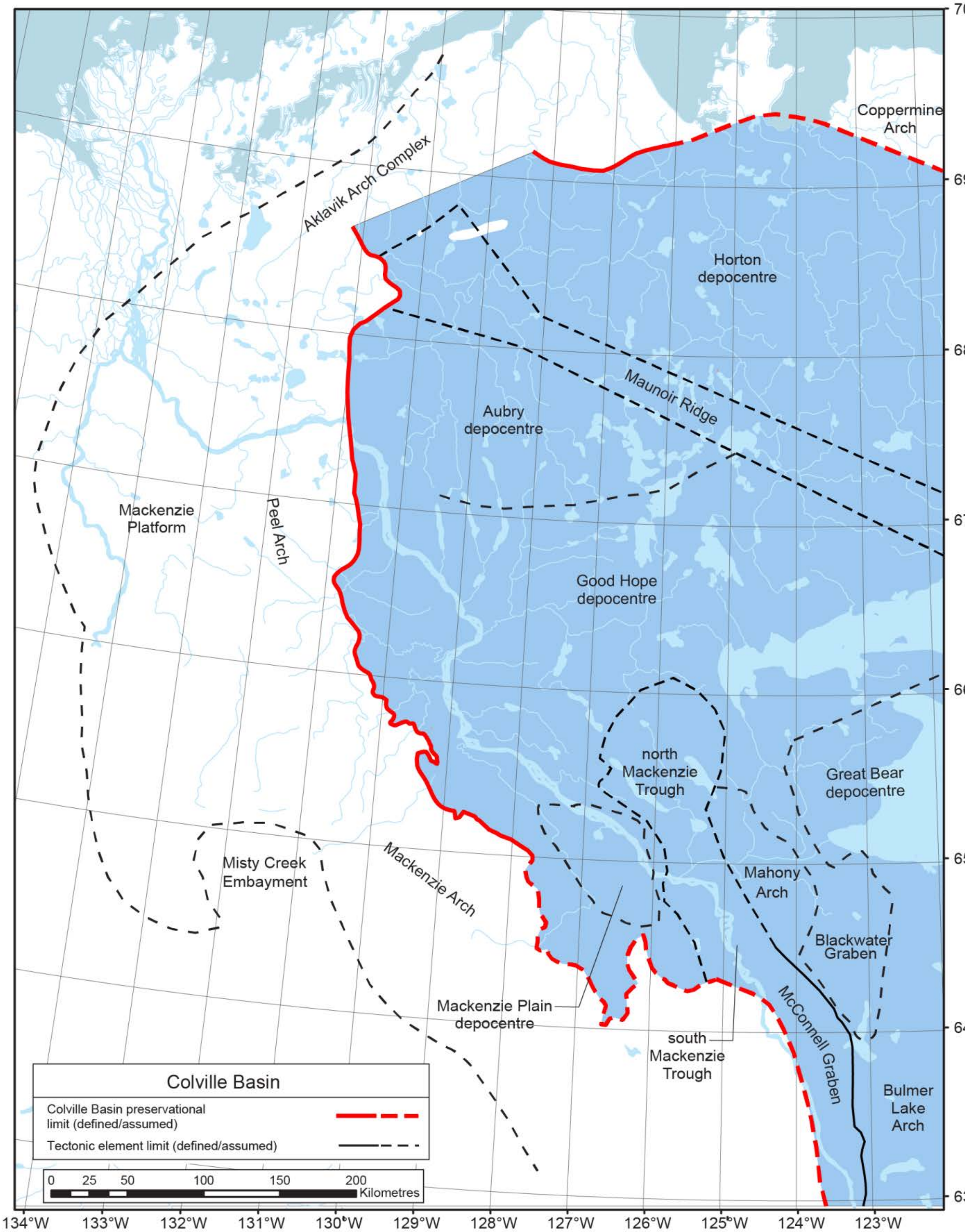


Figure 1-5. Outline of the Colville Basin including depocentres and paleo-highs. Compiled from MacLean (2011) and Hannigan et al. (2011).

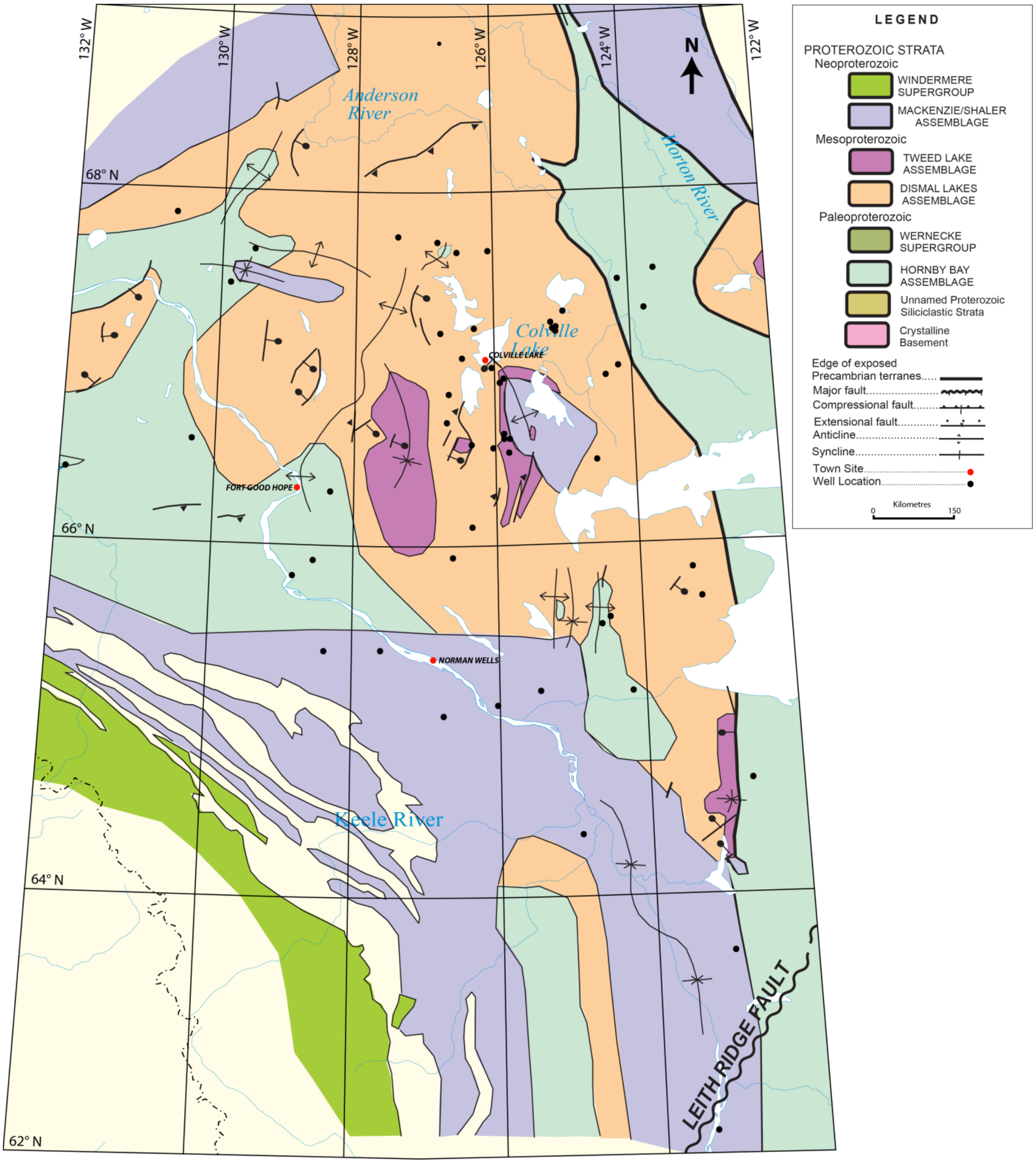


Figure 1-6. Proterozoic assemblages below the sub-Cambrian unconformity with structural elements. Modified from Hannigan et al. (2011).

CHAPTER 2: FACIES ANALYSIS OF CAMBRIAN MOUNT CLARK AND MOUNT CAP FORMATIONS

INTRODUCTION

Cambrian formations across much of the mainland Northwest Territories were deposited in a semi-enclosed, epicontinental basin, herein referred to as the Colville Basin, with a present-day zero edge that onlaps the Canadian Shield or Precambrian sedimentary strata (Dixon and Stasiuk, 1998). During the beginning of Cambrian deposition, large volumes of siliciclastic sediments were deposited in shallow seas as a result of prolonged eolian action on a barren, un-vegetated craton, in addition to extensive braided fluvial networks (Dalrymple et al., 1985; MacNaughton et al., 1997; Long and Yip; 2009). Throughout the Cambrian, Laurentia straddled the equator and in response to the breakup of Rodinia, the craton's margins underwent ongoing subsidence (Figure 1-1). During the Middle Cambrian, a rise in eustastic sea level resulting from a global greenhouse climate provided excellent conditions for the development of broad carbonate platforms and ramps (Bond and Kominz, 1984; Scotese and McKerrow, 1990; Levy and Christie-Blick, 1991).

The subsurface Cambrian succession in the Colville Hills area has been known to host reserves of conventional oil and gas of economic significance since gas was first discovered in the Mount Clark Formation sandstones in 1974 (MacLean, 2011). Described as the "Cambrian Siliciclastics Play" situated in the Interior Platform Province of the mainland Northwest Territories, this play has been assessed to potentially contain nearly one billion barrels of oil and

10.8 TCF of gas (Hannigan et al., 2011). Despite this economic potential of these strata, work to date has consisted of preliminary or regional-scale studies, or based on selected cores (Aitken et al., 1973; MacQueen and Mackenzie, 1973; Meijer Drees, 1974; Williams, 1987; Hamblin; 1990; Pugh, 1993; Dixon, 1997; Dixon and Stasiuk, 1998; Janicki, 2004). Tassonyi (1969) first documented the subsurface Cambrian succession from Mobil Colville Hills E-15 core. This research and drilling activity kick-started subsequent coring of 9 additional wells in the Colville Basin. The latest study to construct a basin-wide model was conducted by Dixon and Stasiuk (1998), however subsequent wells have been drilled since its publication which lack public depositional analyses. Moreover, Herbers et al. (2016) completed facies analysis in the Colville Basin but was limited in geographical extent to the Tweed Lake area and specific to the Mount Clark Formation.

Depositional environment interpretation is significantly enhanced when identifying both physical sedimentology (for example, lithology, grain size and sorting, sedimentary structures) and ichnology (for example, bioturbation intensity, ichnogenera, ichno-diversity) (Seilacher, 1978; Pemberton et al., 1992a; MacEachern and Bann, 2008; MacEachern, et al., 2010). Through the works of several researchers, ichnology has become a significant contribution to the scientific community as this tool has yielded a greater understanding of both physical and chemical variables on ecosystems at the time of deposition, and post-deposition, which in turn can be used for high-resolution paleo-environmental reconstructions (Gingras et al., 2011).

This study will examine sedimentological and ichnological properties of the three Cambrian stratigraphic units exclusively preserved in the Colville Basin that comprise the

Cambrian Siliciclastics Play: Mount Clark Formation, Mount Cap Formation, and Saline River Formation (Figure 1-1). Each formation plays a vital role in the overall petroleum system, generally as the reservoir rock, source rock, and seal, respectively. The present work will improve the understanding of the stratigraphic complexities in the Colville Basin, with the goal of aiding future exploration and reservoir exploitation.

PREVIOUS WORK

A number of workers have investigated the regional stratigraphy of Cambrian strata in the Northwest Territories, less in the Interior Plains due to previous subsurface data constraints. The first Cambrian succession descriptions consisting of Mount Clark, Mount Cap and Saline River formations were completed by Williams (1922, 1923) in outcrop located in the Franklin Mountain close to Wrigley, NWT. The Old Fort Island Formation was first described by Norris (1965) in outcrop along the western shores of the north arm of Great Slave Lake. Lithological similarities between the initially established Mount Clark Formation and the Old Fort Island Formation resulted in the abandonment of the latter, with Williams' previously published name taking priority (Dixon and Stasiuk, 1998). Moreover, the La Martre Falls Formation described by Norris (1965) was also abandoned for the same reasons, as it was a junior equivalent to the Mount Cap and Saline River formations (Dixon, 1997). The northern Franklin Mountains are considered to be genetically linked the subsurface Cambrian strata in the Colville Hills area and therefore the nomenclature is carried across (Cook and Aitken, 1973, Cook 1983). Mount Clark, Mount Cap, and Saline River formations were first documented in the subsurface by Tassonyi (1969). Macqueen and Mackenzie (1973) later evaluated Mobil Colville Hills E-15, the first well drilled in the Colville Hills area. Subsequent subsurface research focusing on sedimentological descriptions and lateral extent was published by Aitken et al. (1973), Meijer Drees (1974, 1986), Williams (1974, 1987), Pugh (1983, 1993), Hamblin (1990), Dixon (1997), MacLean et al. (2014) and Herbers et al. (2016). Regional structure and depositional trends were established by MacLean (2011), who also highlighted the need for a high-resolution facies analysis. Petroleum evaluations and establishment of the Cambrian Siliciclastics Play were conducted by Hamblin (1990), Dixon and Stasiuk (1998), Janicki (2004), Hannigan et al. (2011), and MacLean (2011).

GEOLOGICAL SETTING

The Lower and Middle Cambrian succession (Figure 1-3) constrained within the study area is described as being deposited in a semi-enclosed, epicontinental marine basin (Dixon and Stasiuk, 1998) overlying thick (>10 km) Proterozoic strata (MacLean and Cook, 1998; Janicki, 2004; Hannigan et al. 2011). Proterozoic and Phanerozoic sediments are separated by a major discontinuity, termed the sub-Cambrian unconformity, the result of intense erosion and extended periods of uplift (Hannigan et al., 2011). The Colville Basin opened to a continental shelf to the south-west (Dixon and Stasiuk, 1998) and was influenced by Proterozoic paleotopographic positive tectonic features (Figure 1-4). To the west, Cambrian strata were bounded by the Mackenzie Arch and Peel Arch, separating them from the further west Selwyn Basin (Aitken et al., 1973; Williams, 1987; Cook and MacLean, 2004). Nearing the northern part of the study area, Maunoir Ridge coincided with an elongated gravity trend and thin Cambrian deposition (Dixon and Stasiuk, 1998) while in the east was an established zero edge as sediments were onlapping the Canadian Shield (Cook and Aitken, 1970; Janicki, 2004).

STRATIGRAPHY

The Mount Clark Formation is a quartz-rich basal sandstone deposited in shallow- to marginal-marine environments reaching a maximum thickness of 88m in well Good Hope A-40

(Hamblin, 1990; Dixon and Stasiuk, 1998; Herbers et al., 2016). Sandstones near the sub-Cambrian unconformity are commonly cross-bedded and are coarser grained than those up-section, which commonly are finer and bioturbated predominantly by *Skolithos* (Hamblin, 1990; Dixon, 1997). The presence or absence of Mount Clark strata in the Colville Basin was largely influenced by available accommodation space as a result of Precambrian topography (Dixon and Stasiuk, 1998). The Mount Clark is the primary reservoir component to the Cambrian Siliciclastics Play hosting oil and gas pools (Hannigan et al., 2011). The contact between the Mount Clark and Mount Cap can be sharp or rapidly gradational and typically denoted by bioturbated nodular dolostone beds. A facies change has been suggested by Dixon and Stasiuk (1998), however there is little evidence of interfingering or a transitional zone between the Mount Clark and Mount Cap within the study area.

The Mount Cap Formation may have been deposited in an interior sea that was semi-enclosed, suggesting normal marine salinities, possible deposition below wave base, low levels of tidal influence or high wave-energy environments with declining siliciclastic input (Aitken et al., 1973; Pugh, 1983; Dixon, 1997; MacLean, 2011). The Mount Cap Formation consists of a shale-dominated succession with sporadic dolostone and carbonate-cemented sandstone intervals (Dixon and Stasiuk, 1998). Shales are commonly dark grey to green and sandstone beds are generally grey, thinly-bedded, fine-grained and bioturbated. Dolostones commonly have a mottled fabric and appear nodular. Trilobite and brachiopod fragments are uncommon. Trilobite faunas dating the formation were described by MacLean (2011) and by MacNaughton and Fallas (2014) to be as old as Dyeran (late Early Cambrian; *Bonnia-Olenellus* Zone) and as young as late Delamaran (mid-Middle Cambrian; *Glossopleura* Zone). A transgression coupled with syndepositional normal faulting from rifting resulted in an overall deepening of the basin (Maclean, 2011). Anomalously thick shale deposits of the Mount Cap were observed in K'Alo B-62 in the Mackenzie Trough (up to 901 m), suggesting a low-energy, deep-water environment. Outside of the trough, 192 m thick Mount Cap was observed in the Nogha O-47 well (Dixon, 1997; MacLean, 2011). The La Martre Falls Formation is equivalent to the Mount Cap and Saline River formations and was identified by Norris (1965) in the La Martre Depocentre, however has been since abandoned (Meijer Drees, 1974; Williams, 1987; Dixon and Stasiuk, 1998). The primary hydrocarbon source component of the Cambrian Siliciclastics Play are the organic algal shales of the Mount Cap Formation. These contain Type I and II kerogens, with TOC values ranging up to 9.5% and T_{max} values between 400 to 455 °C suggesting high variability of thermal maturity throughout the basin (Macauley, 1987; Snowdon and Williams, 1986; Wielens et al., 1990; Dixon and Stasiuk, 1998).

The Mount Cap is unconformably overlain by the Saline River Formation. This regional unconformity, informally referred to as the Sub-Saline Unconformity (Dixon, 1997), suggests a change from a deep marine, shale-dominated succession to a shallow, carbonate-dominated succession as a result of periods of uplift and/or sea level drop (Dixon and Stasiuk, 1998; MacLean, 2010). The Saline River is divided into three members: Lower clastics member, Evaporite member, and Upper clastic member (Aitken et al., 1973; Meijer Drees, 1974). The Colville Basin was very tectonically active during Saline River deposition, predominantly during the Evaporite member deposition (Dixon and Stasiuk, 1998). The Lower clastics member in the Colville Basin consists of interbedded shale, dolostone, limestone and occasional anhydrite beds suggesting normal marine to elevated salinities being a segue to anhydrite and gypsum environmental conditions. The contact with the overlying Evaporite member is commonly sharp to rapidly gradational. The lithologies consist of predominantly halite with thin interbedded shales, dolostones and anhydrite, excluding the basin margins where halite deposits are absent (Dixon and Stasiuk, 1998; MacLean, 2011). The nature of this contact suggests that the shift to hypersaline conditions was relatively quick, with sub-tidal conditions dominating within major depocentres and peritidal environments such as sabkahs dominating the basin margins (Meijer Drees, 1986; MacLean, 2011). Well to the west, the Mackenzie Arch separated the further west Selwyn Basin from the Colville Basin (Aitken et al., 1973). Moreover, islands formed during tectonic uplift may have restricted circulation patterns, thus creating the restricted basin environment necessary for development of hypersaline conditions during deposition of the Saline River Formation evaporites (Pugh, 1983; Janicki, 2004). The contact between the Evaporite member and overlying Upper clastics member is an abrupt change from dolostone to a shale-dominated succession with thin interbeds of dolostone and anhydrites with occasional halite laminae and lenses (Dixon and Stasiuk, 1998). The thick, regionally extensive Evaporite member provides an excellent seal for the Cambrian Siliciclastics Play (Hannigan et al., 2011).

DATASET AND METHODOLOGY

The study area is located in the Colville Hills area, Northwest Territories, centered approximately around the Colville Lake townsite, and bounded approximately between latitudes 62.5°N to 69°N and longitudes 122°W to 132°W, spanning more than 300,000 km^2 (Figure 1-3). The dataset consisted of 10 cored wells (Table 2-1) ranging from 4 m (Ewekka C-11) to 230 m (Colville E-15) long, all of which were stored at the Geological Survey of Canada Sample Repository. Additionally, LAS and raster image wireline logs supplied by the Geological Survey of Canada and geoSCOUT© were used to verify cored depth intervals. For each core logged, detailed observations were recorded of: lithology, primary sedimentary structures, accessory minerals, grain-size, sorting, roundness, bioturbation intensity (following Taylor and Goldring, 1993), and trace fossils. Core was logged at the individual box scale (commonly 1.5 m) using AppleCORE© logging software. However, box scale varied among wells, such as Mobil Colville E-15 which was comprised of three columns of core per box instead of the conventional two columns, and depth ranges were provided over multiple boxes rather than each individual box. As a result, to maintain consistency among all previously logged cores and to best maintain depth accuracy, each box was measured and split in the center of the middle column, thereby creating two overall columns for each individual box. Sedimentological and ichnological descriptions are most thorough for the Mount Clark Formation as this interval was mostly thoroughly represented in core as it was of most interest to exploration companies. However, cores also sporadically included some Proterozoic and lower Mount Cap strata. Core available for the upper Mount Cap and Saline River formations was especially limited as only one core, from Mobile Colville E-15, covered this interval and was poorly preserved. Therefore, observations and interpretations were necessarily limited for facies 17 to 20.

FACIES DESCRIPTIONS AND INTERPRETATIONS

The following section contains facies descriptions and paleoenvironmental discussions of each facies based on observations in core. A total of 20 facies were delineated into 4 facies associations (Table 2-2) within the Mount Clark, Mount Cap and Saline River formations. Individual facies were identified based on lithology, grain-size, primary sedimentological character and ichnological character. Facies 1 is acknowledged to not be a conventional use of the term 'facies' but is a compilation of all Proterozoic lithofacies encountered in core for the sake of convenience and being concise. Facies associations, and to a lesser extent individual facies, were correlated across the study area from cored wells to non-cored wells using wireline signatures in conjunction with drill cutting sample descriptions found in geological well reports and striplogs. Correlations and basin reconstructions will be further discussed in Chapter 3. Individual facies are described in the order they first appeared across the study area using the first common maximum flooding surface as a datum.

Facies 1: Precambrian Lithofacies

Description:

Sedimentology: Five wells in the study area penetrate the Precambrian. F1 encompasses variable lithologies that are dependent on the well location with a sharp contacts with overlying Mount Clark. In well Tweed Lake A-67, F1 consisted of massive, maroon basalt units likely from the Tweed Lake Assemblage. In Tweed Lake C-12, it consisted of light to medium grey, dissolution-brecciated dolostone with evaporitic fill, stylolites, and abundant chert. Rare high-angle bedding was observed. In North Colville L-21, F1 consisted of maroon to medium grey, very fine-grained, well-sorted, low-angle bedded, thin bedded sandstone. The contact with overlying Mount Clark is a 0.25 m thick dissolution breccia with pale green clay fill. In Ontadek Lake N-39, F1 consisted of dark grey dolostone with mm-scale laminae, rare pyrite, rare chert horizons, common quartz veins which are occasionally micro-faulted, low- to high-angle bedding with rare wavy bedding and occasional dissolution breccia. The N-39 cored interval ranged from 1792 to 1797 m, too deep to intercept the Precambrian-Cambrian unconformity; however, wireline logs suggest that the overlying formation is Mount Cap. In Colville E-15, F1 consisted of medium green to maroon shales, predominantly planar-bedded with occasional low-angle bedding and rare 10cm thick dolostone beds. The sub-Cambrian unconformity is demarcated by a high-angle contact of Precambrian blackish-red dolostone with overlying sand-rich Mount Clark.

Ichnology: F1 typically lacks bioturbation and trace fossils. However, a *Glossifungites* surface is observed at the Precambrian – Cambrian unconformity in Tweed Lake A-67 with a BI range of 1 – 3 extending down 0.5 m, traces consist of very fine- to fine-grained sand-filled burrows, potentially *Skolithos* and *Thalassinoides*.

Interpretation:

F1 (Figure 2-1) illustrates the high degree of lithologic variability preserved below the sub-Cambrian unconformity. Sub-surface mapping completed by Cook and MacLean (2004) and Hannigan et al. (2011) helped assign these diverse strata to appropriate formations. Tweed Lake A-67 is interpreted to be basalt as a result of geochemical data extracted from a neighbouring well, Tweed Lake M-47 located approximately 2 km north, that correlated Tweed Lake basalts with distant Coppermine basalts, suggesting the two are “nearly identical” (Sevigny et al., 1991). F1 found in wells Tweed Lake C-12, Colville E-15 and North Colville L-21 is of the Dismal Lakes Assemblage while N-39 is from the Hornby Bay Assemblage Syntectonic Unit (Cook and MacLean, 2004; Hannigan; 2011).

Facies 2: Dark Grey Shale

Description:

Sedimentology: F2 is characterized by a dark grey shale and commonly is parallel-laminated. Current ripples, asymmetrical starved ripples, discontinuous mud beds, and wavy parallel laminae are present but rare. Fossil debris is very occasionally observed, constining of inarticulate brachiopods and trilobites which commonly have only the cephalons preserved. Trilobite fauna encountered are potentially *Albertella* or *Glossopleura* as identified by Fritz (1973) in the Colville E-15 well from depths correlated to Mount Cap deposition. In the lower Mount Cap succession, shales are commonly siliceous while in the upper Mount Cap, shales are commonly calcareous to dolomitic. F2 is the most common facies observed throughout the dataset. It is highly correlatable across the basin and very thick, representing the majority of the Mount Cap deposition. F2 is found in Mount Clark and Mount Cap formations.

Ichnology: F2 is commonly barren (BI = 0) but can locally range up to a BI of 2. Ichnogenera are commonly diminutive and monospecific to *Planolites*, however can include: *Arenicolites, Chondrites*, *Lockeia* and *Palaeophycus*.

Interpretation:

F2 (Figure 2-2) is dominated by fine-grained siliciclastic lithologies that resulted from suspension fallout, with lesser evidence for low-energy sedimentary structures, sporadic clastic input of sand-size sediments up to 1 cm thick beds, and rare instances of producing ripple currents. F2 is inferred to represent a lower offshore setting of the *Cruziana* Ichnofacies (Vossler and Pemberton, 1989; MacEachern et al., 1999). Ichnological evidence of a diminutive and generally monospecific suite of *Planolites* coupled with minimal levels to complete absence of bioturbation suggests that the environment was stressful for ichnofauna, which could be the result of low or depleted dissolved oxygen conditions (MacEachern et al., 2005; MacEachern et al., 2007).

Facies 3: Bioturbated Mudstone and Sandstone Interbeds

Description:

Sedimentology: F3 was observed in both the Mount Clark and Mount Cap formations, and is characterized by predominantly parallel-bedded, thinly-bedded mudstone with light grey, fine-grained, well-sorted, parallel-laminated sandstone beds that are 1 – 2 cm thick. Contacts between sandstone and mudstone units are commonly sharp. Additional sedimentary structures consist of: synaeresis cracks, current ripples, wavy parallel laminae, low-angle bedding, micro-faulting, mud drapes, graded beds and pinstripe laminae. Occasional glauconite and pyrite were observed.

Ichnology: F3 is typified by low to moderate levels of bioturbation (BI = 1 – 4) from a diverse, diminutive ichnological assemblage consisting of: *Arenicolites*, *Asterosoma*, *Chondrites, Cylindrichnus*, *Diplocraterion,* fugichnia, *Lockeia, Palaeophycus, Planolites*, and *Teichichnus*. Bioturbation intensity levels are predominantly higher in mudstone beds and commonly absent to sporadic in sandstone beds. In rare examples, fugichnia are preserved as singular entity within an otherwise barren sandstone unit.

Interpretation:

F3 (Figure 2-3) is predominantly a fine-sediment sized lithology. This, coupled with sharp contacts on the bottom and tops of fine-grained sandstone beds, and the presence of rare synaeresis cracks suggests an environment that is nearly full-marine with episodic freshwater mixing from hyperpycnal discharge (Coates and MacEachern, 1999; Pemberton and Wightman, 1992). Tempestite beds support a storm-influence interpretation in conjunction with the sporadic deposition of relatively coarser sediments that were carried into the basin as event beds; these are consistently barren of bioturbation (Vossler and Pemberton, 1989). Moreover, these beds preserve wavy, mm-scale laminations suggesting low-velocity bottom flowing currents (O'Brien, 1996). The ichnological suite is diverse and more tolerant of slightly stressful conditions from slightly brackish waters. The barren nature of common overlying sandstone beds and rarely preserved fugichnia suggest that deposition was rapid and irregular (MacEachern et al., 2005). As a result, F3 was interpreted to represent prodelta deposits of the proximal *Cruziana* Ichnofacies in a storm-influenced setting.

Facies 4: Low- to High-Angle Cross-Stratified Dominated Sandstone

Description:

Sedimentology: F4 is observed exclusively in the Mount Clark and is characterized by tan to salt-and-pepper, fine- to medium-grained, well-sorted quartz arenite with low- to high-angle cross-stratification. Additional sedimentary structures include: trough cross-bedding, hummocky cross-stratification (HCS), reactivation surfaces and current ripples. Reduction spheres, silica cement and accessory lithic grains are common with occasional cobbles and an isolated occurrence of soft sediment deformation in Tweed Lake A-67. In Colville D-45 at a depth of 978 m, a 9 cm thick pale green-grey, soft, noncalcareous clay fill was observed, a feature not seen elsewhere. F4 is commonly seen in the lower levels of the Mount Clark and is highly correlatable across the dataset with probable lateral continuity between wells Colville D-45, Colville E-15, and Tweed Lake C-12.

Ichnology: F4 is commonly barren to rarely bioturbated (BI = 0 – 3). Only *Diplocraterion* was reliably observed, however cryptic bioturbation may be evident due to an overall fuzzy appearance and a massive-appearing sedimentary texture.

Interpretation:

F4 (Figure 2-4) is interpreted be from a storm-influenced middle shoreface environment. HCS beds are a result of oscillatory wave action producing large 2D and 3D subaqueous dunes in a storm-influenced area (Harms, 1975; Duke et al., 1991; Dumas and Arnott, 2006). This interpretation is further strengthened by the presence of multiple stacked reactivation surfaces recording sedimentation and erosional events due to abrupt changes in flow regime (Messina et al., 2014). Common absence of bioturbation suggests an uninhabitable environment due to high-energy wave action coupled with high sedimentation rates and shifting substrates (Bromley, 1996; Gingras et al., 2011). The lone observed *Diplocraterion* in conjunction with the lithological analysis suggests ichnofauna were likely suspension feeding organisms from the *Skolithos*

Ichnofacies. In Tweed Lake A-67 was an isolated observation of soft sediment deformation, likely a result of rapid deposition and loading (Owen and Moretti, 2008), cyclic storm-waves (Poldsaar and Ainsaar, 2015) or seismicity (Jewell and Ettensohn, 2004), or plausibly a combination of the aforementioned factors (Owen et al., 2011). Foreshore and upper shoreface successions were not observed in this storm-influenced environment and were likely eroded and transported to deeper water depths by large waves and strong unidirectional currents (Vincent et al., 1982; Snedden et al., 1988). As a result, F4 is the top facies of the FA1 storm-influenced Shoreface succession. Tan coloured strata are likely a result of oil staining though no petroliferous smells were observed.

Facies 5: Vertically-Bioturbated Sandstone – "Piperock"

Description:

Sedimentology: F5 was observed exclusively in the Mount Clark and is characterized by tan to medium brown, medium-grained, moderately well- to well-sorted sandstone beds with occasional low-angle bedding. Grain-size ranged from very fine to coarse, though in occasional instances there were silt-sized particles plugging pore spaces. F5 is wide-spread throughout the dataset and common in the lower stratigraphy of the Mount Clark Formation.

Ichnology: F5 is dominated by moderately- to intensely-burrowed (BI = 3 – 6), unlined vertical trace fossils of *Skolithos* and *Altichnus*.

Interpretation:

F5 (Figure 2-5) is considered to represent deposition in a fully marine, moderate wave energy environment of the foreshore and fringe upper shoreface in a fairweather setting. Relative to other facies observed in the study area, F5 had an increased grain size in frequently moderate- to completely biogenically-reworked sediments which obscured any primary sedimentary structures. Despite wave-energy being high enough to transport these coarser grains, the ecosystem remained robust, resulting in the high intensity of biogenically-reworked sediments. Moreover, these deposits consist of monospecific assemblages showcasing an archetypal example of proximal *Skolithos* Ichnofacies (Droser and Bottjer, 1989; Droser, 1991; Desjardins et al., 2010). Suspension-feeding organisms thrive in this environment as the food supply is dominantly in the water column. Additionally, wave-energy was high enough that other ichnofauna could not survive. Biogenic reworking commonly outpaced sedimentation rates, except in rare examples of low-angle bedding inferred to represent swash zone environments (Droser and Bottjer, 1989). The term "piperock" originated from researchers Peach and Horne (1884) and later was emphasized by Hallam and Swett (1966) to describe a dense-distribution of *Skolithos* trace fossils. During the Paleozoic, piperock was most prevalent during the Cambrian and decreased in frequency as time went on (Droser, 1991). More specifically, Fang et al. (2012) suggested that the start of the Middle Cambrian marked the global onset of decreasing piperock frequency as a result of decreased nearshore siliciclastic deposits, low oxygen levels and available nutrients. Tan coloured strata are likely a result of oil staining though no petroliferous smells were observed.

Facies 6: Coarser-Grained Bioturbated Sandstone

Description:

Sedimentology: F6 is characterized by light grey, cream to maroon, fine- to medium-grained, moderately well- to well-sorted, quartz-dominated sandstone beds. Accessory minerals included: rare glauconite, occasional green silt clasts and laminae, and uncommon ferrous grains observed as dark grey grains with rusty coloured halos. Uncommon planar-parallel bedding was observed with rare instances of reactivation surfaces and low-angle planar bedding. Exclusively in Stopover K-44, patchy maroon to pink staining was prevalent throughout. F6 primarily occurred throughout Stopover K-44, occasionally in Tweed Lake C-12 and a single instance in Tweed Lake A-67 in the Mount Clark.

Ichnology: F6 is characterized by moderately- to intensely-burrowed (BI = 3 – 6) sediments consisting of ichnological assemblage composed of: *Arenicolites, Cylindrichnus*, *Lockeia, Palaeophycus*, and *Skolithos*. In structureless-appearing beds, trace fossils were rarely observed. Ichnological diversity was overall low as traces from *Skolithos* were predominant.

Interpretation:

F6 (Figure 2-6) is interpreted to represent deposition in a high-energy environment dominated by wave action. F6 is composed of predominantly well-winnowed, well-sorted, quartz-dominated, fine-grained to more commonly medium-grained sandstones, with low-angle to planar-parallel bedding. These features suggest an upper shoreface to foreshore environment, which is part of the proximal *Skolithos* Ichnofacies (MacEachern and Pemberton, 1992; Pemberton et al., 2012). Bioturbation intensities of 5 or above appear predominantly as structureless sand bodies that were completely reworked obscuring any primary sedimentary structures. Ichnological diversity was overall low as only specific suspension-feeding ichnofauna, such as the predominantly observed traces of *Skolithos,* are capable of surviving in such stressful high-energy environments where food sources are suspended in the water column due to wave agitation (Howard and Frey, 1984; MacEachern and Pemberton, 1992; MacEachern, et al. 2010). Moreover, organisms could adjust well to shifting substrates and increased sedimentation rates relative to deposit feeding fauna. Meiofauna may have been present during time of deposition, feeding on food particles that adhered to sand grains such as bacteria and algae, which could lead to an overall cryptically bioturbated appearance (Pemberton et al., 2008). The irregular staining pattern and colour that commonly cross-cut bedding planes is suggested to be diagenetic liesegang banding (Jacob et al., 1994) that had not developed a more typical concentric-ringed character.

Facies 7: Thinly Parallel-Bedded Sandstone

Description:

Sedimentology: F7 is characterized by maroon to pink, and tan to light grey, very fine- to medium-grained, well-sorted quartz-dominated sandstone. Bed thickness is highly variable, ranging from 4 – 40 cm with occasional 1 cm rhythmicity observed within those beds. Bioturbated green silty laminae are common throughout. Primary sedimentary structures include: planar-parallel laminae, current ripples, trough cross-bedding, discontinuous mud beds, convolute bedding, reactivation surfaces, wavy-parallel bedding, reverse grading and rip-up clasts. Rip-up clasts are light green, 1 – 2 cm clasts composed of mudstone. Diagnostic of this facies in Stopover K-44 was a pink to maroon staining that commonly cross-cut bedding surfaces and primary sedimentary structures, often appearing as patches or blotches against a host tan quartz arenite. In rare examples, this staining followed bedding planes. F7 was exclusively observed in the Mount Clark, and was prolific in Stopover K-44 but otherwise restricted to less than 1 meter in North Colville L-21 and appeared either above or below F6.

Ichnology: F7 is characterized by low to moderate levels of bioturbation (BI = 0 – 3) with ichnogenera consisting of *Palaeophycus*, *Planolites* and *Skolithos*. Trace fossils are commonly diminutive. Beds that appear structureless with a slightly fuzzy appearance may be cryptically bioturbated.

