THE SEDIMENTOLOGY AND STRATIGRAPHY OF THE LOWER CRETACEOUS CLEARWATER FORMATION AT MARTEN HILLS AND NIPISI, ALBERTA, CANADA

by

Cole Liam Ross

A thesis submitted to the faculty of graduate studies in partial fulfillment of the requirements for the degree of

Master of Science

Department of Earth and Atmospheric Sciences
University of Alberta

Abstract

The Lower Cretaceous (Albian) Clearwater Formation at Marten Hills and Nipisi in north-central Alberta contain two members (Wabiskaw and the newly proposed Marten Hills Member), which sit disconformably above the sub-Cretaceous unconformity. Both the Marten Hills and Nipisi regions are currently being explored for oil resources; however, the region suffers from a paucity of previous studies. A robust interpretation of paleoenvironmental settings and stratigraphic architecture is required to further delineate the Marten Hills Member of the Clearwater Formation.

The Wabiskaw marker bed separates the underlying Wabiskaw Member from the Marten Hills Member and is interpreted to represent a regionally extensive maximum flooding surface. This flooding surface is in turn overlain by a series of subsequent cleaning upwards profiles, each of which is capped by a marine flooding surface and represents transgressive-regressive cycles of the Boreal Seaway. Sedimentologic and ichnologic analysis indicate the presence of a range of depositional settings, from deltaic distributary channels to fully marine offshore environments. Within the study region, the Marten Hills Member consists of six interpreted stratigraphic intervals (Marten A-F) deposited above the Wabiskaw Member. Core and well-log interpretations reveal a series progradational and aggradational shoreline parasequence sets indicative of a wave-influenced shoreline complex.

The Nipisi and Marten Hills oil pools are predominantly producing from the Marten B and C intervals (respectively) and represent deposition of marginal marine sandstones associated with a wave- and storm-dominated shoreline. Insights from this thesis provide a foundation for future work to build upon and further evaluate the Marten Hills Member in north-central Alberta.

Dedication

I dedicate this thesis to my mother, Anita and my father, Ken for their constant love, support, encouragement, and generosity. Without them none of this would have been possible and I am forever indebted for everything they have provided me with and their relentless support throughout my life, from soccer tournaments across the globe to financial assistance throughout both my undergraduate and graduate degrees. Your sacrifices and selflessness are what made this possible and I am eternally grateful.

Acknowledgements

The opportunity to pursue my masters at the U of A has been one of the greatest and most challenging experiences throughout my early career. It has shaped me in many ways and enabled me to grow both as a young geologist and as a person. There are a multitude of people that are responsible for helping me get to this point, and I am truly grateful for everyone that I have met throughout this process and will forever look back on this experience with joy.

I am indebted to my supervisor, Dr. Murray Gingras, for his supervision, guidance, and support throughout this study. His door was always open, and I truly cherished the conversations and insights that he provided throughout the duration of my time at the UofA (in addition to the NHL banter that comes with being a Flames fan in Oiler nation). His superlative knowledge of Ichnology and the ability to creatively interpret complex settings is a rare skill that he demonstrates effortlessly. Further, I would like to thank my thesis defense committee members: Dr. Michael Ranger, Dr. Mark Caplan, and Scott Hadley for providing constructive feedback, insights, and conversations. The input you provided greatly improved the quality of this thesis.

One of my greatest influences throughout my early career has been the mentorship of Scott Hadley at Woodcote Petroleum Inc. His comprehensive knowledge set and true passion for the geosciences is unequaled in industry and has greatly improved who I am as a geologist. His genuine commitment and eagerness to help others succeed is something that I will strive to replicate throughout the duration of my career. Without his guidance and support this thesis wouldn't have been possible, and I am forever grateful for the opportunities he has provided me with.

My time at the University of Alberta has been an exceptionally enjoyable experience, and this is largely attributed to the people that I was surrounded with throughout my tenure in Edmonton. Thanks to the members of the Ichnology Research Group for making long hours spent at the University so enjoyable: Scott Melnyk, Sara Biddle, Skye Lybbert, Maya LaGrange, Brette Harris, Derek Hayes, Scott Botterill, Daniel Baker, Chundi Shan, Qi Chen, and honorary member Ryan Millar. Even though I missed a few (all) of the field trips – our lunchtime discussions were always a delight, even though I rarely brought a lunch.. A special thanks to my office mates, Scott Melnyk, Skye Lybbert, Sara Biddle, Chenyang Feng, Logan Swaren, among others, I wouldn't share a 40-year-old couch with anyone else in the world. Additionally, I would like to thank Derek Hayes, Ryan Millar, and Scott Melnyk for always being up to indulge in the finer things in life – namely cheap beer, crib, and the odd game of pool. I didn't know how to play crib before I came to Edmonton, but boy did I sure know by the time I left. I would also like to thank Scott Melnyk individually for the countless edits and conversations we shared, the insights provided were exceptional and I am extremely grateful for his friendship.

I would like to thank my brother Logan, who paved the way throughout my undergraduate degree. Without his support and selflessness, I would not be where I am today. Thanks to my roommate Ciaran Dunn for always helping me unwind with an episode of Friends and making my stay in Edmonton so enjoyable. I would like to thank Alessia D'Adamo for her encouragement and patience as I wrote my thesis. Your relentless support (and amazing focaccia) was critical in helping me finish my thesis and I am extremely grateful.

Thanks to MainSail Energy for providing the preliminary funding to kickstart this program. Thanks to Cenovus Energy for providing additional funding and comprehensive datasets that substantially assisted in the writing of this thesis. I would like to thank Staff Explorationist Lyle Hanch individually, whose guidance and mentorship were top class. His kind demeanor and ability to explain complex concepts in easy-to-understand analogies is unmatched. Additionally, I would like to thank Cenovus for bringing me into the office and including me in the summer student training program which was a great experience. I would like to thank Matt Young and Spur Petroleum for their intellectual contributions and data provided throughout the duration of my studies. Without the support of such amazing industry partners, this work would not be possible, and any contributions provided were extremely gratefully received.

Lastly, I would like to thank the Late Dr. S. George Pemberton. I was extremely fortunate to learn from such an outstanding academic scholar and even better human being. The short duration I spent with Dr. Pemberton at the University of Alberta had a lasting impression, which is a true testament to the amazing individual that he was.

Table of Contents

List of Figures

Tables

Chapter One: Introduction

1.1 Project Motivation:

Lower Cretaceous strata of the Western Canadian Sedimentary Basin host vast quantities of hydrocarbon rich resources. This includes an estimated 219 billion barrels of heavy oil throughout the Clearwater Formation in the Cold Lake region of eastern Alberta, and 1,750 Tcf of gas in place within the Deep Basin of western Alberta (Fig. 1A) (Masters 1984; Hayes *et al.,* 1994; McCrimmon and Arnott, 2002; Ranger and Gingras, 2010; Currie, 2011). The Marten Hills and Nipisi areas, north of Edmonton, have recently seen a surge in oil development in the Clearwater Formation. This area is down-dip from the heavy oil production of eastern Alberta where cyclic steam stimulation (CSS) and steam-assisted gravity drainage (SAGD) are required for hydrocarbon extraction in the subsurface), and up-dip from the gas-dominated production of the Deep Basin (Fig. 1B). Historically, the Marten Hills/Nipisi area saw abundant vertical wellbore drilling as a result of a Wabiskaw gas discovery (~920 BCF) made in 1961 by Pan American through a wildcat well initially aimed at the deeper Leduc reefs (Bradley and Pemberton, 1992).

The Marten Hills and Nipisi regions were initially explored in the early 80's through vertical drilling. Operators recorded numerous oil indicators in the Clearwater, but the low permeability and higher viscosity produced unsatisfactory production results. Several operators attempted horizontal drilling and hydraulic fracturing of the Clearwater sands, however the associated drilling and completion fluids had adverse effects on the Clearwater reservoirs and proved to be an ineffective exploitation technique. Recently, exploration in these regions has been revitalized through advancements in open-hole, multi-lateral horizontal drilling, aimed at exploiting the medium-gravity oil in several Clearwater sandstone intervals. Marten Hills is one of the first regions where horizontal cold-flow production was established because of the combination of high-quality Clearwater reservoir sandstones, oil quality, and an estimate of over 5 billion bbls in place (Hadley, S., pers comm.). Indeed, sandstone reservoirs within Marten Hills are laterally extensive and can exceed 30 metres in thickness with hydrocarbon properties of 14-24 API and viscosities ranging between <250 to 4000cP making them excellent multilateral exploitation targets. These Clearwater sandstones were overlooked for years as operators pursued the underlying Wabiskaw and Wabamun gas reserves. Suppressed wireline log signatures, and the impression that oil quality was too viscous for economic recovery, produced a bypass pay opportunity. The significant thicknesses of these Clearwater sandstones, combined with the multilateral drilling method, allows for economic production. The rapid increase in development over the last 4 years throughout this region is exciting, with current Clearwater production from multilateral wells now exceeding 31,000 bbl/d.

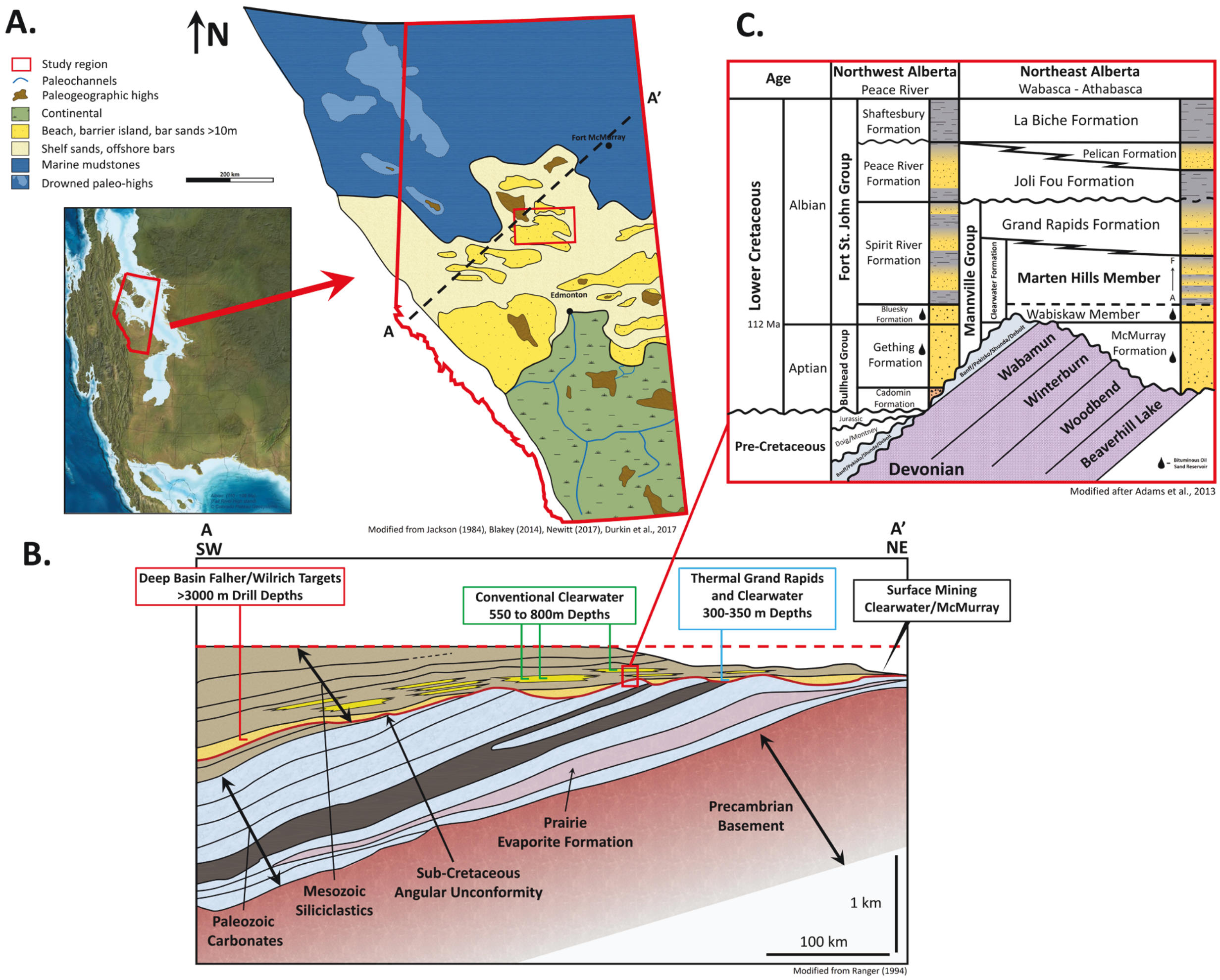


Figure 1. A) Paleogeographic mapping schematics of depositional settings at approximate Clearwater time. Blakey (2014) paleogeographic reconstruction of 108-110 Ma (Albian). Paleogeographic highs that were exposed during much of the McMurray Formation have been subsequently drowned throughout the transgression of the Boreal Seaway. **1B)** Represents a cross section from SW to NE of 1A, and displays the general stratigraphic relationship of underlying Paleozoic strata from the overlying Mesozoic Siliciclastics. Figure 1B also displays the transition from deep basing drilling through to surface mining in the NE. This demonstrates the conventional Clearwater Formation production within the study region is observed between "deep" and "shallow" development. **1C)** Detailed stratigraphic breakdown of the central Alberta proposed stratigraphy (introducing the Marten Hills Member) and includes time equivalent formations observed within the deep basin.

Both the Marten Hills and Nipisi regions are void of academic literature with regards to the Clearwater Formation, aside from a study conducted by Bradley and Pemberton in 1992 analyzing the ichnofossil assemblages of Wabiskaw Member sandstones. As the Marten Hills and Nipisi regions began to experience increased drilling activity, unpredictable production results underscored the need to better understand the regional geology. Utilization of the multi-lateral drilling method requires a detailed understanding of both the sedimentology and stratigraphy of reservoir intervals to optimize production by strategically geosteering and landing laterals within the highest quality reservoir.

The depositional environments, lateral facies distributions, and stratigraphic architecture of Clearwater sandstones is contested and not fully understood. Initial interpretations were that of a marginal-marine, single cleaning upwards, shoreface dominated environment (Minken, 1974; Harrison *et al.,* 1981; Jackson, 1984; Dekker *et al.,* 1987; Hutcheon *et al.,* 1989; Leckie and Smith, 1992; McCrimmon, 1996; McCrimmon and Arnott, 2002; Feldman *et al.,* 2008; Currie, 2011). However, given the substantial thicknesses of the Marten Hills reservoir intervals (sometimes exceeding 30m), and that production results from these sandstones display variable performance within the same stratigraphic interval, reservoir heterogeneity is now largely accepted but poorly understood. A detailed understanding of the sedimentology and stratigraphy within the Clearwater in this region is required to properly understand the internal reservoir complexity of these oil charged sandstones.

Research Objectives:

The goals of this study are to characterize the internal reservoir geometry of Clearwater sandstones through a detailed sedimentologic and ichnologic analysis, thus permitting detailed paleoenvironmental reconstructions. In addition, the study aims at providing a stratigraphic framework that enables a regional correlation of reservoir sandstones to adjacent areas within Alberta. This work provides a thorough analysis of the spatial distribution of Clearwater reservoirs both laterally and vertically throughout the Marten Hills and Nipisi regions of north central Alberta, which should assist in the future exploration and development of these areas.

1.2 Geologic Background:

The Western Canada Sedimentary Basin (WCSB) is defined as a retro-arc foreland basin that resulted from a series of allochthonous terrane accretion events which occurred in western North America throughout the Mesozoic (Cant and Stockmal, 1989; Leckie and Smith, 1992; Jackson, 1984; Price, 1994). Sequential terrane accretion resulted in compressional and collisional tectonism in addition to an overthrusted western Cordilleran margin, forming what is now known as the Rocky Mountains in the process (Porter *et al.,* 1982; Jackson, 1984; Beck *et al.,* 1988; Shuquing *et al.,* 2008). Consequently, a southwest-dipping asymmetrical foreland basin developed in the interior of North America (a result of flexural subsidence of pre-Jurassic strata and subsequent sediment accumulation in the foredeep) (Caldwell, 1984; Cant and Abrahamson, 1996; Tufano and Pietras, 2017). Given the southwest dip orientation, older Devonian strata subcrops along the eastern flanks of the foreland basin, with younger strata subcropping to the southwest (Fig. 1B). Pre-Jurassic strata predominantly consist of carbonates, evaporites, and shales deposited on the passive margin that persisted prior to Mesozoic terrane accretion (Porter *et al.,* 1982; Price, 1994). This was followed by a period of prolonged tectonic quiescence, isostatic uplift, and sea level fall, where erosion and non-deposition were experienced across the basin from the late Jurassic to the Early Cretaceous (Cant and Abrahamson, 1996; Shuquing *et al.,* 2008). This erosional surface is referred to as the Sub-Cretaceous (angular) unconformity (SCU), and marks a 20–30-million-year hiatus in deposition which separates low-angle, southwest dipping “sub Cretaceous” deposits from the overlying Cretaceous strata (Leckie and Smith, 1992; Cant and Abrahamson, 1996).

Given the variable geologic properties of sub-cropping pre-Jurassic strata, differential erosion provided significant paleotopographic relief generating highs and lows across the basin. This topography also largely controlled continental drainage pathways through the Aptian to early Albian, where fluvial systems drained to the north and deposited sediments into the northern Boreal Seaway (Jackson, 1984; Leckie and Smith, 1992; Ranger, 1994; Cant and Abrahamson, 1996; Horner *et al.,* 2019). Accommodation space in the overlying Lower Cretaceous was initially controlled by the paleotopography associated with the SCU and localized tectonic activity (Stockmal and Beaumont, 1987; Cant and Stockmal, 1989; Hauck *et al.,* 2017). Within the study region, the SCU separates the Devonian- and Mississippian-aged formations from the overlying Cretaceous formations (Bradley and Pemberton, 1992). This played an important role regionally, as paleotopographic lows were likely the first to be filled during the initial onset of Cretaceous deposition and associated southward marine transgression of the Boreal Seaway. As transgression continued, the inundation of topographic lows led to the development of an island archipelago system (Ranger, M., pers comm), where remnant Devonian and Mississippian highs likely had significant control on initial Cretaceous paleoshoreline orientation.

Within the research area, deposition following the SCU consists of siliciclastic sediments associated with the Mannville Group of the Lower Cretaceous. In central eastern Alberta, the Mannville Group is broken up into three Formations: The McMurray, Clearwater, and Grand Rapids formations (Fig. 1C). Initial deposition of the Aptian McMurray Formation was dominated by quartz-rich sediments which were locally sourced from the northeastern Canadian shield, in addition to partial sourcing from both the western cordillera, and central United States, and were deposited in thick paleovalleys (Jackson, 1984; Smith *et al.,* 1984; Leckie and Smith, 1992; Benyon *et al.,* 2016). The McMurray Formation is disconformably overlain by the Clearwater Formation which includes the basal Wabiskaw Member, and subsequently overlying Marten Hills Member (proposed within this research). The Clearwater Formation is disconformably overlain by the Grand Rapids Formation, which is capped by the regional marine shales of the Joli-Fou Formation. The Clearwater and Grand Rapids formations are identified by a lithological change from the quartz-dominated sediments observed in the underlying McMurray Formation, to feldspathic litharenites with abundant chert in the overlying Clearwater and Grand Rapids formations. This indicates a change in provenance, with increased influence from western cordilleran sources (Putnam and Pedskalny, 1983; Potocki and Hutcheon, 1992; Jackson, 1984; Cant and Abrahamson, 1997; Feldman *et al.,* 2008). Both the Clearwater and Grand Rapids formations display a range of depositional settings including non-marine, marginal marine, and shallow marine environments (Fig. 1A) (Minken, 1974; Putnam and Pedskalny, 1983; McCrimmon, 1996; McCrimmon and Arnott, 2002; Feldman *et al.,* 2008; Currie, 2011). Marine-dominated environments within these formations, and throughout the WCSB, are the result of both a global sea-level (eustatic) rise and tectonically driven subsidence, which formed a north to south oriented shallow epeiric seaway (referred to as the Boreal Seaway) (Caldwell, 1984; Stott, 1984; Leckie, 1986). This shallow seaway experienced maximum depths <100 metres at the deepest portions of the foredeep within the WCSB, and ultimately joined the northward transgressing Gulfian Seaway to form the Western Interior Seaway (McLean and Wall, 1981; Leckie and Smith, 1992).

Prior to deposition of the Clearwater Formation, accommodation space along the easternmost limits of the study region is inferred to have been moderate, as McMurray sediments are present directly above the SCU. This changes within the central and western limits, where the McMurray Formation thins rapidly to the west and paleotopographic highs (associated with the Red Earth Highlands) restricted deposition. When present, a regional flooding surface disconformably separates the McMurray Formation from the overlying Clearwater Formation. In the central and western portions of the study region, the McMurray Formation is notably absent. This is most apparent to the west, where paleotopographic highs were observed, restricting Wabiskaw deposition to only a thin interval above Mississippian Banff and Pekisko deposits. Both the Clearwater and Grand Rapids Formations were likely deposited as the result of marginal marine environments that prograded/retrograded along paleo-shorelines as a result of smaller-scale transgressive and regressive cycles throughout the overall large-scale transgression of the Boreal Seaway (Minken, 1974; Jackson, 1984; Smith *et al.,* 1984; McCrimmon and Arnott, 2002) (Fig. 1A). Following deposition of the Mannville, clastic deposition continued into the Tertiary, which resulted in thick siliciclastic successions (Jackson, 1984; Smith *et al.,* 1984; Leckie and Smith, 1992). Pre-Cretaceous evaporite dissolution, in addition to the antiformal structure associated with the forebulge of the WCSB foreland basin (which has been referred to as the Athabasca Anticline), provided a regionally extensive structural trapping mechanism (Masters, 1984; Ranger, 1994; Peacock, 2010). This was subsequently filled through hydrocarbon migration throughout the late Cretaceous to- early Tertiary, resulting in one of the largest hydrocarbon accumulations in the world (Ranger, 1994; Tozer *et al.,* 2014). This hydrocarbon accumulation was subsequently breached through glacial scouring and erosion, resulting in the surface exposure of what is now referred to as the WCSB oil sands (Ranger, 1994).

1.3 Study Area/ Dataset:

The study region is located in north-central Alberta, north of the town of Slave Lake and east of Lesser Slave Lake. It encompasses Townships 71-78, Ranges 21W4-8W5, and consists of several "strike or field" names including: Canal, Smith, Marten Hills, Marten, and Nipisi (Fig. 2). The Marten Hills and Nipisi regions are currently the most actively developed areas within the Clearwater Formation conventional oil play, which is 150-200km west of the heavy oilsands development within the Cold Lake region. Throughout the study region, the Clearwater Formation is found at depths between 600-800m. The study covers an extensive surface area of over 10,000 km2 and contains over 3,250 vertical and deviated wells, with ample wireline log measurements. Over 50,000 stratigraphic user tops were correlated and mapped from this wireline log data. With the advent of multi-lateral drilling, horizontal well count is substantially high and tightly spaced throughout the region, with >1650 laterals drilled since 2016. Additionally, this research used over 60 cored wells (totaling over 1.4km of described core), which have been integrated with the wireline log interpretations. Core and well control throughout the production fairways are sufficient in allowing detailed stratigraphic and sedimentologic observations to be made and correlated throughout the study region.

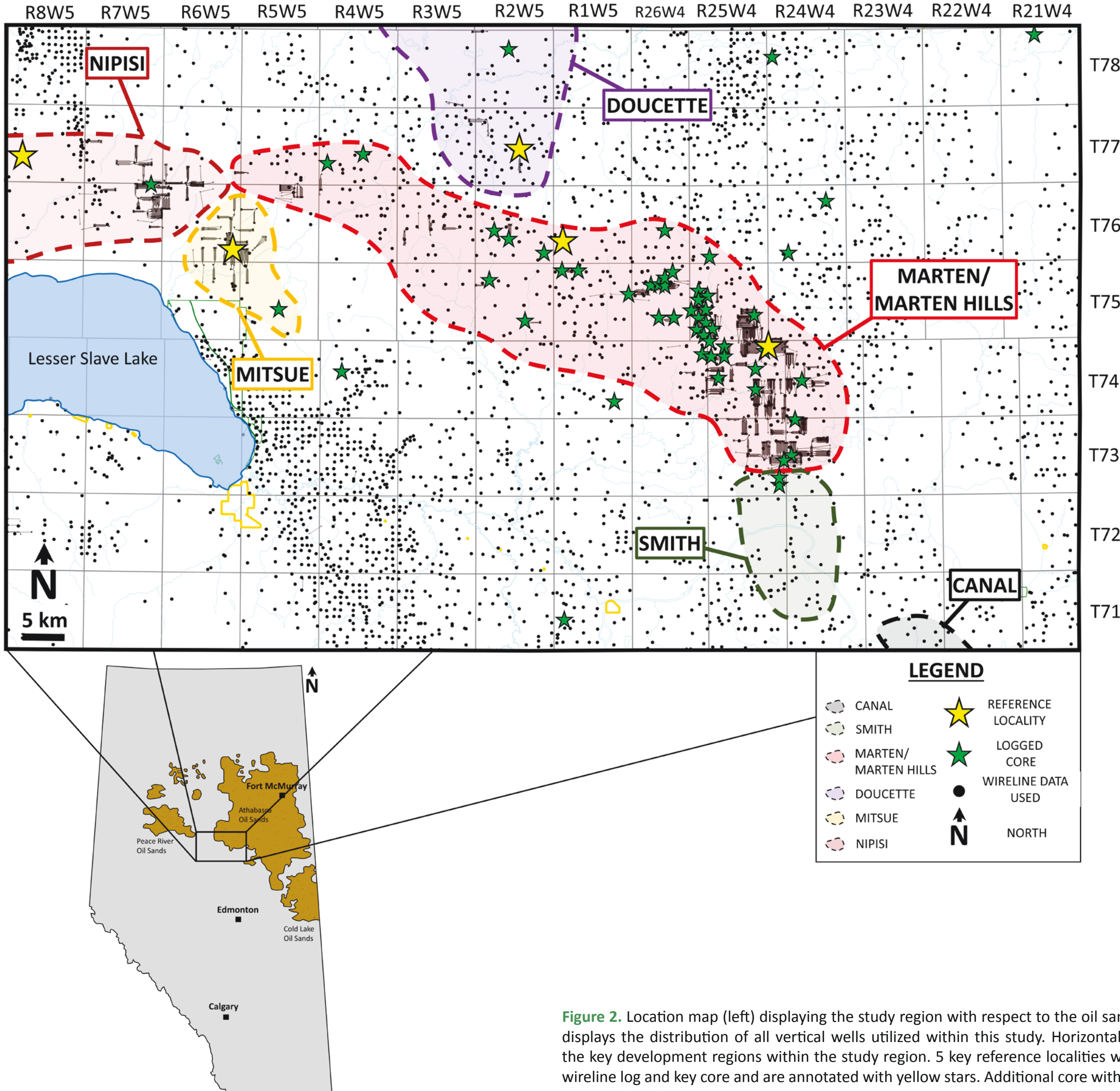


Figure 2. Location map (left) displaying the study region with respect to the oil sands in Alberta. Zoomed in image displays the distribution of all vertical wells utilized within this study. Horizontal wells were included to display the key development regions within the study region. 5 key reference localities were selected that included both wireline log and key core and are annotated with yellow stars. Additional core within the Clearwater Formation are annotated with green stars.

1.4 Methodology:

Over 3,250 wireline raster well logs were analyzed, and 60 cored intervals were logged at the Alberta Core Research Centre (Fig. 2). Detailed observations of physical and biogenic sedimentary structures, lithology, lithologic accessories, grain size, contacts, and general observations pertaining to secondary processes such as diagenesis were recorded for each core at the bed scale using AppleCore© software. In addition, complete photo-documentation of all logged core was completed to provide a digital reference of all observed rock fabrics. Bioturbation intensity was quantified through the use of the Bioturbation Index (BI) (Reineck, 1963; Taylor and Goldring, 1993). This semi-quantitative method describes sedimentary fabrics ranging from unborrowed media, which is assigned a BI of 0, to pervasively bioturbated, or biogenically homogenized media, which is assigned a BI of 6. In addition to bioturbation intensity, ichnogenera (listed in relative abundance) and ichnologic diversity also contributed to the identification of ichnofacies, and were integrated with sedimentologic attributes to better refine the interpretation of depositional environments and sub-environments (Seilacher, 1967; Howard and Frey, 1984; Bann and Fielding, 2004; MacEachern *et al.,* 2008; Gani *et al.,* 2009; Gingras *et al.,* 2011; MacEachern *et al.,* 2012).

Depositional environments were characterized based on the Ainsworth *et al.,* (2011) ternary framework which describes depositional settings based on the relative abundance of sedimentologic and ichnologic attributes associated with wave, fluvial, and tidal processes. Wave-influence is characterized by abundant low-angle planar stratification in addition to wavy or quasi-planar laminations, and oscillatory bedding. Additionally, wave-dominated shoreface environments were further subdivided based upon the degree of impact of storms on the shoreline, distinguishing between storm-dominated, storm-influenced, and storm-affected shorefaces. This allows the establishment of a robust model representing a spectrum of storm activity. Storm-dominated shoreface environments have the highest preservation potential of storm-related deposits (tempestites) (Leckie and Walker, 1982; Frey, 1990; MacEachern and Pemberton, 1992; Dashtgard *et al.,* 2012; Pemberton *et al.,* 2012). Fluvial influenced environments were inferred from high-angle parallel-planar bedding, cross-bedding, pebble and granule lags, wood-debris, and overall increased organic detrital material. Tidally influenced environments commonly display bi-directional cross-lamination, double mud drapes, and tidal rhythmites.

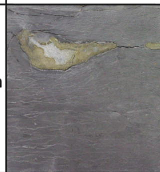
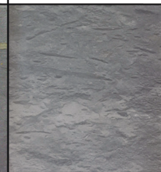
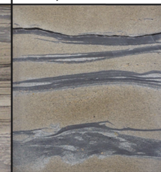
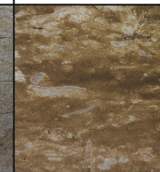
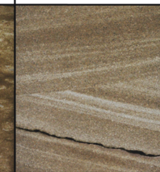
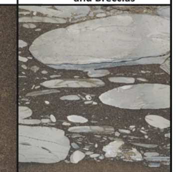
Wireline log measurements considered in this study include gamma ray, caliper, photoelectric factor, sonic interval transit time, neutron porosity, bulk density, density porosity, spontaneous potential, and resistivity. Detailed core observations were correlated to available wireline log data at each well, which provided a log marker framework. From this, five reference localities containing core in multiple stratigraphic intervals were selected to provide a near-full sedimentologic and stratigraphic succession. Additionally, multiple strike and dip oriented stratigraphic cross-sections were constructed to show the stratal relationships of the various Clearwater members. Subsea elevation maps were constructed for each stratigraphic interval to identify structural trends, in addition to gross isopach maps and gross sand isopach maps using Accumap and Surfer mapping software.

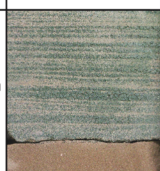
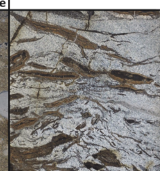
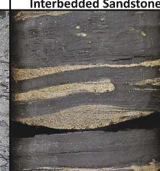
Chapter Two: Geology of Marten Hills and Nipisi

Chapter 2A: Facies Description and Interpretations:

2.1 Facies and Interpretations:

Twelve facies are recognized from detailed examination of core stored at the Core Research Centre (CRC) in Calgary, Alberta (Table 1). Facies are classified based on sedimentologic, lithologic, and ichnologic attributes and are named based on the most dominant characteristics observed. Additionally, average thickness, relative facies abundance throughout all studied core, and internal facies variability were also characterized. Facies abundance percentages are included to provide additional confidence in interpretation quality as frequently recurring facies display subtle variations that are more challenging to capture in facies that only recur in several core. Additionally, observing facies abundance enables a stronger interpretation when interpreting the depositional settings that dominated the rock record both laterally and vertically throughout the study region. It should be noted however, that the paucity of certain facies does not directly in itself exclude its existence from the rock record as it may not have been a targeted interval (as is often the case with facies 1).

Facies	1 Dark Grey Fissile Mudstone	2a Pervasively Bioturbated Silty Mudstone	2b Pervasively Bioturbated Sandy Mudstone	3a Sporadically Bioturbated Interbedded Sandstone and Mudstone	3b Cross Stratified Interbedded Sandstone w. Weakly Bioturbated Mudstone	4 Bioturbated Silty to Muddy Massive Sandstone	5 Lam-Scram Bioturbated Cross-Stratified Silty Sandstone	6 Hummocky- Cross Stratified Sandstone	7 Massive Structureless Sandstone	8 Poorly-Sorted Matrix Supported Conglomerate and Breccias
Typical Core Expression										
Lithology & Grain Size	Dark grey mudstone, Silt interbeds (mm)	Dark grey mudstone, light grey silty mudstone, vf grained sandstone	Silty to sandy mudstone, vf grained sandstone 2-10cm sandstone beds	Sandstone Vf to FL Siltstone, mudstone mm to cm sandstone beds	Sandstone VfU to FL Thin mudstone beds	Sandstone VfU to FL grained Variable silt and mud Moderate to well sorted	Sandstone FL to FU Low to moderate silt Poor to moderate sorting	Sandstone VfU to FU grained Well sorted	Sandstone F to ML grained Very well sorted	Sandstone FU to ML grained Sub-angular to sub-rounded Poorly sorted mud clasts
Physical Sedimentary Structures	Massive appearing, Micro HCS, normal grading	Normal grading, (r) mm-cm LAP bedding (r), SSD (r), Mantle & swirl (r)	Sharp based LAP, Normal grading,	Normally graded beds Wavy LAP, LAP, QPL, Oscillatory bedding (r), Wave ripples (r), Flame Structures (r)	Massive sandstone, LAP, wavy-oscillatory beds, Wavy laminated muds	Massive appearing Osc. ripple cross lam, symm. wave-ripple lam LAP (r), QPL (r),	Oscillation ripples Wavy LAP (r) Cross-strat. Fluidization structures (r)	LAP, PPL, QPL, Oscillation & SCS SSD (r), BdCr (r), CCr	Massive appearing LAP(r), Wavy LAP (r) "Fuzzy bedding"	Massive sandstone slight imbrication (r) Structureless to normally graded clasts
Lithologic Accessories	Pyrite nodule, Glauconite, silt laminae	Pyrite nodule, Phytodetrital laminae (r) iron staining (r)	Phytodetrital lamine (r) Pyrite nodules & diss. (r) 1-2mm siderite clasts (r)	Siderite nodules (mm), Pyrite nodules, detrital organics (mm)	Mud drapes, double mud drapes, siderite clasts, wood clasts, synaeresis, phytodetrital laminae, Rip-up clasts	Mud rip-up clasts (<1cm), siderite, pyrite, wispy organics, wood clasts	Wispy organic laminae, Organic clasts (mm), thin silt and mud beds	Phytodetrital laminae, organic rip-up clasts, siderite, pyrite	Organic debris (r), PDL, pyrite (r), rounded pebbles, siderite, berthierine cement (r)	Organic rip-up clasts, Shell fragments, pyrite Glauc. clasts, massive muds
Ichnogenera	*Ch, Cr, He, Pl, Sc, Sch f, Zo*	*As, Ch, Cr, Cy, Fu, He, Ph, Pl, Ro, Sc, Sch f, Te, Th, Zo*	*As, Ch, Cr, Cy, Fu, He, Ph, Pl, Ro, Sch f, Sk, Te, Th, Zo*	*Ar, As, Ch, Cr, Cy, Fu, He, Lo, Pa, Ph, Pl, Ro, Sc, Sch f, Sk, Te, Th, Zo*	*Cy, Fu, Ha, Pl, Th* (Sand) *As, Ch, Cr, Ma, Ph, Th, Zo* (Mud)	*Ar, As, Ch, Co, Cy, Di, Fu, Ma, Op, Pa, Ph, Pl, Ro, Sch f, Th, Zo*	*As, Cy, Di, Lo, Pa, Pl, Ro, Sk, Th*	*Di, Ma, Pa, Pl, Th*	*Cy, Di, Ha, Ma, Te, Th*	*Ph, Ch* (some clasts) *Pl, Sk* (sands)
Ichnological Characteristics	BI (3-5) Difficult to observe Mod-High Diversity Distal *Cruziana* to Proximal *Zoophycos*	BI (4-5) High diversity Homogenous distr. *Cruziana* Ichnofacies	BI (3-5) High diversity Homogenous distr. *Cruziana* Ichnofacies	Interbedded Mud BI (2-4) Sandstone BI (0-2) High diversity *Cruziana/Skolithos* Ichnofacies	BI (0-2) Sand BI (0-3) Mud Low to Moderate Diversity Sporadic distr.	BI (3-5) Cryptic Bioturbation BI (6) High Diversity Sporadic distr. Prox. *Cruziana* Ichnofacies	BI (3-5) Moderate Diversity Sporadic distr. Proximal *Cruziana* to Dist *Skolithos* Ichnofacies	BI (0-1) Cryptic Bioturbation BI (6) Low diversity Sporadic distr. Proximal *Cruziana* to Dist *Skolithos* Ichnofacies	Cryptic Bioturbation BI (6) Low diversity Sporadic distr.	BI (0-2) Low diversity Sparsely distr.
Depositional Environment	Offshore (upper/lower) Max. Flooding Surface	Offshore (Distal Upper)	Proximal Offshore	Storm-influenced, Distal Lower Shoreface/ Prodelta	Tidally Influenced Distal Delta-Front	Storm-affected Distal Lower Shoreface	Storm- affected, Proximal Lower Shoreface	Storm-dominated, Distal Middle Shoreface	Storm-dominated Proximal Middle Shoreface, distal upper shoreface, DeltaFront	Transgressive Lag Regressive shoreface

Facies	9 Glauconitic Sandstone	10a Medium-Grained Cross-Stratified to Structureless Sandstone	10b Organic Clast Dominated Sandstone	11 Weakly Bioturbated Mudstone with Interbedded Sandstone	12 Clay Rich Mudstone
Typical Core Expression					
Lithology & Grain Size	Sandstone VfU to FL grained Variable sand/mud content	Sandstone M. Grained Rounded clasts Poorly to Mod. Sorting	FU to ML sandstone, Organic debris (3mm to >7cm) Poorly sorted	2-5cm thick mudstone beds, F to ML grained sandstone	Clay-rich mudstone, Interbedded silty mudstone, VF sandstone
Physical Sedimentary Structures	LAP, QPL, Oscillatory bedding	HAP, LAP, PPL, Massive sandstones, SSD, mud drapes (r)	LAP, HAP, Massive organic rich sand, Wavy LAP (r)	Structureless mud, lenticular bedding (r), Oscillatory bedding (r), Flame & cone-in-cone structures, SSD (r), LAP (r), M&S	Desiccation cracks, Roots, normal grading, Lenticular bedding (r)
Lithologic Accessories	Glauconite, pyrite, 3-5cm wood clasts, siderite, phytodetrital laminae,	Wood debris, pyrite, siderite, Phytodetrital laminae, shell fragments (r), round mud clasts	Wood clasts (cm), pyrite, Phytodetrital laminae, Siderite, chert/mud clasts	Phytodetrital laminae, Wood clasts, pyrite, rounded rip-up clasts	Phytodetrital laminae, Organic debris, siderite, synaeresis cracks (r)
Ichnogenera	*As, Ch, Di, Ph, Pl, Sk, Te, Th*	*Pl*	*Pl, Td*	*Ar, Ch, Cy, Dp, Ph, Pl, Sk, Te*	*As, Fu, Ph, Pl, Sk*
Ichnological Characteristics	BI (1-3) Moderate diversity Sporadic distr. *Glossifungites* Ichnofacies	BI (0-1) Scarce distr.	BI (0-1) Low diversity, Scarce distr.	BI (0-2), Moderately Diverse, Opportunistic colonisation Monospecific suites	BI (1-3) Low diversity, Sporadic distr. *Skolithos* Ichnofacies
Depositional Environment	Marine Transgression	Delta Front or Distributary Channel	Fluvial Channel, Distributary Channel Thalweg	Fluid Muds or Hyperpycnal Mud Plumes	Tide-influenced Marsh or Delta Plain

Abbreviation Key

Sedimentary Structures

HCS - Hummocky Cross-Stratification
LAP - Low Angle Planar Bedding
SSD - Soft Sediment Deformation
QPL - Quasi-Planar Lamination
Osc. - Oscillation Ripple
SCS - Swaley Cross-Stratification
HAP - High Angle Planar Bedding
PPL - Planar Parallel Bedding
BdCr - Bi-Directional Current Ripple
CCr - Climbing Current Ripple
GB- Ghost Bedding

Accessories

Ms- Mantle and Swirl
Pc- Patchy Cement
PL- Phytodetrital Laminae
Py- Pyrite
Sp - Siderite Pellets
Sf- Skeletal Fragments
Wd- Wood Debris
Wo - Wispy Organic Debris

Ichnogenera

Ar - Arenicolites
As- Asterosoma
Ch- Chondrites
Co- Conichnus
Cr- Cosmorhaphe
Cy- Cylindrichnus
Di- Diplocraterion
Fu- Fugichnia
Ha- Harenaparietis
He- Helminthopsis
Lo- Lockeia
Ma- Macaronichnus
Op- Ophiomorpha
Pa- Palaeophycus
Ph- Phycosiphon
Pl- Planolites
Ro- Rosselia
Sc- Scolicia
Sch f- Schaubcylindrichnus freyi
Si- Siphonichnus
Sk- Skolithos
Te- Teichichnus
Th- Thalassinoides
Zo- Zoophycos

LEGEND

PHYSICAL SEDIMENTARY STRUCTURES

CLIMBING RIPPLES
CURRENT RIPPLE LAMINAE
FLAME STRUCTURE
GRADED BEDDING
HOMOGENOUS WAVY BEDDING
HUMMOCKY CROSS-STRATIFICATION
LENTICULAR BEDDING
LOW-ANGLE CROSS-STRATIFICATION
MASSIVE APPEARING
OSCILLATION RIPPLE LAMINAE
PLANAR BEDDING
SCOUR SURFACE
SOFT SEDIMENT DEFORMATION
TIGHT STREAK
TROUGH CROSS-STRATIFICATION
WAVY LOW-ANGLE CROSS-STRATIFICATION

LITHOLOGICAL ACCESSORIES

FRACTURES
GLAUCONITE
MUD DRAPES
PEBBLES/GRANULES
PHYTODETRITAL LAMINAE
PYRITE
RIP-UP CLASTS
SIDERITE
SHALE LAMINAE
SHELL FRAGMENTS
SILT LAMINAE
WISPY ORGANIC LAMINAE
WOOD DEBRIS

ICHNOLOGY

ARENICOLITES
ASTEROSOMA
CHONDRITES
COSMORHAPHE
CYLINDRICHNUS
DIPLOCRATERION
FISH FEEDING PIT
FUGICHNIA
HELMINTHOPSIS
LOCKEIA
MACARONICHNUS
OPHIOMORPHA
PALAEOPHYCUS
PHYCOSIPHON
PLANOLITES
ROSSELIA
SCOLICIA
SHAUBCYLINDRICHNUS FREYI
SIPHONICHNUS
SKOLITHOS
TEICHICHNUS
THALASSINOIDES
ZOOPHYCOS

Table 1. Table of facies observed within the study region including a visual representation (core photograph) in addition to the sedimentologic and biogenic attributes of each representative facies.

The twelve facies discussed are subsequently grouped into four facies associations based on recurring vertical facies relationships. Facies contacts are often gradational or cyclical, and the contact between individual facies was a subjective decision. Generally, facies within the Clearwater Marten Hills Member show an increasing grain-size upwards with individual facies thicknesses varying from 50 centimetres to over 10 metres. To provide a comprehensive vertical facies relationship for multiple stratigraphic intervals, and to display facies variability across the study region, a lithostratigraphic type-well is utilized (Fig. 3) to display five reference localities (Fig. 4 to 8).

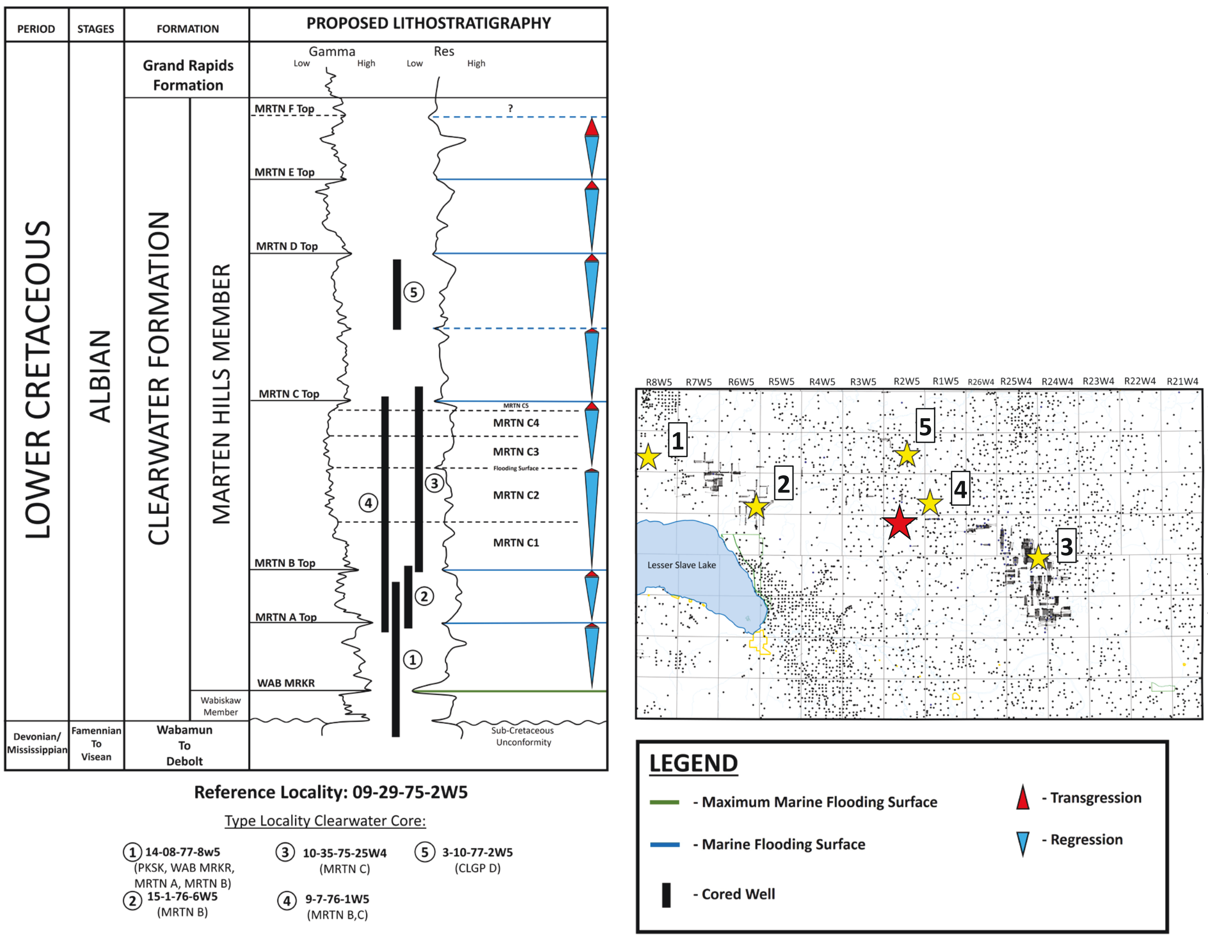


Figure 3. Lithostratigraphic framework for the Clearwater Formation and proposed Marten Hills Member. Five reference localities were selected based upon both regional and vertical coverage of the entire Marten Hills Member stratigraphic intervals. Reference locality "type-well" was additionally provided as it adequately captured multiple characteristic successions of each stratigraphic interval and is noted by the red star on the map. Interpreted transgression/regression cycles are included on the right side of the figure in addition to marine flooding surfaces and maximum flooding surfaces. All other numbered yellow stars indicate reference localities throughout the study region.

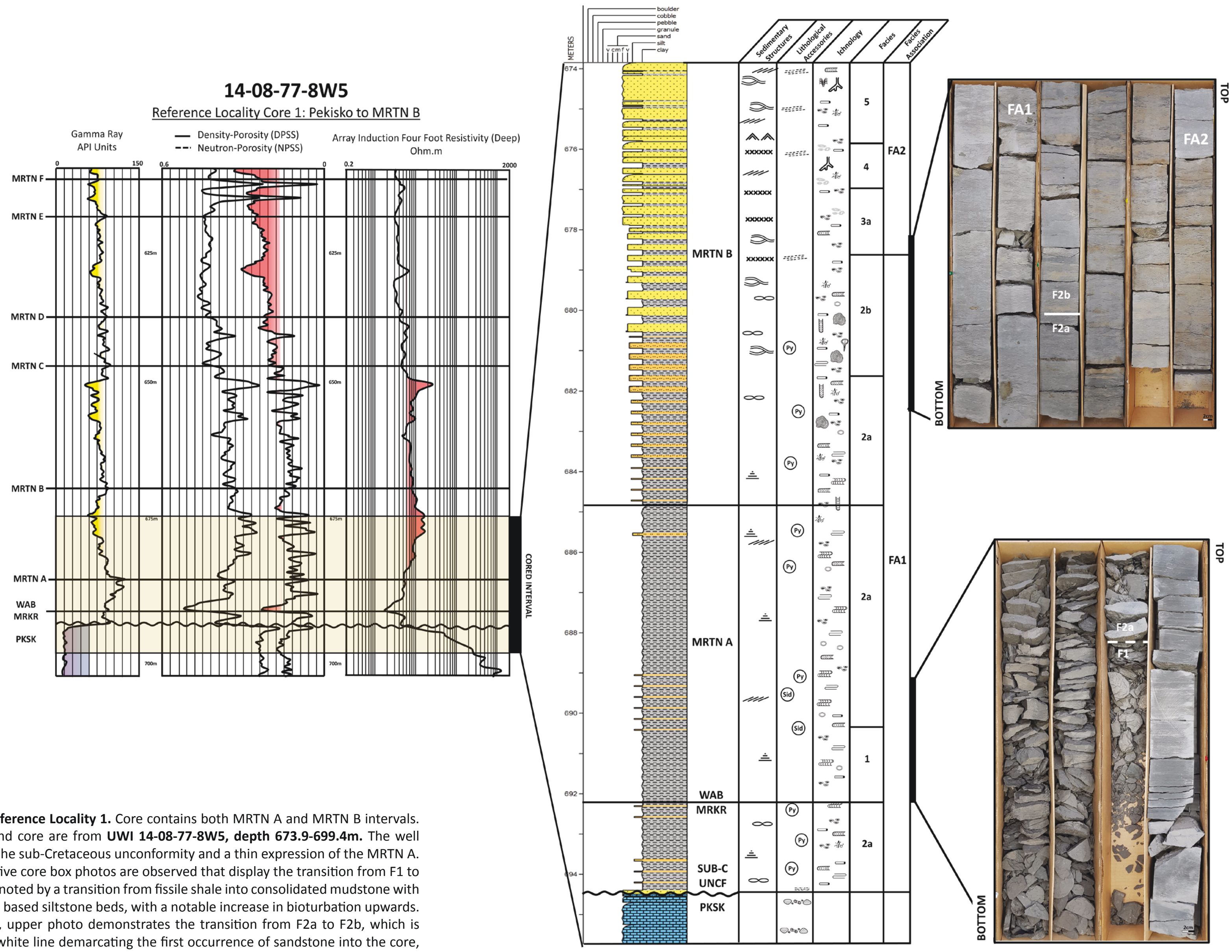


Figure 4. **Reference Locality 1.** Core contains both MRTN A and MRTN B intervals. Both logs and core are from **UWI 14-08-77-8W5, depth 673.9-699.4m.** The well penetrates the sub-Cretaceous unconformity and a thin expression of the MRTN A. Representative core box photos are observed that display the transition from F1 to F2, which is noted by a transition from fissile shale into consolidated mudstone with minor sharp based siltstone beds, with a notable increase in bioturbation upwards. Additionally, upper photo demonstrates the transition from F2a to F2b, which is noted by a white line demarcating the first occurrence of sandstone into the core, with both F2a and F2b representing a heavy bioturbation

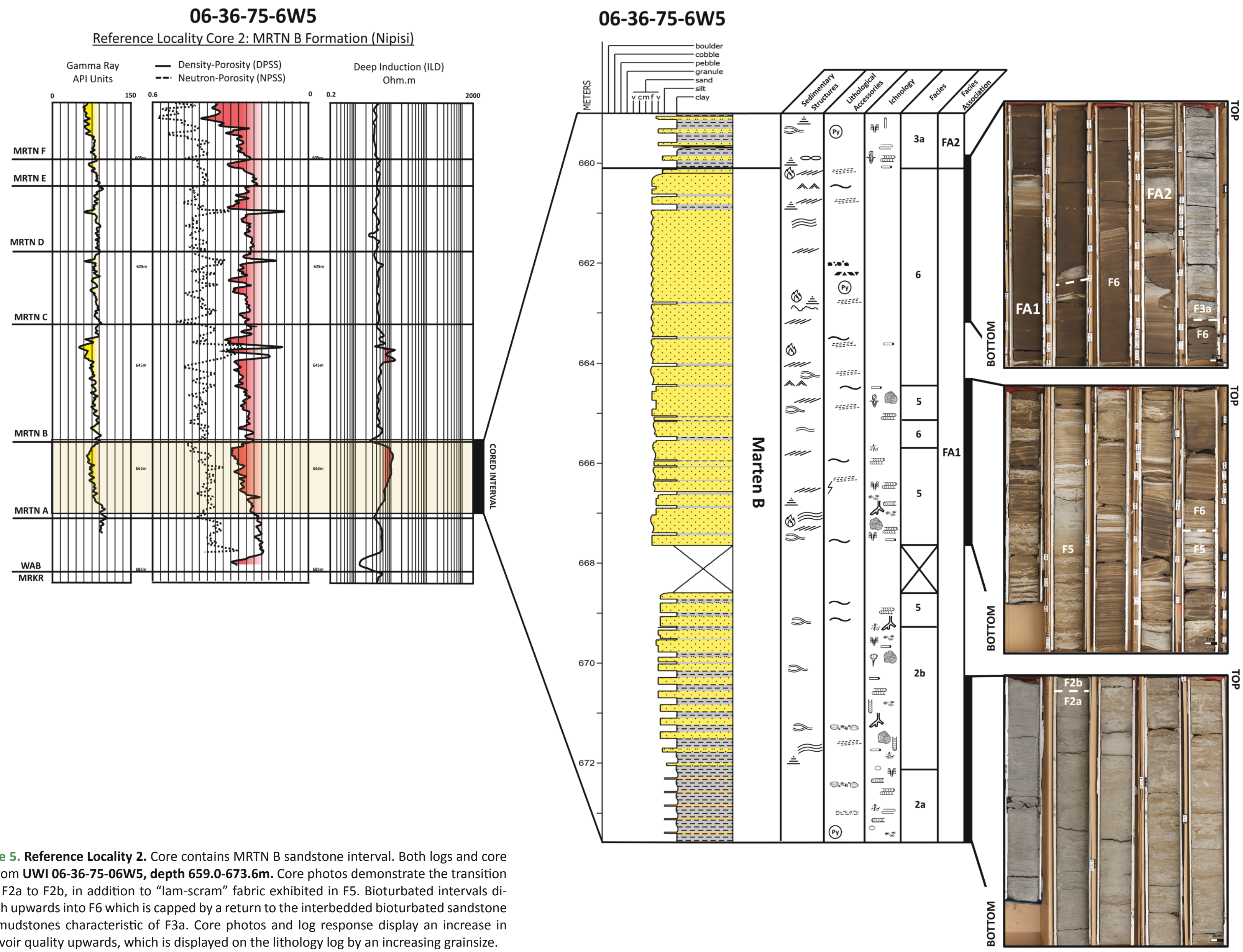


Figure 5. Reference Locality 2. Core contains MRTN B sandstone interval. Both logs and core are from **UWI 06-36-75-06W5, depth 659.0-673.6m.** Core photos demonstrate the transition from F2a to F2b, in addition to "lam-scram" fabric exhibited in F5. Bioturbated intervals diminish upwards into F6 which is capped by a return to the interbedded bioturbated sandstone and mudstones characteristic of F3a. Core photos and log response display an increase in reservoir quality upwards, which is displayed on the lithology log by an increasing grainsize.

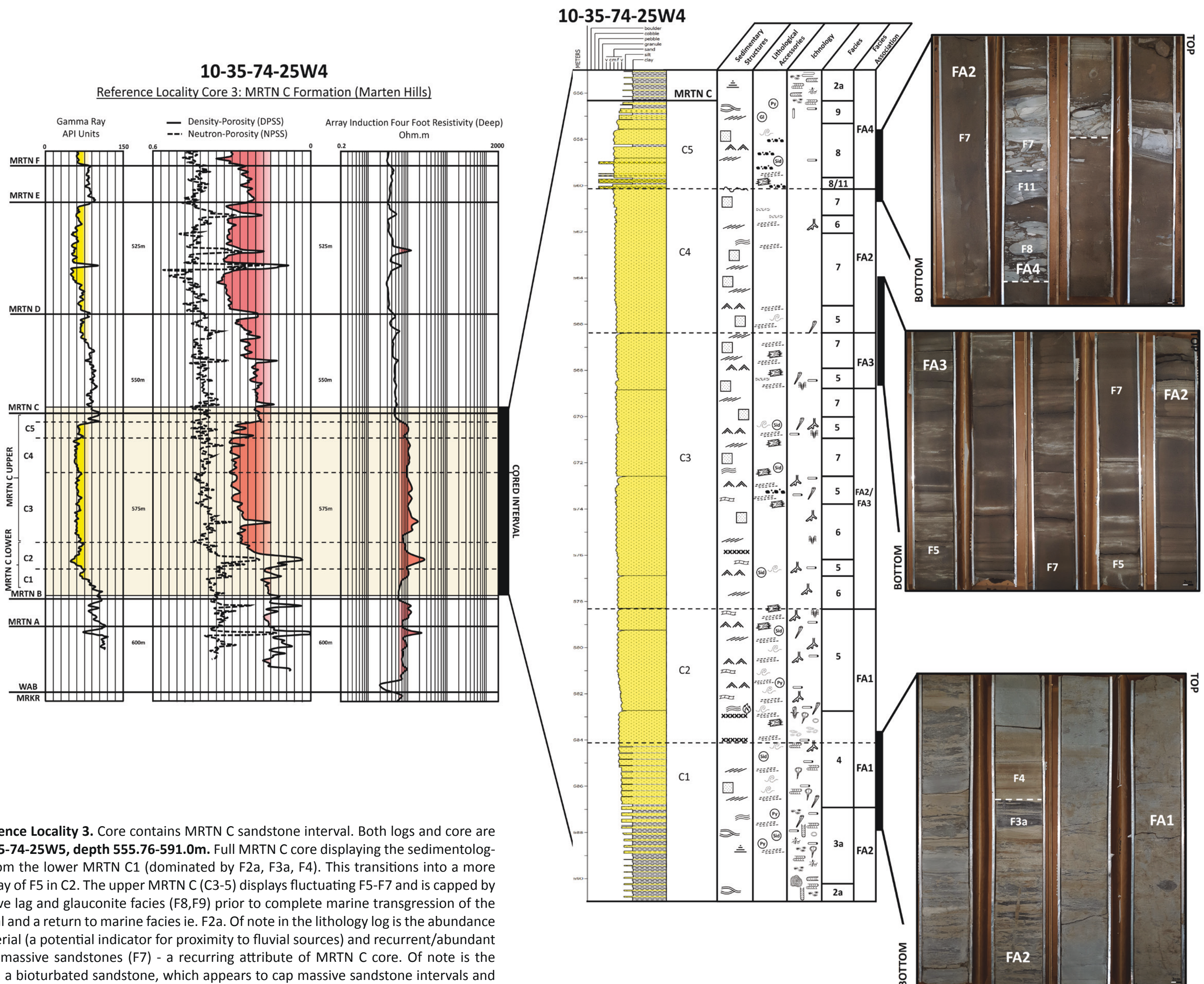


Figure 6. Reference Locality 3. Core contains MRTN C sandstone interval. Both logs and core are from **UWI 10-35-74-25W5, depth 555.76-591.0m.** Full MRTN C core displaying the sedimentologic variability from the lower MRTN C1 (dominated by F2a, F3a, F4). This transitions into a more abundant display of F5 in C2. The upper MRTN C (C3-5) displays fluctuating F5-F7 and is capped by the transgressive lag and glauconite facies (F8,F9) prior to complete marine transgression of the MRTN C interval and a return to marine facies ie. F2a. Of note in the lithology log is the abundance of organic material (a potential indicator for proximity to fluvial sources) and recurrent/abundant distribution of massive sandstones (F7) - a recurring attribute of MRTN C core. Of note is the presence of F5, a bioturbated sandstone, which appears to cap massive sandstone intervals and potentially suggests a return to fairweather conditions.

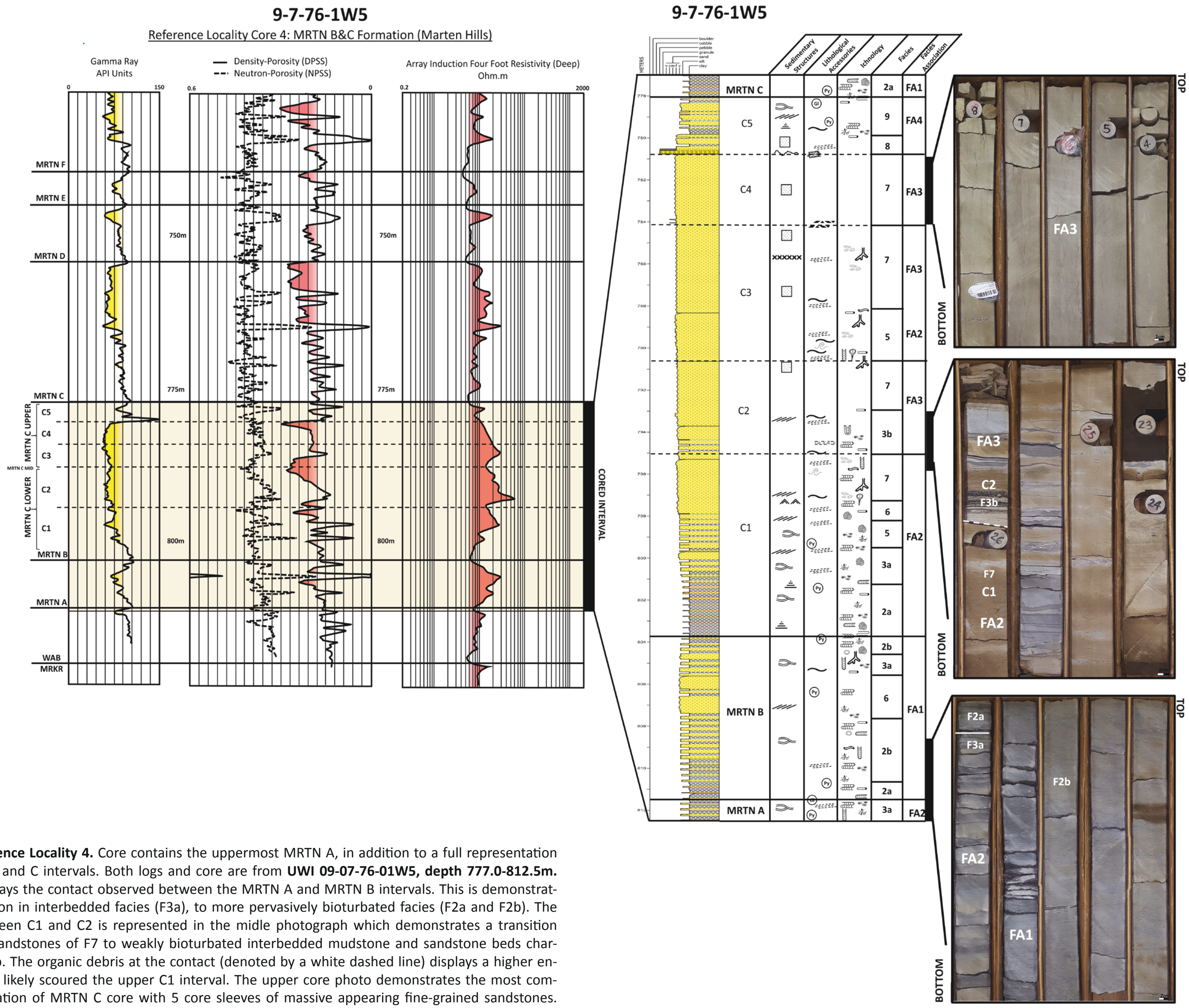


Figure 7. Reference Locality 4. Core contains the uppermost MRTN A, in addition to a full representation of the MRTN B and C intervals. Both logs and core are from **UWI 09-07-76-01W5, depth 777.0-812.5m.** Basal core displays the contact observed between the MRTN A and MRTN B intervals. This is demonstrated by a transition in interbedded facies (F3a), to more pervasively bioturbated facies (F2a and F2b). The transition between C1 and C2 is represented in the midle photograph which demonstrates a transition from massive sandstones of F7 to weakly bioturbated interbedded mudstone and sandstone beds characteristic of F3b. The organic debris at the contact (denoted by a white dashed line) displays a higher energy event that likely scoured the upper C1 interval. The upper core photo demonstrates the most common representation of MRTN C core with 5 core sleeves of massive appearing fine-grained sandstones.