Interpretation:

F7 (Figure 2-7) is interpreted to represent deposition of a generally quiescent, brackish environment with episodic deposition of coarser-grained beds as a result of storm activity. The laminated bedforms, predominantly very fine grain size, general lack of bioturbation, and spatial-relation to fringe uppershore/foreshore of F6 deposits suggests F7 was deposited in a lagoonal environment behind a barrier island (Pemberton and Wightman, 1992). Therefore, brackish water chemical stresses likely were the predominant variable which resulted in little to no bioturbation activity (Pemberton and Wightman, 1992; Gingras et al., 2011; Angulo and Buatois, 2012). Sandstones commonly were very fine-grained and planar bedded, but had relatively high variability which suggests an episodic increase in flow regime with the capacity to transport heavier grains landward. These coarser-grained beds also had erosional bases, rip-up clasts, and load casts, and were barren of bioturbation. Thus, such beds were interpreted as wash-over fan deposits, reflecting additional physiological stresses of increased wave-energy and sudden burial for ichnofauna (Pemberton et al., 1992b; Gingras et al., 2011). Where bioturbation was present, vertical unlined traces of *Skolithos* dominated the facies suggesting that wave energy was high for a period of time long enough to suspend food particles in the water column for ichnofauna to live (Howard and Frey, 1984; MacEachern and Pemberton, 1992; MacEachern, et al. 2010). Diagenetic liesegang banding is inferred to explain the irregular staining pattern and colour that commonly cross-cut bedding planes (Jacob et al., 1994). F7 was inferred to be correlated along the northern and eastern edges of the basin using well cutting reports close to the zero edge of the Mount Clark and not seen elsewhere in the basin. A result, F7 is interpreted to represent a lagoonal environment with wash-over fan deposits as a result of storm activity.

Facies 8: Bioturbated Heterolithic Sandstone and Mudstone

Description:

Sedimentology: F8 is characterized by light brown to light grey, very fine- to fine-grained, well sorted, heterolithic sandstone beds that commonly lack preserved sedimentary structures.

Rare instances of discontinuous mud beds, wavy parallel bedding, low-angle bedding and planar-parallel bedding were observed and commonly have sharp bases and gradational tops. Accessory minerals consisted of occasional black lithics that were commonly bundled together within bedsets with rare examples of pyrite. F8 was observed in the Mount Clark and Mount Cap.

Ichnology: F8 is characterized by moderate to intense levels of bioturbation ranging (BI = 2 – 5). Ichnogenera observed include: *Arenicolites*, *Asterosoma*, *Chondrites*, *Cylindrichnus*, *Lockeia*, *Palaeophycus*, *Planolites*, and *Teichichnus*.

Interpretation:

F8 (Figure 2-8) is interpreted to represent deposition subject to attenuated or sheltered wave conditions, abundant food supply, low sedimentation rates, and normal marine salinities. Ichnologically, the presence of *Asterosoma* suggests relatively stable, near-marine salinities (Pemberton et al., 1992c; MacEachern et al., 2005; Gingras et al., 2011). The general absence of structures is inferred to be the result of biogenic reworking. Bioturbation levels were commonly intense suggesting that ichnofauna were able to thrive for long periods of time (Buatois et al., 2003). Rare cases of low-angle and planar-parallel bedding are interpreted to represent periods of episodic progradation that shifted the facies temporarily basinward into an upper shoreface environment where a prograding succession would be deposited separated by erosional contacts. The ichnological assemblage is composed of predominantly deposit-feeding ichnogenera coupled with very fine- to fine-grained heterolithic sandstone and mudstone beds that suggests a fairweather proximal lower shoreface environment of the most distal expression of the *Skolithos* Ichnofacies (MacEachern and Pemberton, 1992; MacEachern et al., 2010).

Facies 9: Poorly-Sorted Sandstone

Description:

Sedimentology: F9 is characterized by tan to light brown, medium- to very coarse-grained, poorly-sorted sandstone with grains up to pebble. The facies generally lacks sedimentary structures, appearing overall massive with occasional rip-up clasts and mud drapes. F9 is not widely preserved in the dataset but where present has an erosional basal contact and a sharp contact with overlying facies (F2 and F14) in the Mount Clark and Mount Cap Formations.

Ichnology: F9 characteristically lacks bioturbation. In rare examples, biogenic reworking was observed (BI = 1) with a single *Skolithos* trace fossil observed.

Interpretation:

F9 (Figure 2-9) preserves few distinctive sedimentary features and its interpretation depends crucially on the depositional context provided by adjacent facies. F9 commonly occurs at the top of subtle coarsening-up sequences with an erosional base, always followed by a sharp contact with either overlying facies F2 or F14 above, which are interpreted to represent offshore deposition. This punctuated deepening is critical to understanding how this facies was deposited in the succession and can assist in building a model for sequence stratigraphy (Cattaneo and Steel, 2003). Poorly-sorted sandstone units with rip-up clasts and spatial context with underlying and overlying facies suggest an environment with enough wave-energy to scour the seafloor and redistribute previously lithified sediments. It is suggested that F9 represents transgressive lag deposits in a shoreface-offshore transition as a result of shoreface reworking by waves and current action (Nummedal and Swift, 1987; MacEachern et al., 1992).

Facies 10: Bioturbated Nodular Dolostone

Description:

Sedimentology: F10 is characterized by medium to dark grey, very fine- to fine-crystalline, nodular dolostone with sparse to common, irregularly bedded mm-scale black mudstone laminae.

Physical sedimentary structures include rare rip-up clasts and sporadic vugs ranging from 0.5 – 2 cm in width. These vugs are filled with calcite or dolomite crystals or in rare examples, red, bladed evaporite minerals (?gypsum). Interbedded pale green claystone is common while sporadic beds that consist of abundant black grains are 1 to 2 cm thick with erosional bases and pyrite masses up to 1.5 cm wide. F10 has rapidly gradational (<1 m) or sharp contacts and is widespread throughout the dataset. F10 is found exclusively in the Mount Cap. In most instances, F10 is observed at the base of the Mount Cap and can be correlated across the study area reliably.

Ichnology: F10 is characterized by a bioturbate texture ranging from BI of 1 to 5. High intensity bioturbated horizons were commonly within mudstone laminae and surrounding horizons. Ichnogenera include: *Arenicolites*, *Asterosoma*, *Palaeophycus* and *Planolites*. Rare instances of hydraulically-filled open burrows were observed measuring up to 1 cm wide.

Interpretation:

Where present, F10 (Figure 2-10) first occurred at the base of the Mount Cap Formation. F10 was rarely subjected to storm activity, as indicated by the rare instances of rip-up clasts and storm deposits (e.g. HCS). Despite the limited trace fossil assemblage, the overall highly bioturbated texture in conjunction with *Asterosoma* confirm F10 was deposited in a fully-marine environment (Pemberton et al., 1992c; MacEachern et al., 2005; Gingras et al., 2011). Moreover, intense bioturbation suggests that the environment had few chemical and physical stresses but rather ichnofauna were able to thrive with robust food supplies and predictable habitats. Vugs were uncommon and typically isolated which suggest that as marine water was replaced by meteoric water during burial, dissolution was controlled by the minerology of selective grains (Moore, 2001; Moore and Wade, 2012). The nodular texture, or pinch and swell-like fabric, is interpreted to be a result of rapid lithification and differential rates of compaction and cementation due to variable rates of fluid flow through the pore network (Lawrence, 1993; Moore and Wade, 2012). As a result of intense biogenic reworking in conjunction with observation of *Asterosoma* and predominantly fine crystallinity, F10 is interpreted to have been deposited in middle to lower shoreface environments.

Facies 11: Fine-Grained Bioturbated Sandstone

Description:

Sedimentology: F11 is characterized by off-white to light grey, fine- to medium-grained, well-sorted sandstone units of commonly alternating bioturbated and non-bioturbated interbeds. Sedimentary structures include planar-parallel bedding, wavy-parallel laminae, low-angle bedding and massive or structureless-appearing beds. Lithological accessories include concretions, reduction spheres denoted by dark grains with rusty halos, occasionally very hard, silica-cemented beds, glauconite, ferrous grains, and very hard lithics (black chert grains). Beds with limited bioturbation were commonly thin (3 – 10 cm thick) with sharp bases and tops, with the concentration of bioturbation limited to bed tops such that ichnofauna penetrated into the bed up to a maximum of 2 cm but generally less (0.5 – 1 cm). F11 is distributed widely in the dataset and could be correlated reliably in the Tweed Lake area but elsewhere was observed isolated 1 – 2 m intervals. F11 was observed in both the Mount Clark and Mount Cap.

Ichnology: Bioturbation was generally intense (BI = 3 – 6) but in some beds as minimal (BI = 1 – 2). The ichnogenera observed were diverse and included: *Arenicolites*, *Chondrites*, *Cylindrichnus*, *Diplocraterion*, Equilibrichnia, Fugichnia, *Lingulichnus*, *Palaeophycus*, *Planolites*, *Rhizocorallium*, *Skolithos* and *Teichichnus*.

Interpretation:

F11 (Figure 2-11) is interpreted to have been deposited in a fairweather middle shoreface environment which was subjected to very occasional storm activity. Grain size distribution suggests that wave-energy needed to be high enough to transport grains up to medium size, but low enough to accommodate both filter-feeding and deposit-feeding organisms (Howard, 1975; Dashtgard, et al., 2012; Pemberton et al., 2012). Sediments were winnowed thoroughly, as indicated by the general lack of mud-size sediments which were likely transported further into the basin. Mud-sized sediments were observed but commonly only as part of the mud-lining of *Cylindrichnus* and *Planolites*. Bioturbated sandstone beds of moderate to high intensity and moderate diversity make up the majority of the facies, but are occasionally punctuated by commonly non-bioturbated, laminated sandstone beds suggesting a sudden surge in wave-energy that rapidly redistributed sediments. As a result, alternating laminated-and-scrambled bedsets or a "lam-scram" fabric is showcased (Pemberton and MacEachern, 1997; Schmidt and Pemberton, 2004; Hansen and MacEachern, 2007). Fugichnia and equilibrichnia suggest that ichnofauna were shifting back up to the sediment-water interface after being unexpected buried during episodic storms (Bromley, 1996; Davies et al. 2008).

Facies 12: Graded Sandstone and Heterolithic Mudstone

Description:

Sedimentology: F12 is characterized by tan to medium grey, very fine to medium-grained, moderately well sorted sandstones with load casts, soft sediment deformation, abundant black lithics, typically 3 – 6 cm thick beds with erosional basal contacts that grade upwards. Heterolithic sandstone and mudstone beds with commonly irregular bedding and sporadic planar laminae are typical throughout the facies. These beds are moderately-sorted and silt-sized to coarse-grained, occasionally bioturbated, and grade upwards overall. Lithological accessories consist of chert grains, ferrous grains, pyrite and lithic grains. F12 was exclusively observed in the Tweed Lake area from the Mount Clark.

Ichnology: Bioturbation was observed predominantly in heterolithic beds with a BI range of 1 – 5, however lithic-rich sandstones were slightly to moderately reworked (BI = 1 – 3). The ichnogenera observed included: *Arenicolites*, *Chondrites*, *Diplocraterion*, *Lockeia*, *Palaeophycus*, *Planolites*, and *Teichichnus*.

Interpretation:

F12 (Figure 2-12) predominantly consisted of fine-grained, interbedded graded sandstone and bioturbated, heterolithic mudstone successions suggesting a low-energy environment (Vossler and Pemberton, 1989; MacEachern et al., 1999; Pemberton et al., 2012). The lithic-rich sandstone units had abrupt, erosional convex basal contacts suggesting episodic bed loading from transported sediment. Heterolithic sandstone and mudstone beds were sparsely to intensely bioturbated indicating that sedimentation rates and wave energy were sporadically favourable for ichnofauna. An ichnological suite composed predominantly of suspension-feeders reworked tempestite beds, top-down, which suggests opportunistic burrowing in an overall high wave-energy environment (Grassle and Grassle, 1974; Pemberton et al., 1992b; Pemberton and MacEachern, 1997; Hansen and MacEachern, 2007; Bann et al., 2008). Furthermore, episodic deposition of graded beds related to storm activity in a mixed *Skolithos* and *Cruziana* Ichnofacies suggest that deposition occurred in water depths found between fairweather and storm-weather wave bases, i.e., in a storm-influenced, Shoreface to offshore-transition environment (Gingras et al., 2007; Bann et al., 2008; Pemberton et al., 2012).

Facies 13: Bioturbated Heterolithic Mudstone and Sandstone

Description:

Sedimentology: F13 is characterized by heterolithic, predominantly dark grey mudstone and tan to light grey, very fine- to fine-grained, well-sorted sandstone beds. Physical sedimentary structures included: wavy-parallel laminae, planar-parallel bedding, soft-sediment deformation, convolute bedding, micro-HCS, rip-up clasts, nodular bedding, current ripples, and planar laminae. Sandstone units are commonly thinly bedded (1 – 3 cm) and, where preserved, had sharp bases and tops. Lithological accessories included glauconite, ferrous grains indicated by dark black grains with rusty coloured halos, black lithic grains, pyrite and occasional dolomitic cement.

Ichnology: F13 is characterized by moderate to intense levels of bioturbation, typically in mudstone units punctuated by sandstone beds, ranging from absent to near absent levels of bioturbation (BI = 0 – 1) to nearly reworked (BI = 2 – 5) examples best described as lam-scram fabric. Ichnogenera observed include: *Arenicolites*, *Asterosoma*, *Chondrites*, *Cylindrichnus*, *Diplocraterion*, *Equilibrichnia*, *Palaeophycus*, *Planolites* and *Teichichnus*.

Interpretation:

F13 (Figure 2-13) is interpreted to represent deposition subjected to episodic storm activity in an otherwise low-energy environment with normal marine salinities. Moderately to intensely bioturbated mudstone beds dominate the facies and suggest a predominantly low-energy environment with ichnofauna under the influence of low to moderate sedimentation rates of silt-sized particles with a robust food supply (Gingras et al., 2007). Wavy-parallel laminae suggest minor to moderate wave influence coupled with sporadic erosional bottom currents (Raychaudhuri et al. 1992). The majority of the trace makers were deposit-feeders and mobile carnivores, whereas suspension-feeders likely dominated during storms, possibly having been transported seaward to storm waves (Frey and Pemberton, 1984; Raychaudhuri et al. 1992). Storm deposits were preserved as thinly-bedded, fine-grained sandstone beds with occasional micro-HCS and current ripples. Moreover these sandstone beds ranged from unbioturbated to being intensely reworked. This suggests that wave energy flucuated between storm events as some ichnofauna would have had time to recolonize new sediments or were under severe stress and lacked the opportunity to flourish (Gingras et al., 2007; MacEachern et al., 2007). In cases of the latter, rare examples of e*quilibrichnia* can be seen as organisms are attempted to come back to the sediment-water interface. The presence of *Asterosoma* suggests that deposition occurred in a fully marine environment (Pemberton et al., 1992c; MacEachern et al., 2005; Gingras et al., 2011). A result, facies F13 is interpreted to represent a storm-influenced distal lower shoreface of mixed proximal *Cruziana* and distal *Skolithos* Ichnofacies.

Facies 14: Bioturbated Green Mudstone

Description:

Sedimentology: F14 is characterized by medium to dark green and medium grey-green mudstone that is medium bedded (10 – 15 cm). Sedimentary structures include: wavy-parallel bedding, current ripples, rip-up clasts, load casts, discontinuous mud beds, and planar-parallel bedding. Lithological accessories include: glauconite, black lithic grains, pyrite, brachiopod fragments, trilobite fragments, and ferrous grains. This facies can be correlated over a significant portion of the study area, occurring in the Mount Clark and Mount Cap Formations.

Ichnology: F14 is characterized by moderate to intense bioturbation activity from predominantly diminutive *Palaeophycus*, *Planolites* and *Teichichnus*, though rare examples of *Arenicolites*, *Chondrites*, *Cylindrichnus*(?) and *Lockeia* were observed, bioturbation intensities ranged from 1 to 5.

Interpretation:

F14 (Figure 2-14) is interpreted to represent a predominantly low-energy, ichnologically stressed environment. The facies consists of mud-sized grains that were commonly reworked by a low diversity, deposit-feeding ichnofauna of diminutive size. This suggests that these organisms were living in a slightly to moderately stressed environment despite the moderate to intense bioturbation levels (MacEachern et al., 2007; MacEachern et al., 2010). *Teichichnus*, *Planolites* and *Palaeophycus* dominate this facies, providing evidence they were capable of adapting to this environment which could have had unusual geochemical properties. The lack of synaeresis cracks don't support a brackish environment and observed bioturbation levels support an environment with abundant food and predictable sedimentation rates (Gingras et al., 2007). It is plausible that dissolved oxygen levels were too low for many other ichnofauna to survive, however a key assemblage of resilient organisms with high tolerances were able to thrive. Facies F14 is seen in multiple wells and correlates across much of the basin commonly with facies F2 directly above. As noted previously, F2 is theorized to be nearly devoid of dissolved oxygen due to an overwhelming absence of bioturbation and monotonous planar bedding. Therefore, it is suggested that dissolved oxygen content was continually decreasing as a result of allocyclic factors across the entire basin (MacEachern et al., 2007). As a result F14 is suggested to represent deposition on the upper offshore in a stunted dissolved oxygen environment.

Facies 15: Fairweather Bioturbated Heterolithic Sandstone and Mudstone

Description:

Sedimentology: F15 is characterized by heterolithic tan, very fine-grained, well sorted, silty sandstone and light grey mudstone that lacked preservation of primary sedimentary structures. Only in rare examples were planar laminae, low-angle bedding and very slightly dolomitic nodular fabrics observed. Pyrite was uncommon. Additionally, glauconite and black lithics were observed in a single bed in Colville D-45. The ratio of sand-to-mud in F15 was approximately 60:40.

Ichnology: F15 is characterized by a moderately intense bioturbate texture (BI = 4 – 5) with uncommon beds of low to moderate bioturbation levels (BI = 1 – 3). The ichnological suite was composed of: *Asterosoma*, *Arenicolites*, *Chondrites*, *Cylindrichnus*, *Diplocraterion*, *Palaeophycus*, *Planolites*, and *Teichichnus*.

Interpretation:

F15 (Figure 2-15) is interpreted to represent deposition in a well-oxygenated, fully-marine environment with normal marine salinity levels, predictable or low sedimentation rates and an abundant food supply (Gingras et al., 2007). No storm activity can be demonstrated in this facies, which suggests that the environment was sheltered from storms by palaeogeographical barriers. Additionally, any storm beds that may have been deposited were likely thin and completely biogenically reworked (Raychaudhuri et al. 1992; Pemberton et al, 2012). Rare cases of low-angle and planar-parallel bedding are interpreted to represent periods of episodic progradation that shifted the facies temporarily basinward, or episodic influx of sediment that was partially bioturbated before lithification (Pemberton et al., 1992b). The observation of multiple *Asterosoma* suggests stable, fully-marine salinities (Pemberton, et al., 1992c; MacEachern et al., 2005; Gingras et al., 2011). Primary sedimentary structures are rarely preserved as a result of intense biogenic reworking, suggesting that ichnofauna were able to thrive for long periods of time (Pemberton et al., 1992a; Buatois et al., 2003). Deposit-feeding organisms dominate this facies in a thoroughly heterolithic, highly-bioturbated, very-fine grained, well-sorted sandstone and mudstone lithology, which suggests a distal lower shoreface succession of the most proximal *Cruziana* Ichnofacies in a fairweather depositional environment (Pemberton et al., 1992a; Pemberton and MacEachern, 1997; MacEachern et al., 1998; Pemberton et al., 2012).

Facies 16: Glauconite-Dominated "Sandstone"

Description:

Sedimentology: F16 is characterized by a lithology composed almost entirely out of very fine-grained, well-sorted glauconite grains with commonly abundant black lithics. Bedding appears structureless and overall facies thickness is commonly less than 25 centimeters thick, reaching a maximum of 75 centimeters in Colville D-45. F16 typically underlies F10 and occasionally F2 and F14, facies that tend to be widely correlated across the basin. Despite this, F16 was very difficult to correlate reliably, although it was observed in multiple cores across the basin.

Ichnology: Bioturbation intensity ranged from predominantly absent up to moderate (BI = 0 – 4). The physical appearance of this facies precludes reliable observations as the abundant glauconite coupled with black lithics obscured the cut surface whether wet or dry. In rare examples, ichnogenera that could be reliably identified included *Palaeophycus* and *Planolites*.

Interpretation:

The term glauconite facies was replaced by Odin and Matter (1981) to glaucony, which applies to a lithology with variable morphology and chemical and the physical properties of glauconite minerals and minerals similar to glauconite. The formation of glauconite, commonly nucleating on faecal pellets that are subjected to dissolution and maturation, can occur in a multitude of environments ranging from lagoonal to deep-ocean. Specifically, in the modern this process occurs in water depths from 50 – 500 meters where sedimentation rates are low for long durations and can serve as a transgressive indicator (Odin and Matter, 1981; Huggett and Gale, 1997; Mei et al., 2008; Amorosi, 2012). With respect to stacking patterns of facies, this appears to be supported by observation of F16 typically underlying offshore lithosomes of F2 or F14. However as Chafetz and Reid (2000) have observed, glauconitic minerals in such high abundance described as "glaucarenites" of Cambrian Wilberns Formation in southwestern US, which are similarly observed in F16 strata (Figure 2-16), may not always be used as reliable indicators for ancient depositional environment proxies. In contrast to depositional models for modern environments, they argue that during the Cambrian (and continuing into the Ordovician) glaucony also formed in high wave-energy environments in water depths approximately 10 meters deep with moderate to high sedimentation rates. Additionally, Eoff (2014) observed exceptionally glauconitic sandstone or "greenstone" beds with well-developed HCS in the Cambrian Reno Member, which formed also under high wave-energy environments that allowed winnowing and later accumulation during fairweather conditions. Of the whole Phanerozoic, the Furongian (Late Cambrian) in Laurentia had the greatest percentage of glauconite-bearing siliciclastic rocks (Peters and Gaines, 2012; Lee et al., 2015). Peters and Gaines (2012) attribute this to intense continental weathering from widespread epicontinental basins, which ultimately changed the alkalinity of the oceans leading to rapid authigenesis of glauconite. Therefore, F16 is interpreted to represent a storm-influenced middle to lower shoreface succession at a time with extreme continental chemical weathering.

Facies 17: Interbedded Shale and Carbonate

Description:

Sedimentology: F17 is characterized by medium to dark grey calcareous and dolomitic shales and mudstones, interbedded or locally interfingering with light to medium grey, fine-crystalline, structureless to nodular dolostone and light grey to tan, crypto- to fine-crystalline, centimeter-scale bedded limestone. Nodular carbonates appear as 5 cm-thick stacks of alternating dolostone and limestone beds. Sedimentary structures include: convolute bedding, load casts, low-angle bedding, planar-parallel bedding, rip-up clasts, micro-faulting, stylolites, nodular fabric and rarely vuggy. Lithological accessories include: calcareous and dolomitic cements, pyrite, glauconite, black lithics, trilobite fragments, brachiopod fragments, and algal laminations. F17 was observed in the upper Mount Cap in Colville E-15 and using wireline could be correlated throughout the basin.

Ichnology: Bioturbation intensities were commonly absent to low (BI = 0 – 2) however did range up to intense (BI = 6) in isolated nodular dolostone beds where F17 first appeared. Ichnogenera include: *Cylindrichnus*, *Paleophycus*, *Planolites* and *Teichichnus*. Bioturbation decreased up-section from where F17 first appeared.

Interpretation:

F17 (Figure 2-17) is interpreted to represent deposition that shifted throughout the deep ramp sub-section of a carbonate ramp, which resided between fairweather and storm wave. The facies is dominated by planar-parallel to low-angle laminated calcareous to dolomitic shales suggesting that wave energy was commonly low and deposition was a result of fine suspension fall-out (Dillard et al., 2010; Jones, 2010). Abundant shales represent a distal part of the facies while rhythmically-bedded nodular carbonates suggest deposition in a proximal environment closer to fairweather wave base likely due to bioturbation and early cementation (Tucker and Wright, 1990; Pope et al., 2012). The irregular appearance of alternating dolostone and limestone nodules is the result of inconsistent or patchy cementation rates, potentially from bioturbation influence or recording storm and current deposition (Tucker and Wright, 1990; Dilliard, 2006; Pope et al., 2012).

Facies 18: Organic Mudstone and Conglomerate

Description:

Sedimentology: F18 is characterized by predominantly black to dark brown, petroliferous, planar-parallel bedded mudstones with a bed approximately 1.5 m thick of matrix-supported conglomerate. The matrix consisted of light grey to tan, fine- to medium-grained, moderately well sorted, dolomitic sandstone with cm-scale bedding while clasts were dark grey, fine-grained up to upper pebble and well-rounded composed of carbonate mudstone. Clasts are very sporadic and appear to indent underlying strata. A single 0.25 m thick bulbous algal-mound was identified in isolation from surrounding core as these sections were missing in the core box. Contacts between mudstone and conglomeratic lithosomes are sharp, as are cm-scale beds within the conglomerate.

Ichnology: F18 is devoid of bioturbation and no trace fossils were identified.

Interpretation: Basin of Carbonate Ramp

F18 (Figure 2-17) is characterized dark brown to black, petroliferous mudstones and episodic deposition of conglomerates and allochthonous algal-mounds, suggesting deposition in a deep-water basin environment below storm wavebase on a carbonate ramp. Large allochthonous mudstone clasts that load strata beneath suggest early lithification in conjunction with tectonic instability across the ramp resulting in sediment gravity flows (Dilliard et al, 2006; Pope et al, 2012). Planar-parallel to low-angle laminated mudstone lithosomes record deposition of sediments that were transported from the mid- to deep-ramp as a result of suspension fallout and storm-initiated turbidity currents (Jones, 2010). Geochemical work by Dixon and Stasiuk (1998) identified the petroliferous mudstones to be an algal-rich Type I kerogen ranging from mature to immature source rock observed in the upper Mount Cap Formation. The petroliferous smell found exclusively in F18 mudstones supports this assessment. Moreover, the origin of the mudstones is likely the result of an accumulation of organic materials with no post-depositional biological influence (Landing, 2012).

Facies 19: Interbedded Sandy Carbonate and Shale

Description:

Sedimentology: F19 is characterized by light to dark grey, sandy, crypto- to fine-crystalline dolostone and light to medium grey, fine-grained, well-sorted dolomitic sandstones with abundant black lithic grains. Interbedded throughout are dark grey to rarely dark green, soft shales that are sporadically dolomitic and that range between 0.25 to 1.0 m thick. Sedimentary structures include: Low-angle bedding, planar-parallel bedding, convolute bedding, isolated algal lamination beds and uncommon red anhydrite chips. Contacts are commonly sharp and erosional, appearing as knife-sharp or scour features.

Ichnology: F19 is devoid of bioturbation and no trace fossils were identified.

Interpretation:

F19 (Figure 2-18) is interpreted to represent deposition on a carbonate ramp in the shallow ramp zone above fairweather wave base where wave-energy and clastic input are relatively high. Sandstone and algal beds are interpreted to be mixed clastic and carbonate shoals that acted as hydrodynamic barriers to the lagoon situated behind it (Dilliard et al., 2006; Jones, 2010, Thomson et al., 2014). The seafloor in this environment would be under constant agitation and susceptible to erosion from storms, which is supported by the multiple erosional contacts throughout the facies. Lack of bioturbation in this facies may have resulted from fluvial input (Pope et al., 2012). Shales are interpreted to be lagoonal deposits between or behind shoals and islands (Burchette and Wright, 1992; Jones, 2010; Thomson et al., 2014; James and Jones, 2016).

Facies 20: Interbedded Evaporite, Mudstone and Dolostone

Description:

Sedimentology: F20 is characterized by translucent brown to pale orange massive, thickly-bedded halite with hints of parallel-laminated structures, interbedded with light grey-green to maroon, planar-parallel to low-angle bedded mudstones, scattered bright orange anhydrite deposits and light grey, cryptocrystalline, centimeter-scale bedded dolostone with occasional peloids. Additional sedimentary structures include: current ripples, chaotic bedding and high-angle bedding. The basal 10 meters of the facies is predominantly interbedded mudstone and dolostone, with very little to no influence of salt intrusions, only appearing as mm-scale fracture fills. Up-section of this, the occurrence and influence of halite lithosomes is abundant which resulted in a brecciated fabric with mudstone clasts that appeared to be floating in a halite matrix. F20 appeared exclusively in the Colville E-15 well but can be reliably correlated throughout the basin using wireline logs.

Ichnology: F20 is devoid of bioturbation and no trace fossils were identified.

Interpretation:

F20 (Figure 2-18) is composed primarily of thick halite beds with interbedded mudstones and dolostones. Mudstones and dolostones beds are interpreted to represent restricted conditions in small-scale lagoonal environments in conjunction with substantial storm or flooding events (Dilliard, 2006; Dilliard et al., 2007; Pope et al., 2012). Tens of meters-thick halite deposits, observed up-section from the basal lagoonal and flood deposits, are correlated throughout the basin using wireline logs. These massive deposits of halite could be attributed to a closed-basin environment, resulting from paleogeographic highs that effectively helped cut-off any external influence from the open-ocean resulting in the formation of a deep brine fluid (Kendall, 2010). A faintly laminated fabric was observed in the thick halite beds which suggests that deposition occurred as "deepwater evaporites" that develop as evaporites formed at the brine-air interface, or as deep as 2 meters, crystallize and rain down on the basin floor (Warren, 2006).

FACIES ASSOCIATIONS DISCUSSION

Twenty different facies have been grouped into four facies associations within the study area and are summarized in Table 2-2. Lateral and vertical successions of these facies associations are shown as schematics in Figure 2-19 and will be further discussed in Chapter 3.

FA1 – Storm-Influenced Shoreface

Facies: 4, 7, 12, 13, 16

FA1 is characterized by facies that record deposition in environments with moderate to high wave energy, episodic and high rates of sediment deposition, absent to moderate bioturbation levels, restricted ichno-diversity, and generally diminutive ichnofauna. Grain sizes range from very fine to coarse and sorting from poor to well. Primary sedimentary structures are commonly preserved, such as HCS, trough cross-bedding, convolute bedding, rip-up clasts and load casts. Opportunistic ichnofauna partially reworked the top of storm deposits which commonly had sharp, erosional bases, creating a laminated-scrambled or "lam-scram" fabric most predominantly in the lower shoreface successions. FA1 is unpredictable in nature with respect to shifting substrates, sedimentation loads, wave energy and variable salinity levels resulting in a stressful environment for ichnofauna to survive throughout the shoreface profile. Stacking of individual facies is often not predictable. FA1 depositional environments ranged from lagoon, proximal *Skolithos* Ichnofacies, to distal lower shoreface, proximal *Cruziana* Ichnofacies.

FA2 – Fairweather Shoreface

Facies: 5, 6, 8, 10, 11, 15

FA2 is characterized by deposition in environments with moderately to intensely bioturbated sandstones, and heterolithic sandstones and mudstones, ranging in grain size from very fine- to medium (occasionally coarse), and nodular dolostone of F10. The ichnological suite is relatively more robust and diverse than other facies associations as a result of ample food supplies, low sedimentation rates, fully marine salinities, and wave-energy that was attenuated or blocked in sheltered environments which allowed ichnofauna to thrive. This abundance of bioturbation throughout FA2 led to extensive reworking and poor preservation of primary sedimentary structures. The fairweather paleoenvironment interpretation is primarily based on high ichno-diversity and the abundance of bioturbation throughout. Moreover, the lack of observed sedimentary structures such as HCS or tempestites further minimizes support for major storm influence. Record of such events occurring likely would have been too extensively biogenically reworked to be reliably identified. In rare examples, facies stacked in a consecutive shallowing order (F15, F8, F11 in Colville D-45 from 930 – 924 m, for example), however it was more common to observe a sporadic succession of facies. FA2 depositional environments ranged from upper shoreface, proximal *Skolithos* Ichnofacies, to distal lower shoreface, proximal *Cruziana* Ichnofacies.

FA3 – Offshore

Facies: 2, 3, 9, 14

FA3 is characterized by fine-grained deposits dominantly consisting of mudstones and shales with occasionally bioturbated heterolithic mudstones and sandstones. F14 is commonly observed directly below F2, which is interpreted as an overall deepening of the basin and decrease in dissolved oxygen levels as bioturbation intensities dropped substantially. In exceptional examples, transgressive lag deposits of F9 are preserved below F14. Wave-energy was commonly low, with deposition occurring from fairweather wave base to below storm wave base of the upper to lower offshore, *Cruziana* Ichnofacies.

FA4 – Carbonate Ramp

Facies: 17, 18, 19, 20

FA4 is characterized by deposition along a shallow carbonate ramp in an overall prograding succession ranging from deep basin to supratidal/sabkha. A thin interval of black, petroliferous mudstones and conglomerates (F18) represent deposition in an anoxic, deep basin environment below storm wave base. Interbedded shales and carbonate beds (F17) represent deposition between fairweather and storm wave base and comprise a significant portion of the observed lithologies through the facies association. The only facies that had observable bioturbation was F17, which suggests that oxygen levels and food supplies were stressful but could support for resilient ichnofauna. F19 is a thin interval of mixed carbonate and clastic input with relatively high amounts of algal lamination representing deposition above fairweather wave base as a barrier to F20. Thin dolostone and mudstone interbeds with occasional anhydrite chips are interpreted as sabkha deposits while thick-bedded halite packages represent more basin-ward evaporites formed from the settling of crystallized evaporites at the surface, and comprises the majority of the observed lithosomes in the facies.

CONCLUSIONS

A high-resolution facies analysis utilizing sedimentological and ichnological observations of the Lower and Middle Cambrian succession in the Colville Basin has recognized in 20 different facies representing 4 distinct different facies associations. FA1 represents depositional environments that have been subjected to storm surges, variable marine salinities and episodic sedimentation yielding little to no bioturbation along a shoreface profile. In contrast, FA2 represents facies deposited also along a shoreface profile, but which contain evidence for suggests robust food supplies, low sedimentation rates and intense sediment reworking by diverse ichnofauna. FA3 represents facies of transgressive and deep ocean environments where low to absent dissolved oxygen levels severely hindered the success of ecosystems. FA4 represents facies that comprise all sub-environments of a carbonate ramp and include both Mount Cap and Saline River formations. The variety of facies and facies associations is in part from the inclusion of three different formations that were likely deposited in significantly different basin architectures. However, the sharp contrast between fairweather and storm-influenced paleoenvironments observed within the Mount Clark and lower Mount Cap is partly attributed to the large geographical distances between well locations. To further complicate matters, deposition at the locations of these wells within the Colville Basin is greatly influenced by paleotectonic features and basin configuration. Despite these challenges, reliable and correlatable facies were described and that can future exploration and exploitation within the Colville Basin.

FIGURES

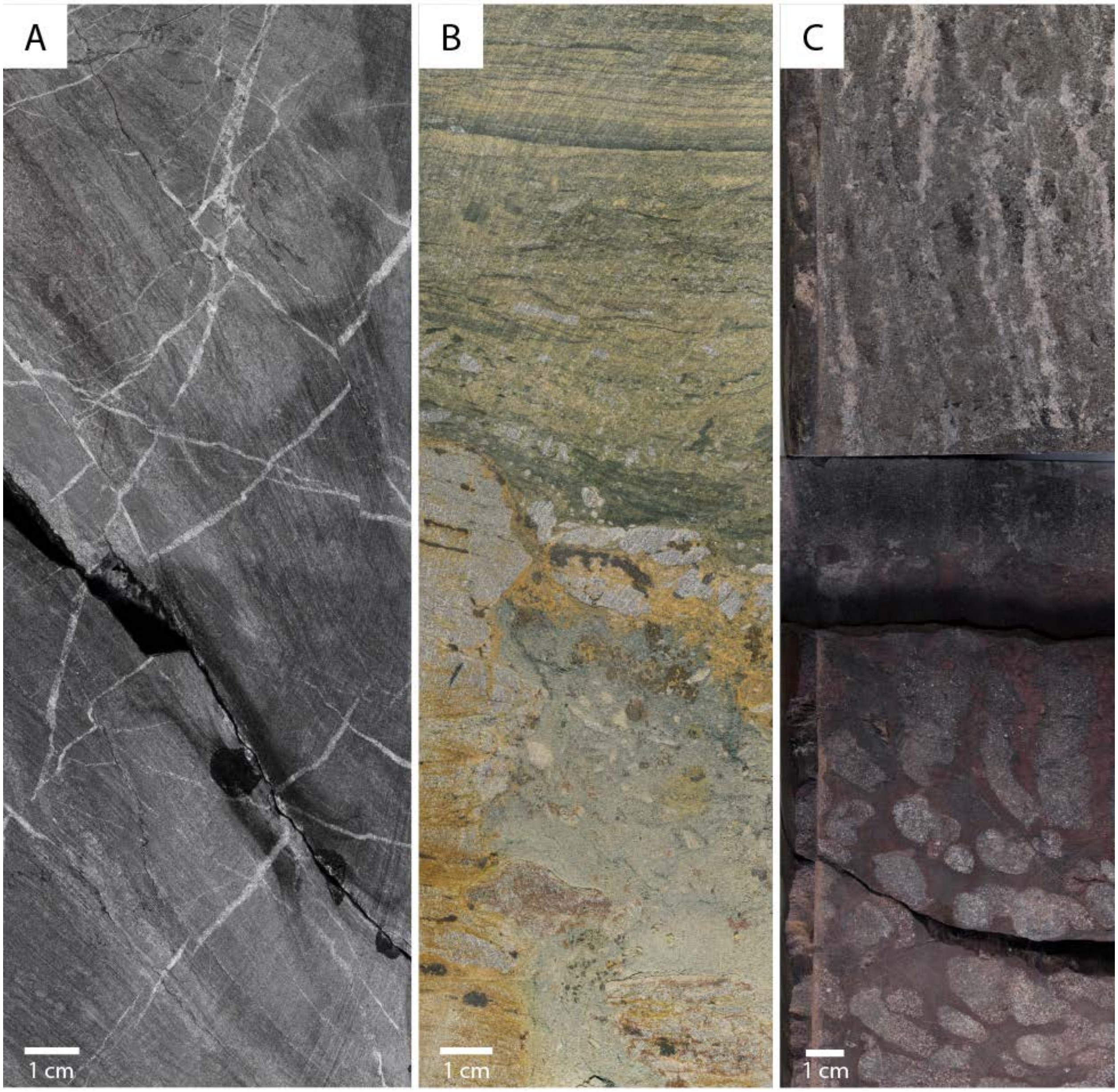


Figure 2-1. Facies Plate 1 (Facies 1)

(**A**) High-angle bedding with fractured and offset quartz veins in black dolostone host rock of Hornby Bay Assemblage. Ontadek Lake N-39.
(**B**) Sub-Cambrian unconfirmity dissolution cavity with pale green clay fill; above is F7 of Mount Clark. North Colville L-21.
(**C**) Sub-Cambrian unconformity *Glossifungites* surface with overlying F5 facies "piperock" composed of unlined *Skolithos* traces and below are fine-grained sand filled burrows of ?*Thalassinoides* and ?*Skolithos* trace fossils in a host maroon basalt of Tweed Lake Assemblage. Tweed Lake A-67.

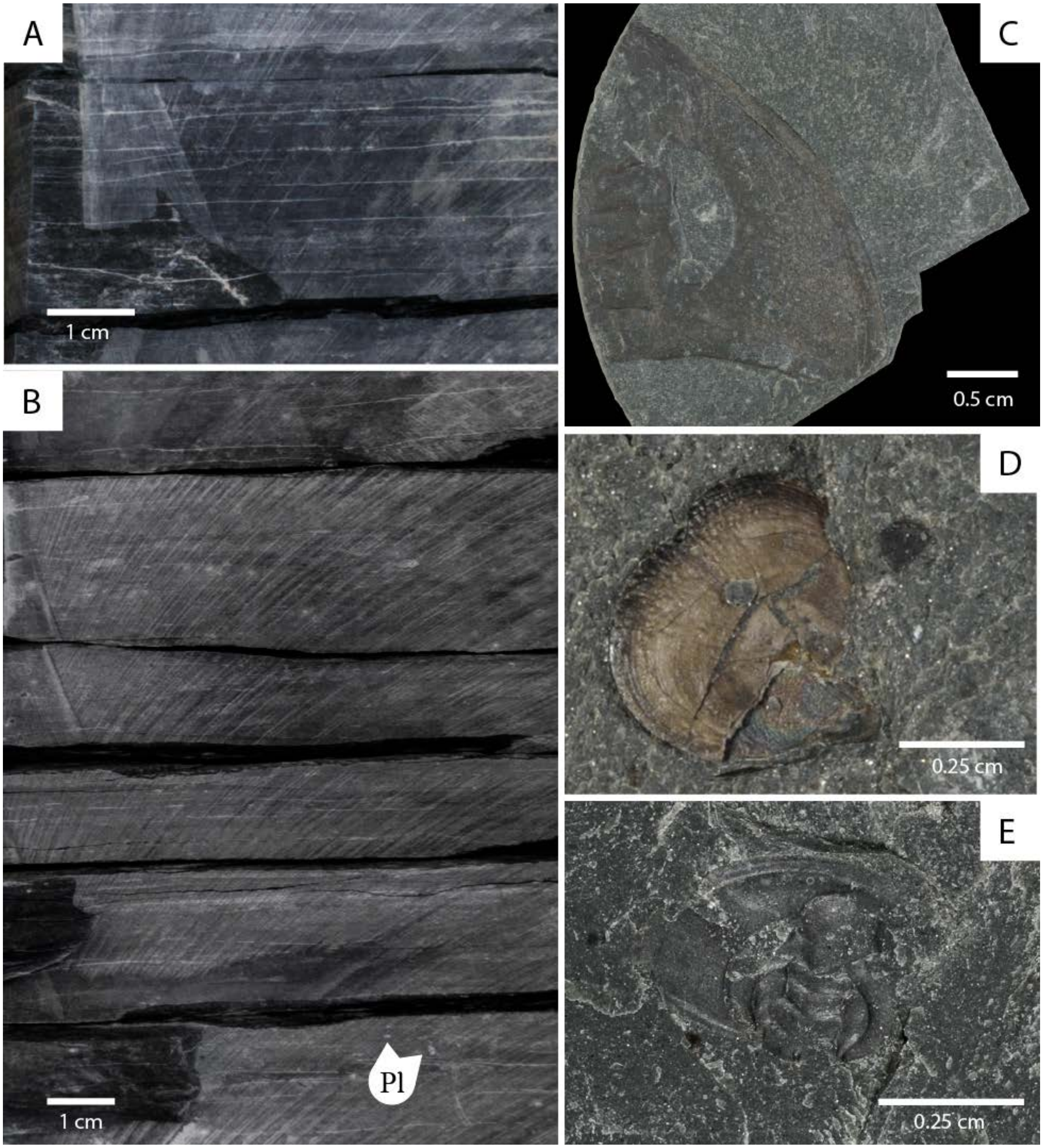


Figure 2-2. Facies Plate 2 (Facies 2)

(**A**) Archetypal facies F2 illustrating dark grey, parallel-bedded shale with mm-scale very fine-grained sandstone interbed. Tweed Lake A-67.
(**B**) Archetypal facies F2 illustrating dark grey, parallel-bedded shale with isolated diminutive *Planolites* (*Pl*). Tweed Lake C-12.
(**C**) Trilobite cephalon fragment. North Colville L-21.
(**D**) Brachiopod fragment. North Colville L-21.
(**E**) Trilobite cephalon fragment. North Colville L-21.

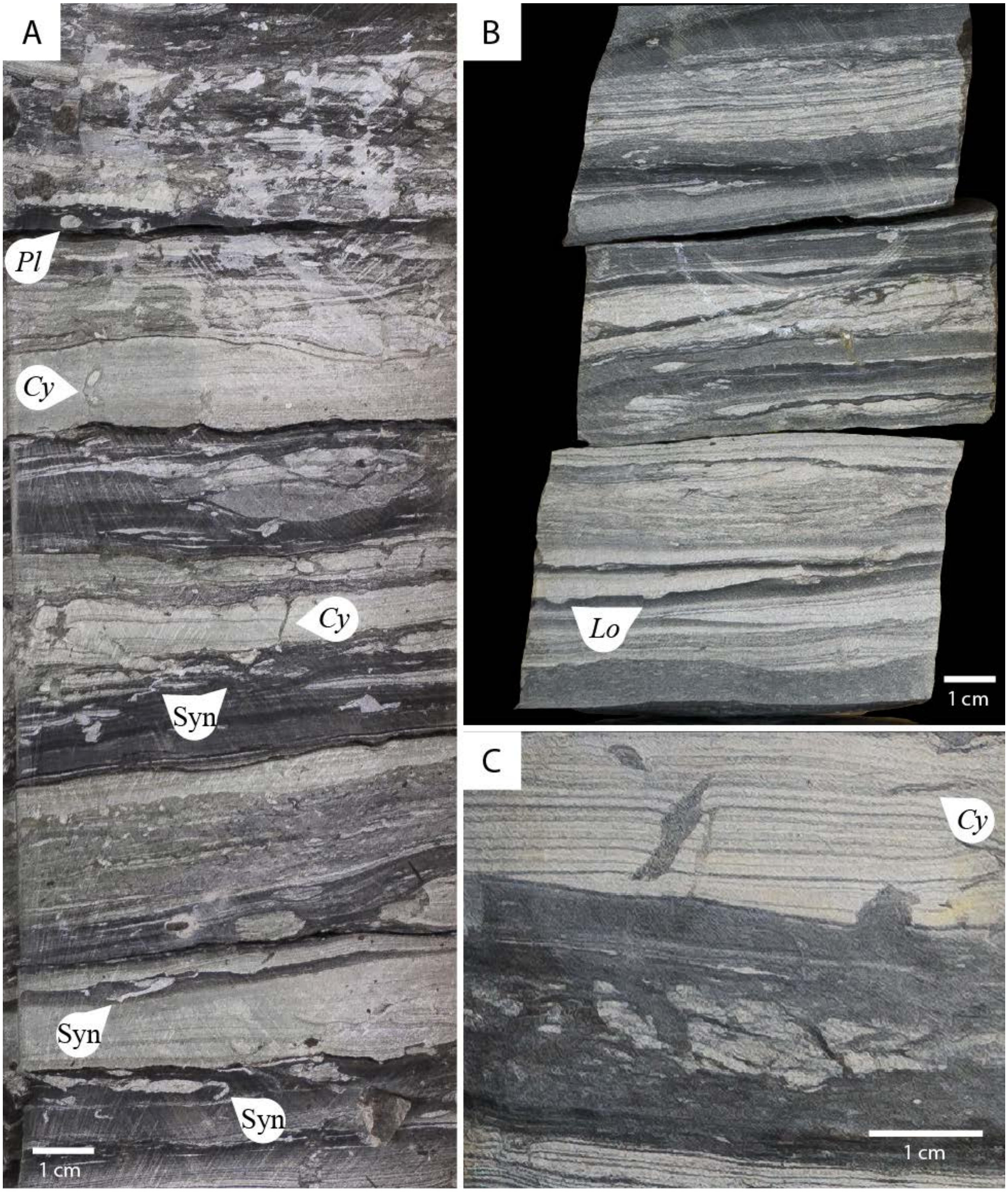


Figure 2-3. Facies Plate 3 (Facies 3)

(**A**) Sharp bases and tops of laminated very fine-grained sandstones interbedded with dark grey bioturbated mudstones of prodelta successions with noteable synaeresis cracks (Syn), and *Cylindrichnus* (*Cy*) and *Planolites* (*Pl*) trace fossils. Tweed Lake M-47.
(**B**) Well bedded very fine-grained sandstones and mudstone beds with rare *Lockeia* (*Lo*) traces. Colville D-45.
(**C**) Zoomed in photo showing the sharp base and tops of laminated sandstone beds with rare trace fossils of *Cylindrichnus* (*Cy*). Colville D-45.

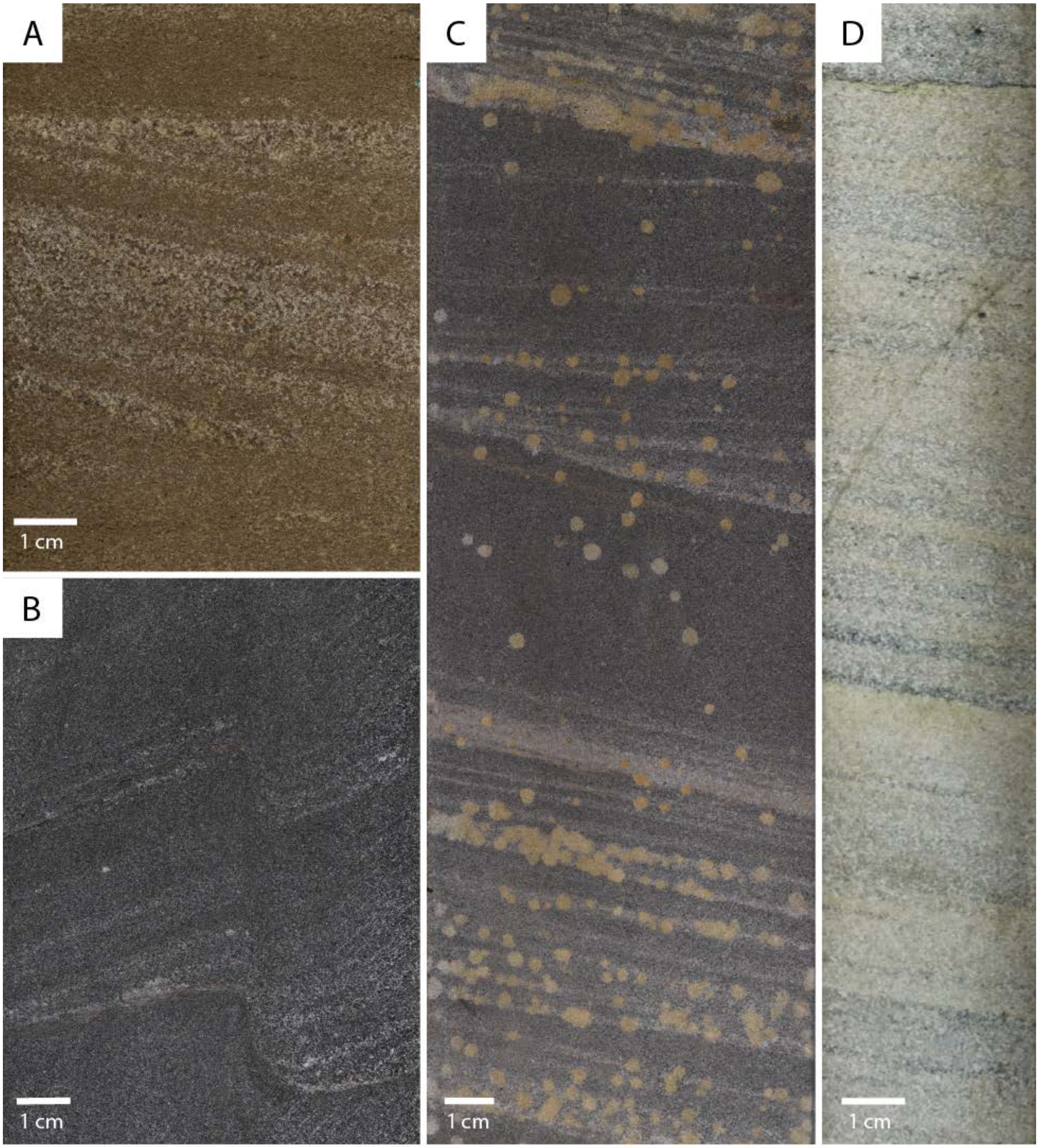


Figure 2-4. Facies Plate 4 (Facies 4)

(**A**) Oil-stained medium-grained sandstone with high-angle bedding topped by a reactivation surface. Colville D-45.
(**B**) Soft-sediment deformation likely resulted from some combination of rapid deposition and loading, seismicity and cyclic storm activity. Tweed Lake A-67.
(**C**) Low- to high-angle bedding grading into HCS beds. Orange spots throughout are reduction spheres. Tweed Lake A-67.
(**D**) Typical low-angle bedding found throughout F4. Colville E-15.

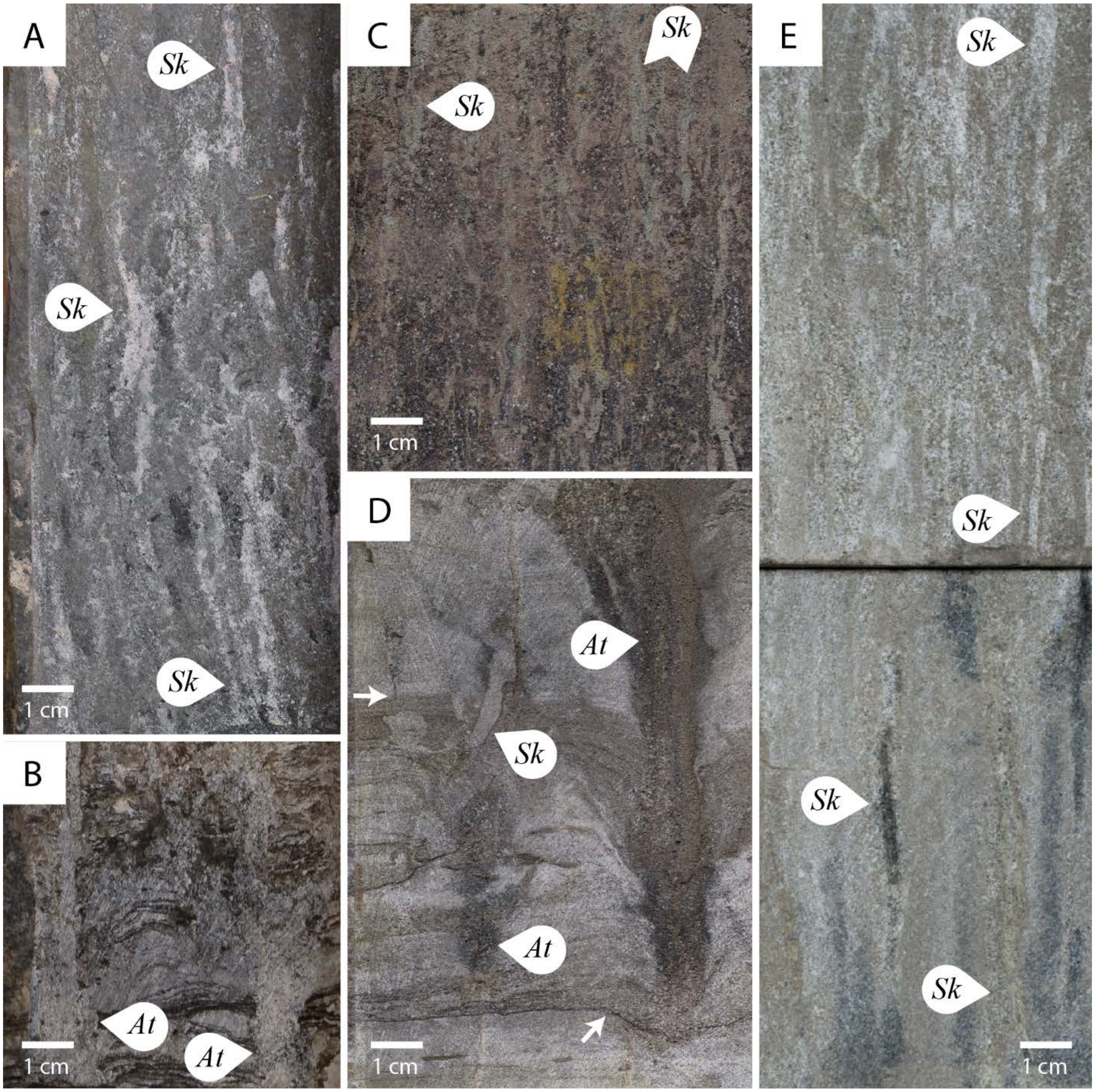


Figure 2-5. Facies Plate 5 (Facies 5)

(**A**) Intensely bioturbated sandstone with abundant *Skolithos* (*Sk*). Tweed Lake A-67.
(**B**) Moderately bioturbated sandstone with *Altichnus* (*At*) traces. North Colville L-21.
(**C**) Intensely bioturbated fine-grained sandstone with abundant *Skolithos* (*Sk*). Tweed Lake C-12.
(**D**) Moderately bioturbated sandstone with *Skolithos* (*Sk*) and *Altichnus* (*At*) trace fossils shifting upwards to adjust for the increased sedimentation rates. White arrows denote bed boundaries. Tweed Lake A-67.
(E**)** Intensely bioturbated medium-grained sandstone with abundant *Skolithos* (*Sk*). Tweed Lake A-67.

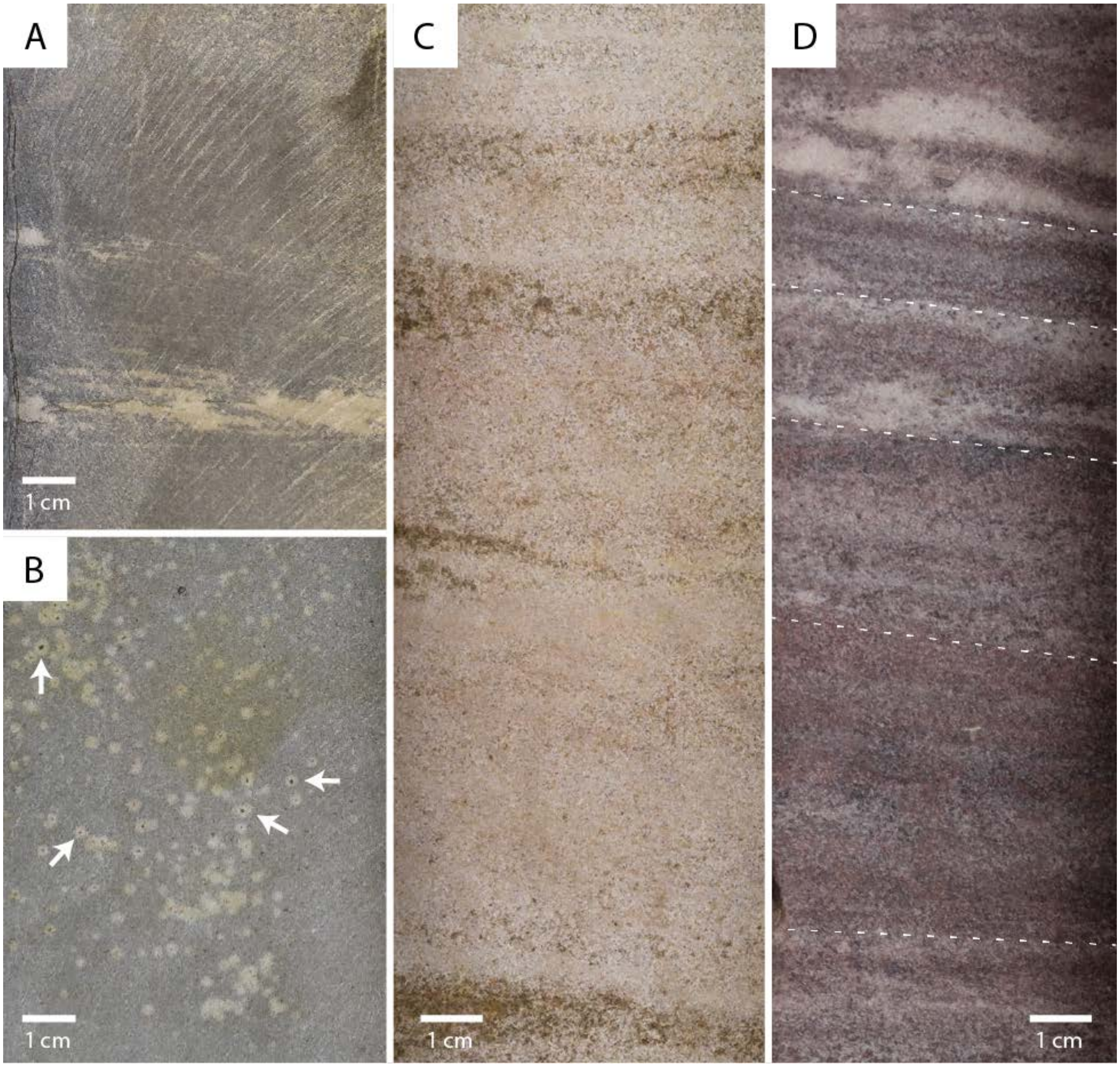
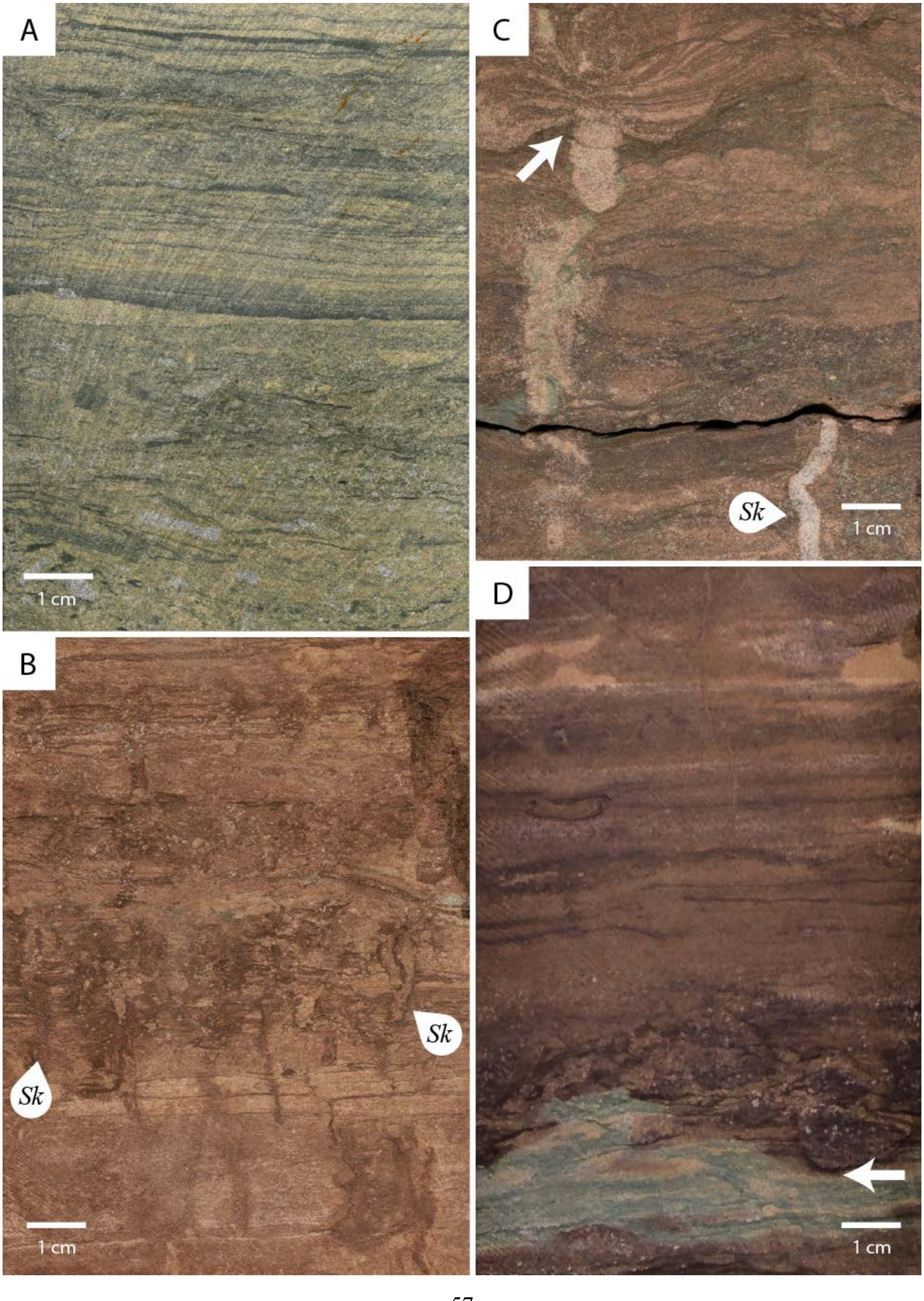


Figure 2-6. Facies Plate 6 (Facies 6)

(**A**) Faintly low-angle to parallel bedded, very fine- to fine-grained sandstone. Tweed Lake C-12.
(**B**) Structureless appearing very fine- to fine-grained sandstone with ferrous grains and light orange halos with black centers (white arrows).Tweed Lake A-67.
(**C**) Structureless appearing medium-grained quartz arenite sandstone. Stopover K-44.
(**D**) Low-angle bedded (dashed white lines), medium-grained sandstone with slightly patchy liesegang banding. Stopover K-44.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1 cm
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Figure 2-7. Facies plate 7 (Facies 7)

(**A**) Thinly-bedded very fine-grained sandstone with rip-up clasts at base. North Colville L-21.
(**B**) Typical faintly-bedded lagoon deposits with diminutive *Skolithos (Sk)*. Stopover K-44.
(**C**) Storm-influenced deposits of heterolithic very fine-grained sandstone and green clay with single *Skolithos* (*Sk*) trace fossil. (Load feature? white arrow). Stopover K-44.
(**D**) Convolute-bedded (white arrow) green clay laminae and sandstone with reverse grading from medium- to very fine-grained. Stopover K-44.

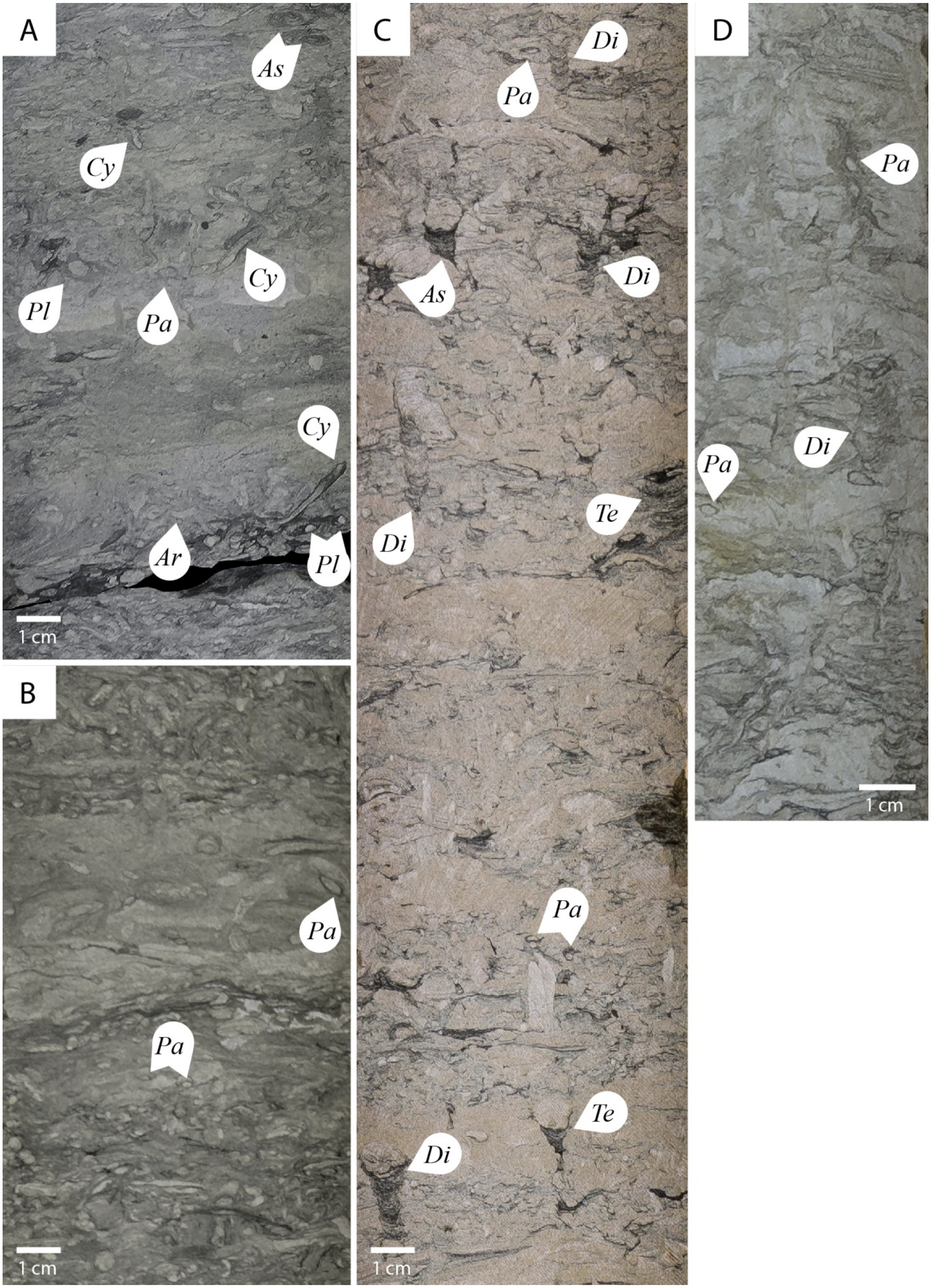

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Figure 2-8. Facies plate 8 (Facies 8)

(**A**) Intensely bioturbated very fine-grained heterolithic sandstone and mudstone with *Arenicolites* (*Ar*), *Cylindrichnus* (*Cy*), *Palaeophycus* (*Pa*) and *Planolites* (*Pl*). Colville D-45.
(**B**) Intensely bioturbated very fine-grained heterolithic sandstone and mudstone with *Palaeophycus* (*Pa*). Colville D-45.
(**C**) Intensely bioturbated very fine-grained sandstone with *Asterosoma* (*As*), *Diplocraterion* (*Di*), *Palaeophycus* (*Pa*), and *Teichichnus* (*Te*). North Colville L-21.
(**D**) Moderately intense bioturbation throughout a very fine-grained sandstone with *Diplocraterion* (*Di*) and *Palaeophycus* (*Pa*). Colville E-15.

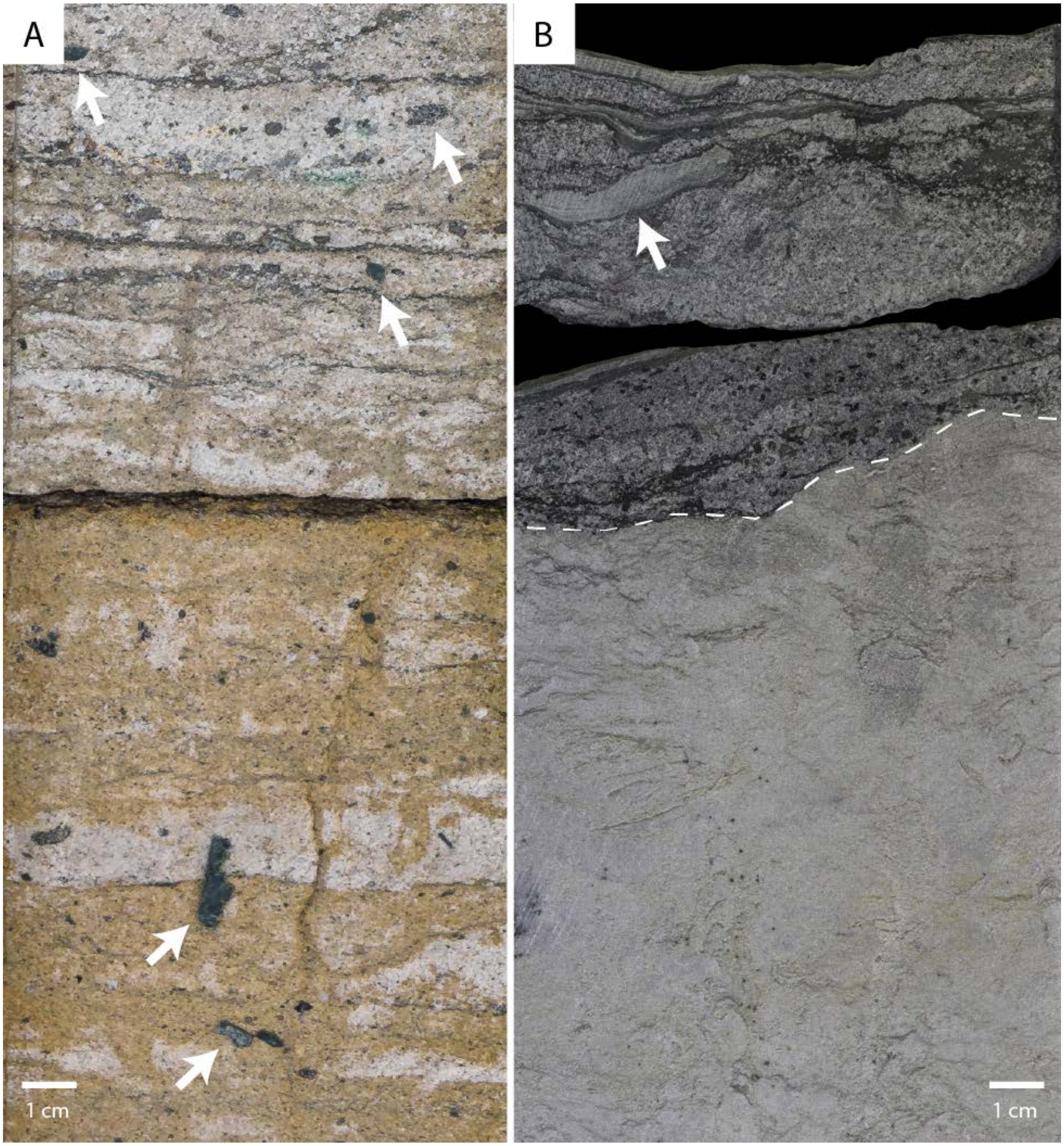

Figure 2-9. Facies Plate 9 (Facies 9)

(**A**) Transgressive lag deposits with green shale rip-up clasts from facies F14 (white arrows) in a moderately poor-sorted sandstone. Tweed Lake A-67.
(**B**) Abrupt erosional contact (dashed white line) with underlying facies F11 and overlying facies F9. A large lag deposit (white arrow), abundant black lithics and very thin green laminae are also present in a moderately-sorted sandstone. Tweed Lake C-12.