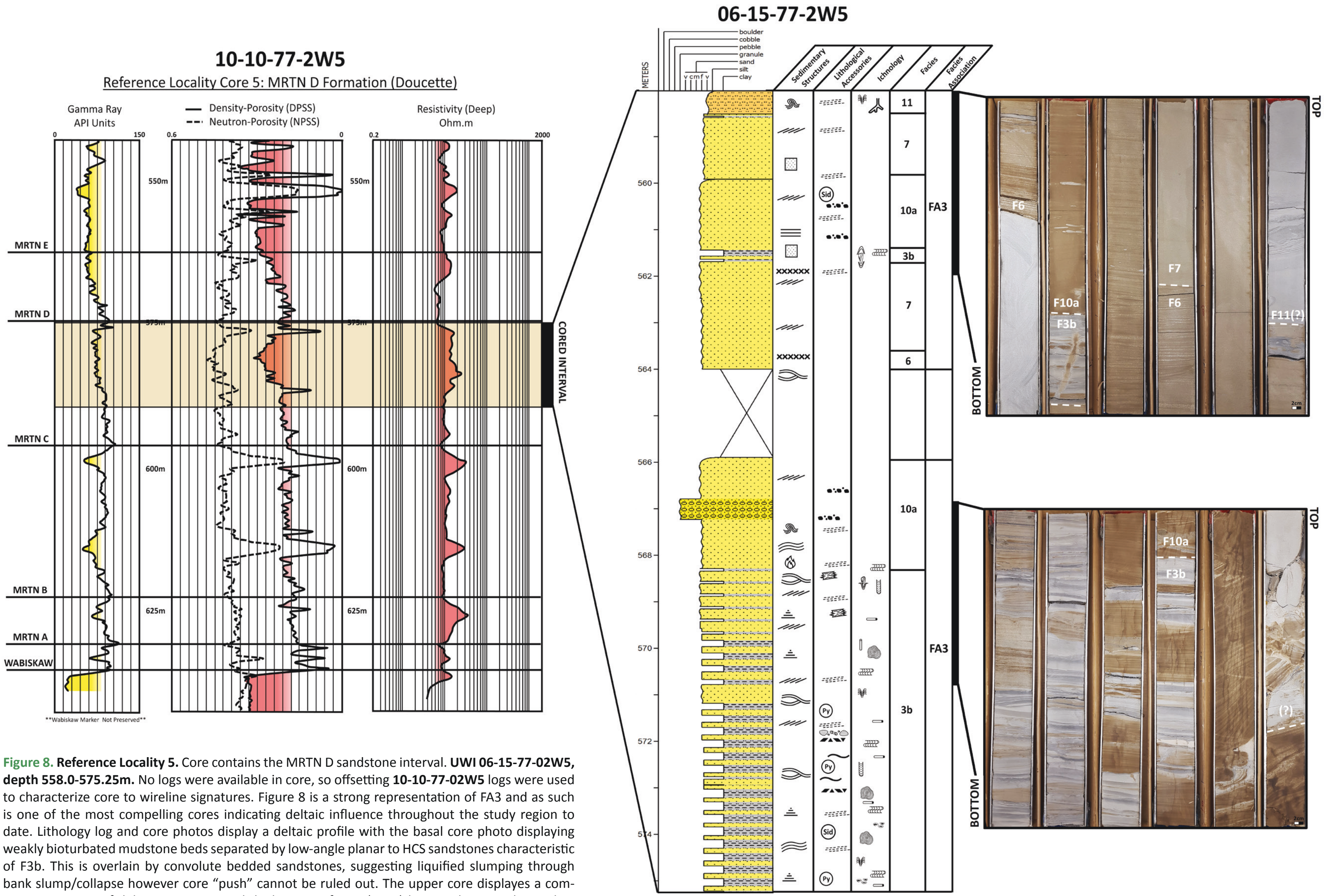


Figure 8. Reference Locality 5. Core contains the MRTN D sandstone interval. **UWI 06-15-77-02W5, depth 558.0-575.25m.** No logs were available in core, so offsetting **10-10-77-02W5** logs were used to characterize core to wireline signatures. Figure 8 is a strong representation of FA3 and as such is one of the most compelling cores indicating deltaic influence throughout the study region to date. Lithology log and core photos display a deltaic profile with the basal core photo displaying weakly bioturbated mudstone beds separated by low-angle planar to HCS sandstones characteristic of F3b. This is overlain by convolute bedded sandstones, suggesting liquified slumping through bank slump/collapse however core "push" cannot be ruled out. The upper core displayes a common expression of deltaic processes with high energy facies (F10a) being subsequently overlain by wave reworking (F6) and demonstrate that deltaic evidence can rapidly be removed through wave action. Additionally, a *Siphonichnus* (or potential fluidization structure) is observed prior to wave reworking.

2.2 Facies 1 (F1): Dark Grey Fissile Mudstone:

Sedimentologic Description: F1 is the most mud-dominated facies observed within the Clearwater Formation in this study and is only observed within 6 cores (10%). F1 is typically observed at the top of the Wabiskaw Member (Fig. 4) and consists of predominantly black to dark grey mudstone (95%) interbedded with thin (millimetre-scale) low-angle siltstone and whitish grey mudstone (5%) (Fig. 9A). F1 overlies Wabiskaw sandstones, facies 2, and is commonly gradationally overlain by facies 2,4a,4b throughout the study region. Silt beds increase upwards in frequency, but millimetre scale persists throughout F1. The thickness of F1 is variable throughout the study region but is generally less than 5 metres. Due to the dark colour of the facies (presumed to represent elevated organic matter) and fissility of the core, physical sedimentary structures are difficult to discern and mudstones appear structureless (Fig. 9B). Thin siltstone interbeds display rare examples of micro hummocky cross-stratification (HCS) and are often sharp based intervals that normally grade into the darker mudstone (possible starved current ripples). Lithologic accessories within this facies consist of large (4 centimetre) authigenic pyrite nodules, sometimes partially replacing burrows.

Ichnology: Bioturbation intensity within this facies is difficult to discern given the homogenous nature and dark grey color of the mudstone obscuring the identification of biogenic fabrics and represents both bioturbated and “lam-scram” structures sensu MacEachern and Pemberton, 1992. In several cored intervals, where silt content is slightly greater, pervasive bioturbation is observed (BI 3-5). Trace fossils consist of: *Helminthopsis*, *Cosmorhaphe*, *Chondrites*, *Zoophycos*, with subordinate *Schaubcylindrichnus freyi*, *Planolites*, and diminutive *Scolicia* (in order of relative abundance). These traces display a diverse trace fossil suite and are interpreted to represent the distal *Cruziana* to proximal *Zoophycos* ichnofacies.

Interpretation: The thin, sharp-based siltstones with micro HCS observed in the uppermost limits of F1 likely represent unidirectional, waning oscillatory flows of rapidly deposited distal tempestites or hyperpycnal flows (Leckie and Walker, 1982; Frey, 1990; Myrow and Southard, 1996; Pemberton *et al.,* 2012). The increasing siltstone preservation is likely the result of emplacement well below the fair-weather base where physical processes are unable to adequately modify them (Wheatcroft, 1990; Bann *et al.,* 2004). Mudstone deposition was likely through low-energy suspension of clays, which were subsequently punctuated by rapid bed load deposition events and represent sediment starved deep water environments (Caplan, pers comm.). The lateral distribution of this facies observed on wireline logs is extensive, making the stratigraphic significance (and therefore sedimentologic significance) of this interval critical. This facies is characteristically associated with an abrupt decrease in resistivity, often in addition to caliper washout. The ichnologic suite that is observed in siltier portions of this facies is indicative of the proximal *Zoophycos* to distal *Cruziana* Ichnofacies, suggesting a lower energy fully marine environment (Gingras *et al.,* 2011; Pemberton *et al.,* 2012). In several cores, the facies has been “washed-out” or broken up due to the increased fissility of the dark mudstones. The degree of fissility has been found to rely on a combination of several factors such as the mineral alignment of micaceous clays or the degree of bioturbation, with higher rates of bioturbation decreasing fissility (Ingram, 1953; Byers, 1974). The difficulty of viewing bioturbation in mudstone dominated intervals, in addition to darker colour and fissile nature may indicate oxygen stressed conditions (Wallace and Lavigne, 2011; Gingras *et al.,* 2011). Given the mudstone dominated nature of this facies, and minor preservation of distal tempestites, F1 is interpreted to be represent episodic deposition in a distal marine environment. F1 is also directly associated with a maximum flooding surface referred to as the Wabiskaw marker throughout the study region.

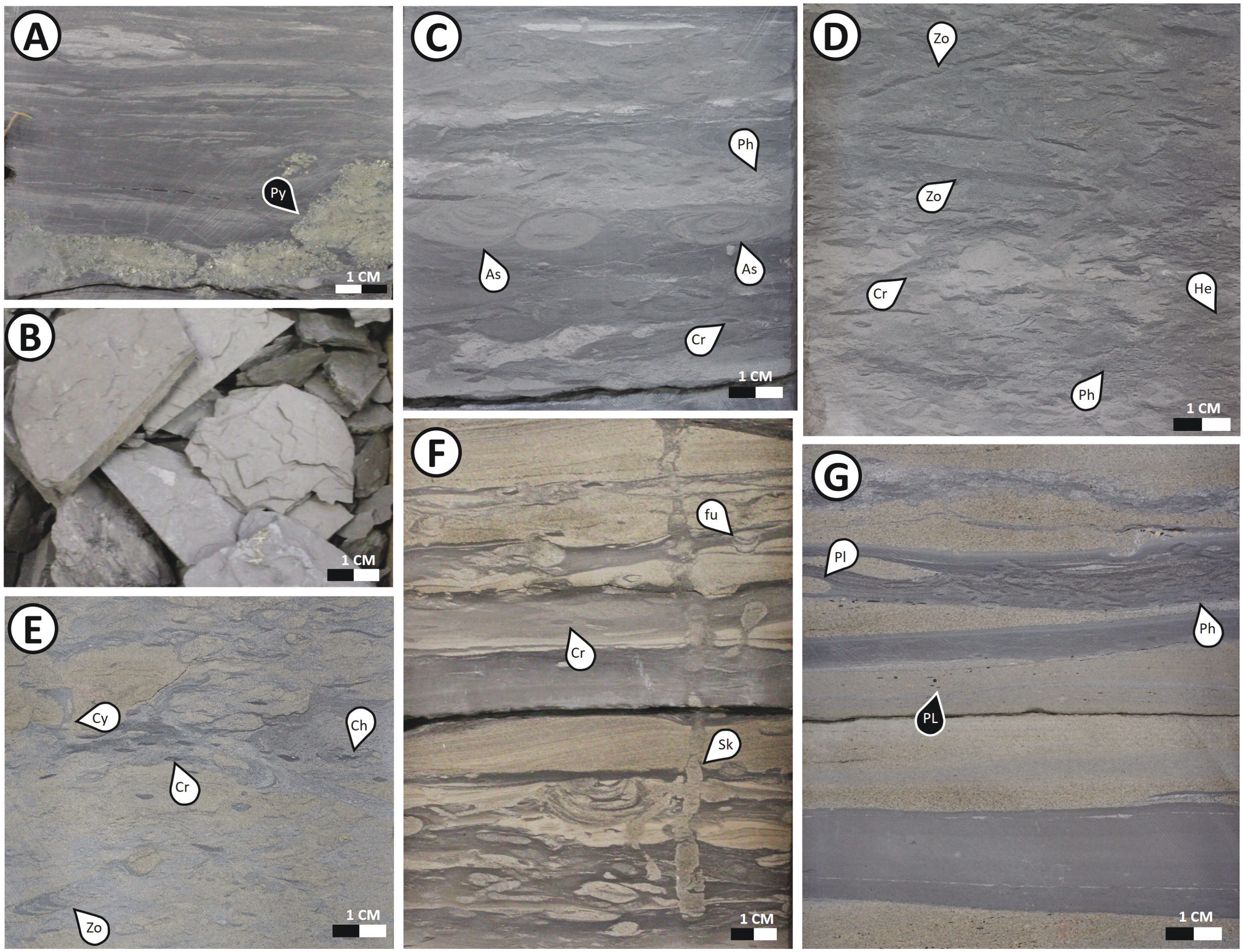


Figure 9. A) **F1:** Dark structureless mudstone with minor bioturbation, thin low-angle siltstone beds, and pyrite nodules (py). **UWI 14-08-77-08W5, depth 689.4m;** B) **F1:** Fissile mudstone. **UWI 14-08-77-08W5, depth 691.7m**; C) **F2a:** Pervasively bioturbated silty mudstone with robust *Asterosoma, Cosmorhaphe*, and *Phycosiphon* in addition to heavily bioturbated tempestites. **UWI 02/15-09-76-02W5, depth 725.5m;** D) **F2a**: Representation of the diverse ichnologic suite with *Zoophycos, Helminthopsis, Cosmorhaphe, Phycosiphon,* and little evidence of sediment structures. **UWI 10-10-75-26W4, depth 740.98m;** E) **F2b:** Pervasive bioturbation wish *Cosmorhaphe, Zoophychos, Chondrites (?), Cylindrichnus* in a sandy mudstone. Physical sedimentary structures precluded by high degrees of bioturbation. **UWI 09-07-76-01W5, depth 807.82m**; F) **F3a**: Interbedded sharp-based sandstones containing micro HCS, with heavily bioturbated mudstones including vertical *Skolithos* traces. **UWI 10-20-74-4W5, depth 725.52m**; G) **F3b:** Interbedded sandstone and mudstone with variable degrees of bioturbation in mudstones ranging from unbioturbated (lower) to opportunistically colonised by *Phycosiphon* (upper). Trace amounts of phytodetrital material also observed. **UWI 02/15-09-76-02W5, depth 716.05m.**

2.3 Facies 2a (F2a): Pervasively Bioturbated Silty Mudstone Facies:

Sedimentologic Description: F2a consists of dark-grey mudstone to light-grey silty mudstone and ranges in thickness between 1-4metresand is observed in 23 cores (38%). F2a commonly sharply overlies F3a, 3b and gradationally transitions upwards into F2b or F3a. Mudstone beds are composed of variable silt and very-fine grained sand (10-30%), with silt being the more common secondary lithology. Siltstone and sandstone content increase vertically throughout F2a and clean upwards to the 30% facies threshold at which point a Facies 2b classification is made. Physical sedimentary structures are rarely preserved due to a high degree of biogenic reworking but can include normally-graded beds, millimetre to rare centimetre thick low-angle planar siltstone or sandstone beds (Fig. 9C). Subordinate soft sediment deformation with mantle and swirl textures are also present. Sandstone-dominated beds are often sharp-based and normally-grade upwards into mudstone. Common lithologic accessories include pyrite nodules, rare phytodetrital laminae and iron staining.

Ichnology: F2a is characterised by a highly bioturbated, diverse trace fossil suite. The BI within this facies varies between 4-5 but is most often on the higher end of the scale. Trace fossils are distributed uniformly throughout and the ichnologic suite comprises *Phycosiphon*, *Cosmorhaphe*, *Zoophycos*, *Chondrites*, *Asterosoma*, *Helminthopsis*, *Schaubcylindrichnus freyi*, *Teichichnus*, *Thalassinoides*, *Planolites*, and *Scolicia* with rare, often diminutive *Rosselia*, Cylindrichnus, and escape traces (fugichnia). Bioturbation is representative of a distal to archetypal expression of the *Cruziana* ichnofacies, predominantly consisting of deposit-feeding structures (Fig. 9D). The sharp-based siltstone layers often consist of lesser degrees of bioturbation (BI 3-4) confined to the uppermost portions, which suggest rapid deposition inhibiting complete bioturbation (Pemberton and MacEachern, 1997; Gingras *et al.,* 2011). Colonisation windows are inferred to be high however, given most siltstone beds are pervasively colonized (Pemberton *et al.,* 1992a; Mángano *et al.,* 2005) (Fig. 9D). Deeper-tier trace fossils (*Rosselia*, *Thalassinoides*) display secondary bioturbation produced by opportunistic colonizers (*Chondrites* and *Phycosiphon*).

Interpretation: Primary physical sedimentary structures are mostly precluded by the biogenic homogenization, with little to no evidence of current or wave processes. The rare occurrence of sharp-based, low-angle planar-bedded sandstone with lesser degrees of biogenic reworking (BI 3) are indicative of high-energy, rapid deposition by storm events (tempestites) and are interpreted as micro-hummocky cross-stratification (Leckie and Walker, 1982; Frey, 1990; Coates and MacEachern, 2009; Pemberton *et* *al.,* 2012). The dominant presence of pervasive and diverse bioturbation (BI 3-5), in addition to high mud content, is indicative of a deeper open marine setting below the fair-weather wave-base. Thin bioturbated tempestites indicate a depositional environment where sedimentation rates between storm events are interpreted to be slow but consistent (Wheatcroft, 1990; Hampson and Storms, 2003; Hampson *et al.,* 2008). The ichnologic suite is representative of a distal to archetypal expression of the *Cruziana* Ichnofacies displaying abundant deposit-feeding strategies in lower energy marine conditions (Pemberton *et al.,* 2012). The intensely bioturbated mudstone intervals that dominate the facies likely reflect hiatuses between storm events and subsequent return to fairweather conditions, allowing for the complete colonization of the substrate (Taylor *et al.,* 2003). The rare nature of tempestites within this facies indicates either infrequent storm activity, or more likely that the facies represents the lower limit of storm wave base with only severe events being preserved (Wheatcroft, 1990; Myrow and Southard, 1996). F2a is interpreted to be representative of deposition within a low-energy fully marine setting and given a diverse ichnologic assemblage and high bioturbation intensity, a distal-upper offshore environment is inferred, however proximal lower offshore environment is also possible. Given its intense biogenic reworking and diverse ichnologic suite, a distal pro-deltaic environment is not inferred however cannot be fully ruled out.

2.4 Facies 2b (F2b): Pervasively Bioturbated Sandy Mudstone:

Sedimentologic Description: F2b primarily consists of silty-to sandy-mudstones with very fine-grained sandstone beds sporadically distributed throughout and is observed in 18 cores (30%). F2b ranges in thickness between 50 centimetres to 4.5 metres and is gradationally underlain by F2a, and gradationally overlain by F4 or sharply overlain by F2a, F3a, or F6. Mudstone units are light-to dark-grey with silt and sand content increasing upwards from 30-55%. In addition, grain-size increases upwards from silty sandstone to a very-fine grained sandstone. Sandstone beds are distributed homogeneously throughout the interval or observed in weakly bioturbated (BI 1-2), ranging from 2-10-centimetre-thick beds. Physical sedimentary structures are often precluded by high degrees of biogenic reworking (Fig. 9E); however, there is low to moderate preservation of sharp-based low-angle planar beds, and normally-graded beds. Lithological accessories consist of phytodetrital laminae, often deposited along bedding surfaces, in addition to rare pyrite nodules, disseminated pyrite, and small (~1-2 millimetres in diameter) siderite clasts.

Ichnology: F2b is highly bioturbated (BI 3-5) and displays a diverse trace fossil suite. Bioturbation within this facies is an archetypal expression of the *Cruziana* Ichnofacies characterized by deposit-feeding strategies. Mud-dominated intervals contain considerably higher degrees of bioturbation with observable trace fossils consisting of *Planolites*, *Cosmorhaphe*, *Helminthopsis*, *Teichichnus*, *Asterosoma*, *Zoophycos*, *Phycosiphon* with subordinate forms interpreted as *Chondrites*, *Thalassinoides*, *Rosselia*, *Skolithos*, *Schaubcylindrichnus freyi*, and Cylindrichnus. Trace fossils within the sharp-based, low-angle planar sandstone intervals consist predominantly of escape traces (fugichnia), sediment swimming structures (navichnia) (Gingras *et al.,* 2007), and evidence of opportunistic colonisation of the uppermost intervals.

Interpretation: F2b is similar to F2a in that they are both highly bioturbated (BI 3-5), mud-dominated facies; however, F2b contains a higher abundance of sand (Table 1 and Fig. 9D, 9E). Tempestites deposited under the influence of heightened sedimentation rates during storm events are also more common. Tempestites often contain escape traces (fugichnia) and display a decrease in burrowing intensity from the top down (Myrow and Southard, 1996; and Pemberton and MacEachern, 1997). These events are followed by waning storm energy and a return to fairweather conditions where sedimentation rates are reduced, and open colonization windows persist. The ichnologic diversity and overall high abundance is inferred to represent an offshore environment as opposed to a wave dominated distal pro-delta however the two are difficult to discern (Coates and MacEachern, 2009). F2b often exhibits an upwards increase in grain-size from mud-dominated to mixed mudstone and sandstone, which is inferred to represent increasing proximity to paleoshoreline. Pervasive bioturbation in the mud-dominated intervals of the facies often display opportunistic colonization by grazing and deposit-feeding infauna such as *Phycosiphon* (Pemberton *et al.,* 2012; MacEachern and Bann, 2020). The increase in tempestite occurrence, in addition to increased sand content, is suggestive of a closer proximity to the paleoshoreline than F2a (cf. Pemberton and Frey, 1985). Contrastingly, the high degree of bioturbation intensity interpreted to represent fair-weather conditions and overall moderate mud content still suggests a depositional setting that is below the fair-weather wave base. This makes the upper offshore setting a probable depositional environment (MacEachern and Pemberton, 1992; Pemberton *et al.,* 1992a; Pemberton and MacEachern 1997; Pemberton *et al.,* 2012). The introduction of rarely observed phytodetrital material within tempestites differs from F2a and is inferred to represent an increasing proximity to paleoshoreline. While this may also be related to a subaqueous pro-deltaic environment, the occurrence of robust traces within the gradationally overlying F4 suggests a more likely upper offshore environment.

2.5 Facies 3a (F3a): Sporadically Bioturbated Interbedded Sandstone and Mudstone:

Sedimentologic Description: F3a consists of very-fine to lower fine-grained sandstones that are interbedded with siltstone and mudstone and are observed in 31 cores (52%). F3a ranges in thickness from 2-9 metres with individual beds ranging from millimetre to several centimetre in thickness. Sandstone content ranges from 50% to over 70% of the total lithologic composition (increasing upwards). F3a is commonly gradationally underlain by F2a, F2b, and overlain by F2a, 3b, F4, F5, and F6. Sandstone beds typically consist of sharp or undulous contacts and can normally grade upward into siltstone (Fig. 9F). Sedimentary structures include normally-graded bedding, wavy to low-angle planar (LAP) bedding, and quasi-planar lamination (QPL) (Arnott, 1993), with rare occurrences of oscillatory bedding, wave ripples, fluid muds, and flame structures. Lithologic accessories observed within this facies include small (millimetre scale) siderite nodules commonly associated with very-fine grained detrital organic material, pyrite nodules, phytodetrital laminae deposited along bedding surfaces, and rare wood clasts.

Ichnology: Facies 3a contains varying degrees of bioturbation dependent on the dominant lithology. When mud content is around 50%, BI ranges from 2-4 with a diverse trace fossil suite that consists of a multitude of feeding and dwelling traces: *Planolites*, *Phycosiphon*, *Zoophycos*, *Asterosoma*, *Chondrites*, *Cosmorhaphe*, *Thalassinoides*, *Scolicia* with subordinate *Rosselia*, Cylindrichnus, *Helminthopsis*, *Skolithos*, *Teichichnus*, *Arenicolites*, *Schaubcylindrichnus freyi*, *Palaeophycus* and *Lockeia*. The ichnologic suite is characteristic of the proximal *Cruziana* and distal *Skolithos* ichnofacies (Pemberton *et al.,* 2012). Additionally, some mudstone beds are opportunistically colonized, and are interpreted as representing the *Phycosiphon* ichnofacies. When sandstone comprises the dominant lithology (>75%), BI typically ranges between 0-2, often preserving only escape traces (fugichnia) or top-down colonization of the uppermost sand beds.

Interpretation: F3a differs from 3b in that mudstone intervals are typically thicker, consist of normally graded intervals, and consist of a more diverse and abundant ichnologic assemblage. F3a typically consists of a coarsening-upwards succession with high variability that consists of variable mud content, bed thickness, and bioturbation intensity, all of which are interpreted to represent episodic high-energy deposition events (cf Pemberton and MacEachern, 1997). The moderate to high preservation of storm deposits or high energy deposition events, in addition to physical sedimentary structures such as wavy low-angle, quasi-planar bedding, and moderate to high BI, suggest this facies represents a distal expression of a storm-influenced lower shoreface or pro-delta environment (Arnott, 1993; Dott and Bourgeois, 1982; MacEachern and Pemberton, 1992; Dumas and Arnott, 2006; Pemberton *et al.,* 2012; Baniak *et al.,* 2014). Storm deposits within this facies were likely high frequency, moderate to high energy events due to the thin but abundant tempestites containing physical sedimentary structures consistent with micro hummocky cross-stratification (Dott and Bourgeois, 1982; Dyson, 1995; Dumas and Arnott, 2006). The bioturbation intensity is generally lower than the deeper marine facies (BI 2-4), could be a result of more frequent exposure to storm action which scours fairweather deposits and shortens the colonisation window (Frey, 1990; MacEachern and Pemberton, 1992; Plint, 2010). Fairweather wave influence is likely low due to the interbedded nature of episodic deposition events, however the increased presence of oscillatory ripple cross-laminated sedimentary structures, phytodetrital organic material, detrital siderite grains, and larger wood clasts, suggest a more proximal environment, likely that of the distal lower shoreface. The observation of several structureless, mud dominated intervals (fluid muds) with decreased bioturbation intensity, but diverse ichnogenera may also imply deltaic influence (distal prodelta) (Bhattacharya and Giosan, 2003; Coates and MacEachern, 2009; Hansen and MacEachern, 2007). The fluctuating sandstone and mudstone depositional sequence confines this interval to either a storm-dominated distal lower shoreface, or a distal prodeltaic environment.

2.6 Facies 3b (F3b): Cross-Stratified Interbedded Sandstone with Weakly Bioturbated Mudstone

Sedimentologic Description: F3b consists of very fine (upper) to lower fine-grained sandstone with thin (5 millimetre to 4 centimetre thick) mudstone interbeds and is observed in 10 cores (17%). F3b thickness varies between 2 to 9 metres. Facies 3b is commonly gradationally underlain by F3a, and gradationally overlain by F4, F5, F6 and F7. Mud content ranges between 10-30% of the bulk lithology often with minimal silt content that decreases upwards. Physical sedimentary structures include: abundant massive-appearing sandstone with subordinate displays of low-angle planar bedding, wavy oscillatory bedding, and rare normally graded bedding. Contacts between mud and sand are often sharp, with normally graded transitions far less common (Fig. 9G). Mudstone beds commonly display little to no evidence of bedding and are often massive appearing (Fig. 9G). Lithological accessories that often accompany these physical structures include abundant mud drapes, small (millimetre-scale) siderite pellets, abundant phytodetrital laminae, wood clasts <5 centimetre, scattered rounded mud rip-up clasts, flame structures, with rare synaeresis cracks. Phytodetrital laminae, siderite pellets, and rip-up clasts are all commonly observed along bedding surfaces.

Ichnology: F3b is characterised by lower bioturbation intensities. Within the sandstone units, bioturbation is scarce (BI 0-2) with rarely observed Cylindrichnus, *Harenaparietis*, *Planolites*, and *Thalassinoides* in addition to rare escape traces (fugichnia). Within the mud-dominated intervals, bioturbation is slightly higher, yet still quite variable depending on the unit (BI 0-3). The common trace fossil suite within mud-dominated intervals consists of *Phycosiphon*, *Planolites*, *Chondrites*, *Asterosoma*, and *Thalassinoides* with more rarely observed *Cosmorhaphe*, *Macaronichnus*, and *Zoophychos*. This facies likely represents a *Phycosiphon* Ichnofacies given the sporadic and opportunistic colonisation strategies (MacEachern and Bann, 2020). When silt and mud content decreases upwards, a potential *Rosselia* ichnofacies is interpreted given the presence dwelling and re-equilibration structures suggesting high episodic sedimentation rates.

Interpretation: When comparing F3a to F3b, there is significantly less ichnologic diversity, and general abundance in bioturbation in the latter (Fig. 9F and 9G). This is particularly true within the mudstone intervals where dark-grey to black, organic-rich, laminated muds could have been sourced from flood events (i.e., freshet deposits) which emanate from a delta (Gani *et al.,* 2009; Caplan, pers comm). This facies varies from other interbedded facies in that the mudstone beds are thinner, and the overall degree of bioturbation is significantly reduced. Siltstone and mudstone beds are most commonly observed as thin mud-drapes that range from 3 millimetres to several centimetres in thickness, consisting of soft sediment deformation with load and flame structures indicative of rapid emplacement onto a soupy mudstone bed (Caplan pers comm). The sedimentologic structures and accessories such as structureless un-burrowed mudstone beds, mud-drapes, massive appearing sand/mud, and low-angle planar bedding commonly occur along sharp-based interbeds, which is suggestive of episodic rapid sedimentation with structureless sandstones representing meiofaunal “cryptic-bioturbation (Carmona *et al.,* 2009; Ahmed *et al.,* 2014; MacEachern and Bann, 2020). Thin (millimetre to centimetre scale) mud-drapes represents suspension settling of during slack water conditions, potentially through hyperpycnal flows related to freshet (freshwater flooding) events, or geostrophic currents (Gani *et al.,* 2009; Bhattacharya and MacEachern, 2009; Carmona *et al.,* 2009; Mackay and Dalrymple, 2011). Thicker massive appearing mudstone beds that lack normal grading may be indicative of fluid muds, with rare synaeresis cracks indicating a variable salinity environment (Hovikoski *et al.,* 2008; Ichaso and Dalrymple, 2009; Mackay and Dalrymple, 2011). In addition to mud drapes, small, rounded mud rip-up clasts with sharp-based reactivation surfaces and organic material that ranges from <1 millimetre to >2 centimetre in diameter, indicate basinward deposition of proximally sourced material through storm/flooding events (Elias and van der Spek, 2006). The sedimentologic characteristics listed above, in addition to the variable bioturbation intensity (characteristic of the *Phycosiphon* ichnofacies), likely indicate a stressed environment that was subjected to episodic, but high sedimentation rates. Such conditions are common in distal delta-front environments (MacEachern and Bann, 2020). Mudstone beds that do contain bioturbation consist of monospecific trace fossil suites (e.g., *Phycosiphon*) that are representative of opportunistic colonization or potentially “doomed-pioneers” and are observed between sedimentation events allowing organisms to colonize the substrate (Föllmi and Grimm, 1990; MacEachern and Pemberton, 1992; MacEachern and Bann, 2020). As differentiating between wave dominated delta-front environments and storm-dominated strand plain environments is challenging (Coates and MacEachern, 2009), when F3a directly underlies F3b, deltaic environments are more confidently suggested.

2.7 Facies 4 (F4): Bioturbated Silty to Muddy Massive Sandstone

Sedimentologic Description: F4 consists of upper very-fine to fine-grained sandstone sporadically distributed siltstone and mudstone that ranges from 5-25% of the bulk lithology and is observed in 23 cores (38%). F4 ranges in thickness from 1 to 5 metres and is commonly gradationally underlain by F2b, F3a, or sharply overlying F2a. It is gradationally overlain by F5 or F6. Sandstones are moderately-to well-sorted and often observed in association with sporadic calcite cementation. Calcite cemented sands are abundant and result in a patchy rock fabric, with cements cross cutting pre-existing inferred bedding surfaces. Physical sedimentary structures observed within this facies include: Oscillatory ripple-cross-lamination, symmetrical wave-ripples and wave cross laminations, rare low-angle planar bedding, quasi-planar bedding, and flame structures are observed in several cores, however cementation greatly inhibits physical sedimentary structure observations. Lithological accessories consist of small (<1 centimetre) mud rip-up clasts, abundant siderite pellets, phytodetrital laminae, wispy organic debris, rare wood clasts, pyrite nodules, and rarely observed mud drapes.

Ichnology: The massive-appearing sandstone of F4 is often overprinted by robust trace fossils (primarily *Rosselia*, Cylindrichnus, and *Ophiomorpha*) with an inferred BI ranging from 3-5 (Fig. 10A). Traces observed within this facies consist of robust *Rosselia*, *Ophiomorpha*, *Asterosoma*, *Macaronichnus*, Cylindrichnus, *Schaubcylindrichnus freyi*, *Planolites*, *Chondrites*, *Phycosiphon*, *Palaeophycus*, *Arenicolites*, *Thalassinoides*, with subordinate *Zoophycos*, *Diplocraterion*, *Skolithos*, *Conichnus*, and escape traces (fugichnia) (listed in relative abundance). The F4 likely represents the proximal Cruiziana to distal *Skolithos* Ichnofacies. The massive nature of the sandstone may also be attributed to bioturbation of meiofauna, allowing for the complete biogenic reworking of the sandstones (BI 6). Observable bioturbation within this facies consists of a mix between robust trace fossils and thin opportunistic coloniser silt/mudstone beds.

Interpretation: F4 is a sand-dominated facies that contains a considerable amount of lithological variability and is most easily observed by robust trace fossils, and abundant pinkish siderite grains commonly observed with organic debris (Fig. 10A). Mud content within this facies ranges from 5-30% but is commonly very fine-grained, sand-dominated, and lacking physical structures. Structureless sandstone is typically overprinted by marine (often robust) mud-dominated trace fossils with a diverse expression of the *Cruziana* and *Skolithos* Ichnofacies (MacEachern *et al.,* 2008). Trace diversity likely suggests well-oxygenated environments however lack of abundance in trace distribution could suggest sedimentation rates as an ichnologic stress and indicate distal delta front conditions (Bann and Fielding, 2004; Gingras *et al.,* 2011). The structureless sandstone units have several potential mechanics of origin ranging from rapid episodic sedimentation to cryptic bioturbation (Arnott and Hand, 1989; Frey and Goldring, 1992; McCrimmon , 1996; Pemberton and Gingras, 2005; Gingras *et al.,* 2011). Bromley (1996) and Howard and Frey (1975) speculated that complete biogenic homogenization of grains could occur within only several days following deposition. This potentially is a mechanism that followed tempestite deposition, and following a return to fairweather conditions, would allow robust deposit feeders of the *Cruziana* Ichnofacies to re-establish dominance. Symmetrical wave-ripples and wave cross laminations are rarely observed within this facies but likely indicate low or infrequent storm activity (Wesolowski *et al.,* 2018). Lithologic accessories such as wispy organic material (potential pasichnia – Gingras pers comm), disseminated phytodetrital material, and small sideritic clasts, provide partial evidence of deltaically influenced systems and are inferred to represent the cannibalized remnants of these environments that were deposited basinward following storm abatement (Rice *et al.,* 1986; MacEachern *et al.,* 2005). Based on the sedimentologic evidence of oscillation ripple-cross lamination, in addition to the robust and diverse ichnologic assemblage, it is inferred that the depositional setting is likely a proximal expression of a storm affected to storm influenced lower shoreface.

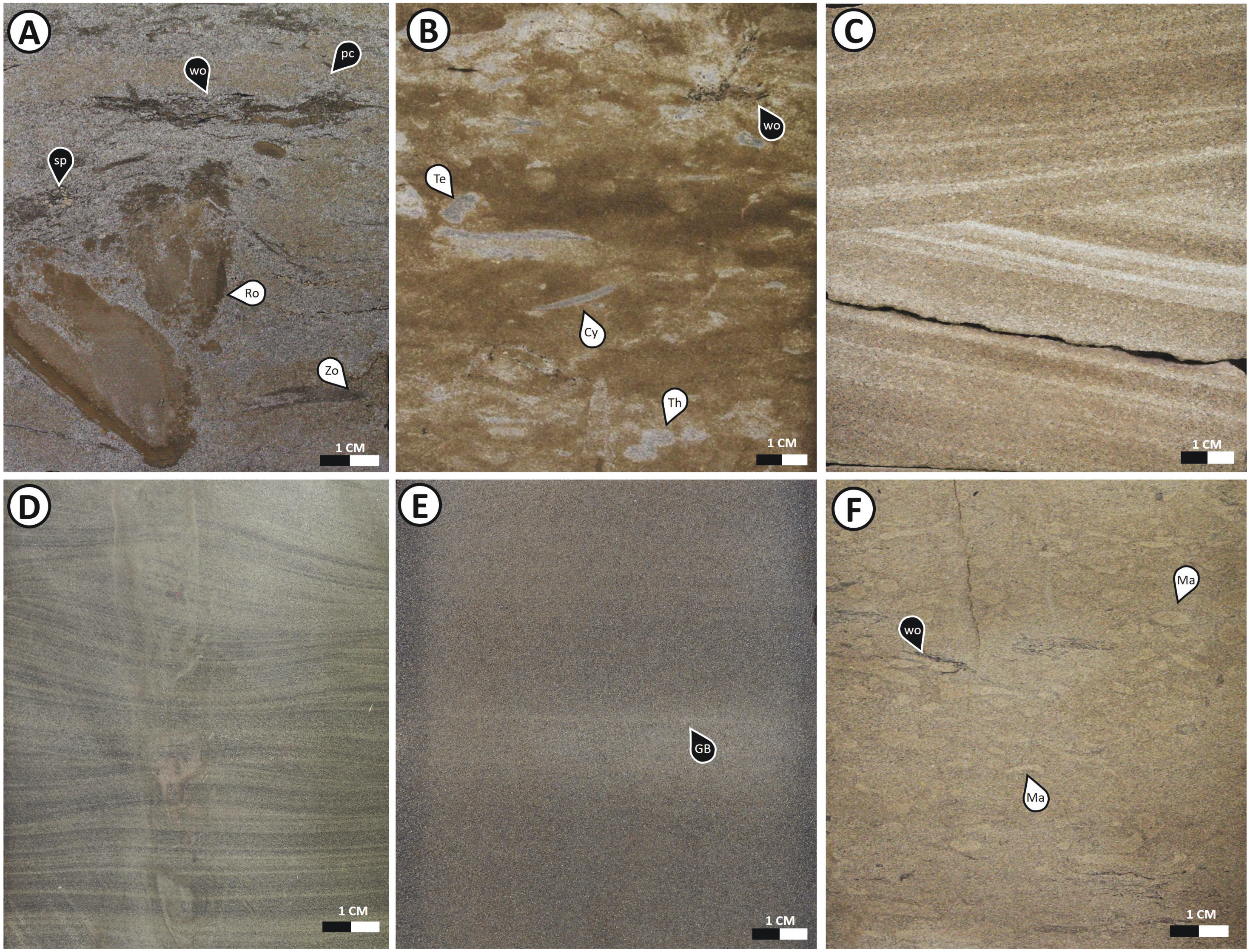


Figure 10. A) **F4:** Robust *Rosselia* trace fossil in addition to *Zoophycos*. Wispy organic debris and phytodetrital laminae also abundantly observed. Small pink siderite grains commonly associated with organics. Patchy calcite cement commonly observed with mud-lined trace fossils, pink siderite grains, and organic detrital material. **UWI 102/09-13-73-25W4, depth 529.53m;** B) **F5:** Bioturbated silty sandstone with wispy organic material. Silt filled/lined burrows observed (*Cylindrichnus*), in addition to *Teichichnus*, and *Thalassinoides*. **UWI 07-12-73-25W4, depth 546.24m**; C) **F6:** Low-angle bedding (inferred HCS). **UWI 102/16-11-75-25W4, depth 572.30m;** D) **F6**: Oscillatory and combined-flow ripples. **UWI 09-07-76-01W5, depth 778.95m;** E) **F7:** Massive appearing sandstone with faint "ghost-bedding. **UWI 102/09-13-73-25W4, depth 514.30m**; F) **F7**: Massive appearing sandstone with wispy phytodetrital material and a monospecific *Macaronichnus* trace suite **UWI 07-28-78-02W5, depth 524.2m**.

2.8 Facies 5 (F5): Lam-Scram Bioturbated Cross-Stratified Silty Sandstone

Sedimentologic Description: Sandstone beds within F5 consist of lower to upper fine-grained sand with low to moderate silt content (10-30%), and poor-to moderate-sorting throughout. F5 is observed in 13 cores (22%), and is commonly gradationally underlain by F4 and F6, and is gradationally overlain by F7. Additionally, F5 is also abruptly overlain by F6, with a sharp contact often observed. Grain-size increases upwards to more fine-grained sandstones. Physical sedimentary structures are often precluded by biogenic reworking; however, cross-stratification and oscillation ripples can be observed. In addition, rare wavy low-angle planar bedding and fluidization structures are sporadically distributed throughout this facies. Lithologic accessories consist of wispy organic laminae, small (millimetre) sized scattered organic clasts, thin discontinuous mudstone and siltstone beds, small <2 millimetre siderite pellets, and disseminated pyrite.

Ichnology: Bioturbation intensity within F5 is relatively variable (BI 3-5). Biogenic reworking is commonly observed disrupting physical sedimentary structures, making bedding surfaces difficult to distinguish (Fig. 10B). Trace fossils within this facies consist of: *Thalassinoides*, Cylindrichnus, *Rosselia*, *Planolites*, *Asterosoma* with subordinate *Skolithos*, *Diplocraterion*, *Lockeia*, *Palaeophycus*. Bioturbated intervals are observed in a series of episodic events, characteristic of "lam-scram" structures (sensu MacEachern and Pemberton, 1992) (Fig. 11). The trace fossils observed are most commonly associated with the proximal *Cruziana* Ichnofacies with some elements of the distal *Skolithos* or potentially the *Rosselia* Ichnofacies.

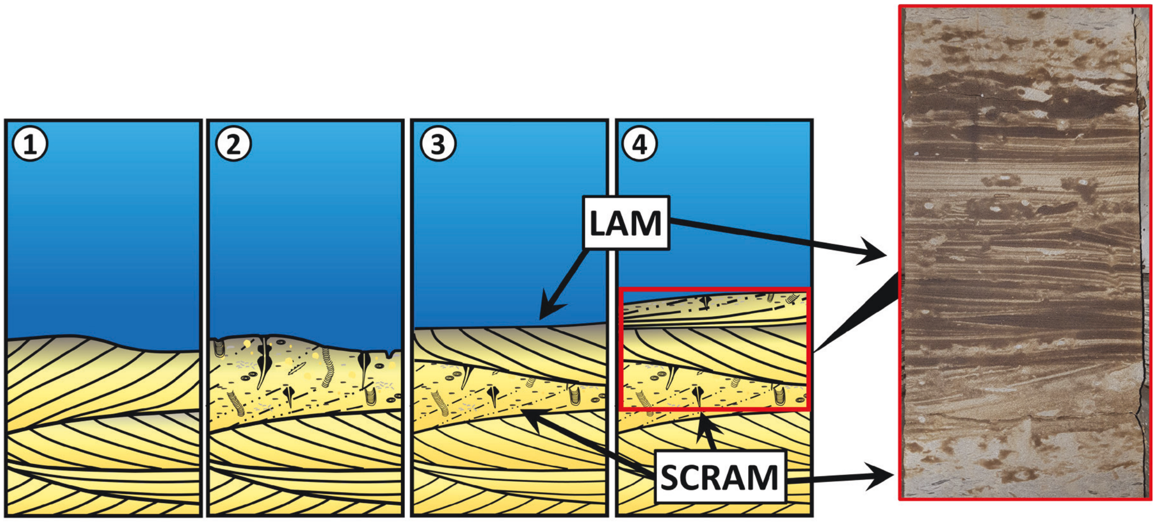


Figure 11. Time-lapse of a archetypal "lam-scram" cross-stratified sandstone characteristic of F5 where the uppermost interval is colonised by top-down bioturbation. The heavily bioturbated silt dominated upper sandstone is erosively scoured by a high energy event such as a tempestite, depositing cross-stratified sandstones. This is subsequently deposited by sandstones which fine-upwards as a result of waning energy, permitting more open colonisation windows and the re-establishment of the uppermost silt dominated beds. Core photo (right) is taken from **UWI 15-01-76-06W5, depth 664.80-664.96m.**

Interpretation: F5 is a sand-dominated and is intermixed with sporadic distributions of silt, mud, and organic matter. This facies subtly varies from F4, with the key difference being the coarser grain size and overall reduced silt/mud content in addition to the lack of robust trace fossils. Physical sedimentary structures are sporadically preserved due to significant degree of biogenic reworking, with observable trace fossils characteristic of the *Cruziana* Ichnofacies. Silt and mud content within this facies are minimal and commonly occur as linings of burrows such as Cylindrichnus and *Palaeophycus* traces. Physical sedimentary structures include oscillation ripples and wavy low-angle planar bedding are interpreted to represent deposition during fairweather conditions, with cross-stratified sandstones indicating rapid sedimentation (Howard and Frey, 1975; Kumar and Sanders, 1976). Organic material within this facies is predominately millimetre-sized clasts which indicate a more distal relationship to inferred sediment sources and is characteristic of a fully marine setting, where coarser organic material has been reworked and carried basinward during subsequent wave reworking and storm action with "wispy" organic laminae potentially displaying remnant Pischichnus or fish resting burrows. Due to the high degree of bioturbation characteristic of the *Cruziana* Ichnofacies, and episodic storm influence (tempestites), it is interpreted that deposition likely occurred within a wave-influenced, storm-affected shallow marine environment consistent with the proximal lower shoreface. This may also represent a distal delta front environment, however the abundance and diversity of ichnologic attributes within colonised intervals suggests open marine unstressed conditions during fairweather periods following rapid sedimentation events.

2.9 Facies 6 (F6): Hummocky Cross-Stratified Sandstone

Sedimentologic Description: F6 consists of upper very-fine to upper fine-grained sand within sandstone beds that increases in grain-size upwards and is rarely observed with minor amounts of mud or silt. F6 is observed in 25 cores (41%), and ranges in thickness between 20 centimetre to 4.5 metres. This facies sharply overlies F3a, F3b, F4, F5, and is commonly gradationally overlain by F5 and F7. Physical sedimentary structures consist predominantly of low-angle planar bedding (Fig. 10C), swaley cross-stratified (SCS), and hummocky cross-stratified (HCS) with more rarely observed planar cross-stratification, quasi planer laminations (QPL), oscillation ripples (Fig. 10D), low-angle climbing cross-laminations (Fig. 10D), and asymmetrical ripple cross-laminations, with very rarely observed soft sediment deformation and bi-directional current ripples. Lithologic accessories consist of phytodetrital laminae, organic rip-up clasts, small (<2 millimetre) siderite pellets, pebble lags, disseminated pyrite, and carbonate cemented laminae.

Ichnology: Trace fossils are very rarely observed within this facies. Escape traces (fugichnia) are the most commonly observed traces with subordinate *Planolites*, *Palaeophycus*, *Diplocraterion*, *Thalassinoides*, and *Macaronichnus* traces observed. Bioturbation intensity is low within this facies often between 0-1. Fuzzy laminae are interpreted to represent "Cryptic Bioturbation" which is complete biogenic reworking of the sandstones BI 6. The overall paucity in trace fossils makes the classification of an ichnofacies challenging, as elements of both the proximal *Cruziana* and *Skolithos* ichnofacies are observed.

Interpretation: F6 is sand-dominated with abundant low-angle planar bedding and very little evidence of biogenic reworking aside from recurrent escape structures suggestive of episodic high sedimentation rates (Bann and Fielding, 2004). The lack of observed bioturbation may also be related to storm activity actively scouring the bioturbated fair-weather events from the record, preserving only high-to-waning energy events (Herbers *et al.,* 2016). Low-angle and parallel-planar laminated beds, characteristic of wave reworking, are also sporadically capped by oscillatory bedding which is interpreted to represent the preservation of waning storm energy deposits during fairweather conditions (Kumar and Sanders, 1976; Brenchley *et al.,* 1993). In areas where this is absent, it is likely that erosional amalgamation cannibalizes the wave dominated oscillatory beds and displays a stacked amalgamation of storm deposits (Brenchley *et al.,* 1993; Pemberton *et al.,* 2012). The bedding observed within F6 displays high energy sedimentation events such as HCS and SCS, consistent with storm deposits (tempestites) (Leckie and Krystinik, 1989; Walker and Plint, 1992). This facies likely represents deposition within a storm-dominated, wave influenced shallow water setting consistent within the proximal lower shoreface to middle shoreface conditions (MacEachern and Pemberton, 1992; Brenchley *et al.,* 1993; Pemberton *et al.,* 2012). Preservation and stacking of subsequent storm events within the middle shoreface, that erosionally amalgamate and winnowed mud/silt toward deeper marine settings is inferred (Dashtgard *et al.,* 2012; Pemberton *et al.,* 2012). Sharp laminated beds are also seldom preserved, often a more "fuzzy" appearance of bedding persists which may be the result of biogenic homogenization through either a monospecific trace suite or potentially meiofaunal organisms/amphipods (Bromley, 1996; Howard and Frey, 1984; Gingras *et al.,* 2015). These conditions could also occur within a delta front environment, however distinguishing between the delta front and a storm-dominated strand plain is extremely challenging in storm-dominated conditions (Bhattacharya and Walker, 1991). Common sedimentologic attributes observed in F6 indicative of deltas include low-angle climbing cross-laminations which represent uni-directional flow and rapid sedimentation rates commonly observed on the delta-front (Ashley *et al.,* 1982); Additionally, organic rich pulses, woody material suggest the possibility of deltaic influence and proximity to deltaic environments (Moslow and Pemberton, 1988). It is interpreted that low-angle planar stratification associated with HCS and SCS likely represents middle shoreface conditions, while sharp-based, climbing cross-laminations and increased organic detrital material is likely associated with deltaic conditions making both depositional environments possible within F6.

2.10 Facies 7 (F7): Massive Structureless Sandstone

Sedimentologic Description: F7 is by far the most dominant facies observed within Clearwater core throughout the study region observed in 47 cores (78%). Massive-appearing sandstones range in thickness between 50 centimetre to over 10 metres and often appear as seemingly homogeneous intervals with little lithologic variability (Fig. 10E). Grain-size appears to be relatively consistent throughout sandstone intervals, but in general trends increasing upwards from fine to lower medium-grained. F7 is observed gradationally above F3b, F5, F6, and is abruptly overlain by F8 and F9. F7 consists of a very well sorted fine- to lower medium-grained sandstone with no observed mudstone or siltstone. Physical structures are rare, with massive appearing sandstones dominating the facies. Subordinate low-angle planar, wavy low-angle planar beds, and soft sediment deformation are very rarely observed. Massive appearing sandstones occasionally display faint evidence of remnant bedding termed “ghost-bedding” where faint bedding surfaces are observed in a predominantly homogenized appearing sandstone. Lithologic accessories consist of disseminated phytodetritus and pyrite. Organic rip-up clasts, rounded pebbles, berthierine cements, and siderite grains are rarely observed and often sporadically distributed throughout the massive sandstone.

Ichnology: Evidence of bioturbation is extremely challenging to identify within this facies due to the massive nature of the sandstone. Monospecific *Macaronichnus* trace suites can be observed sporadically throughout the facies (Fig. 10F), with subordinate examples of Cylindrichnus, *Harenaparietis*, *Macaronichnus*, *Teichichnus*, *Thalassinoides*, *Diplocraterion*, but these are very sparse and often not observed. This trace suite represents a combination of the *Skolithos* and *Rosselia* ichnofacies although it represents a low diversity expression of both. Cryptic bioturbation is inferred based on the significant thickness of this facies, which may be the result of monospecific trace fossil suites homogenizing the bedding or meiofauna reworking the sandstone (Pemberton *et al.,* 2008). BI is interpreted to be high (BI 6) due to the cryptic bioturbation with more robust traces mentioned above representing only a small fraction of the total biogenic activity. Additionally, cryptic bioturbation is a common attribute within amalgamated tempestite sands associated with the *Rosselia* ichnofacies (MacEachern and Bann, 2020).

Interpretation: Faintly observed low-angle planar bedding termed here as "ghost-bedding" are sporadically observed within the seemingly homogeneous massive sandstones (Fig. 10E). Sparsely distributed trace fossils associated with the *Skolithos* ichnofacies are observed but in extremely low abundance. Ghost bedding, although sporadic, demonstrates that the massive-appearing sandstones were not deposited initially as structureless sandstones commonly associated with rapid sedimentation events (Howard and Frey, 1975). It is more likely that the beds were deposited as a series of amalgamated events preserving HCS and SCS through storm action and wave reworking, which were subsequently altered by post- or syn-depositional biogenic processes (cryptic bioturbation) (Pemberton *et al.,* 2008; Pemberton *et al.,* 2012, Gingras *et al.,* 2015; MacEachern and Bann, 2020). Cryptic bioturbation can result in the complete reworking (BI 6) of a sandstone interval, however due to the reduced size of the organisms colonising the strata or an absence in lithologic variability, there can be little to no evidence that colonisation took place at all (Pemberton and Gingras, 2005; Pemberton *et al.,* 2008; Gingras *et al.,* 2015). This biogenic texture is often subtle and can be rapid, producing faint or fuzzy bedding contacts (ghost-bedding), with little to no disruption of underlying physical sedimentary structures, and as such can be easily overlooked (Gingras *et al.,* 2008; Pemberton *et al.,* 2008 Gingras *et al.,* 2015). This has been observed within Cretaceous sandstones in the past where Saunders et al. (1994) and Rouble and Walker (1997) observed "fuzzy burrowing" associated with cryptic or "crypto" bioturbation within hummocky and swaley cross-stratified sandstone units of storm-dominated shorefaces (Pemberton *et al.,* 2008). Rare thin monospecific *Macaronichnus* intervals likely indicate partial preservation of the upper shoreface (Moslow and Pemberton, 1988; Dafoe *et al.,* 2009). Other potential factors that can result in massive appearing intervals can be a lack of grain-size variability, high sedimentation rates, and soft sediment deformation events (Gingras *et al.,* 2015). While the first two are alternative theories for massive appearing sandstones, soft sediment deformation is not applicable to F7. The rare occurrence of lithological accessories such as organic rip-up clasts, rounded pebbles, and phytodetrital material, and medium grain-size preserve the possibility that deltaic influence and related rapid-sedimentation within this facies is not entirely absent (Bhattacharya and Walker, 1991). Based on the significant thickness of this massive sandstone facies, faint evidence of high and low-angle bedding, and low bioturbation, this facies most likely represents a series of amalgamated, cryptically bioturbated sandstones deposited within a proximal, storm-dominated, middle shoreface to upper shoreface environment. Additionally, structureless sands that lack ghost-bedding, and consist of truly massive sands with medium grain-size and rounded pebbles indicative of rapid sedimentation events indicate deltaic influence within an inferred delta-front environment.

2.11 Facies 8 (F8): Poorly-Sorted Matrix Supported Conglomerate and Breccias

Sedimentologic Description: F8 consists of an upper fine to lower medium grained sandstone matrix with sub-angular to sub-rounded mudstone clasts. F8 is observed in 23 cores (38%), and ranges in thickness between 5-80 centimetres. This facies commonly erosively overlies F7 and F10a, and is commonly gradationally overlain by F9 and F11, however it is also overlain more rarely by F6 and F7. Clast composition rarely deviates from being mud-dominated, however chert, siderite, and glauconite rich clasts have also been rarely observed. Clast sizes range from fine to upper-coarse pebbles, with variable color ranging from dark-grey to light-green and consist of massive muds with graded internal silt beds. This facies is considered to be poorly-sorted with variable clast sizes; however, clasts typically constitute 40-50% of the bulk lithology (Fig. 12A). The sandstone matrix generally exhibits a fining-upwards trend. Physical sedimentary structures are seldomly observed within this facies as the matrix sandstones are commonly massive, however slight grading and rare imbrication of clasts may be present. Lithological accessories are common within this facies and include organic rip-up clasts, shell fragments, massive mud beds, disseminated glauconite and glauconite rich clasts, and disseminated pyrite.

Ichnology: Ichnology within F8 is extremely scarce. Bioturbation is limited (BI 0-2) with rare *Planolites* and *Skolithos* traces observed within the sandstone matrix. The clasts within this facies are predominantly unbioturbated, consisting of massive to slightly bedded mudstone and siltstones however, several clasts displayed evidence of *Phycosiphon* and *Chondrites* trace fossils in monospecific suites. As clasts are inferred to be allochthonous, internal bioturbation within clasts is not representative of depositional setting, however it does provide evidence that clasts were likely sourced within a brackish marine setting given impoverished trace fossil suites.

Interpretation: The stratigraphic location of this facies is significant as it commonly overlies sandstone dominated facies F6 and F7 and is overlain by more marine associated facies F9 and F11. In addition, the sharp basal contact with underlying facies suggests erosive scouring, commonly observed in channels or transgressive lags. Organic rip-up clasts ranging from millimetre to centimetre in size are sporadically observed within this facies that indicate proximity to landward settings in some regions, while fossiliferous debris like shell fragments are also observed within this facies which support the interpretation of transgressive lag deposits (Kidwell, 1989). It is likely that the mudstone clasts are cannibalized remnants of a proximal setting like a lagoon or bay environment that were eroded away during marine transgression (Walker, 1995). The absence of diverse trace suites associated with the lower shoreface/offshore *Cruziana* Ichnofacies within the mudstone clasts indicates that it is unlikely these were derived from deeper marine settings and, as such, are more likely to have originated in a proximal setting (Pemberton *et al.,* 2012). Clast maturity also provides evidence that transport distance is relatively short as some large sub-angular to sub-rounded mudstone clasts were observed and would likely have been broken down and rounded with greater transport distances and likely eliminates channel deposits (Cattaneo and Steel, 2003). Some faint evidence of stratification can be related to wave or storm processes that persist throughout shoreline retreat (Walker, 1995). This facies has also been observed to occur in "pulses" where conglomeratic material is deposited in several events. This is likely the result of several pulses or smaller transgressional events taking place during the regional transgression (Swift *et al.,* 1991; Cattaneo and Steel, 2003). This facies likely represents a transgressive shoreface lag deposit, where landward settings such as lagoons or updip shoreface material are erosively scoured during transgression, resulting in a sharp based ravinement surface, concentrating coarser material along the shoreface, producing a lag deposit (Walker, 1995). Only one core (102-16-11-75-25W4) consists of a mudstone dominated conglomerate that is not subsequently overlain by immediate transgression, and may be the result of an anomalous high energy event such as an earthquake, however as it is only observed once, it is difficult to confirm.

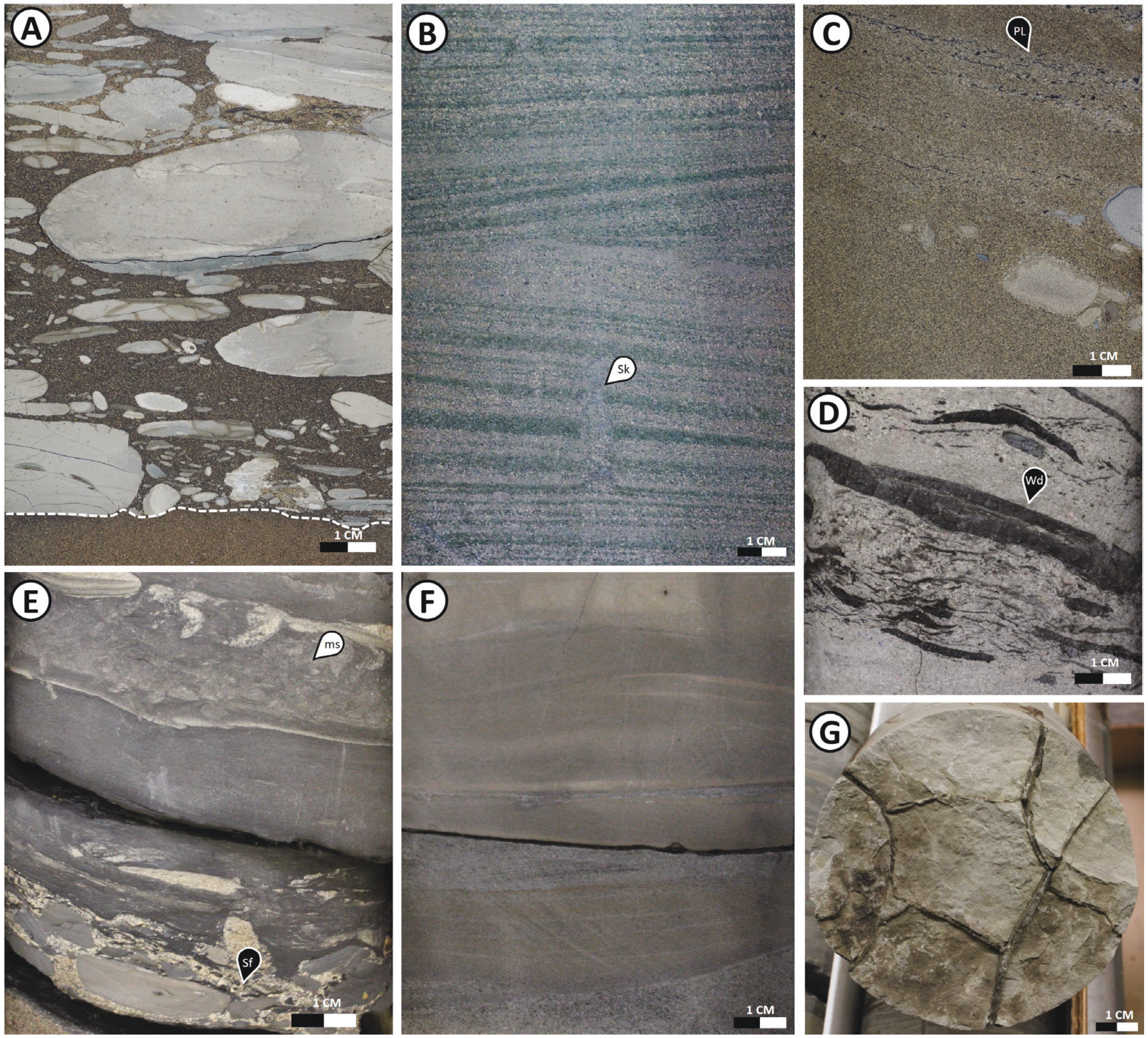


Figure 12. A) **F8:** Sharp-based lag deposit. Clasts are poorly sorted and elongate although not inferred to be imbricated. Composition consists of mudstone (unbioturbated). Organic detrital material is also observed. **UWI 10-35-74-25W4, depth 560.17m;** B) **F9:** Pine green glauconite with *Skolithos* traces. Glauconitic interval displays cross-laminations. **UWI 09-11-75-26W4, depth 694.0m**; C) **F10a:** Medium grained sand with apparent high-angle bedding surfaces. Rounded to sub-rounded chert and mudstone clasts in addition to finely disseminated organic material. **UWI 09-11-75-26W4, depth 699.16m;** D) **F10b**: Abundant poorly sorted organic debris including large wood clasts. **UWI 01-35-75-26W5, depth 761.93m;** E) **F11:** Massive mudstone underlain by a thin lag deposit with finely dispersed shell fragments. Upper mudstone interval contains thin beds of heavily bioturbated mantle & swirl fabric, and represents "doomed-pioneers". **UWI 13-26-75-26W4, depth 784.2m**; F) **F11**: Faint oscillatory bedding and inter-mudstone laminations observed unlike what is observed in figure E. Internal bedding structure is observed and bioturbation appears to be entirely absent. **UWI 15-01-73-25W4 depth 526.22m;** G) **F12:** Polygonal mudcracks or desiccation cracks observed in plan view. **UWI 10-07-77-04W5, depth 612.21m**.

2.12 Facies 9 (F9): Glauconitic Sandstone:

Sedimentologic Description: F9 consists of lower fine- to upper very fine-grained sandstone that y fines upwards and is observed in 15 cores (25%). F9 oftentimes abruptly overlies F7 and F8 and is commonly gradationally overlain by F2a, F2b, F3a. Facies thickness ranges from 10 to 80 centimetres. Lithology is variable, ranging from sandstone dominated to interbedded sandstone and siltstone to sandy mudstone. Physical sedimentary structures consist of low-angle planar bedding (Fig. 12B), oscillatory bedding, QPL, and interpreted HCS. Lithological accessories within this facies consist primarily of abundant pine green colored glauconite, with locally observed large (3-5 centimetre) wood clasts, phytodetrital laminae, siderite clasts, pyrite nodules, and glauconitic clasts.

Ichnology: The bioturbation within this facies is low to moderate (BI 1-3) with observable trace fossils consisting of *Skolithos*, *Phycosiphon*, *Chondrites*, *Asterosoma*, *Planolites*, *Thalassinoides*, *Diplocraterion*, *Teichichnus*. These traces are representative of the *Skolithos* Ichnofacies, however towards the seaward limit of the facies, as the mud content increases, the bioturbation becomes more characteristic of the proximal *Cruziana* Ichnofacies. In addition, passively filled, vertical, unlined burrows are associated with firm-ground conditions (i.e., the *Glossifungites* Ichnofacies), and are conspicuously filled with green sandstone.

Interpretation: This facies is distinguished by its pine green colour (Fig. 12B), which indicates a high concentration of the mineral glauconite (Odin and Matter, 1981). Glauconite-rich intervals are known to persist in marine environments with low sedimentation rates. Although several mechanisms of origin have been proposed, it is most commonly associated with fecal pellet (peloid) alteration (e.g., Van Houten and Purucker, 1984; Kapoutsos, 2005). These fecal pellets are believed to be the result of suspension or filter feeding organisms (commonly associated with the *Skolithos* Ichnofacies), concentrating clay and silt material in the form of fecal aggregates (Kapoutsos, 2005; Pemberton *et al.,* 2012). This facies is predominantly sharp-based and sometimes consists of vertical unlined burrows that penetrate inferred "firm-ground" facies and are passively infilled with glauconitic sand. These assemblages represent the *Glossifungites* Ichnofacies and are most often associated with erosional discontinuities such as transgressive surfaces of erosion (Pemberton and Frey, 1985; Pemberton and MacEachern, 1995; MacEachern *et al.,* 1992, Pemberton and Gingras, 2005). F9 is marked by an upwards increase in mud and deposit-feeding strategies, which is also suggestive of marine incursion. Given the sharp-based nature of the basal contact with underlying facies, and fining upwards trend of this facies, as well as the abundant glauconite and ichnologic evidence of a *Glossifungites* surface, this facies likely represents the early stages of a marine transgression

2.13 Facies 10a (F10a): Medium-Grained Cross-Stratified to Structureless Sandstone

Sedimentologic Description: F10a consists of medium-grained sandstone that fines upwards with variable degrees of sorting ranging from poorly to moderately well-sorted and is observed in 7 cores (12%). It is most commonly observed as sharply overlying F3b and F7 and can be sharply overlain by F6 or F8. F10a is commonly 1 to 5 metres in thickness. Organic debris and rounded pebble-sized clasts ranging in diameter from 3 millimetre to 3 centimetre accumulate along bedding surfaces (Fig. 12C). Physical sedimentary structures within F10a consists of a mixture of high-angle planar, low-angle planar, and planar parallel bedding, as well as interpreted fining upwards trough cross-bedding, and massive or structureless sandstones. In addition to this, convolute or soft sediment deformation, mud drapes and potential double mud drapes, have also been observed locally. Poorly sorted sub-angular to sub-rounded clasts are composed of mudstone and occasionally chert. Lithologic accessories consist of abundantly observed organic material such as wood debris and smaller phytodetrital material that is commonly deposited along bedding surfaces intermixed with rounded chert and mud clasts and occasionally shell fragments. Pyrite nodules, disseminated pyrite, and small 2-4 millimetre siderite grains are also common within this facies.

Ichnology: Bioturbation within this interval is low to absent (BI0-1). *Planolites* is rarely observed and is distributed sporadically throughout the facies.

Interpretation: The primary characteristic for this facies that differs from similarly described facies above (F7) is the medium grain size, presence of high-angle planar bedding, and general lack of bioturbation. Several facies previously discussed consist of structureless sandstones or cross-stratified sandstones, however they are typically dominated by fine grain sizes and usually associated with some form of bioturbation. The medium grain size suggests a higher energy environment and a closer proximity to the shoreline, where hydrodynamic processes control grain-size distributions (Liu and Zarillo, 1989; Pemberton *et al.,* 2012). Medium-grained sandstones are commonly restricted to the middle-upper shoreface and foreshore environments in marine-dominated systems (Liu and Zarillo, 1989; Pemberton *et al.,* 2012). Physical sedimentary structures such as high-angle planar, trough cross-bedding and massive fining upwards sandstones in addition to coarse organic material and sub-rounded to sub-angular clasts provide evidence for high energy (potentially uni-directional) environments, close to source (Olariu and Bhattacharya, 2006). Intervals where sub-angular clasts are abundant are likely suggestive of rapid emplacement. Lack of bioturbation in F10a is likely the result of physico-chemical stresses such as increased current velocity and turbidity, rapid sedimentation rates, or fluctuating salinities (Gingras *et al.,* 2011). Based on the evidence of a high-energy environment, and abundance of terrestrially-derived organic material, it is suggested that this facies represents a channel deposits, likely in a wave-dominated delta front environment.

2.14 Facies 10b (F10b): Organic Clast Dominated Sandstone:

Sedimentologic Description: F10b consists of abundant organic debris ranging in size from 3 millimetres to >7 centimetre in length and is found in 9 cores (15%). F10b is underlain by F6 and F7 and separated by a sharp basal contact. F10b is gradationally and sharply overlain by F7 and F10a. The organic material is poorly-sorted and ranges from 30-50% of the bulk lithology, with the remainder making up the upper fine- to lower medium-grained sandstone matrix and trace amounts of coal. Physical sedimentary structures within this facies consist of low- to high-angle planar bedding, massive organic rich sandstones and very rare wavy low-angle planar bedding. Lithologic accessories within this facies consist of wood clasts, phytodetrital laminae, and siderite clasts (millimetre scale), with less common pyrite nodules, rounded chert and angular to wispy mudstone clasts. Partial to complete post-depositional carbonate cementation is also sometimes observed within this facies.

Ichnology: The Ichnology within this facies is relatively scarce with a BI ranging between 0-1. Although trace abundance is quite low, several *Planolites* have been observed. In addition to *Planolites*, *Teredolites* have also been identified in some allochthonous wood clasts.

Interpretation: F10b is distinguished from F10a primarily by the abundance of organic material (Fig. 12D). Both the large size of the wooden clasts (some over 7 centimetre), and overall abundance of organic material within the sandstone matrix distinguish this facies from other sandstone dominated facies (such as F6, F7, F10a). The sharp-base and fine- to medium-grained sandstone infill with coarse organic debris observed at the base of this facies, likely suggests erosive scouring, commonly seen in channel systems (Nichols and Fisher, 2007). In addition to the erosive base, rapid deposition is suggested due to the structureless nature and occasionally observed high-angle cross-bedding which are likely a result of high-energy conditions observed in fluvial settings (Coleman *et al.,* 1964). Although *Teredolites* has been observed within the core, it is rare; the wood clasts are predominantly non-bored. The rare occurrence of coal also suggests that this facies was at least partially deposited on low-lying grounds with organic material being incorporated through flooding or storm-related deposition on a delta of floodplain environment (McCabe, 1984). The high energy nature of this facies given by the large clast size, in addition to the presence of high angle and structureless sandstones, combined with little to no ichnologic evidence, suggests that this facies was likely deposited under fluvial conditions (possibly that of a distributary channel thalweg). Distributary channels widened in a seaward direction, which decreases the overall velocity and transport ability of the channels (Coleman *et al.,* 1964). This allows coarser and heavier organic material to settle in proximal settings where it was more likely to be preserved due to the lack of high-energy wave-reworking more typical of delta-front or middle shoreface environments (Coleman *et al.,* 1964; Pemberton *et al.,* 2012).

2.15 Facies 11 (F11): Weakly Bioturbated Mudstone with Interbedded Sandstone

Sedimentologic Description: F11 is a subtle facies that is only observed within 16 cores (27%) and is commonly reserved to the upper limits of the cored intervals oftentimes being associated with transgression related facies (facies 8 and 9). Facies 11 consists of 2- to 5-centimetre-thick mudstone beds interbedded with fine- to medium-grained sandstone with minor silt content (Fig. 12E). The thickness of this facies is variable, with a maximum thickness of 30 centimetre. Mudstones are predominantly dark (suggesting high organic content) and structureless, but locally exhibit lenticular bedding. Additionally, clay rich tan-colored mudstone beds have been observed within this facies displaying either faint oscillatory bedding or structureless appearance, but these are far less common (Fig. 12F). Other physical sedimentary structures observed consist of flame structures, cone-in-cone structures, and rare soft-sediment deformation. Sandstone units are predominantly massive with faint low-angle bedding, incipient ripples, and lenticular bedding observed within several core. Lithologic accessories consist of phytodetrital laminae, wood clasts, pyrite nodules, and rip-up clasts (4 millimetre-3 centimetre in size). Rip-up clasts are often rounded and are always observed within sandstone beds. Several vertical fractures are also observed within the massive mudstone units that had been post-depositionally healed by calcite cementation.

Ichnology: Ichnology within this facies is quite variable but ranges between 0-3 BI. Observable trace fossils include *Phycosiphon*, *Skolithos*, *Teichichnus*, *Planolites*, *Chondrites* with subordinate examples of Cylindrichnus, *Diplocraterion* and *Arenicolites*. In addition, “mantle and swirl” biogenic structures are also identified within the facies (Fig. 12E). Bioturbation although seemingly diverse, commonly is displayed as monospecific suites and occurs in thin intervals, often overlain by unbioturbated intervals of the same lithology. Vertical traces such as *Skolithos* often cross-cut multiple beds and as such are likely the result of tiered bioturbation.

Interpretation: F11 consists of structureless to moderately bedded mudstone beds, with little evidence of bioturbation (BI 0-3) aside from the thin (centimetre-scale) colonisation intervals interpreted as "doomed-pioneers" (Föllmi and Grimm, 1990). The mudstone ranges from internally homogenous to weakly laminated, which likely is representative of variable sediment concentrations and overall flow velocity of the system (MacKay and Dalrymple, 2011). The nature of the mudstone (structureless to laminated) may be the result of dynamically deposited fluid mud layers associated with hyperpycnal and potentially collapsed Hypopycnal mud-plumes (Hovikoski *et al.,* 2008; Bhattacharya and MacEachern, 2009; MacKay and Dalrymple, 2011; Ranger pers comm). This is also reinforced by the presence of mantle and swirl textures, representative of bioturbation within intervals that contain high amounts of interstitial fluid, similar to fluid muds of Bhattacharya and MacEachern 2009. Bioturbation commonly occurs within the uppermost portion, and as such is inferred to represent opportunistic colonisation following the rapid deposition of the massive mudstone interval (Vossler and Pemberton, 1988; MacEachern and Pemberton, 1992). Other environmental stresses such as reduced oxygen (associated with organic-rich muds) may also be responsible for reduced ichnologic content (MacEachern *et al.,* 2005; Gingras *et al.,* 2011). The presence of rip-up clasts and entrained sediment, rich in organic material, is commonly associated with the basal portion of this facies and suggests that deposition is likely intrinsically related to high-energy events with proximity to terrestrial settings (Mulder and Syvitsky, 1996; Mulder *et al.,* 2003; MacEachern *et al.,* 2005). These fluid mud layers are inferred to be deposited in a relatively proximal setting due to the fine to medium grain size of sandstone interbeds, and likely is the result of storm-related wave action transporting fluid mud across the shelf (Bhattacharya and MacEachern, 2009). Preservation of this facies is only possible when delta-associated rapid sedimentation events subsequently cover the massive mudstone prior to biogenic reworking or cannibalization through wave and storm action in the middle to upper shoreface environments.

2.16 Facies 12: Clay-Rich Mudstone

Sedimentology: F12 consists of a combination of whitish-grey, clay-rich mudstone and interbedded silty mudstone and very fine-grained sandstones. This facies is extremely rare within the study region only being observed in 1 core, however it is significant. The facies is 60 centimetres thick and is observed sharply above and below facies 3b. Physical sedimentary structures include desiccation cracks, normally graded mud beds and rare lenticular bedding (Fig. 12G). Lithological accessories within this facies consist of phytodetrital laminae in addition to organic material, synaeresis cracks and siderite.

Ichnology: Bioturbation within this facies is confined to the mud- and silt-dominated lithologies, with trace fossils consisting of *Planolites*, *Asterosoma*, *Skolithos*, *Phycosiphon* and fugichnia. Clay-dominated mudstone consists of few observable trace fossils which are sporadically distributed in relatively low abundance (BI 1-3). Traces are representative of the *Skolithos* Ichnofacies.

Interpretation: F12, although rare, provides evidence of subaerial exposure within the Clearwater Formation. F12 is observed between two intervals of facies 3b and is approximately 60 centimetre in thickness. Indeed, the key distinguishing feature for this facies is the polygonal mud cracks observed on the bedding contacts, but more subtle characteristics such as heightened clay content, evidence of pedogenically altered siltstone, rooted beds, and a diminished trace fossil suite are also characteristic of this facies. Desiccation cracks are commonly associated with environments such as tidal flats, lacustrine shorelines, or potential fluvial floodplain environments (Plummer and Gostin, 1981). The presence of desiccation cracks in addition to roots and phytodetrital material indicate possible lake or overbank environments that are frequently subjected to subaerial exposure events that results in shrinkage of the exposed surface (Pontén and Plink-Björklund, 2007). Desiccation cracks may also be the result of storm deposits that are carried landward onto open-marine marshes with levee deposits subsequently subjected to subaerial exposure following storm abatement (Goodbred and Hine, 1995). Based on the evidence of subaerial exposure, combined with the high mud content, organic material, synaeresis cracks, and overall diminished/stressed ichnologic suite, it is suggested that the environment was potentially a tidally-influenced marsh or deltaic plain environment that was subjected to subaerial exposure.

Chapter 2B: Facies Associations, Descriptions, and Interpretations:

2.17 Facies Associations:

Within marginal-marine to shallow marine coastal environments, it has been widely recognized in both the modern and ancient rock record that depositional processes (wave, tidal, and fluvial influence) ultimately control the geometry and architecture of the shoreline (Howell *et al.,* 2008; Ainsworth *et al.,* 2011; Nyberg and Howell, 2016; Rossi *et al.,* 2017). Typically, these processes are dynamic, and can occur concomitantly with two or three environments coexisting simultaneously (Ainsworth *et al.,* 2008; Bhattacharya and Giosan, 2003; Yoshida *et al.,* 2007; Vakarelov and Ainsworth, 2013). Several studies have attempted to identify dominant processes by a series of methods such as sedimentary structure frequency, shoreline morphology, sediment accommodation to supply ratios, and ichnologic distribution (Raychaudhuri and Pemberton, 1992; Ainsworth *et al.,* 2008; Rossi *et al.,* 2017). Mixed-process systems are highly complex as dominant processes are subject to change both laterally along depositional strike and dip, as well as vertically throughout the rock record, often preserving significant heterogeneity over short spatial distances (Yoshida *et al.,* 2007; Ainsworth *et al.,* 2011). The wide range in observed sedimentary structures and ichnologic distribution as well as the overall large scope of the study region infers that marginal-marine environments in Marten Hills and Nipisi were likely subject to varying degrees of influence from all 3 depositional processes at one time or another. In addition to the depositional processes listed above, the impact of high-energy storm events have also been observed to influence facies distributions within shallow marine environments (Leckie and Walker, 1982).

Within the study region, four distinct facies associations have been identified (FA1-FA4) which are distinguished based upon the vertical recurrence of facies observed through core analysis (Table 2, Fig. 13, 14, 15). Facies associations are interpreted based on the common sedimentary structures and ichnologic distribution as well as grain size distribution throughout cored sections (Table 2). The facies associations include: FA1: Wave-dominated fairweather offshore to regressive shoreface (Fig. 13A); FA2: Storm-dominated, wave-influenced regressive shoreface (Fig. 13B); FA3: Wave-dominated, fluvial-influenced delta (Fig. 14); and FA4 Wave-dominated, transgressive shoreface (Fig. 13C). These facies associations are often observed in partial successions, with subsequent intervals cannibalizing the uppermost portions of underlying facies associations. This often leads to stacked intervals of repeating facies and is interpreted to represent small-scale fluctuations in sea level, delta-lobe avulsion, or transgression-related scouring. FA1 and FA2 are most frequently observed in the lower portions of the observed core, oftentimes alternating vertically through the rock record as storm influence varies. FA3 is commonly observed above FA2, with FA4 almost exclusively occurring at the top of the interval, erosively scouring underlying facies. The four facies associations that are observed likely record a wave-dominated shoreline that prograded from the SW to the NE during normal and forced regressions that subsequently were capped by marine transgression followed by the inundation of the Boreal Seaway.

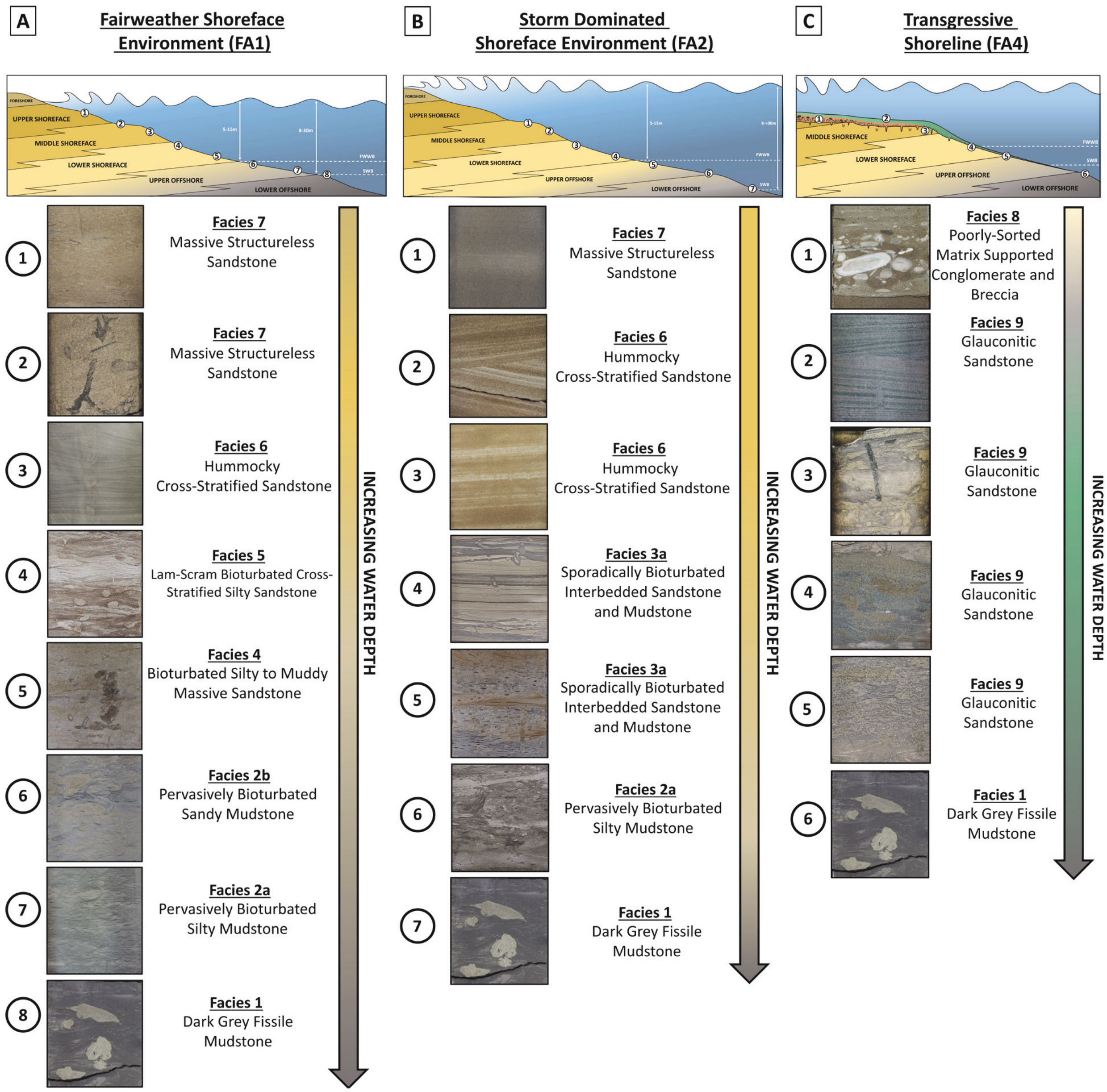


Figure 13. Dip oriented schematics of FA1, FA2, FA4, for shoreline depositional environments. Depth increases downwards (displayed by 3 vertical arrows, with the uppermost photographs representing the most proximal expression of each FA. Some core photos are representative of the same facies and are meant to display internal variability observed within facies (Eg under image C there are 4 examples of facies 9 to display the facies variability observed in sands that display abundant glauconite). FA1 typically demonstrates more intense degrees of bioturbation up into the middle shoreface at which point bioturbation becomes more scarce **(A)**. FA2 is heavily influenced by storms, which is most commonly displayed by interbedded facies within distal settings. Bioturbation decreases abruptly upwards where lower shoreface sands are less bioturbated than what is observed in FA1 **(B)**. FA4 is an example of a transgressive shoreline. The cartoon schematic demonstrates a sea level rise, which includes a transgressive lag and the abundance of glauconite, in addition to the *Glossifungites* Ichnofacies being observed in several core (indicative of a TST) **(C)**. Parameters for the shoreline schematic were modified after Walker and Plint 1992; and Evoy and Moslow, 1995.

	Marten Hills Member Facies Associations			
	Facies Association 1 (FA1)	Facies Association 2 (FA2)	Facies Association 3 (FA3)	Facies Association 4 (FA4)
Facies	1 2a 2b 3a 3b 4 5 6 7 8 9 10a 10b 11 12	1 2a 2b 3a 3b 4 5 6 7 8 9 10a 10b 11 12	1 2a 2b 3a 3b 4 5 6 7 8 9 10a 10b 11 12	1 2a 2b 3a 3b 4 5 6 7 8 9 10a 10b 11 12
Relative Facies Abundance				
Facies Association Abundance (in observed core)	60%	50%	45%	40%
Sedimentology and Lithologic Accessories	Symmetrical wave ripples, LAP, QPL, massive sandstones, rare phytodetrital laminae, millimetre scale siderite nodules	HCS and micro-HCS, abundant LAP, QPL, PPL, oscillatory bedding, wave ripples, cross laminations, phytodetrital laminae	Massive sandstones, soft sediment deformation, unbioturbated mud drapes, abundant organic debris and phytodetrital laminae, rounded chert clasts, desiccation cracks	Massive sands, LAP, QPL, oscillatory bedding, fluid mud, sub-angular to sub-rounded matrix supported rip-up clasts, pine-green glauconite
Dominant Depositional Process(es)	Waves during Fairweather Conditions	Storm currents and Waves	Waves, Rivers (feeder distributary channels)	Waves, rising sea-level
Ichnologic Attributes	Pervasive bioturbation common (BI 4-5), Robust trace fossils, archetypal *Cruziana* ichnofaces. Cryptic bioturbation is common in middle shoreface	Sporadic bioturbation representing frequent "Lam-Scram" intervals. Sand BI (0-2) Silt and mud BI (2-4), distal *Cruziana* to proximal *Skolithos*, opportunisitc colonisation	Sporadic bioturbation fluctuating between BI 1-4 in mudstone and BI 0-2 in sandstone. *Phycosiphon*, and *Rosselia* ichnofacies dominate FA3. Opportunistic colonisation present in sandstone dominated facies	*Glossifungites* and *Skolithos* ichnofacies, filter feeders provided fecal matter required for peloid alteration to glauconite. Bioturbation is mild to moderate (BI 1-3) increasing upwards into mud dominated facies where bioturbation is high (BI 4-5)
Regional Distribution	Commonly observed on the eastern and western flanks of the lower MRTN C sandbody (C1,C2), also commonly observed in the MRTN B interval	Located throughout entire study region, present in MRTN A,B,C,D cored intervals	Located predominantly in the central portions of the study region, commonly erosively overlies FA2 in the upper MRTN C interval. Also observed in MRTN D	This facies is sporadically distributed throughout the study region, only observed in the uppermost MRTN C intervals prior to deposition of MRTN D
Distinguishing Features	Distinguished by robust trace fossils, patchy carbonate cementation, high degree of bioturbation due to prolonged colonisation windows	Distinguished by fluctuating periods of colonisation, and high energy rapid sedimentation events. Tempestites increase in abundance upwards	Distinguished by mild to moderately stressed ichnologic suites combined with evidence of rapid sedimentation (massive sands, soft sediment deformation)	Distinguished by pine-green glauconite in addition to episodic pulses of matrix supported conglomerates and breccias, with less common fluid mudstone deposits. *Glossifungites* surface indicative of transgression
Depositional Environment	**Wave-Dominated Fairweather Regressive Shoreface to Offshore Environment**	**Storm-Dominated Regressive Shoreface to Upper Offshore**	**Wave Dominated Delta**	**Wave Dominated Transgressive Shoreface**

Facies Recurrence

Not Observed	Low	Moderate	Common

Table 2. Display of the key attributes that comprise each interpreted FA in addition to the distribution within MRTN subunits. The abundance of facies within each facies association is color coordinated based on recurring abundance. The depositional environment row represents the overall interpretted setting and does not include the local depositional sub-environment complexities which are discussed in greater detail within Table 1 and Chapter 2A.

2.18 Facies Association 1: Wave-Dominated Fairweather Regressive Shoreface to Offshore (Offshore to Middle Shoreface) – (Figure 13A)

Facies Association 1 (FA1) is widely distributed, having been observed in over 60% of all logged cores throughout the study region. FA1 is predominantly observed on the eastern and western flanks throughout the study region, however it can also be observed within the lowermost components of several central core in the Marten Hills Region (Fig. 16). Within FA1, F1 is found across the region as it represents a maximum flooding surface referred to as the Wabiskaw Marker (Fig. 4). FA1 is almost exclusively confined to the lowermost portions of cored intervals and is interpreted to represent lower offshore through middle shoreface deposition in a low-energy environment during fairweather conditions. Additionally, very fine-grained sandstones within the lower shoreface commonly display partial "patchy" carbonate cementation of F4, which is almost exclusively observed within this facies association. FA1 consists of F1, F2a, F2b, 3a (rare), F4, F5, F6, F7 and is commonly associated with a cleaning/coarsening upward succession that may be truncated abruptly by FA2 and FA3. The lowermost interval within FA1 consist of a single gradational transition upwards from mud-dominated offshore (F1 and F2a) to proximal offshore (F2b) (Fig. 5-7). This is commonly followed by 1 to 3 cycles of coarsening upwards trends moving from a fairweather lower shoreface (F4 and F5) to a middle shoreface succession (F6 and F7) above the fairweather wave base (FWB). Wave processes appear to dominate deposition within FA1, with little evidence of storm preservation seaward of the middle shoreface due to biogenic reworking. Evidence of fluvial or tidal processes is absent. Physical sedimentary structures are seldom preserved throughout much of FA1 due to the high degrees of biogenic reworking associated with ambient marine environments (Gingras *et al.,* 2011). Symmetrical wave ripples combined with the rare occurrence of LAP and QPL bedding however, suggests that low energy conditions dominate FA1 within sandstone-dominated facies of the lower and middle shorefaces (F4, F5, F6). Within facies associated with offshore deposition (F1, F2a, F2b), sedimentary structures are rare to absent due to the high degree of biogenic reworking with evidence of storm deposition (tempestites) rarely observed. In addition to sedimentary structures, lithologic accessories such as rarely observed phytodetrital laminae and small (several millimetres in scale) siderite nodules provide evidence of a distal relationship to paleoshoreline, however both are commonly obscured by the impact of intense biogenic reworking.

The ichnologic characteristics of FA1 is a key distinguishing criterion for FA1 and FA2, as the fairweather conditions observed in FA1 permit open colonisation windows, which result in highly bioturbated intervals.

Bioturbation within the mud-dominated facies (F1,F2a,F2b) is often high (BI 4-5) and is homogeneously distributed throughout much of FA1, which is dominated by deposit-feeding and grazing structures attributable to the *Cruziana* Ichnofacies. Physical sedimentary structures are often precluded by the high degrees of bioturbation and trace fossil suites are characteristic of normal marine conditions with diverse and abundant trace fossils such as *Asterosoma*, *Chondrites*, *Cosmorhaphe*, *Helminthopsis*, *Phycosiphon*, *Schaubcylindrichnus freyi*, *Scolicia*, *Teichichnus*, and *Zoophycos*. Within the distal lower shoreface (F4), robust trace fossils such as Cylindrichnus, *Rosselia*, and *Ophiomorpha* are observed in several cores, indicative of ambient fully marine conditions (Gingras *et al.,* 2011). Massive appearing sands within this distal lower shoreface facies may also be the result of meiofaunal “cryptic bioturbation” that homogenizes the interval, which is subsequently overprinted by the robust traces discussed above. The presence of silt and mud lined traces and overall high degree of bioturbation (BI 3-5) within the distal-proximal lower shoreface (F4, F5 respectively) and lack of LAP bedding, further suggests that storms were likely infrequent, permitting abundant biogenic reworking. Sporadic *Diplocraterion* and *Thalassinoides* traces within the middle shoreface of FA1 are rarely observed but provide additional evidence that colonisation windows were still open even in higher energy conditions characteristic of the middle shoreface.

Due to the increased presence of mudstone and siltstone, in addition to robust mud-lined trace fossils and partial calcite cementation of sandstones (F4), the wireline log signature within this facies is often classified as irregular. Cleaning upwards profiles are exhibited, however reservoir quality within FA1 is interpreted as moderate to poor. Additionally, the stratigraphic position of FA1 at the base of most Marten Hills Members intervals, might suggest the possibility that this Facies Association is actually genetically different than the subsequently deposited FA2-FA4, and as such represents a separate depositional setting, where wave action is reduced, and robust colonization windows persisted.

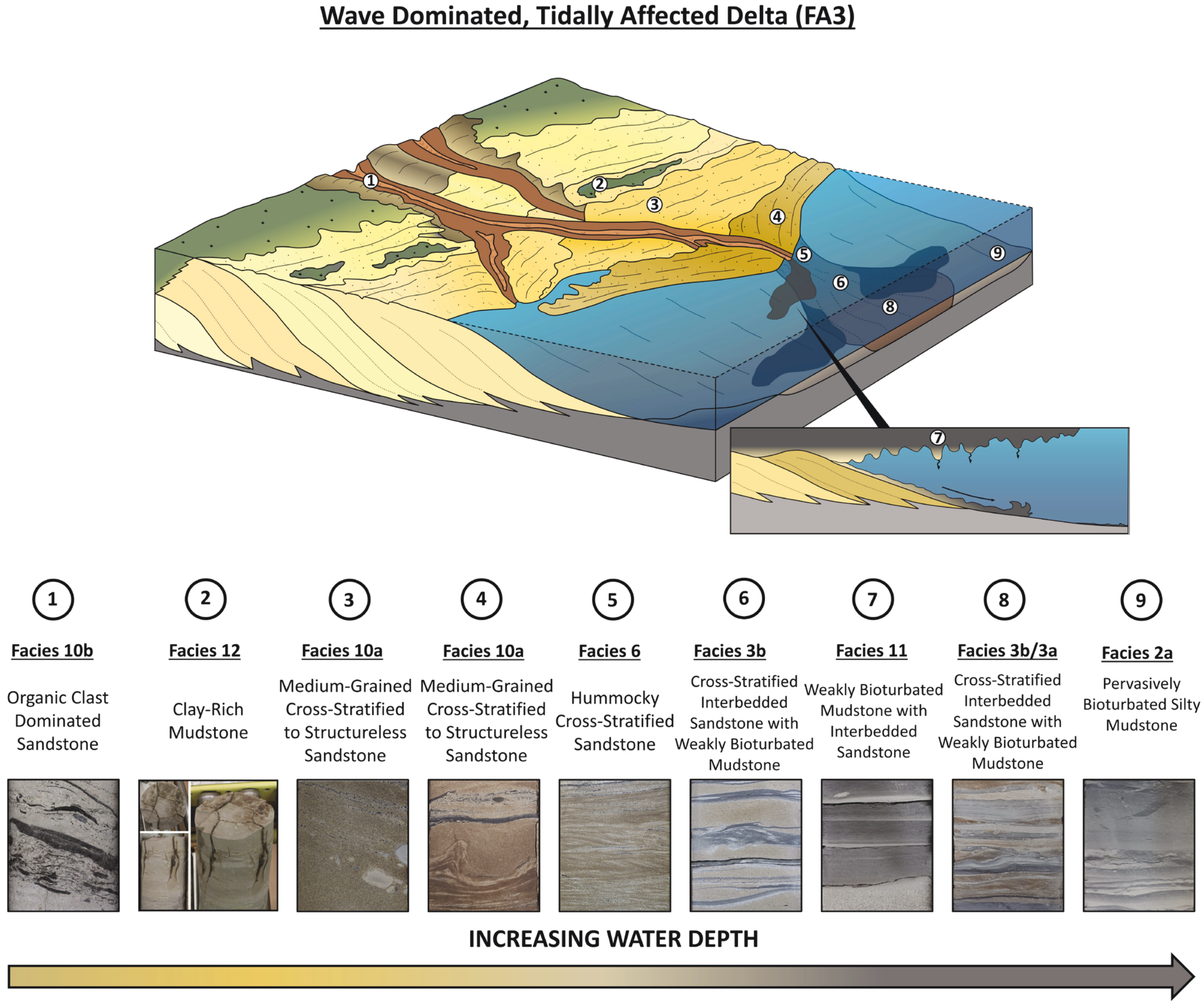


Figure 14. Cartoon schematic of a wave dominated delta environment modelled after Weise, 1980: This schematic is an inferred representation of deltaic conditions present within the Marten member. Facies range from proximal distributary channel associated facies (F10b) to the distal prodelta/storm dominated lower shoreface facies of 3b and 2a. Image 9 is selected to show that increased lateral distance from deltaic feeder channels display a more "shoreface-like" representation of sedimentologic and ichnologic attributes. Facies 11 can be observed above several facies and its location in this schematic is not a direct indication of where it will always be observed within FA3. These attributes are often intermixed with FA2 making distinguishing between FA2 and FA3 sometimes challenging. Note: synaeresis cracks are also rarely observed throughout this FA, however fluid muds and potential tidal doublets indicate that tidal presence were potentially also present. Hypopycnal plume and hyperpycnal flow cartoon (7) is modelled after Bhattacharya and MacEachern 2009.

2.19 Facies Association 2: Storm-Dominated Regressive Shoreface to Upper Offshore (Proximal Offshore to Middle/Upper Shoreface) – (Figure 13B)

Facies Association 2 (FA2) is observed in over 50% of all logged core. In addition to its occurrence on the eastern and western flanks of the study region where it overlies FA1, FA2 is also present in greater abundance within the centrally located cored intervals (Fig. 16). FA2 is interpreted to represent deposition in an environment where tempestites punctuate fairweather conditions and increase in abundance vertically through the succession record as storm and wave influence increases. This high energy episodic deposition within FA2 commonly abruptly truncates the quiescent FA1. Several facies that are observed in the offshore realm of FA1 are also observed in FA2 (F2a and F2b), however there is a subtle increase in storm deposits that consist of unbioturbated micro HCS beds (centimetre scale) which indicates increasing storm influence (Leckie and Walker, 1982; Cheel and Leckie, 1993). Facies 3a and 3b, which consist of interbedded sandstone and mudstone preserving both fairweather and storm deposits that cleans upwards, also occurs in FA3, as distal pro-deltaic deposits are similar to those seen in a storm influenced distal lower shoreface environment. Sand content increases vertically, with a logical conclusion being that the increasing sand and diminishing mud content in this interbedded facies is the result of a shallower position along the storm-influenced lower shoreface. Additional facies include F6 and F7 characteristic of the middle shoreface. Unlike FA1, bioturbation is rarely observed within these facies, as wave reworking and high-energy events dominate the rock record. Like FA1, FA2 displays a cleaning/coarsening upward succession that transitions from very fine-grained sandstone interbedded with siltstone and mudstone to upper fine- and medium-grained sandstone indicative of shallower settings of the middle shoreface. Physical sedimentary structures observed within FA2 are often consistent with storm deposits (tempestites) and high degrees of wave reworking which include frequently observed LAP, QPL, PPL, oscillatory bedding, wave ripples and cross laminations. These physical sedimentary structures are often interbedded with bioturbated mudstones in the distal lower shoreface and offshore related facies and are interpreted to represent fairweather conditions between storm events. Lithologic accessories are also more readily observed in FA2 when compared with FA1, consisting of abundant phytodetrital laminae, siderite clasts, wispy organic debris, and organic rip up clasts. These accessories are likely the result of high-energy events mobilizing coarser organic material associated with freshets into the deeper-marine environments such as the distal lower shoreface facies (3a).

The Ichnologic characteristics of FA2 are distinct from FA1 in that bioturbation is confined to mudstone and siltstone-dominated facies of FA2 (F2a, F3a) and is mostly absent from the proximal lower to middle shoreface facies (F6, F7). Bioturbation within mudstone intervals is commonly moderate (BI 2-4) with sandstone intervals displaying a paucity in biogenic reworking (BI 0-2). Within the mudstone units, diverse trace suites displaying feeding and dwelling strategies consistent with that of the *Cruziana* and distal *Skolithos* ichnofacies are observed. In addition, opportunistic colonisation of some thinner mudstone events that cap tempestite sandstones are also observed (commonly *Phycosiphon* and *Chondrites*). The ichnologic assemblage consists predominantly of *Asterosoma*, *Chondrites*, *Cosmorhaphe*, Cylindrichnus, *Planolites*, *Phycosiphon*, *Thalassinoides*, *Scolicia*, and *Zoophycos*, with subordinate occurrences of *Arenicolites*, Cylindrichnus, *Helminthopsis*, *Lockeia*, *Palaeophycus*, *Rosselia*, *Teichichnus*, *Schaubcylindrichnus freyi*, and *Skolithos*. Sandstone beds also contain escape traces (fugichnia), which provides further evidence of rapidly deposited sediments characteristic of tempestite deposits. The proximal facies (F6 and F7) display little to no evidence of bioturbation, commonly preserving thick (7-10 metre) wave-reworked sandstone units. One of the most challenging interpretations arises in intervals of FA2 where bedding contacts appear fuzzy, or where massive-appearing sandstone units persist throughout the majority of the core. This potentially is the result of cryptic bioturbation, where meiofaunal reworking has cryptically altered the sandstone interval making it appear barren of physical or biogenic sedimentary structures. In these cases, bioturbation intensity may conversely be extremely high (BI6).

The increase in prevalence of high energy tempestites that deposit coarser material in deeper waters is represented on wireline logs by a cleaner gamma ray signature, however the interbedded nature of basal facies within FA2 is expressed as an irregular log response as is seen in FA1. This changes vertically, as increased wave reworking throughout FA2 provides a consistent grain size and sandstone dominated lithologies. Additionally, cryptic bioturbation is inferred throughout FA2, which homogenizes the sandstones providing a very clean, porous, and continuous log response. FA2 is interpreted to represent the optimal reservoir facies association throughout the region.

Several cored intervals of FA2 contain abrupt facies dislocations in the form of sharp-based shorefaces, characteristic of a forced regression, where interpreted middle shoreface sandstone units (F6, F7), truncate facies associated with the lower offshore (F2a). This sharp-based shoreface commonly overlies the marine dominated facies of FA1. Additionally, facies dislocations display alternating expressions of FA2 and FA3 leading to complex and unpredictable alternating successions, however the most common stacking pattern is for FA3 to erosively overlie FA2. Both FA2 and FA3 are interpreted to be genetically related, with

FA2 representing deposition in environments that are restricted from fluvial sources (Fig. 15A). This absence of fluvial influence subjects the shoreline to increased wave and storm action, which is represented by the dominant preservation of tempestites within FA2. The increased amount of phytodetrital material within tempestite sands does however indicate that fluvial settings were present throughout deposition of FA2, however wave reworking has winnowed organic material into finely distributed organic laminae within high energy tempestite beds. Additionally, in cored intervals where FA3 is absent, FA4 has also been observed as erosively truncating the upper portions of FA2.

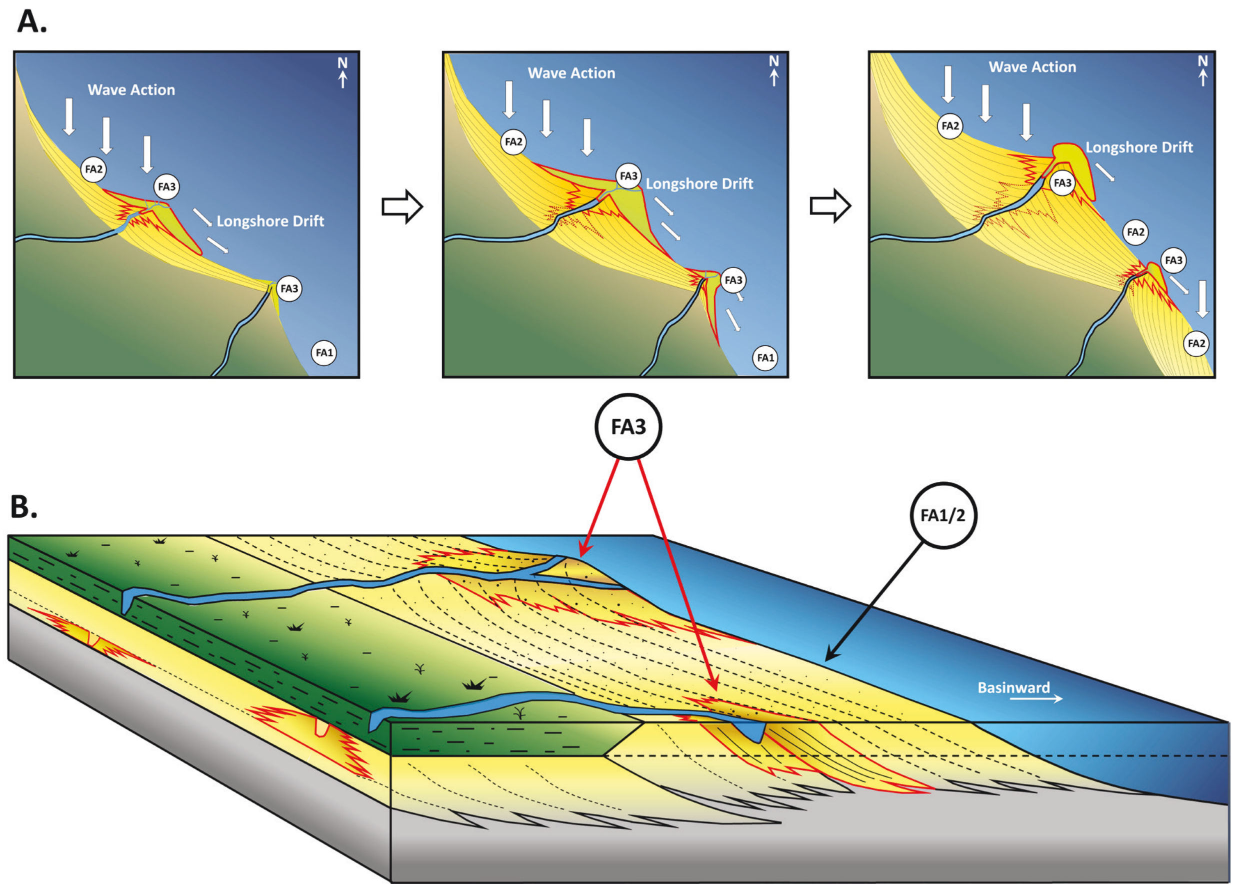


Figure 15. Figure 15A represents the progradational transition of a wave influenced shoreline over time. THis demonstrates the combined influence of fluvially sourced deltaic environments (red) and wave (or storm) dominated shoreface environments. FA3 is associated with deltaic environments and as such is represented on the schematics in a red outline illustrating an approximation of regions that would preserve the greatest evidence of deltaic systems. In figure 15A, maroon outlines were utilized to display remnant deltaic deposits that would potentially be preserved even after a new deltaic lobe has formed or the delta progrades. Laterally, as deltaic channels avulse or the sediment supply diminishes, wave and storm dominated processes take over resulting in more typical shoreface deposits (FA2). FA1 is interpreted to either persist in regions where wave, storm, fluvial influence is minimal (i.e. due to shoreline protection, or a different depositional setting altogether). As the shoreline builds out (left to right), the strandplain builds basinward (to the NE on the 15A schematics with wave influence and geostrophic currents modifying the paleoshoreline through longshore drift. Figure 15B demonstrates the lateral continuum that exists on a wave influenced shoreline where deltaic environments are present proximal to a fluvial source. However, as distance from fluvial channels increases, the preservation of wave and storm dominated processes increases. As a result, remodification of deltaic deposits occurs. Image 15B is modified aftert Eide *et al.,* 2014.

2.20 Facies Association 3: Wave Dominated Delta – (Figure 14)

Facies Association 3 (FA3) is found within 45% of all logged core and is often observed within the central portions of the study area and is absent on both the eastern and westernmost areas (Fig. 16). Deposition within FA3 is interpreted to represent a wave-dominated delta system that often coalesces with fairweather and storm-dominated shoreface environments observed within FA1 and FA2 respectively. FA3 erosively overlies storm-dominated shoreface deposits of FA2 and is commonly erosively overlain by FA4. FA3 consists of facies 3a, 3b, 5, 6, 7, 10a, 10b, 11, 12, and is characteristically interpreted as a cleaning/coarsening upwards profile in both core and wireline log signatures. The coarsening upward profile is often associated with a transition from upper fine- to medium-grained sandstones. In several cores, facies dislocations are observed where facies characteristic of FA3 are gradationally overlain by additional cycles of FA2 making for unpredictable and complex stacking patterns. This is likely the result of distributary channel avulsion, allowing wave processes of the middle and lower shoreface to rework inactive deltaic deposits and display facies associations more characteristic of FA2. The preferential preservation of FA3 in the uppermost portions of cored intervals suggests that wave processes likely were unable to sufficiently rework the deltaic deposits prior to marine transgression associated with FA4. The main challenge arises when differentiating between storm-dominated shorefaces and wave-dominated deltas, particularly the subaqueous delta front, as sedimentologic signatures are virtually indistinguishable due to the strong impact that wave and storm actions have on preservation (MacEachern and Pemberton, 1992). There are, however, several key indicators noted in FA3 which aid in the interpretation of a wave-dominated delta based on sedimentologic deviations from FA2. Physical sedimentary structures such as unbioturbated mud drapes and double mud drapes found in wavy to massive-appearing sandstone units (F10a) are more likely to be the result of deltaic environments such as the distal delta front, as wave action within the middle shoreface leads to the winnowing of muds which are subsequently redistributed basinward towards the lower shoreface (Fig. 8). This is also observed in Facies 11, where thick structureless mudstone blankets medium-grained sandstone interpreted to represent fluid muds or hyperpycnal mud plumes when internal bedding is observed. Additionally, evidence of high-energy environments with sharp (erosive) bases are observed that comprise abundant coarse organic material, rounded clasts, and low-angle climbing ripple cross-laminations (F10b and F6, respectively), which more appropriately represent distributary channels and delta front environments. Further evidence is provided by desiccation cracks (F12, Fig. 12G), which provide substantial evidence of subaerial exposure, something that is commonly observed within a tidally-influenced marsh or delta plain environment. Although rare, soft sediment deformation has also been observed, a feature indicative of rapid sedimentation and dewatering events commonly observed in deltaic environments (Carmona *et al.,* 2009). A less conclusive deltaic feature of FA3, is observed in Facies 10a, where high-angle planar (HAP), parallel-planar lamination (PPL), and LAP bedding is associated with rounded clasts and medium-grained unbioturbated sandstone that potentially represents deposition within a delta plain or distal distributary channel system. In addition to the physical sedimentary structures listed above, lithological accessories also provide evidence of deltaic environments through the presence of abundant phytodetrital pulses, wood clasts and synaeresis cracks.

The Ichnologic signature of FA3 is widely variable given the impact that fluctuating wave processes have on deltaic systems. Prodeltaic facies (3b) are of particular importance as they represent a deviation from standard fairweather shoreface conditions. The interbedded facies is variable with regards to bioturbation intensity but is commonly low to moderate (BI 1-4) within the mud-dominated beds, and low (BI 0-2) in sand-dominated beds representative of episodic sedimentation events. Mudstone beds are often weakly bioturbated, which is an interpreted product of enhanced deltaically related fluvial discharge, which can rapidly deposit muds, leading to impoverished trace suites indicative of environmental stresses (Gingras *et al.,* 2011). The common ichnofacies associated with shoreface environments (*Cruziana* and *Skolithos*) are difficult to apply within much of FA3 given the frequent opportunistic colonisation and cryptic bioturbation. A better representation of ichnofacies for FA3 is inferred based on MacEachern and Bann 2020's *Phycosiphon* and *Rosselia* ichnofacies, which are the deltaic variations of the *Cruziana* and *Skolithos* Ichnofacies (respectively). The ichnologic assemblage most commonly observed throughout FA3 represents *Phycosiphon* and *Rosselia* ichnofacies and consists of abundant *Asterosoma*, *Chondrites*, *Cosmorhaphe*, fugichnia, *Helminthopsis*, *Palaeophycus*, *Phycosiphon*, *Planolites*, *Schaubcylindrichnus freyi*, *Thalassinoides*, and *Zoophycos*, with rarely observed *Arenicolites*, Cylindrichnus, *Harenaparietis*, *Helminthopsis*, *Lockeia*, *Rosselia*, *Scolicia*, *Skolithos*, and *Teichichnus* traces. Deposit feeding is the predominant ethology, with suspension feeding and grazing traces are also observed in significantly lower abundance. Opportunistic colonisation of thinner normally graded silty to organic rich mudstone characteristic of a prodelta and distal delta front (F3b and 11) are commonly observed, often characterized by monospecific trace suites of *Phycosiphon* and *Chondrites* traces. Bioturbation intensity within facies associated with more proximal deltaic settings (F10a-12) are significantly reduced given the environmental stresses, and a reduced expression of the *Skolithos* ichnofacies is also observed as a result of the inability for filter feeding associated with deltaic environments (Gingras *et al.,* 2011). In particular, facies 10a and 10b are characterized by extremely low degrees of bioturbation (BI 0-1), and when combined with the physical sedimentary structures discussed above and high organic content, it demonstrates that high-energy conditions were likely inhospitable for biogenic reworking. This is interpreted to represent the presence of fluvial and distributary channels within the depositional setting.

FA3 is a challenging facies association given its similarities to FA2 and dislocated facies associations. The evidence of fluvial feeder systems and subaerial exposure within the study area, in addition to physical and biogenic sedimentary structures commonly associated with deltaic settings, help infer that deltaic processes play a role within the Clearwater Formation in Marten Hills and Nipisi. Figure 8 is one of the most representative core throughout the study region that demonstrate deltaic influence within the study region and is a full vertical succession of the facies that comprise FA3. The high amounts of organic content observed throughout FA2 and FA3 is therefore explained by it being sourced from the terrestrial realm, and although wave reworking can winnow much of this into smaller phytodetrital beds, coarser (centimetre scale) organic debris likely indicates direct or closer proximity to fluvially-related environments. It is interpreted that within the study region, deposition of FA2 and FA3 was likely penecontemporaneous, with increasing preservation of FA3 suggesting more proximal deposition with respect to fluvial systems feeding the inferred wave dominated delta (Fig. 15B). Given the coarser grain-size (upper fine- to medium-grained), FA3 represents moderate to high reservoir quality, however given its often unpredictable occurrence (as a result of delta lobe avulsion), making correlative interpretations is challenging when core control is poor.

2.21 Facies Association 4: Wave dominated Transgressive Shoreface – (Figure 13C)

Facies Association 4 (FA4) is observed within 40% of all logged core and is predominantly seen in the eastern half of the study region where core control is most dense (Fig. 16). FA4 is interpreted to represent a transgressive shoreface that includes a transgressive lag. Due to the erosive nature of transgressional environments, FA4 is invariably sharp based with both FA2 and FA3 being observed directly beneath FA4. Unlike the other Facies Associations described (FA1,FA2,FA3), FA4 is characterized by a fining upwards trend that transitions from medium- and fine-grained sandstone into bioturbated marine-dominated mudstone. This is commonly associated with a “dirtying upward” log profile, given the increase in mud content upwards and is associated with a reduction in core and log derived porosities. Oftentimes, several small-scale “pulses” or cycles of transgression are inferred from intervals of mud-dominated rip-up clasts (F8), which are interpreted as cannibalized remnants of the foreshore and upper shoreface as well as lagoonal deposits (Fig. 6). Several facies are observed within FA4 that have been identified in previously discussed facies associations (F6, F7, F11) however two facies that are observed solely in FA4 are F8 and F9. Physical sedimentary structures identified within FA4 consist of massive sands, LAP, QPL, and oscillatory bedding in addition to structureless mudstone deposits. Structureless mudstones may be the result of transgression, converting distributary channel mouths into tidally-modulated estuaries where the preservation of fluid muds is favourable (e.g. Mackay and Dalrymple, 2011), however additional evidence of tidal processes is rare to absent. Much of these sedimentary structures are observed throughout FA1-3 however within FA4, lithological accessories provide evidence that separate it from the formerly discussed facies associations. Two main lithological accessories provide evidence for marine transgression: 1) concentrations of rounded to sub-angular, matrix-supported rip-up clasts consisting predominantly of unbioturbated mudstone (F8); and 2) the abundant presence of the pine-green mineral glauconite (F9). Facies 8 underlies Facies 9 and consists of a matrix-supported conglomerate where large (2-7 centimetre) clasts are mud dominated, weakly bioturbated, and sub-rounded to rounded. This suggests deposition of a transgressive lag, where erosion has cannibalized landward settings such as lagoons or coarser up-dip material and were not subjected to large transport distances. Above Facies 8, several facies (F6, F7, F11) are observed and likely represent wave processes during transgressional hiatuses. The presence of abundant glauconite, as is observed in Facies 9, has long been associated with marine transgression. The formation of glauconite is interpreted as a result of fecal pellet alteration in environments dominated by low sedimentation rates (Van Houten and Purucker, 1984; Kapoutsos, 2005). Glauconitic sands are observed both within sand-dominated intervals as well as pervasively bioturbated sandy mudstone units and can be observed with LAP sandstone. In several cores, glauconitic clasts are also observed in the form of thin lag deposits. In addition to the lithological accessories discussed above, organic material, shell fragments, and pyrite nodules are also observed within FA4, which are likely the product of transgressional erosion of proximal up-dip settings. Based on the sedimentary structures and lithological accessories listed above, it is interpreted that several transgressional events occurred, resulting in erosion of the paleoshoreline. This resulted in a ravinement surface, which deposited coarser material in the form of transgressional lags that were subsequently subject to wave reworking and decreased sedimentation rates prior to the inundation of the Boreal Seaway and a return to deeper marine conditions.

The Ichnologic signature of FA4 is comparable to that observed in FA1 within the upper marine-dominated intervals associated with advanced marine transgression. Above the erosive contact associated with transgressive lags, allochthonous mudstone clasts consist of unbioturbated to impoverished trace suites (consisting of monospecific *Phycosiphon*, *Chondrites*) suggestive of stressed marginal marine environments. These conditions may have been present within lagoonal or tidally-influenced environments up-dip, as transgression began to envelop the progradational shoreline, however cored evidence of these environments is absent. Glauconite-rich sands are observed within pervasively bioturbated sandy mudstones with moderate bioturbation intensities (BI 1-3). Trace fossils predominantly represent the *Skolithos* ichnofacies, with filter feeding organisms likely sourcing the fecal matter needed for peloidal glauconite alteration (Kapoutsos, 2005; Pemberton *et al.,* 2012). As transgression continues however, a return to more distal ethologies characteristic of the *Cruziana* ichnofacies begin to dominate the rock record. The trace suite is characterized by *Skolithos*, *Phycosiphon*, *Chondrites*, *Asterosoma*, *Planolites*, *Thalassinoides*, *Diplocraterion*, and *Teichichnus*. Vertical unlined burrows display passive infilling of interpreted firm ground substrates, indicative of the *Glossifungites* ichnofacies, and on occasion, vertical burrows are infilled by green glauconite rich sands, in otherwise glauconite absent intervals. The significance of *Glossifungites* surfaces within several core should not be overlooked as they represent discontinuities characteristic of transgressive surfaces of erosion and further conclude that these facies are the result of a transgressional environment (Pemberton and Frey, 1985; MacEachern and Pemberton, 1992).

2.22 Facies Summary:

An evaluation of the facies associations suggests that sand bodies within Marten Hills and Nipisi were initially the result of a prograding wave- and storm-dominated shoreline. Evidence of both the falling stage and lowstand systems tracts are observed based on the presence of sharp-based, forced regressional shorefaces and overall progradational nature seen throughout the study region. This shoreline likely preserved areas where storm action played a weaker role (FA1) (perhaps due to crenulated coastlines) and permitted fairweather conditions to dominate the preserved rock record, seen more abundantly on the western and eastern edges of the study area. Longshore drift may also have carried sediment down-current (inferred to the SE) where they are partially protected or baffled from storm influence. This could explain why robust trace-fossil assemblages and fairweather conditions are predominantly observed on the southeastern-most cored intervals and why central cores are more heavily exposed to storm and wave action. This interpretation would also explain why storm-dominated shorefaces (FA2) and wave-dominated deltas (FA3) dominate the rock record throughout the central regions. This interpretation results FA1-FA3 all being deposited penecontemporaneously with FA3 representing proximal deposition to fluvial sources, FA2 representing transitional settings between deltaic and fairweather conditions, and FA1 representing deposition that preserves no evidence of fluvial input and instead preserves only fairweather environments. This however, does not explain the regional preservation of frequently observed episodic high-energy deposition characteristically associated with storm-influenced environments. An alternative theory results from the stratigraphic position of FA1, which commonly occurs in the lowermost intervals of the Marten Hills sandstone units. This suggests that fairweather conditions were, at one time present across the paleoshoreline throughout the much of the study region. The abundance of high-energy facies characteristic of FA2 and FA3 (Facies 3a, 3b, 6, 7, 10a, 10b) overlying FA1 can be interpreted as the subsequent deposition of stratigraphically younger units and indicates a transition from fairweather conditions to environments where wave, storm, and deltaic processes dominated. This would make FA1 genetically older, but maintain the penecontemporaneous relationship of FA2 and FA3, however, further work is required to provide additional supporting evidence for this interpretation.

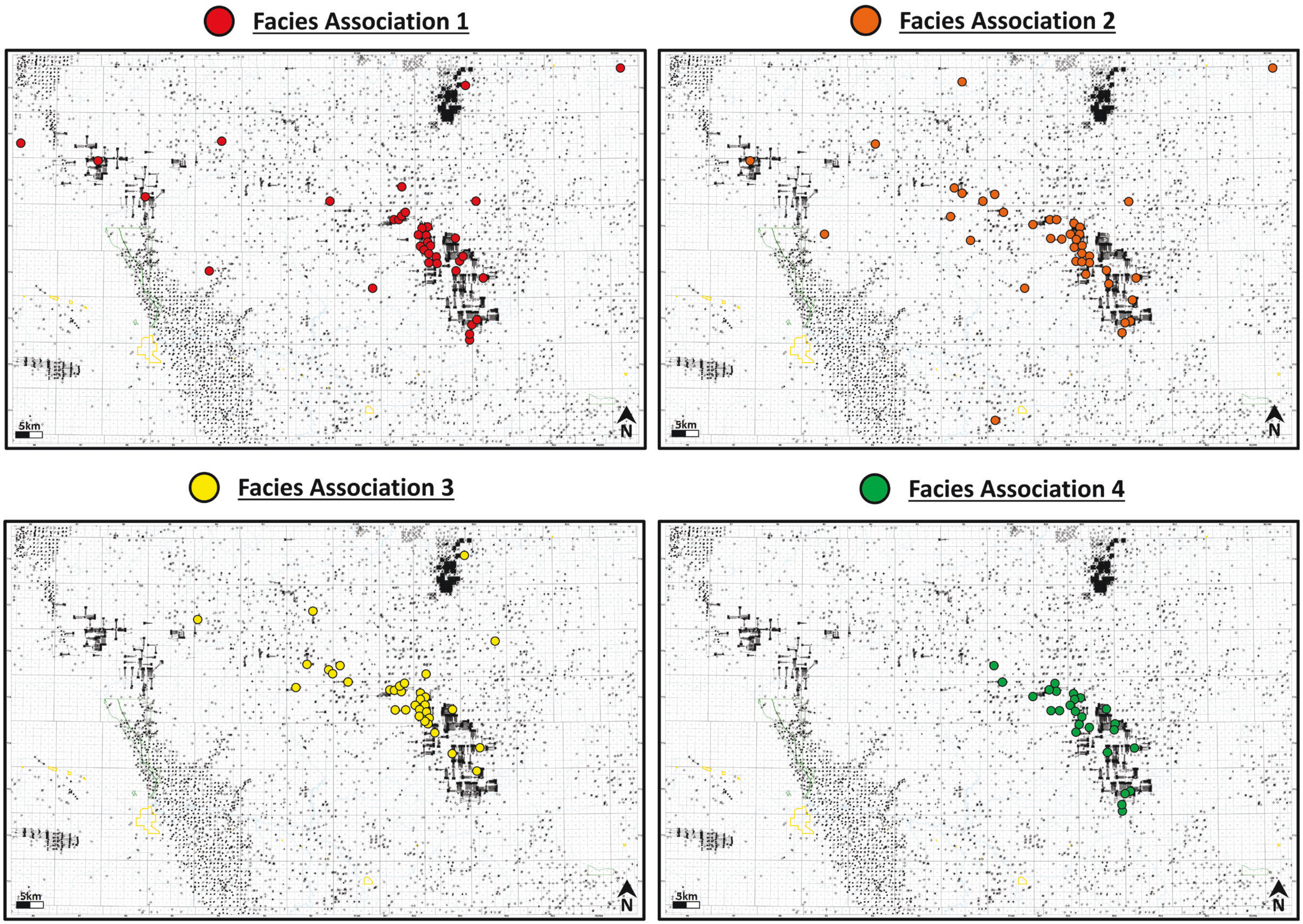


Figure 16. Four maps of the study region each displaying the lateral distribution of FA 1-4. It should be noted that several cored intervals showed multiple facies associations (some demonstrated evidence of all four). This indicates that depositional environments likely changed over geologic time as wave/storm influence fluctuated, delta lobes avulsed, and transgression subsequently inundated the paleoshoreline. Lateral variability confirmed through core observations also demonstrates that different depositional environments were likely active at the same time given the scope of the study region. FA1 tends to be more widely distributed to the outer flanks of the study region, with more central cores demonstrating greater abundances of FA2 and FA3. The relationship of multiple facies associations being observed within a single core also provides evidence that vertical stacking may demonstrate genetically different intervals being deposited.

Deltaic environments were fed by narrow distributary channels, likely separated by great distances, which is why they are rarely observed in the core. These channels were also likely subjected to immense wave reworking following channel/delta lobe avulsion, overprinting these deposits with wave-dominated facies (Fig. 15). A modern-day analog for this environment is the wave influenced shoreline in Tabasco, Mexico (Fig. 23). FA3 likely gradationally transitions towards FA2 and FA1 along depositional strike, as the fluvial input diminishes, and wave dominated settings take over representing a transitional shoreline continuum. The overall stacking pattern of the middle shoreface and deltaic sediments indicates that aggradational settings took over, leading to thick repeating successions of storm-dominated shorefaces and wave-dominated delta settings, which are observed consistently throughout the central and eastern cored intervals. The vertical thicknesses of the Clearwater prograding sandbodies is however anomalous, given that prograding shorelines rarely exceed ten metres in thickness (Clifton, 2006). As the environment transitioned from an aggradational shoreline to a transgressive shoreline (FA4), erosional processes cannibalized nearshore sediments, leaving behind transgressive lags. Transgressive erosion is likely the reason that no foreshore or upper shoreface environments are preserved in core. This marine transgression would also transition progradational distributary channel systems into retrogradational brackish estuaries where tidal effects could suspend and deposit mud above the erosive transgressive lag. It is inferred that if a greater abundance of landward core were available, bi-directional currents and combined flow ripples in addition to tidal doublets and brackish trace suites would also be observed as they would be subject to lower rates of wave reworking. Finally, as transgression continued, sedimentation rates were diminished, providing a window for glauconitization to occur resulting in abundant glauconite-rich sands across the study region. This was subsequently followed by a continued southward transgression of the Boreal Seaway and the return to fully marine conditions.

Chapter Three: Marten Hills and Nipisi Regional Stratigraphy

3.1 Clearwater Stratigraphic Architecture:

The Clearwater Formation is composed of two key members: The Wabiskaw Member at the base which disconformably overlies the McMurray Formation, and what is being proposed within this study as the Marten Hills Member. The Marten Hills Member is disconformably overlain by the Grand Rapids Formation and is separated at its base by a marine shale known as the Wabiskaw Marker. To accurately map and correlate reservoir sandstones within the Marten Hills Member, a detailed stratigraphic framework was developed to display the internal elements of the Clearwater Formation. Marine flooding surfaces (mFs) are utilized within this study to separate individual cleaning upwards trends or parasequences (Van Wagoner *et al.,* 1988; Van Wagoner *et al.,* 1990). These flooding surfaces are interpreted as regionally extensive events resulting from increased water depths associated with subsidence or rising sea levels, (Van Wagoner *et al.,* 1988; Galloway, 1989; Bhattacharya, 1993). Flooding surfaces are noted by distinct log signatures (increased gamma ray radioactivity, and a sharp decrease in resistivity signatures (Fig. 3). Additionally, transgressive surfaces of erosion (TSE) are observed at the top of several cored intervals, indicating the onset of marine transgression and represent a diachronous surface. This is seen as a gradational increase in gamma-ray (GR) response with several metres separating the TSE from the marine flooding surfaces. The inflection point beneath the highest gamma ray and lowest resistivity signature, indicative of marine flooding surfaces, are selected to indicate the uppermost limit of each individual informal unit within the Marten Hills Member. The goal for this stratigraphic framework was to not only correlate wireline log signatures with core observations, but to set the foundation for future work in adjacent areas of Alberta.