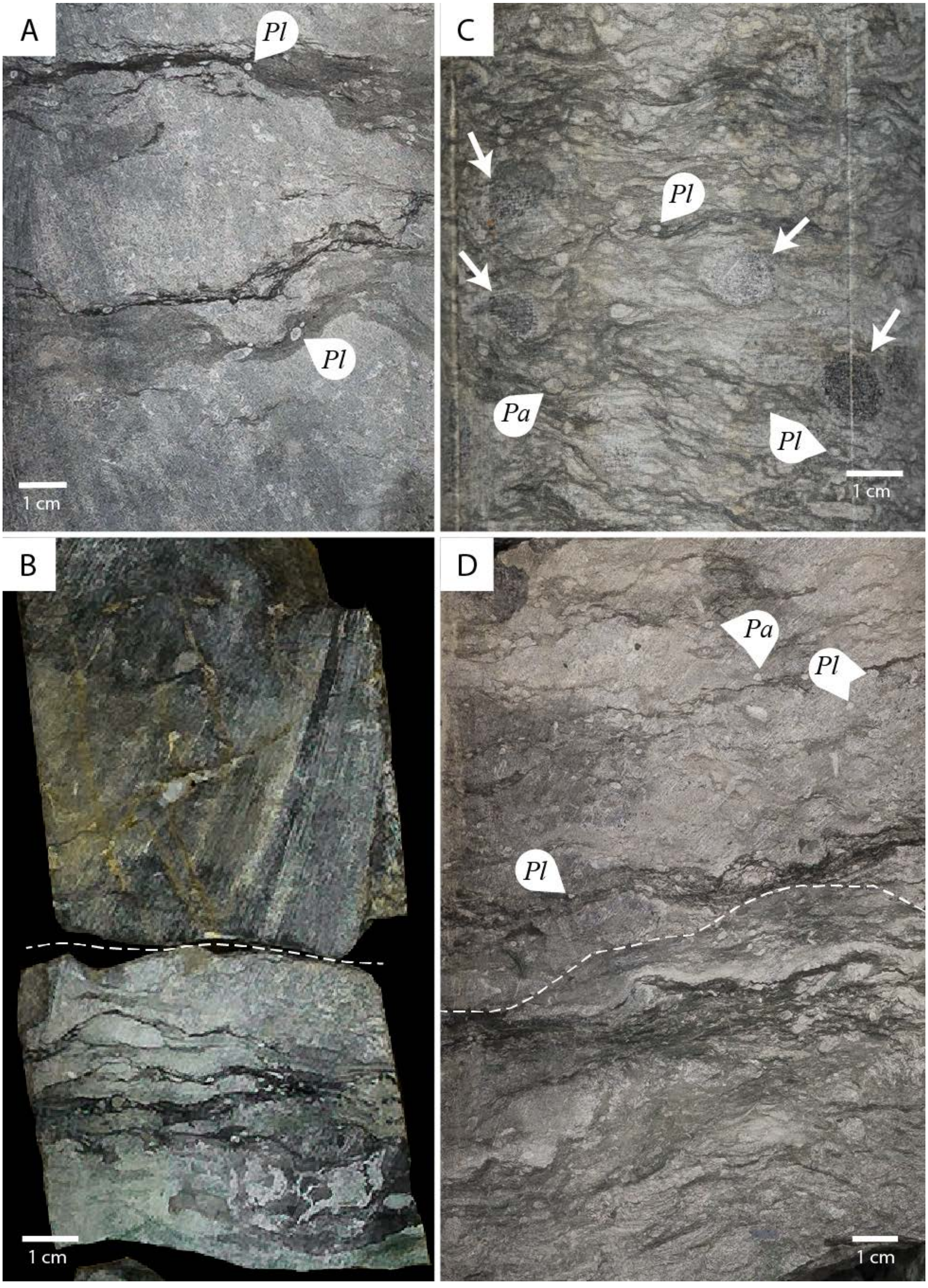
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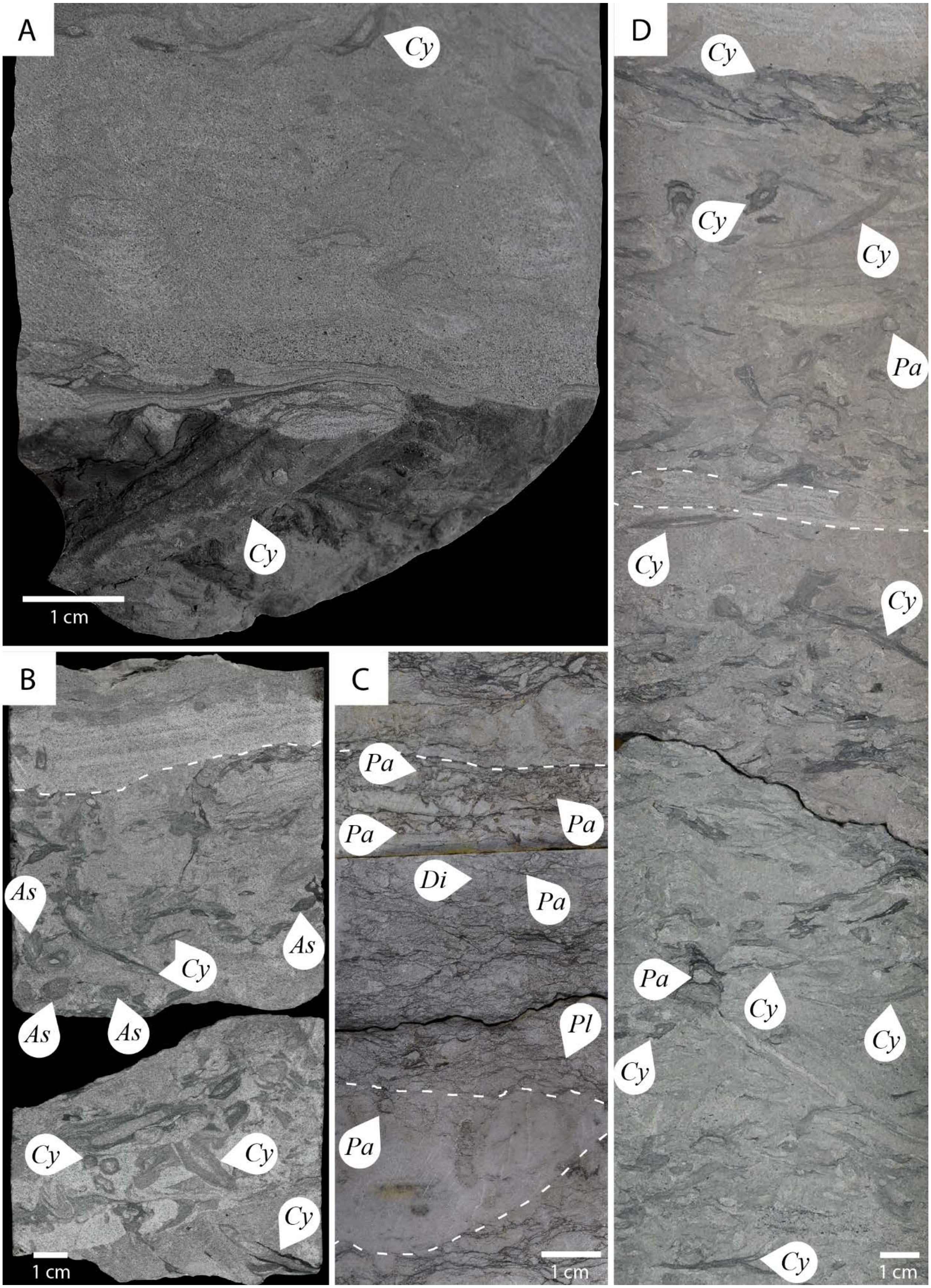
Figure 2-10. Facies 10 Plate (Facies 10)

(**A**) Common F10 character of dark grey nodular dolostone with convolute, mm-scale black mudstone laminae. Occasional *Planolites* (*Pl*) and *Palaeophycus* (*Pa*) are observed. Tweed Lake A-67.
(**B**) White dashed line indicating contact between the green shale of F14 in underlying Mount Clark with overlying dark grey nodular dolostone of F10 in Mount Cap. Colville E-15.
(**C**) White arrows indicated open burrows which were hydraulically filled with fine-grained sand with occasional *Planolites* (*Pl*) and *Palaeophycus* (*Pa*) trace fossils. Colville D-45.
(**D**) White dashed line indicating contact between the green shale of F14 in underlying Mount Clark with overlying dark grey nodular dolostone of F10 in Mount Cap. Occasional *Planolites* (*Pl*) and *Palaeophycus* (*Pa*) are observed. Bele O-35.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1 cm
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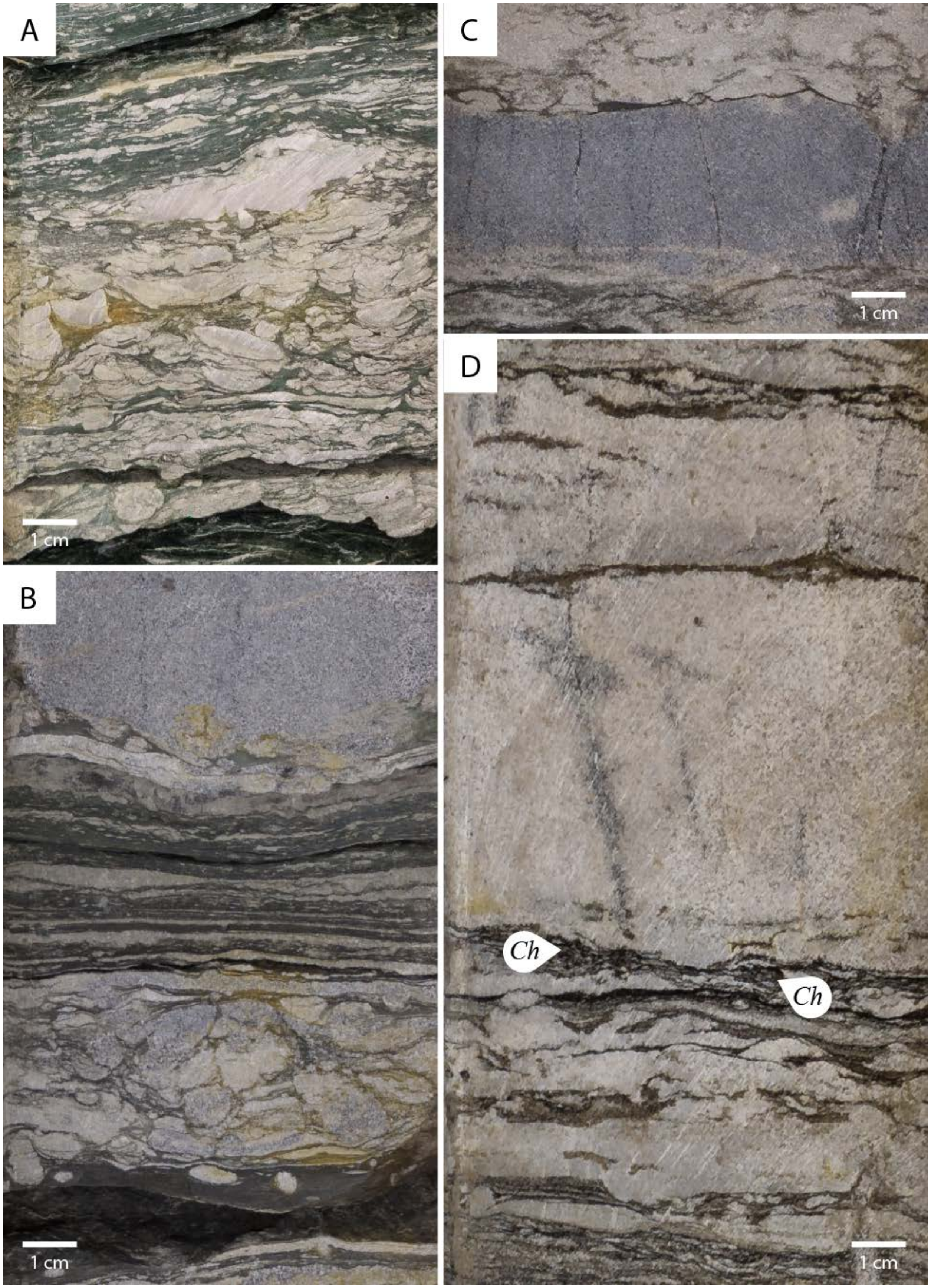
Figure 2-11. Facies plate 11 (Facies 11)

(**A**) Excellent example of *Cylindrichnus* (*Cy*) with 3D relief. Colville D-45.
(**B**) Intensely bioturbated very fine- to fine-grained sandstone with abundant *Asterosoma* (*As*) and *Cylindrichnus* (*Cy*). The base of a storm bed is noted by the white dashed line. Colville D-45.
(**C**) Intensely bioturbated very fine-grained sandstone with *Diplocraterion* (*Di*), *Palaeophycus* (*Pa*) and *Planolites* (*Pl*) traces. Occasional storm beds are outlined by the white dashed line. Bele O-35.
(**D**) Intensely bioturbated very fine- to fine-grained sandstone with *Asterosoma* (*As*), *Cylindrichnus* (*Cy*), *Palaeophycus* (*Pa*) and *Planolites* (*Pl*) traces. A partial biologically-reworked storm bed is outlined by the white dashed line. Colville D-45.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C
1 cm
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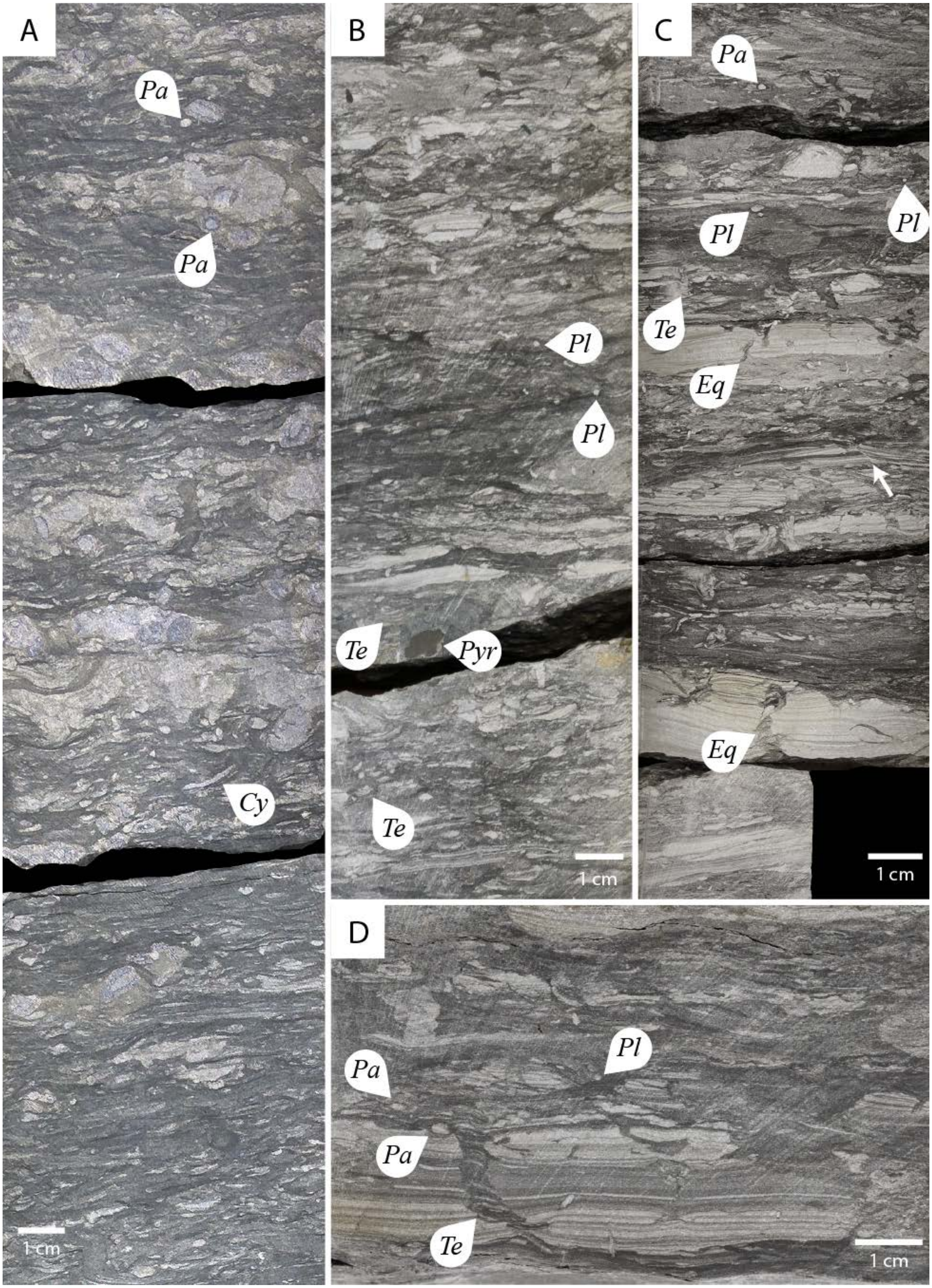
Figure 2-12. Facies plate 12 (Facies 12)

(**A**) Slightly bioturbated mudstone with tempestite deposits of hydraulically-reworked sandstone below. Bele O-35.
(**B**) Sediment loading from tempestite beds on dark green mudstone deposits with lag deposits below. Note the sharp contacts throughout.Tweed Lake M-47.
(**C**) Strucutreless-appearing sandstone beds from mass-sediment transport shown here as two events indicated by a contrast in grey and tan sandstones. Tweed Lake C-12.
(**D**) Slightly bioturbated mudstone laminae with *Chondrites* (*Ch*) and structureless-appearing sandstone tempestite beds above which buried organisms below. Tweed Lake M-47.


A
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Pa
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1 cm
B
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Pa
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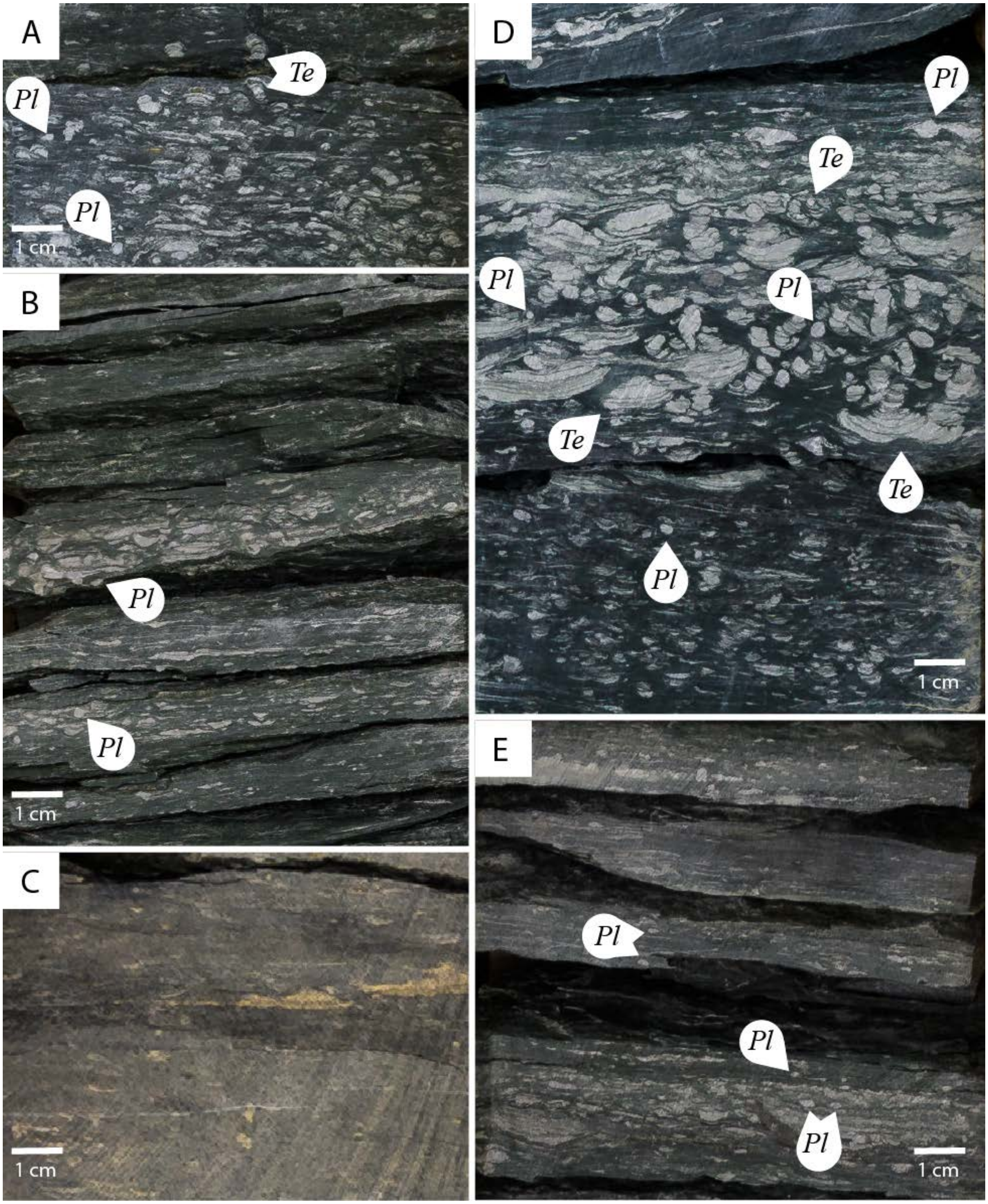
1 cm
D
Pl
Pa
Pa
Te
1 cm

Figure 2-13. Facies plate 13 (Facies 13)

(**A**) Moderately intense bioturbated heterolithic mudstone and sandstone with biogenically-reworked sandstone deposits, here dolomitic with rare diminutive *Cylindrichnus* (*Cy*) and *Palaeophycus* (*Pa*). Colville D-45.
(**B**) Moderately intense bioturbated heterolithic mudstone and sandstone with biogenically-reworked laminated very fine-grained sandstone beds. A single case of a large pyrite (Pyr) deposit with rare and diminutive *Planolites* (*Pl*) and *Teichichnus* (*Te*) traces. Tweed Lake C-12.
(**C**) Typical lam-scram appearance of a storm-influenced environment. Note the micro-faulting (white arrow) and Equilibrichnia (Eq), *Palaeophycus* (*Pa*), *Planolites* (*Pl*) and *Teichichnus* (*Te*) traces. Bele O-35.
(**D**) Moderately bioturbated heterolithic mudstone and sandstones with occasional *Palaeophycus* (*Pa*) and *Planolites* (*Pl*) traces. An exceptional example of a *Teichichnus* (*Te*) burrowing into thin, laminated, post-storm very fine-grained sandstone deposit is shown. Bele O-35.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E
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Pl
Pl
1 cm

Figure 2-14. Facies plate 14 (Facies 14)

(**A**) Intensely bioturbated green mudstone with *Planolites* (*Pl*) and *Teichichnus* (*Te*). Tweed Lake C-12.
(**B**) Green bioturbated mudstone with *Planolites* (*Pl*). Bele O-35.
(**C**) Moderately bioturbated green-grey mudstone. North Colville L-21.
(**D**) Intensely bioturbated green mudstone bed with *Planolites* (*Pl*) and *Teichichnus* (*Te*). Tweed Lake A-67.
(**E**) Moderate to intensely bioturbated green mudstone with *Planolites* (*Pl*). Tweed Lake M-47.

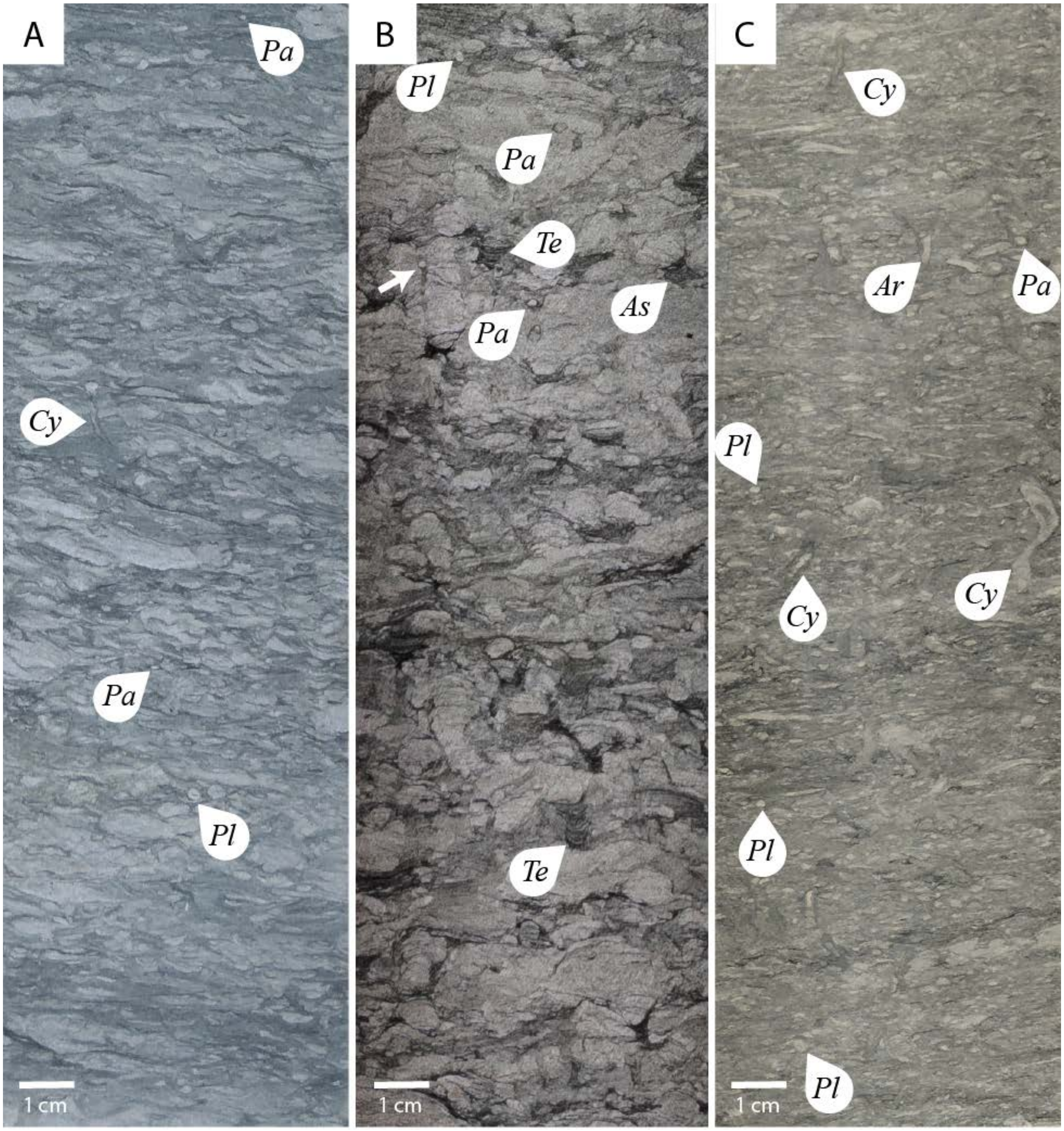

Figure 2-15. Facies plate 15 (Facies 15)

(**A**) Intensely bioturbated heterolithic mudstone and very fine-grained sandstone show examples of *Cylindrichnus* (*Cy*), *Palaeophycus* (*Pa*) and *Planolites* (*Pl*). Colville D-45.
(**B**) Intensely bioturbated heterolithic mudstone and very fine-grained sandstone with *Asterosoma* (*As*), *Palaeophycus* (*Pa*), *Planolites* (*Pl*) and *Teichichnus* (*Te*). A *Paleophycus* example (white arrow) illustrates upwards shifting to keep pace with sedimentation rates. North Colville L-21.
(**C**) Intensely bioturbated heterolithic mudstone and very fine-grained sandstone with identifiable *Arenicolites* (*Ar*), *Cylindrichnus* (*Cy*), *Palaeophycus* (*Pa*) and *Planolites* (*Pl*). Colville D-45.

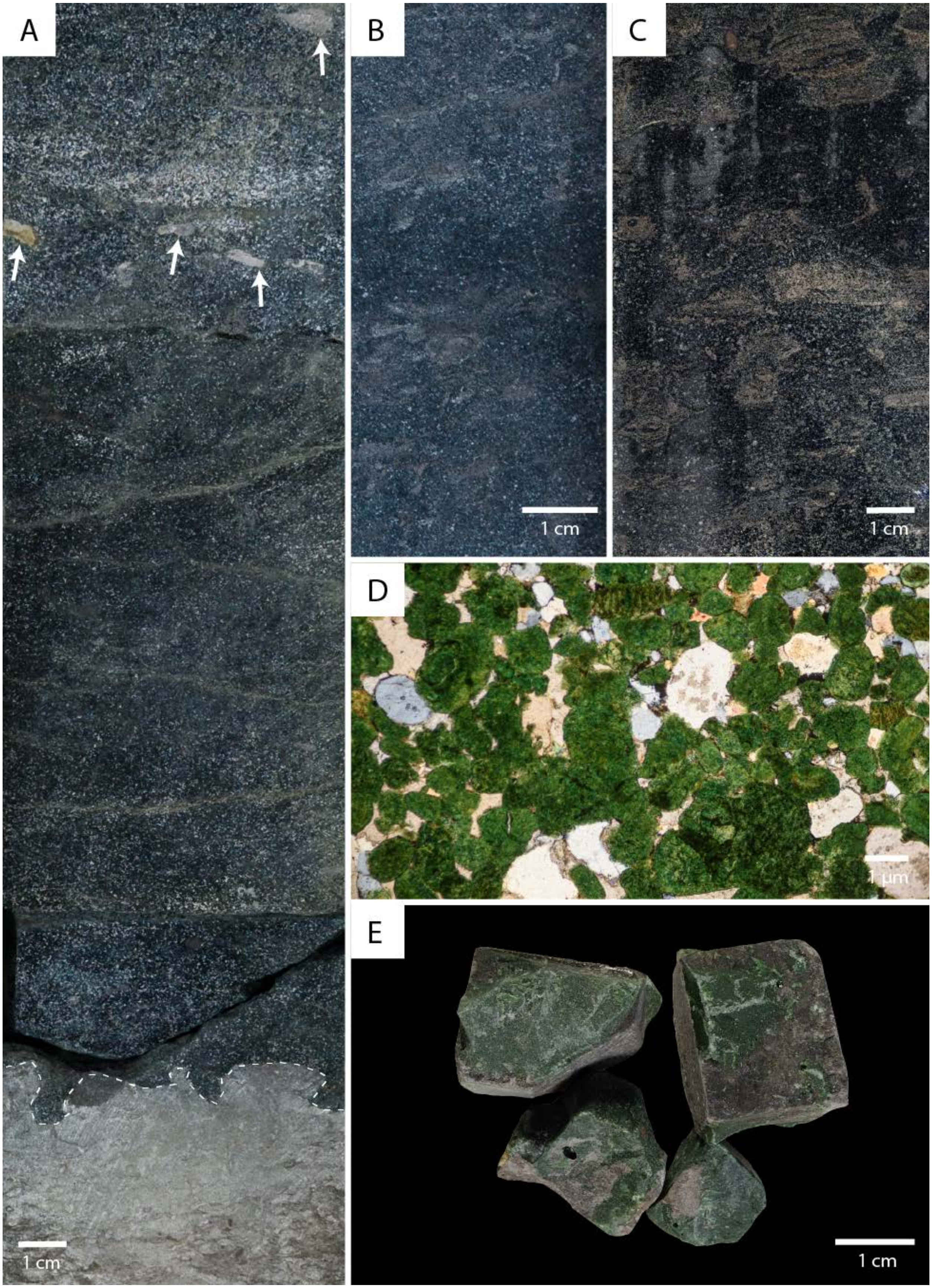

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Figure 2-16. Facies plate 16 (Facies 16)

(**A**) Erosional contact (white dashed line) with F13 underlying F16. Note small flat pebble lag deposits (white arrows). Bele O-35.
(**B**) Extensively glauconitic lithology, referred as "greenstone" by Eoff (2013) or "glaucarenite" by Chafetz and Reid (2000). Colville D-45.
(**C**) Bioturbated sediments in a glauconite-rich and lithics-rich lithology. Colville D-45.
(**D**) Thin section of F16 showcasing abundant compacted glauconite grains. Colville D-45.
(**E**) Glauconitic cement(?) samples provided with core boxes in re-sealable containers. Tweed Lake M-47.


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C
D
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1 cm

Figure 2-17. Facies plate 17 (Facies 17 & 18)

(**A**) Alternating deposits of limestone and dolostone of Facies 17. Colville E-15.
(**B**) Vuggy limestone deposits with very minor trace fossils observed at top of Facies 17. Colville E-15.
(**C**) Dark grey calcareous mudstones and shales of Facies 17. Colville E-15.
(**D**) Well-bedded conglomerate deposits of Facies 18. Colville E-15.

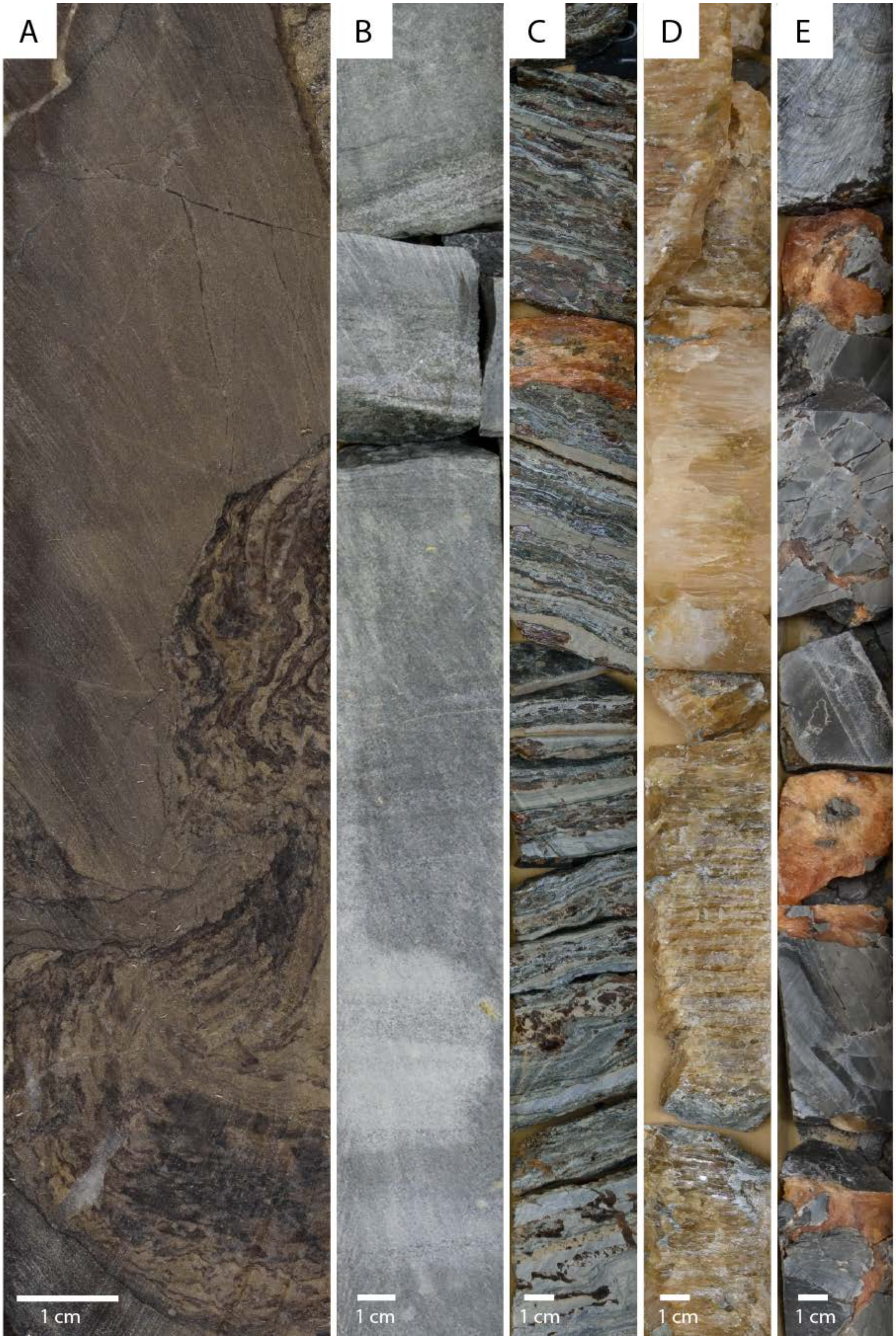
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Figure 2-18. Facies plate 18 (Facies 19 & 20)

(**A**) Early cementation of algal deposits in a high-energy environment of Facies 19. Colville E-15.
(**B**) Fine-grained dolomitic sandstone barrier deposits of Facies 19. Colville E-15.
(**C**) Interbedded thin mudstone and dolostone beds with heterolithic halite of Facies 20. Colville E-15.
(**D**) Thick-bedded, faintly laminated halite of Facies 20. Colville E-15.
(**E**) Brecciated mudstone from mobile evaporites of Facies 20. Colville E-15.