East of the study area, in the Cold Lake and Athabasca regions, there is an abundance of literature focusing on the detailed stratigraphic elements of the McMurray, Clearwater, and Grand Rapids formations (e.g. Minken, 1974; Beynon, 1992; Wickert, 1992; McCrimmon and Arnott, 2002; Feldman *et al.,* 2008; Currie, 2011; Hathaway, 2016). The stratigraphy in the Cold Lake region is informal, and identifies stratigraphic intervals based on transgressive or "T" surfaces. This has been successfully utilized by Hayes et al (1994) and Hathaway (2016) to display regional trends, however its applicability in the study region was unsuccessful given significant lateral stratigraphic complexity. To keep stratigraphic correlations consistent, an attempt was made to correlate the regional stratigraphy of the Clearwater Formation in eastern Alberta

(Feldman *et al.,* 2008; Hathaway, 2016), with the proposed Marten Hills Member stratigraphic framework (Fig. 17). This study employs a “bottom-up” stratigraphic naming scheme wherein the interval above the Wabiskaw Member is Marten Hills Member A, and so forth (Fig. 3). This contrasts similarly aged strata of western Canada which uses a “top-down” member naming scheme (e.g. the Falher and Wilrich members of the Spirit River Formation). This stratigraphic framework was combined with sedimentologic observations to correlate equivalent intervals and to map the distribution of members both laterally and vertically throughout the Clearwater successions. All core penetrating the Clearwater Formation within the study area were analyzed and depth matched with wireline log signatures to correlate flooding surfaces and lithologies throughout the Marten Hills Member. This enabled the identification of depositional trends by mapping the reservoir sandstone thickness (gross sandstone isopach), structure, and stratigraphic correlations across the study region. Two key stratigraphic intervals of Lower Clearwater sandstones, Marten Hills B and C, are emphasized in this study given their economic significance.

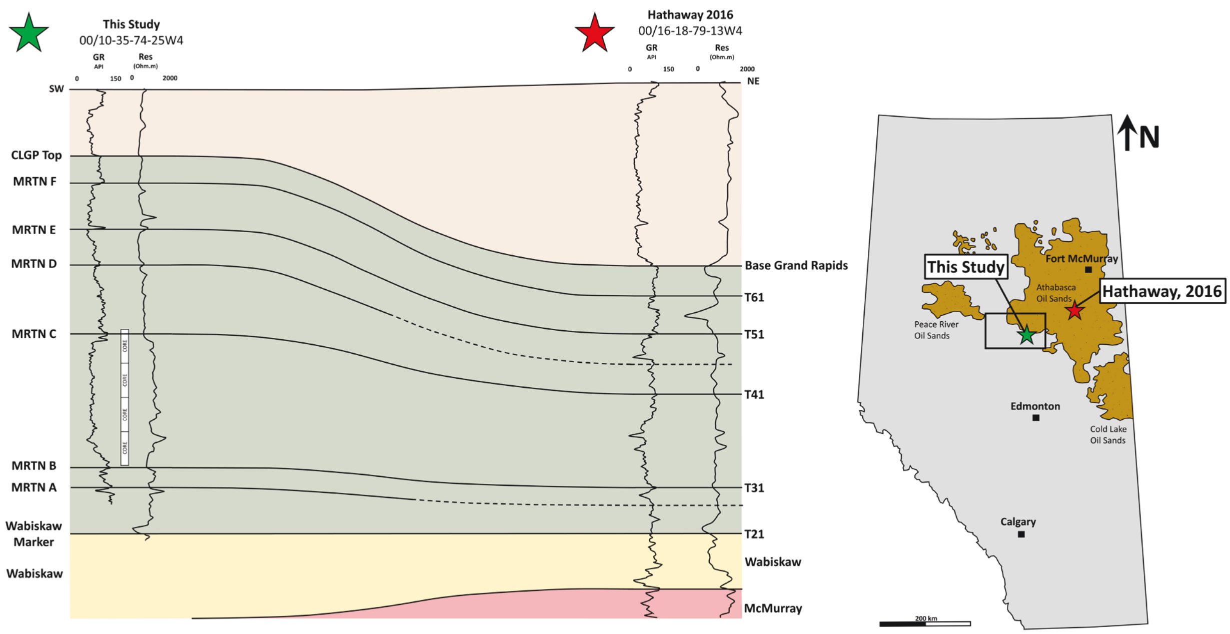


Figure 17. A regional stratigraphic correlation with previous literature (Hathaway, 2016). The cross section shows the T21 surface used by Hathaway is correlative to the Wabiskaw marker utilized within this study.

Figure 17. A regional stratigraphic correlation with previous literature (Hathaway, 2016). The cross section shows the T21 surface used by Hathaway is correlative to the Wabiskaw marker utilized within this study.

Several sedimentologic attributes are consistent throughout the Clearwater Formation, including an abundance of organic content in the form of "phytodetrital debris". Additionally, small pink siderite grains occur in association with phytodetrital organic material with the two allochthonous grains appearing to be intrinsically related (Fig. 10A, Fig. 12D). Massive to disseminated pyrite occurs persistently through Clearwater sandstones. Calcite cemented sandstones are also commonly observed in core as cemented sandstones devoid of hydrocarbon saturation and are easily interpreted from wireline log signatures (low gamma ray API, high bulk density, and high resistivity measurements). Although these tightly cemented intervals appear to be correlative, they are likely preserved in the subsurface as more of a "boulder-field", similar to what is observed in outcrop along the Athabasca River (Kramers, 1974). The size of the cemented sandstones ranges dramatically from decimetre to metre scale, with their lateral extent potentially being even longer (several metres).

The calcite cemented intervals are interpreted to represent early diagenetic events which formed as a result of freshwater potentiometric flow leaching reactive minerals and mixing with marginal marine fluids (Colquhoun, 1999). Lobate cemented intervals predominantly occur at facies transition zones/boundaries, where abrupt grain size changes are apparent, with coarser material preferentially being cemented. Stratiform cemented sandstones are also observed within some of the lower stratigraphic intervals (MRTN A and B). These cemented intervals are significantly thinner (centimetre scale) and are often interbedded with sandstones and silty mudstones. In this case, coarser sandstone units likely allowed preferential groundwater flow and as a result are more laterally extensive. Readers are referred to the work of Colquhoun (1999) for a more detailed discussion on the calcite-cemented sandstones in the Clearwater Formation.

3.2 CLEARWATER FORMATION:

Wabiskaw Member and Wabiskaw Marker:

Towards the central and western sections of the study region, the Wabiskaw Member is observed directly above the Devonian and Mississippian units separated by the SCU. In the westernmost sections of the study region, remnant paleotopographic highs are observed, with the geologically younger Marten A Unit sitting directly above the SCU. The top of the Wabiskaw Member is capped by a maximum flooding surface (MFS), referred to as the Wabiskaw Marker bed (Wightman *et al.,* 1997; Hein and Cotterill, 2006). The Wabiskaw Marker is regionally extensive over hundreds of kilometres and is the only MFS interpreted within the study region. All subsequent flooding surfaces throughout the Marten Hills Member are classified as marine flooding surfaces as they extend throughout the study region, but not at the same regional scale as the Wabiskaw Marker. In core, the Wabiskaw Marker is observed as a fissile shale that is commonly associated with washout in wireline logs (F1), (Fig. 4 and 9A). The isopach thickness of the shale marker bed is between 0-4.5metreswith the vast majority of Marten Hills ranging from 2.5-3.0 m. Given its predictable log expression (most easily identified by a sharp, distinctive decrease in resistivity and increase in bulk density) and significant regional distribution, the Wabiskaw Marker was selected as a stratigraphic datum for this study. This study does not provide the detailed geologic attributes of the Wabiskaw Member aside from the utilization of the uppermost Wabiskaw Marker bed as a stratigraphic datum.

3.3 Marten Hills A (MRTN A):

The Marten Hills A (MRTN A) is bounded above and below by marine flooding surfaces. It was deposited above the Wabiskaw Marker and is overlain by the Marten Hills B (MRTN B) (Fig. 4). Isopach mapping of the MRTN A shows a thickening trend from east to west, where thickness decreases from 15 metres in the south, to <1 metre in the north. Interbedded siltstones, very fine-grained sandstones, and mudstones are the most dominant facies observed within cored intervals of MRTN A, however pervasively bioturbated mudstones and siltstones occur locally (F3a, F2a respectively). Reference locality #1 (14-08-77-8W5) displays the transition from the SCU through the Wabiskaw marker, MRTN A, and lower MRTN Bs and exhibits the mudstone dominated marine extent of MRTN A sedimentology and Ichnology.

As cored intervals of MRTN A are sporadically distributed, wireline log signatures were used to correlate this stratigraphic interval. Gamma ray signatures fluctuate between 80API to 120API, which is largely attributed to the very fine-grained sandstones interbedded with siltstone and mudstone resulting in a serrated log response. Apparent porosities derived from sonic, neutron, and density logs are low (3-9%), and resistivity logs provide minimal evidence of hydrocarbon presence. Additionally, within the 11 cored intervals including the MRTN A, thin very-fine grained sandstone interbeds contained minor oil staining making this interval a poor exploration target.

The MRTN A is interpreted to represent deposition within the shallow Boreal Seaway likely within a storm-dominated distal lower shoreface to lower offshore or distal pro-delta environment given the abundance of F3a. The vertical facies association mostly represents an incomplete display of FA2. Paleoshoreline is inferred to the south given a slight increase in sand content, however this cannot be confirmed. Alternatively, the shoreline may have been scoured through subsequent transgressive erosion. To the north, the MRTN A downlaps onto the underlying Wabiskaw Member where isopach thicknesses decrease to <1 metres making correlations challenging. Evidence of the underlying Wabiskaw Marker bed also diminishes to the north outside of the study region, further complicating wireline correlations. Given both the interbedded/ mudstone dominated facies, and irregular log signature that slightly cleans upwards, it is interpreted that MRTN A was once a prograding shoreline with only the distal expressions being preserved. This was subsequently overlain by transgression of the Boreal Seaway prior to deposition of the Marten Hills B.

3.4 Marten Hills B (MRTN B):

The Marten Hills B (MRTN B) is confined between two flooding surfaces observed throughout the entirety of the study region, separating it from the underlying MRTN A, and the overlying Marten C (MRTN C) intervals (Fig. 5). In the Nipisi area, the MRTN B is an important reservoir, with most multilateral drilling targeting a 10 to 12 metre sandstone interval. Isopach mapping between flooding surfaces displays a significant range in thicknesses of the MRTN B. In the east and northernmost portions of the study region, isopach thickness ranges from 1-5 metres in thickness, whereas to the west, and southwest, gross isopach thickness is over 43 m. The major thickness trend is observed in the SW corner of the study region, trending in a NW to SE direction and extends outside the scope of this study (Fig. 18). In addition, there is also evidence of a broader W-E oriented depositional trend to the north. The northern sandbody likely represents a stratigraphically younger interval, however given the absence of core data in the SW, detailed stratigraphic relationships are challenging (Fig. 19). This broader depositional trend contains the majority of production to date within the Nipisi and Mitsue regions (Fig. 5, Fig. 20). Isopach mapping shows a thinning between the two sandbodies, however the presence of Lesser Slave Lake prevented drilling and restricted datapoints that would further confine the potential connectivity of these sandstones. There are 22 cores within the study region that partially or fully penetrate the MRTN B; of these only 3 penetrate the full interval. These MRTN B core are critical in the understanding of depositional process throughout the interval as they record the entire depositional record.

Sedimentologic interpretations of MRTN B cored intervals provide evidence of both storm and fairweather shoreface environments. An offshore transition which grades upwards into a middle to upper shoreface is also observed (Fig. 5). Cores that penetrate the entire MRTN B interval display a full marine suite at the base, with abundant clay-rich mudstones and shales with intense degrees of bioturbation (F2a). High mud content and intense bioturbation is the result of deposit-feeding strategies in lower energy conditions, such as those found in the distal lower shoreface to offshore marine environments of the distal *Cruziana* ichnofacies (Pemberton *et al.,* 1992b; Taylor *et al.,* 2003; Pemberton *et al.,* 2012). Sand content gradationally increases upwards with heavily bioturbated sandy mudstones grading upwards into interbedded mudstones with sporadically to seldomly bioturbated tempestites characteristic of a storm-affected lower shoreface (MacEachern and Pemberton, 1992; Brenchley *et al.,* 1993; Pemberton *et al.,* 2012). FA1 is the most predominant facies association within the MRTN B, however FA2 is also observed in the uppermost intervals. Additionally, Facies Associations vary along depositional strike which likely is a result of varying shoreline geometries being affected by storms differently given their paleogeographic position along the interpreted paleoshoreline. Mud content decreases upwards as the overall grain size increases, with sandstone units commonly consisting of fine-grained feldspathic litharenites. Bioturbation becomes more sporadic, as colonization windows of burrowing animals shorten, owing to an increase in storm and wave action. Low-angle planar sandstones dominate the uppermost interval of the MRTN B and are interpreted to represent deposition within the middle shoreface, where consistent wave reworking prevents bioturbation and winnows mud, transporting it in a basinward direction (Howard and Frey, 1984; MacEachern and Pemberton, 1992; Pemberton *et al.,* 2012). Reference locality #2 (15-1-76-6W5) is an excellent example of the gradational transition described above showing an offshore transition into the middle shoreface in a storm-influenced shoreface environment.

MRTN B Gross Sand Isopach Thickness Map

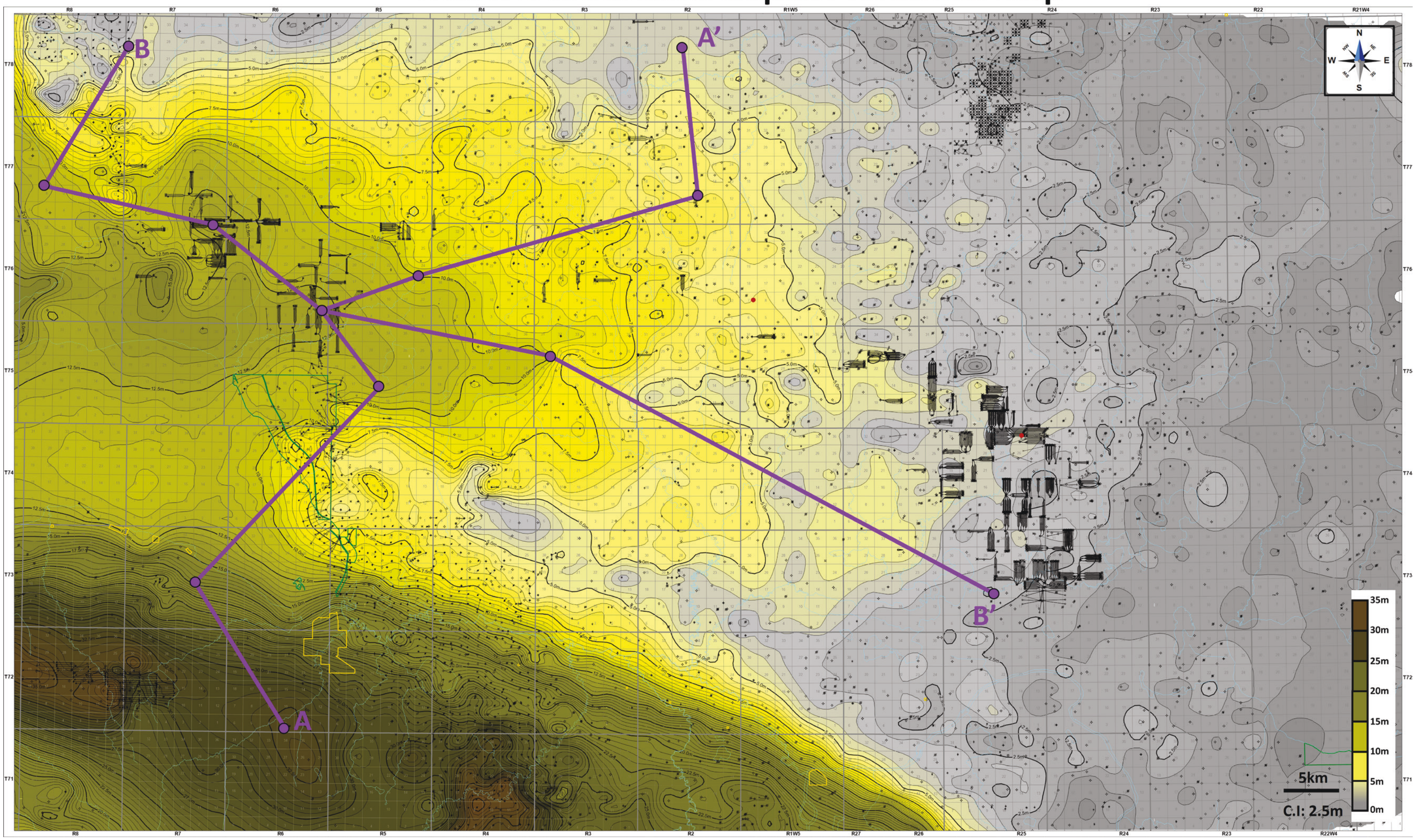
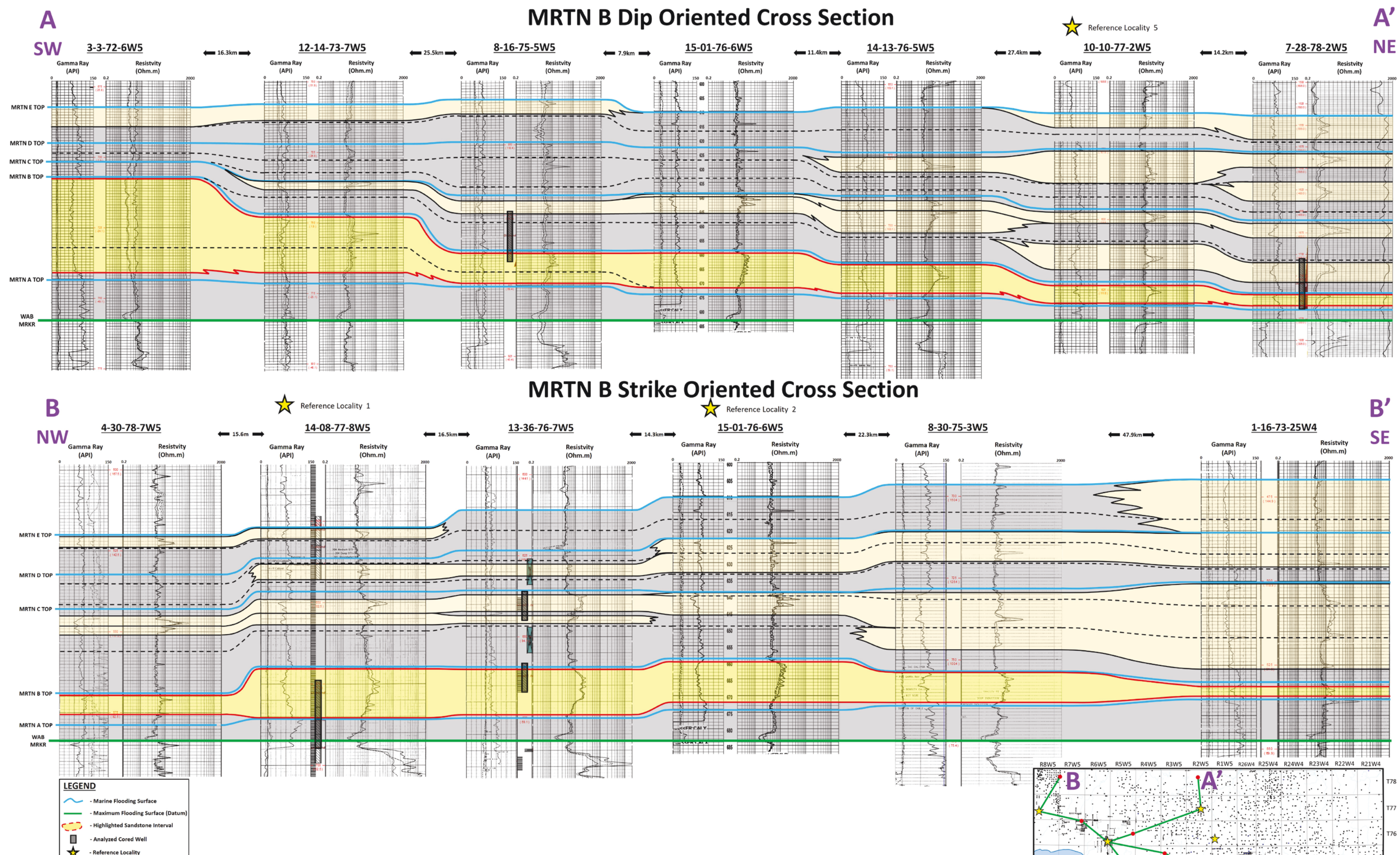


Figure 18. Gross sandstone map of the MRTN B sandstone. Depositional thickness trend observed in the SW corner of the map trending in a NW to SE orientation. Development within the MRTN B interval appears to be focused within the second depositional trend observed to the north of the major thickness trend in the Nipisi and Mitsue regions.

Two regional cross sections are used to display the stratigraphic relationships in both strike and dip directions (Fig. 19). The dip oriented cross section (Fig. 19 upper) runs from the SW to the NE and displays the thinning of MRTN B to the northeast. Both cross sections show two cleaning upwards trends present within the MRTN B. The lower interval thins from 10 metres in the SW to 0 metres in the NE, where only the upper MRTN B is preserved. The upper interval decreases in thickness from over 25 metres to 12 metres in the Nipisi region, where oil production is focused in the uppermost MRTN B interval. The second regional cross section is strike-oriented and goes from the NW to the SE (Fig. 19 lower). This cross section shows the main producing areas of the MRTN B reservoir and clearly displays the lateral thinning to the NW and SE. Typical log signatures show cleaning upwards GR profiles, core and log derived porosities ranging between 21-30%, and increased resistivities, although resistivity signatures are often muted (sub 10 ohm.m). These log attributes are interpreted to represent an increase in grain-size and decrease in mud/silt content. Muted resistivity signatures may be attributed to the mineralogic impact pyrite has on suppressing resistivity logs, as abundant disseminated and nodular pyrite are observed within the MRTN B (Clavier *et al.,* 1976). Additionally, the effect that clays such as chlorite and smectite have on resistivity suppression cannot be excluded (Caplan pers comm).



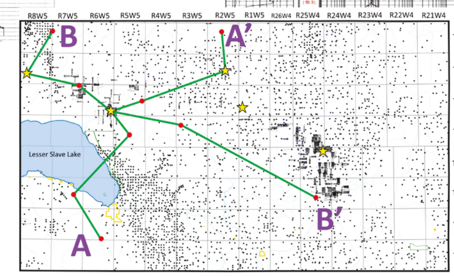


Figure 19. Two regional cross sections: A-A' representing a dip oriented cross section from SW to NE. This cross section displays a significant decrease in stratigraphic thickness within the MRTN B member to the NE. B-B' represents a strike oriented cross section going from NW to SE. This cross section demonstrates the lateral thinning of the MRTN B member to the NW and SE and is oriented through the major producing MRTN B interval in the Nipisi and Mitsue regions.

Marten Hills Member B Interval: Nipisi and Mitsue Regions – Evidence of Transgression

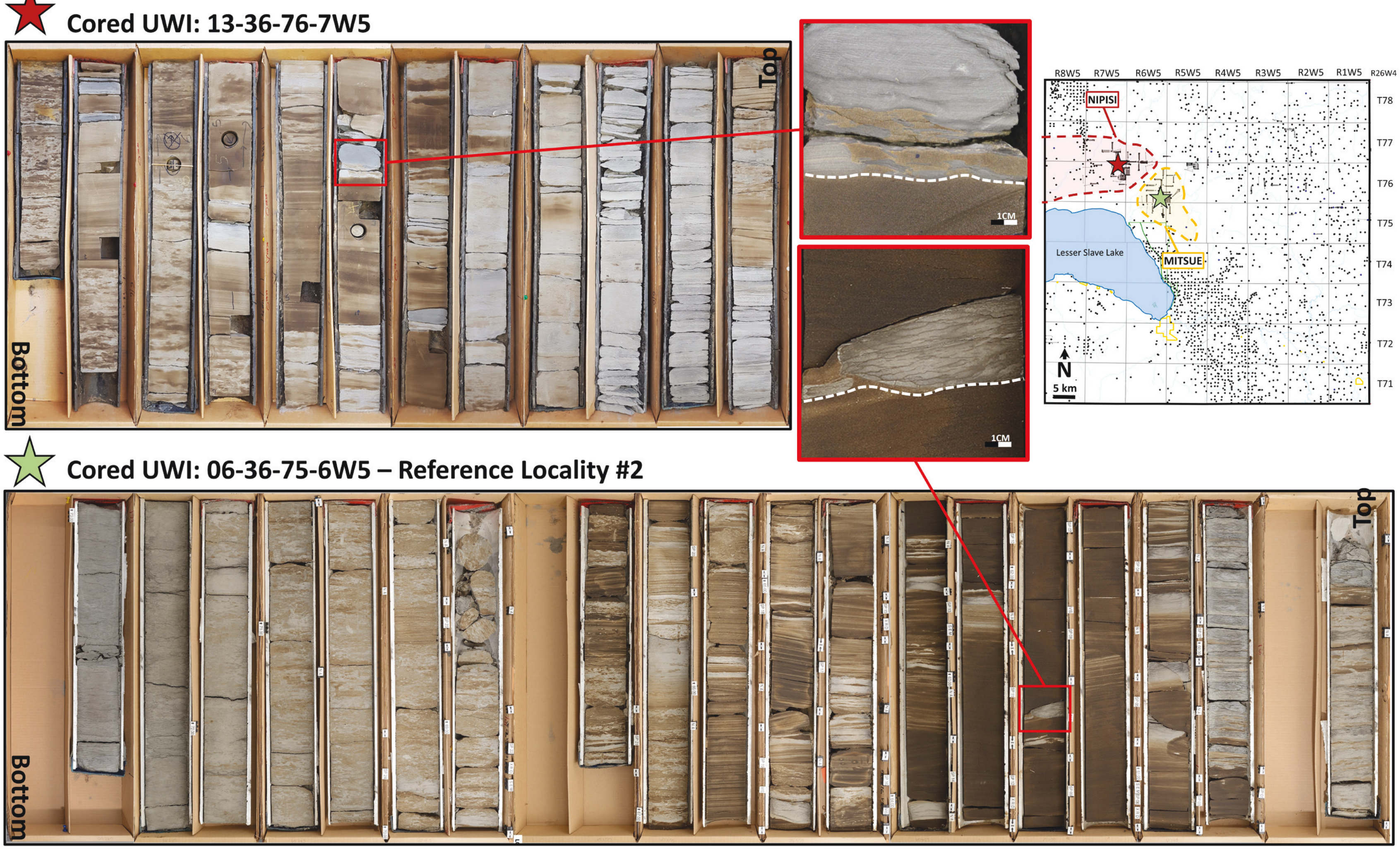


Figure 20. Two core demonstrating the sedimentology of the Marten Hills Member B interval. Upper core **(UWI 13-36-76-07W5, Depth 658.0-666.7m)** demonstrates the uppermost half of the sandstone displays a series of thin, sharp-based mudstone rip-up clast contracts (highlighted with a red box and contact being displayed by a white dashed line). This is characteristic of transgressive lags, and is further supported by the increasing abundance of bioturbated siltstone and mudstone above characteristic of more distal marine environments. The intial lag is interpreted to mark the onset of marine transgression and corresponds to a “dirty-ing” upwards log trend. Evidence of transgressive lags within the MRTN B is observed in core (**UWI 06-36-75-06W5, 659.0-673.6m)** within the Mitsue region, where a sharp contact and mudstone dominated rip-up clast is observed prior to the onset of pervasively bioturbated marine strata. For a detailed facies breakdown of Reference Locality #2, readers are referred to figure 5.

The MRTN B is interpreted to represent a period of aggradation and progradation. The presence of 45-metre thick sandstone intervals in the south suggest significant accommodation space and high sedimentation rates matching the rate of transgression. The broader MRTN B sandbody to the north provides further evidence of progradation prior to transgression. Both sandbodies are oriented in a NW to SE orientation which contrasts the W-E orientation observed in the underlying MRTN A. Transgressive erosion likely truncated the uppermost MRTN B, which is supported by thin lag deposits (Fig. 20) and trace amounts glauconite in core. Downlapping of the MRTN B onto the lower MRTN A is observed to the north, where both units continue to thin outside of the study area. Similar to MRTN A, the MRTN B appears to have been a north-northeast prograding shoreline that was influenced by variable to weak storm influence predominantly displaying characteristics of FA1 (with subordinate displays of FA2), and was then overlain by marine shales as a subsequent southward transgression of the boreal sea inundated the MRTN B paleo-shorelines prior to deposition of the MRTN C interval.

3.5 Marten Hills C (MRTN C):

The Marten Hills C (MRTN C) is confined above and below by regional flooding surfaces, equivalent to T41 and T31, respectively, and contains the most internal stratigraphic complexity. Throughout the study region, the MRTN C remains consistently thick with an average thickness between 25-30 metres. The MRTN C is the main reservoir unit and is thickest in the east-central Marten Hills and Smith region, where the isopach thickness is over 35 metres. Gross sand mapping shows two thickness trends in the MRTN C termed C and C' (Fig. 21 and 22). A regional strike oriented cross section D-D' demonstrates the lateral thinning trends and internal stratigraphic complexity within the MTRN C sandstone (Fig. 23). This sandstone is oriented in a NW to SE direction, ranging in thickness from 5 to >30 metres and represents the main sandstone being exploited in Marten Hills. The C sandstone thins rapidly to the NE and is interpreted to represent a basinward direction. The second thickness trend (C') is observed in the east/northeastern regions and is oriented N-S with thicknesses ranging from 5 to 17.5 metres, which is displayed in dip oriented cross section C-C' (Fig. 24). There are currently 53 cores that partially or fully penetrate the MRTN C, with the majority observed within the central Marten Hills region. The abundance of tightly spaced core data is beneficial in recording the lateral heterogeneities at a local scale which permits more detailed stratigraphic correlations. To the west, a scarcity of MRTN C cores makes high resolution interpretations challenging. Several cores enabled characterization of the regional depositional environments. The internal stratigraphy of MRTN C is broken into lower and upper units, which are separated by a partially continuous flooding surface. Subtle GR responses that corresponded with inflection points in porosity logs and resistivity logs are inferred to represent lithological changes which are correlated locally through cored observations, and then applied to a regional scale. This resulted in five main intervals being interpreted throughout the MRTN C interval (MRTN C 1-5), however this is a subjective interpretation and additional units may be interpreted (Fig, 22 and 23). Within the MRTN C, all four Facies Associations (FA1-4) are observed throughout the study region. FA1 is predominantly observed in the lowermost vertical intervals, and laterally is observed on the SE and NW edges of the depositional trend. FA2 and FA3 are observed throughout the middle to upper portions of the Marten C (MRTN 3-5), with FA4 exclusively being observed in the uppermost MRTN C intervals (MRTN C 5/6).

MRTN C Gross Isopach Thickness Map

0.5m Contour Interval

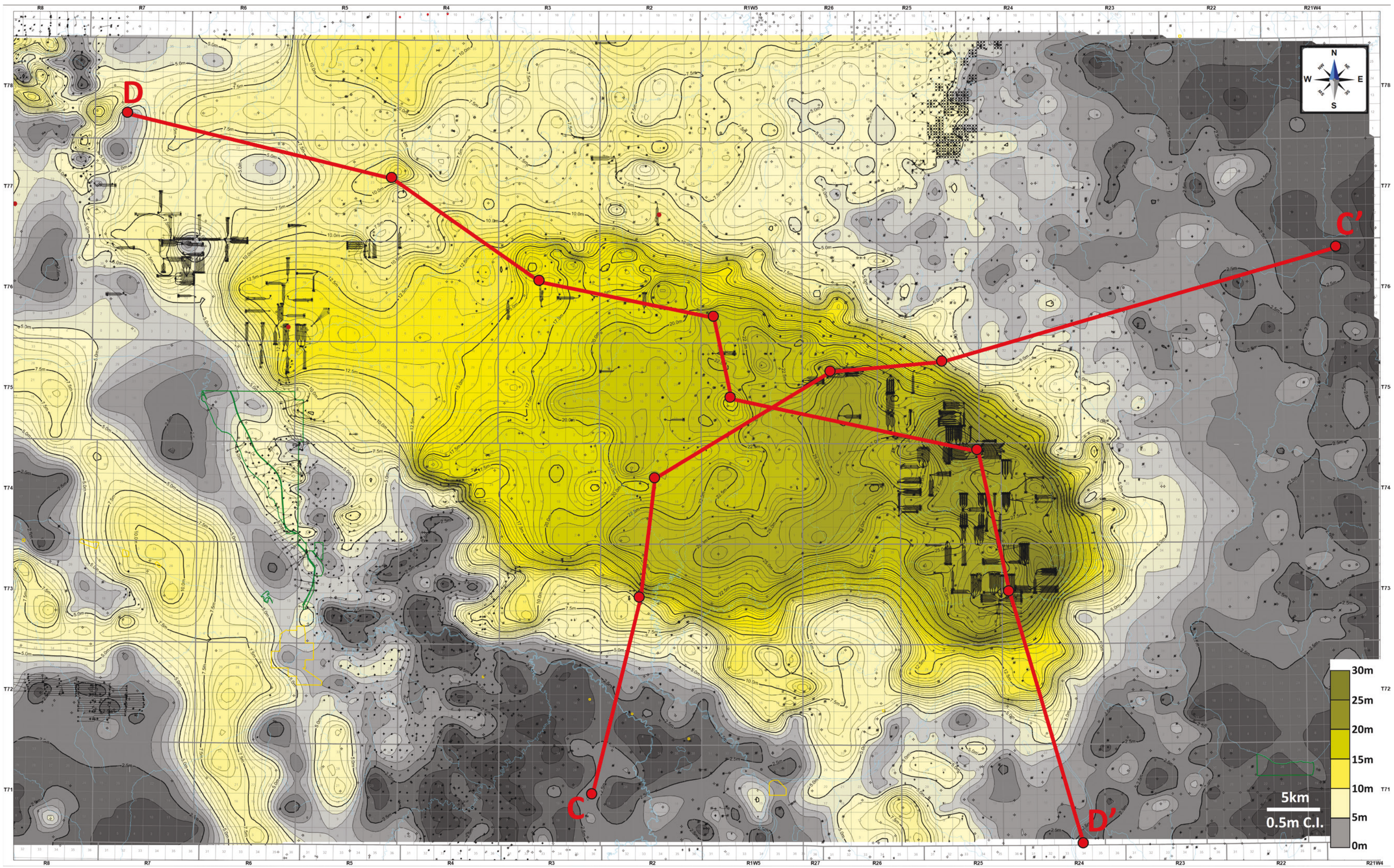


Figure 21. MRTN C gross sandstone map displaying the primary thickness trend in Smith, Marten Hills, and the Marten region (Fig. 2). Production is predominantly observed on the eastern flank of the thickness trend. Of note is the rapid decrease in gross sandstone thickness to the east and northeast (transitioning from 30 metres to <2 metres in a short distance).

MRTN C' Gross Sand Isopach Thickness Map

0.5m Contour Interval

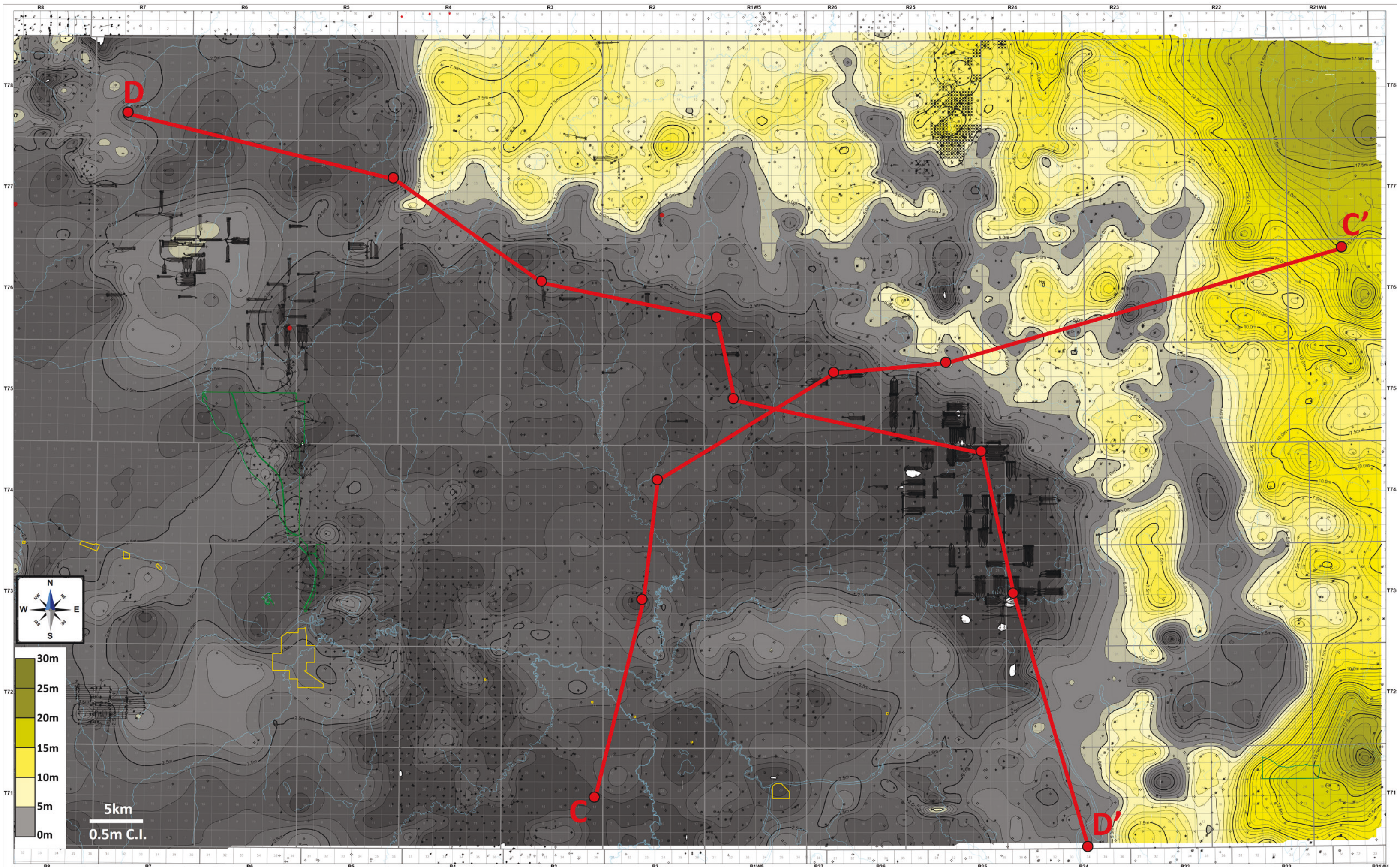


Figure 22. Above figure demonstrates the distribution of the C' sandstone interval. This unit thickens to the east and northeast, and represents a stratigraphically younger interval that is observed subsequently after the main MRTN C sandstone observed in figure 21. It should be noted that both the MRTN C and C' intervals are deposited below the marine flooding surface that is interpreted to cap the MRTN C interval. This flooding surface marks the transition between deposition of the MRTN C and D units.

3.5 (a) Lower Marten C

The lower MRTN C consists of a series of cleaning upwards sand bodies with two recurrent cycles classified as C1 and C2 (reference localities 3 and 4), (Fig. 24), and is overlain by the upper MRTN C. The most common facies association at the base of the MRTN C is a gradational transition from bioturbated marine muddy siltstones (F2a, F2b) to interbedded sandstones and mudstones (Facies 3a) (Fig. 6 and 7). Cycles indicate a cleaning-upwards trend as the interpreted proximity to paleoshoreline increases. A key characteristic of the lowermost MRTN C is the presence of robust mud-lined trace fossils in a sandstone matrix. These trace fossils are commonly Cylindrichnus and *Rosselia* often displaying secondary colonisation of *Phycosiphon* and are commonly associated with the *Cruziana* Ichnofacies. The robust nature of these trace fossils in sand-dominated facies also suggest a fairweather lower shoreface environment (Gingras *et al.,* 2011) and is representative of FA1. In addition, the lower MRTN C consists of a sporadic, but distinctive, fabric composed of partial calcite-cemented sandstones that results in a patchy appearance (F4). Bioturbated sandstones clean upwards decreasing in bioturbation intensity and consist of very fine to fine grain-sizes with low-angle planar bedding, characteristic of a middle shoreface. Cyclical colonisation of tempestite sands in the lower shoreface also indicate recurrent storm influence throughout the lower MRTN C. Cores often display a vertical "back-stepping" of facies, where bioturbated sandstones of the lower shoreface subsequently overlie middle shoreface sandstones and are interpreted to represent stacked depositional events as a result of fluctuating sea-levels. Rooted desiccation cracks observed in the NW part of the study region at the top of C1 indicate a fall in sea-level, which exposed parts of the lower MRTN C, preserving a subaerial exposure event (observed in core 10-07-77-4W5, Fig. 12G). This provides evidence that the lower MRTN C was not deposited as one conformable succession, but rather a series of more complex stacking assemblages. Several cores within the Marten Hills trend display evidence of a "sharp-based" shoreface, where clean sandstones sharply truncate marine mudstones and siltstones and indicate a forced regression, where migration of the shoreline in the basinward direction is directly associated with a sea level fall (Posamentier and Morris, 2000). This regression leads to wave scouring resulting in the dislocation of the traditionally observed FA1 and FA2. Several lower MRTN C cores also display pulses of organic material rich in large centimetre-scale wood clasts (F10b) which potentially resulted from incision of distributary channel systems, responding to a fall in sea level (Hart and Long, 1996). Additional evidence that deltaic systems are at least locally present include thin fluid mud beds, soft sediment deformation, synaeresis cracks, and dessication cracks.

The lower MRTN C1 and C2 log responses consist of a series of cleaning-upwards gamma ray log signatures displayed above the underlying flooding surface associated with the MRTN B. Two cleaning upwards cycles are observed on logs with interpreted suppressed gamma ray values. This suggests relatively clean sands with abundant feldspar and radioactive clay content, resulting in dirtier gamma-ray log responses. Additionally, the lower shoreface bioturbated sandstones of F4 contain increased silt and mud content which reduces gamma ray API values. Partial cementation and overall finer grain size of these lower MRTN C sands are observed both in core and log calculated porosities consistently fluctuate between 12-24% with wireline and core derived porosities relatively matching. Resistivity signatures are often muted suggesting increased water saturation, however mineralogic factors such as increased disseminated pyrite are known to suppress the resistivity measurement (Clavier *et al.,* 1976), in addition to certain clays including smectite and chlorite (Caplan pers comm.). Spatially, the lower MRTN C thins to the SE, where only 10 metres is preserved beneath the upper MRTN C. The presence of both fairweather shoreface and delta-related facies are evidence that a continuum of depositional environments are present across the lower MRTN C intervals. Combined with evidence of a forced regression, an interpretation of a lowstand shoreface/deltaic system is inferred. The cleaning upward trends observed in the C1 and C2 cycles (Lower MRTN C) are subsequently overlain by the MRTN C (C3).

3.5 (b) Upper Marten C

The upper MRTN C consists of 3-4 stratigraphic intervals referred to as C3-C5 (C6?), with the lowermost C3 interval consisting of a flooding surface at its base separating the upper C3 unit from the underlying C2. The C3 flooding surface ranges in thickness between 0-3 metres and is not consistently present throughout the study region. It is only observed in 6 cores (Fig. 23), however distinct wireline log signatures permit regional correlations within the study area. The flooding surface is predominantly observed on the SW (landward) side of the sandstone thickness trend and is notably absent in the central Marten Hills region where MRTN C sandstone thickness is greatest. Characteristics of the upper MRTN C3 flooding surface are also observed to the north in the inferred basinward direction. The basal C3 flooding surface abruptly overlies the lower MRTN C2 and consists of an interbedded silty to sandy mudstone that fines upward into silty mudstone and consists of moderate to intense bioturbation (BI 3-5). Bioturbation consists of *Cosmorhaphe*, *Helminthopsis*, Phycoshiphon, *Schaubcylindrichnus freyi*, and *Thalassinoides* representing a marine trace fossil suite. There is also evidence of the complete pyritization of several *Thalassinoides* in addition to nodular pyrite. Aside from thin low-angle planar interlaminated siltstone beds and normal grading, physical sedimentary structures throughout this unit are obscured due to biogenic reworking.

The flooding surface associated with the MRTN C3 interval has a log response common with most flooding surfaces. Gamma ray records a higher API given the higher concentration of radioactive elements within the mudstones/shales. Additionally, core and log porosities are quite low (5-15%) and resistivities are significantly reduced (<3 ohm.m). This flooding surface is significant as the vertical thickness acts as an intraformational seal separating the lower C2 oil reservoir from the upper MRTN C3-5 sandstone reservoir intervals. In order to show the characteristics of this flooding surface, cross sections are provided along depositional strike and dip to display several key features (Fig. 23 and 24). In the southeast, the flooding surface is observed stratigraphically lower in the MRTN C. This indicates that the reservoir in eastern Marten Hills is predominantly composed of the upper MRTN C3-5. This contrasts with the central region where the flooding surface is observed approximately in the middle, and the west where it is observed in the upper third of the gross sandstone isopach (Fig. 23).

Initial interpretations hypothesized a potential lagoonal environment on the landward side (SW) of the reservoir sandstones. This is challenged by the ichnologic diversity, regional correlative nature of this surface that spans 10's of kilometres, and its re-appearance basinward of the sandstone thickness trend. The ichnologic and sedimentologic evidence, as well as the fining upwards trend, provides evidence that this basal C3 unit is likely a flooding surface that represents the inundation of the underlying lower MRTN C units (C1 and C2). In the central region, the absence of the C3 flooding surface is likely due to erosive scouring and cannibalization due to subsequent wave reworking of the overlying upper MRTN C, making stratigraphic identification of the C2 and C3 contact extremely challenging. Most production throughout the Marten Hills and Smith regions are from these upper Marten Hills C intervals. Given the significant lateral complexity and spatial distribution of the Upper Marten C intervals (Fig. 23), the isolation of an optimal internal interval is challenging. Above the flooding surface, the upper MRTN C consists of a series of cleaning/coarsening upwards trends classified in reference localities 3 and 4 as MRTN C3, C4. These cycles are subsequently followed by a fining upwards profile referred to as MRTN C5. There are 41 cored intervals within the study region that include the upper MRTN C, with the majority observed throughout the Marten Hills production fairway. Gross isopach thickness of the upper MRTN C ranges from <5 metres in the west to over 25 metres in the central Marten Hills region. Production trends appear to correspond closest with isopach thicknesses of this upper MRTN C interval, with the majority of the upper MRTN C interpreted as middle to upper shoreface, and delta front environments.

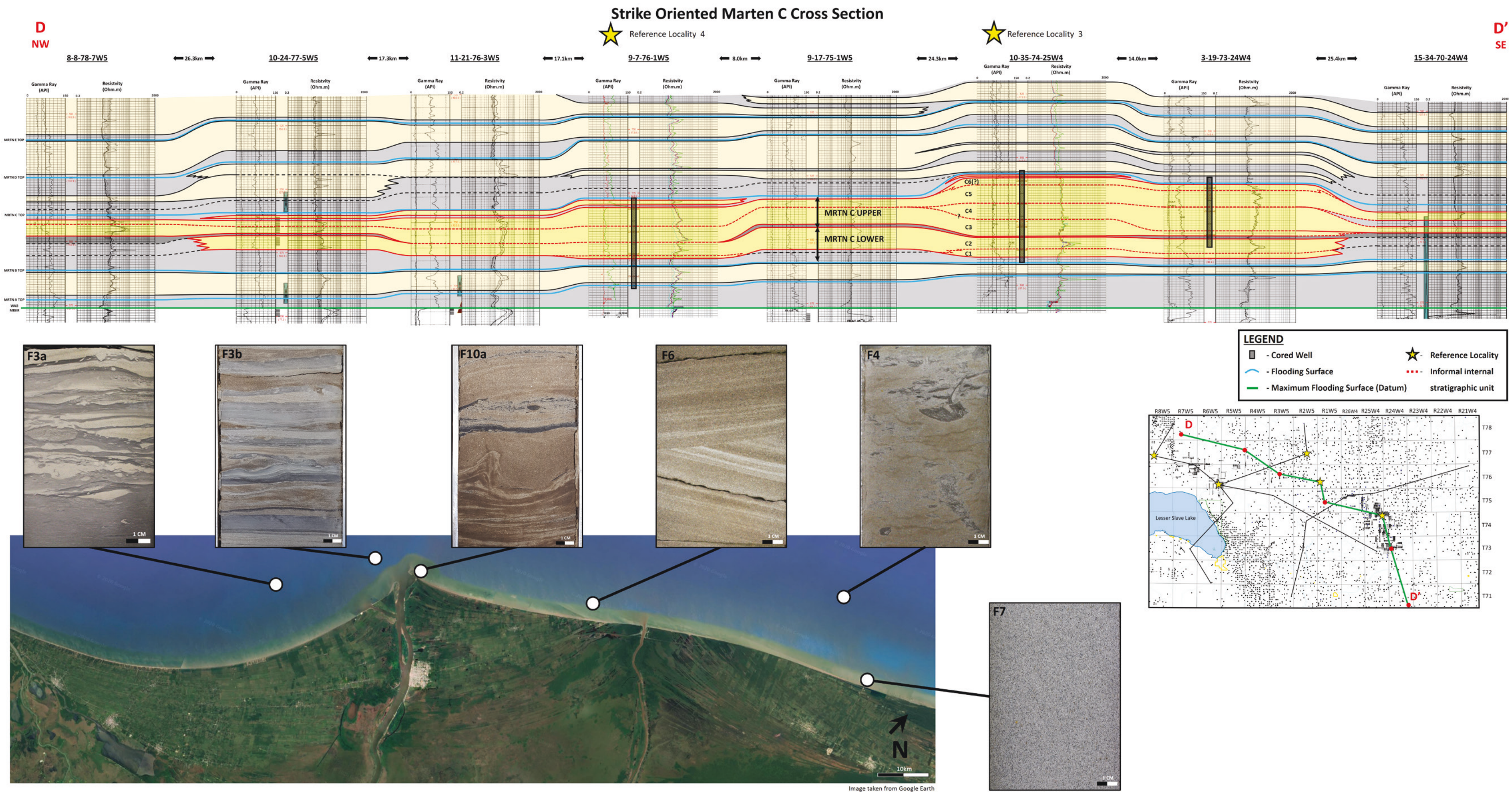


Figure 23. Upper image is a regional strike oriented stratigraphic cross-section focused on the MRTN C interval going from D to D' (see map). The stratigraphic datum selected was the Wabiskaw marker given its relative consisten isopach thickness and regional extent across the study region. Lateral thinning is observed along both the eastern and western flanks of the cross section. Internal stratigraphic complexity is observed with 5-6 internal stratigraphic units (C1-C6) observed. A satellite image of a modern wave dominated delta from Tabasco Mexico is displayed (bottom). Tabasco Mexico was selected given its similar scale to the MRTN C sandstone trend, in addition to the depositional environments observed in satellite imagery compared to inferred environments descerned from core observations. Core photos displayed on the satellite image are representative of commonly observed facies in Marten Hills. The variability of facies observed in core translates to the variable environments that likely persisted along depositional strike of the trend. Note: evidence of distributary channels is rarely observed in the 60 logged Clearwater core throughout the study region. This translates to the modern analog as over the 100km trend, only two narrow distributary channel systems are observed feeding sediment to the shoreline. This modern analog combined with MRTN C core data attempts to display how the increasing distance from fluvial sources will likely display more common shoreface sedimentologic characteristics.

The upper MRTN C is characteristically defined by thick (6-12 metre) intervals composed of massive appearing upper-fine to lower medium-grained sandstones (F7). The abundance of massive sands observed within the upper MRTN C may potentially be the result of: 1) a lack of grain-size variability, which inhibits the definition of sedimentary laminations; 2) high sedimentation rates (i.e. rivers and deltas); or 3) heightened degrees of biogenic reworking (cryptic bioturbation) which represents a BI of 6 (Pemberton *et al.,* 2008; Gingras *et al.,* 2015). An interpretation of cryptic-bioturbation is provided whenever: thin section analysis of massive sands could determine biogenic reworking, faint remnant bedding was observed (referred to as "ghost-bedding", or fuzzy-lamination/ contacts are observed (Pemberton *et al.,* 2008; Gingras *et al.,* 2015). The most common vertical facies associations observed in the upper MRTN C consist of thinly interbedded sandstones and low-angle planar bedding that transition upwards into massive appearing sandstones. The recurrence of thin intervals of low-angle planar bedding, mud-drapes, and phytodetrital laminae that punctuate massive sandstones are interpreted to represent basal components of subsequent events that were not as heavily impacted by cryptic bioturbation (Howard and Frey, 1975; Pemberton and Gingras., 2005; Gingras *et al.,* 2015). The massive appearance is interpreted to represent deposits that underwent a degree of meiofaunal biogenic reworking and when indicative of cryptic bioturbation, can indicate the *Phycosiphon* and *Rosselia* Ichnofacies, commonly associated with deltaic conditions (MacEachern and Bann, 2020). Additionally, several sporadically distributed mud-lined trace fossils are observed including Cylindrichnus, *Diplocraterion*, *Rosselia*, and *Ophiomorpha* and are more likely to be associated with fairweather middle shoreface conditions. Although this explains how thick massive sandstone can be observed on a wave influenced middle shoreface, evidence of massive sandstones related to deltaic processes are also observed within upper C3-C4 intervals. Organic rich channel lags provide evidence of distributary channel systems. High-angle planar and organic rich sandstones also suggest high energy environments. Deltaic environments in the upper MRTN C are commonly limited to the uppermost sandstone succession of the C4 interval and are associated with FA3. In core, this is observed as a transition from fine- to medium-grained sandstone, rich in rounded pebbles and coarser organic debris. Gamma ray log signatures appear slightly cleaner, with lower API values and increased apparent porosities compared to underlying sandstone intervals. Interbedded mudstone within the upper MRTN C exhibits low bioturbation (aside from doomed-pioneers, Föllmi and Grimm, 1990) and can be observed as structureless (fluid muds) or with low angle internal bedding and very fine-grained organic debris. This represents fluid mud deposition along the delta front/plain. Alternatively, mud beds with laminar bedding may represent hyperpycnites (dynamically deposited mud deposits from hyperpycnal plumes) which were rapidly deposited onto deltaic and shoreface environments (Bhattacharya and MacEachern, 2009; MacKay and Dalrymple, 2011). Above the shoreface and delta deposits (FA2 and FA3), the C5 interval is represented by a fining upward trend with interbedded mudstones and transgressional lags and is associated with a TSE (FA4). Lags are observed in several events or "pulses" and are interpreted to represent episodic transgressional events prior to marine inundation and deposition of FA2. In addition, pine-green, glauconite-rich sandstones are common in the uppermost C5. These sandstones include evidence of "*Glossifungites*" surfaces. Such surfaces are associated with the *Glossifungites* Ichnofacies, which is indicative of transgression (Pemberton and Frey, 1985). Mud content increases upwards into a heavily bioturbated mudstone representing the full marine transgression capping the MRTN C.

Wireline log signatures within the upper MRTN C display several cleaning upwards trends, observed in gamma ray as fluctuations between 60-75 API suggesting cleaner sands. Core and log derived porosities are relatively close, both averaging around 28-33% throughout the upper C3-C4 intervals. Resistivity within the upper MRTN C varies widely but is most commonly between 10-20 ohm.m. Evidence of a subsequent marine transgression within the C5 interval is observed as a distinct gradational increase in gamma ray log response and a decrease in apparent porosities as mud content increased. The abundance of massive sandstone makes internal stratigraphic correlations challenging as the majority of the upper MRTN C displays a relatively consistent GR and resistivity signature. This makes for a simplified "gross sand" interpretation, however subtle wireline log signatures can be correlated and break down the reservoir internally (Fig. 23).

The upper MRTN C3-C5 intervals have the best reservoir attributes across the study region. This is seen as increased thickness trends correspond to higher multilateral well density throughout the study region. Deposition within this upper C3 to C5 interval likely represents stacked aggradation of a wave-dominated shoreline, where low-angle planar sandstones of the middle shoreface were deposited in several successions and subsequently reworked by meiofauna, producing massive appearing sands and faintly observed ghost bedding (Bromley, 1996; Howard and Frey, 1975; Gingras *et al.,* 2015). In addition to a wave-dominated shoreface, evidence of wave-dominated delta environments includes synaeresis cracks, high angle planar bedding, coarse organic debris, and convolute bedding. As this is inferred to be a lowstand environment, relative sea level fall and associated fluvial incision likely supplied sediment from the SW, to the NE prograding shoreline prior to marine transgression. A potential explanation for deltaic deposits preferentially being observed within the uppermost sandstone interval (upper C4) is that they were subject to lower degrees of wave reworking and were the uppermost progradational interval prior to marine transgression. As a deltaic lobe avulses, deltaic sediments are subject to wave reworking making them nearly indistinguishable from middle shoreface environments (Bhattacharya and Walker, 1991; Bhattacharya and Giosan, 2003). The onset of transgression transitions fluvial distributary systems into estuarine environments and introduces brackish water into the system facilitating the flocculation of mildly-burrowed fluid mud layers. Transgression of the C5 is capped by a regional flooding surface that separates MRTN C from the overlying upper Marten Hills Member intervals.

Given its large regional extent, the MRTN C interval was initially interpreted as a marginal marine sandstone influenced by shoreface and delta environments. While this is largely correct, the substantial thicknesses observed make a single depositional event unlikely. After investigation of all core and log information, it is now interpreted as a series of multiple depositional cycles with at least five internal cycles (Fig. 23). Laterally, MRTN C also bifurcates to the NE, where a separate thickness trend extended to the east outside of the study region. This is now shown within the dip oriented cross section (Fig. 24) where a C and C' sandstone is displayed. The C' interval represents a "younger" MRTN C progradational lobe, and bifurcation is associated with the downlapping of the C interval. This demonstrates that stratigraphic complexity exists both vertically and laterally. Although this C' interval is consistently picked within the eastern limits of the study region, no cored intervals that included C' sandstones were observed and as such facies and facies associations for this stratigraphically younger interval are not inferred.

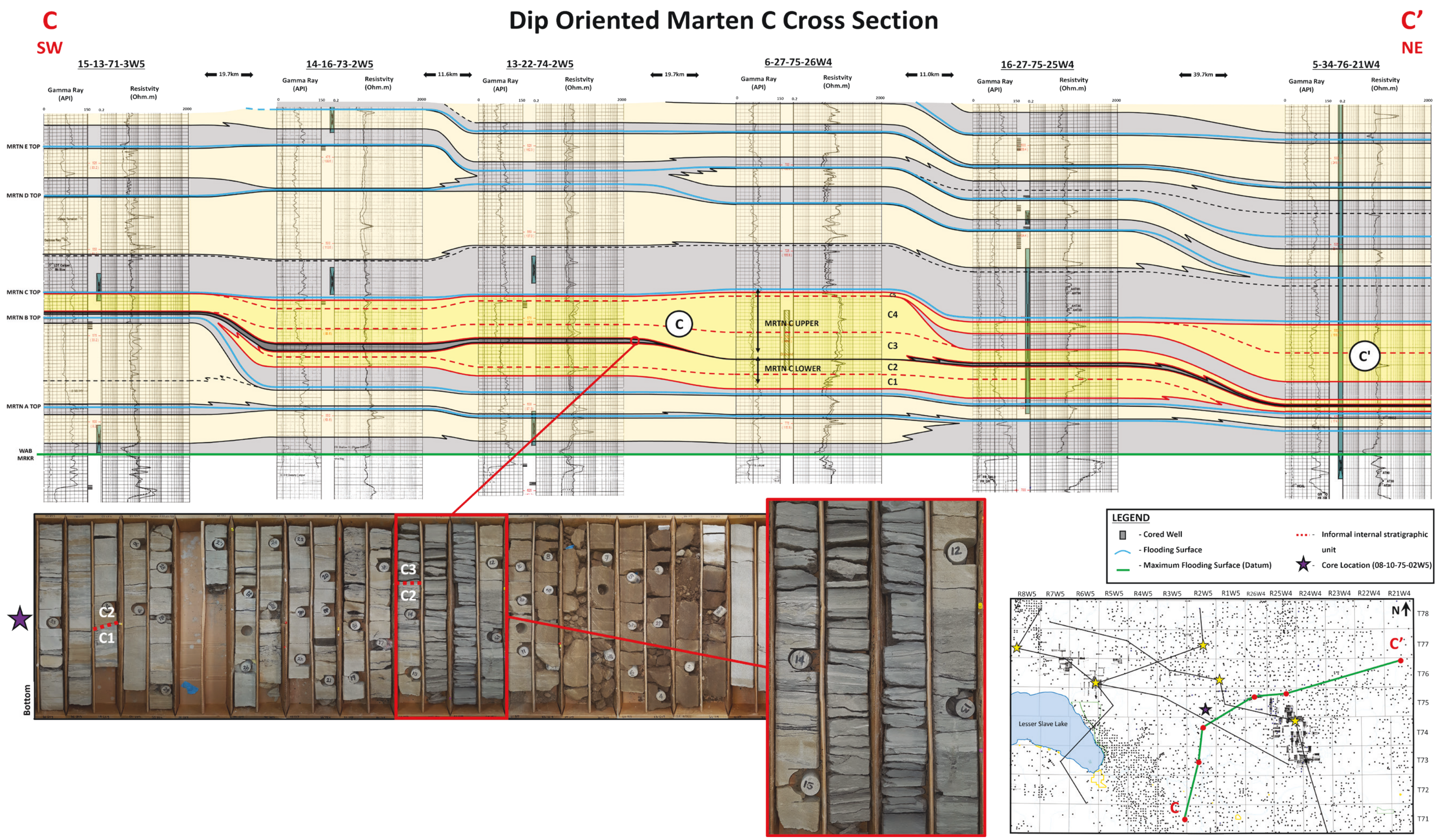


Figure 24. Regional dip oriented stratigraphic cross section C-C'. Cross section is oriented from SW to NE and is datumed on the Wabiskaw marker. The upper cross section demonstrates the aforementioned stratigraphically younger C' sandstone that thickens to the east outside of the study region (also demonstrated by the gross sandstone map in figure 22). The dip-oriented stratigraphic cross section also captures the significant middle mudstone that appears to separate the MRTN C into an "upper" and "lower". This mudstone is interpreted as a flooding surface that abbreviates the lower (MRTN C1 and C2) and upper (C3-C5) and observed in the lower core box display (**08-10-75-02W5, Depth 610.0 -635.0m).** The zoomed in image is designed to represent the internal sedimentologic attributes of the C3 flooding surface which consists of moderately bioturbated silty mudstones. Additionally, abundant pyritized *Thalassinoides* burrows were also observed throughout this interval. This flooding surface is significant as it brackets the upper and lower sandbodies however throughout the central production fairway of the MRTN C intervals, the C3 flooding surface is absent (likely due to subsequent scouring throughout the deposition of the C3 sandbody). Within the core boxes, internal stratigraphic complexity is annotated by dashed red lines and displays the C1,C2,C3 intervals. The cored location is noted on the map by a purple star.

3.6 Upper Marten Hills Intervals (MRTN D-F):

Historically, Clearwater exploration has been focused on the MRTN B and C stratigraphic intervals, with the majority of core concentrated within these two intervals. More recently however, stratigraphically younger intervals have begun to attract exploration interest, north of the main Marten Hills and Nipisi production areas. Three main intervals above the flooding surface, which overlies the MRTN C, are observed in this study and are classified as MRTN D through F. These intervals display similar attributes to underlying intervals, with cleaning upwards profiles above each flooding surface followed by a fining upwards interval prior to the onset of a subsequent marine transgression. The only variation is observed within the MRTN E, where a blockier wireline signature is observed, however no cored intervals have penetrated this interval to confirm the sedimentologic relationship with wireline log attributes. The upper MRTN F interval is capped by a marine flooding surface that is loosely classified as the “Top Clearwater/ Base Grand Rapids” however this pick is entirely subjective, and as a gamma ray/resistivity marker exists only partially throughout the study region, its large scale correlatability is challenged.