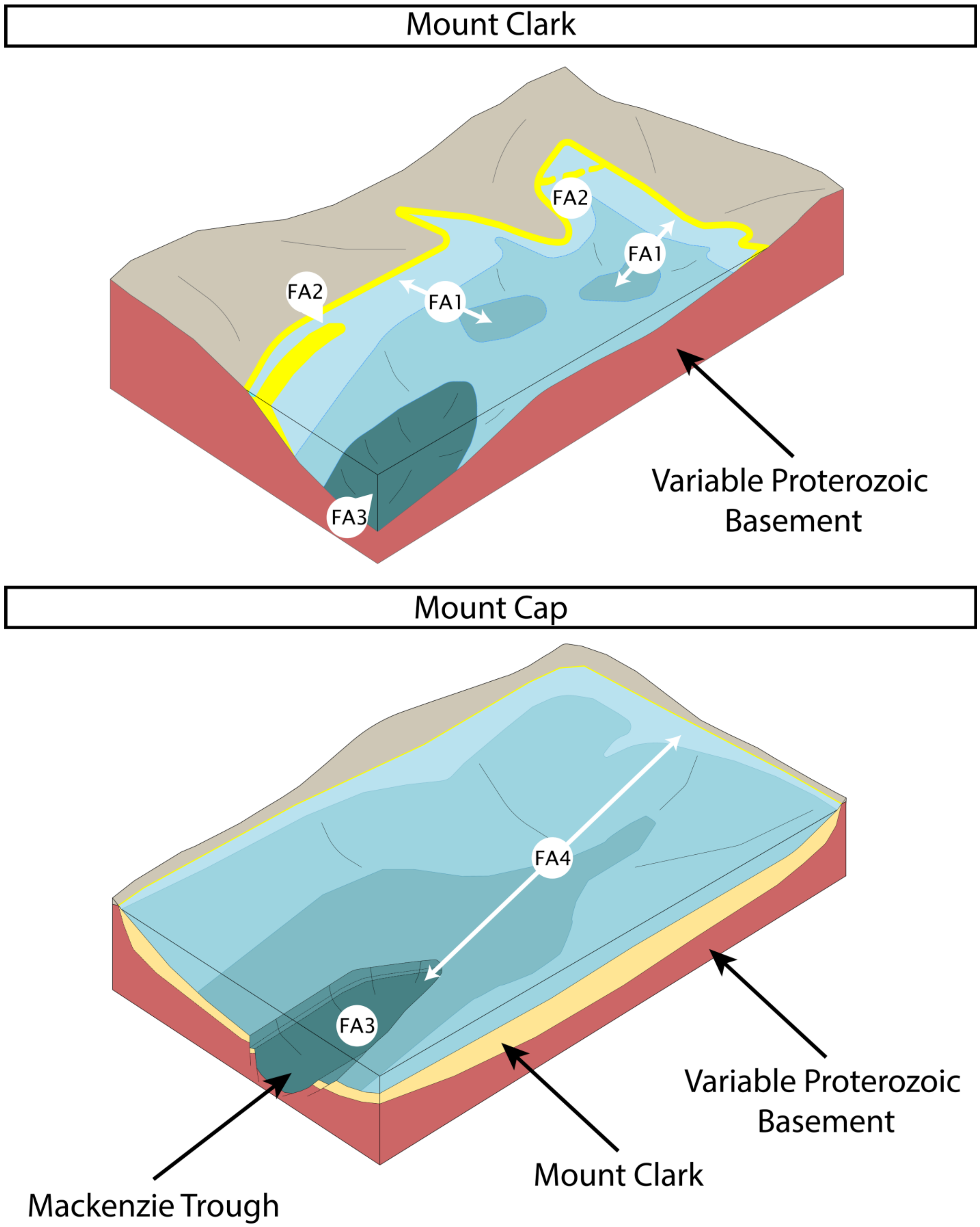

Figure 2-19. Schematics of basic basin configuration during deposition of Mount Clark and Mount Cap. FA1 – Storm-influenced, FA2 – Fairweather, FA3 – Offshore, FA4 – Carbonate ramp.

TABLES

Well Name	Unique Well ID	Well Spudded	Cored Interval (m)	Org. Operator Name
MOBIL INC NCO SUN ONTADEK LK N-39	300/N-39-6620-12815/0	4/13/1970	1791.7 – 1797.7	Mobil Oil Cda Ltd
MOBIL COLVILLE E-15	300/E-15-6720-12615/0	4/18/1970	1307.6 – 1539.2	Mobil Oil Cda Ltd
UNION MOBIL COLVILLE D-45	300/D-45-6720-12500/0	3/29/1973	919.4 – 985.4	Unocal Cda Lmtd
UNION IOL STOPOVER K-44	300/K-44-6740-12330/0	2/15/1975	838.2 – 865.6	Forward Rsrcs Ltd
SUNCOR NORTH COLVILLE L-21	300/L-21-6750-12600/0	1/27/1978	1120.5 – 1146.0	Petro-Canada Entrpr Inc
FORWARD ET AL EWEKKA C-11	300/C-11-6750-12630/0	2/15/1984	1278.9 – 1281.9	Forward Rsrcs Ltd
SUNCOR ET AL TWEED LAKE M-47	300/M-47-6700-12545/0	1/11/1985	1216.5 – 1224.0	Petro Cda Inc
SUNCOR TWEED LAKE A-67	300/A-67-6700-12545/0	11/13/1985	1275.0 – 1302.0	Petro Cda Inc
PCI CANTERRA BELE O-35	300/O-35-6640-12615/0	2/14/1986	1329.2 – 1353.2	Petro Cda Inc
SUNCOR ET AL NW TWEED LAKE C-12	300/C-12-6710-12600/0	2/25/1986	1309.3 – 1328.8	Petro Cda Inc

Table 2-1. Table of cored wells used in this study by spud date. Well locations can be found on Figure 1-2 indicated as orange stars.

Facies Association	**Facies**	**Depositional Influence**	**Sub-Environments**
FA1	4, 7, 12, 13, 16	Storm-Influenced Shoreface	Lagoon to Distal Lower Shoreface
FA2	5, 6, 8, 10, 11, 15	Fairweather Shoreface	Upper Shoreface to Distal Lower Shoreface
FA3	2, 3, 9, 14	Offshore	Upper to Lower Offshore
FA4	17, 18, 19, 20	Carbonate Ramp	Back Ramp to Basin

Table 2-2. Summary table showing individual facies with corresponding facies associations FA1 – FA4 and sub-environments.

Facies	Facies Title	Physical Sedimentary Structures	BI	Trace Fossils	Grain Size	Lithologic Accessories	Depositional Interpretation
F1	Precambrian	Parallel laminae, Low-angle bedding, Karst-collapse, Scours, High-angle bedding, Stylolites	-	*Glossifungites, Skolithos*	N/A	Dolostone clasts, Fe-rich sandstones, Chert, Anhydrite, Dissolution breccia	Sand Tidal Flat (L-21), Offshore (E-15), Karst (C-12), Igneous intrusion (A-67)
F2	Dark grey shale	Parallel laminae, Starved ripples, Current ripples, Discontinuous mud beds, Wavy parallel laminae	0-2	*Planolites, Chondrites, Lockeia, Paleophycus, Arenicolites*	Silt	Pyrite, Trilobite fragments, Brachiopod fragments	Lower Offshore
F3	Bioturbated mudstone and sandstone interbeds	Synaeresis cracks, Current ripples, Planar parallel laminae, Tempestites, Starved ripples, Wavy parallel laminae, Low-angle bedding, Microfault, Mud drapes, Pinstripe Laminae	1-4	*Teichichnus, Paleophycus, Chondrites, Lockeia, Arenicolites, Asterosoma, Cylindrichnus, Planolites, Diplocriterion*	Silt - Very fine	Pyrite, Glauconite	Upper Offshore / Prodelta
F4	Low-angle dominated sandstone	Low-angle bedding, high-angle bedding, Trough cross-bedding, HCS, Reactivation surfaces, Current ripples	0-3?	*Diplocriterion, Ophiomorpha(?), Cryptic bioturbation(?)*	Fine - Medium	Lithics, Reduction spheres, Silica cement, Calcarous fill, Occassional cobble-size grains	Storm-influenced Middle Shoreface / Sand Sheet complex
F5	Vertically-bioturbated sandstone "Piperock"	Planar parallel bedding, Reverse grading	3-6	*Skolithos, Altichnus, Glossifungites, Diplocriterion, Paleophycus*	Very fine - Coarse	-	Upper Shoreface / Foreshore
F6	Bioturbated sandstone	Low-angle bedding, planar parallel bedding, Reactivation surfaces	3-6	*Arenicolites, Skolithos, Lockeia, Cylindrichnus, Paleophycus*	Fine - Medium	Ferrous grains, Glauconite	Upper Shoreface
F7	Thinly parallel-bedded sandstone	Planar laminae, Current ripples, Trough cross-bedding, discontinuous mud beds, convolute bedding, reactivation surfaces, wavy-parallel bedding, Reverse grading, Rip-up clasts, Synaeresis cracks(?)	0-3	*Planolites, Paleophycus, Skolithos,* Cryptic Bioturbation	Very fine - Medium	Green silt laminae, Liesegang banding	Storm-Influenced Lagoon/Washover Fan

Facies	Facies Title	Physical Sedimentary Structures	BI	Trace Fossils	Grain Size	Lithologic Accessories	Depositional Interpretation
F8	Bioturbated heterolithic sandstone and mudstone	Low-angle planar bedding, Planar laminae, Wavy-parallel bedding	2-5	*Arenicolites, Paleophycus, Chondrites, Teichichnus, Asterosoma, Cylindrichnus, Planolites, Lockeia*	Very fine - fine	Pyrite, Lithics	Fairweather Proximal Lower Shoreface
F9	Poorly sorted sandstone	Mud drapes, Rip-up clasts	0-1	*Skolithos*	-	Up to Fine to pebble-sized grains, Glauconite	Transgressive Lag
F10	Bioturbated nodular dolostone	Nodular, Vuggy, Rip-up clasts, Irregular mudstone laminae interbeds	1-5	*Paleophycus, Planolites, Asterosoma, Arenicolites*	Crypto-fine xcl	Lithics, Green clays, Calcite and dolomite vug fill, Evaporite fill, Pyrite	Middle to Distal Lower Shoreface
F11	Bioturbated sandstone	Planar parallel bedding, Wavy parallel laminae, Low-angle bedding, Massive	1-6	*Planolites, Paleophycus, Diplocriterion, Teichichnus, Arenicolites, Cylindrichnus, Chondrites, Lingulichnus, Skolithos,Rhizocorallium,* Cryptic bioturbation(?)	Very fine - Medium	Concretions, Reduction spheres, Silica cement, Lithics, Glauconite, Ferrous grains, Cherty	Middle Shoreface
F12	Tempestite beds	Load casts, Planar laminae,	0-5	*Planolites, Arenicolites, Paleophycus, Chondrites, Teichichnus, Lockeia, Diplocriterion*	Silt - Coarse	Cherty, Ferrous grains, Pyrite, Lithics	Shoreface - Offshore Transition
F13	Bioturbated heterolithic mudstone and sandstone	Wavy parallel laminae, Planar parallel bedding, Soft-sed deformation, Convolute bedding, Normal grading, Rip-up clasts, Nodular, Current ripples, Planar laminae, Lam-Scram	0-5	*Planolites, Paleophycus, Teichichnus, Asterosoma, Cylindrichnus, Chondrites, Arenicolites, Diplocriterion, Equilibrichnia*	Silt - Fine	Glauconite, Ferrous grains, Lithics, Pyrite, Dolomitic	Storm-influenced Distal Lower Shoreface
F14	Bioturbated green mudstone	Reactivation surface, Wavy parallel wedding, Planar parallel bedding, Discontinuous mud beds, Starved ripples, Rip-up clasts, Load casts	1-5	*Planolites, Chondrites, Lockeia, Paleophycus, Arenicolites, Teichichnus, Cylindrichnus(?)*	Silt	Glauconite, Lithics, Pyrite, Brachiopod fragments, Trilobite fragments, Iron grains	Upper Offshore

Facies	Facies Title	Physical Sedimentary Structures	BI	Trace Fossils	Grain Size	Lithologic Accessories	Depositional Interpretation
F15	Bioturbated heterolithic sandstone and mudstone	Planar laminae, Low-angle bedding	1-5	*Cylindrichnus, Teichichnus, Chondrites, Planolites, Paleophycus, Arenicolites, Diplocriterion, Asterosoma*	Very fine	Pyrite, Glauconite, Lithics	Fairweather Distal Lower Shoreface
F16	Bioturbated glaucony facies	HCS(?)	0-4	*Planolites, Paleophycus, Teichichnus*	Very fine	Glauconite, Lithics, Pyrite	Lower / Middle Shoreface
F17	Interbedded shale and carbonate	Convolute bedding, Load casts, Low-angle bedding, Planar-parallel bedding, Rip-up clasts, micro-faulting, Stylolites, Nodular, Vuggy	1-6	*Cylindrichnus, Paleophycus, Planolites, Teichichnus,*	Silt - fine xcl	Calcareous, Dolomitic, Pyrite, Glauconite, Lithics, Algal lamination, Trilobite fragments, Brachiopods	Deep Ramp
F18	Organic mudstone and conglomerate	Rip-ups, Brecciated horizons, Low-angle bedding, Planar-parallel bedding,	-	-	Silt - pebble	Dolomitic, Petroliferous, Organics, Oil stained, Algal debris,	Basin
F19	Sandy carbonate and shale	Convolute bedding, Low-angle bedding, Planar-parallel bedding, Rip-up clasts	-	-	Silt - fine	Algal laminae, Anhydrite	Shallow Ramp
F20	Interbedded Evaporite, Shale and Dolostone	Brecciated horizons, planar-parallel bedding, Chaotic bedding, low-angle bedding, Current ripples, High-angle bedding	-	-	Silt to crypto	Algal laminae	Back Ramp

Table 2-3. Summary table showing individual facies with corresponding physical, chemical and biological characteristics for an interpreted depositional environment.

CHAPTER 3: LITHOSTRATIGRAPHIC CORRELATIONS AND SEQUENCE STRATIGRAPHIC FRAMEWORK OF THE LOWER AND MIDDLE CAMBRIAN SUCCESSION IN THE COLVILLE HILLS AREA, NORTHWEST TERRITORIES

INTRODUCTION

The Lower and Middle Cambrian succession (Figure 1-1) in the Colville Basin is composed of myriad facies representing storm-influenced, fairweather or offshore deposits in a semi-enclosed, epicontinental shallow marine basin (Dixon and Stasiuk, 1998). During this time, Laurentia was situated in a region with an equatorial climate (Figure 1-2). The present-day interior plains of the Northwest Territories experienced subsidence as a result of rift-related extension from the breakup of Rodinia (MacLean, 2011). Large volumes of siliciclastic debris was eroded and transported into a shallow marine sea from a barren, un-vegetated landscape by extensive fluvial networks and wind action (Dalrymple et al., 1985; MacNaughton et al., 1997; Long and Yip; 2009). Eustatic sea level continued to rise during the Middle Cambrian in response to a global greenhouse climate that led to widespread transgression resulting in broad carbonate platforms and ramps (Bond and Kominz, 1984; Scotese and McKerrow, 1990; Levy and Christie-Blick, 1991).

Sloss (1963) documented that the North American depositional record from the late Neoproterozoic to the present day can be subdivided into six major sequences, each bounded by interregional unconformities. The oldest documented unconformity is at the base of the Sauk Sequence, coinciding with the regionally extensive sub-Cambrian unconformity; the Mount Clark and Mount Cap formations are part of the Sauk I Sequence (Sloss, 1963; Dixon and Stasiuk, 1998; Pyle, 2012).

Identifying cyclicity is important on a continental scale but is also valuable on relatively smaller scales to understand a specific basin's development over time. Two methods that can be used for basin reconstruction are lithostratigraphy and sequence stratigraphy. Lithostratigraphic frameworks are constructed by correlating similar lithological properties via core, outcrop or wireline data to demonstrate the vertical and lateral extent of that particular lithology; such correlations are not concerned with a time component (Hedberg, 1976 Catuneanu, 2006). Sequence stratigraphy analyzes stacking patterns of lithofacies and identification of the correlatable surfaces that bound these stratal packages, both of which can vary depending on rates of sedimentation and the position of base level over time (Mitchum, 1977; Van Wagoner et al., 1988; Catuneanu, 2006; Catuneanu et al., 2009). A sequence consists of genetically-related strata that are further divided into systems tracts, the definition of which varies depending on the model used (Hunter and Tucker, 1992). Systems tracts are established by interpreting stacking patterns of strata that can be progradational, aggradational, or retrogradational. When lithostratigraphic correlations and sequence stratigraphic frameworks are combined, higher-resolution basin architecture through time can be illustrated.

This study will examine the stacking patterns of facies and lithologies of the lower Cambrian Mount Cap and Mount Clark formations. This work will improve upon the understanding of Colville Basin evolution and lithological distribution to aid future research and resource exploration.

PREVIOUS WORK

Additional to the foundational research referred to in Chapter 2, notable work had been conducted that outlined a lithological framework of the Lower and Middle Cambrian succession on a regional-scale using wireline, core and seismic data. Initial work in the subsurface Colville Basin and surrounding area was completed by Tassonyi (1969) and after a decade of little economic development, oil and gas exploration activity increased allowing for further subsurface lithostratigraphic correlation work to be completed by Pugh (1983; 1993), Williams (1987; 1989), Hamblin (1990), Dixon (1997), Janicki (2004) and Dixon and Stasiuk (1998) using core and wireline logs. Additional Cambrian succession mapping, highlighting tectonic features and zero edge outlines, was developed by MacLean (2011) using reflection-seismic data. As a result, the Aubry, Good Hope and Great Bear depocentres, north to south, respectively, were delineated across the Mackenzie Platform.

Until now, sequence stratigraphic interpretations and a basin evolution framework had not been thoroughly investigated.

DATASET AND METHODOLOGY

The study area was located primarily in the Colville Hills region, Northwest Territories centered approximately on the Colville Lake town site. Additional subsurface control was also considered from the broader Mackenzie Corridor, bounded approximately between latitudes 62.5°N to 69°N and longitudes 122°W to 132°W spanning over 300,000 square kilometers (Figure 1-3). The dataset included 54 wells that penetrated the Lower and Middle Cambrian succession, however some wells were not drilled deep enough to cover the entire succession of interest, and as such, only 45 wells penetrated the Precambrian to yield full coverage (Table 3-1).

Wells provided wireline log data consisting of Log ASCII Standard (LAS) and raster images of gamma ray (GR), neutron/density (N/D), sonic, photo electric (PE) and resistivity (shallow, medium and deep) curves provided by the Geological Survey of Canada; where LAS files were missing, geoSCOUT© digitizing services was used. Additionally, any available well reports documenting formation tops, drill cuttings, core descriptions, summaries of formations and striplogs obtained from the Geological Survey of Canada Repository were used to assist in making reliable correlations. However, the entire suite of wireline curves was not available for all wells. In rare cases, no wireline data covered the Lower Cambrian succession interval of interest, and instead lithological and rate of penetration (ROP) logs from drilling were used to estimate formation tops. Additionally, 10 cores were logged (as described in Chapter 2); these provided important data for picking lithostratigraphic and sequence stratigraphic surfaces that then were extrapolated to surrounding wells that lacked core. Correlations, hand contoured isopachs and cross-sections were completed on geoSCOUT© and Adobe Illustrator©.

The sparse data density for such a vast study area was a significant limitation and often resulted in approximation and necessitated far-reaching extrapolation of depositional environments and thicknesses. Published seismic data (MacLean, 2011) was used in conjunction with the completed facies analysis of Chapter 2 and the author's own interpretations of wireline data, which maximized the quality of correlations permitted by the data. The focus of this chapter will be predominantly on the Mount Clark and lower Mount Cap formations, for which stratigraphic correlations are the most robust.

SUBSURFACE CORRELATIONS

A summary of formation contacts and lithological markers can be observed from the selected reference well, Tweed Lake M-47 (Figure 3-1), located approximately in the center of the basin. Correlations conducted in the subsurface Colville Basin were confined to the Mount Clark and Mount Cap formations. The sub-Cambrian unconformity was commonly observed as a sharp decrease in API on gamma ray logs coupled with a decrease in resistivity. Located approximately in the middle of the Mount Clark succession is a regionally-extensive shale package interpreted to record a flooding event. This was correlated reliably throughout a significant portion of the basin, which was picked on the highest gamma API within the shale package, or the transition from green to grey shale in core, and labelled as MFS_Mt.Clark. The base of the Mount Cap was denoted by the first occurrence of carbonate deposition. This sharp to gradational contact indicates a basin-wide change in deposition towards limited clastic input and increased carbonate cementation. In core, this change was commonly marked by a 3 to 5 meter thick bioturbated, nodular dolostone of F10, while on wireline as a sharp, drastic increase in resistivity, slight increase in PE and in some wells a shift to very low API on GR logs. The Mount Cap is herein informally divided into upper and lower members. The strata of the lower Mount Cap consisted of dominantly shale of F2, observed on wireline as thick successions of high API values on GR, with occasional spikes of very low API values on GR representing thin beds of nodular dolostone of F10, or prodelta deposits of F3 observed in Colville D-45. Four regionally-extensive carbonate markers are preserved in the lower Mount Cap, labelled Carb. 1 through Carb. 4, ascending up-section. Additionally, a laterally-extensive high API value on GR logs occurred between markers Carb. 2 and 3, which was interpreted to reflect a major flooding event and labelled as Carb 2_MFS. The upper and lower Mount Cap is separated at the top of the fourth regionally-correlated dolostone marker, labelled as

Carb._4. The upper Mount Cap was predominantly composed of calcareous and dolomitic shales with minor thin carbonate marker-beds, which were generally discontinuous and sporadic, and difficult to correlate. A notable trend observed in the single core available (Colville E-15) in the upper Mount Cap was where carbonates were observed, a change from sandy nodular dolostone beds to interbedded patchy-cemented limestone and dolostone beds and rare sandstone beds occurred gradually up-section. The Mount Cap – Saline River contact is demarcated at the top of a calcareous to dolomitic shale-dominated succession of F2, into a sudden carbonate-dominated succession. The contact is commonly sharp and sporadically gradational, and appears on wireline logs as a sharp change to low API value on GR, a sharp decrease on sonic and gradual increase on resistivity. Despite these common signatures on wireline logs, this contact could not be reliably identified in the single core available (Colville E-15). The wireline contact suggests a sudden change, although no obvious erosional contact was observed.

LITHOSTRATIGRAPHIC FRAMEWORK

Lithostratigraphic correlations of the Mount Clark Formation suggest an overall undulating erosional basal contact with the underlying Precambrian below (Figure 3-2, Figure 3-3, Figure 3-4: B-B', C-C', and D-D'). As a result, the Colville Basin had numerous depressions that resulted in a 5 – 10 m thick clastic package. The lowermost succession in the Mount Clark commonly consisted of FA1 storm-influenced facies in locations where these depressions were the deepest. FA1 appeared in core as decimeter- to meter-scale upward-coarsening sequences of prograding to aggrading sandstone deposits which transitioned upwards to fairweather FA2 sandstone beds then to heterolithic sandstone and mudstone deposits also of FA2. A widespread shale package caps the basal coarsening-up sequences; however, basin-margin deposits were not observed in any cores. As such, an offshore to distal lower shoreface succession of FA3 of Mount Clark was preserved in the dataset. Above this shale package, facies associations are variable. In the Lac Maunoir area, north-west of Colville Lake, FA1 storm-influenced deposits are overwhelmingly aggrading, to slightly prograding; these facies also occurred locally in the Nogha area located directly south of Colville Lake. The remainder of the basin was observed as progradational FA2 fairweather upwards-coarsening sequences up to the base of the Mount Cap Formation, where a sharp to rapidly gradational change to a carbonate-dominated succession occurred. Two isopachs within the Mount Clark Formation (Figures 3-5, 3-6) illustrated multiple inlets resulting from a highly-sinuous pale-shoreline adjacent to the Peel, Mackenzie and Redstone Arch complex with a notable, elongate paleo-high in the north-east corner that corresponded to Maunoir Ridge (Figure 1-4). The geometry of Maunoir Ridge as illustrated by MacLean (2011), refined from Dixon and Stasiuk (1998), was confirmed in this study as wireline logs and core data strongly suggest that basin-margin Mount Clark successions are preserved in the northern part of the study area (Figure 3-3: B-B').

Stopover K-44 preserved a significantly different Mount Clark succession than all other studied wells in the Colville Basin. This well was the only location that preserved lagoonal F7 deposits, which were also interbedded with predominantly thick beds of upper shoreface F6. Given its proximal location to Maunoir Ridge and the depositional environments preserved, this may suggest that Stopover K-44 was proximal to a basin-margin, likely sheltered, and was largely influenced by sea level fluctuations. Thus, high API values within the Mount Clark succession are interpreted on wireline logs to be lagoonal deposits rather than FA3 offshore deposits that were more prevalent throughout the basin.

At the base of the Mount Cap is a bioturbated, nodular, sandy dolostone that signifies the last major large pulse of coarse-grained clastic input and a change to a carbonate-dominated, offshore environment. The lower and upper Mount Cap members are dominated by thick successions of offshore shale deposits, punctuated by sandy dolostone intervals. Active extensional tectonism and sea-level rise were important factors influencing the depositional history of the Mount Cap Formation. The most prominent evidence of active extension was the development of the Mackenzie Trough (Figure 1-4) located at the most southern part of the study area where hundreds of meters of shale were deposited. Accommodation space varied throughout lower Mount Cap deposition. For example, using carbonate markers Carb. 1 to Carb. 4 in addition to high API flooding surfaces, such as Carb.2 _MFS and Regional_MFS (Figure 3-1), comparing thicknesses between these horizons across two or more wells suggests syndepositional normal faulting. The upper Mount Cap is composed of predominantly calcareous and dolomitic shales indicative of a carbonate ramp environment as described in Chapter 2 (Facies 17 – 19); sporadic and discontinuous thin carbonate beds that were difficult to correlate. An isopach (Figure 3-7) of the complete Mount Cap succession suggests a significant increase in accommodation space throughout the basin relative to Mount Clark deposition. Moreover, notable small-scale depocenters in the Lac Maunoir and Nogha areas can be observed. The coastline during Mount Cap deposition was generally oval-shaped and trended north-south; a paleo-high, indicated by the zero-edge (Mahony Arch), and the major paleo-low, indicated by the significant thickness in well Kalo B-62 (Mackenzie Trough) are evident. A regional unconformity marks the top of Mount Cap carbonate ramp deposits, which eventually transitioned to a restricted basin depositing the Saline River Formation.

The most comprehensive lithostratigraphic correlations had previously been completed by Williams (1987), Pugh (1993) and Dixon and Stasiuk (1998). Formation contacts between the Precambrian, Mount Clark and Mount Cap chosen for this study are very similar to previous studies. However, this study builds on that work by subdividing the Mount Clark Formation into three correlatable packages and assigning each of them a facies association, generally FA1, FA3 and FA1/FA2 in ascending order up to the base of the Mount Cap (Figure 3-3, Figure 3-4: B-B', C-C', and D-D'). Moving up-section, in this study the Mount Cap Formation was informally divided into lower and upper members, where markers within the lower Mount Cap differ considerably in contrast to previous studies. Additional well control made available since those studies were published could account for the disparity. While documented lithologies among all the studies are similar, the correlation of those lithologies is where there is a divergence of interpretations, which would account for the differences shown in cross-sections and isopachs.

SEQUENCE STRATIGRAPHIC MODEL

The base of the Lower and Middle Cambrian succession is the sub-Cambrian unconformity, which is the regionally extensive, first-order sequence boundary that marks the base of the Sauk Sequence (Sloss, 1963; Bond and Kominz, 1984; Scotese and McKerrow, 1990; Levy and Christie-Blick, 1991). Sequence stratigraphic interpretations were initially made in core and expanded to wireline-only wells where possible across the basin. Interpretations from logged core were of higher resolution (see Appendix) than wireline. Observations of stacking patterns of facies in core could sufficiently support a Depositional Sequence IV model (Hunt and Tucker, 1992; Plint and Nummedal, 2000; Catuneanu, 2006). In this model (Figure 3-8), the recognized system tracts consist of the falling-stage systems tract (FSST), lowstand systems tract (LST), transgressive systems tract (TST) and highstand systems tract (HST), which can be delineated using a combination of core observations and wireline interpretations. Notably, at some well locations, a clear indication of a FSST stacking pattern occurred with the onset of base-level fall demarcated by a basal surface of forced regression (BSFR). For example, F2 lower offshore deposits which directly underlying F11 middle shoreface deposits from Colville D-45 (Figure 3-2A). While isolated cases of separating LST and FSST system tracts could be clearly established in core, identifying a clear difference between a BSFR and correlative conformity (CC) to separate FSST and LST, in both wireline and core, was problematic. For example, Tweed Lake A-67 (Figure 3-9) preserved clear examples of most sequence stratigraphic surfaces but differentiating a BSFR versus a CC was quite difficult. Further, a Depositional Sequence IV model's level of detail observed in core could not be extrapolated to a basin-wide scale and very rarely even to neighbouring cored intervals, which is attributed to the sparse data density and lack of a high-resolution seismic dataset. Therefore, a T-R Sequence model (Embry, 1995, 2002; Catuneanu, 2006) was chosen that combined the HST, FSST and LST from Depositional Sequence IV model into a single systems tract labelled Regressive Systems Tract (RST). Within this study, the RST is recognized as an overall prograding geobody ranging from shallow marine to offshore depositional environments. The base of the RST is the end of transgression demarcated by the MFS, picked at the highest API value on GR logs in an overall transgressive succession, and capped by an MRS, picked at the lowest API in the overlying prograding succession. It must be emphasized that both of these sequence stratigraphic surfaces were chosen based on their aforementioned properties as observed in wireline logs and correlatable nature over much of the basin. Parasequence sets within the RST and TST could be delineated in some instances, but could not be correlated regionally. Lithologies and stacking patterns were determined by evaluating well reports of cuttings, core, striplogs, and wireline data. Maximum flooding surfaces were the most reliable and extensive surfaces to correlate within the Lower and Middle Cambrian succession across the basin. Moreover, within each of these packages an MRS was picked to appropriately bound each sequence boundary and adheres to the T-R model, thereby yielding three MRSs and three MFSs. As a result, three T-R sequences were interpreted in the Mount Clark and lower Mount Cap formations (Figure 3-3 and Figure 3-4: B-B', C-C', and D-D').

In core from well Colville E-15 (from 1472 m into the Saline River Formation), sequence stratigraphic interpretations changed from a Depositional Sequence IV model to a T-R Sequences model as facies were commonly less specific in the upper Mount Cap and Saline River. As a result, more generic stacking patterns were observed that illustrated retrograding or prograding stacking patterns. MRS and MFS were identified with respective RSTs and TSTs. Despite this interval being outside the focus for this study due to the difficulty in reliably correlating surfaces, effort was put forth to best interpret the data available. Moreover, core from Stopover K-44 had little facies variation and therefore was limited to T-R sequences and was the only well location where relatively high API values over the cored interval corresponded to a MRS rather than a MFS as being interpreted as lagoonal facies and not offshore deposits.

CONCLUSION

A lithostratigraphic and sequence stratigraphic framework of the Lower and Middle Cambrian succession, consisting of the Mount Clark and lower Mount Cap formations, was established using a compilation of wireline, well report and core data from 45 wells. At the base of the Cambrian is a regional-scale sequence boundary, the sub-Cambrian unconformity, which that separates the Cambrian and Precambrian successions. Overlying were typically FA1 storm-influenced sandstone deposits of the basal Mount Clark formation, which were organized into parasequence sets. These strata were capped by the first major MFS labelled MFS_Mt. Clark which lies within offshore facies of F2 or F14. Above the flooding surface, locations of FA1 (storm-influenced) and FA2 (fairweather) deposits observed varied considerably throughout the basin; FA1, typically in the center of the basin where deeper waters accommodated the high wave-energy required to generate HCS deposits, and FA2, located in environments that were either sheltered or wave-attenuated. During Mount Clark deposition, clastic sedimentation dominated the succession. Conversely, the base of the Mount Cap is an abrupt facies change demarcated by the first instance of carbonate cementation of F10 deposits, generally coinciding with a BSFR or CC. The lower Mount Cap consisted of predominantly offshore F2 shale deposits interbedded with four regional-scale carbonate beds capped by a regional MFS. During this time, syndepositional normal faulting coupled with eustatic sea level rise resulted in abrupt, localized changes in accommodation space throughout the basin, resulting in the development of such features as the Mackenzie Trough in the southern part of the study area. Three T-R sequences could be delineated in the lower Mount Cap and Mount Clark successions across much of the Colville Basin. In core, more detailed interpretations were made using the Depositional Sequence IV model, however these could be not correlated reliably on a regional scale. Above the fourth carbonate marker of the lower Mount cap is a regionally-extensive MFS. Above this, smaller-scale correlations could be established however nothing on a regional-scale was observed.

FIGURES

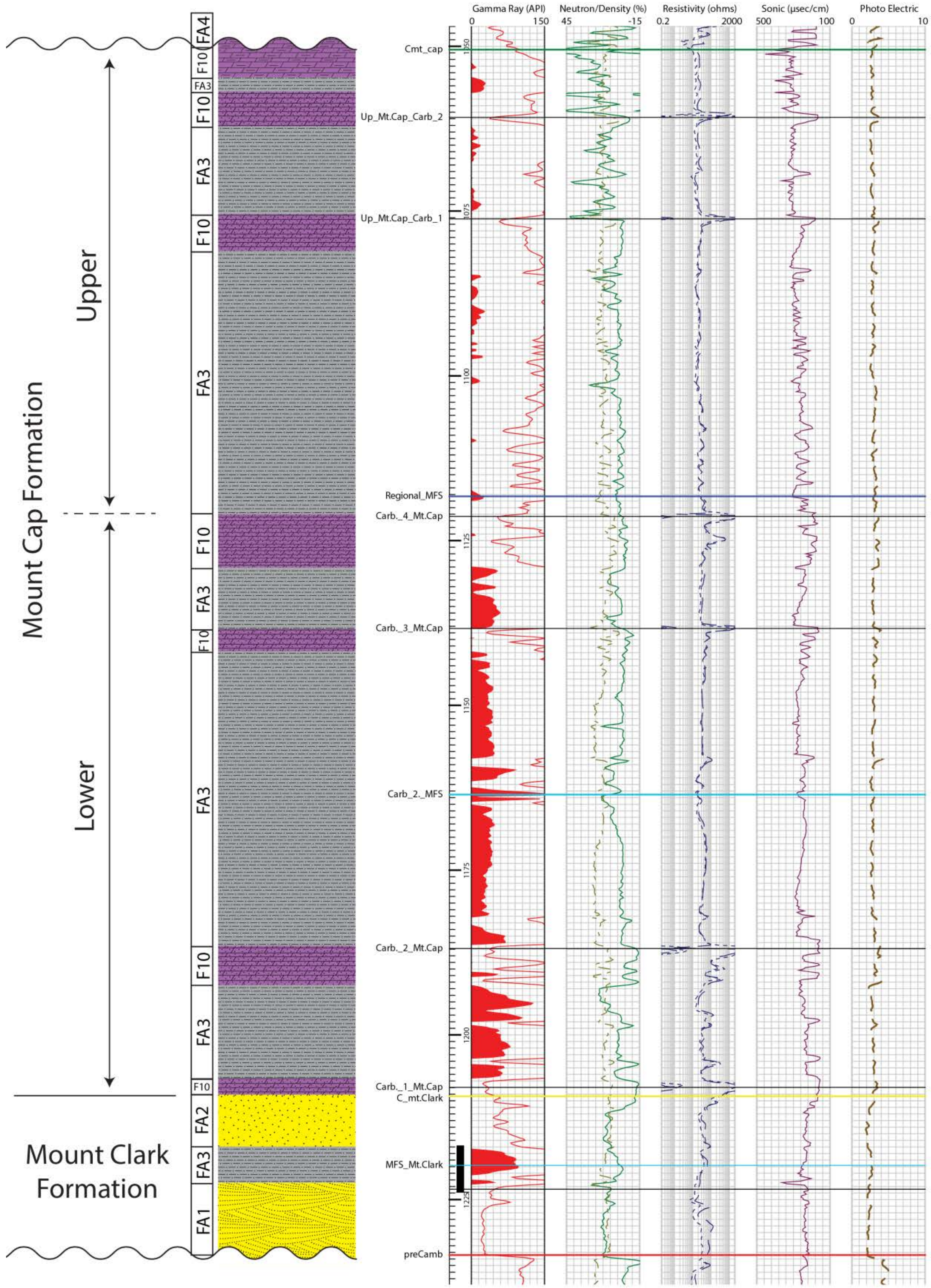
Mount Cap Formation
Upper
Lower
Mount Clark Formation
FA4
F10
FA3
F10
FA3
F10
FA3
F10
FA3
F10
FA3
F10
FA3
F10
FA2
FA3
FA1
Gamma Ray (API)
0
150
Neutron/Density (%)
45
-15
Resistivity (ohms)
0.2
2000
Sonic (µsec/cm)
500
100
Photo Electric
0
10
Cmt_cap
Up_Mt.Cap_Carb_2
Up_Mt.Cap_Carb_1
Regional_MFS
Carb._4_Mt.Cap
Carb._3_Mt.Cap
Carb_2._MFS
Carb._2_Mt.Cap
Carb._1_Mt.Cap
C_mt.Clark
MFS_Mt.Clark
preCamb
1050
1075
1100
1125
1150
1175
1200
1225

Figure 3-1. Reference log with idealized stratigraphic column showing dominant facies and facies associations with corresponding wireline signatures – some variation exists. Tweed Lake M-47.