Throughout MRTN D-F, there are six cored wells that include partial intervals of upper Clearwater stratigraphy. Of the six upper Clearwater cores, one is within the MRTN F, two are within the MRTN D sandstones and the remaining three capture only the lowermost portions of MRTN D. The two key cores observed within the study region that include the MRTN D sandstone are 02/07-05-76-25W4 and 06-15-77-2W5. The latter is observed in Reference Locality #5 (Fig. 8), however both cores display significant evidence of deltaic environments (FA3) which marks a deviation from the shoreface dominated MRTN C cores and was the only cored interval to not include FA1. Sedimentologic evidence of deltaic environments observed in the MRTN D sandstone includes unbioturbated mud drapes, synaeresis cracks, convolute bedding, high organic material, and upper-fine to medium grained sandstones with high angle bedding. These features are indicative of high energy environments and rapid deposition rates that are commonly associated with deltaic environments (Bhattacharya and Walker, 1992; Bhattacharya, 1993). In addition to the sedimentology, ichnologic evidence displays opportunistic colonisation of *Phycosiphon*, observed in “top-down” colonisation events within mud beds. In addition to this, *Conichnus*, *Siphonichnus Teichichnus*, *Thalassinoides*, and *Zoophychos* traces are all observed but BI was moderate to low (BI 2-4). The upper Marten Hills Member sandstones are interpreted to be litharenite/feldspathic litharenites, with high degrees of kaolinite clays which was confirmed through thin section analysis.

Wireline log signatures remain consistent with what is observed throughout much of the underlying Clearwater stratigraphy. Gamma ray responses in the upper Marten Hills Member intervals fluctuate between 65-90 API, with core and log porosities averaging between 27-33%. Well 02/07-05-76-25W4 displays neutron-density inflectional mirroring and moderate crossover, potentially indicating gas, which is likely why hydrocarbon staining within the interval is minimal. This is anomalous as most upper Marten Hills Member cored sandstones display oil saturation.

MRTN D-F likely represent small scale progradational events where shorelines were able to re-establish during hiatuses in the southward transgression of the Boreal Seaway as a result of increased sedimentation rates due to tectonic activity /basin subsidence. Future work on the delineation of sedimentologic and stratigraphic complexity of these upper Clearwater intervals will continue as exploration and development proceeds in the region.

The stratigraphic interpretation of the Marten Hills Member internal units A-F displays evidence that progradational and aggradational shorelines were continually deposited throughout the overall southward transgression of the Boreal Seaway. Fluvial sourcing to these shorelines was likely continuous given the high phytodetrital organic material found in every stratigraphic interval. The lack of abundant fluvial evidence in cored intervals suggests distributary channels were likely narrow, and widely separated from one another. Depositional environments associated with these fluvial sediment sources likely represent a continuum where wave dominated delta environments persist near channel outlets, and distal deposits are preferentially preserve evidence of shoreface assemblages (Figure 3D MODEL).

Chapter Four: Conclusions and Future Works

4.1 Summary

The ichnologic and sedimentologic attributes of the facies developed for this study is important for delineating distal facies relationships and their respective facies associations. Trace fossil size, diversity, and distribution provided insight into interpreted environmental conditions and physical or chemical stresses that could have been present throughout deposition of the Marten Hills Member. Depositional settings are all inferred to represent a wave-dominated shoreline continuum where multiple environments likely persisted concomitantly along depositional strike across the study region. Additionally, facies associations were utilized in the development of a stratigraphic framework which supports the establishment of a new stratigraphic interval referred to as the Marten Hills Member of the Clearwater Formation. This newly proposed framework enabled the correlation of multiple stratigraphic intervals which are subdivisions of the Marten Hills Member herein named the Marten Hills A- to F. Five reference localities are selected to provide a complete cored section throughout the Marten Hills Member to assist in regional correlations. A series of strike and dip oriented cross sections enabled the mapping of gross isopach thickness and gross sand thickness trends for each subunit. These maps display the depositional trends associated with each stratigraphic interval. The stratigraphic framework and mapping may aid in the future evaluation of similar depositional environments throughout the WCSB, particularly the Clearwater Formation and its equivalent formations in adjacent areas of central Alberta.

The sedimentologic, lithological, and ichnologic relationships of the Marten Hills Member have been identified and correlated on a regional scale (through the integration of core data and wireline attributes). Twelve recurrent facies and four facies associations show the vertical relationships throughout the region, with four depositional environments interpreted as follows: 1) Wave-dominated fairweather regressive shoreface to offshore (offshore to middle shoreface); 2) Storm-dominated regressive shoreface to upper offshore (proximal offshore to middle/upper shoreface); 3) wave dominated, delta, and; 4) Wave dominated, transgressive shoreface, each summarized as follows:

1) Wave-dominated fairweather depositional environment interpretations (comprising Facies Association 1) are based on the robust and diverse ichnologic attributes observed in facies 2a, 2b, 4, and 5 throughout the offshore to lower shoreface environments. Oscillatory bedding and SCS within facies 4, 5, 6 combined with sporadic bioturbation indicate a lower to middle shoreface setting with less intense depositional processes than those observed in storm-dominated environments.

2) Storm-dominated regressive shoreface depositional environment interpretations (comprising Facies Association 1 and 2) are based on the recurrent presence of storm deposits (tempestites) throughout the upper offshore to the middle shoreface setting. Interbedded facies (F3a) with highly biogenically reworked mudstones represented hiatuses between storm events with proximal settings based on the abundant HCS and traditional SCS deposits.

3) Wave-dominated, deltaic conditions (comprising Facies Association 3) are inferred based on the presence of rapid sedimentation deposits (eg. F10a, F10b, F11), weakly bioturbated mudstones (F11),

suggesting episodic event beds derived from flood deposits on a deltaic environment, in addition to subaerial exposure and synaeresis cracks.

4) Wave-dominated, transgressive shoreface depositional environment interpretations (comprising Facies Association 4) are based on the presence of a recurrent lag, fluid muds, abundant pine green glauconite, and the persistent fining upward succession capped by a fully marine facies (F2a).

4.2 Future Work

Ongoing exploration and development drilling of the Clearwater Formation suggests future work should integrate the proposed stratigraphic framework and facies relationships with a detailed analysis of the reservoir attributes observed within the Marten Hills Member. Diagenetic timing will provide greater insight into the role that cementation and grain dissolution had on inhibiting or enhancing reservoir quality. A more detailed analysis on the mineralogic attributes within the proposed stratigraphic intervals will likely provide further support for internal stratigraphic complexity observed within Marten Hills Member sandstones throughout the study region. Additionally, the incorporation of a more comprehensive sequence stratigraphic analysis throughout the region (in addition to the north and south outside the scope of this study), will further refine the stratigraphic and sedimentologic interpretations provided throughout this study. The ichnology of the Clearwater Formation throughout the study region provided significant supporting evidence for depositional environments. Further analysis on the ichnologic classification of massive appearing sands may delineate some of the additional challenges associated with internal reservoir complexity. Finally, the role hydrodynamic processes have within the Clearwater Formation and the impact on reservoir fluid quality may also provide insights into reservoir heterogeneity. This study developed a regional stratigraphic framework with a comprehensive facies analysis that should refine future works, enabling detailed analyses throughout the wide spectrum of petroleum geology now that a regional context for the Marten Hills Member has been set.

4.3 References:

Adams, J., Larter, S., Bennett, B., Huang, H., Westrich, J. and van Kruisdijk, C., 2013. The dynamic interplay of oil mixing, charge timing, and biodegradation in forming the Alberta oil sands. Insights from geologic modeling and biogeochemistry. pp. 23-102.

Ahmed, S., Bhattacharya, J.P., Garza, D.E. and Li, Y., 2014. Facies architecture and stratigraphic evolution of a river-dominated delta front, Turonian Ferron Sandstone, Utah, USA: Journal of Sedimentary Research, v.

84, no. 2, pp. 97-121.

Ainsworth, R.B., Flint, S.S. and Howell, J.A., 2008. Predicting coastal depositional style: influence of basin morphology and accommodation to sediment supply ratio within a sequence stratigraphic framework. In Recent advances in models of siliciclastic shallow-marine stratigraphy, v. 90, pp.237-263.

Ainsworth, R.B., Vakarelov, B.K. and Nanson, R.A., 2011. Dynamic spatial and temporal prediction of changes in depositional processes on clastic shorelines: Toward improved subsurface uncertainty reduction and management. American Association of Petroleum Geologists, v. 95, pp.267-297.

Arnott, R.W., 1993. Quasi-planar-laminated sandstone beds of the Lower Cretaceous Bootlegger Member, north-central Montana; evidence of combined-flow sedimentation: Journal of Sedimentary Petrology, v. 63, pp. 488-494.

Arnott, R.W.C. and Hand, B.M., 1989. Bedforms, primary structures and grain fabric in the presence of suspended sediment rain. Journal of Sedimentary Petrology, v. 59, pp. 1062-1069.

Ashley G.M., Southard, J.B. and Boothroyd, J.C., 1982. Deposition of climbing ripple beds: a flume simulation. Sedimentology, v. 29, pp. 67–79.

Baniak, G.M., Gingras, M.K., Burns, B.A. and Pemberton, S.G., 2014. An example of a highly bioturbated, storm-influenced shoreface deposit: Upper Jurassic Ula Formation, Norwegian North Sea. Sedimentology 61, pp. 1261-1285.

Bann, K.L. and Fielding, C.R., 2004. An integrated ichnologic and sedimentologic comparison of non-deltaic shoreface and subaqueous delta deposits in Permian reservoir units in Australia. In McIlroy, D., ed., The Application of Ichnology to Palaeoenvironmental and stratigraphic Analysis: Geological Society, London, Special Publication, v. 228(1), pp. 273-310.

Bann, K.L., Fielding, C.R., MacEachern, J.A. and Tye, S.C., 2004. Differentiation of estuarine and offshore marine deposits using integrated ichnology and sedimentology: Permian Pebbley Beach Formation, Sydney Basin, Australia: In McIlroy, D., ed., The Application of Ichnology to Palaeoenvironmental and Stratigraphic Analysis: Geological Society of London Special Publication v. 228, pp. 179-211.

Beck, R.A., Vondra, C.F., Filikins, J.E. and Olander, J.D., 1988. Syntectonic sedimentation and Laramide Basement thrusting, Cordilleran foreland; timing and deformation. In Schmidt, C.J. and Perry, W.J. (Eds.), Interaction of the Rocky Mountain Foreland and the Cordilleran Thrust Belt. Geological Society of America Memoir v. 171, pp. 465-487.

Benyon, C., Leier, A.L., Leckie, D.A., Hubbard, S.M. and Gehrels, G.E., 2016. Sandstone provenance and insights into the paleogeography of the McMurray Formation from detrital zircon geochronology, Athabasca Oil Sands, Canada. AAPG Bulletin, v. 100(02). pp. 269-287.

Beynon, B.M., 1992. Sedimentology and petroleum geology of the Lower Cretaceous Grand Rapids Formation Cold Lake oil sands area, Alberta.

Bhattacharya, J. and Walker, R.G., 1992. Deltas. In Walker, R.G., James, N.P. (Eds.), Facies Models: Response to Sea Level Change. Geological Association of Canada, St. John's. pp. 157-177.

Bhattacharya, J.P. and Walker, R.G., 1991. River- and wave- dominated depositional systems of the Upper Cretaceous Dunvegan Formation, northwestern Alberta. Bulletin of Canadian Petroleum Geology, v. 39 (2), pp. 165-191.

Bhattacharya, J.P., 1993. The expression and interpretation of marine flooding surfaces and erosional surfaces in core; examples from the Upper Cretaceous Dunvegan Formation, Alberta foreland basin, Canada, In Posamentier, H.W., Summerhayes, C.P., Haq, B.U. and Allen, G.P. (eds.) Sequence Stratigraphy and Facies Associations. International Association of Sedimentologists Special Publication, v.18, pp. 125-160.

Bhattacharya, J.P. and Giosan, L., 2003. Wave-influenced deltas: geomorphological implications for facies reconstruction. Sedimentology 50, pp. 187-210.

Bhattacharya, J.P. and MacEachern, J.A., 2009. Hyperpycnal rivers and prodeltaic shelves in the Cretaceous seaway of North America: Journal of Sedimentary Research, v. 79, pp. 184-209.

Bradley, T.L. and Pemberton, S.G., 1992. Examples of Ichnofossil assemblages in the lower Cretaceous Wabiskaw Member and the Clearwater Formation of the Marten Hills gas field, north-central Alberta, Canada. Society for Sedimentary Geology (SEPM) Applications of Ichnology to Petroleum Exploration (CW17), pp. 383-399.

Brenchley, P.J., Pickerill, R.K. and Stromberg, J., 1993. The role of wave reworking on the architecture of storm sandstone facies, Bell Island Group (Lower Ordovician), eastern Newfoundland. Sedimentology, v40. pp. 359-382.

Bromley, R.G., 1996. Trace Fossils, Biology, Taphonomy and Applications, second ed. Chapman and Hall, London, 361 p.

Byers, C.W., 1974, Shale Fissility: Relation to Bioturbation: Sedimentology, v. 21, pp. 479-484.

Caldwell, W.G.E., 1984. Early Cretaceous transgressions and regressions in the southern interior plains, In Stott, D.F., and Glass, D.J., eds., The Mesozoic of the middle North America: Canadian Society of Petroleum Geologists Memoir 9, pp. 173-204.

Cant, D.J. and Abrahamson, B., 1996. Regional distribution and internal stratigraphy of the Lower Mannville. Bulletin of Canadian Petroleum Geology, v. 44, pp. 508-529.

Cant, D.J. and Abrahamson, B., 1997. Regional stratigraphy, sedimentology and petroleum geology of the Grand Rapids Formation, Mannville Group, northeastern Alberta. Bulletin of Canadian Petroleum Geology, v. 45, pp. 141-154.

Cant, D.J. and Stockmal, G.S., 1989. The Alberta foreland basin: relationship between stratigraphy and Cordilleran terrane-accretion events. Canadian Journal of Earth Sciences, v. 26 (10), pp. 1964-1975.

Carmona, N.B., Buatois, L.A., Ponce, J.J. and Mángano, M.G. 2009, Ichnology and Sedimentology of a tide-influenced delta, Lower Miocene Chenque Formation, Patagonia, Argentina: Trace-fossil Distribution and response to environmental stresses. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 273, pp. 75-86.

Cattaneo, A. and Steel, R.J., 2003. Transgressive deposits: A review of their variability. Earth Science Reviews, v. 62(3-4) pp. 187-228.

Cheel, R.J. and Leckie, D.A., 1993. “Hummocky cross-stratification.” In Sedimentology review 1, v. 1, pp. 103-122. Blackwell.

Clavier, C., Heia, A. and Scala, C., 1976. Effect of pyrite on resistivity and other logging measurements. SPWLA Seventeenth annual logging symposium. Society of Professional Well-Log Analysts. Houston, TX, United Sates, Denver, Colorado, United States.

Clifton, H.E., 2006. A re-examination of facies models for clastic shorelines. In Posamentier, H.W., Walker, R.G., (Eds.), Facies Models Revisited: SEPM Special Publication, v. 84, pp. 293-337.

Coates, L. and MacEachern, J.A., 2009. The ichnologic signatures of river- and wave-dominated delta complexes: differentiating deltaic and non-deltaic shallow marine successions, Lower Cretaceous Viking Formation and Upper Cretaceous Dunvegan Formation, west-central Alberta, In MacEachern, J.A., Bann, K.L., Gingras, M.K., Pemberton, S.G., eds., Applied Ichnology: SEPM, Short Course Notes 52, pp. 227-254.

Coleman, J.M., Gagliano, S.M. and Webb, J.E., 1964. Minor sedimentary structures in a prograding distributary. Marine Geology, v. 1(3), pp.240-258.

Colquhoun, I.M., 1999. On the Origin of Calcite-cemented Sandstones in the Clearwater Formation Oilsands, Alberta. Faculty of Graduate Studies, PhD thesis, University of Western Ontario, London, Ontario.

Currie, C.F., 2011. Sedimentology, Ichnology and Stratigraphy of the Clearwater Formation, Cold Lake, Alberta. Unpublished M.Sc. thesis, University of Alberta, Edmonton, Alberta.

Dafoe, L.T., 2009. Building upon ichnologic principles: modern biogenic structures, ichnotaxonomic classification, and palaeoecological and stratigraphic significance of ichnofossil assemblages. Unpublished Ph.D. Thesis, University of Alberta. 127. p

Dashtgard, S.E., MacEachern, J.A., Frey, S.E. and Gingras, M.K., 2012. Tidal effects on the shoreface: towards a conceptual framework. Sedimentary Geology v. 279, pp. 42-61.

Dekker, F., Visser, C. and Dankers, P., 1987. The Primrose-Kirby area in southern Athabasca, Alberta, Canada: a detailed geological investigation. American Association of Petroleum Geologists, Studies in Geology, v. 25, pp. 507-520.

Dott, R.H. and Bourgeois, J. 1982. Hummocky stratification: significance of its variable bedding sequences. Geological Society of America Bulletin, v. 93, pp. 663-680.

Dumas, S. and Arnott, R.W.C., 2006. Origin of hummocky and swaley cross-stratification – the controlling influence of unidirectional current strength and aggradation rate. Geology v. 34, pp. 1073-1076.

Durkin, P.R., Boyd, R.L., Hubbard, S.M., Shultz, A.W. and Blum, M.D., 2017. Three-dimensional reconstruction of meander-belt evolution, Cretaceous McMurray Formation, Alberta foreland basin, Canada. Journal of Sedimentary Research, v. 87(10), pp.1075-1099.

Dyson, I.A., 1995. A review of storm deposits in the geological record. PESA Journal. v. 23, pp. 39-50.

Eide, C.H., Howell, J. and Buckley, S., 2014. Distribution of discontinuous mudstone beds within wave-dominated shallow-marine deposits: Star Point sandstone and Blackhawk Formation, eastern Utah. AAPG bulletin, v. 98(7), pp. 1401-1429.

Elias, E.P.L. and van der Spek, A.J.F., 2006. Long-term morphodynamic evolution of Texel Inlet and its ebb-tidal delta (The Netherlands). Marine Geology, v. 225, pp. 5-21.

Feldman, H.R., McCrimmon, G.G. and Freitas, T.A. 2008. Fluvial to Estuarine valley-fill models without age-equivalent sandy shoreline deposits, based on the Clearwater Formation (Cretaceous) at Cold Lake, Alberta, Canada. In Recent Advances in Models of Siliciclastic Shallow Marine Stratigraphy: SEPM, Special Publication v. 90, pp. 443-472.

Föllmi, K.B. and Grimm, K.A., 1990. Doomed Pioneers: Gravity-flow deposition and bioturbation in marine oxygen-deficient environments: Geology, v. 18, pp. 1069-1072.

Frey, R.W., 1990. Trace fossils and hummocky cross-stratification, Upper Cretaceous of Utah: Palaios, v. 5, pp. 203-218.

Frey, R.W. and Goldring, R., 1992. Marine event beds and recolonization surfaces as revealed by trace fossil analysis. Geological Magazine v. 129, pp. 325-335.

Galloway, W.E., 1989. Genetic stratigraphic sequences in basin analysis I: architecture and genesis of flooding-surface bounded depositional units. AAPG bulletin, v. 73(2), pp. 125-142.

Gani, M.R., Bhattacharya, J.P. and MacEachern, J.A., 2009. Using ichnology to determine relative influence of waves, storms, tides, and rivers in deltaic deposits: examples from Cretaceous Western Interior Seaway, USA.

Gingras, M.K., Bann, K.L., MacEachern, J.A. and Pemberton, S.G., 2007. A conceptual framework for the application of trace fossils. In MacEachern, J.A., Bann, K.L., Gingras, M.K., Pemberton, S.G. (Eds.), Applied Ichnology. Society of Economic Paleontologists and Mineralogists: Short Course Notes, v. 52, pp. 1-25.

Gingras, M.K., Pemberton, S.G., Dashtgard, S.E. and Dafoe, L., 2008. How fast do invertebrates burrow? Palaeogeography, Palaeoclimatology, Palaeoecology, v. 270. pp.280-286.

Gingras, M.K., MacEachern, J.A. and Dashtgard, S.E., 2011. Process ichnology and the elucidation of physico-chemical stress. Sedimentary Geology. v. 237, pp. 115-134.

Gingras, M.K., Pemberton, S.G. and Smith, M., 2015. Bioturbation: reworking sediments for better or worse. Oilfield Review, v. 26 (4). pp. 46-58.

Goodbred Jr, S.L. and Hine, A.C., 1995. Coastal storm deposition: Salt-marsh response to a severe extratropical storm, March 1993, west-central Florida. Geology, v. 23(8), pp. 679-682.

Hampson, G.J. and Storms, J.E.A., 2003. Geomorphological and sequence stratigraphic variability in wave-dominated, shoreface-shelf parasequences. Sedimentology, v. 50, pp. 667-701.

Hampson, G.J., Rodriguez, A.B., Storms, J.E.A., Johnson, H.D. and Meyer, C.T., 2008. Geomorphology and high-resolution stratigraphy of progradational wave-dominated shoreline deposits: impact on reservoir-scale facies architecture. In Hampson, G.J., Steel, R.J., Burgess, P.M. and Dalrymple, R.W. (Eds.), Recent Advances in Models of Siliciclastic Shallow-Marine Stratigraphy. SEPM Special Publication, v. 90, pp. 117-142.

Hansen, C.D. and MacEachern, J.A., 2007. Application of the asymmetric delta model to along-strike facies variations in a mixed wave- and river-influenced delta lobe, Upper Cretaceous Basal Belly River Formation, Central Alberta. In MacEachern, J.A., Bann, K.L., Gingras, M.K., Pemberton, S.G. (Eds.), Applied Ichnology. SEPM Short Course Notes, v. 52, pp. 255-271.

Harrison, D.B., Glaister, R.P. and Nelson, H.W. 1981. Reservoir description of the Clearwater oil sands, Cold Lake, Alberta, Canada. In First UNITAR Conference: The Future of Heavy Crude and Tar Sands, Edmonton, Canada, pp. 264-279.

Hart, B.S. and Long, B.F., 1996. Forced regressions and lowstand deltas; Holocene Canadian examples. Journal of Sedimentary Research, v. 66 (4), pp.820-829.

Hathaway, B., 2016. Regional subsurface mapping of the Clearwater Formation, Lower Cretaceous, Northeast Alberta. abstract. AAPG Annual Convention and Exhibition.

Hauck, T.E., Peterson, J.T., Hathaway, B., Grobe, M., MacCormack, K. and Cotterill, D., 2017. New Insights from regional-scale mapping and modelling of the Paleozoic succession in northeast Alberta: Paleogeography, evaporite dissolution, and controls on Cretaceous depositional patterns on the sub-Cretaceous unconformity. Bulletin of Canadian Petroleum Geology, v. 65(1), pp. 87-114.

Hayes, B.J., Christopher, J.E., Rosenthal, L., Los, G., McKercher, B., Minken D.F., Trembley, Y.M. and Fennel, J., 1994. Cretaceous Mannville Group of the Western Canada Sedimentary Basin. In Mossop, G.D. and Shetsen, I., (eds.) Geological Atlas of the Western Canada Sedimentary Basin. Canadian Society of Petroleum Geologists and Alberta Research Council, Special Report 4, URL http://www.ags.gov.ab.ca/publications/wcsb_atlas/a_ch19/ch_19.html.

Herbers, D.S., MacNaughton, R.B., Timmer, E.R. and Gingras, M.K. 2016. Sedimentology and ichnology of an Early-Middle Cambrian storm influenced barred shoreface succession, Colville Hills, Northwest Territories. Bulletin of Canadian Petroleum Geology, v. 64, pp. 538–554.

Hein, F.J. and Cotterill, D.K., 2006. The Athabasca oil sands- a regional geological perspective, Fort McMurray area, Alberta, Canada. Natural Resources Research, v. 15(2), pp. 85-102.

Horner, S.C., Hubbard, S.M., Martin, H.K. and Hagstrom, C.A., 2019. Reconstructing basin-scale drainage dynamics with regional subsurface mapping and channel-bar scaling, Aptian, Western Canada Foreland Basin. Sedimentary Geology, v. 385, pp. 26-44.

Hovikoski, J., Lemiski, R., Gingras, M.K., Pemberton, S.G. and MacEachern, J.A., 2008, Ichnology and sedimentology of a mud-dominated deltaic coast: Upper Cretaceous Alderson Member (Lea Park Fm), western Canada: Journal of Sedimentary Research, v. 78, pp. 803-824.

Howard, J.D. and Frey, R.W., 1975. Regional animal-sediment characteristics of Georgia estuaries. Senkenb. Marit. v. 7 p. 33-103.

Howard, J.D. and Frey, R.W., 1984. Characteristic trace fossils in nearshore to offshore sequences, Upper

Cretaceous of east-central Utah: Canadian Journal of Earth Sciences, v. 21, pp. 200-219.

Howell, J.A., Skorstad, A., MacDonald, A., Fordham, S., Flint, B., Fjellvoll, B. and Manzocchi, M. 2008. Sedimentologic parameterization of shallow-marine reservoirs. Petroleum Geoscience, v. 14 pp. 17–34.

Hutcheon, I., Abercrombie, H., Putnam, P., Gardner, R. and Krouse, R. 1989. Diagenesis and sedimentology of the Clearwater Formation at Tucker Lake. Bulletin of Canadian Petroleum Geology, v. 37, (1), pp. 83-97.

Ichaso, A.A. and Dalrymple, R.W., 2009, Tide- and wave-generated fluid mud deposits in the Tilje Formation (Jurassic), offshore Norway: Geology, v. 37, pp. 539-542.

Ingram, R.L., 1953, Fissility of mudrocks: Geological Society of America Bulletin, v. 64, pp. 869-878.

Jackson, P., 1984. Paleogeography of the Lower Cretaceous Mannville Group of Western Canada. In Masters, J.A., ed., Elmworth- Case Study of a Deep Basin Gas Field. American Association of Petroleum Geologists, v. 38, pp. 49-78.

Kapoutsos, D., 2005. Provenance changes and glauconite formation in the Broken River to Iron Creek/ Waipara Greensand Formations marks the late Cretaceous-Eocene transgression. Unpublished M.Sc. thesis. University of Canterbury, Christchurch, New Zealand.

Kidwell, S.M., 1989. Stratigraphic condensation of marine transgressive records: origin of major shell deposits in the Miocene of Maryland. The Journal of Geology, v. 97(1). pp. 1-24.

Kramers, J.W., 1974. Geology of the Wabasca A oil sand deposit (Grand Rapids Formation). In Oil Sands: Fuel of the Future, Hills LV (ed.). Canadian Society of Petroleum Geologists, Memoirs 3, Calgary, pp. 68-83.

Kumar, N. and Sanders, J.E., 1976. Characteristics of shoreface storm deposits; modern and ancient examples. Journal of Sedimentary Research, v. 46(1), pp. 145-162.

Leckie, D.A. and Walker, R.G., 1982. Storm- and tide-dominated shorelines in Cretaceous Moosebar-Lower Gates interval-outcrop equivalents of Deep Basin gas trap in western Canada: AAPG bull., v. 66, p. 138-157.

Leckie, D.A., 1986. Rates, Controls, and sand-body geometries of transgressive-regressive cycles: Cretaceous Moosebar and Gates Formations, British Columbia. AAPG Bulletin, 70(5), pp. 516-535.

Leckie, D.A. and Krystinik, L.F., 1989. Is there evidence for geostrophic currents preserved in the sedimentary record of inner to middle-shelf deposits. Journal of Sedimentary Research, 59 (5), pp. 862-870.

Leckie, D.A. and Smith, D.G., 1992. Regional setting, evolution, and depositional cycles of the Western Canada Foreland Basin. In MacQueen, R.W., and Leckie, D. A., eds., Foreland Basins and Fold Belts. American Association of Petroleum Geologists, Memoir 55, pp. 9-46.

Liu, J.T. and Zarillo, G.A., 1989. Distribution of grain sizes across a transgressive shoreface. Marine Geology, v. 87, pp. 121-136.

MacEachern, J.A. and Pemberton, S.G., 1992. Ichnologic aspects of Cretaceous shoreface successions and shoreface variability in the Western Interior Seaway of North America. In Applications of ichnology to petroleum exploration. A core workshop, S.G. Pemberton (ed.) SEPM Core Workshop No. 17, Calgary, Alberta, pp. 57-84.

MacEachern, J.A., Bann, K.L., Bhattacharya, J.P. and Howell, C.D., 2005. Ichnology of deltas, In Giosan, L., and Bhattacharya, J.P., eds., River Deltas: Concepts, Models, and Examples: SEPM, Special Publication 83, pp. 49–85.

MacEachern, J.A., Bann, K.L., Hampson, G.J., Steel, R.J., Burgess, P.M. and Dalrymple, R.W., 2008. The role of ichnology in refining shallow marine facies models. Recent advances in models of siliciclastic shallow-marine stratigraphy, v. 90, pp. 73-116.

MacEachern, J.A., Bann, K.L., Gingras, M.K., Zonneveld, J.P., Dashtgard, S.E. and Pemberton, S.G., 2012. The ichnofacies paradigm. In Developments in Sedimentology v.64, pp. 103-138.

MacEachern, J.A. and Bann, K.L., 2020. The *Phycosiphon* ichnofacies and the *Rosselia* ichnofacies; two new ichnofacies for marine deltaic environments, Journal of Sedimentary Research, v. 90, (8), pp. 855-886.

MacKay, D.A. and Dalrymple, R.W., 2011, Dynamic mud deposition in a tidal environment: the record of fluid-mud deposition in the Cretaceous Bluesky Formation, Alberta, Canada: Journal of Sedimentary Research, v. 81, pp. 901-920.

Mángano, M.G., Buatois, L.A. and Muniz Guinea, F., 2005. Ichnology of the Alfarcito Member (Santa Rosita Formation) of northwest Argentina, animal-substrate interactions in a lower Paleozoic wave-dominated shallow sea. Ameghiniana, 42, pp. 641–668.

Masters, J.A., 1984. Lower Cretaceous Oil and Gas in Western Canada. In Elmworth - Case Study of a Deep Basin Gas Field. J.A. Masters (ed.). American Association of Petroleum Geologists, Memoir 38, pp. 1-33.

McCabe, P.J., 1984. Depositional environments of coal and coalbearing strata. International Association of Sedimentologists. Special Publication (7) pp. 13-42.

McCrimmon, G.G., 1996. Sedimentology and sequence stratigraphy of the Lower Cretaceous Clearwater Formation, Cold Lake, Alberta. Unpublished M.Sc. thesis. University of Ottawa. 281p.

McCrimmon, G. and Arnott, R.W.C. 2002. The Clearwater Formation, Cold Lake, Alberta: a world class hydrocarbon reservoir hosted in a complex succession of a tide-dominated deltaic deposits. Bulletin of Canadian Petroleum Geology, v. 50, (3), pp. 370-392.

McLean, J.R. and Wall, J.H., 1981. The Early Cretaceous Moosebar Sea in Alberta: Bulletin of Canadian Petroleum Geology, v. 29, pp. 334-377.

Minken, D.F., 1974. The Cold Lake oil sands: geology and a reserve estimate. In Hills, L.V., (ed.), Oil Sands, Fuel of the Future. Canadian Society of Petroleum Geologists, Memoir 3, pp. 84-99.

Moslow, T.F. and Pemberton, S.G., 1988. An integrated approach to the sedimentologic analysis of some Lower Cretaceous shoreface and delta front sandstone sequences. pp. 373-386.

Mulder, T., and Syvitski, J.P.M., 1996. Turbidity currents generated at river mouths during exceptional discharges to the world oceans. Journal of Geology v. 103, pp. 285-299.

Myrow, P.M. and Southard, J.B., 1996. Tempestite deposition. Journal of Sedimentary Research, v. 66, pp. 875-887.

Newitt, D., 2017. Integrated sedimentology, sequence stratigraphy, and reservoir characterization of the basal Spirit River Formation, west-central Alberta, M.Sc thesis, Graduate studies, University of Calgary, Alberta.

Nichols, G.J. and Fisher, J.A., 2007. Processes, facies and architecture of fluvial distributary system deposits. Sedimentary Geology, v. 195(1-2), pp. 75-90.

Nyberg, B., and Howell, J.A., 2016. Global distribution of modern shallow marine shorelines. Implications for exploration and reservoir analogue studies: Marine and Petroleum Geology, v. 71, pp .83-104.

Odin, G.S., and Matter, A., 1981. De glauconiarum origine. Sedimentology v. 28. pp. 611-641

Olariu, C., and Bhattacharya, J.P., 2006. Terminal distributary channels and delta-front architecture of river-dominated delta systems. Journal of sedimentary research, v. 76(2), pp. 212-233.

Peacock, M.J., 2010. Athabasca oil sands: reservoir characterization and its impact on thermal and mining opportunities. Geological Society, London, Petroleum Geology Conference series. Geological Society of London, v. 7, pp. 1141-1150.

Pemberton, S.G. and Frey, R.W. 1985: The *Glossifungites* ichnofacies: modern examples from the Georgia coast, U.S.A. In Curran, H.A. (ed.): Biogenic structures: their use in interpreting depositional environments. Society of Economic Paleontologists and Mineralogists, Special Publication v. 35, pp. 237-259.

Pemberton, S.G., MacEachern, J.A. and Ranger, M.J., 1992a. Ichnology and event stratigraphy: the use of trace fossils in recognizing tempestites. In. Pemberton, S.G. (Ed.), Applications of Ichnology to Petroleum exploration, Society of Economic Paleontologists and Mineralogists, Core Workshop v. 17, pp. 85-117.

Pemberton, S.G., Van Wagoner, J.C. and Wach, G.D., 1992b. Ichnofacies of a wave-dominated shoreline. In Applications of ichnology to petroleum exploration. A core workshop, S.G. Pemberton (ed.) SEPM Core Workshop No. 17, Calgary, Alberta, pp. 339-382.

Pemberton, S.G. and MacEachern, J.A., 1995. The sequence stratigraphic significance of trace fossils: examples from the Cretaceous foreland basin of Alberta, In Van Wagoner, J.C., and Bertram, G., eds., Sequence Stratigraphy of Foreland Basin Deposits- Outcrop and Subsurface Examples from the Cretaceous of North America: American Association of Petroleum Geologists, Memoir 64, pp. 429-475.

Pemberton, S.G. and MacEachern, J.A., 1997. The ichnologic signature of storm deposits: the use of trace fossils in event stratigraphy. In Brett, C.E. (Ed.), Paleontological Event Horizons – Ecological and Evolutionary Implications. Columbia University Press, New York, pp. 73-109.

Pemberton, S.G. and Gingras, M.K., 2005, Classification and characterization of biogenically enhanced hydraulic conductivity: American Association of Petroleum Geologists Bulletin, v. 89, pp. 1493-1517.

Pemberton, S.G., MacEachern J.A., Gingras, M.K. and Saunders, T.D.A., 2008. Biogenic chaos: cryptobioturbation and the work of sedimentologically friendly organisms, Palaeogeography, Palaeoclimatology, Palaeoecology, v. 270 (3-4), pp. 273-279.

Pemberton, S.G., MacEachern, J.A., Dashtgard, S.E., Bann, K.L., Gingras, M.K. and Zonneveld, J.P., 2012. Shorefaces. In Knaust, D., Bromley, R.G. (Eds.), Trace Fossils as Indicators of Sedimentary Environments. Developments in Sedimentology, v. 64. Elsevier, Amsterdam, pp. 563-604.

Plint, A.G. 2010. Wave- and storm-dominated shoreline and shallow-marine systems. In James, N.P., Dalrymple, R.W. (Eds.), Facies Models 4, Geological Association of Canada, St. John's, Geotext 6, pp. 167-199.

Plummer, P.S. and Gostin, V.A., 1981: Shrinkage cracks: desiccation or synaeresis? Journal of Sedimentary Petrology v.51, pp. 1147-1156.

Pontén, A. and Plink- Björklund, P.I.R.E.T., 2007. Depositional environments in an extensive tide-influenced delta plain, Middle Devonian Gauja Formation, Devonian Baltic Basin. Sedimentology, v. 54(5), pp. 969-1006.

Porter, J.W., Price, R.A. and McCrossan, R.G., 1982. The Western Canada Sedimentary Basin. Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences v. 305, pp. 169-192.

Posamentier, H.W. and Morris, W.R., 2000. Aspects of the stratal architecture of forced regressive deposits, In Hunt, D., and Gawthorpe, R.L., (eds.), Sedimentary responses to forced regressions: Geological Society of London, Special Publication v. 172, pp. 19-46.

Potocki D. and Hutcheon, I., 1992. Lithology and Diagenesis of Sandstones in the Western Canada Foreland Basin. In Leckie, D.A., and Macqueen, R.W., (eds.), Foreland basins and fold belts: American Association of Petroleum Geologists Memoir v. 55, pp. 229–257.

Price, R.A., 1994. Cordilleran tectonics and the evolution of the Western Canada Sedimentary Basin. In Geological Atlas of the Western Canada Sedimentary Basin. G.D. Mossop and I. Shetsen (compilers), pp. 13-24. Canadian Society of Petroleum Geologists and Alberta Research Council.

Putnam, P.E. and Pedskalny, M.A. 1983. Provenance of Clearwater Formation reservoir sandstones, Cold Lake, Alberta, with comments on feldspar composition. Bulletin of Canadian Petroleum Geology, v. 31, (3), pp. 148-160.

Ranger, M.J., 1994. A Basin Study of the Southern Athabasca Oil Sands Deposit. (Ph.D. thesis). University of Alberta, Edmonton, AB, 290 p.

Ranger, M.J. and Gingras, M.K., 2010. Geology of the Athabasca oil sands: field guide and overview, 5a ed. Canadian Society of Petroleum Geologists, 125 p.

Raychaudhuri, I. and Pemberton, S.G., 1992. Ichnologic and sedimentologic characteristics of open marine to storm-dominated restricted marine settings within the Viking/Bow Island Formations, south-central Alberta. In Applications of ichnology to petroleum exploration: A core workshop, S.G. Pemberton (ed.) SEPM Core Workshop No. 17, Calgary, Alberta, pp. 119-139.

Reineck, H.E., 1963. Sedimentgefüge im Bereichder südlichen Nordsee: Abhandlungen der Senckenbergische naturforschende Gesellschaft, 505 p.

Rice, A.L., D.S.M., Billett, J. Fry, A.W.G., Joh, R.S., Lampitt, R.F.C., Mantoura. and R.J. Morris., 1986. Seasonal deposition of phytodetritus to the deep-sea floor. Royal Society of Edinburgh Proceedings, v. 88B, pp. 205-279.

Rossi, V.M., Perillo, M.M., Steel, R.J. and Olariu, C., 2017. Quantifying mixed-process variability In shallow-marine depositional systems: What are sedimentary structures really telling us?. Journal of Sedimentary Research, v. 87(10), pp. 1060-1074.

Rouble, R. and Walker, R.G., 1997. Sedimentology, high-resolution allostratigraphy, and key stratigraphic surfaces in Falher members A and B, Spirit River Formation, west-central Alberta. In Pemberton, S.G., James, D.P. (Eds.), Petroleum Geology of the Cretaceous Mannville Group, Western Canada. Canadian Society of Petroleum Geologists, Memoir, v. 18, pp. 1–29.

Saunders, T.D.A., MacEachern, J.A. and Pemberton, S.G., 1994. Cadotte Member Sandstone: progradation in a boreal basin prone to winter storms. In Pemberton, S.G., James, D.P., Wightman, D.M. (Eds.), Mannville Core Conferences, Canadian Society of Petroleum Geologists pp. 331-350.

Seilacher, A., 1967. Bathymetry of trace fossils. Marine Geology, v. 5, pp. 412-428.

Shuquing, Z., Haiping, H. and Yuming, L. 2008. Biodegradation and origin of oil sands in the Western Canada Sedimentary Basin. Petroleum Science, v. 5, pp. 87-94.

Smith, D.G., Zorn, C.E. and Sneider, R.M., 1984. The paleogeography of the Lower Cretaceous of western Alberta and Northeastern British Columbia in an adjacent to the deep basin of the Elmworth area. In Masters, J.A., ed., Elmworth – Case Study of a Deep Basin Gas Field. American Association of Petroleum Geologists, Memoir 38, pp. 79-115.

Stockmal, G.S. and Beaumont, C., 1987. Geodynamic models of convergent margin tectonics: the southern Canadian Cordillera and the Swiss Alps, In Beaumont, C. and Tankard, A.J., (eds.), Sedimentary basins and basin-forming mechanisms: Canadian Society of Petroleum Geologists, memoir 12, pp. 393-411.

Stott, D.F., 1984, Cretaceous sequences of the Foothills of the Canadian Rocky Mountains, In Stott, D.F., and Glass, D.J., eds., The Mesozoic of Middle North America: Canadian Society of Petroleum Geologists, Memoir 9, pp. 85-107.

Swift, D.J.P., Phillips, S. and Thorne, J.A., 1991. Sedimentation on continental margins: V, Parasequences. In Swift, D.J.P., Oertel, G.F., Tillman, R.W., Thorne, J.A. (Eds.), Shelf Sand and Sandstone Bodies—Geometry, Facies and Sequence Stratigraphy. International Association of Sedimentologists Special Publication, v. 14, pp. 153 – 187.

Taylor, A.M. and Goldring, R., 1993. Description and analysis of bioturbation and ichnofabric. Journal of the Geological Society, London, v. 150, pp. 141-148.

Taylor, A., Goldring, R. and Gowland, S., 2003. Analysis and application of ichnofabrics. Earth-Sci. Rev. 60, pp. 227-259.

Tozer, R.S., Choi, A.P., Pietras, J.T. and Tanasichuk, D.J., 2014. Athabasca oil sands: Megatrap restoration and charge timing. AAPG bulletin, v. 98(3), pp. 429-447.

Tufano, B.C. and Pietras, J.T., 2017. Coupled flexural-dynamic subsidence modeling approach for retro-foreland basins: Example from the Western Canada Sedimentary Basin. GSA Bulletin, v. 129 (11-12), pp. 1622-1635.

Vakarelov, B.K. and Ainsworth, R.B., 2013. A hierarchical approach to architectural classification in marginal-marine systems: bridging the gap between sedimentology and sequence stratigraphy. AAPG Bull. 97, pp. 1121-1161.

Van Houten, F.B. and Purucker, M.E., 1984. Glauconitic peloids and chamositic ooids. Favorable factors, constraints, and problems. Earth Sci. Rev., 20: pp. 211-243.

Van Wagoner, J.P., Posamentier, H.W., Mitchum, R.M., Vail, P.R., Sarg, J.F., Loutit, T.S. and Hardenbol, J., 1988. An overview of the fundamentals of sequence stratigraphy and key definitions, In Wilgus, C.K., Hasting, B.S., Kendall, C.G. St.C., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C., eds., Sea-Level Changes- An Integrated Approach: SEPM Special Publication, v. 42, pp. 39-45.

Van Wagoner, J.C., Mitchum, R.M., Campion, K.M. and Rahmanian, V.D., 1990. Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: concepts for high-resolution correlation of time and facies: AAPG Methods in Exploration 7. AAPG, Tulsa.

Vossler, S.M. and Pemberton, S.G., 1988. *Skolithos* in the Upper Cretaceous Cardium Formation: an ichnologic example of opportunistic ecology. Lethaia 21, pp. 351-362.

Walker, R.G. and Plint, A.G., 1992, Wave- and storm-dominated shallow marine systems, In Walker, R.G., and James, N.P., eds., Facies Models, Response to Sea Level Change: Geological Association of Canada, pp. 219-238.

Walker, R.G., 1995. Sedimentary and tectonic origin of a transgressive surface of erosion; Viking Formation, Alberta, Canada. Journal of Sedimentary Research, v. 65 (2b) pp. 209-221.

Wallace, J. and Lavigne, J., 2011. The Clearwater Formation: A facies study for SAGD water source in the Athabasca Oil Sands. American Association of Petroleum Geologists, Discovery Article #90173.

Weise, B.R., 1980. Wave-Dominated Deltaic Systems of the Upper Cretaceous San Miguel Formation, Maverick Basin, South Texas (Report of investigations 107). Austin, Texas, Bureau of Economic Geology, pp. 1-39.

Wesolowski, L.J., Buatois, L.A., Mángano, M.G., Ponce, J.J. and Carmona, N.B., 2018. Trace fossils, sedimentary facies and parasequence architecture from the Lower Cretaceous Mulichinco Formation of Argentina: the role of fair-weather waves in shoreface deposits. Sedimentary Geology, v. 367, pp. 146-163.

Wickert, L.M., 1992. Sequence stratigraphy, diagenesis, and hydrogeology of the Lower Cretaceous Clearwater Formation, Cold Lake oil sands deposit, east-central Alberta, Canada. M.Sc. thesis, University of Alberta, 365p.

Wightman, D.M., Strobl, R.S., Cotterill, D.K., Berhane, H. and Attalla, M.N., 1997. Stratigraphy, depositional modelling and resource characterization of the McMurray/Wabiskaw deposit, western portion of the Athabasca oil sands area, northeastern Alberta. Memoirs of the Canadian Society of Petroleum Geologists v. 18, pp. 345-374.

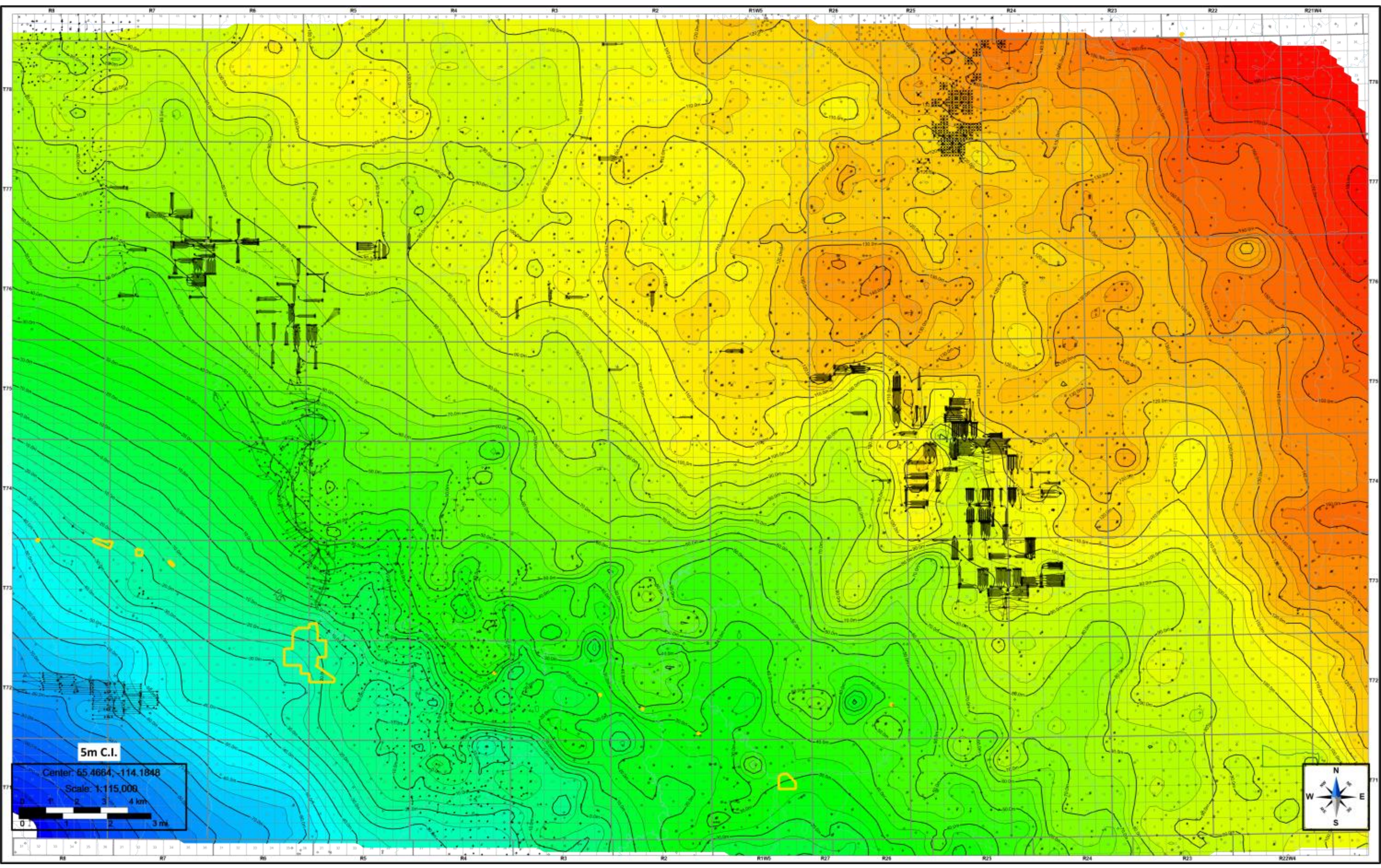
Wheatcroft, R.A., 1990. Preservation potential of sedimentary event layers. Geology, v. 18, pp. 843-845.

Yoshida, S., Steel, R.J. and Dalrymple, R.W., 2007. Changes in depositional processes- an ingredient in a new generation of sequence-stratigraphic models: Journal of Sedimentary Research v. 77, pp. 447-460.

APPENDIX

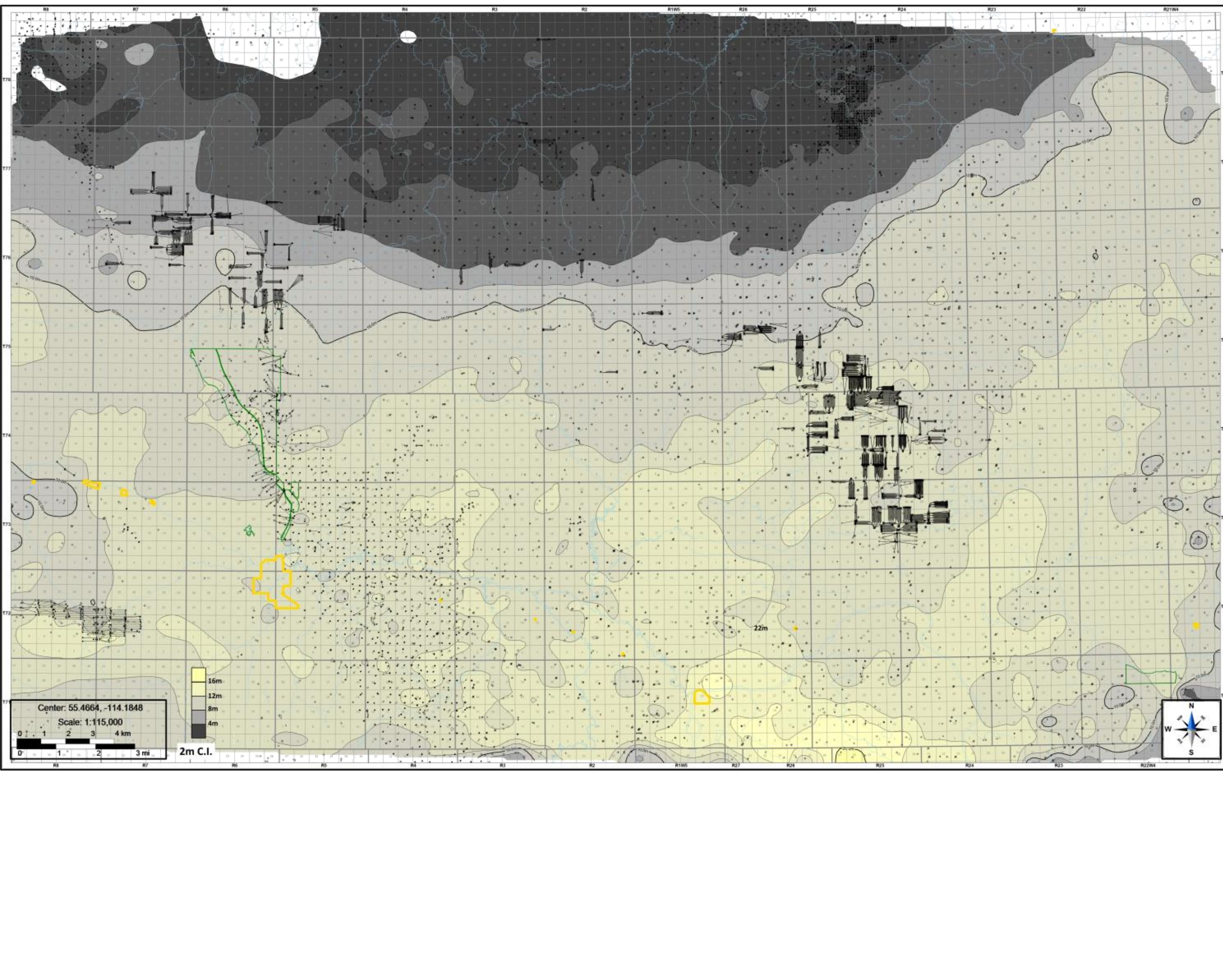
MRTN A Subsea Map

Structural surface picked on marine flooding surface MRTN A (see lithostratigraphic figure 3)



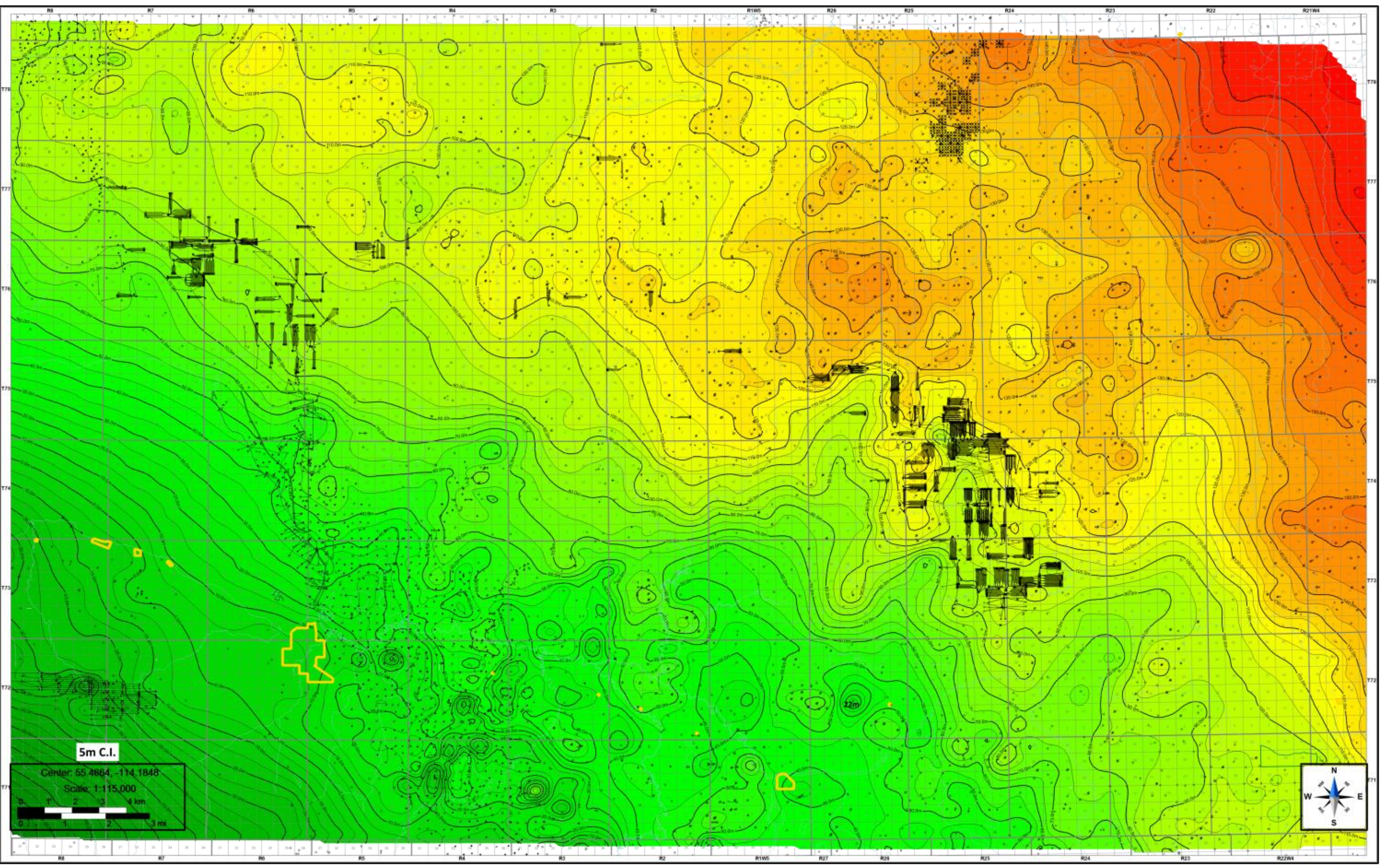
MRTN A Isopach Thickness Map

Isopach thickness map from Wabiskaw marker to top of MRTN A



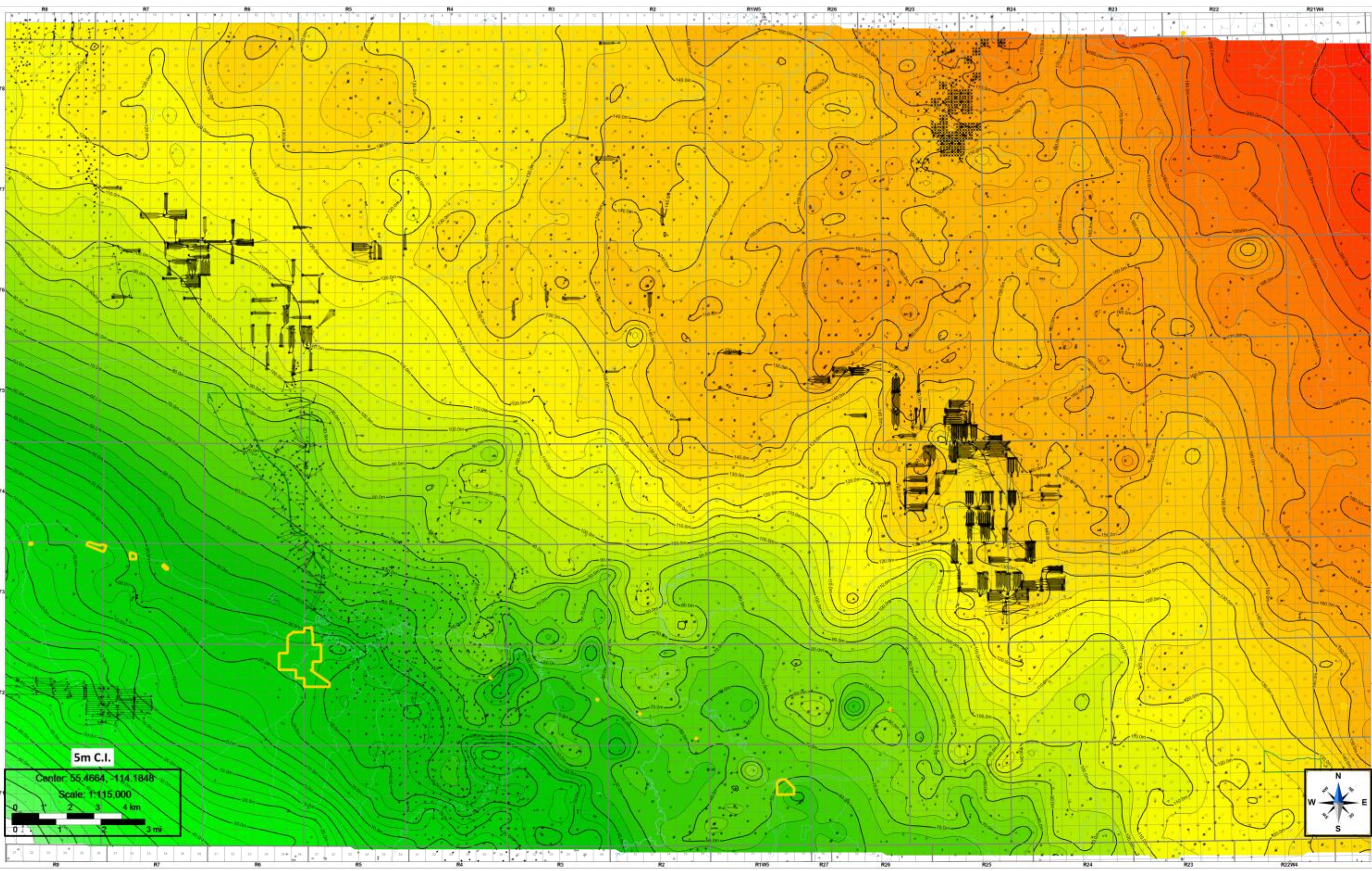
MRTN B Subsea Map

Structural surface picked on marine flooding surface MRTN B (see lithostratigraphic figure 3)



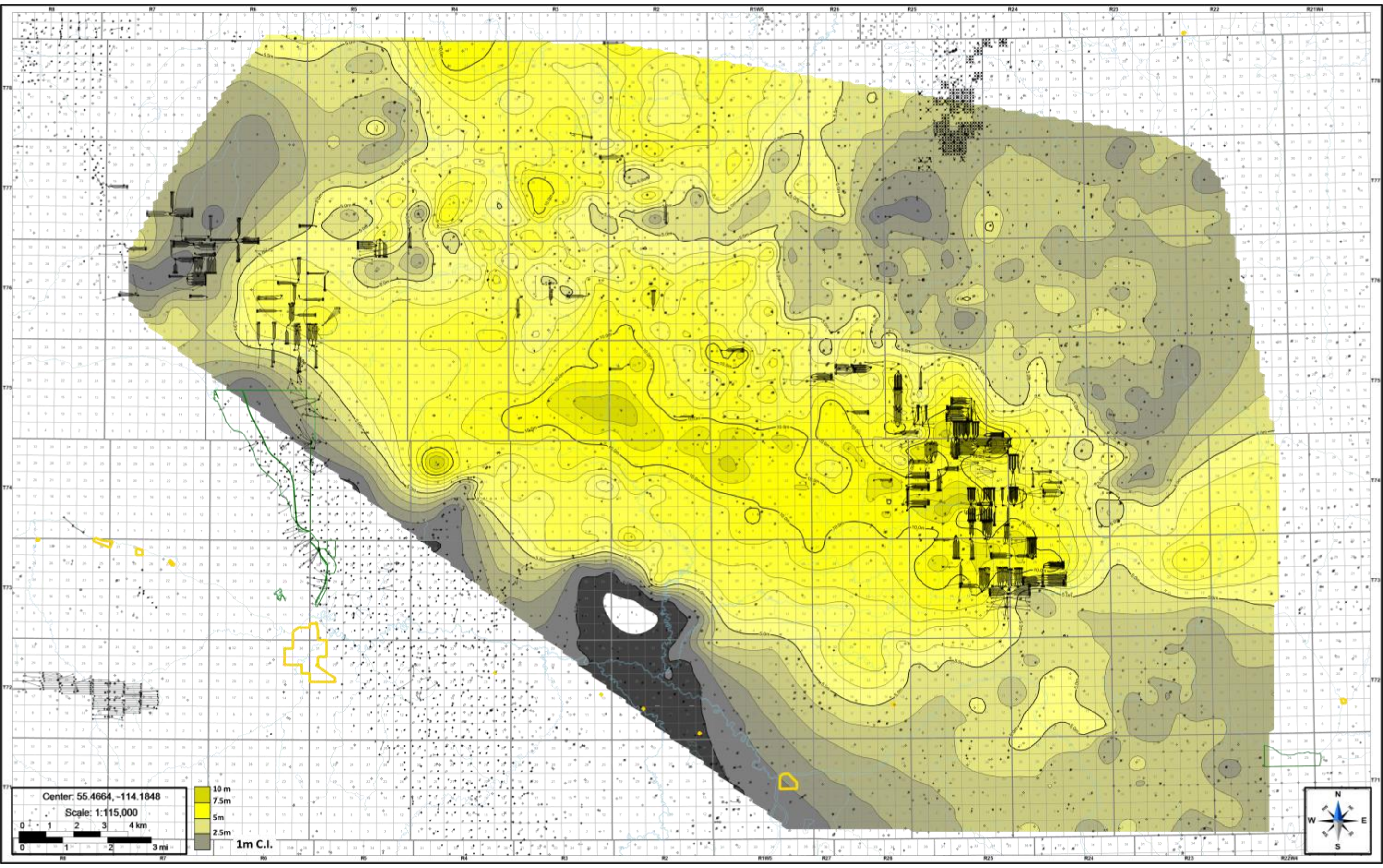
MRTN C Subsea Map

Structural surface picked on marine flooding surface MRTN C (see lithostratigraphic figure 3)