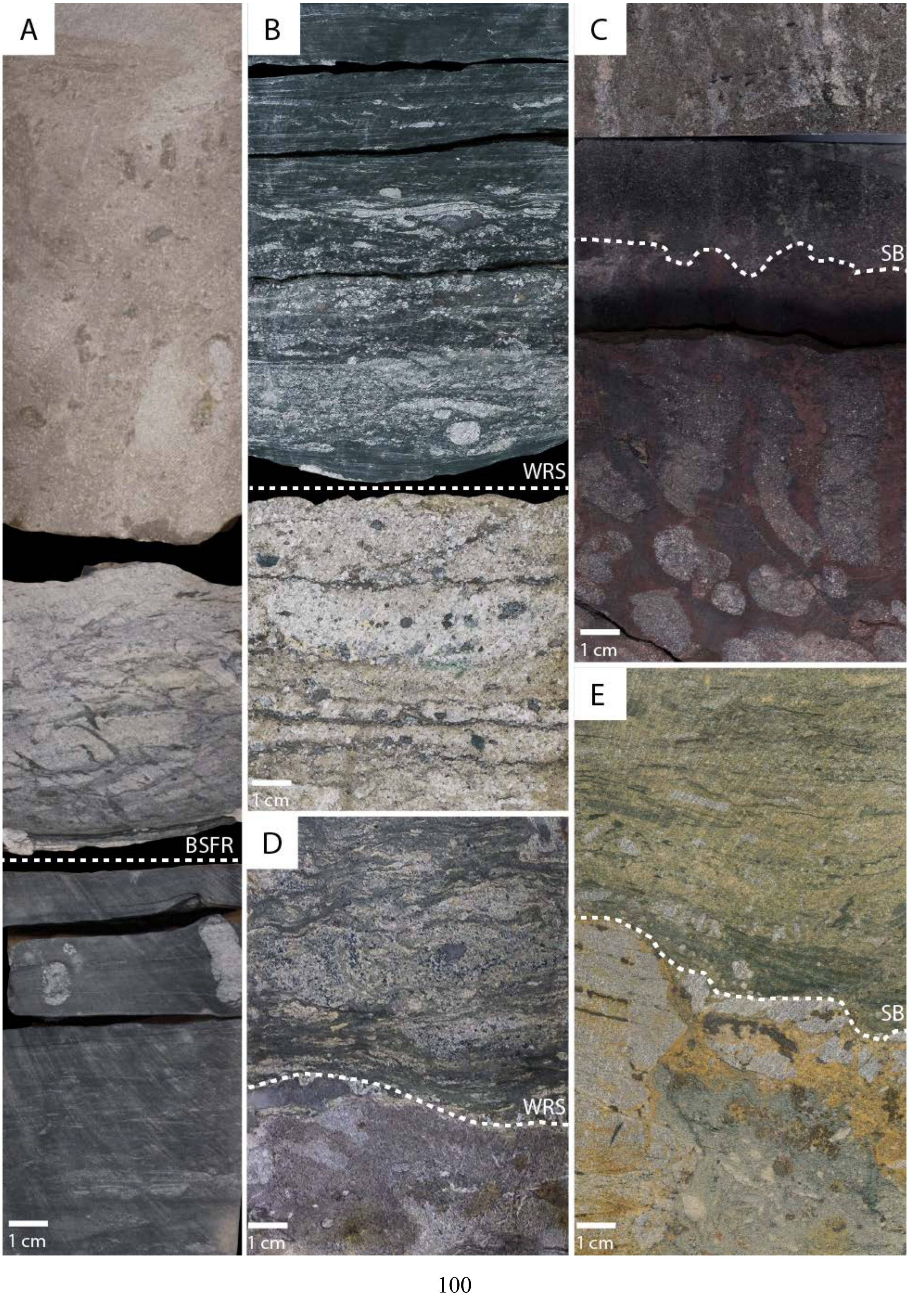
A
B
C
D
E
BSFR
WRS
WRS
SB
SB
1 cm
1 cm
1 cm
1 cm
1 cm

Figure 3-2. Figure plate of sequence stratigraphic surfaces found in core.

(**A**) Lower offshore mudstone of F2 is overlain by middle shoreface of F11 are separated by a basal surface of forced regression (BSFR) which indicates the onset base-level fall. This indicates the start of the falling-stage systems tract (FSST). Colville D-45.
(**B**) A wave ravinement surface (WRS) separates underlying transgressive lag deposits of F9 with overlying F14 upper offshore deposits within a TST. Tweed Lake A-67.
(**C**) Sub-Cambrian unconformity sequence boundary (SB) *Glossifungities* surface. Tweed Lake A-67.
(**D**) A wave ravinement surface (WRS) separates underlying nodular dolostone F10 deposits with overlying upper offshore deposits with a basal of F14 within a TST. North Colville L-21.
(**E**) Sub-Cambrian unconformity sequence boundary (SB) with lagoonal F7 deposits above as a result of being ravined. North Colville L-21.

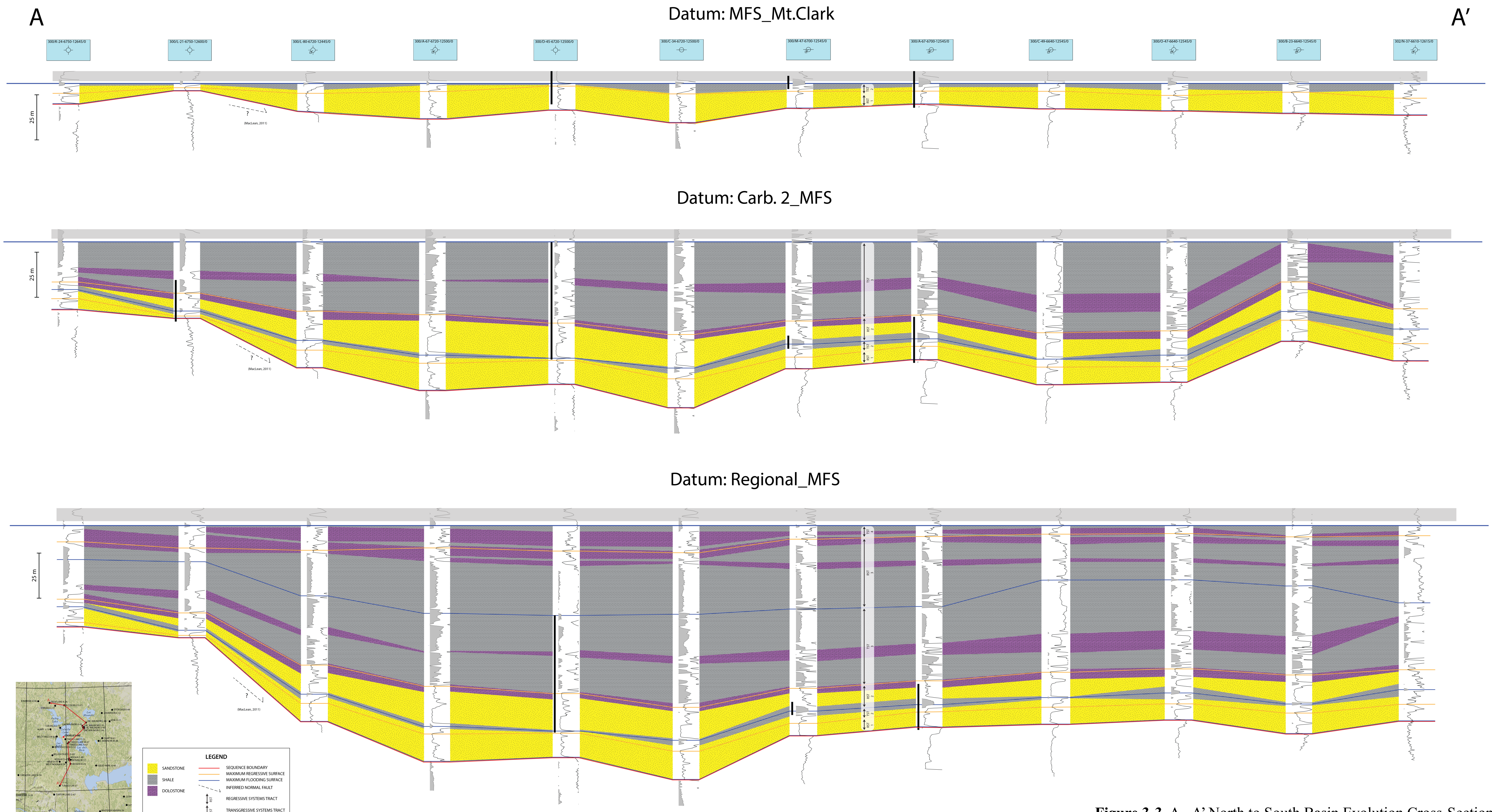

Figure 3-3. A - A' North to South Basin Evolution Cross-Section

Figure 3-3. A-A'north to south orientated cross-sections that showcase basin evolution using gamma ray wireline logs. Inferred normal faults, indicated by dashed arrows between wells, are drawn where cross-section lines intersect faults interpreted by MacLean (2011). Cored intervals appear as solid black boxes adjacent to corresponding wireline logs.

Datum: MFS_Mt.Clark

An undulating erosional contact (sub-Cambrian unconformity seen in red) with overlying basal deposits of the Mount Clark Formation, typically composed of storm-influenced FA1 strata. In wireline, this contact is often sharp except in two instances: Colville L-21 where the contact can be seen in core (Figure 3-2E) and Tunago 2N-37 where Precambrian strata is inferred to be similar a quartzose sandstone composition as basal Mount Clark facies, differentiated by well-cemented strata based on an increase on resistivity logs.

The first MRS (orange line) has been picked at the lowest API value within this stratal package. Above these sandstones are the first regionally-extensive offshore shale deposits of FA3 with the first MFS (blue line as datum) picked at the highest API value within this package.

Datum: Carb. 2_MFS

Above the first shale package is the second phase of predominantly sandstone deposition, however depending on the location within the basin, varied considerably. Aggrading deposits such as the base of the Colville D-45 core tended to be FA1 storm-influenced strata while prograding deposits, as observed in the North Colville L-21 and Tweed Lake A-67 cores, tended to be FA2 fairweather strata.

The Mount Clark – Mount Cap contact lies at the base of the first carbonate marker. Within this nodular, bioturbated dolostone bed of F10 is where the second MRS has been picked. Up-section is a transgressive phase where predominantly offshore shale strata of FA3 were deposited, with a second regionally-extensive carbonate marker in between. The second MFS pick is a high API value correlated across much of the basin.

Datum: Regional_MFS

Above the Carb. 2_MFS is continued offshore FA3 shale deposition with additional regionally-extensive carbonate markers. Within the Carb. 3 marker lies the third MRS. The top of the highest carbonate marker, Carb. 4, demarcates the informal division between the lower and upper Mount Cap members. Above this is a regionally-extensive MFS picked across the basin.

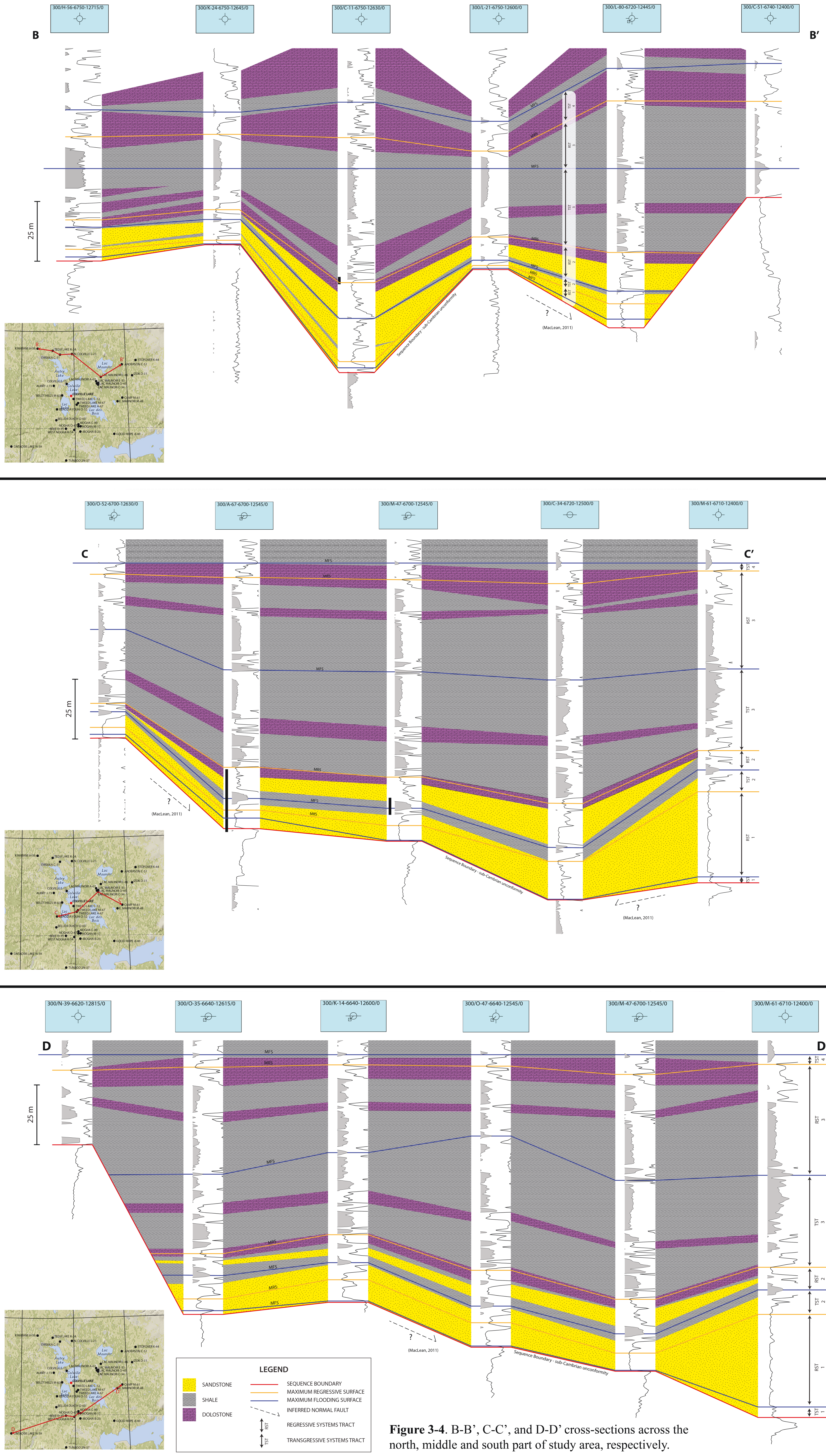

Figure 3-4. B-B', C-C', and D-D' cross-sections across the north, middle and south part of study area, respectively.

Figure 3-4. B-B', C-C' and D-D' cross-sections across the north, middle and south part of the study area, respectively. Inferred normal faults, indicated by dashed arrows between wells, are drawn where cross-section lines intersect faults interpreted by MacLean (2011). Cored intervals appear as solid black boxes adjacent to corresponding wireline logs.

B-B'

A cross-section from west to east showcasing Mount Clark and lower Mount Cap deposition in the north part of the study area. The datum is the second MFS, labelled Carb 2._MFS, which was chosen to best illustrate the considerable differences of accommodation space and showcase the mini-basins or depressions. At the base of these depressions, such as wells C-11 and L-80, are interpreted to be FA1 storm-influenced deposits which is extrapolated from other depressions found within the overall basin that have cored intervals (such as Colville D-45), which also have a generally aggrading wireline signature. To the far east, well C-51 is interpreted to be a paleo-high located on Maunoir Ridge, that was subaerially exposed until deposition of the third offshore shale package of FA3. Purple dolostone markers 1 to 4 of the lower Mount Cap can readily be observed.

C-C'

A cross-section from west to east showcasing Mount Clark and lower Mount Cap deposition across the middle part of the study area; datum is the Regional_MFS marker. Deposition of facies is fairly uniform with the exception of M-61which has considerably thicker basal Mount Clark deposits. Constructed isopachs from Figures 3-5 and 3-6 suggest that the entire eastern part of the study area has much thicker Mount Clark than elsewhere in the basin. Proximal sediment sourcing from the craton is likely a result of this thickening. As with B-B', basal Mount Clark is interpreted to be storm-influenced FA1 sandstone deposits.

D-D'

A cross-section from west to east showcasing Mount Clark and lower Mount Cap deposition across the south part of the study area; datum is the Regional_MFS marker. Deposition of facies is fairly uniform with the exception of well N-39 which is interpreted to be a paleo-high during Mount Clark and much of the lower Mount Cap deposition. This paleo-high may be a distal expression of Mackenzie Arch influence. To the east is the same thickening noted in C-C' in well M-61.

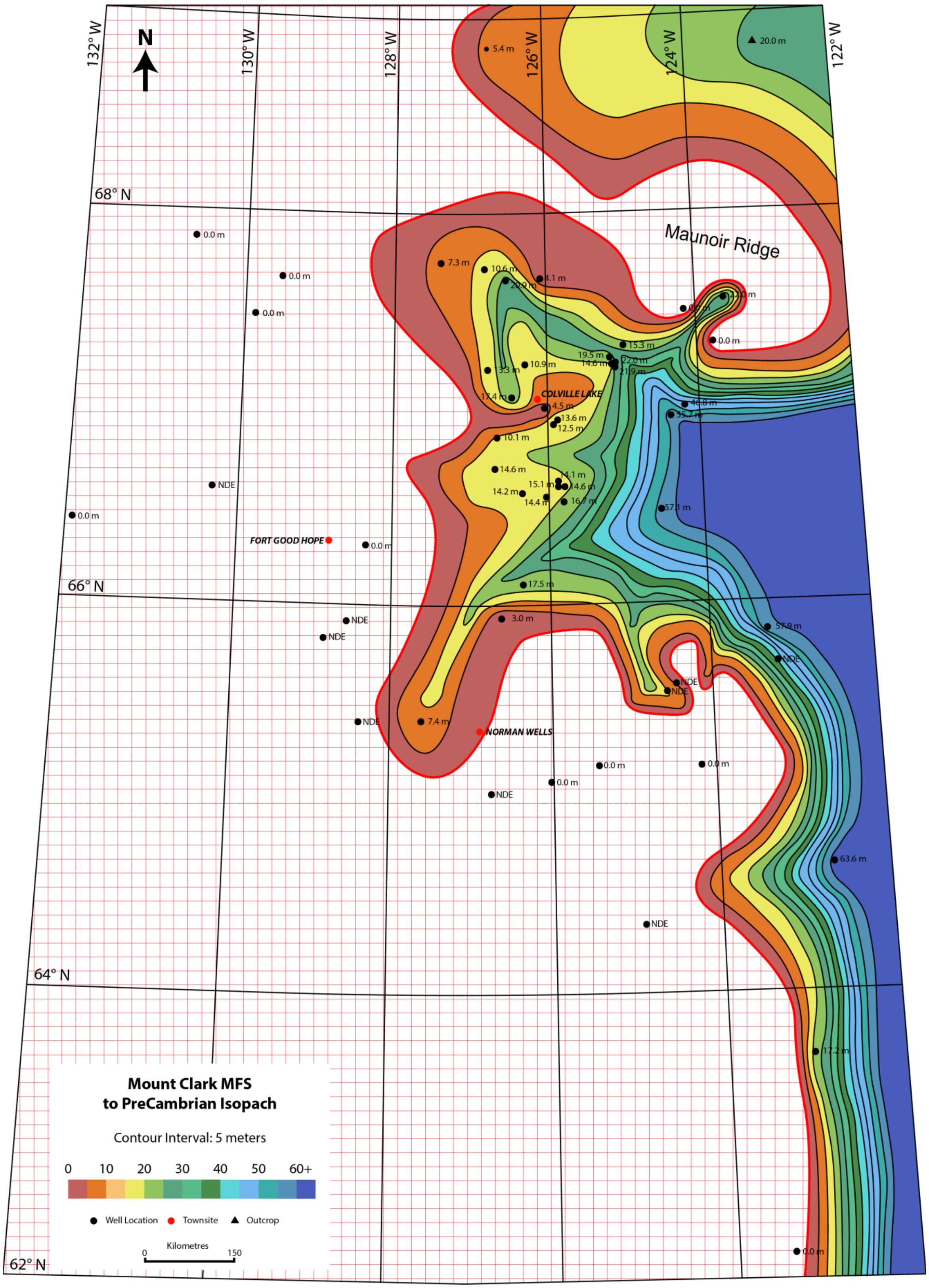

Figure 3-5. Isopach of Mount Clark MFS to sub-Cambrian unconformity. NDE – Not Deep Enough. Zero edge and structural elements modified from MacLean (2011), outcrop data from Bouchard and Turner (2017).

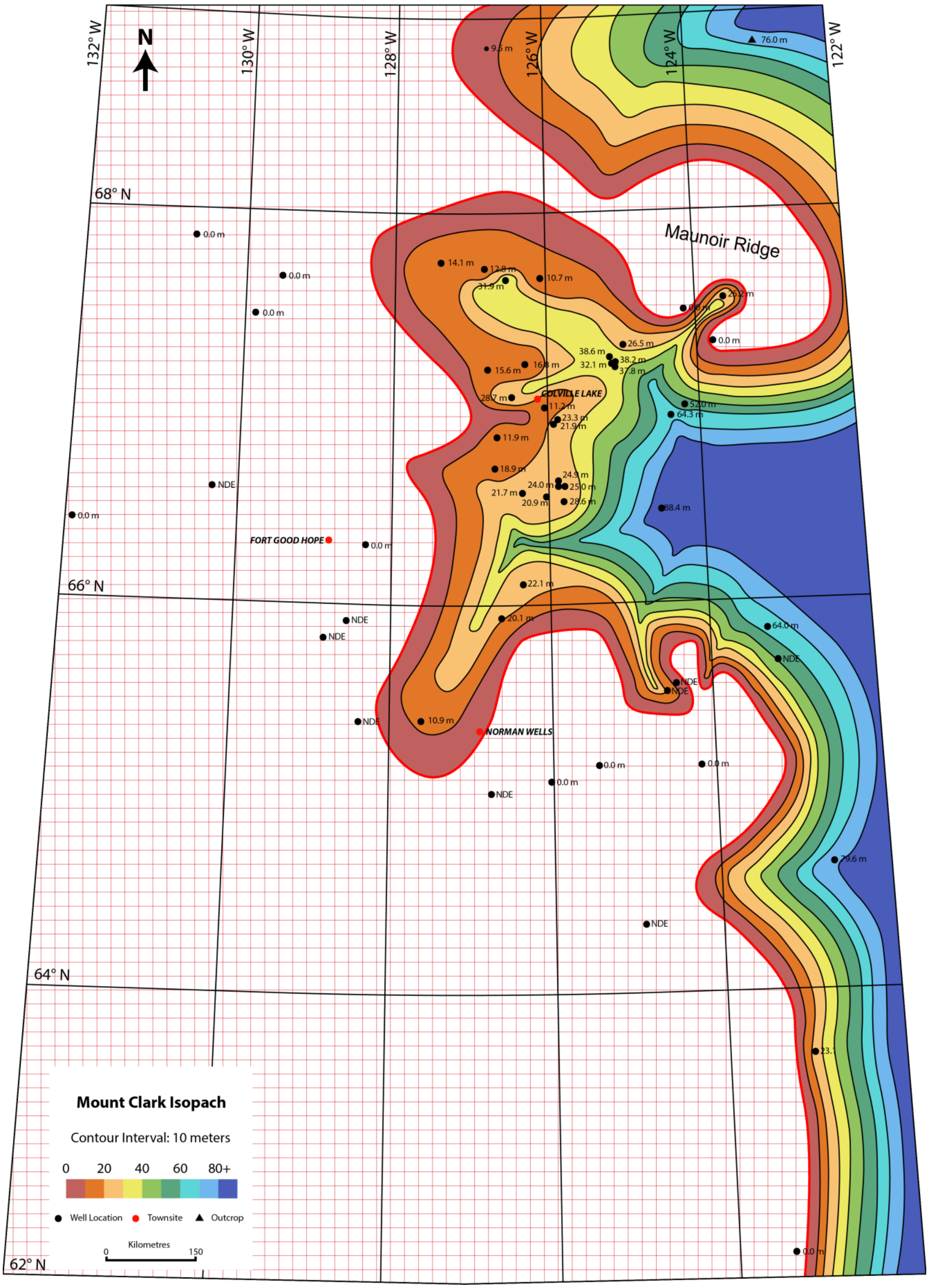

Figure 3-6. Isopach of entire Mount Clark interval to sub-Cambrian unconformity. NDE – Not Deep Enough. Zero edge and structural elements modified from MacLean (2011), outcrop data from Bouchard and Turner (2017).

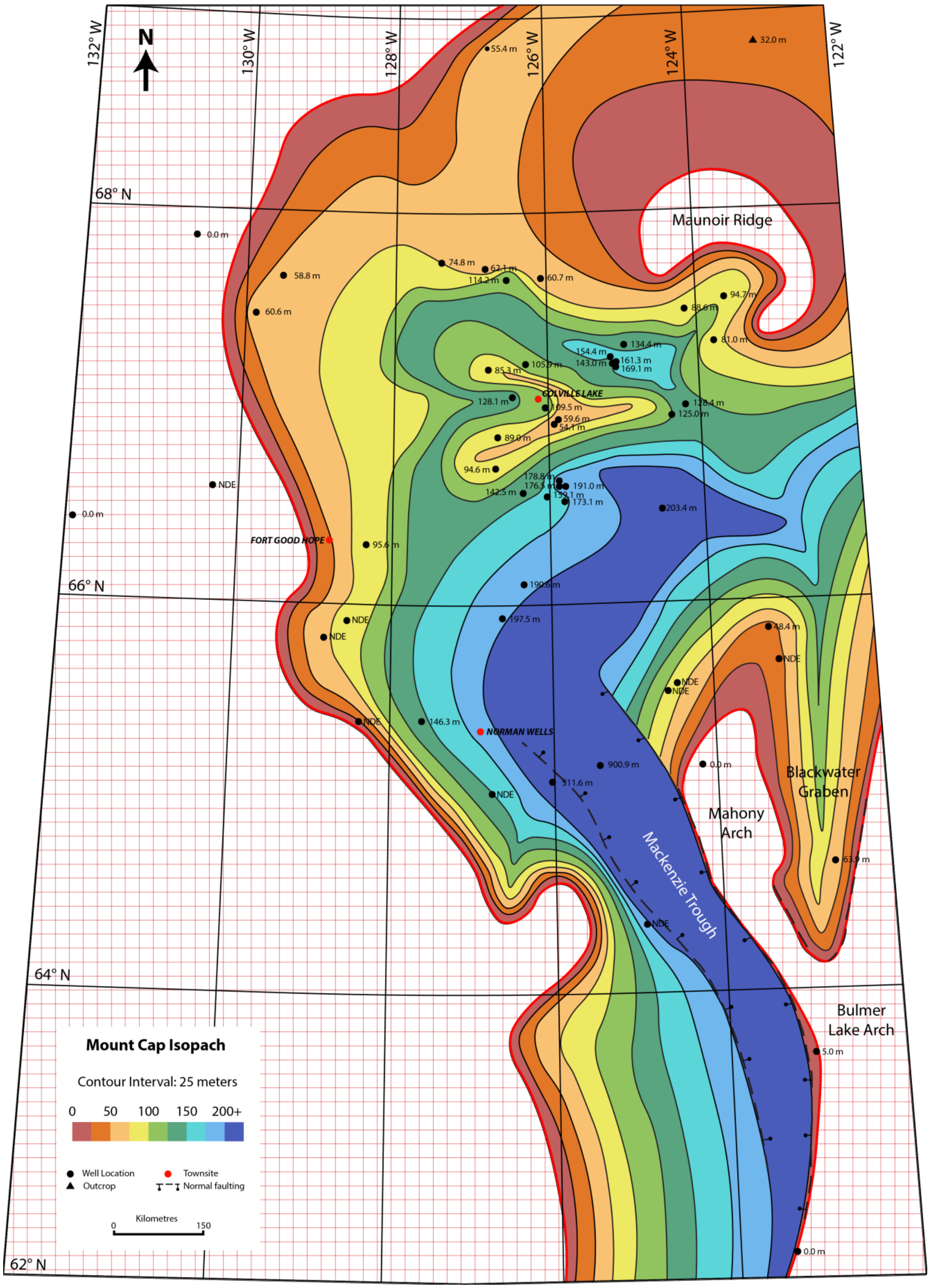

Figure 3-7. Isopach of Mount Cap to Mount Clark (where present) or sub-Cambrian unconformity. NDE – Not Deep Enough. Zero edge and structural elements modified from MacLean (2011), outcrop data from Bouchard and Turner (2017).

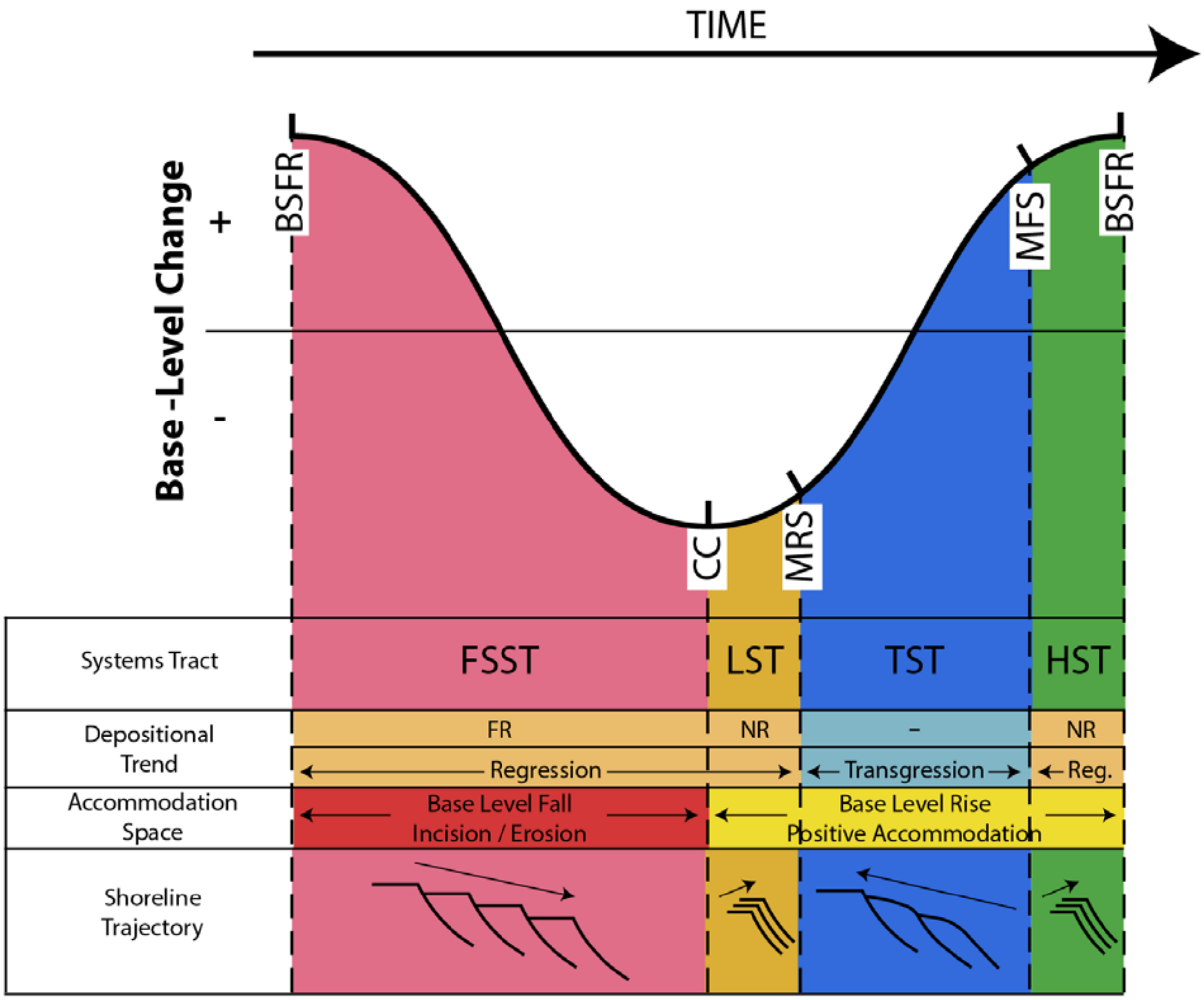

Figure 3-8. System tracts and sequence stratigraphic surfaces in relation to base-level changes based on a Depositional Sequence IV model (Hunt and Tucker, 1992; Plint and Nummedal, 2000, Catuneanu, 2006). A T-R Sequence model combines the HST, FSST and LST into an RST (Embry, 1995, 2002). Abbreviations: BSFR – Basal Surface of Forced Regression, CC – Correlative Conformity, MRS – Maximum Regressive Surface, MFS – Maximum Flooding Surface, FSST – Falling-Stage Systems Tract, LST – Lowstand Systems Tract, TST – Transgressive Systems Tract, HST – Highstand Systems Tract, RST – Regressive Systems Tract, FR – Forced Regression, NR – Normal Regression.

1290.5 m
1290.0 m
MRS
HST
TST
WRS
MFS
HST
BSFR/CC
FSST/LST
Approx. Sea Level
+
-

Figure 3-9. Sequence stratigraphic interpretations from Tweed Lake A-67 core of the Mount Clark Formation with approximate sea level. Abbreviations: BSFR – Basal Surface of Forced Regression, CC – Correlative Conformity, MRS – Maximum Regressive Surface, MFS – Maximum Flooding Surface, FSST – Falling-Stage Systems Tract, LST – Lowstand Systems Tract, TST – Transgressive Systems Tract, HST – Highstand Systems Tract, WRS – Wave Ravinement Surface.

TABLES

Complete Well Name	UWI	Current Operator	Spud Date	MD (m)	TVD (m)
FPC TENNECO ROOT RIVER I-60	300/I-60-6240-12315/0	French Petrl Comp of Cda	12/9/1962	2612.4	2612.4
SUNCOR ARCTIC CIRCLE ONTARATUE H-34	300/H-34-6630-13200/0	Suncor Enrg Inc	12/20/1963	4075.2	4075.2
SUNCOR BEAVERTAIL G-26	300/G-26-6600-12830/0	Suncor Enrg Inc	2/18/1966	1493.5	1493.5
SUNCOR SHOALS C-31	300/C-31-6600-12845/0	Suncor Enrg Inc	4/18/1966	1982.5	1982.5
SINCLAIR WOLVERINE CREEK D-61	300/D-61-6520-12400/0	Sinclair Cda Oil Comp	12/1/1968	1933.1	1933.1
SINCLAIR WHITEFISH RIVER K-76	300/K-76-6540-12415/0	Sinclair Cda Oil Comp	1/30/1969	1608	1608
MOBIL INC NCO SUN ONTADEK L N-39	300/N-39-6620-12815/0	Mobil Oil Cda Ltd	4/13/1970	1798.3	1798.3
MOBIL COLVILLE E-15	300/E-15-6720-12615/0	Mobil Oil Cda Ltd	4/18/1970	1827.6	1827.6
CDR TENLEN A-73	300/A-73-6800-13030/0	Central Del-Rio Oils Ltd	2/1/1971	2595.5	2595.5
MOBIL INEXCO NCO SUN IROQUOIS D-40	300/D-40-6730-12945/0	Mobil Oil Cda Ltd	3/14/1971	2592.5	2592.5
MOBIL AM HESS DODO CANYON K-03	300/K-03-6510-12645/0	Aquitaine Comp of Cda Ltd	11/29/1971	2748	2748
MOBIL BELOT HILLS M-63	300/M-63-6710-12615/0	Mobil Oil Cda Ltd	1/31/1972	1283.5	1283.5
SUNCOR LOST HILL LAKE F-62	300/F-62-6550-12300/0	Suncor Enrg Inc	2/2/1972	1392.6	1392.6
UNION JAPEX BLACKWATER E-11	300/E-11-6350-12300/0	Unocal Cda Lmtd	2/22/1972	2171.6	2171.6
CANDEL ET AL MOBIL GRANDVIEW L-26	300/L-26-6640-13015/0	Candel Oil Ltd	3/9/1972	2397.3	2397.3
SUNCOR WEST WHITEFISH RIVER H-34	300/H-34-6540-12430/0	Suncor Enrg Inc	3/14/1972	1654.5	1654.5
CANDEL MOBIL ET AL IROQUOIS I-11	300/I-11-6750-12930/0	Candel Oil Ltd	4/25/1972	2121.7	2121.7
UNION MOBIL COLVILLE D-45	300/D-45-6720-12500/0	Unocal Cda Lmtd	3/29/1973	1174.2	1174.2
DECALTA DOME LRI ET AL KEELE N-62	300/N-62-6430-12445/0	Westrn Decalta Petrl	9/20/1973	1279.9	1279.9
UNION IOL E. MAUNOIR M-48	300/M-48-6700-12415/0	Unocal Cda Lmtd	1/21/1974	863.1	863.1
ASHLAND ET AL TEDJI LAKE K-24	300/K-24-6750-12645/0	Cdn Ashland Expl Ltd	3/13/1974	1213.9	1213.9
UNION DECALTA GOOD HOPE A-40	300/A-40-6630-12430/0	Unocal Cda Lmtd	12/15/1974	1592.6	1592.6
UNION IMP. STOPOVER K-44	300/K-44-6740-12330/0	Unocal Cda Lmtd	2/15/1975	943	943
BP ET AL LOSH LAKE G-22	300/G-22-6600-12315/0	B P Expl Cda Lmtd	3/15/1975	1226.1	1226.1
MOBIL GULF SADENE D-02	300/D-02-6900-12645/0	Mobil Oil Cda Ltd	3/8/1977	1857.8	1857.8
SUNCOR N. COLVILLE L-21	300/L-21-6750-12600/0	Suncor Enrg Inc	1/27/1978	1195.1	1195.1

Complete Well Name	UWI	Current Operator	Spud Date	MD (m)	TVD (m)
FORWARD ET AL IZOK D-11	300/D-11-6730-12345/0	Forward Rsrcs Ltd	2/15/1983	900	900
FORWARD ET AL ANDERSON C-51	300/C-51-6740-12400/0	Forward Rsrcs Ltd	4/6/1983	1010	1010
FORWARD ET AL CAMP M-61	300/M-61-6710-12400/0	Forward Rsrcs Ltd	1/3/1984	1145	1145
FORWARD ET AL EWEKKA C-11	300/C-11-6750-12630/0	Forward Rsrcs Ltd	2/15/1984	1340	1340
SUNCOR SAMMONS H-55	300/H-55-6530-12815/0	Suncor Enrg Inc	3/14/1984	1710	1708.7
FORWARD ET AL AUBRY J-13	300/J-13-6720-12645/0	Forward Rsrcs Ltd	3/18/1984	1330	1330
SUNCOR ET AL TWEED LAKE M-47	300/M-47-6700-12545/0	Suncor Enrg Inc	1/11/1985	1420	1419.8
EXCO ET AL TUNAGO 2N-37	302/N-37-6610-12615/0	Exco Enrg Ltd	2/4/1985	1626	1616.6
SUNCOR K'AHBAMI H-56	300/H-56-6750-12715/0	Suncor Enrg Inc	3/5/1985	1605	1604.9
SUNCOR TWEED LAKE A-67	300/A-67-6700-12545/0	Suncor Enrg Inc	11/13/1985	1347	1346.1
SUNCOR NOGHA O-47	300/O-47-6640-12545/0	Suncor Enrg Inc	1/13/1986	1416	1415.4
SUNCOR K'ALO B-62	300/B-62-6520-12515/0	Suncor Enrg Inc	1/24/1986	1985	1983
PCI CANTERRA BELE O-35	300/O-35-6640-12615/0	Petro-Cda Inc	2/14/1986	1384	1382
SUNCOR ET AL N W TWEED LAKE C-12	300/C-12-6710-12600/0	Suncor Enrg Inc	2/25/1986	1365	1364.8
CNRL NOTA CREEK C-17	300/C-17-6510-12600/0	Cdn Nat Rsrcs Ltd	12/24/1997	1953	1953
EOG ET AL DEVO CREEK P-45	300/P-45-6530-12730/0	EOG Rsrcs Cda Inc	1/5/2002	2600	2595.9
CNRL BEHDZIA YOUH O-52	300/O-52-6700-12630/0	Cdn Nat Rsrcs Ltd	1/3/2003	1530	1527.8
MGM NOGHA C-49	300/C-49-6640-12545/0	MGM Enrg Corp	1/26/2003	1409	1408.2
CNRES BELLEH DUKEH D-63	300/D-63-6650-12630/0	Cdn Nat Rsrcs Ltd	2/14/2003	1570	1569.9
MGM ET AL NOGHA M-17	300/M-17-6640-12545/0	MGM Enrg Corp	2/25/2003	1394	1393.6
MGM NOGHA B-23	300/B-23-6640-12545/0	MGM Enrg Corp	1/29/2004	1476	1475.8
APACHE PARAMOUNT LAC MAUNOIR C-34	300/C-34-6720-12500/0	Apache Cda Ltd	2/6/2004	944	944
MGM WEST NOGHA K-14	300/K-14-6640-12600/0	MGM Enrg Corp	3/1/2004	1404	1403.9
APACHE PARAMOUNT LAC MAUNOIR A-67	300/A-67-6720-12500/0	Apache Cda Ltd	1/31/2005	1070	1069.8
APACHE PARAMOUNT E. LAC MANOIR L-80	300/L-80-6720-12445/0	Apache Cda Ltd	2/15/2005	1221	1220.9
APACHE PARAMOUNT TURTON LAKE G-47	300/G-47-6600-12630/0	Apache Cda Ltd	2/24/2005	1465	1465
APACHE PARAMOUNT LAC MANOIR E-35	300/E-35-6720-12500/0	Apache Cda Ltd	2/26/2005	1011	1010.8
SUNCOR BLACKWATER KWIJIKA M-59	300/M-59-6440-12230/0	Suncor Inc	11/2/2007	1640	1638.4

Table 3-1. Table of wells used to construct lithostratigraphic and sequence stratigraphic frameworks in this study.

CHAPTER 4: SUMMARY AND CONCLUSIONS

Reconstruction of the Mount Clark and Mount Cap formations in the Colville Basin was established using drill cores, geological reports and petrophysical wireline data. The Lower and Middle Cambrian succession was then divided into 4 facies associations and correlated across the basin using lithostratigraphic and sequence stratigraphic methods. Despite the diminutive dataset for such a substantial study area, this work was able to illustrate and refine the complex depositional evolution of the basin.

Chapter 2 presented a high-resolution facies analysis of the 10 available drill cores that covered the Precambrian to Saline River interval, though predominantly consisted of the Mount Clark succession. Lithological and ichnological interpretations yielded 20 discrete facies based from observations of: lithology, sedimentary structures, lithological accessories, grain-size, and sorting. Ichnological observations that contributed were: bioturbation intensity, ichno-diversity, trace fossil assemblage and trace fossil size. The facies were then categorized into 4 facies associations: (FA1) Storm-Influenced Shoreface, (FA2) Fairweather Shoreface, (FA3) Offshore and (FA4) Carbonate Ramp. Fairweather versus storm-influenced deposits were contrasted by the level of bioturbation in conjunction with grain size and type of contacts between beds. Ichnological observations, where present, in FA1 suggest a stressed environment for ichnofauna as these trace fossils were commonly of low ichno-diversity and diminutive. Conversely, ichnofauna identified in FA2 deposits tended to have high ichno-diversity, high bioturbation intensities and generally are larger in size, which suggests at the time of deposition there was a robust food supply, regular marine salinities, low to moderate sedimentation rates, sufficient oxygen levels and attenuated wave-energy. FA3 offshore deposits dominated the Lower Mount Cap while FA4 carbonate ramp to restricted environment dominated the Upper Mount Cap and Saline River successions.

Chapter 3 took the high-resolution facies analysis conducted from Chapter 2 and extrapolated those observations across the basin using petrophysical wireline logs from 45 wells. A lithostratigraphic framework was created using facies associations as individual facies could not be reliably correlated. At the base of the Mount Clark, FA1 deposits dominated. These were capped by a mudstone package recording the first regional MFS. Above this flooding event, remaining Mount Clark deposits were variable between FA1 and FA2 depending on location in the basin and paleo-water depth. FA1 deposits tended to be centered in the basin where deeper waters could generate storm-influenced features such as HCS while FA2 deposits tended to be on the periphery of the basin or in sheltered environments. Within the Lower Mount Cap, four distinct carbonate beds were correlated across the basin. Stacking patterns of facies associations were then analyzed to build a sequence stratigraphic model. A T-R Sequence model was used which resulted in three sequences in the Lower Mount Cap and Mount Clark successions. Each sequence was bounded by a regionally-correlated MFS or the sub-Cambrian unconformity at the base. Combining these two frameworks illustrated the overall complex deposition and evolution of the basin.

Suggested future work in the Colville Basin may be to conduct chemostratigraphy over the Mount Clark and Mount Cap successions that may result in a more refine sequence stratigraphic model.

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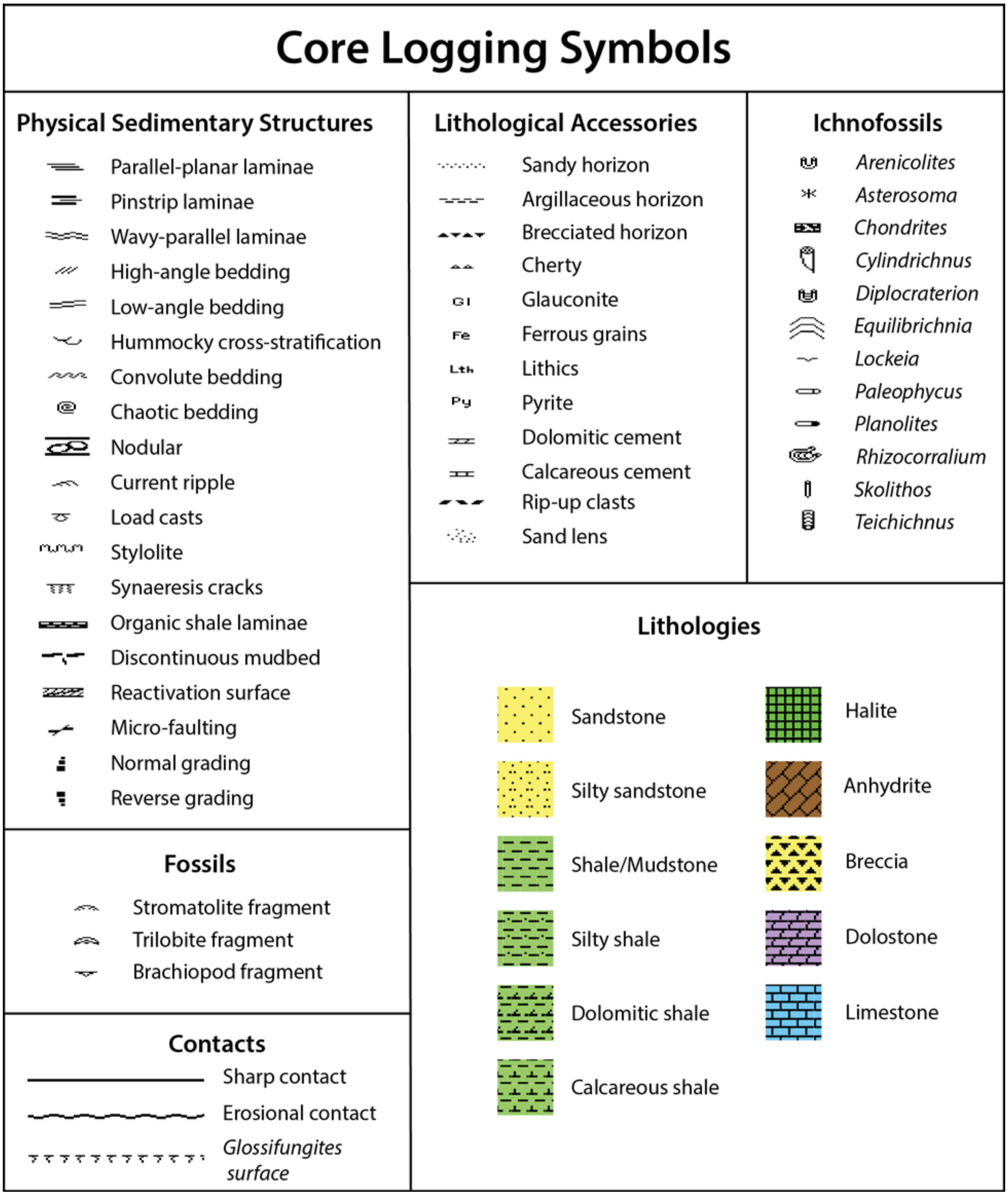
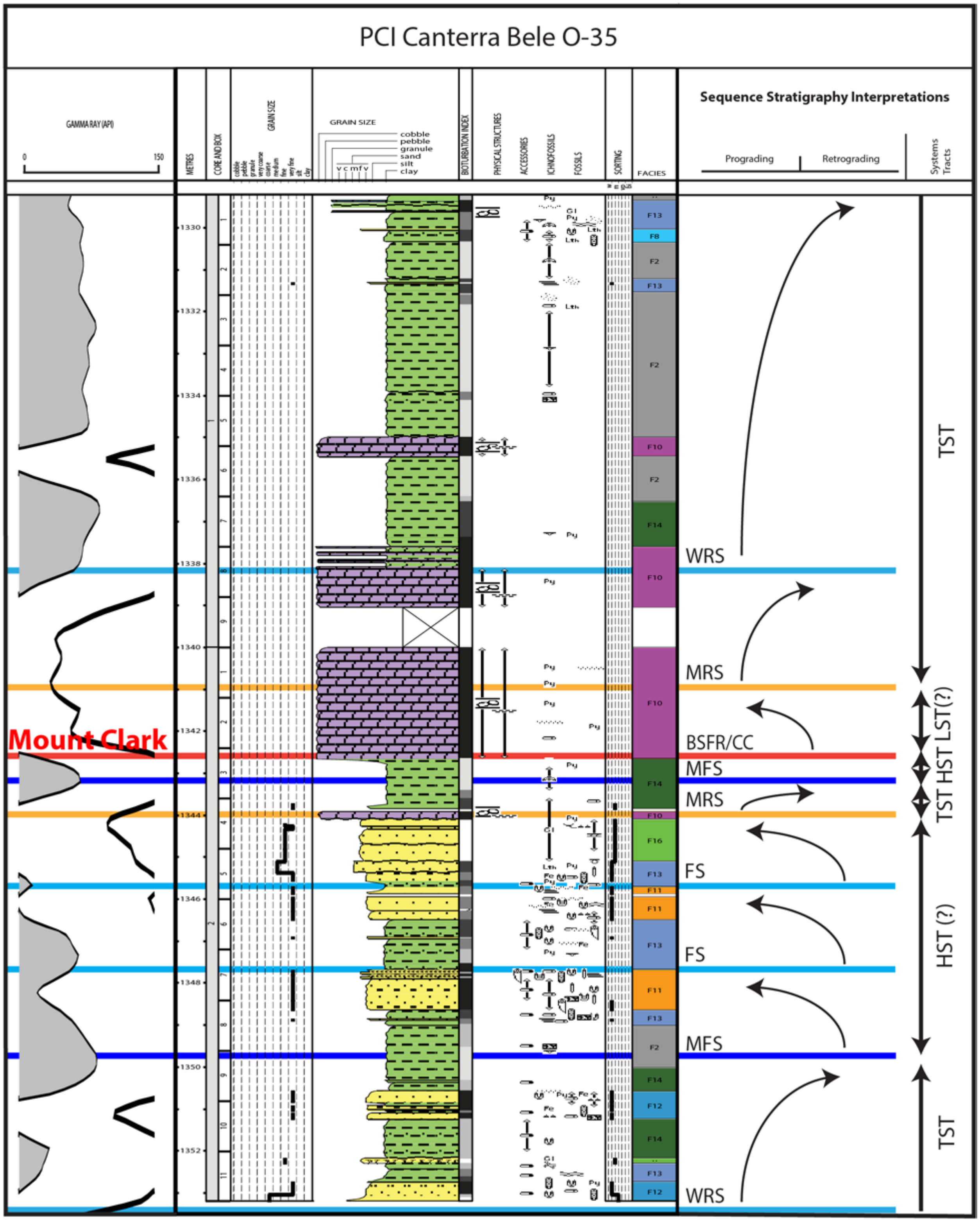
APPENDIX

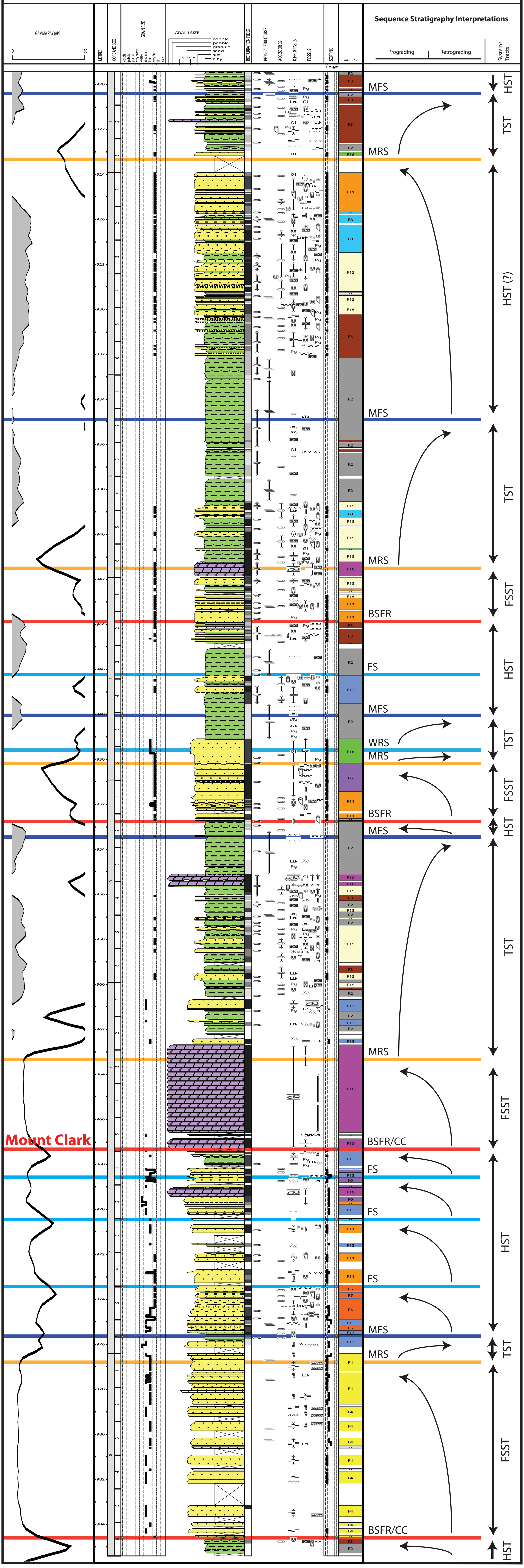

Core Logging Symbols
Physical Sedimentary Structures
Parallel-planar laminae
Pinstrip laminae
Wavy-parallel laminae
High-angle bedding
Low-angle bedding
Hummocky cross-stratification
Convolute bedding
Chaotic bedding
Nodular
Current ripple
Load casts
Stylolite
Synaeresis cracks
Organic shale laminae
Discontinuous mudbed
Reactivation surface
Micro-faulting
Normal grading
Reverse grading
Lithological Accessories
Sandy horizon
Argillaceous horizon
Brecciated horizon
Cherty
Gl
Glauconite
Fe
Ferrous grains
Lth
Lithics
Py
Pyrite
Dolomitic cement
Calcareous cement
Rip-up clasts
Sand lens
Ichnofossils
Arenicolites
Asterosoma
Chondrites
Cylindrichnus
Diplocraterion
Equilibrichnia
Lockeia
Paleophycus
Planolites
Rhizocorralium
Skolithos
Teichichnus
Fossils
Stromatolite fragment
Trilobite fragment
Brachiopod fragment
Contacts
Sharp contact
Erosional contact
Glossifungites surface
Lithologies
Sandstone
Silty sandstone
Shale/Mudstone
Silty shale
Dolomitic shale
Calcareous shale
Halite
Anhydrite
Breccia
Dolostone
Limestone

CORE LOGS

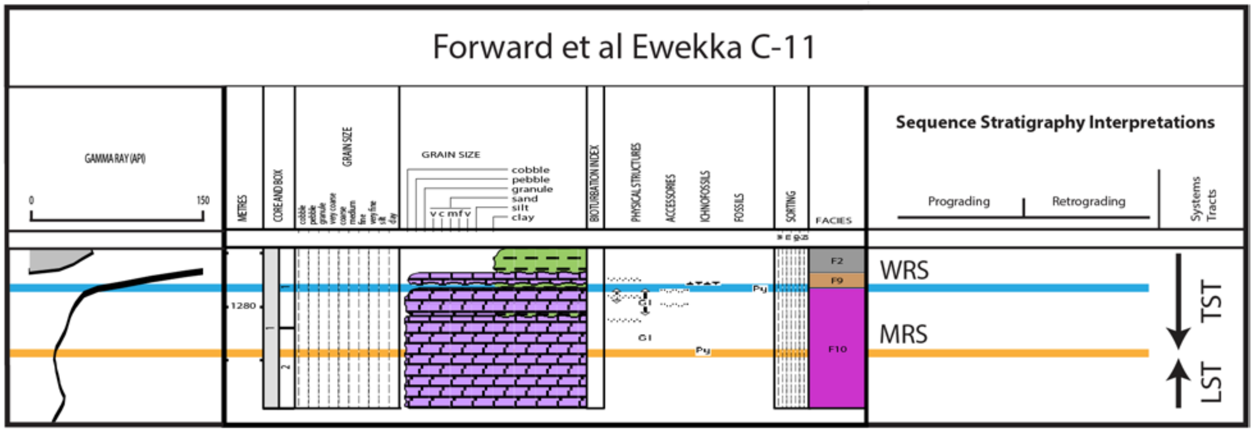


D-45

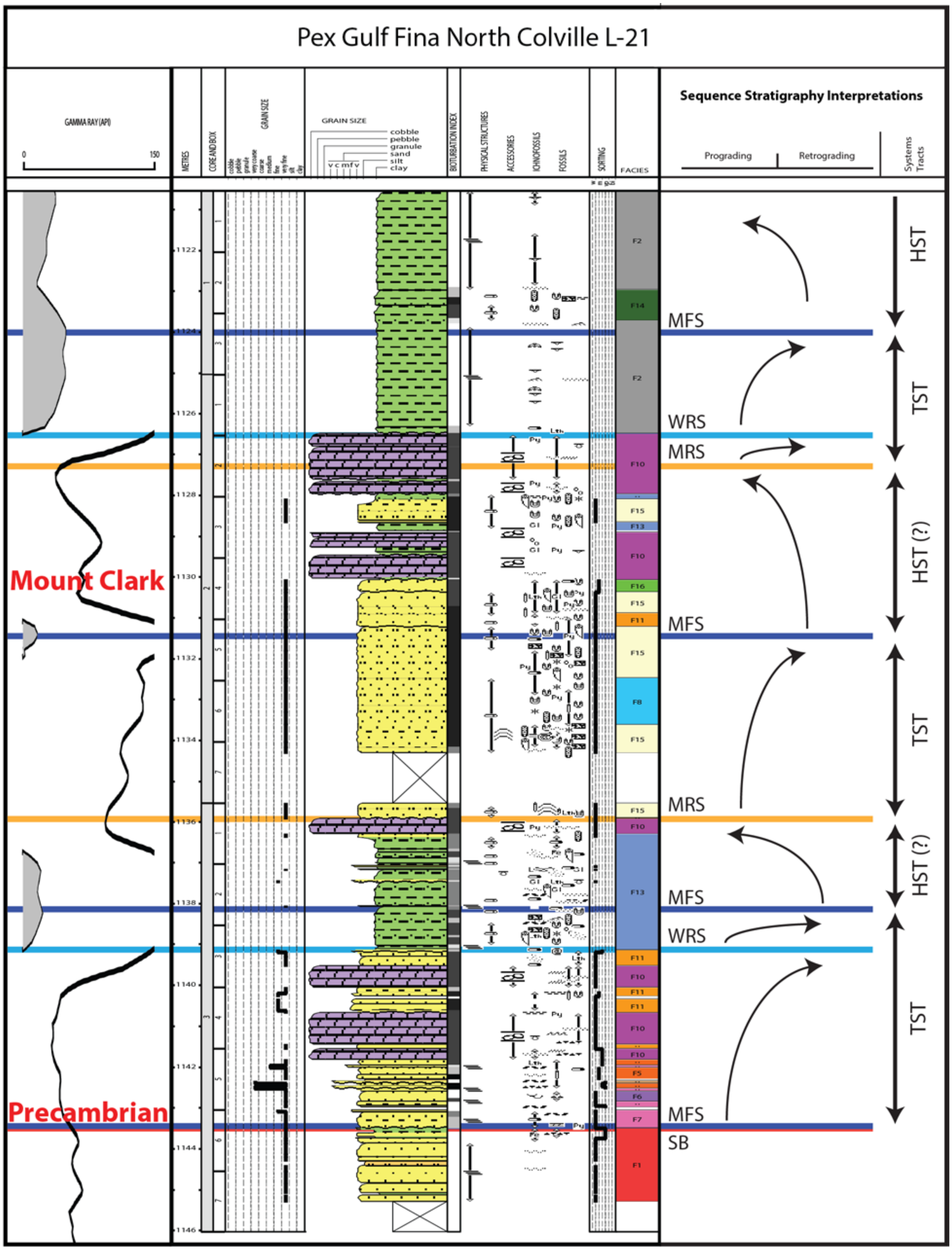
Union Mobil Colville D-45



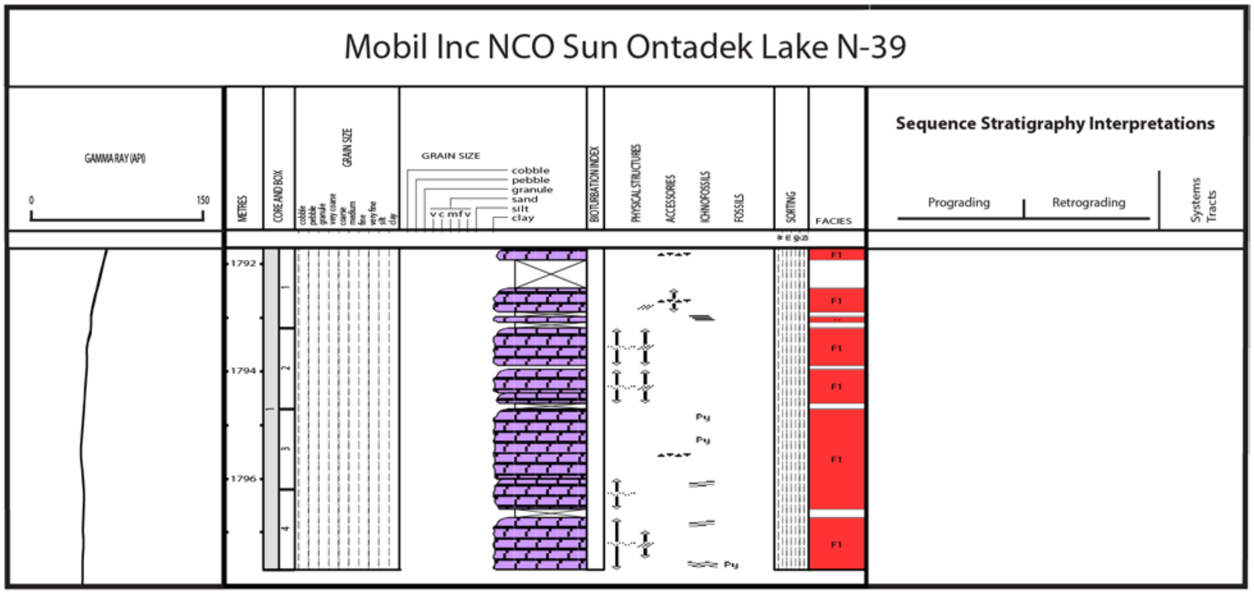

Mobil Colville E-15
GAMMA RAY (API)
0
150
METRES
CORE AND BOX
GRAIN SIZE
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FOSSILS
SORTING
FACIES
Sequence Stratigraphy Interpretations
Prograding
Retrograding
Systems Tracts
Saline River L. Clastics
Mount Cap
L. Mount Cap
Mount Clark
Precambrian
MFS
MRS
WRS
BSFR
FS
SB
RST
TST
FSST/LST
HST
HST (?)



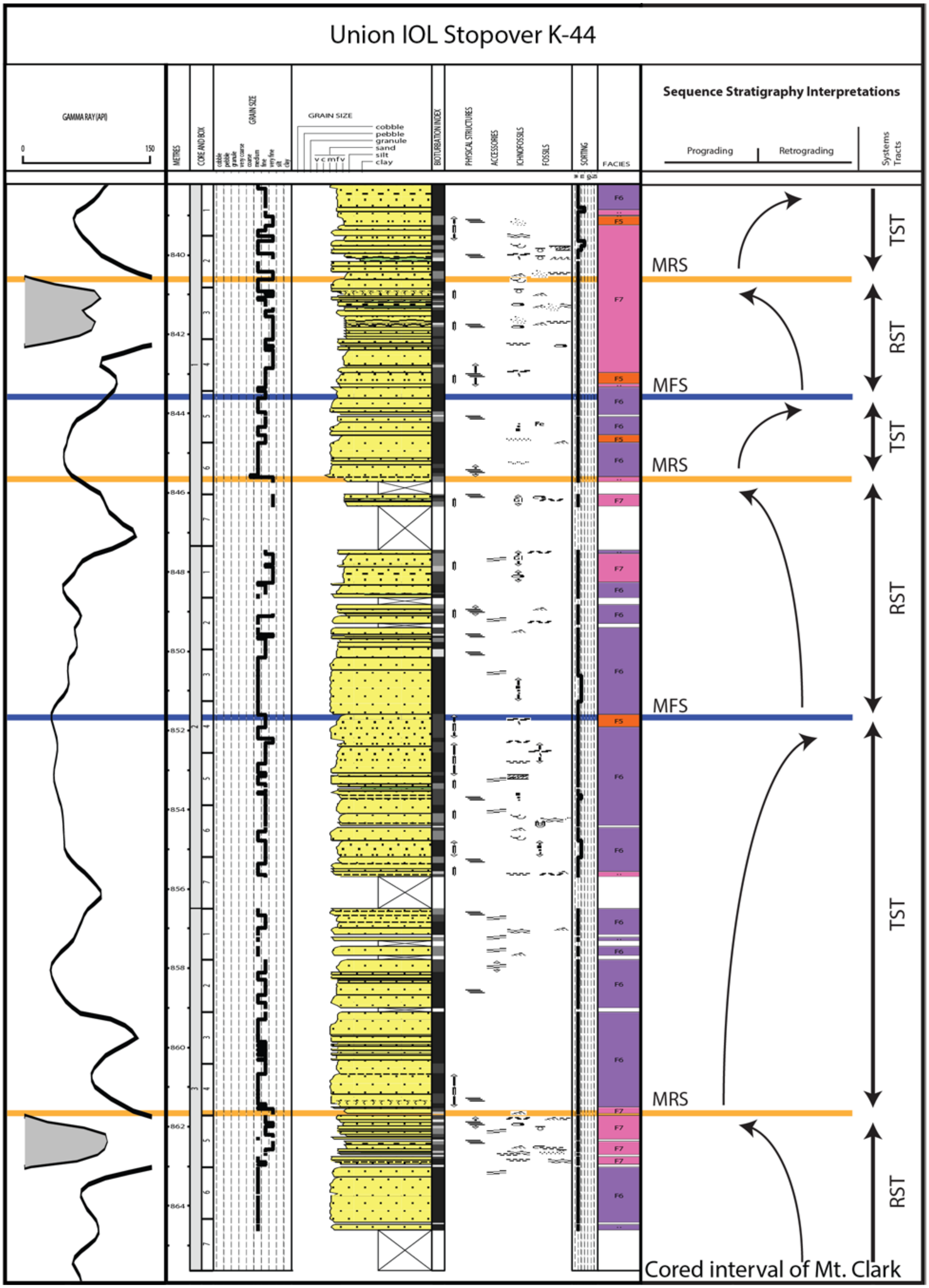
Cored interval of Mount Cap



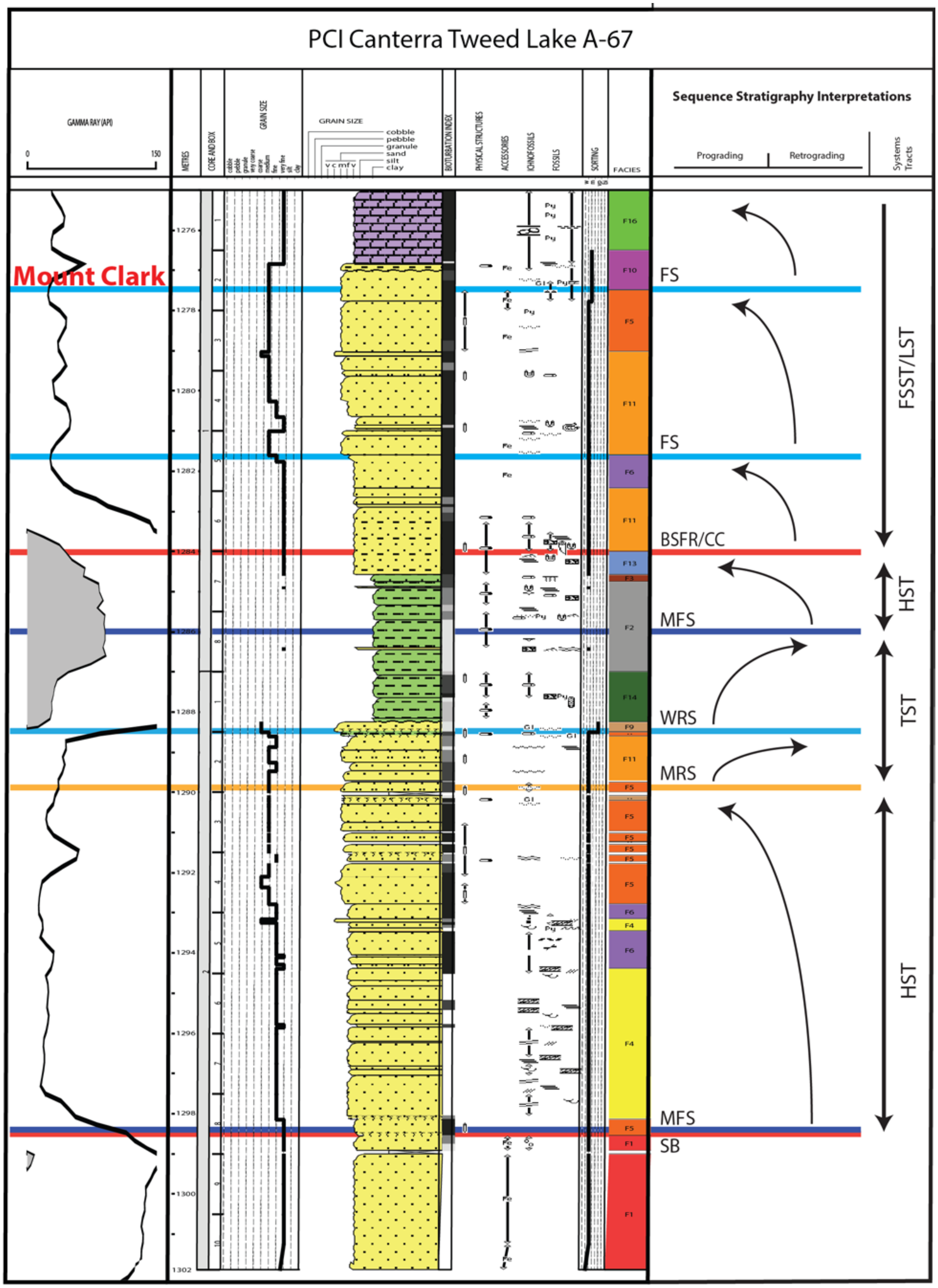
Pex Gulf Fina North Colville L-21
GAMMA RAY (API)
0
150
METRES
CORE AND BOX
GRAIN SIZE
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FOSSILS
SORTING
FACIES
Sequence Stratigraphy Interpretations
Prograding
Retrograding
Systems Tracts
HST
MFS
TST
WRS
MRS
HST (?)
MFS
TST
MRS
HST (?)
MFS
WRS
TST
MFS
SB
Mount Clark
Precambrian



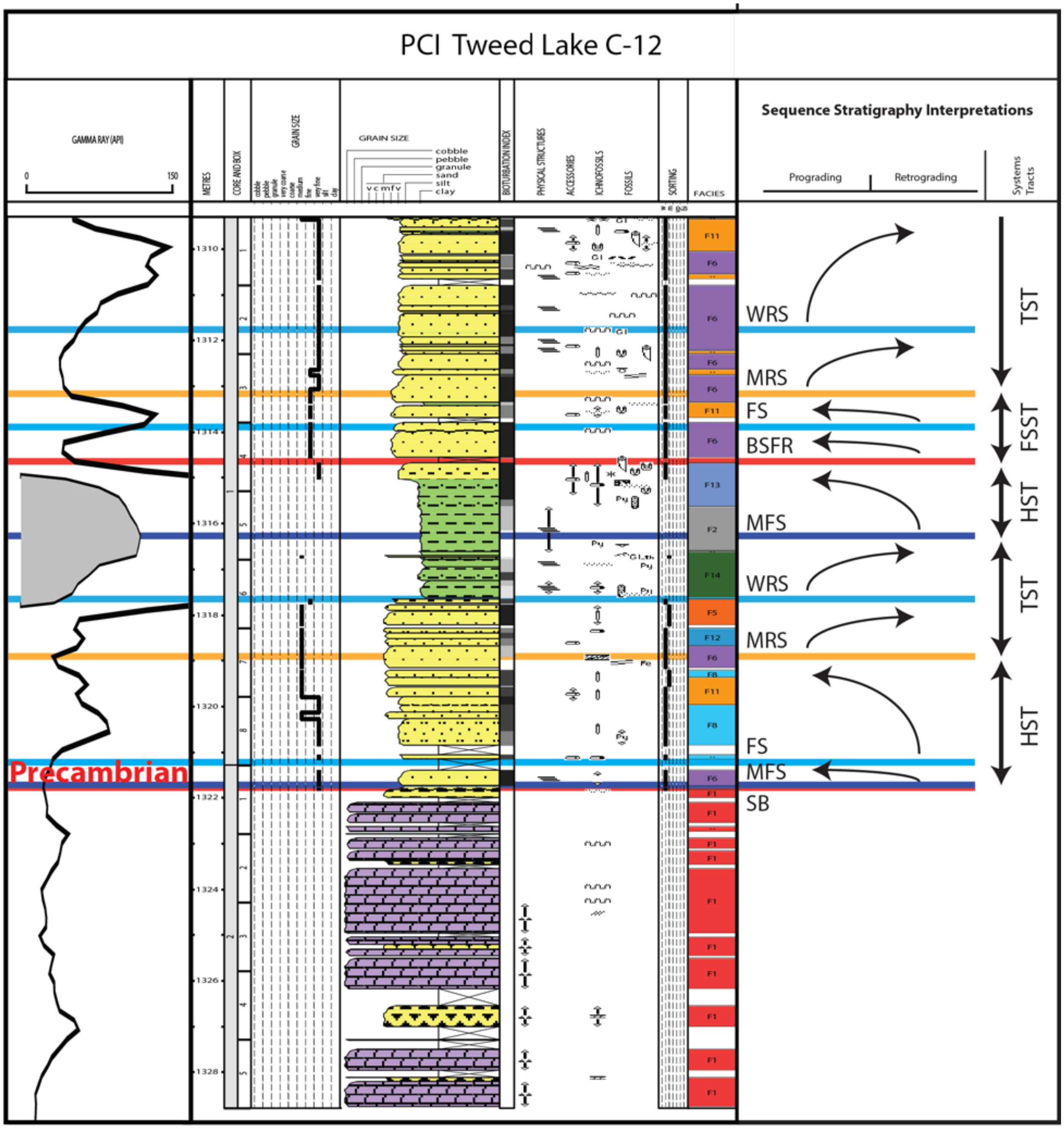
Cored interval of Precambrian (?Hornby Bay Assemblage)

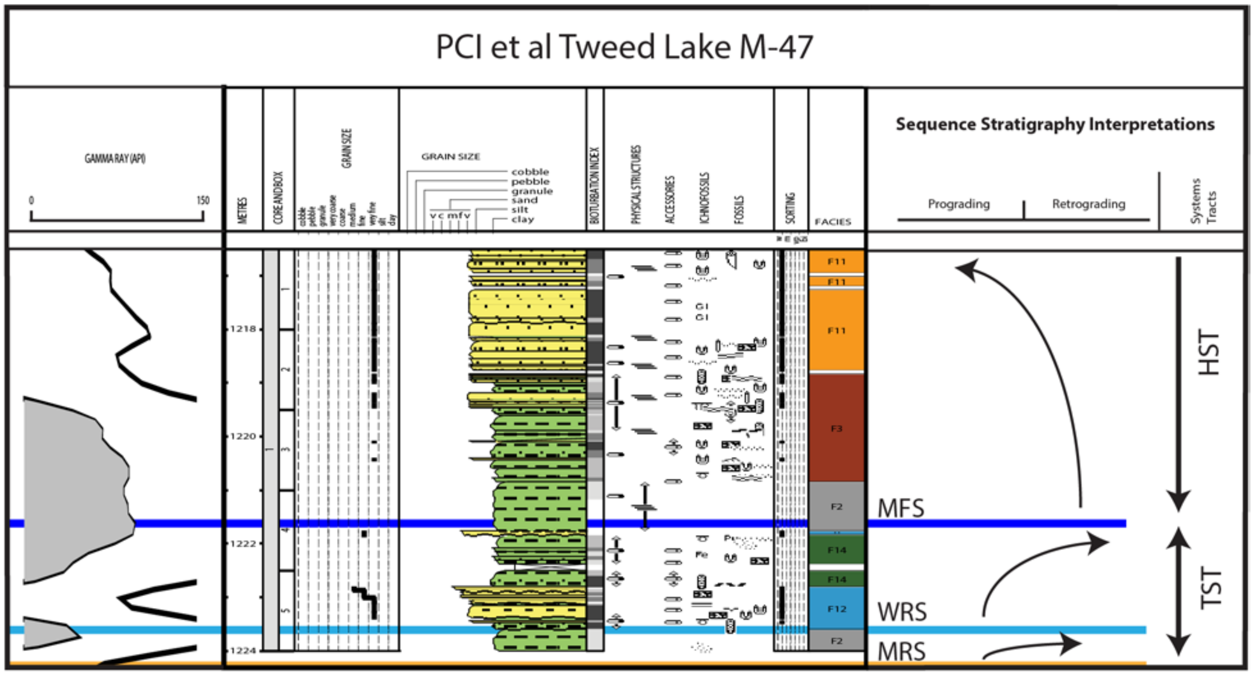


Union IOL Stopover K-44
GAMMA RAY (API)
0
150
METRES
CORE AND BOX
GRAIN SIZE
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FOSSILS
SORTING
FACIES
Sequence Stratigraphy Interpretations
Prograding
Retrograding
Systems Tracts
MRS
MFS
MRS
MFS
MRS
TST
RST
TST
RST
TST
RST
Cored interval of Mt. Clark



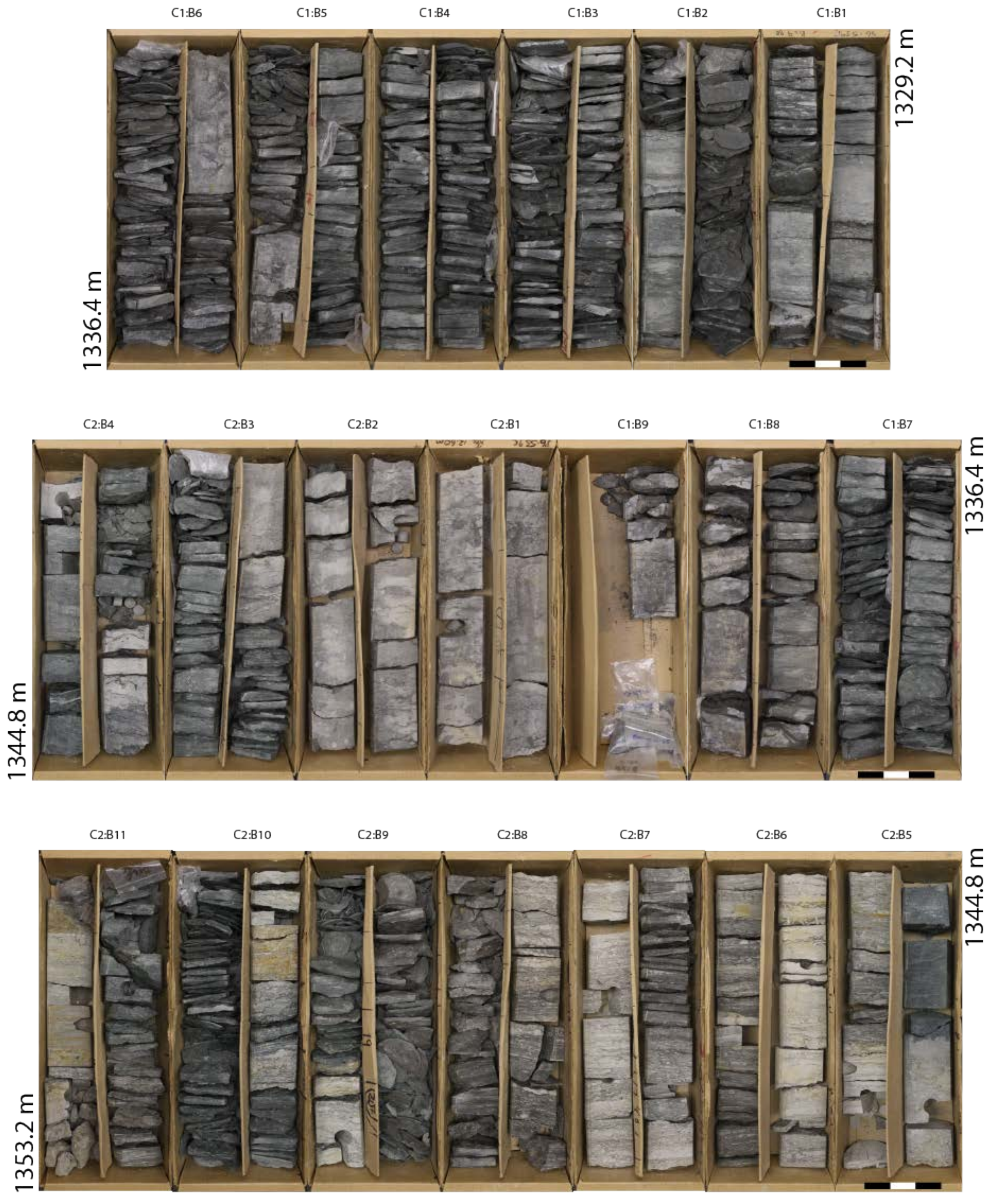
PCI Canterra Tweed Lake A-67
GAMMA RAY (API)
0
150
Mount Clark
METRES
CORE AND BOX
GRAIN SIZE
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FOSSILS
SORTING
FACIES
cobble
pebble
granule
sand
silt
clay
Sequence Stratigraphy Interpretations
Prograding
Retrograding
Systems Tracts
FS
FS
BSFR/CC
MFS
WRS
MRS
MFS
SB
FSST/LST
HST
TST
HST


PCI Tweed Lake C-12
GAMMA RAY (API)
0
150
METRES
CORE AND BOX
GRAIN SIZE
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FOSSILS
SORTING
FACIES
Sequence Stratigraphy Interpretations
Prograding
Retrograding
Systems Tracts
WRS
MRS
FS
BSFR
MFS
WRS
MRS
FS
MFS
SB
TST
FSST
HST
TST
HST
Precambrian

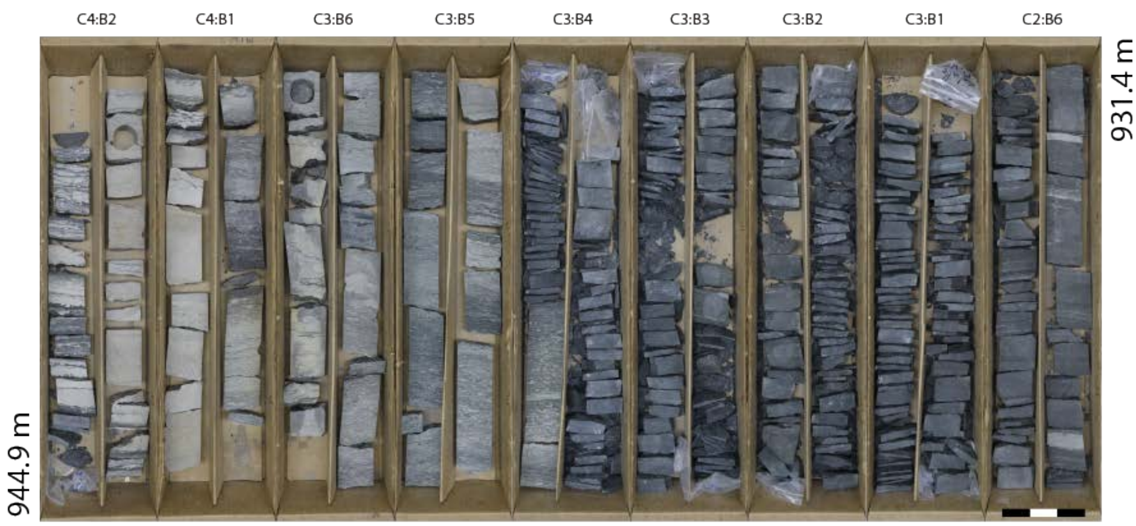


Cored interval of Mount Clark

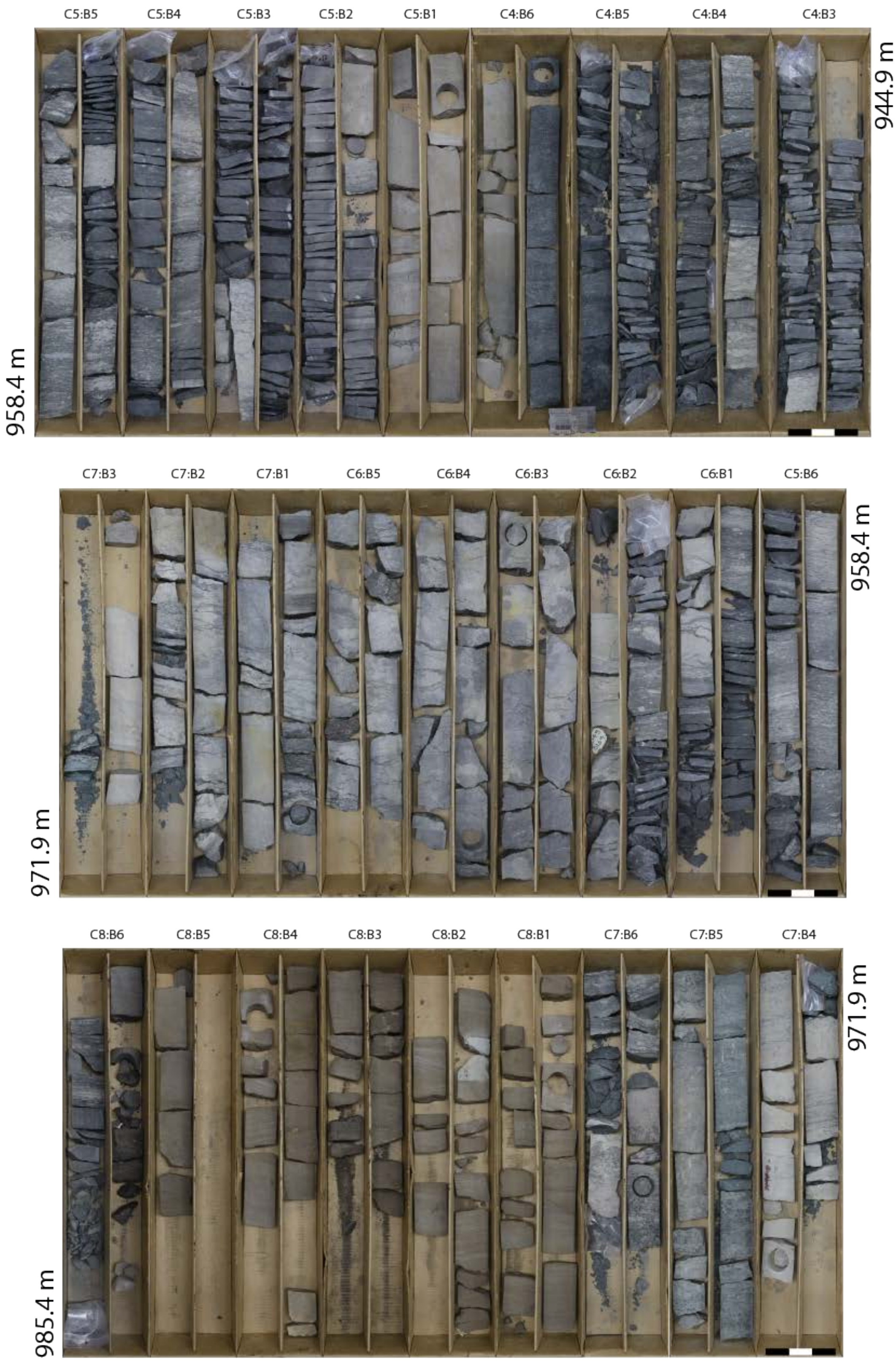
CORE BOXSHOTS



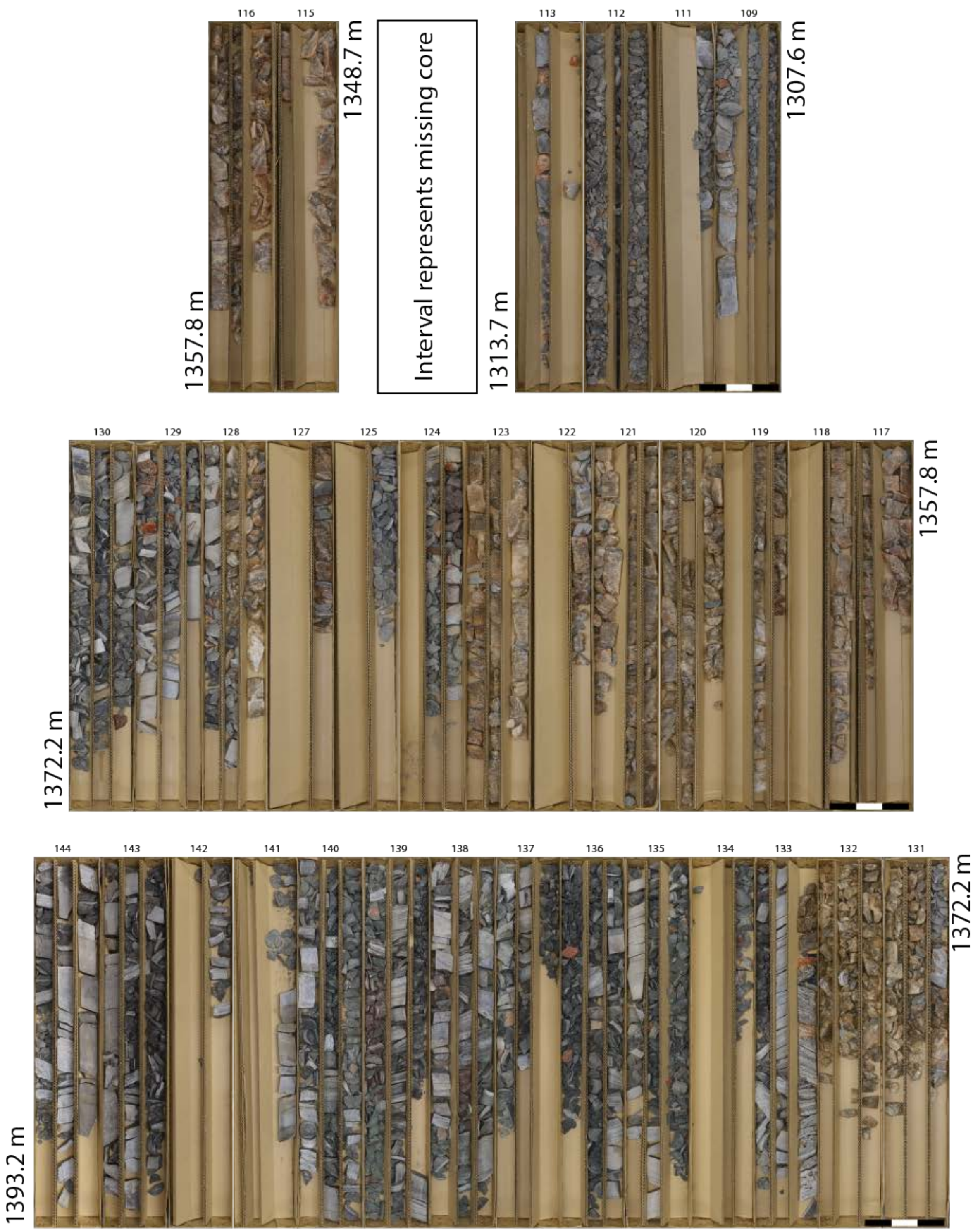
Bele O-35. Scale bars are 15 cm long.



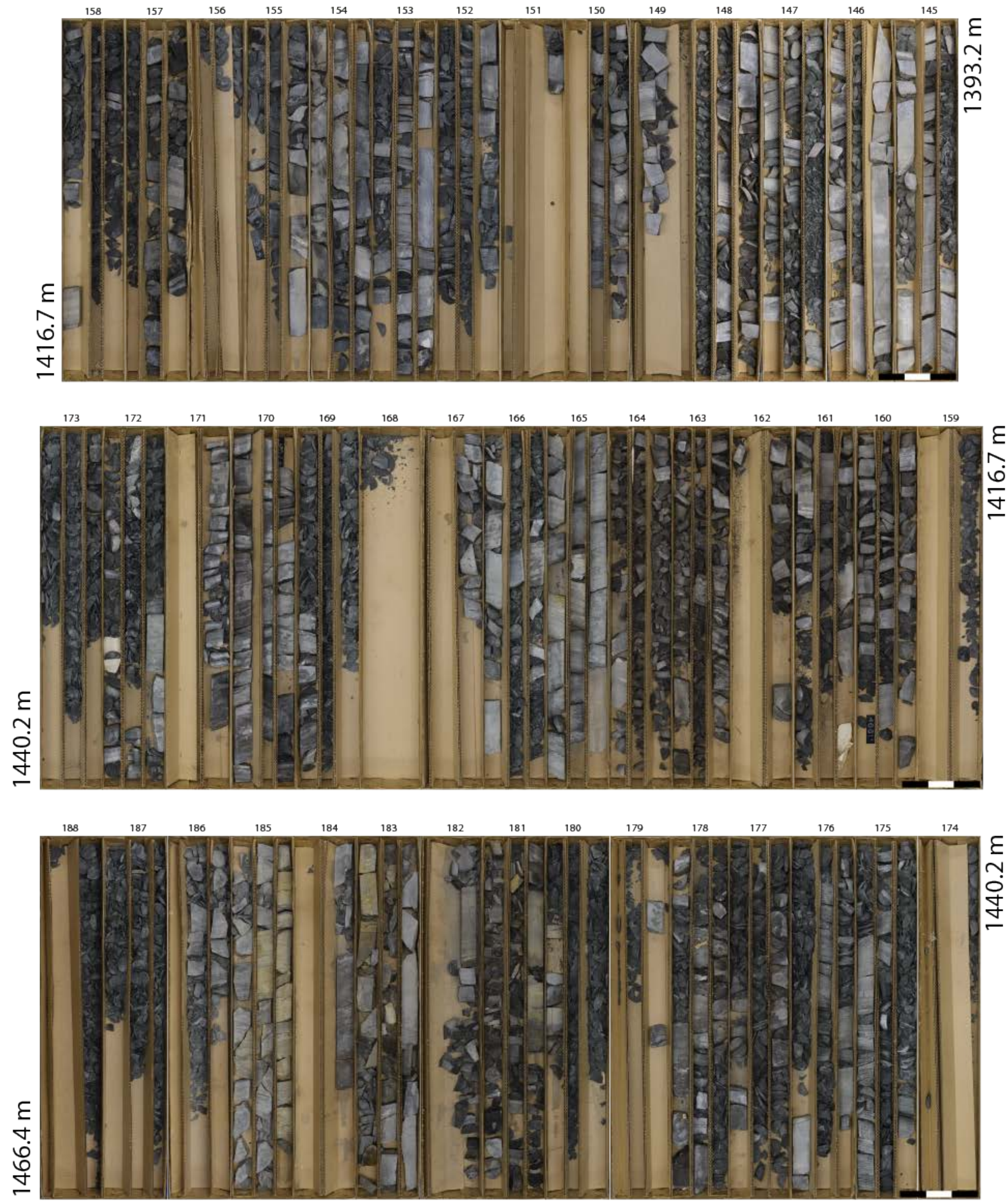
Colville D-45: 1 of 2 (core continues on following page). Scale bars are 15 cm long.



Colville D-45: 2 of 2. Scale bars are 15 cm long.


116
115
1348.7 m
1357.8 m
Interval represents missing core
113
112
111
109
1307.6 m
1313.7 m
130
129
128
127
125
124
123
122
121
120
119
118
117
1357.8 m
1372.2 m
144
143
142
141
140
139
138
137
136
135
134
133
132
131
1372.2 m
1393.2 m

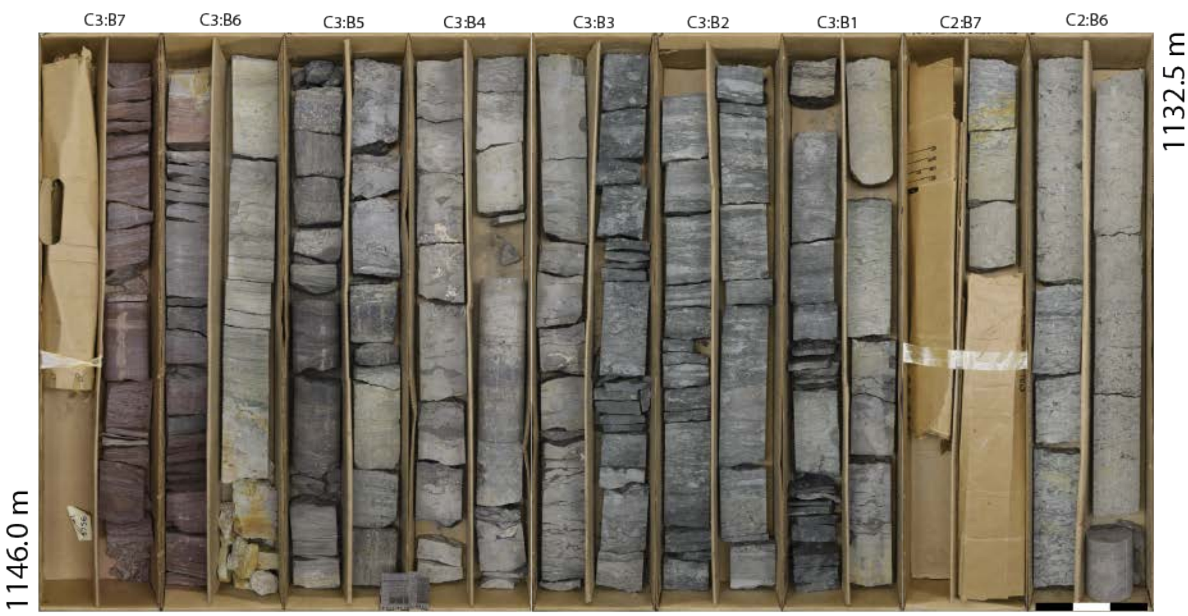
Colville E-15: 1 of 3. Between box 115 and 113 is box 114 which represents a large missing section of core in order to have the appropriate box numbers coincide accurately with available core. Scale bars are 15 cm long.



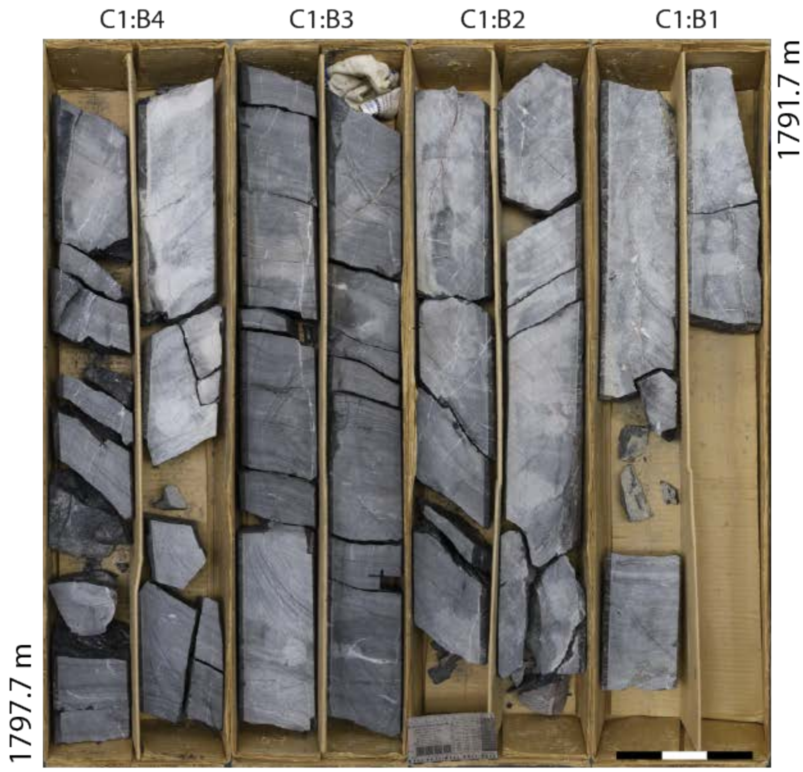
Colville E-15: 2 of 3. Scale bars are 15 cm long.

Colville E-15: 3 of 3. Scale bars are 15 cm long.

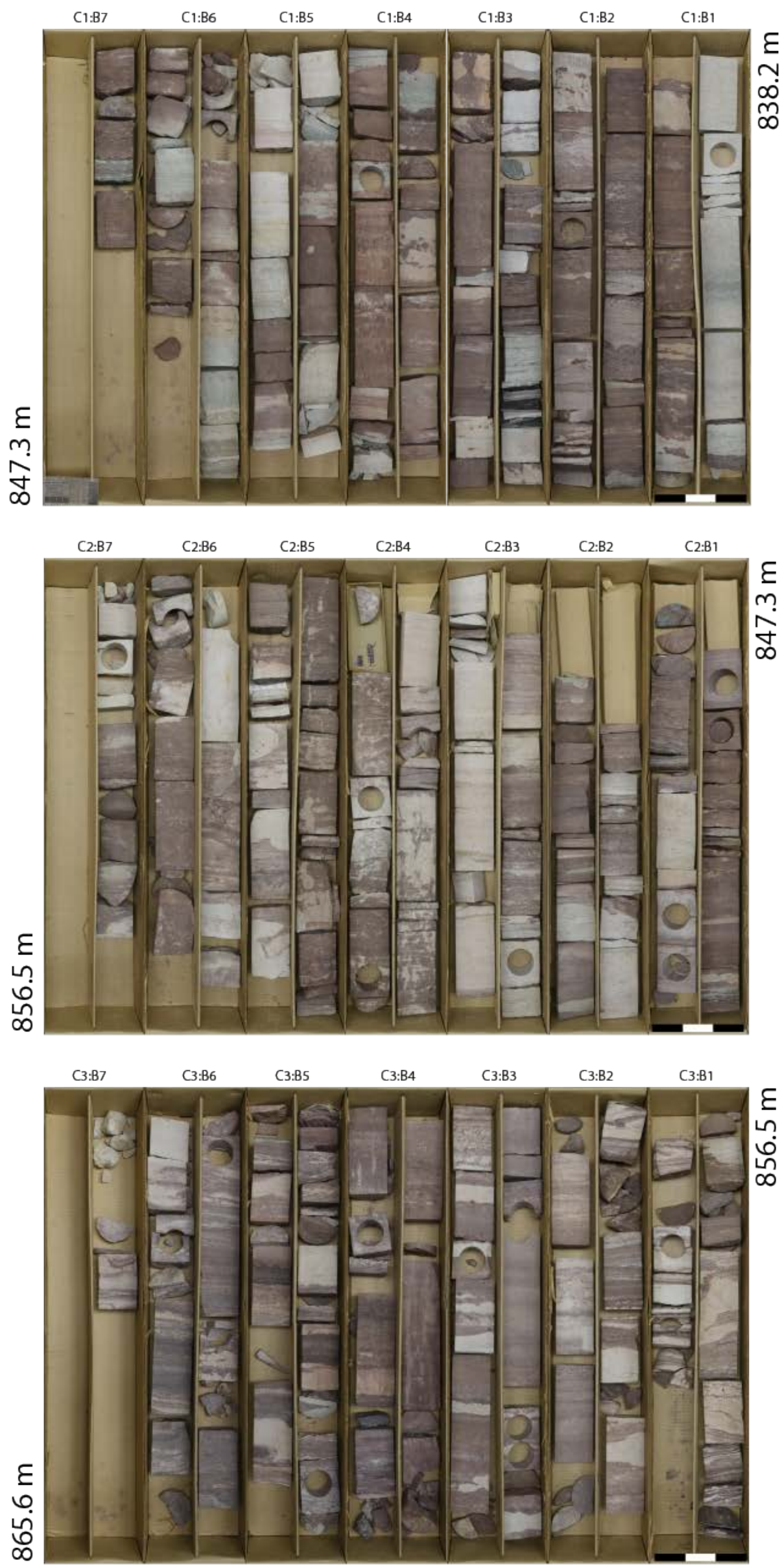
Ewekka C-11. Scale bar is 15 cm long.



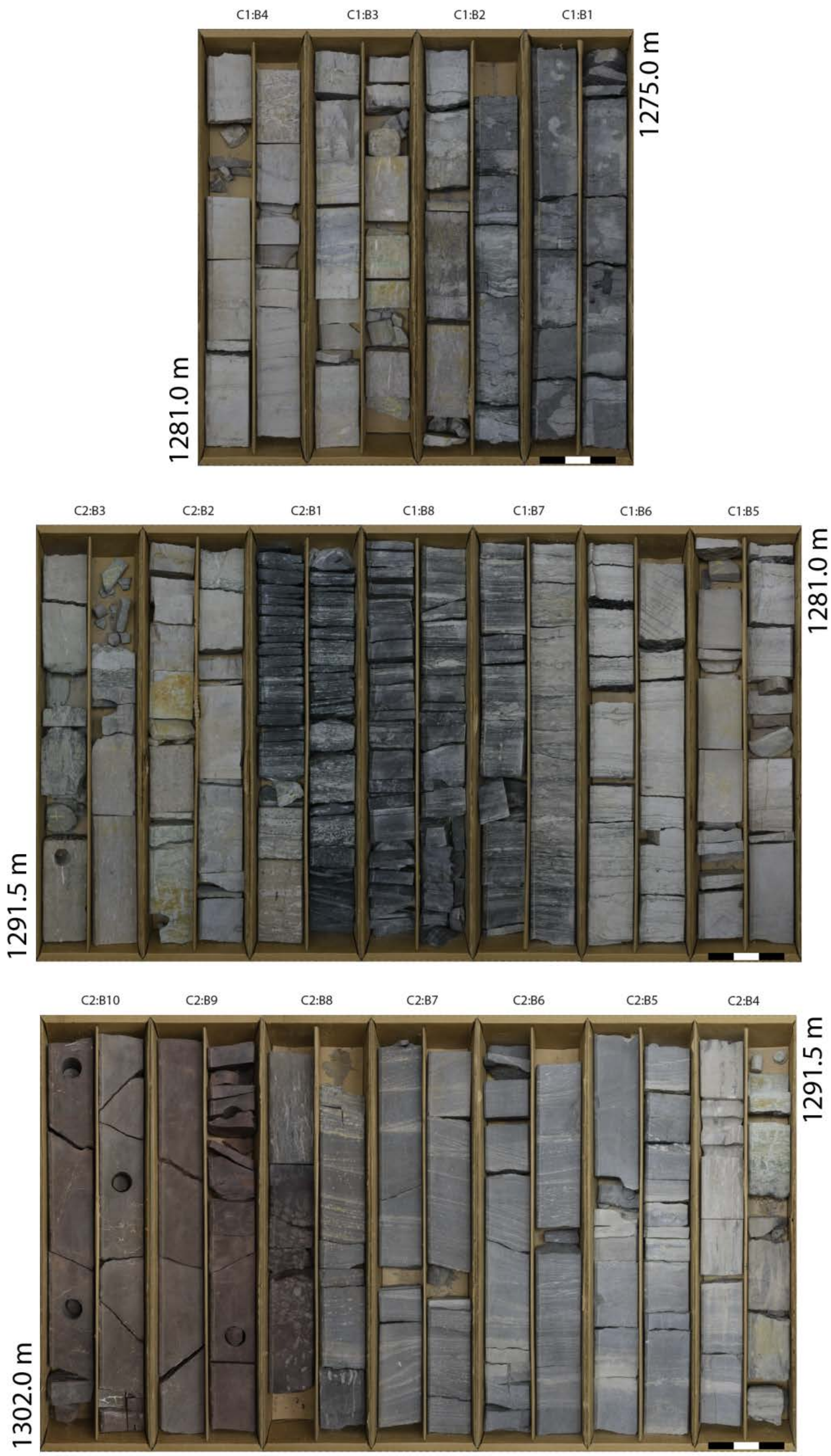
North Colville L-21. Scale bars are 15 cm long.



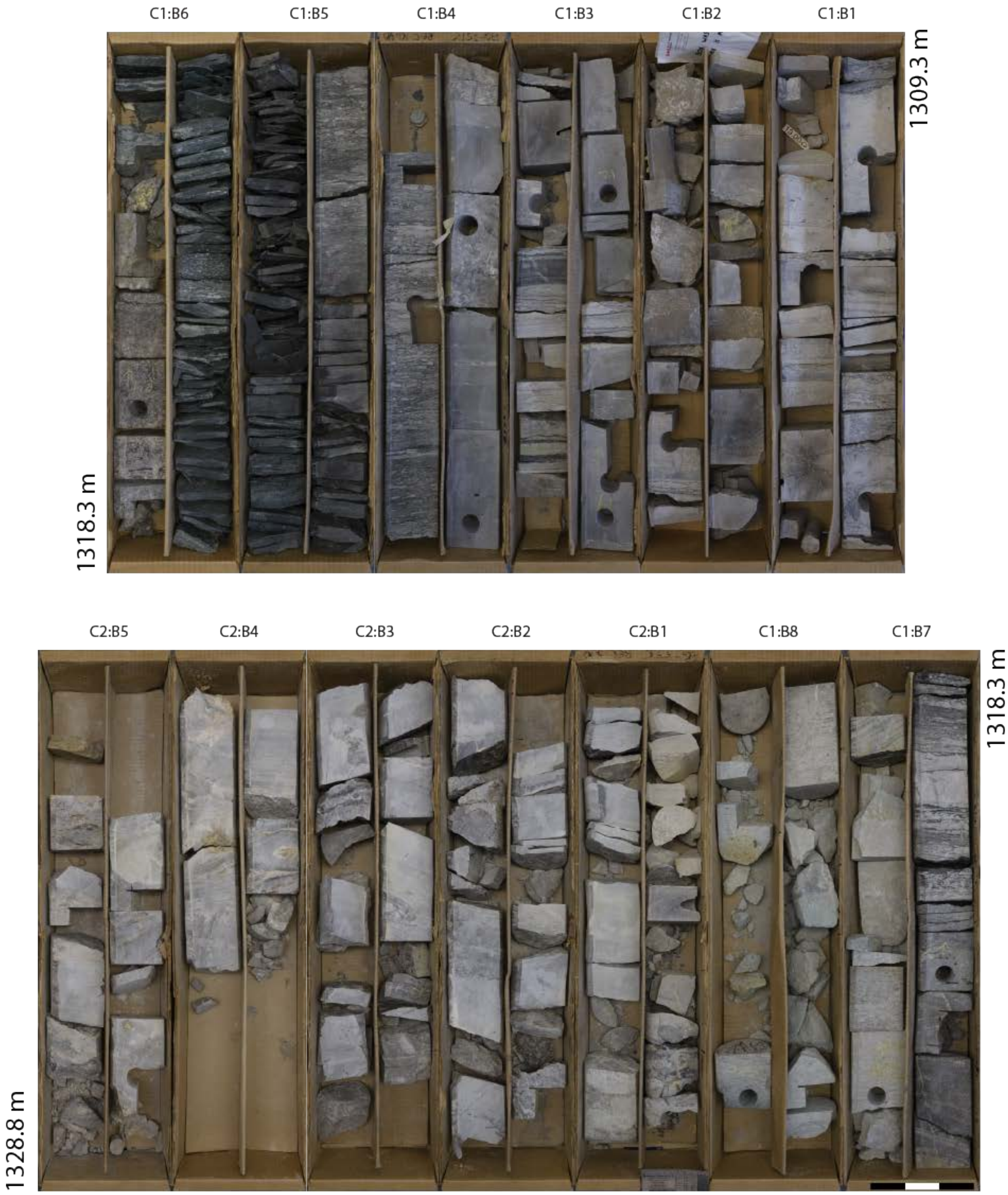
Ontadek Lake N-39. Scale bar is 15 cm long.



Stopover K-44. Scale bars are 15 cm long.



Tweed Lake A-67. Scale bars are 15 cm long



Tweed Lake C-12. Scale bars are 15 cm long.

Tweed Lake M-47. Scale bar is 15 cm long.