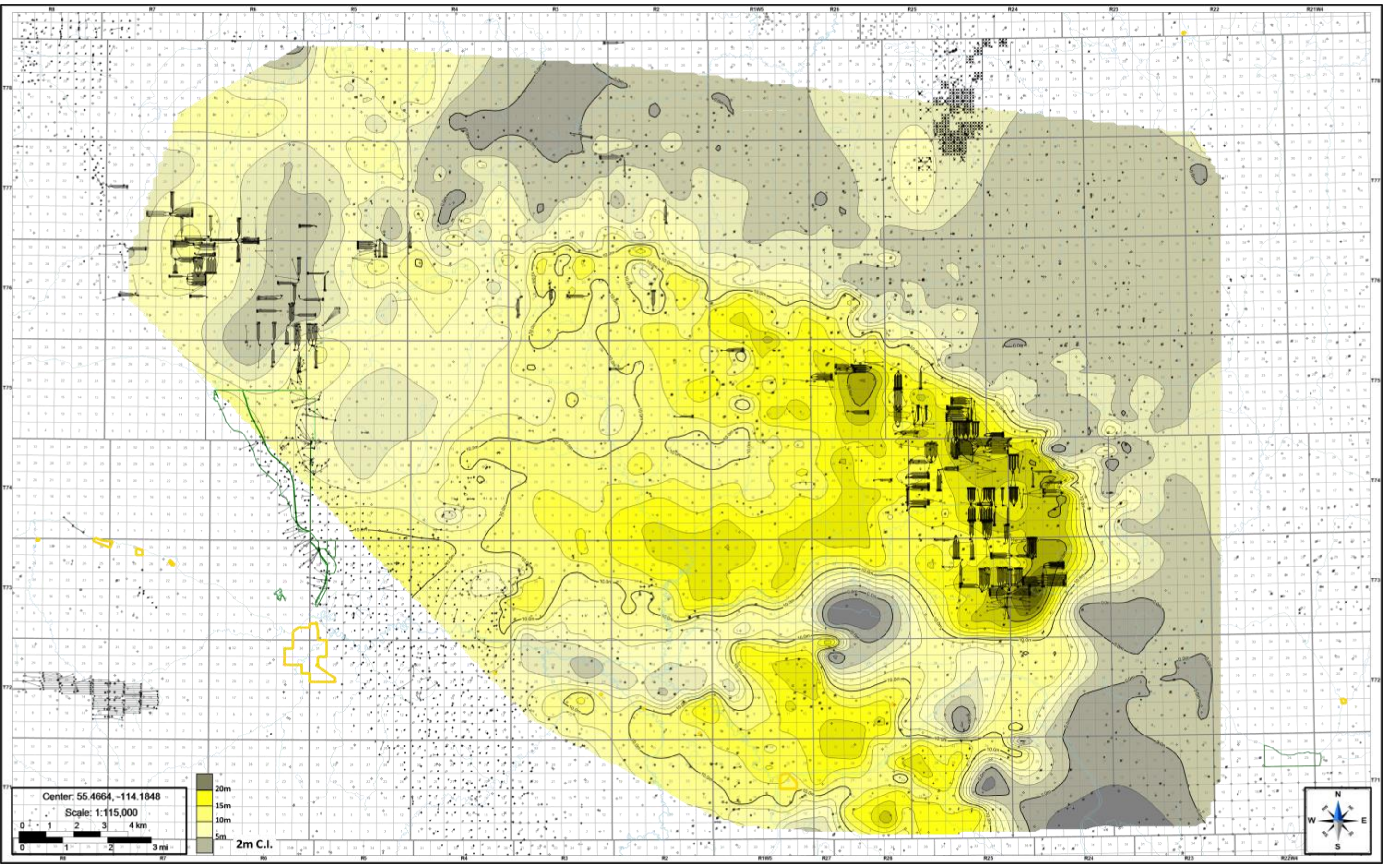
MRTN C "Lower" Gross Sandstone Map

Base of MRTN C base sandstone to top of MRTN C2



MRTN C “Upper” Gross Sandstone Map

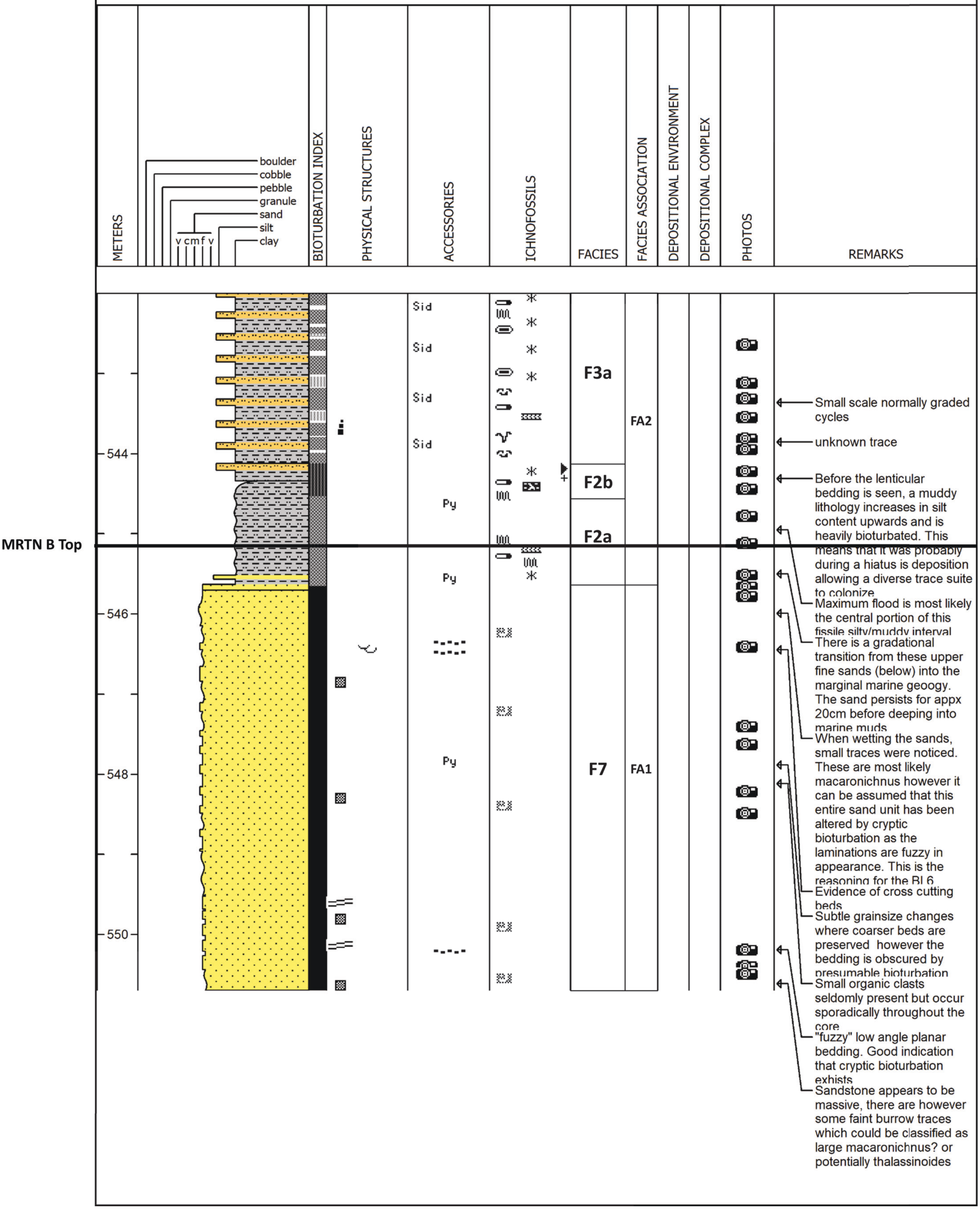
Base of MRTN C3 (excluding flooding surface) to top of MRTN C Sandstone

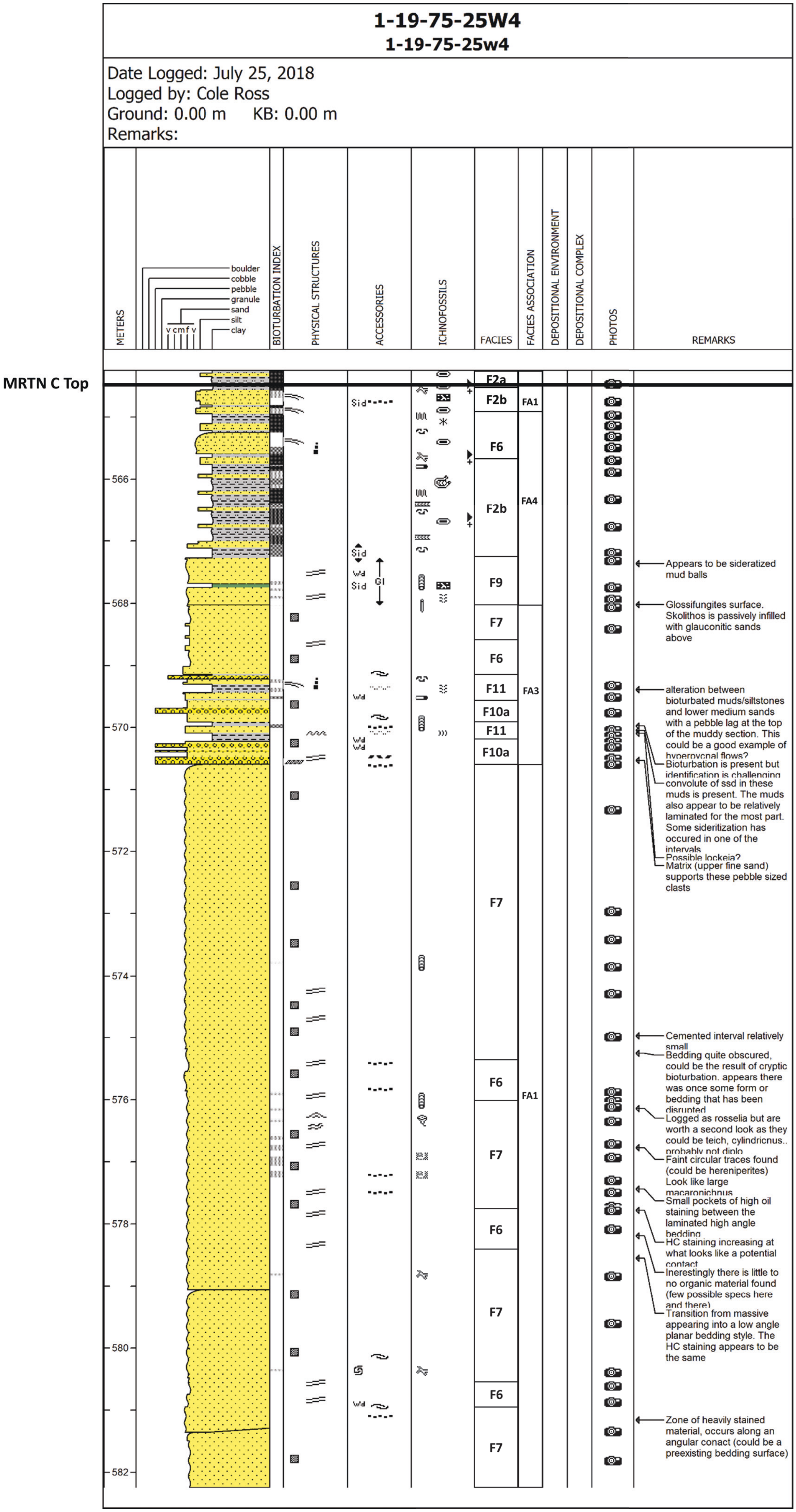


1-18-71-1W5

1-18-71-1w5

Date Logged: August 15, 2018
Logged by:
Ground: 0.00 m KB: 0.00 m
Remarks:



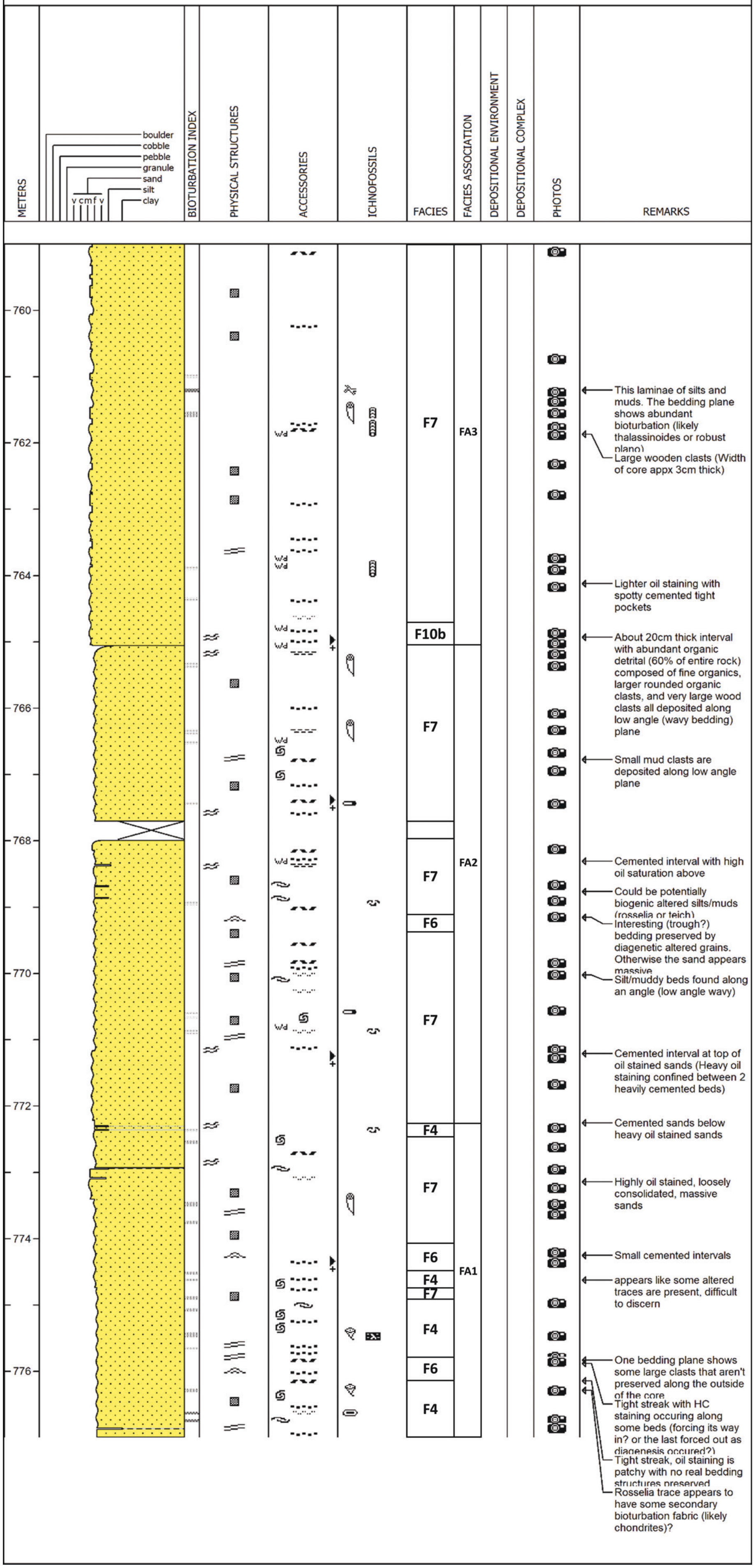


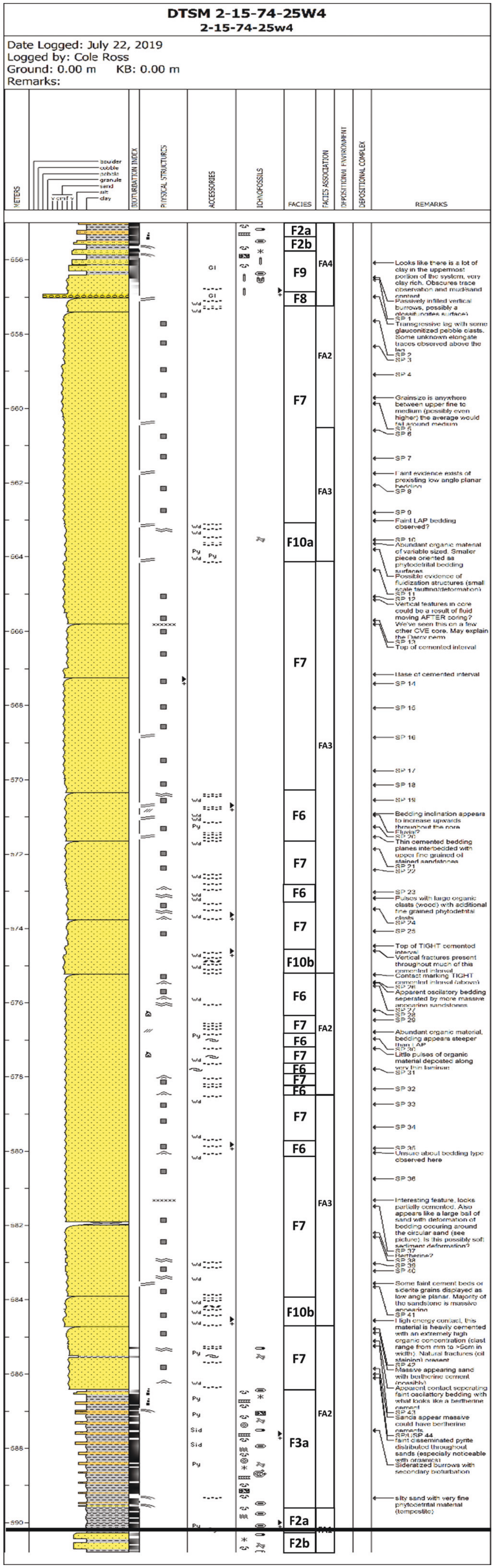
1-19-75-25W4
1-19-75-25w4
Date Logged: July 25, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:
METERS
boulder
cobble
pebble
granule
sand
silt
clay
v c m f v
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
DEPOSITIONAL COMPLEX
PHOTOS
REMARKS
MRTN C Top
566
568
570
572
574
576
578
580
582
Sid
Wd
Gl
F2a
F2b
F6
F2b
F9
F7
F6
F11
F10a
F11
F10a
F7
F6
F7
F6
F7
F6
F7
FA1
FA4
FA3
FA1
Appears to be sideratized mud balls
Glossifungites surface. Skolithos is passively infilled with glauconitic sands above
alteration between bioturbated muds/siltstones and lower medium sands with a pebble lag at the top of the muddy section. This could be a good example of hyperpycnal flows?
Bioturbation is present but identification is challenging
convolute of ssd in these muds is present. The muds also appear to be relatively laminated for the most part. Some sideritization has occured in one of the intervals
Possible lockeia?
Matrix (upper fine sand) supports these pebble sized clasts
Cemented interval relatively small
Bedding quite obscured, could be the result of cryptic bioturbation. appears there was once some form or bedding that has been disrupted
Logged as rosselia but are worth a second look as they could be teich, cylindricnus.. probably not diplo
Faint circular traces found (could be hereniperites) Look like large macaronichnus
Small pockets of high oil staining between the laminated high angle bedding
HC staining increasing at what looks like a potential contact
Inerestingly there is little to no organic material found (few possible specs here and there)
Transition from massive appearing into a low angle planar bedding style. The HC staining appears to be the same
Zone of heavily stained material, occurs along an angular conact (could be a preexisting bedding surface)

1-35-75-26W4

1-35-75-26w4

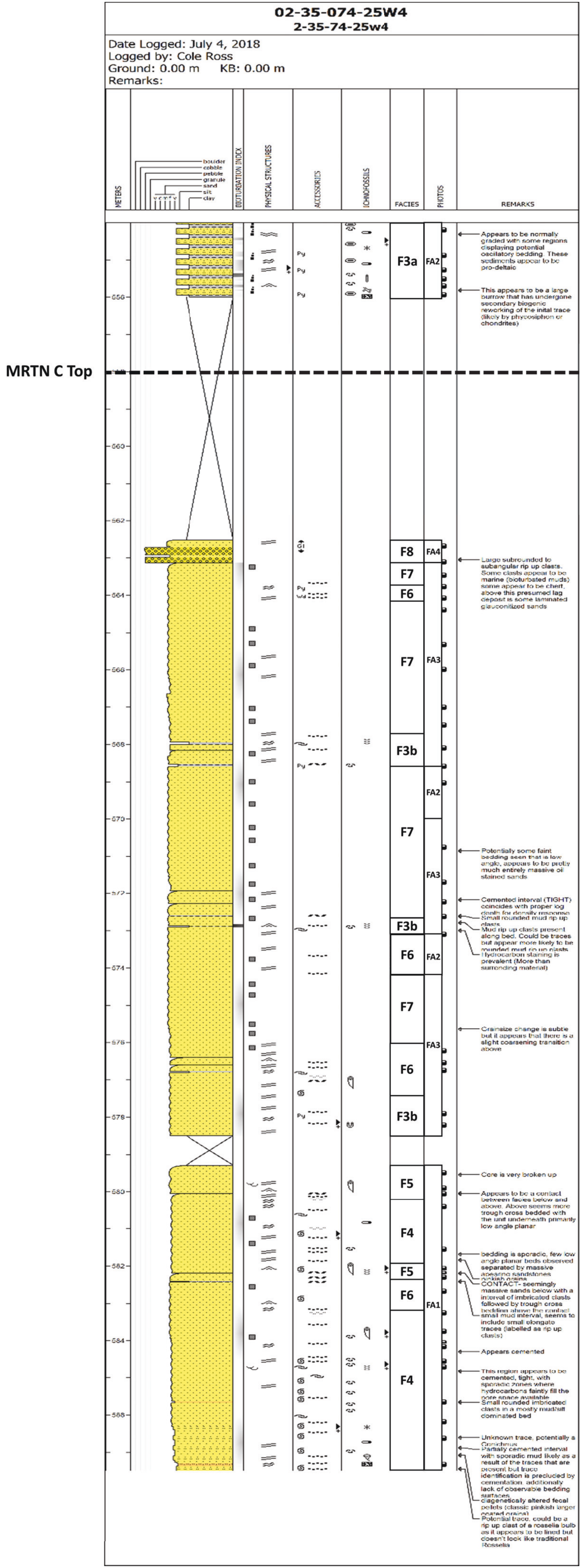
Date Logged: August 10, 2018
Logged by:
Ground: 0.00 m KB: 0.00 m
Remarks:





DTSM 2-15-74-25W4
2-15-74-25w4
Date Logged: July 22, 2019
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:
METERS
boulder
cobble
pebble
granule
sand
silt
clay
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
DEPOSITIONAL COMPLEX
REMARKS
556
558
560
562
564
566
568
570
572
574
576
578
580
582
584
586
588
590
F2a
F2b
F9
F8
F7
F10a
F7
F6
F7
F6
F7
F10b
F6
F7
F6
F7
F6
F7
F6
F7
F6
F7
F10b
F7
F3a
F2a
F2b
FA4
FA2
FA3
FA3
FA2
FA3
FA2
Gl
Py
Sid
Looks like there is a lot of clay in the uppermost portion of the system, very clay rich. Obscures trace observation and mud/sand content
Passively infilled vertical burrows, possibly a glossifungites surface)
SP 1
Transgressive lag with some glauconitized pebble clasts. Some unknown elongate traces observed above the lag
SP 2
SP 3
SP 4
Grainsize is anywhere between upper fine to medium (possibly even higher) the average would fall around medium
SP 5
SP 6
SP 7
Faint evidence exists of prexisting low angle planar bedding
SP 8
SP 9
Faint LAP bedding observed?
SP 10
Abundant organic material of variable sized. Smaller pieces oriented as phytodetrital bedding surfaces
Possible evidence of fluidization structures (small scale faulting/deformation)
SP 11
SP 12
Vertical features in core could be a result of fluid moving AFTER coring? We've seen this on a few other CVE core. May explain the Darcy perm
SP 13
Top of cemented interval
Base of cemented interval
SP 14
SP 15
SP 16
SP 17
SP 18
SP 19
Bedding inclination appears to increase upwards throughout the core
Fluvial?
SP 20
Thin cemented bedding planes interbedded with upper fine grained oil stained sandstones
SP 21
SP 22
SP 23
Pulses with large organic clasts (wood) with additional fine grained phytodetrital clasts
SP 24
SP 25
Top of TIGHT cemented interval
Vertical fractures present throughout much of this cemented interval
Contact marking TIGHT cemented interval (above)
SP 26
Apparent oscilatory bedding seperated by more massive appearing sandstones
SP 27
SP 28
SP 29
Abundant organic material, bedding appears steeper than LAP
SP 30
Little pulses of organic material deposted along very thin laminae
SP 31
SP 32
SP 33
SP 34
SP 35
Unsure about bedding type observed here
SP 36
Interesting feature, looks partially cemented. Also appears like a large ball of sand with deformation of bedding occuring around the circular sand (see picture). Is this possibly soft sediment deformation?
SP 37
Bertherine?
SP 38
SP 39
SP 40
Some faint cement beds or siderite grains displayed as low angle planar. Majority of the sandstone is massive appearing
SP 41
High energy contact, this material is heavily cemented with an extremely high organic concentration (clast range from mm to >5cm in width). Natural fractures (oil staining) present
SP 42
Massive appearing sand with bertherine cement (possibly)
Apparent contact seperating faint oscillatory bedding with what looks like a bertherine cement
SP 43
Sands appear massive could have bertherine cements
SP/USP 44
faint disseminated pyrite distributed throughout sands (especially noticeable with organics)
Sideratized burrows with secondary bioturbation
silty sand with very fine phytodetrital material (tempestite)

MRTN B Top

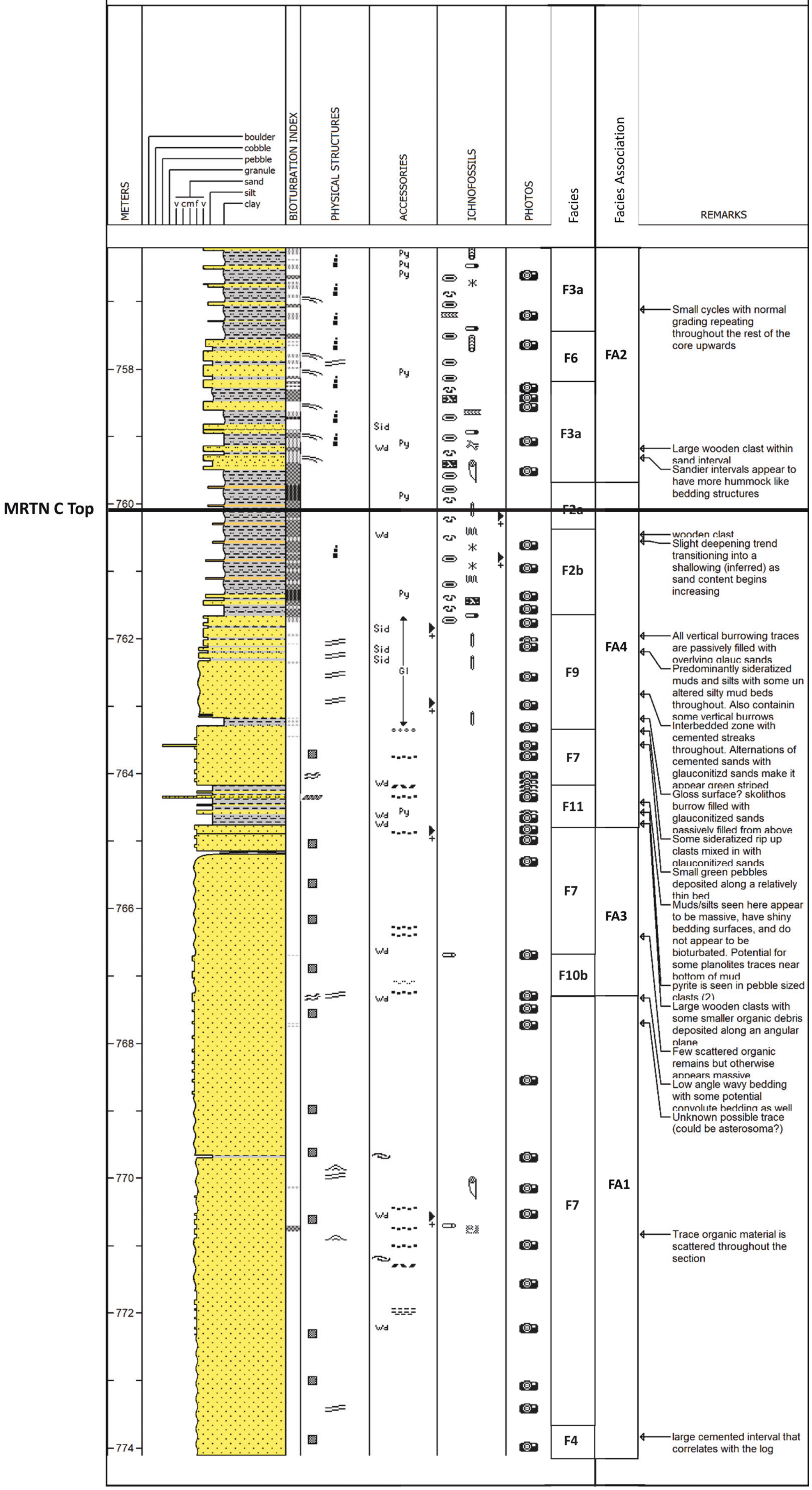


02-35-074-25W4
2-35-74-25w4
Date Logged: July 4, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:
METERS
boulder
cobble
pebble
granule
sand
silt
clay
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FACIES
PHOTOS
REMARKS
MRTN C Top
556
560
562
564
566
568
570
572
574
576
578
580
582
584
586
Py
F3a
FA2
F8
FA4
F7
F6
F7
FA3
F3b
FA2
F7
FA3
F3b
F6
FA2
F7
FA3
F6
F3b
F5
F4
F5
F6
FA1
F4
Appears to be normally graded with some regions displaying potential oscilatory bedding. These sediments appear to be pro-deltaic
This appears to be a large burrow that has undergone secondary biogenic reworking of the inital trace (likely by phycosiphon or chondrites)
Large subrounded to subangular rip up clasts. Some clasts appear to be marine (bioturbated muds) some appear to be chert, above this presumed lag deposit is some laminated glauconitized sands
Potentially some faint bedding seen that is low angle, appears to be pretty much entirely massive oil stained sands
Cemented interval (TIGHT) coincides with proper log depth for density response
Small rounded mud rip up clasts
Mud rip up clasts present along bed. Could be traces but appear more likely to be rounded mud rip up clasts
Hydrocarbon staining is prevalent (More than surronding material)
Grainsize change is subtle but it appears that there is a slight coarsening transition above
Core is very broken up
Appears to be a contact between facies below and above. Above seems more trough cross bedded with the unit underneath primarily low angle planar
bedding is sporadic, few low angle planar beds observed separated by massive appearing sandstones
pinkish grains
CONTACT- seemingly massive sands below with a interval of imbricated clasts followed by trough cross bedding above the contact
small mud interval, seems to include small elongate traces (labelled as rip up clasts)
Appears cemented
This region appears to be cemented, tight, with sporadic zones where hydrocarbons faintly fill the pore space available
Small rounded imbricated clasts in a mostly mud/silt dominated bed
Unknown trace, potentially a Gordichnus
Partially cemented interval with sporadic mud likely as a result of the traces that are present but trace identification is precluded by cementation, additionally lack of observable bedding surfaces
diagenetically altered fecal pelets (classic pinkish larger coated grains)
Potential trace, could be a rip up clast of a rosselia bulb as it appears to be lined but doesn't look like traditional Rosselia

3-26-75-26W4

3-26-75-26w4

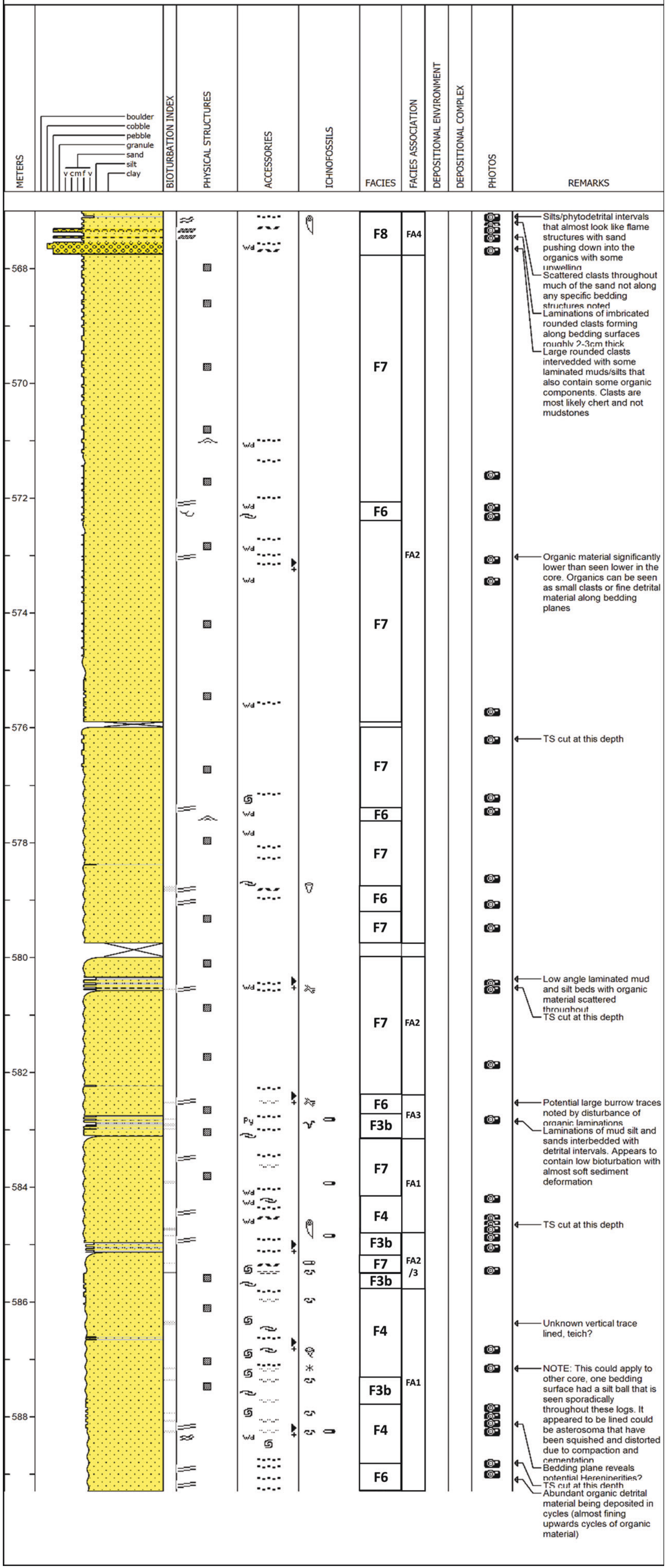
Date Logged: August 1, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:



4-20-75-25W4

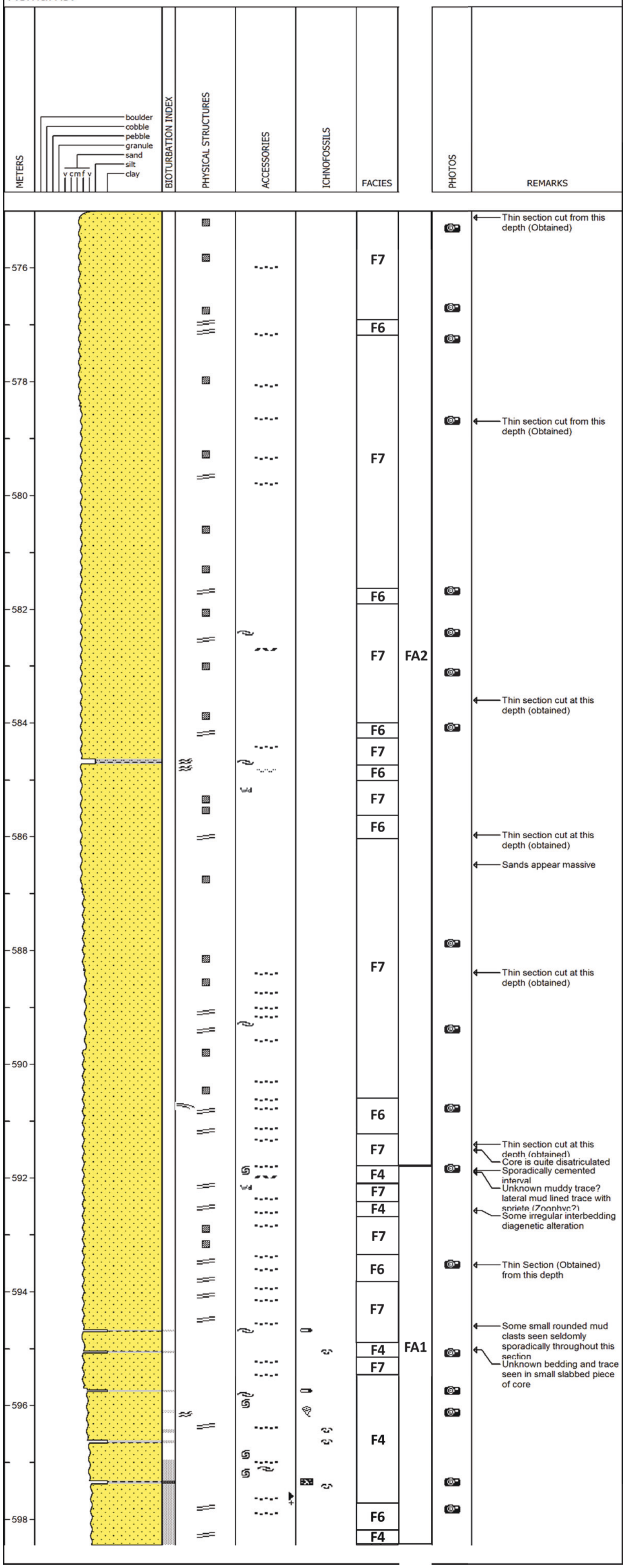
4-20-75-25w4

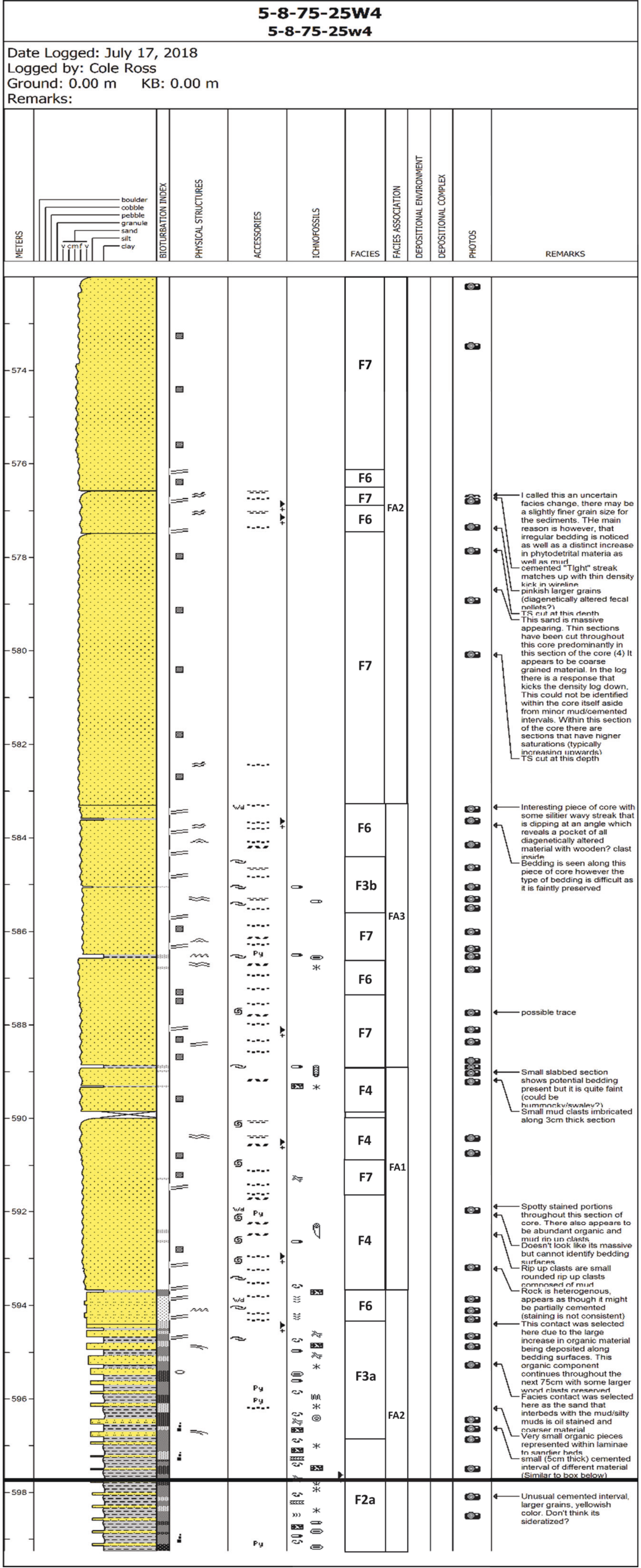
Date Logged: July 31, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:



5-5-75-25W4
5-5-075-25w4

Date Logged: July 3, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:

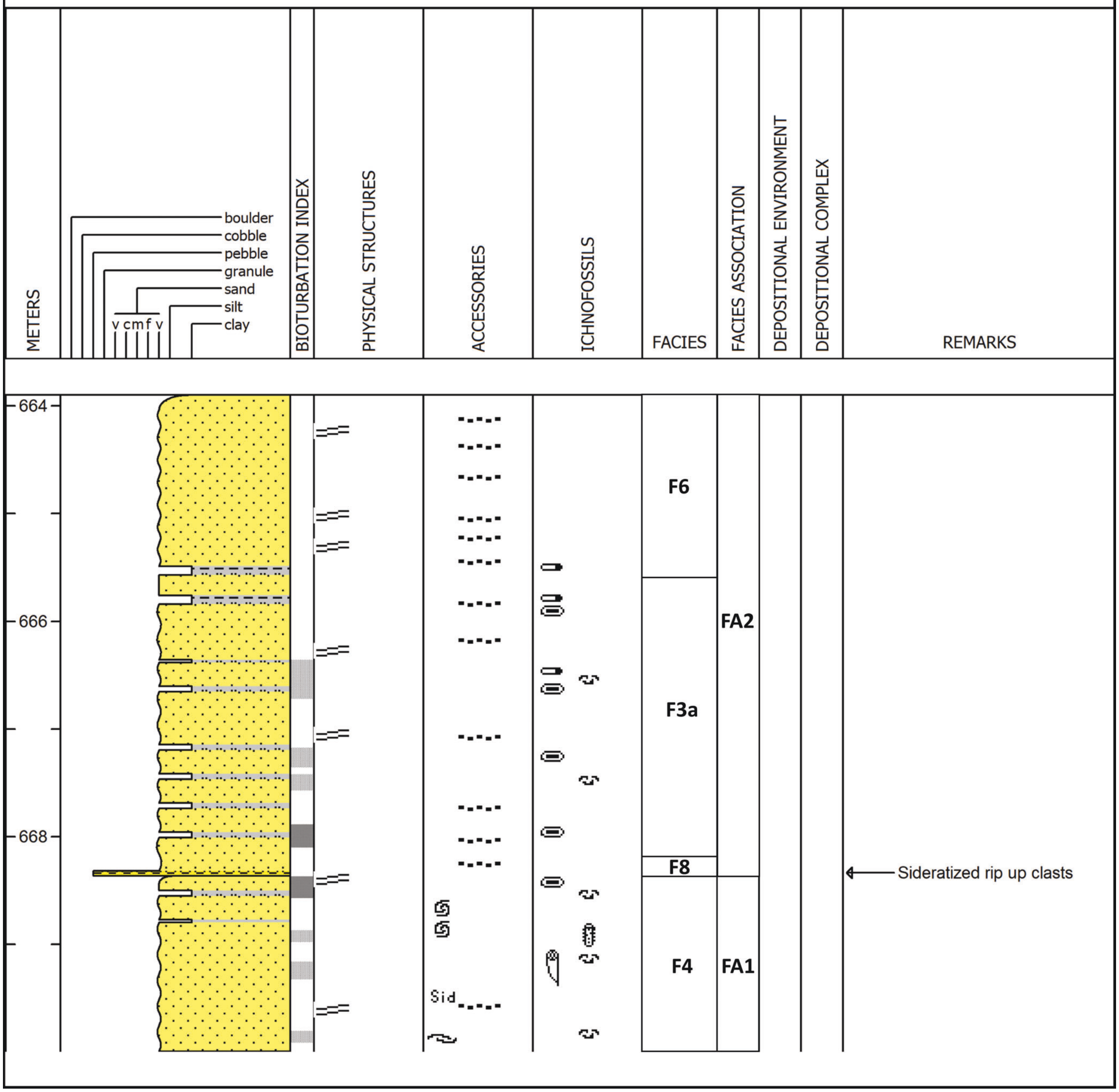



5-8-75-25W4
5-8-75-25w4
Date Logged: July 17, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:
METERS
boulder
cobble
pebble
granule
sand
silt
clay
v c m f v
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
DEPOSITIONAL COMPLEX
PHOTOS
REMARKS
574
576
578
580
582
584
586
588
590
592
594
596
598
F7
F6
F7
F6
F7
F6
F3b
F7
F6
F7
F4
F4
F7
F4
F6
F3a
F2a
FA2
FA3
FA1
FA2
Py
I called this an uncertain facies change, there may be a slightly finer grain size for the sediments. THe main reason is however, that irregular bedding is noticed as well as a distinct increase in phytodetrital materia as well as mud
cemented "TIght" streak matches up with thin density kick in wireline
pinkish larger grains (diagenetically altered fecal pellets?)
TS cut at this depth
This sand is massive appearing. Thin sections have been cut throughout this core predominantly in this section of the core (4) It appears to be coarse grained material. In the log there is a response that kicks the density log down, This could not be identified within the core itself aside from minor mud/cemented intervals. Within this section of the core there are sections that have higher saturations (typically increasing upwards)
TS cut at this depth
Interesting piece of core with some siltier wavy streak that is dipping at an angle which reveals a pocket of all diagenetically altered material with wooden? clast inside
Bedding is seen along this piece of core however the type of bedding is difficult as it is faintly preserved
possible trace
Small slabbed section shows potential bedding present but it is quite faint (could be hummocky/swaley?)
Small mud clasts imbricated along 3cm thick section
Spotty stained portions throughout this section of core. There also appears to be abundant organic and mud rip up clasts
Doesn't look like its massive but cannot identify bedding surfaces
Rip up clasts are small rounded rip up clasts composed of mud
Rock is heterogenous, appears as though it might be partially cemented (staining is not consistent)
This contact was selected here due to the large increase in organic material being deposited along bedding surfaces. This organic component continues throughout the next 75cm with some larger wood clasts preserved
Facies contact was selected here as the sand that interbeds with the mud/silty muds is oil stained and coarser material
Very small organic pieces represented within laminae to sandier beds
small (5cm thick) cemented interval of different material (Similar to box below)
Unusual cemented interval, larger grains, yellowish color. Don't think its sideratized?
MRTN B Top

5-14-76-26W4

5-14-76-26w4

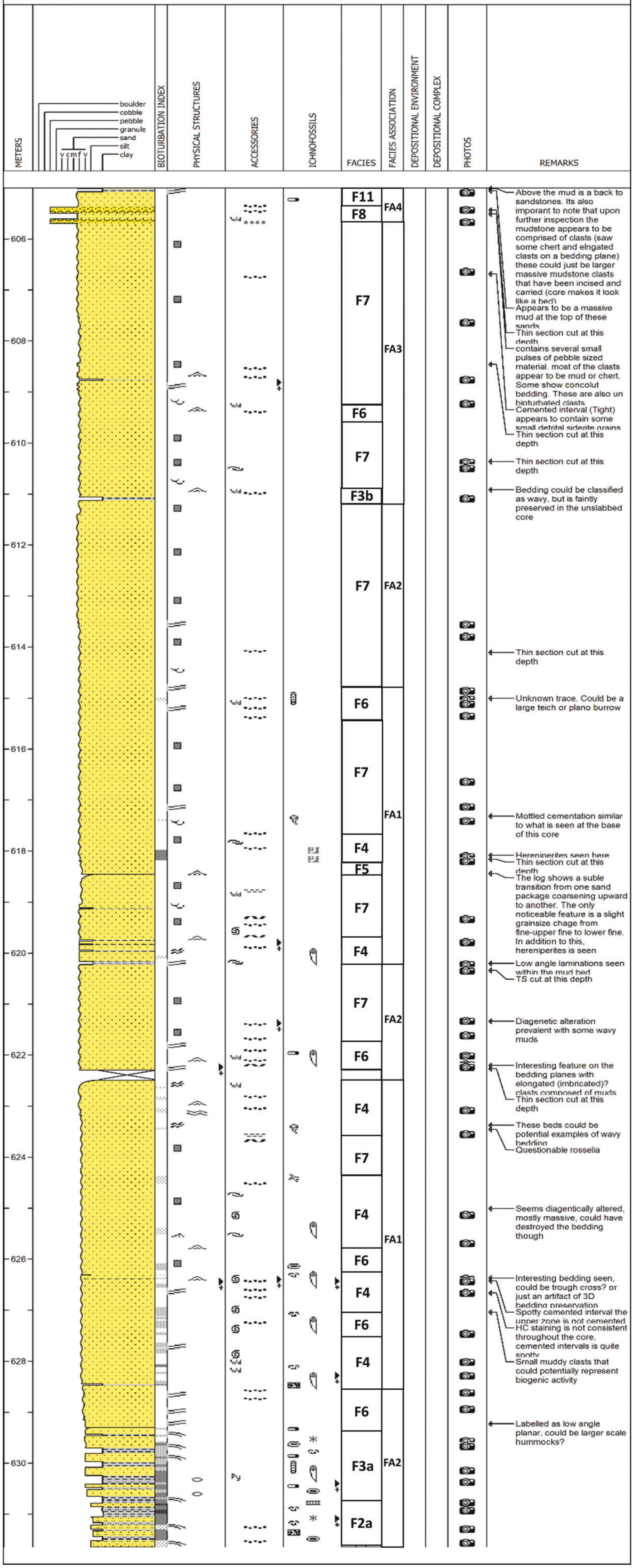
Date Logged: March 26, 2019
Logged by:
Ground: 0.00 m   KB: 0.00 m
Remarks:

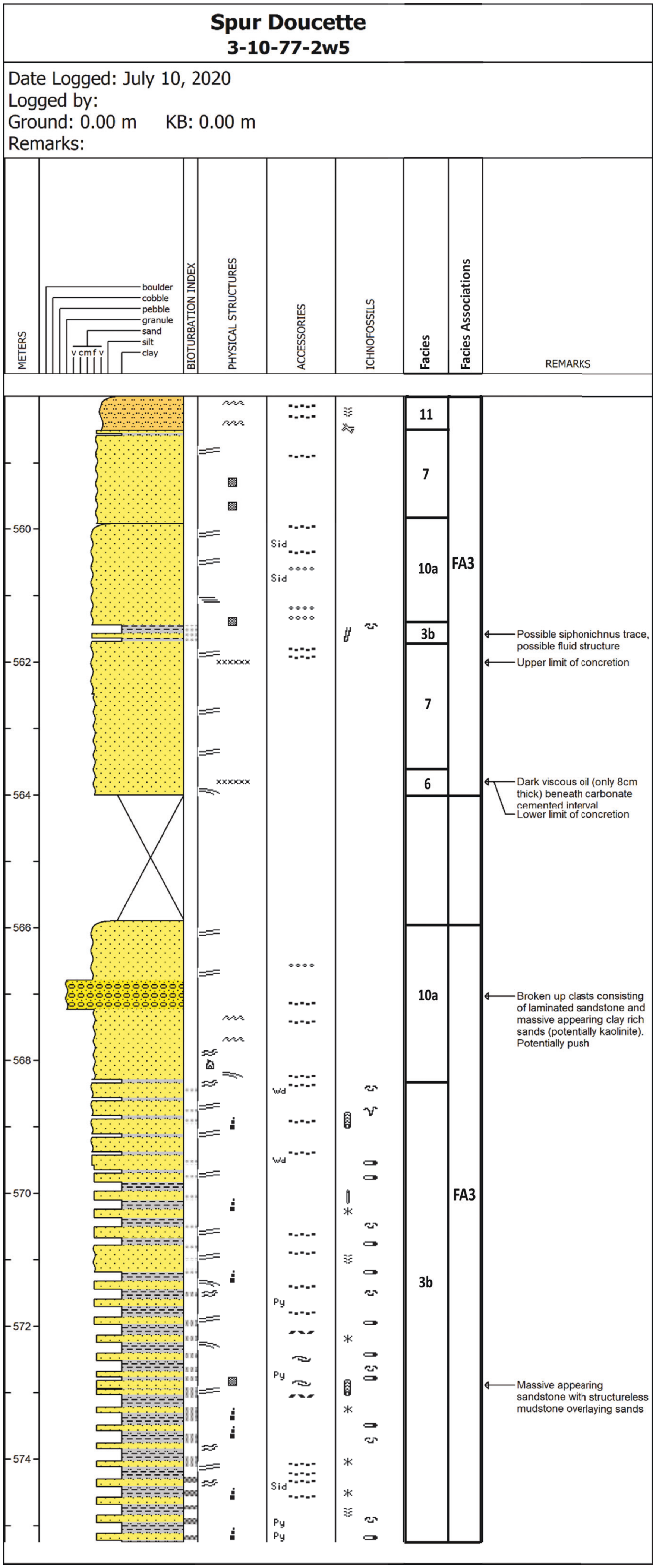


5-18-75-25W4

5-18-75-25w4

Date Logged: July 24, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:

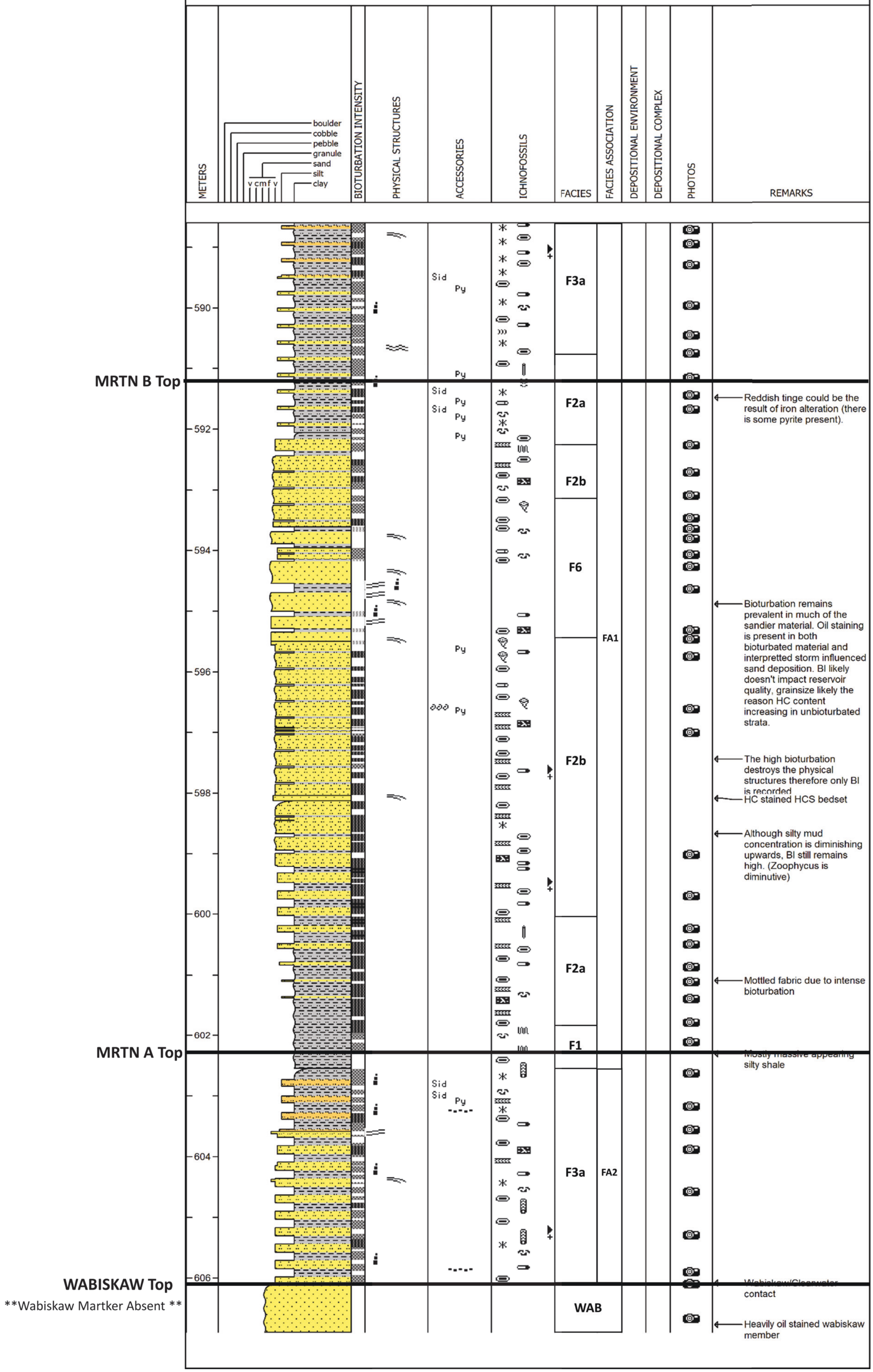


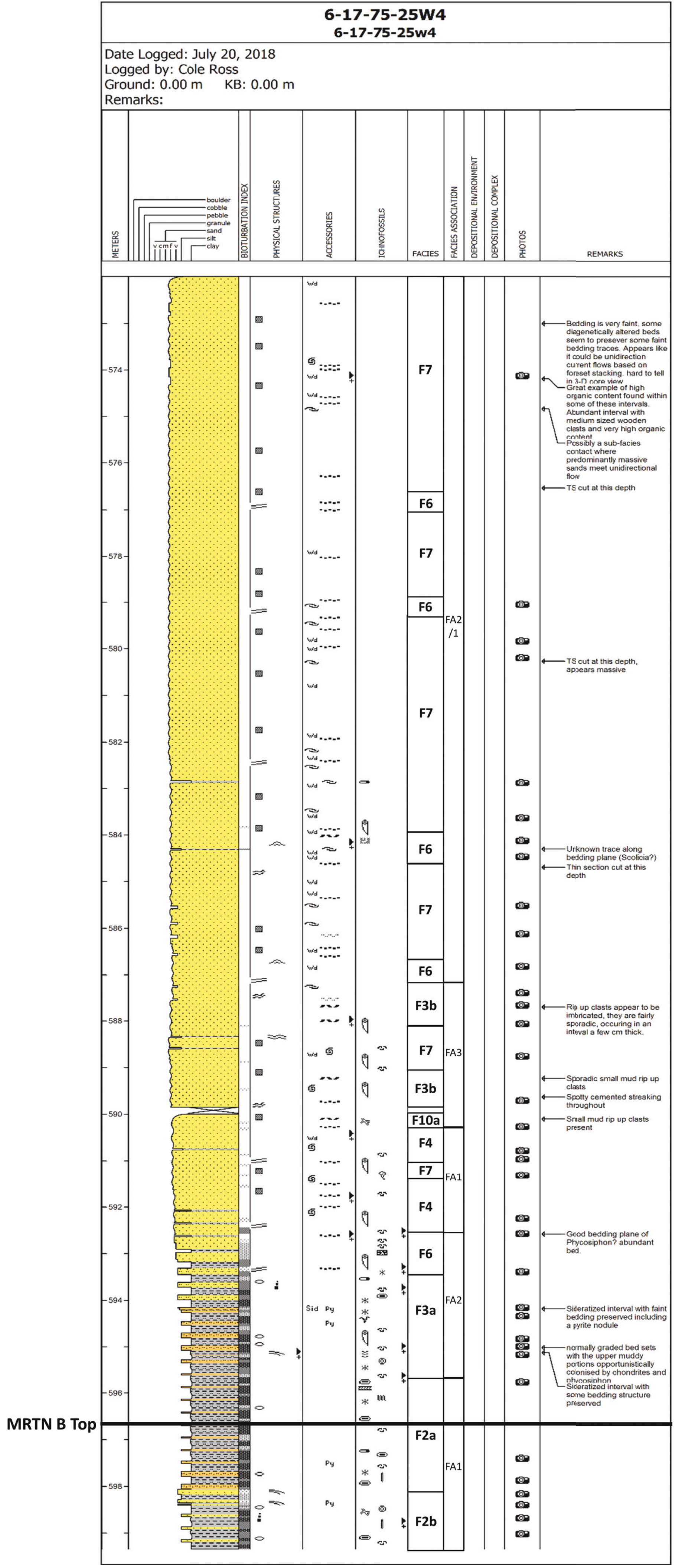


Spur Doucette
3-10-77-2w5
Date Logged: July 10, 2020
Logged by:
Ground: 0.00 m KB: 0.00 m
Remarks:
METERS
boulder
cobble
pebble
granule
sand
silt
clay
v c m f v
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
Facies
Facies Associations
REMARKS
560
562
564
566
568
570
572
574
Sid
Wd
Py
11
7
10a
3b
6
FA3
Possible siphonichnus trace, possible fluid structure
Upper limit of concretion
Dark viscous oil (only 8cm thick) beneath carbonate cemented interval
Lower limit of concretion
Broken up clasts consisting of laminated sandstone and massive appearing clay rich sands (potentially kaolinite). Potentially push
Massive appearing sandstone with structureless mudstone overlaying sands

6-15-77-4W5
6-15-77-4w5

Date Logged: August 23, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:





6-17-75-25W4
6-17-75-25w4
Date Logged: July 20, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:
METERS
boulder
cobble
pebble
granule
sand
silt
clay
v c m f v
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
DEPOSITIONAL COMPLEX
PHOTOS
REMARKS
574
576
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F7
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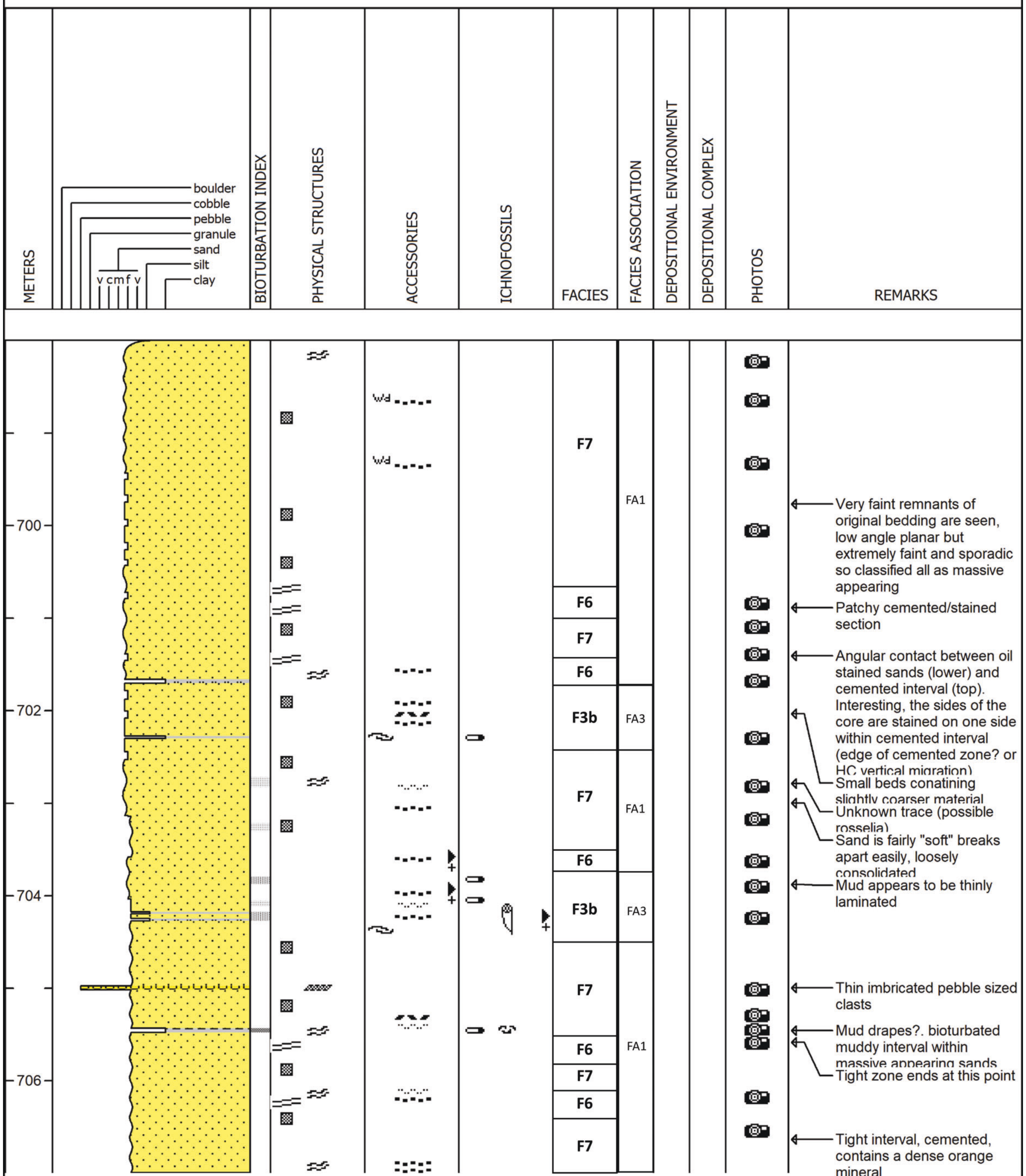
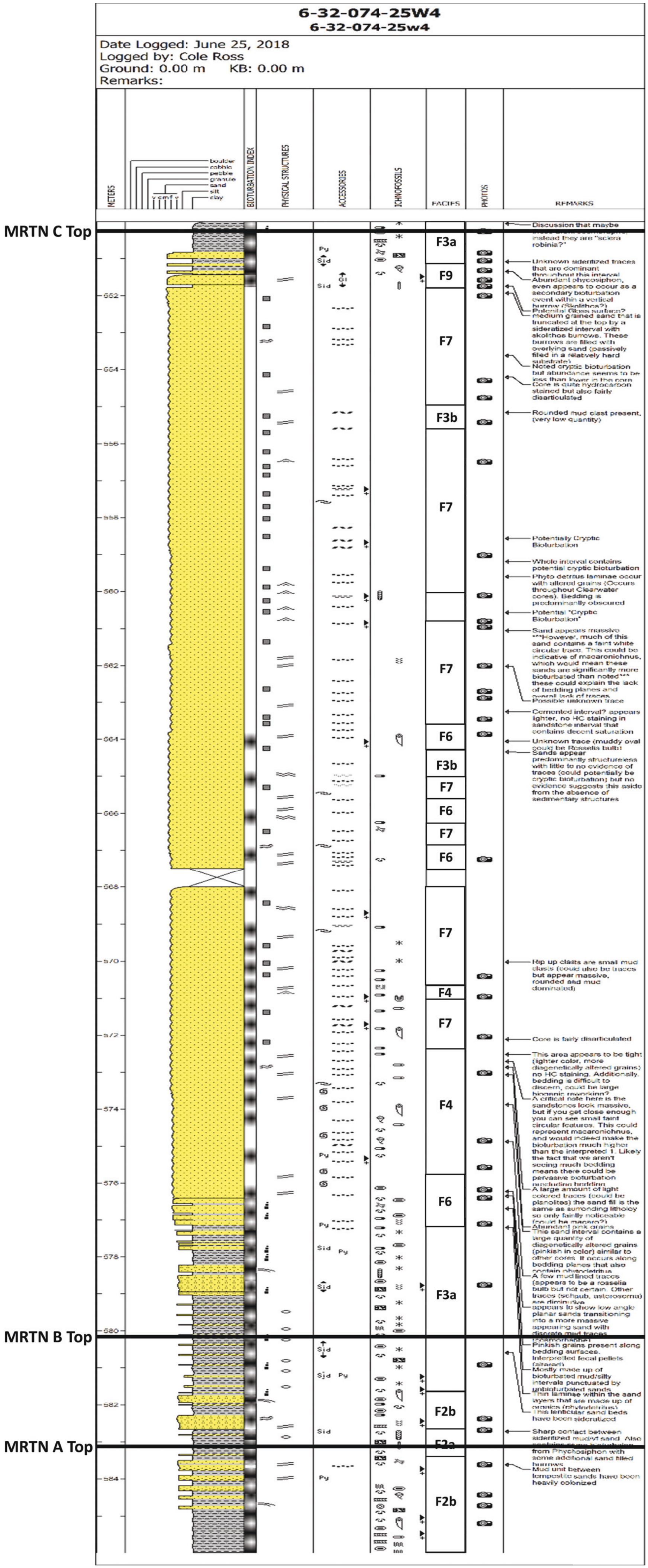
F7
F6
F7
F6
F3b
F7
F3b
F10a
F4
F7
F4
F6
F3a
F2a
F2b
FA2 /1
FA3
FA1
FA2
FA1
Sid
Py
Bedding is very faint, some diagenetically altered beds seem to presever some faint bedding traces. Appears like it could be unidirection current flows based on foreset stacking. hard to tell in 3-D core view
Great example of high organic content found within some of these intervals.
Abundant interval with medium sized wooden clasts and very high organic content
Possibly a sub-facies contact where predominantly massive sands meet unidirectional flow
TS cut at this depth
TS cut at this depth, appears massive
Urknown trace along bedding plane (Scolicia?)
Thin section cut at this depth
Rip up clasts appear to be imbricated, they are fairly sporadic, occuring in an inteval a few cm thick.
Sporadic small mud rip up clasts
Spotty cemented streaking throughout
Small mud rip up clasts present
Good bedding plane of Phycosiphon? abundant bed.
Sideratized interval with faint bedding preserved including a pyrite nodule
normally graded bed sets with the upper muddy portions opportunistically colonised by chondrites and phycosiphon
Sideratized interval with some bedding structure preserved
MRTN B Top

6-17-76-2W5/2
6-17-76-2w5

Date Logged: August 21, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:





6-32-074-25W4
6-32-074-25w4
Date Logged: June 25, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:
METERS
boulder
cobble
pebble
granule
sand
silt
clay
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FACIES
PHOTOS
REMARKS
MRTN C Top
MRTN B Top
MRTN A Top
652
654
656
658
660
662
664
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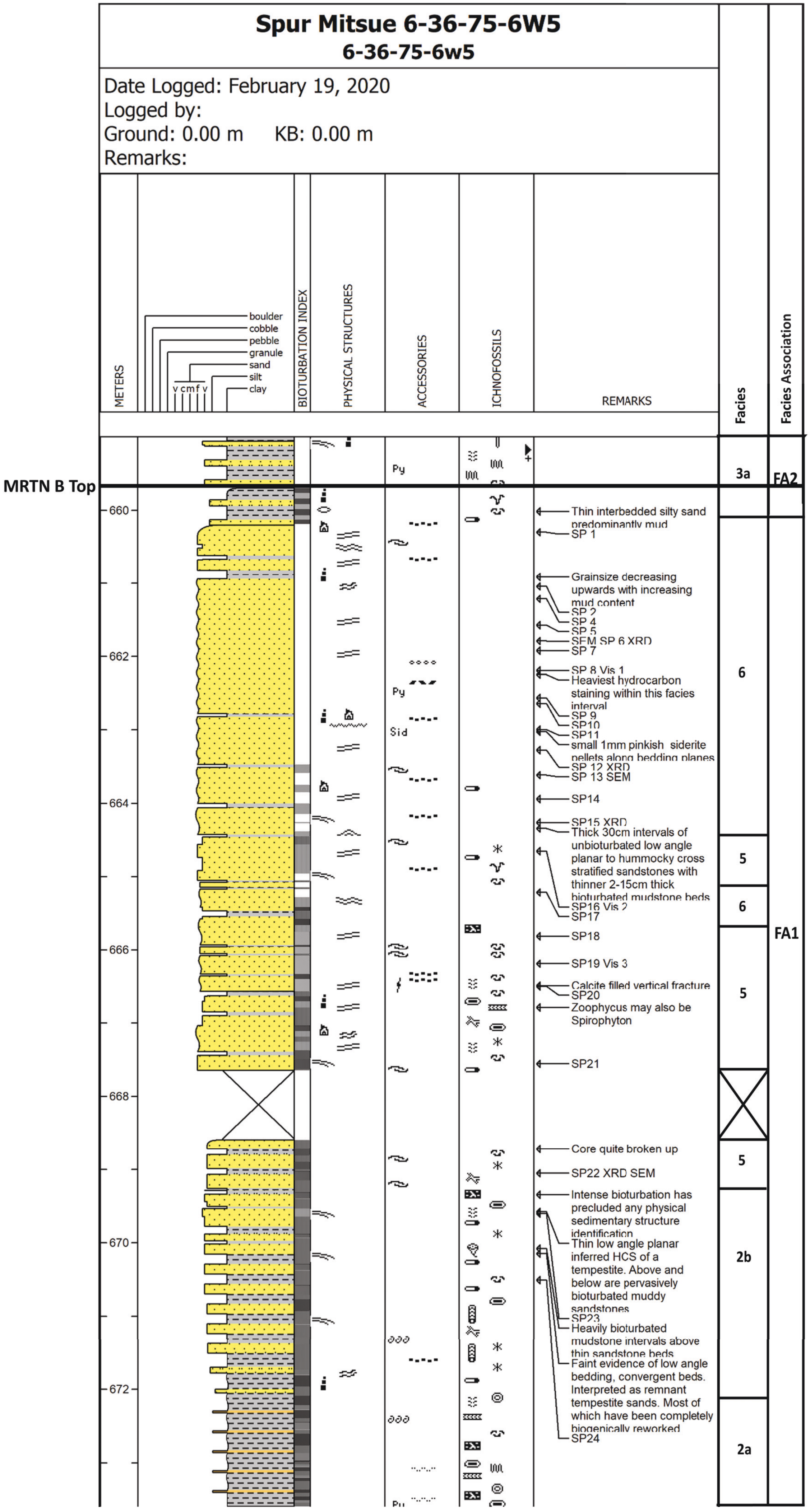
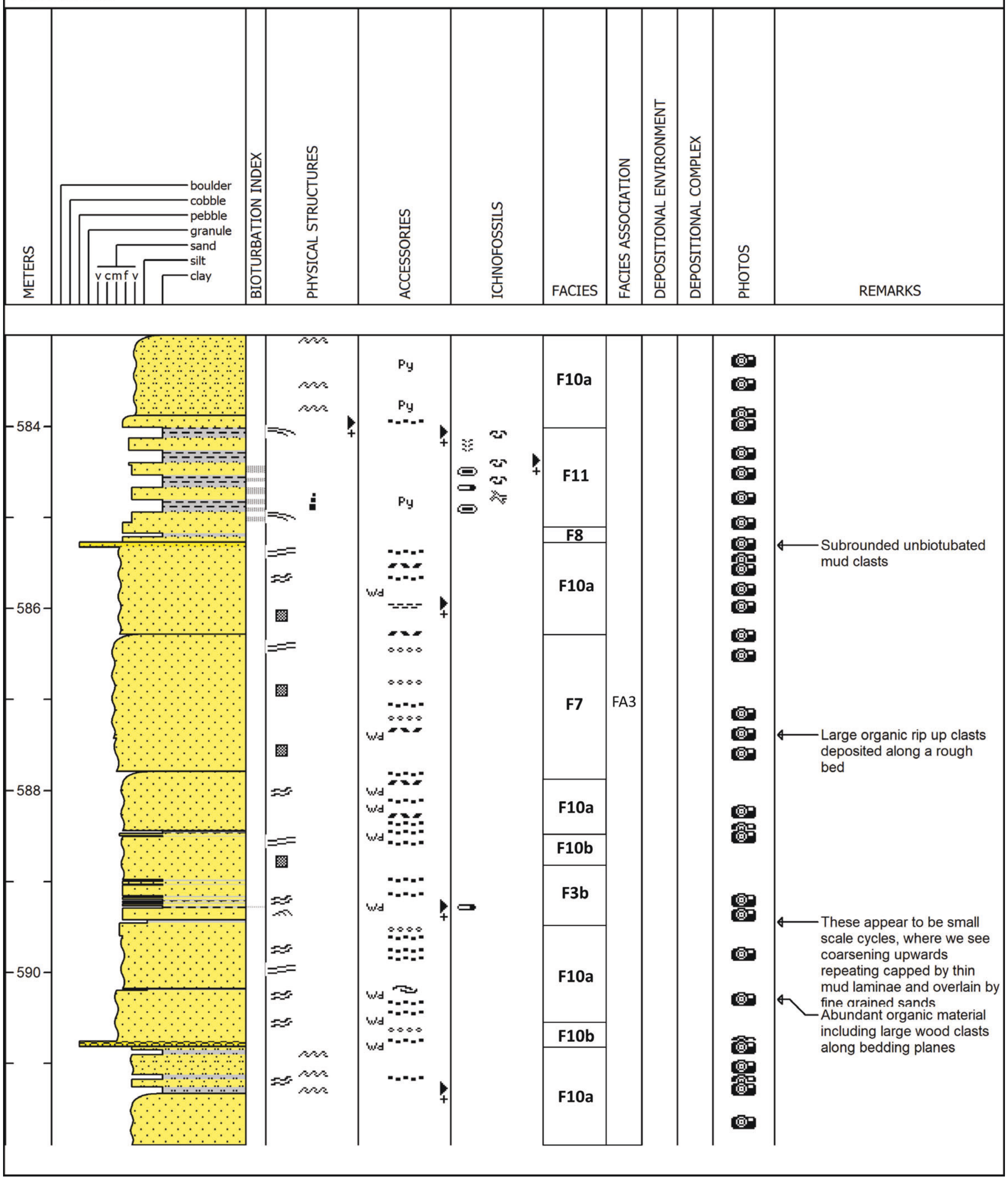
668
670
672
674
676
678
680
682
684
Py
Sid
F3a
F9
F7
F3b
F7
F7
F6
F3b
F7
F6
F7
F6
F7
F4
F7
F4
F6
F3a
F2b
F2a
F2b
Discussion that maybe
instead they are "sclera robinis?"
Unknown sideritized traces that are dominant throughout this interval
Abundant phycosiphon, even appears to occur as a secondary bioturbation event within a vertical burrow (Skolithos?)
Potential Gloss surface?
medium grained sand that is truncated at the top by a sideratized interval with skolithos burrows. These burrows are filled with overlying sand (passively filled in a relatively hard substrate)
Noted cryptic bioturbation but abundance seems to be less than lower in the core
Core is quite hydrocarbon stained but also fairly disarticulated
Rounded mud clast present, (very low quantity)
Potentially Cryptic Bioturbation
Whole interval contains potential cryptic bioturbation
Phyto detritus laminae occur with altered grains (Occurs throughout Clearwater cores). Bedding is predominantly obscured
Potential "Cryptic Bioturbation"
Sand appears massive ***However, much of this sand contains a faint white circular trace. This could be indicative of macaronichnus, which would mean these sands are significantly more bioturbated than noted*** these could explain the lack of bedding planes and overall lack of traces
Possible unknown trace
Cemented interval? appears lighter, no HC staining in sandstone interval that contains decent saturation
Unknown trace (muddy oval could be Rosselia bulb)
Sands appear predominantly structureless with little to no evidence of traces (could potentially be cryptic bioturbation) but no evidence suggests this aside from the absence of sedimentary structures
Rip up clasts are small mud clasts (could also be traces but appear massive, rounded and mud dominated)
Core is fairly disarticulated
This area appears to be tight (lighter color, more diagenetically altered grains) no HC staining. Additionally, bedding is difficult to discern, could be large biogenic reworking?
A critical note here is the sandstones look massive, but if you get close enough you can see small faint circular features. This could represent macaronichnus, and would indeed make the bioturbation much higher than the interpreted 1. Likely the fact that we aren't seeing much bedding means there could be pervasive bioturbation precluding bedding
A large amount of light colored traces (could be planolites) the sand fill is the same as surronding litholgy so only faintly noticeable (could be macaro?)
Abundant pink grains
This sand interval contains a large quantity of diagenetically altered grains (pinkish in color) similar to other cores. It occurs along bedding planes that also contain phytodetritus
A few mud lined traces (appears to be a rosselia bulb but not certain. Other traces (schaub, asterosoma) are diminutive
appears to show low angle planar sands transitioning into a more massive appearing sand with discrete mud traces (cosmorhaphe)
Pinkish grains present along bedding surfaces.
Interpreted fecal pellets (altered)
Mostly made up of bioturbated mud/silty intervals punctuated by unbioturbated sands
Thin laminae within the sand layers that are made up of organics (phytodetritus)
This lenticular sand beds have been sideratized
Sharp contact between sideritized mud/vf sand. Also
from Phychosiphon with some additional sand filled burrows
Mud unit between tempestite sands have been heavily colonized


Spur Mitsue 6-36-75-6W5
6-36-75-6w5
Date Logged: February 19, 2020
Logged by:
Ground: 0.00 m KB: 0.00 m
Remarks:
METERS
boulder
cobble
pebble
granule
sand
silt
clay
v c m f v
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
REMARKS
Facies
Facies Association
MRTN B Top
660
662
664
666
668
670
672
Py
Sid
3a
FA2
6
5
6
5
5
2b
2a
FA1
Thin interbedded silty sand predominantly mud
SP 1
Grainsize decreasing upwards with increasing mud content
SP 2
SP 4
SP 5
SEM SP 6 XRD
SP 7
SP 8 Vis 1
Heaviest hydrocarbon staining within this facies interval
SP 9
SP10
SP11
small 1mm pinkish siderite pellets along bedding planes
SP 12 XRD
SP 13 SEM
SP14
SP15 XRD
Thick 30cm intervals of unbioturbated low angle planar to hummocky cross stratified sandstones with thinner 2-15cm thick bioturbated mudstone beds
SP16 Vis 2
SP17
SP18
SP19 Vis 3
Calcite filled vertical fracture
SP20
Zoophycus may also be Spirophyton
SP21
Core quite broken up
SP22 XRD SEM
Intense bioturbation has precluded any physical sedimentary structure identification
Thin low angle planar inferred HCS of a tempestite. Above and below are pervasively bioturbated muddy sandstones
SP23
Heavily bioturbated mudstone intervals above thin sandstone beds
Faint evidence of low angle bedding, convergent beds. Interpreted as remnant tempestite sands. Most of which have been completely biogenically reworked
SP24

102/7-5-76-25W4
7-5-76-25w4

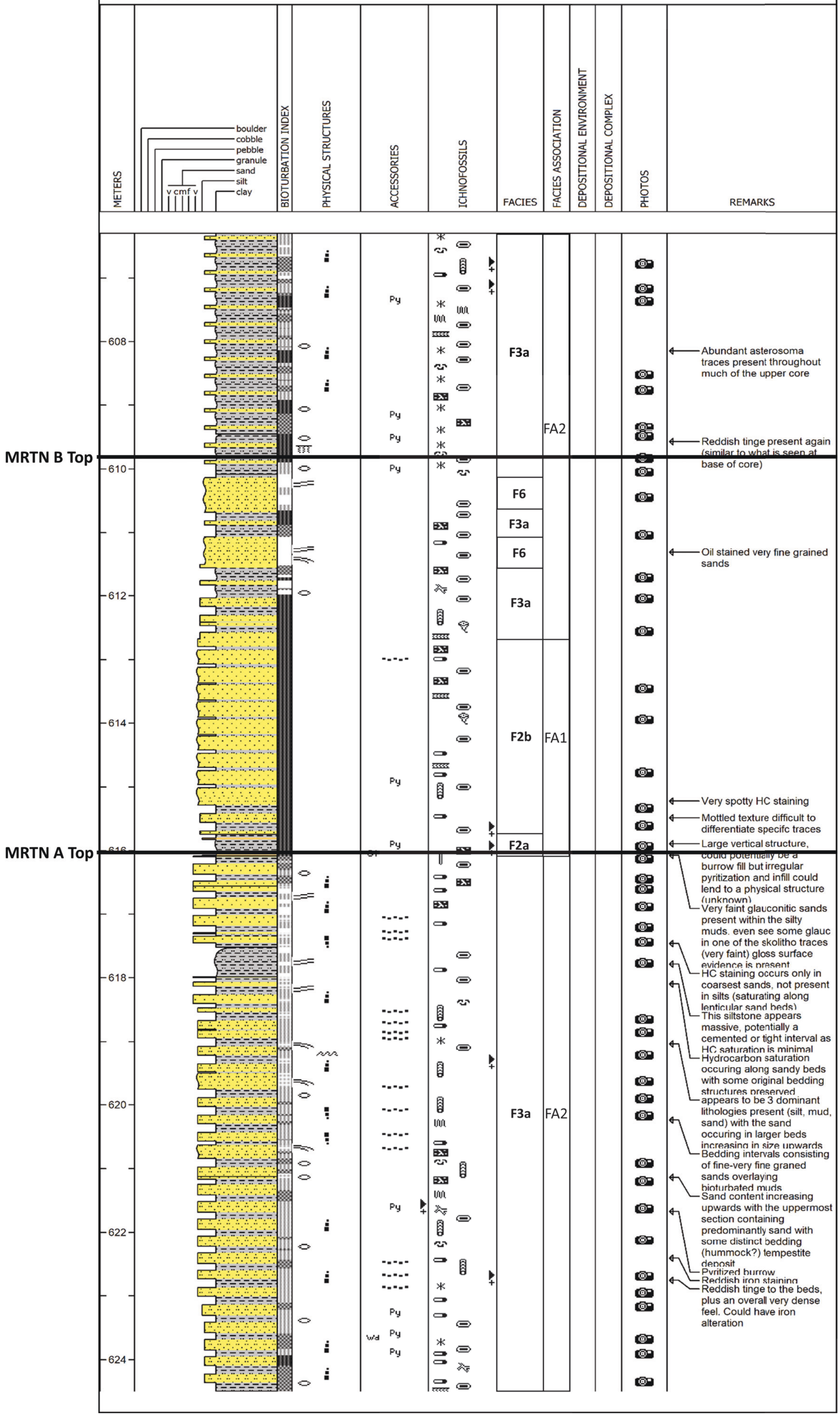
Date Logged: August 31, 2018
Logged by: Cole Ross
Ground: 0.00 m   KB: 0.00 m
Remarks:



7-11-74-1W5

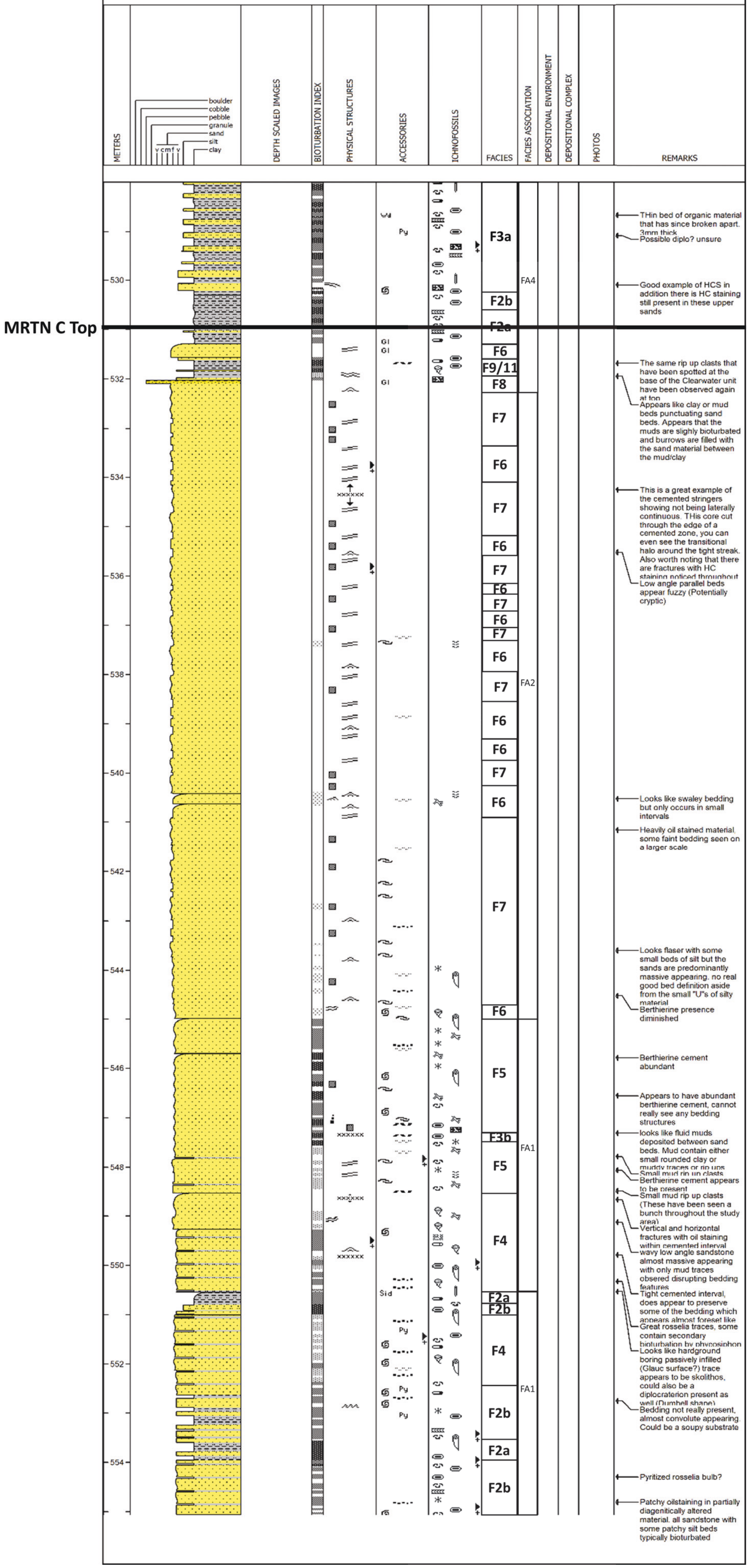
7-11-74-1w5

Date Logged: August 16, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:



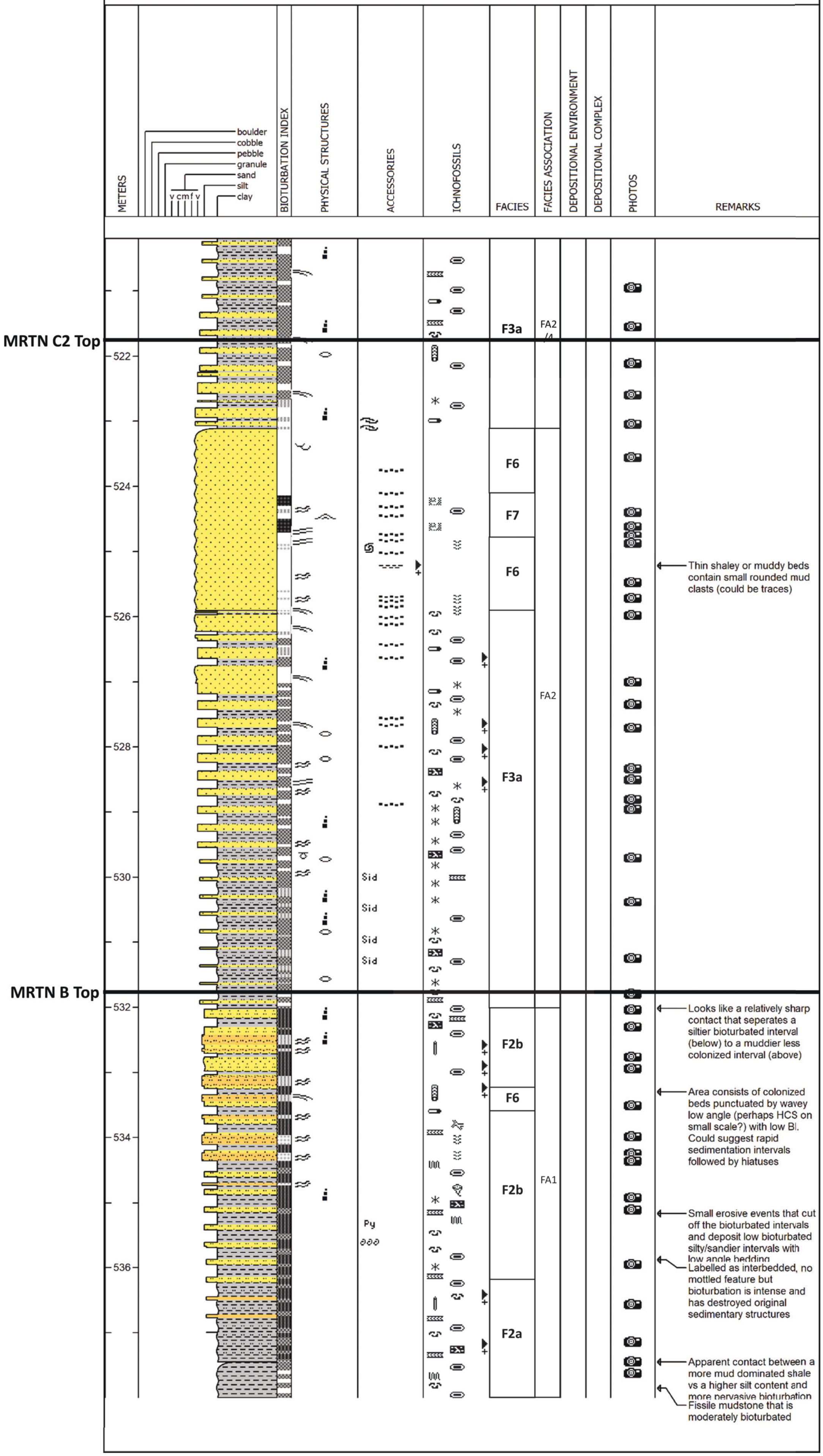
7-12-73-25W4
7-12-73-25w4

Date Logged: October 10, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:



7-28-78-2W5
7-28-78-2w5

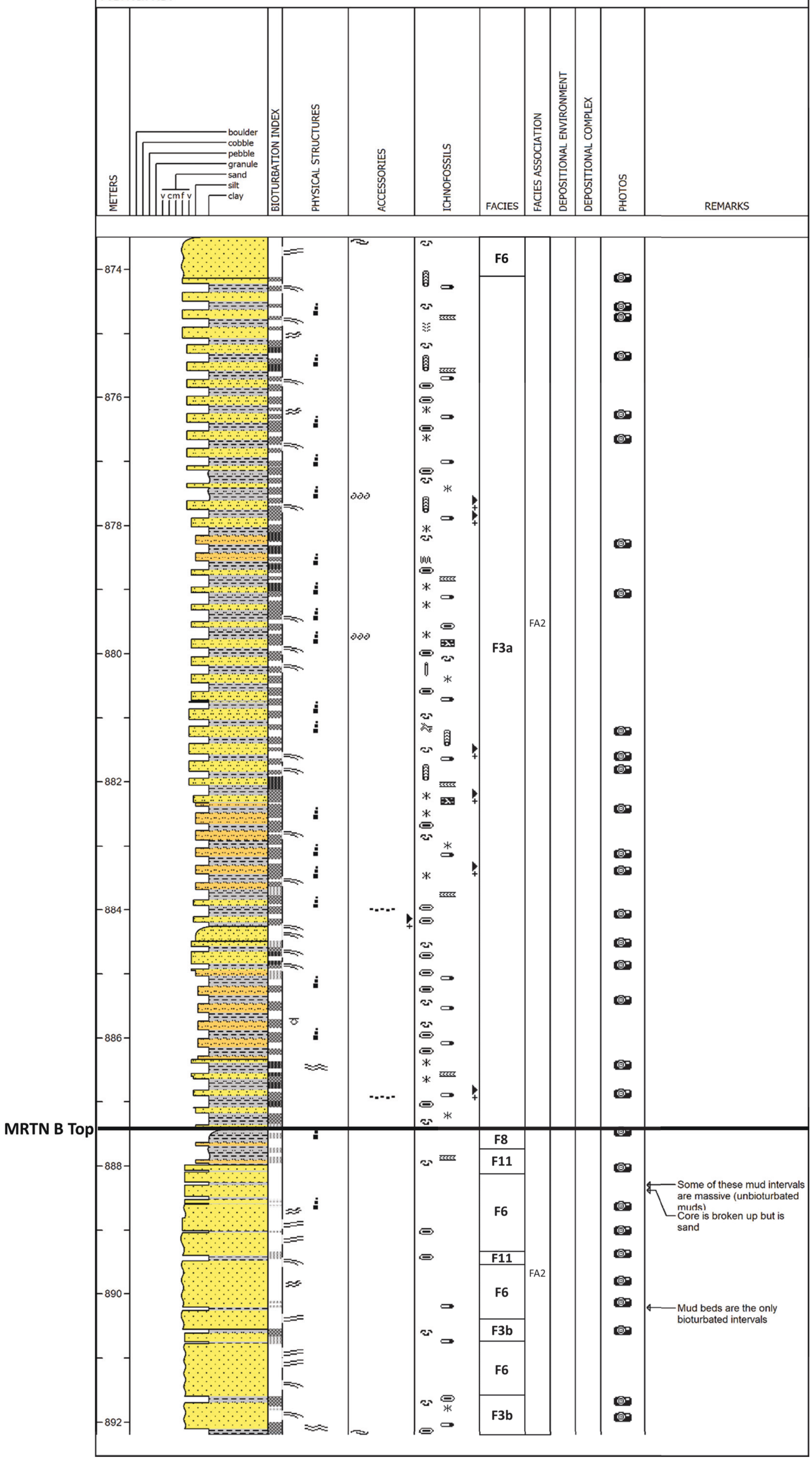
Date Logged: August 29, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:

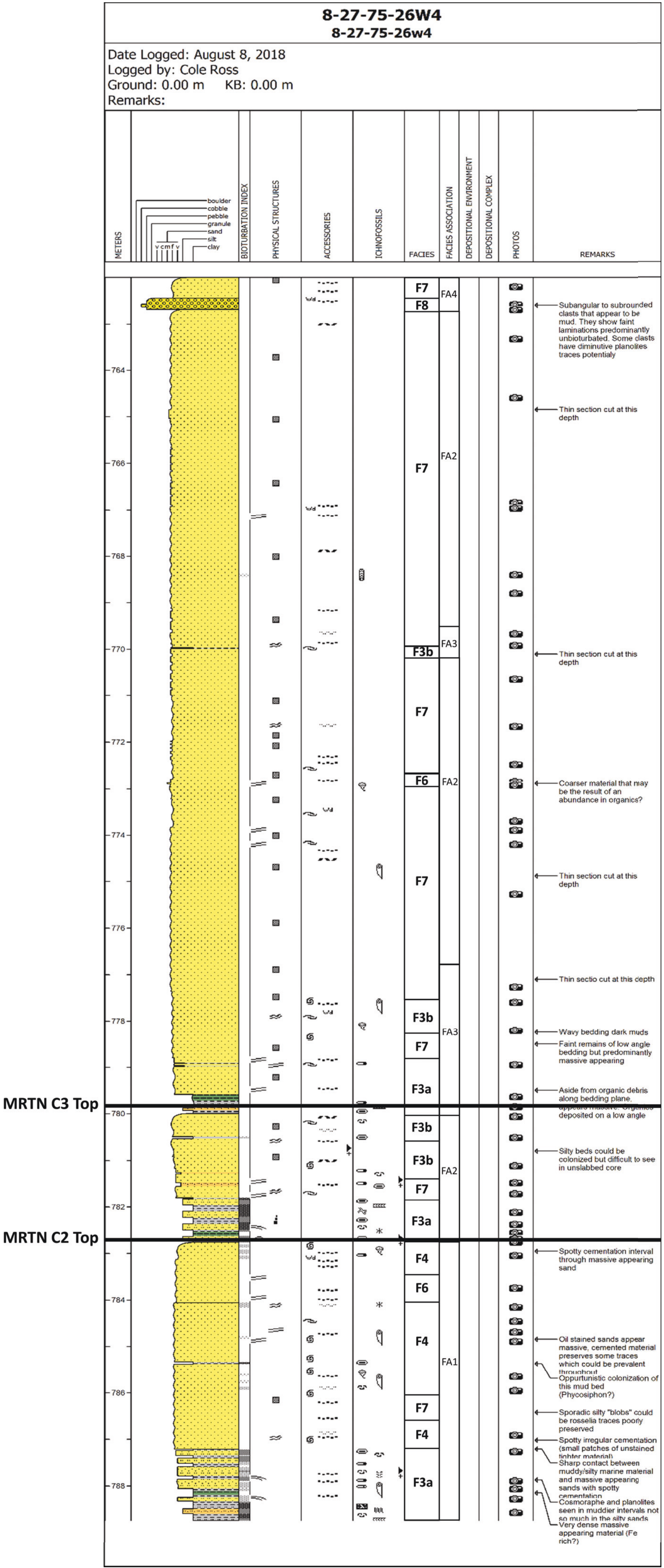


8-16-75-5W5

8-16-75-5w5

Date Logged: September 4, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:

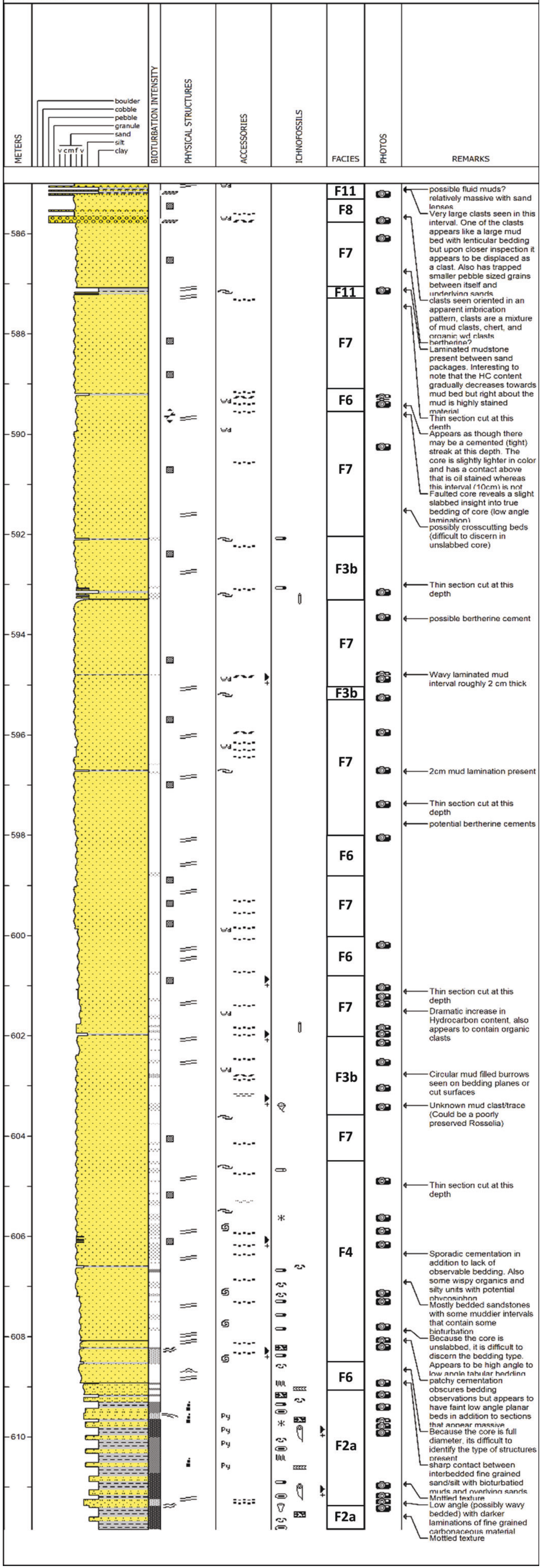


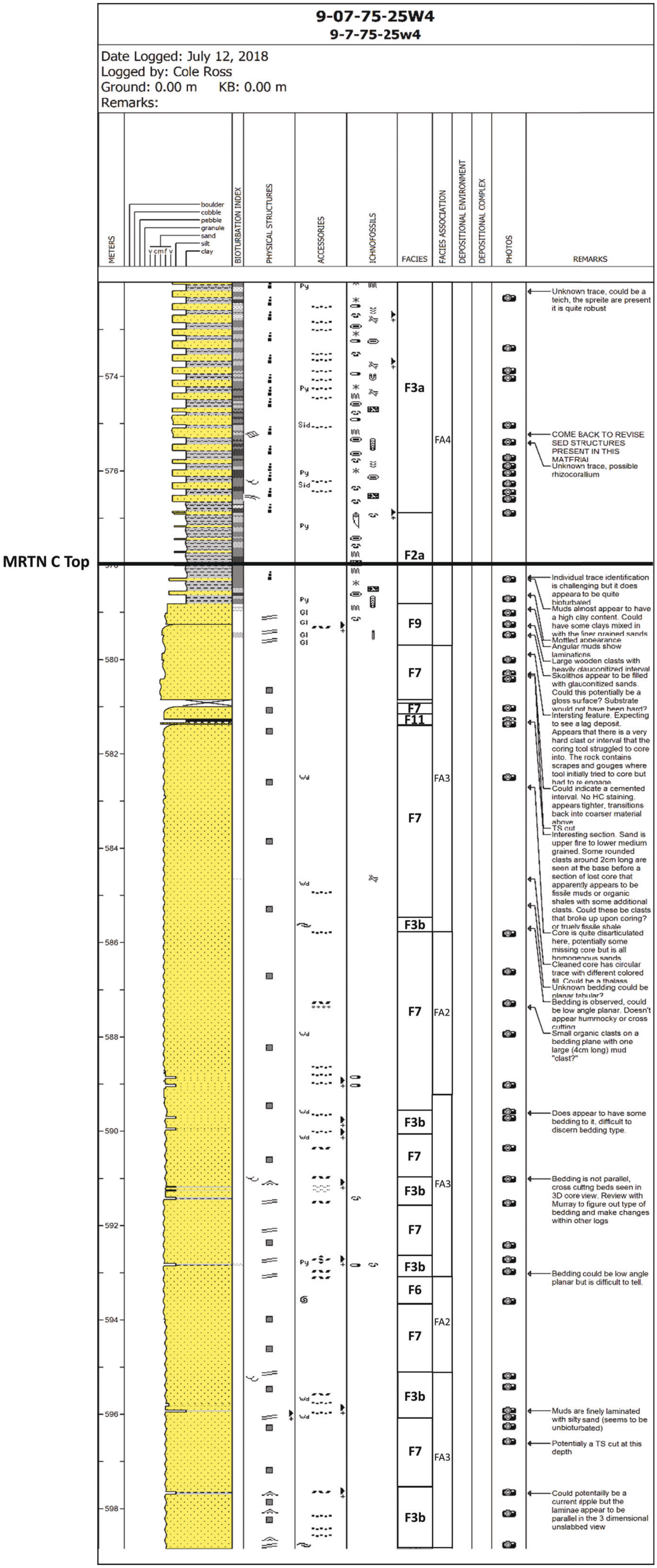


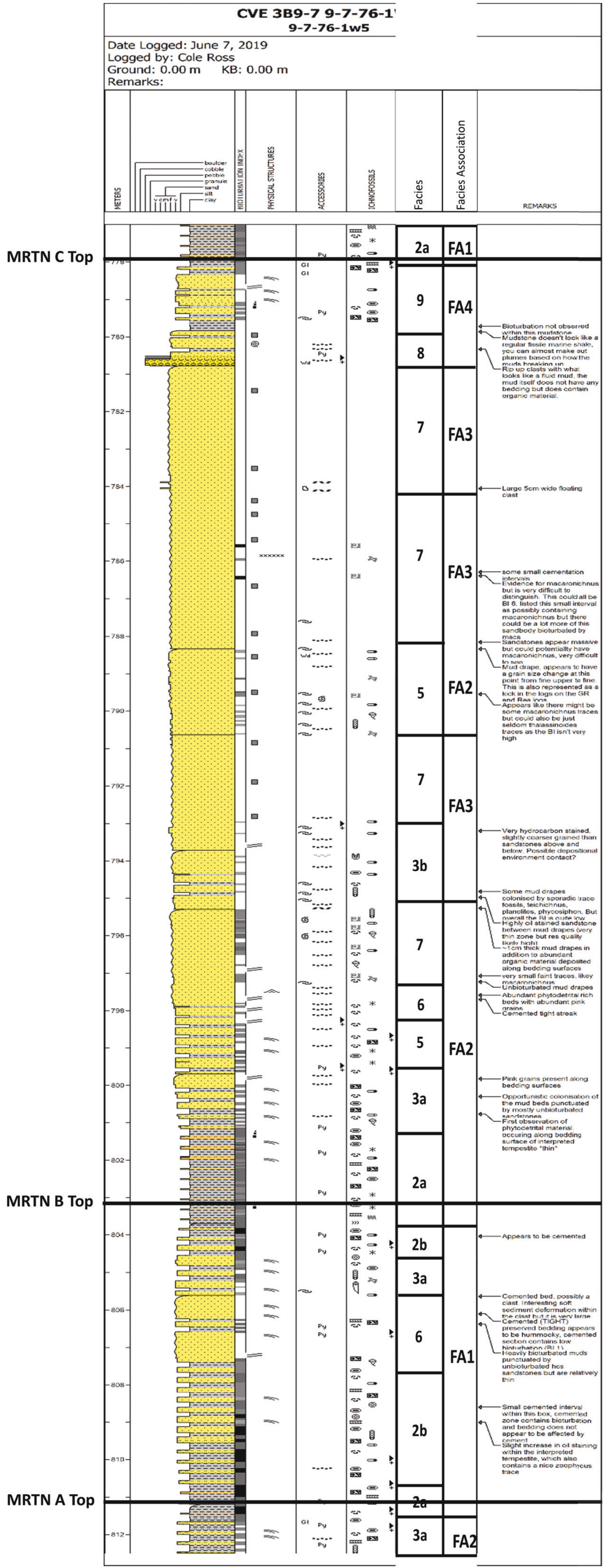
8-27-75-26W4
8-27-75-26w4
Date Logged: August 8, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:
METERS
boulder
cobble
pebble
granule
sand
silt
clay
v c m f v
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
DEPOSITIONAL COMPLEX
PHOTOS
REMARKS
764
766
768
770
772
774
776
778
780
782
784
786
788
F7
F8
FA4
F7
FA2
F3b
FA3
F7
F6
FA2
F7
F3b
F7
F3a
FA3
F3b
F3b
F7
F3a
FA2
F4
F6
F4
F7
F4
F3a
FA1
MRTN C3 Top
MRTN C2 Top
Subangular to subrounded clasts that appear to be mud. They show faint laminations predominantly unbioturbated. Some clasts have diminutive planolites traces potentialy
Thin section cut at this depth
Thin section cut at this depth
Coarser material that may be the result of an abundance in organics?
Thin section cut at this depth
Thin sectio cut at this depth
Wavy bedding dark muds
Faint remains of low angle bedding but predominantly massive appearing
Aside from organic debris along bedding plane, appears massive. Organics deposited on a low angle
Silty beds could be colonized but difficult to see in unslabbed core
Spotty cementation interval through massive appearing sand
Oil stained sands appear massive, cemented material preserves some traces which could be prevalent throughout
Oppurtunistic colonization of this mud bed (Phycosiphon?)
Sporadic silty "blobs" could be rosselia traces poorly preserved
Spotty irregular cementation (small patches of unstained tighter material)
Sharp contact between muddy/silty marine material and massive appearing sands with spotty cementation
Cosmoraphe and planolites seen in muddier intervals not so much in the silty sands
Very dense massive appearing material (Fe rich?)

9-05-75-25W4
9-5-75-25w4

Date Logged: July 6, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:




9-07-75-25W4
9-7-75-25w4
Date Logged: July 12, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:
METERS
boulder
cobble
pebble
granule
sand
silt
clay
v c m f v
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
DEPOSITIONAL COMPLEX
PHOTOS
REMARKS
574
576
578
580
582
584
586
588
590
592
594
596
598
MRTN C Top
F3a
F2a
F9
F7
F7
F11
F7
F3b
F7
F3b
F7
F3b
F7
F3b
F6
F7
F3b
F7
F3b
FA4
FA3
FA2
FA3
FA2
FA3
Py
Sid
Gl
Unknown trace, could be a teich, the spreite are present it is quite robust
COME BACK TO REVISE SED STRUCTURES PRESENT IN THIS MATERIAL
Unknown trace, possible rhizocorallium
Individual trace identification is challenging but it does appeara to be quite bioturbated
Muds almost appear to have a high clay content. Could have some clays mixed in with the finer grained sands
Mottled appearance
Angular muds show laminations
Large wooden clasts with heavily glauconitized interval
Skolithos appear to be filled with glauconitized sands. Could this potentially be a gloss surface? Substrate would not have been hard?
Intersting feature. Expecting to see a lag deposit. Appears that there is a very hard clast or interval that the coring tool struggled to core into. The rock contains scrapes and gouges where tool initially tried to core but had to re engage
Could indicate a cemented interval. No HC staining, appears tighter, transitions back into coarser material above
TS cut
Interesting section. Sand is upper fine to lower medium grained. Some rounded clasts around 2cm long are seen at the base before a section of lost core that apparently appears to be fissile muds or organic shales with some additional clasts. Could these be clasts that broke up upon coring? or truely fissile shale
Core is quite disarticulated here, potentially some missing core but is all homogenous sands
Cleaned core has circular trace with different colored fill. Could be a thalass
Unknown bedding could be planar tabular?
Bedding is observed, could be low angle planar. Doesn't appear hummocky or cross cutting
Small organic clasts on a bedding plane with one large (4cm long) mud "clast?"
Does appear to have some bedding to it, difficult to discern bedding type.
Bedding is not parallel, cross cutting beds seen in 3D core view. Review with Murray to figure out type of bedding and make changes within other logs
Bedding could be low angle planar but is difficult to tell.
Muds are finely laminated with silty sand (seems to be unbioturbated)
Potentially a TS cut at this depth
Could potentially be a current ripple but the laminae appear to be parallel in the 3 dimensional unslabbed view

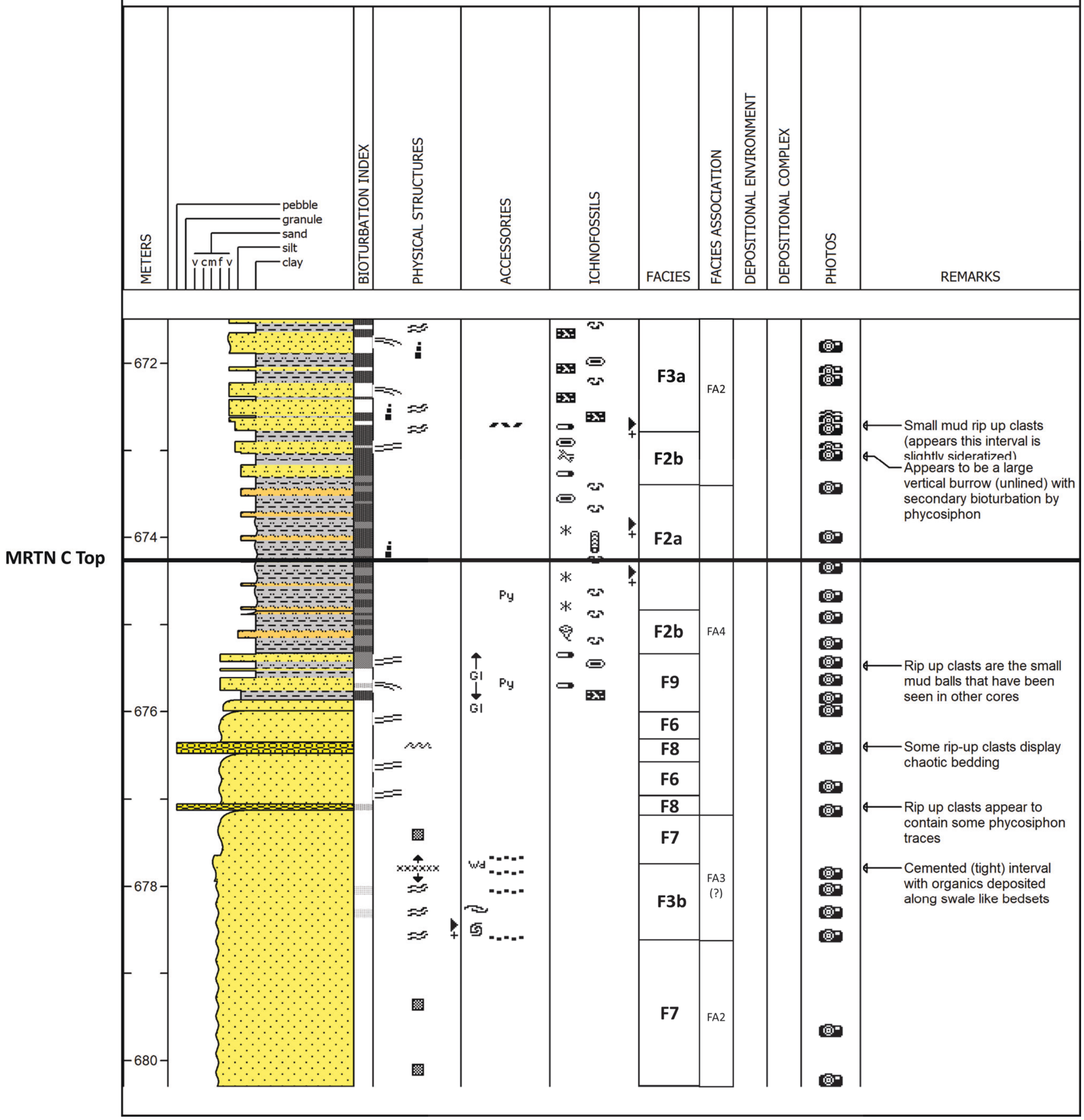


CVE 3B9-7 9-7-76-1'
9-7-76-1w5
Date Logged: June 7, 2019
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:
METERS
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
Facies
Facies Association
REMARKS
MRTN C Top
MRTN B Top
MRTN A Top
2a
FA1
9
FA4
8
7
FA3
7
FA3
5
FA2
7
FA3
3b
7
6
5
FA2
3a
2a
2b
3a
6
FA1
2b
2a
3a
FA2
Bioturbation not observed within this mudstone
Mudstone doesn't look like a regular fissile marine shale, you can almost make out plumes based on how the muds breaking up
Rip up clasts with what looks like a fluid mud, the mud itself does not have any bedding but does contain organic material.
Large 5cm wide floating clast
some small cementation intervals
Evidence for macaronichnus but is very difficult to distinguish. This could all be BI 6, listed this small interval as possibly containing macaronichnus but there could be a lot more of this sandbody bioturbated by macs
Sandstones appear massive but could potentially have macaronichnus, very difficult to see
Mud drape, appears to have a grain size change at this point from fine upper to fine. This is also represented as a kick in the logs on the GR and Res logs
Appears like there might be some macaronichnus traces but could also be just seldom thalassinoides traces as the BI isn't very high
Very hydrocarbon stained, slightly coarser grained than sandstones above and below. Possible depositional environment contact?
Some mud drapes colonised by sporadic trace fossils, teichichnus, planclites, phycosiphon. But overall the BI is quite low
Highly oil stained sandstone between mud drapes (very thin zone but res quality likely high!
~1cm thick mud drapes in addition to abundant organic material deposited along bedding surfaces
very small faint traces, likey macaronichnus
Unbioturbated mud drapes
Abundant phytodetrital rich beds with abundant pink grains
Cemented tight streak
Pink grains present along bedding surfaces
Opportunistic colonisation of the mud beds punctuated by mostly unbioturbated sandstones
First observation of phytodetrital material occuring along bedding surface of interpreted tempestite "thin"
Appears to be cemented
Cemented bed, possibly a clast. Interesting soft sediment deformation within the clast but it is very large
Cemented (TIGHT) preserved bedding appears to be hummocky, cemented section contains low bioturbation (BI 1)
Heavily bioturbated muds punctuated by unbioturbated hcs sandstones but are relatively thin
Small cemented interval within this box, cemented zone contains bioturbation and bedding does not appear to be affected by cement
Slight increase in oil staining within the interpreted tempestite, which also contains a nice zoophycus trace

9-24-75-1W5

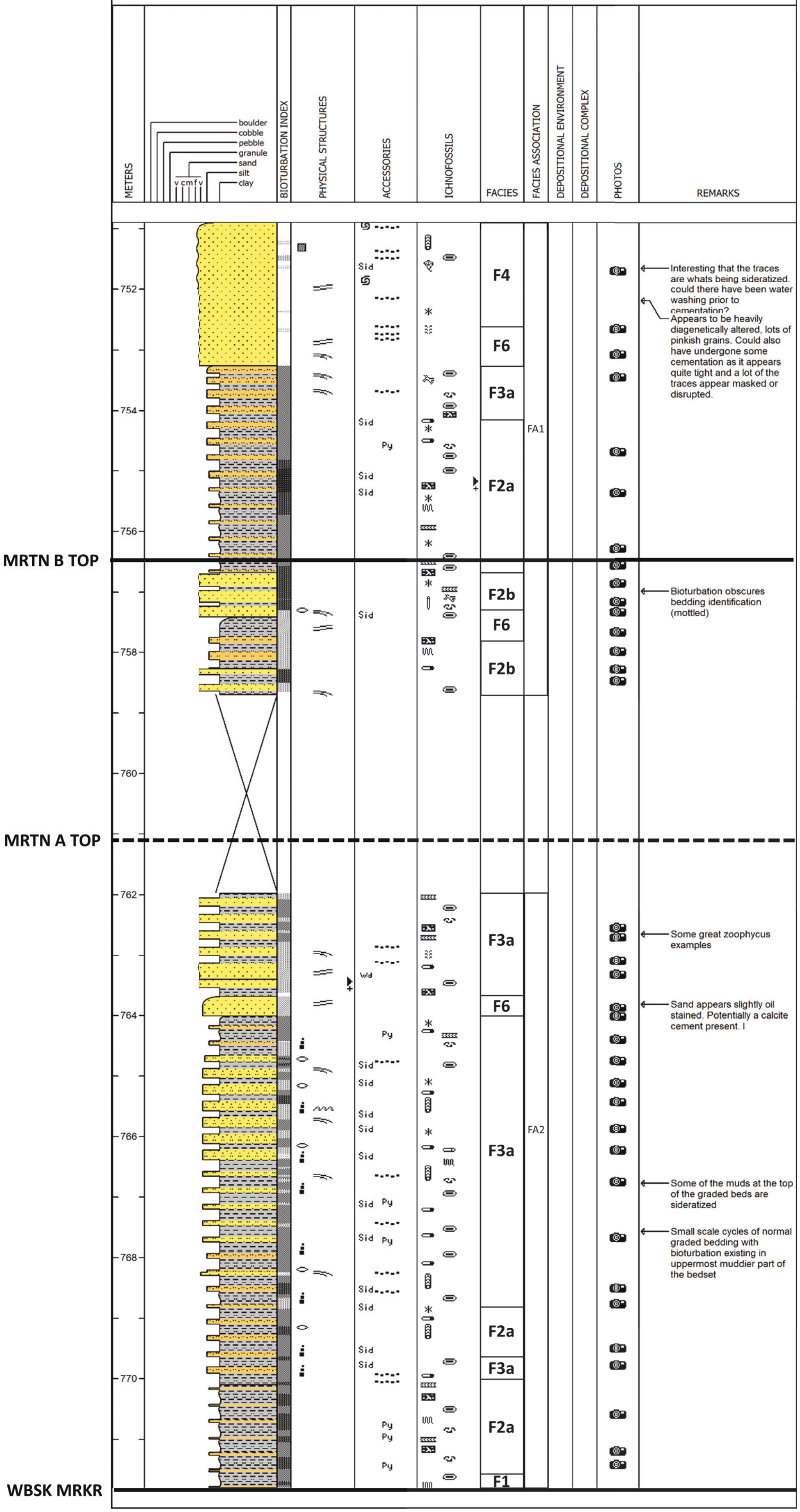
9-24-75-1w5

Date Logged: August 20, 2018
Logged by: Cole Ross
Ground: 0.00 m   KB: 0.00 m
Remarks:



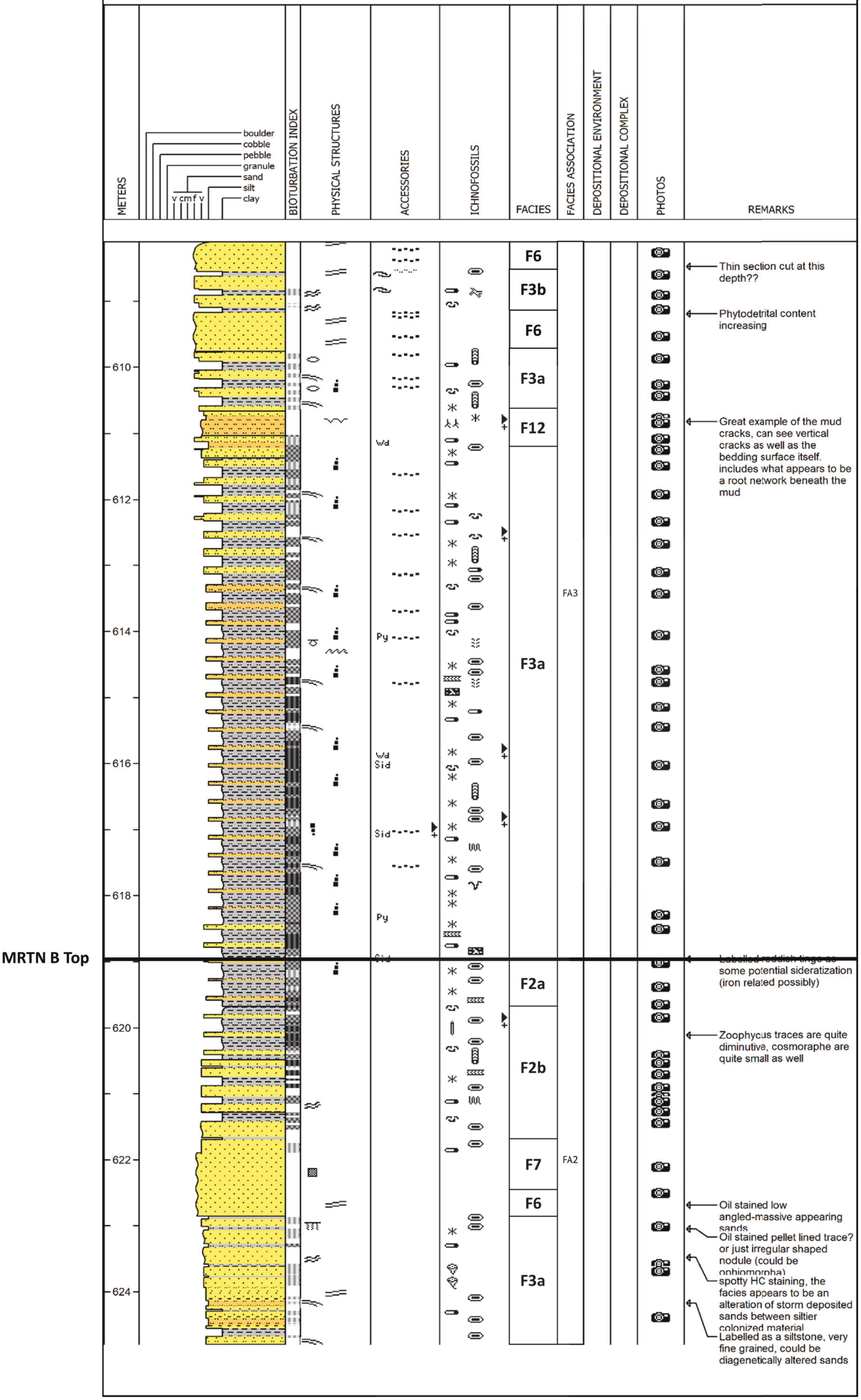
10-05-76-24W4
10-5-76-24w4

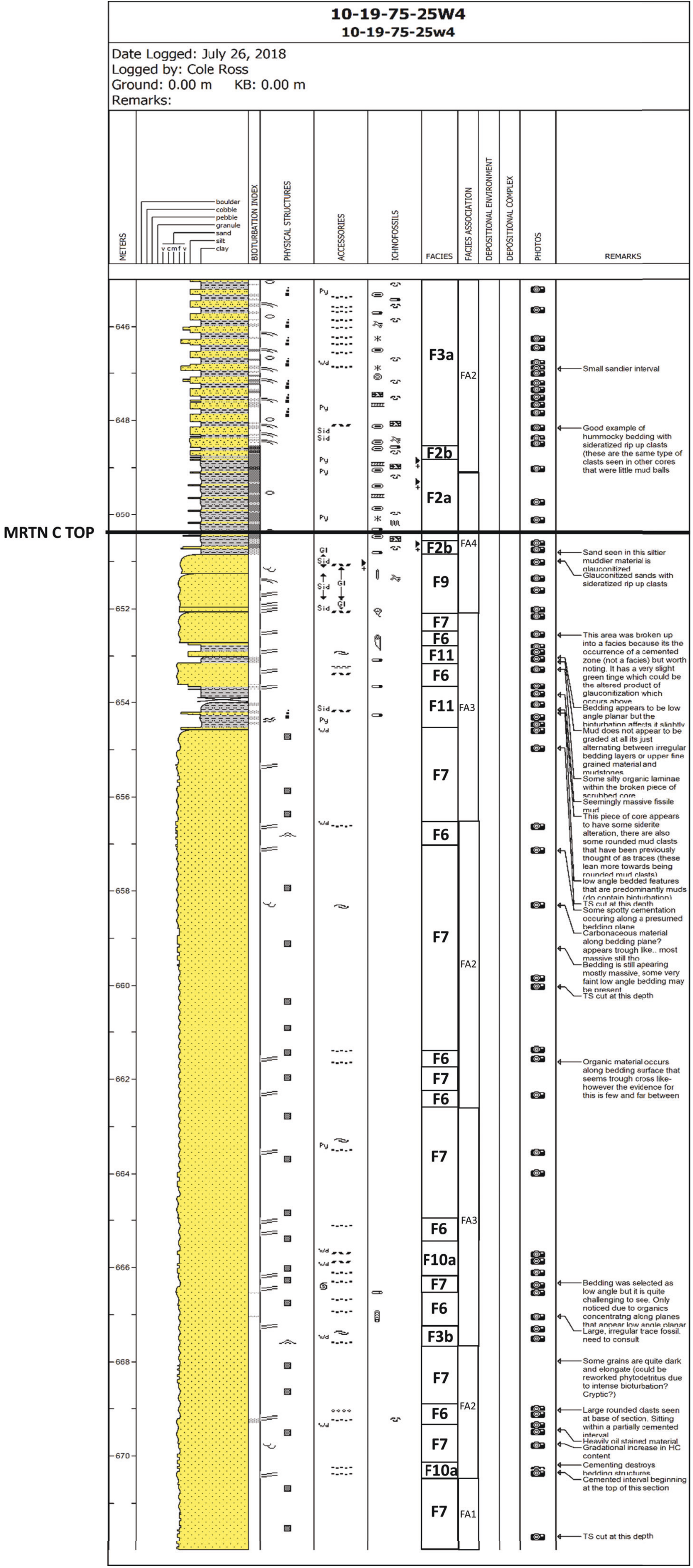
Date Logged: August 13, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:



10-7-77-4W5
10-7-77-4w5

Date Logged: August 22, 2018
Logged by: Cole Ross
Ground: 0.00 m   KB: 0.00 m
Remarks:

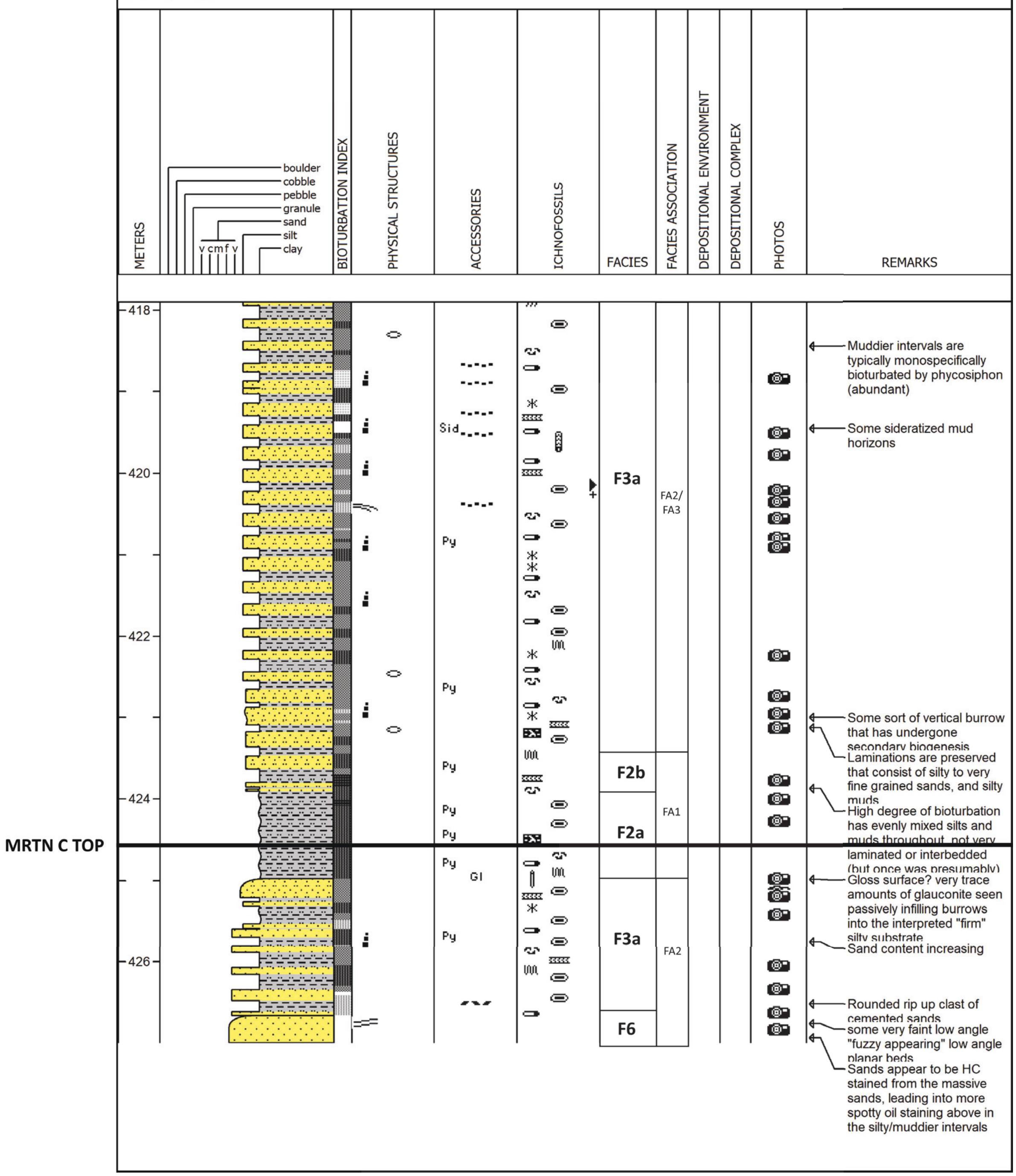



10-19-75-25W4
10-19-75-25w4
Date Logged: July 26, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:
METERS
boulder
cobble
pebble
granule
sand
silt
clay
v c m f v
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
DEPOSITIONAL COMPLEX
PHOTOS
REMARKS
646
648
650
652
654
656
658
660
662
664
666
668
670
MRTN C TOP
Py
Wd
Sid
Gl
F3a
F2b
F2a
F2b
F9
F7
F6
F11
F6
F11
F7
F6
F7
F6
F7
F6
F7
F6
F10a
F7
F6
F3b
F7
F6
F7
F10a
F7
FA2
FA4
FA3
FA2
FA3
FA2
FA1
Small sandier interval
Good example of hummocky bedding with sideratized rip up clasts (these are the same type of clasts seen in other cores that were little mud balls
Sand seen in this siltier muddier material is glauconitized
Glauconitized sands with sideratized rip up clasts
This area was broken up into a facies because its the occurrence of a cemented zone (not a facies) but worth noting. It has a very slight green tinge which could be the altered product of glauconitization which occurs above
Bedding appears to be low angle planar but the bioturbation affects it slightly
Mud does not appear to be graded at all its just alternating between irregular bedding layers or upper fine grained material and mudstones
Some silty organic laminae within the broken piece of scrubbed core
Seemingly massive fissile mud
This piece of core appears to have some siderite alteration, there are also some rounded mud clasts that have been previously thought of as traces (these lean more towards being rounded mud clasts)
low angle bedded features that are predominantly muds (do contain bioturbation)
TS cut at this depth
Some spotty cementation occuring along a presumed bedding plane
Carbonaceous material along bedding plane? appears trough like.. most massive still tho
Bedding is still apearing mostly massive, some very faint low angle bedding may be present
TS cut at this depth
Organic material occurs along bedding surface that seems trough cross like- however the evidence for this is few and far between
Bedding was selected as low angle but it is quite challenging to see. Only noticed due to organics concentratng along planes that appear low angle planar
Large, irregular trace fossil. need to consult
Some grains are quite dark and elongate (could be reworked phytodetritus due to intense bioturbation? Cryptic?)
Large rounded clasts seen at base of section. Sitting within a partially cemented interval
Heavily oil stained material
Gradational increase in HC content
Cementing destroys bedding structures
Cemented interval beginning at the top of this section
TS cut at this depth

10-19-78-24W4

10-19-78-24w4

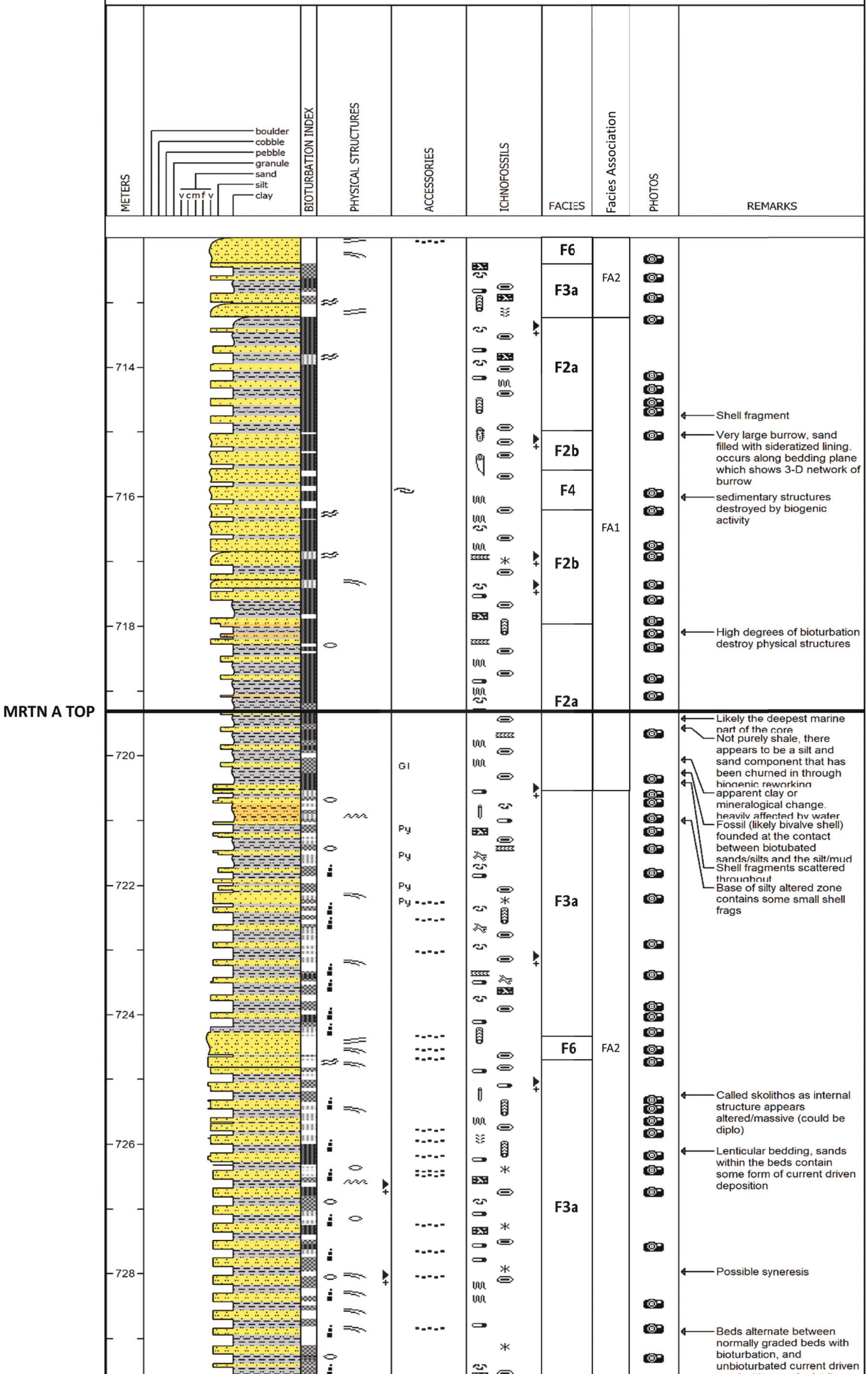
Date Logged: August 14, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:



10-20-74-4W5

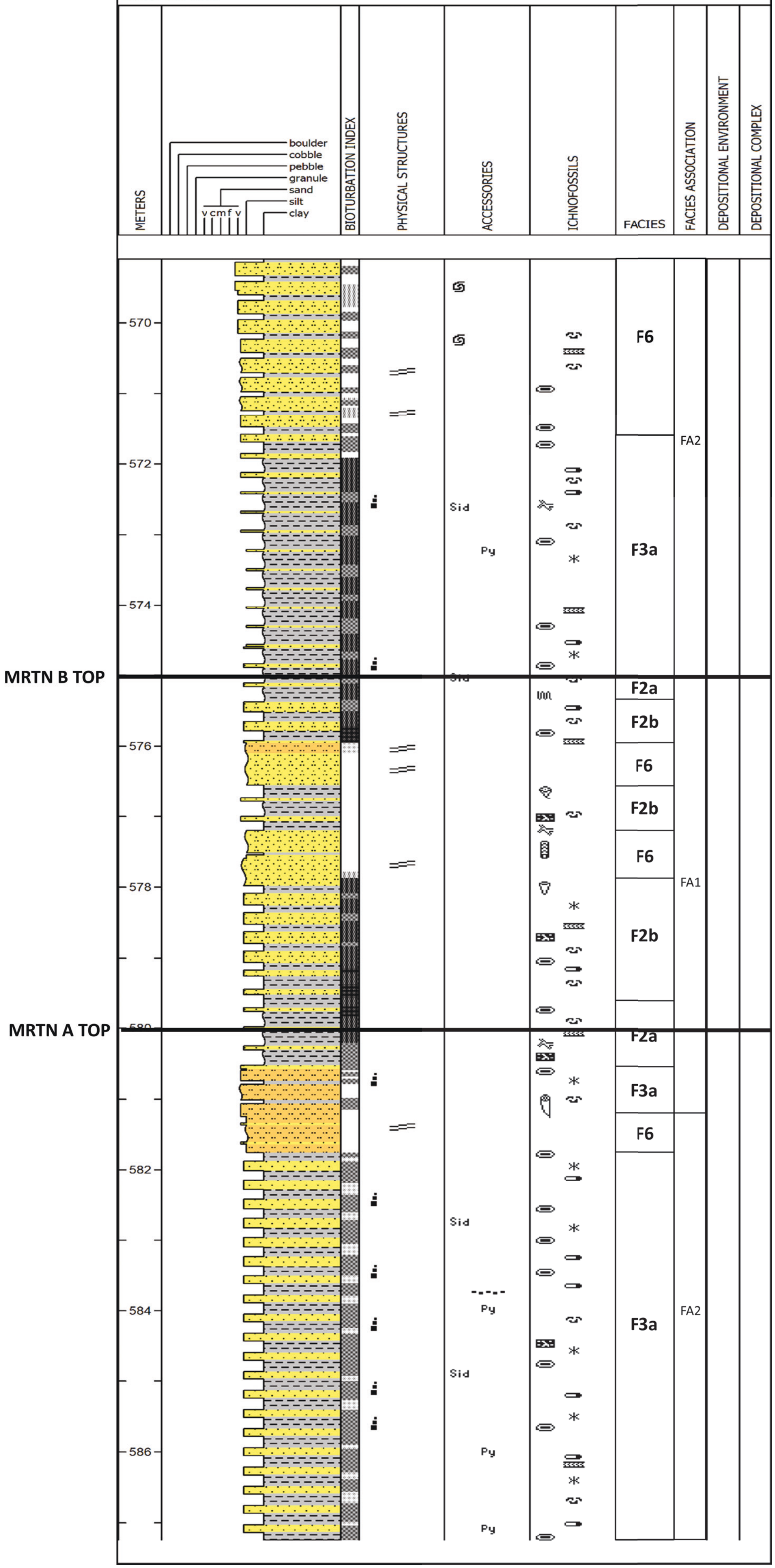
10-20-74-4w5

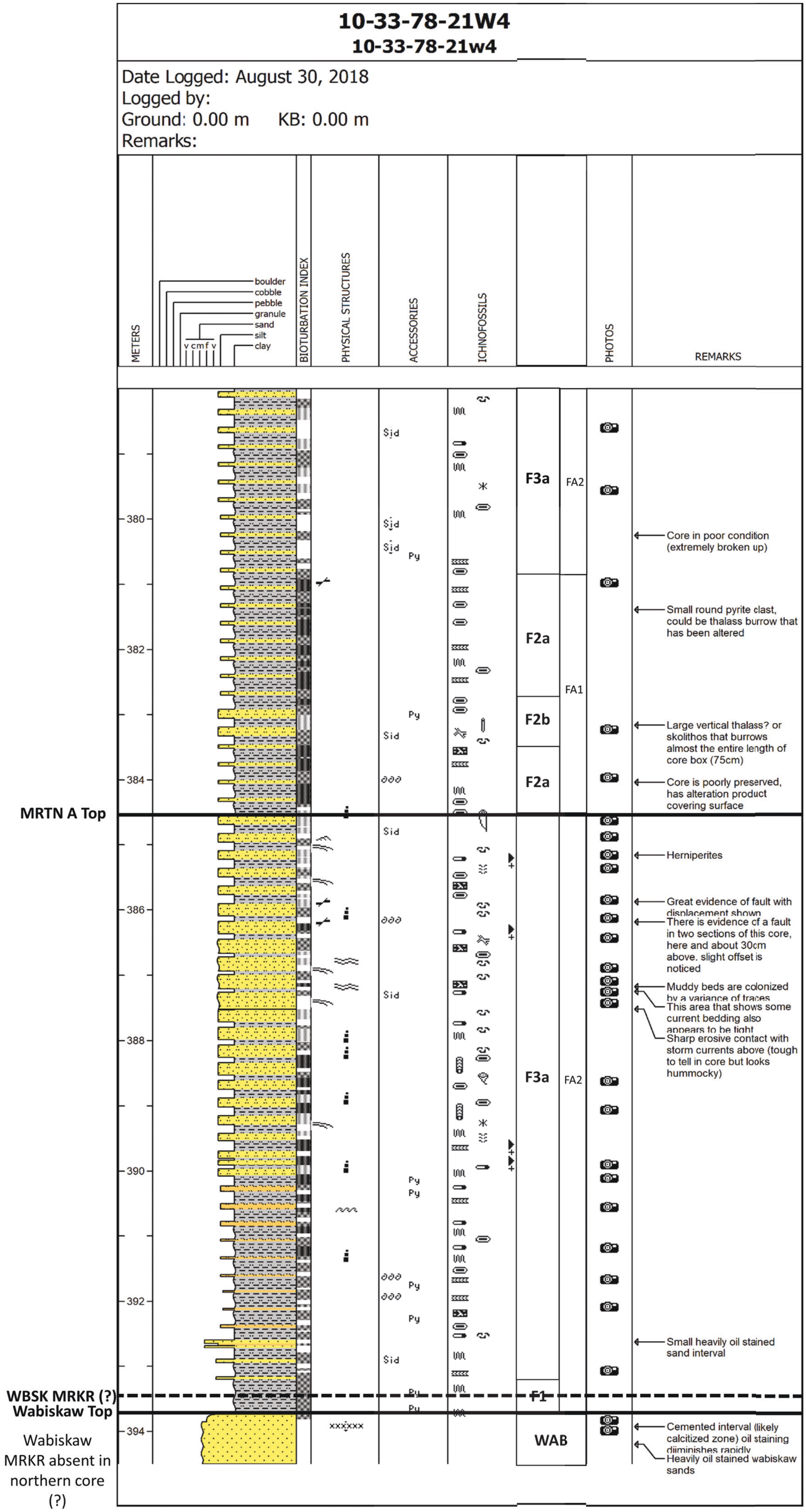
Date Logged: August 17, 2018
Logged by:
Ground: 0.00 m KB: 0.00 m
Remarks:



10-22-74-25W4
10-22-74-25W

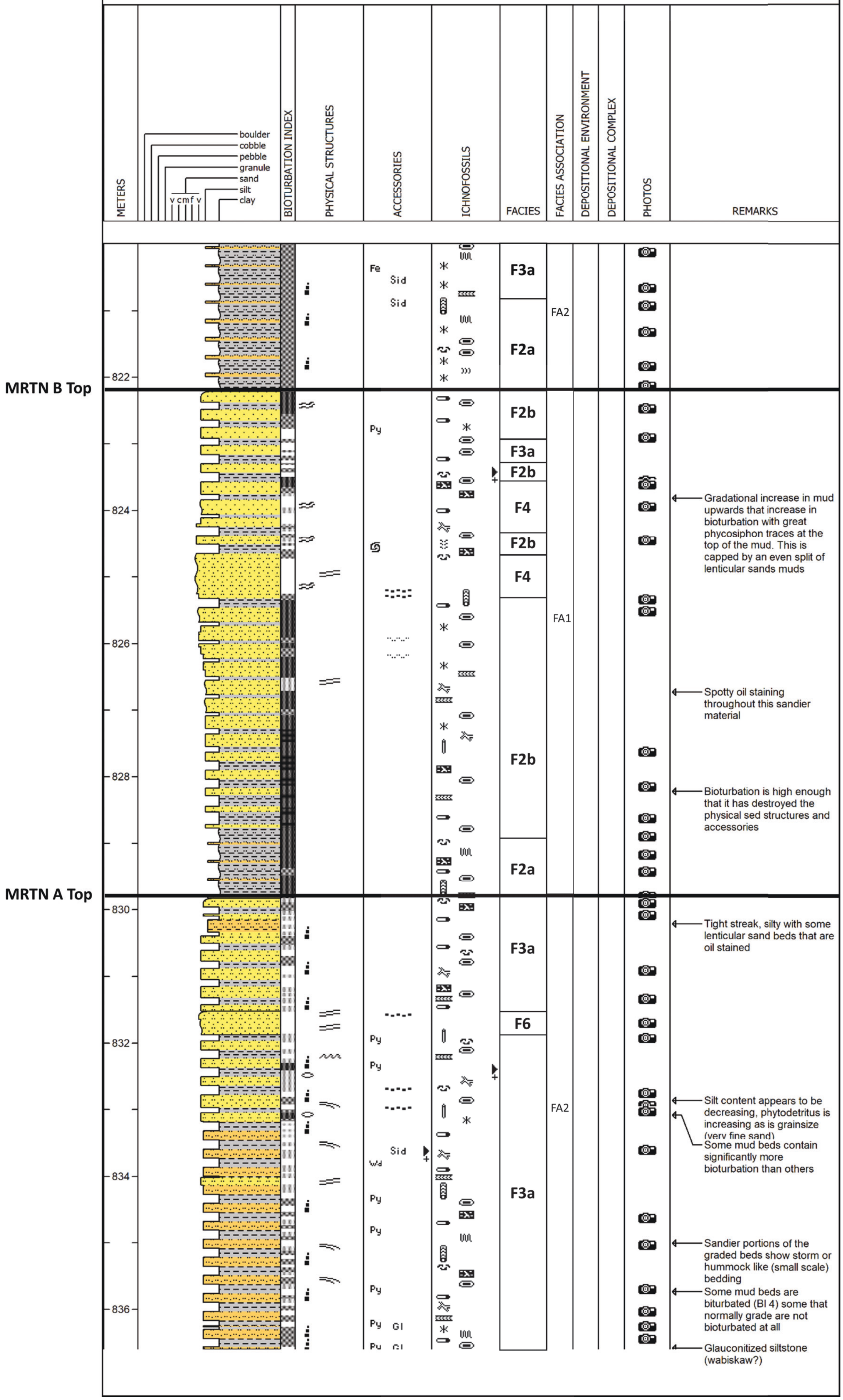
Date Logged: March 21, 2019
Logged by:
Ground: 0.00 m KB: 0.00 m
Remarks:




10-33-78-21W4
10-33-78-21w4
Date Logged: August 30, 2018
Logged by:
Ground: 0.00 m KB: 0.00 m
Remarks:
METERS
boulder
cobble
pebble
granule
sand
silt
clay
v c m f v
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
PHOTOS
REMARKS
380
382
384
386
388
390
392
394
F3a
FA2
F2a
FA1
F2b
F2a
F3a
FA2
F1
WAB
Sid
Py
Core in poor condition (extremely broken up)
Small round pyrite clast, could be thalass burrow that has been altered
Large vertical thalass? or skolithos that burrows almost the entire length of core box (75cm)
Core is poorly preserved, has alteration product covering surface
MRTN A Top
Herniperites
Great evidence of fault with displacement shown
There is evidence of a fault in two sections of this core, here and about 30cm above. slight offset is noticed
Muddy beds are colonized by a variance of traces
This area that shows some current bedding also appears to be tight
Sharp erosive contact with storm currents above (tough to tell in core but looks hummocky)
Small heavily oil stained sand interval
WBSK MRKR (?)
Wabiskaw Top
Cemented interval (likely calcitized zone) oil staining diminishes rapidly
Heavily oil stained wabiskaw sands
Wabiskaw MRKR absent in northern core (?)

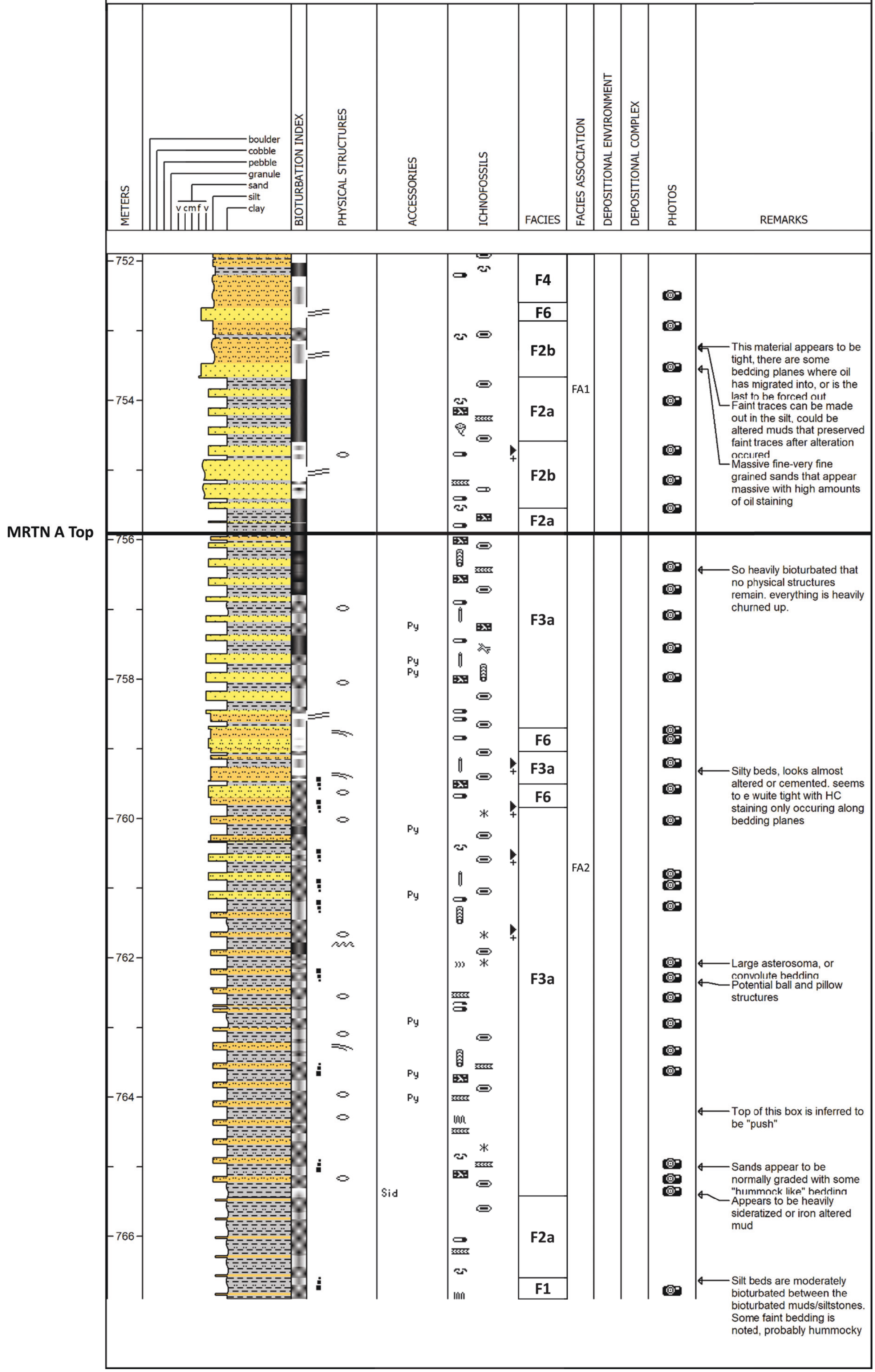
11-01-76-2W5
11-01-76-2w5

Date Logged: August 20, 2018
Logged by:
Ground: 0.00 m KB: 0.00 m
Remarks:



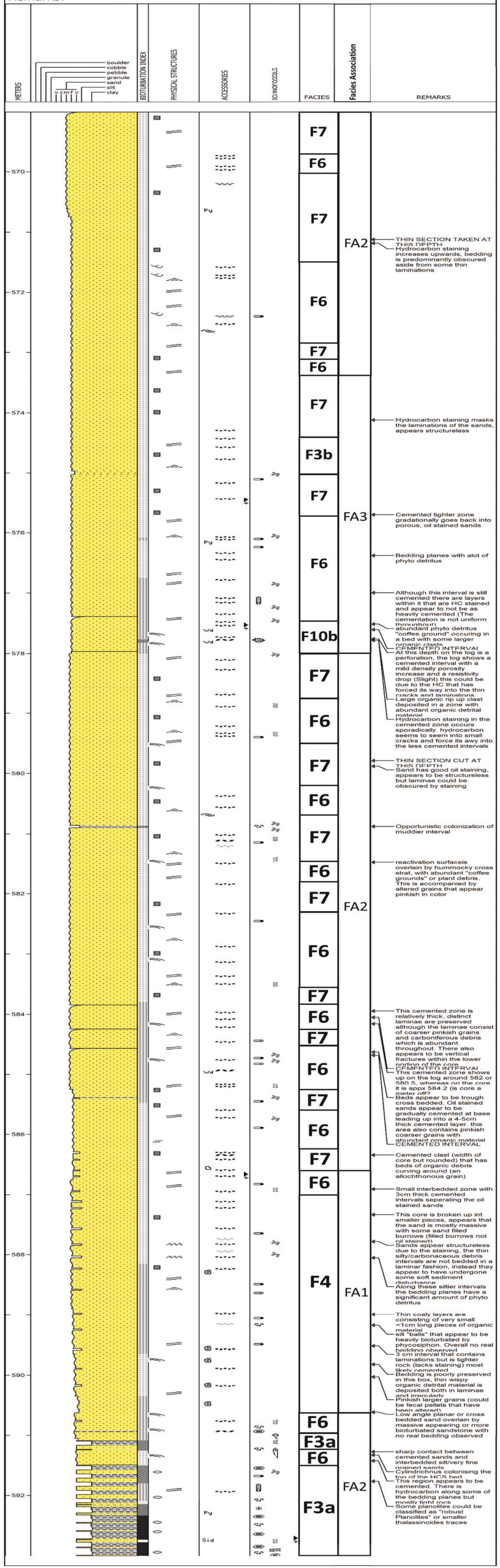
11-26-76-24W4
11-26-76-24w4

Date Logged: August 14, 2018
Logged by: Cole Ross
Ground: 0.00 m   KB: 0.00 m
Remarks:



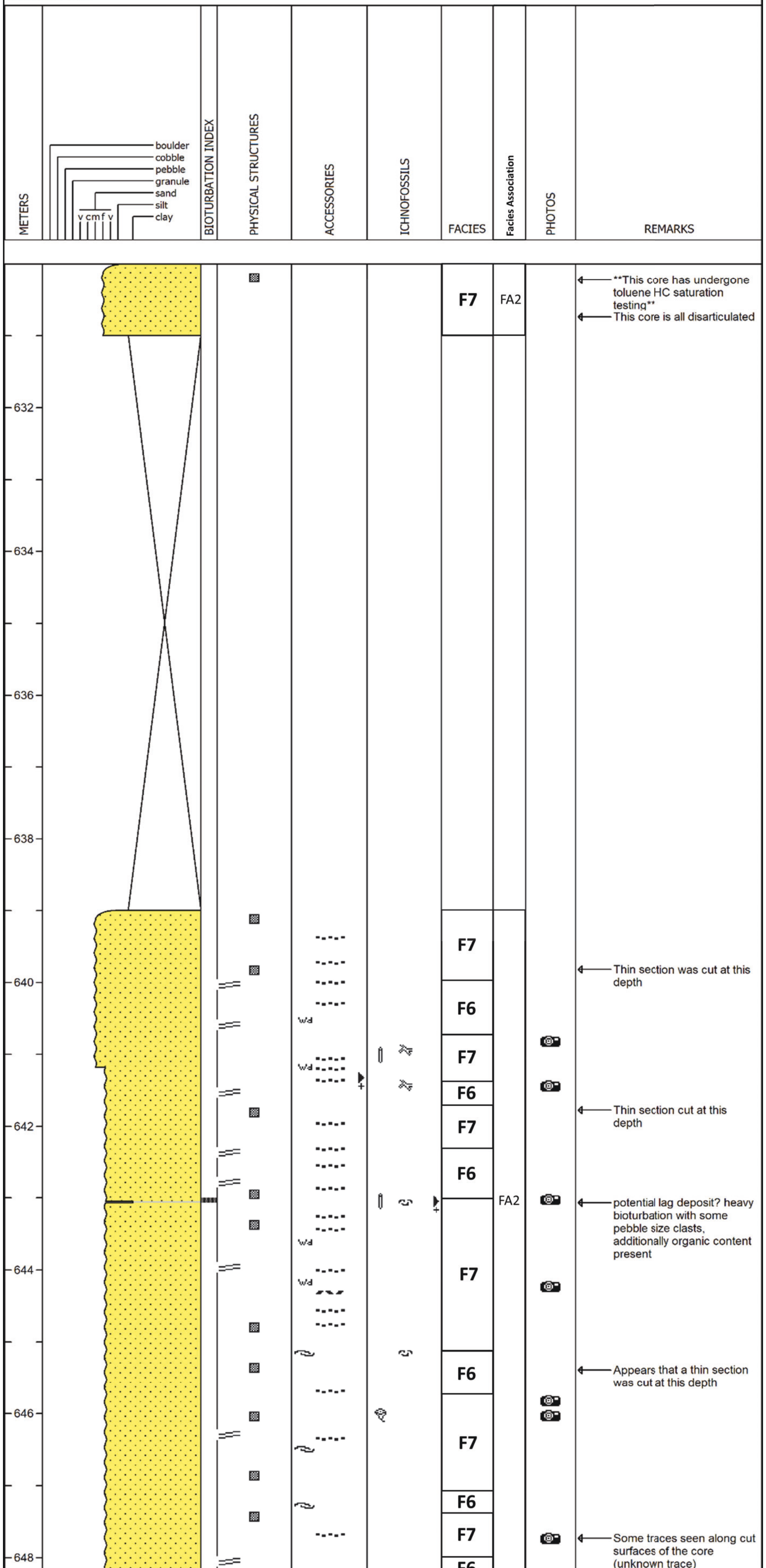
102/11-29-074-25W4
11-29-074-25w4

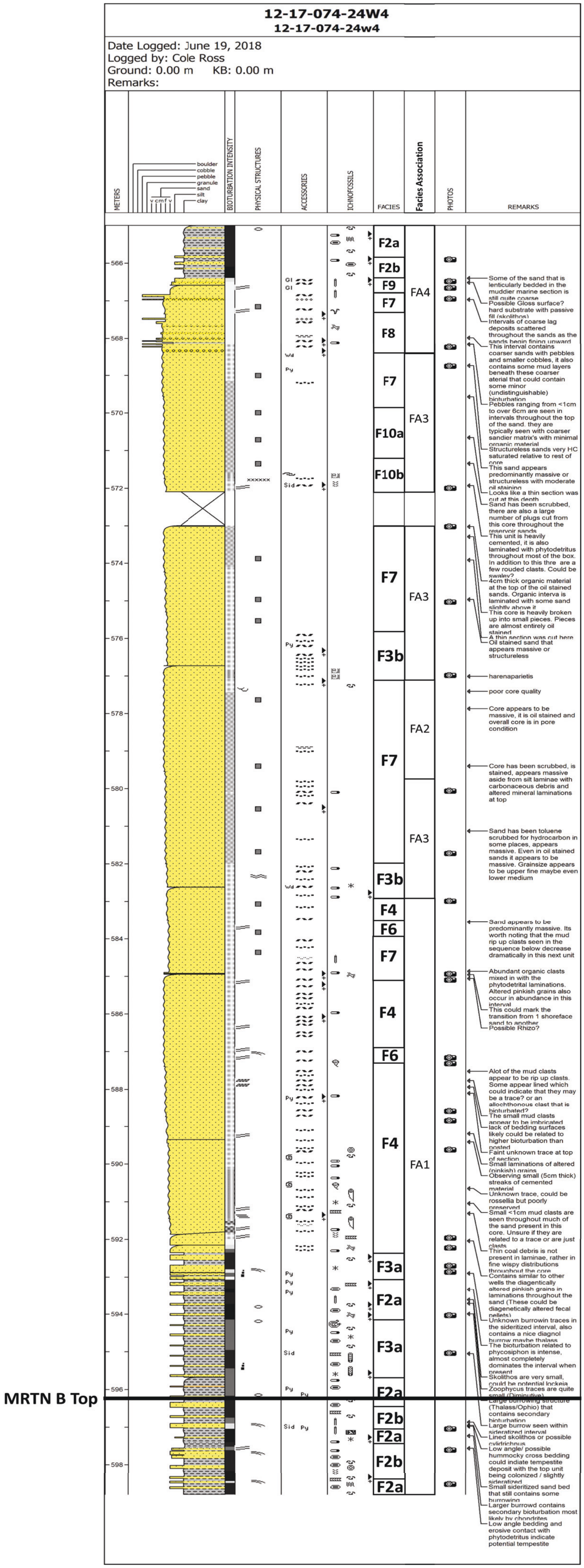
Date Logged: June 15, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:



11-30-074-25W4
11-30-74-25w4

Date Logged: June 19, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:

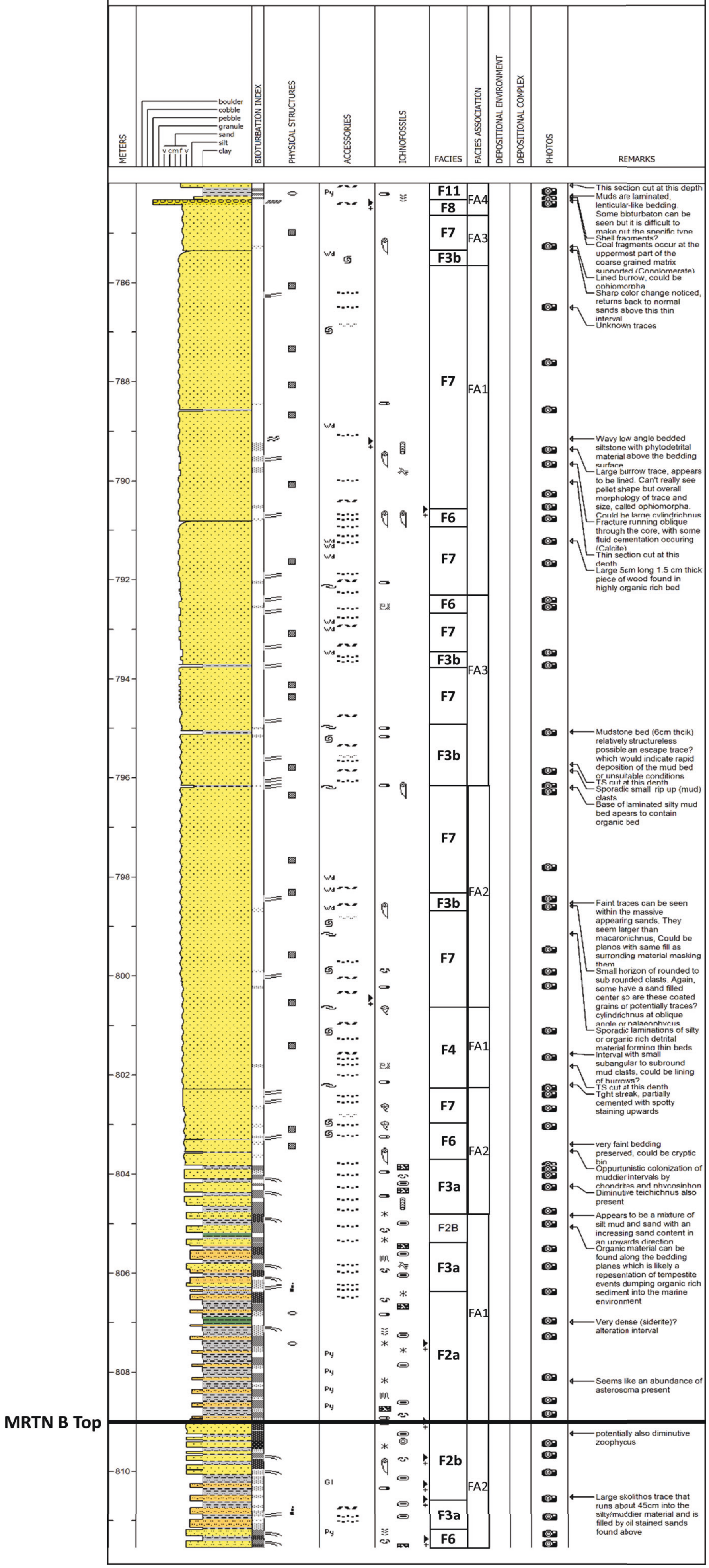



12-17-074-24W4
12-17-074-24w4
Date Logged: June 19, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:
METERS
boulder
cobble
pebble
granule
sand
silt
clay
v c m f v
BIOTURBATION INTENSITY
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FACIES
Facies Association
PHOTOS
REMARKS
566
568
570
572
574
576
578
580
582
584
586
588
590
592
594
596
598
Gl
Wd
Py
Sid
F2a
F2b
F9
F7
F8
F7
F10a
F10b
F7
F3b
F7
F3b
F4
F6
F7
F4
F6
F4
F3a
F2a
F3a
F2a
F2b
F2a
F2b
F2a
FA4
FA3
FA3
FA2
FA3
FA1
Some of the sand that is lenticularly bedded in the muddier marine section is still quite coarse
Possible Gloss surface? hard substrate with passive fill (skolithos)
Intervals of coarse lag deposits scattered throughout the sands as the sands begin fining upward
This interval contains coarser sands with pebbles and smaller cobbles, it also contains some mud layers beneath these coarser aterial that could contain some minor (undistinguishable) bioturbation
Pebbles ranging from <1cm to over 6cm are seen in intervals throughout the top of the sand. they are typically seen with coarser sandier matrix's with minimal organic material
Structureless sands very HC saturated relative to rest of core
This sand appears predominantly massive or structureless with moderate oil staining
Looks like a thin section was cut at this depth
Sand has been scrubbed, there are also a large number of plugs cut from this core throughout the reservoir sands
This unit is heavily cemented, it is also laminated with phytodetritus throughout most of the box. In addition to this thre are a few rouded clasts. Could be swaley?
4cm thick organic material at the top of the oil stained sands. Organic interva is laminated with some sand slightly above it
This core is heavily broken up into small pieces. Pieces are almost entirely oil stained
A thin section was cut here
Oil stained sand that appears massive or structureless
harenaparietis
poor core quality
Core appears to be massive, it is oil stained and overall core is in pore condition
Core has been scrubbed, is stained, appears massive aside from silt laminae with carbonaceous debris and altered mineral laminations at top
Sand has been toluene scrubbed for hydrocarbon in some places, appears massive. Even in oil stained sands it appears to be massive. Grainsize appears to be upper fine maybe even lower medium
Sand appears to be predominantly massive. Its worth noting that the mud rip up clasts seen in the sequence below decrease dramatically in this next unit
Abundant organic clasts mixed in with the phytodetrital laminations. Altered pinkish grains also occur in abundance in this interval
This could mark the transition from 1 shoreface sand to another
Possible Rhizo?
Alot of the mud clasts appear to be rip up clasts. Some appear lined which could indicate that they may be a trace? or an allochthonous clast that is bioturbated?
The small mud clasts appear to be imbricated
lack of bedding surfaces likely could be related to higher bioturbation than posted
Faint unknown trace at top of section
Small laminations of altered (pinkish) grains
Observing small (5cm thick) streaks of cemented material
Unknown trace, could be rossellia but poorly preserved
Small <1cm mud clasts are seen throughout much of the sand present in this core. Unsure if they are related to a trace or are just clasts
Thin coal debris is not present in laminae, rather in fine wispy distributions throughout the core
Contains similar to other wells the diagentically altered pinkish grains in laminations throughout the sand (These could be diagenetically altered fecal pellets)
Unknown burrowin traces in the sideritized interval, also contains a nice diagnol burrow maybe thalass
The bioturbation related to phycosiphon is intense, almost completely dominates the interval when present
Skolithos are very small, could be potential lockeia
Zoophycus traces are quite small (Diminutive)
Large burrowing structure (Thalass/Ophio) that contains secondary bioturbation
Large burrow seen within sideratized interval
Lined skolithos or possible cylidrichnus
Low angle/ possible hummocky cross bedding could indiate tempestite deposit with the top unit being colonized / slightly sideratized
Small sideritized sand bed that still contains some burrowing
Larger burrowd contains secondary bioturbation most likely by chondrites
Low angle bedding and erosive contact with phytodetritus indicate potential tempestite
MRTN B Top

13-26-75-26W4

13-26-75-26w4

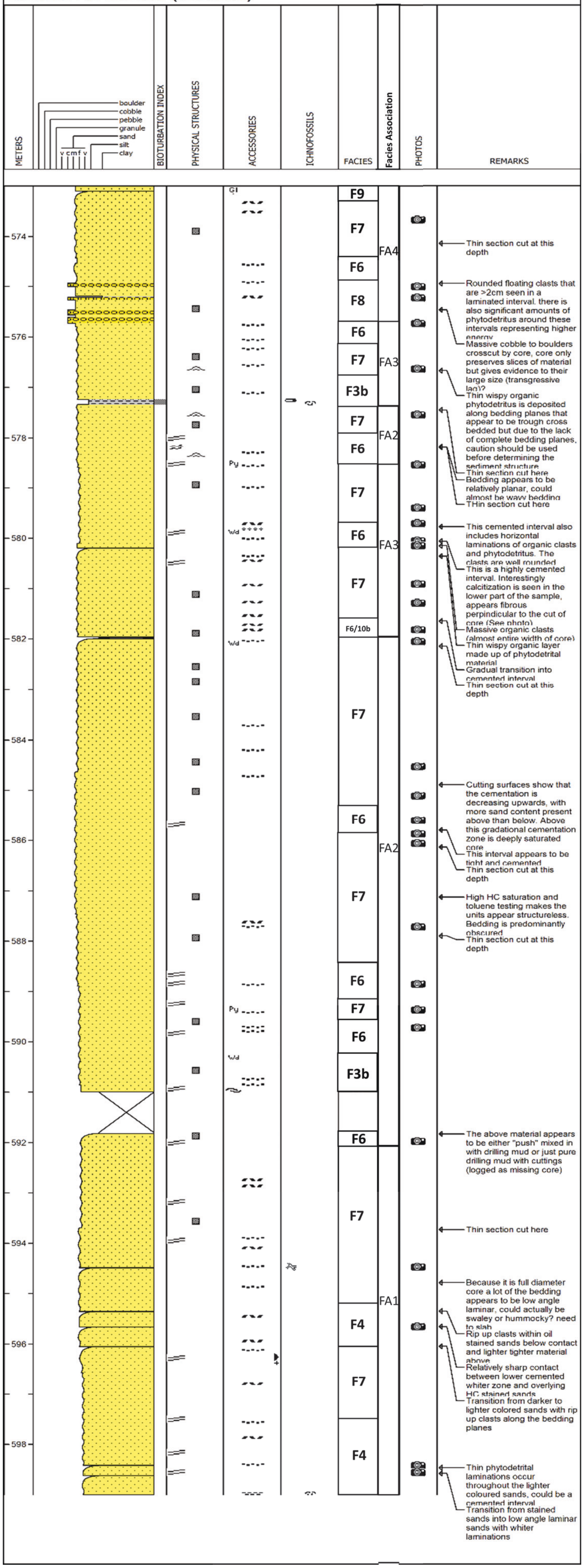
Date Logged: August 3, 2018
Logged by: Cole Ross
Ground: 0.00 m   KB: 0.00 m
Remarks:

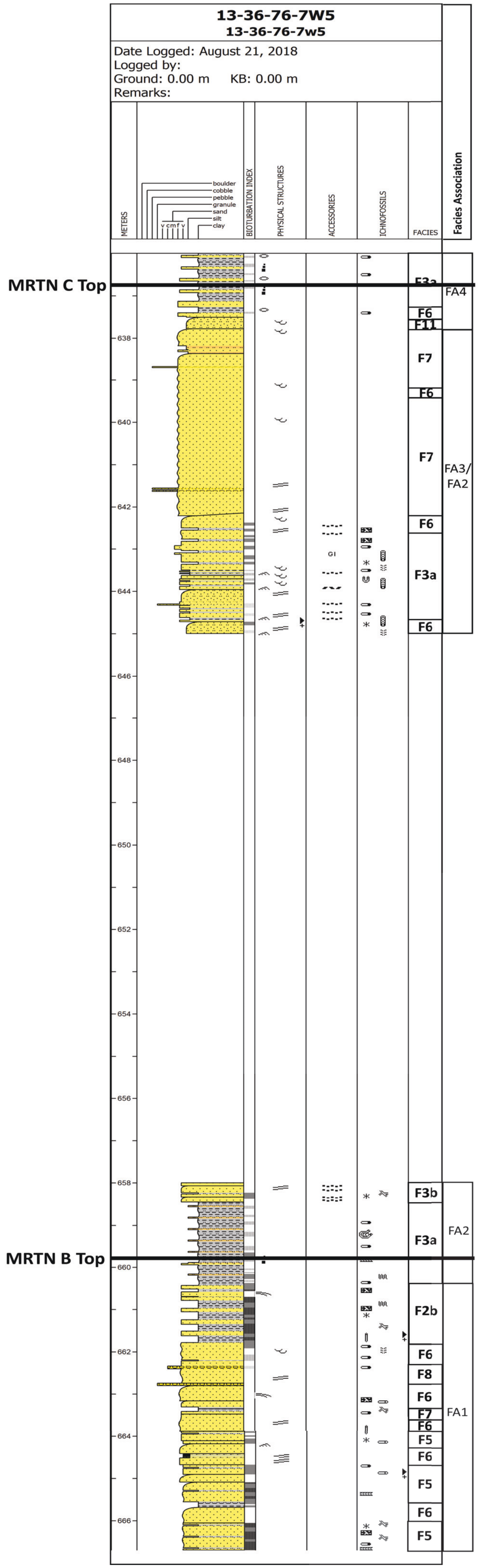


13-31-074-25W4

13-31-074-25w4

Date Logged: June 22, 2018
Logged by:
Ground: 0.00 m KB: 0.00 m
Remarks: Full Diameter (unslabbed)




13-36-76-7W5
13-36-76-7w5
Date Logged: August 21, 2018
Logged by:
Ground: 0.00 m KB: 0.00 m
Remarks:
METERS
boulder
cobble
pebble
granule
sand
silt
clay
v c m f v
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FACIES
Facies Association
MRTN C Top
MRTN B Top
638
640
642
644
646
648
650
652
654
656
658
660
662
664
666
F3a
F6
F11
F7
F6
F7
F6
F3a
F6
F3b
F3a
F2b
F6
F8
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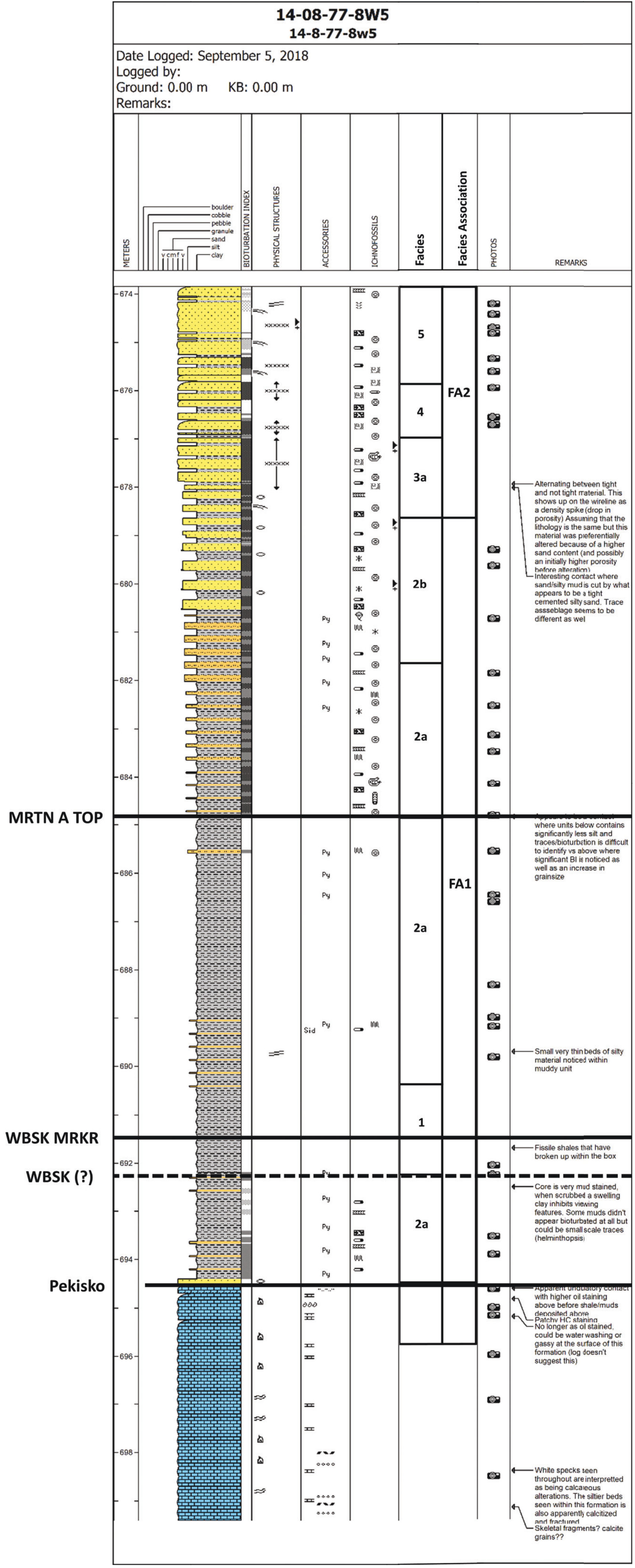
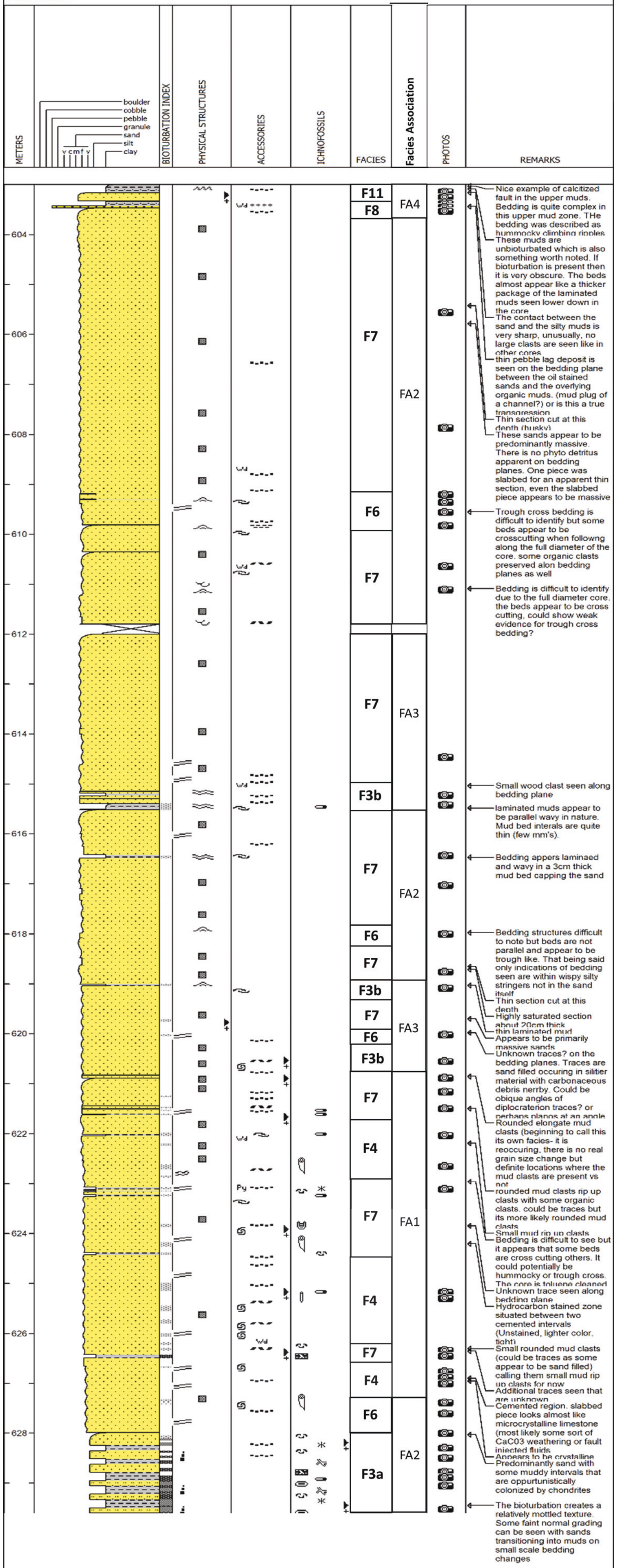
F5
F6
F5
FA4
FA3/
FA2
FA2
FA1
GI



14-08-77-8W5
14-8-77-8w5
Date Logged: September 5, 2018
Logged by:
Ground: 0.00 m KB: 0.00 m
Remarks:
METERS
boulder
cobble
pebble
granule
sand
silt
clay
v c m f v
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
Facies
Facies Association
PHOTOS
REMARKS
674
676
678
680
682
684
686
688
690
692
694
696
698
5
4
3a
2b
2a
2a
1
2a
FA2
FA1
Py
Sid
MRTN A TOP
WBSK MRKR
WBSK (?)
Pekisko
Alternating between tight and not tight material. This shows up on the wireline as a density spike (drop in porosity) Assuming that the lithology is the same but this material was preferentially altered because of a higher sand content (and possibly an initially higher porosity before alteration)
Interesting contact where sand/silty mud is cut by what appears to be a tight cemented silty sand. Trace assseblage seems to be different as wel
Appears to be a contact where units below contains significantly less silt and traces/bioturbation is difficult to identify vs above where significant BI is noticed as well as an increase in grainsize
Small very thin beds of silty material noticed within muddy unit
Fissile shales that have broken up within the box
Core is very mud stained, when scrubbed a swelling clay inhibits viewing features. Some muds didn't appear bioturbated at all but could be small scale traces (helminthopsis)
Apparent undulatory contact with higher oil staining above before shale/muds deposited above
Patchy HC staining
No longer as oil stained, could be water washing or gassy at the surface of this formation (log doesn't suggest this)
White specks seen throughout are interpretted as being calcareous alterations. The siltier beds seen within this formation is also apparently calcitized and fractured
Skeletal fragments? calcite grains??

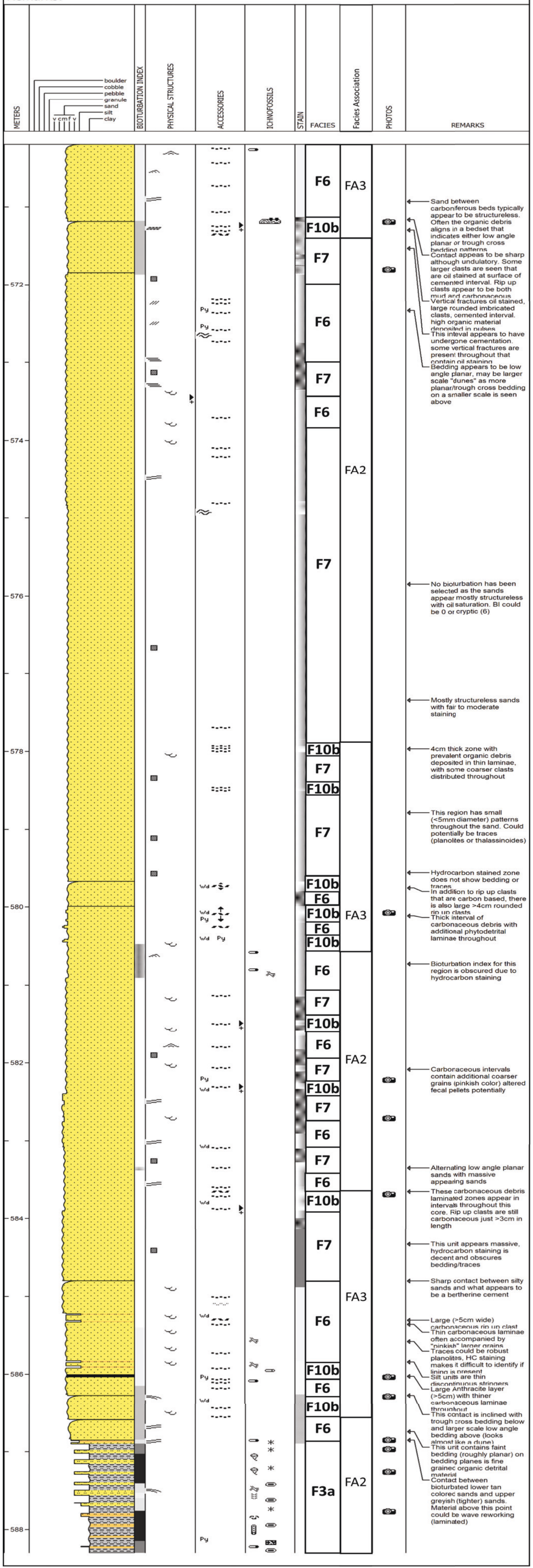
16-06-75-25W4
16-6-75-25w4

Date Logged: July 10, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:



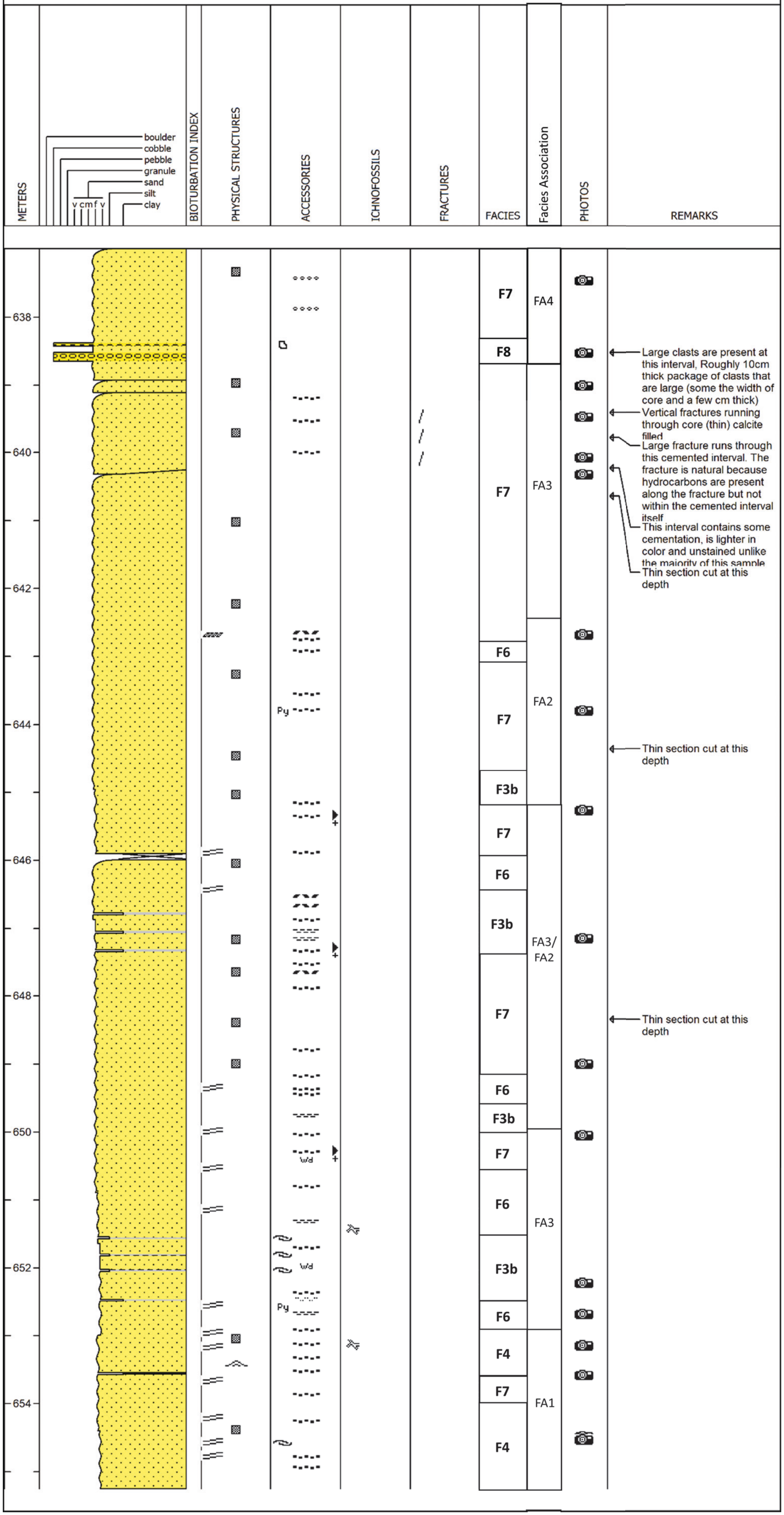
03/16-18-074-25W4
16-18-74-25w4 Marten Hill s

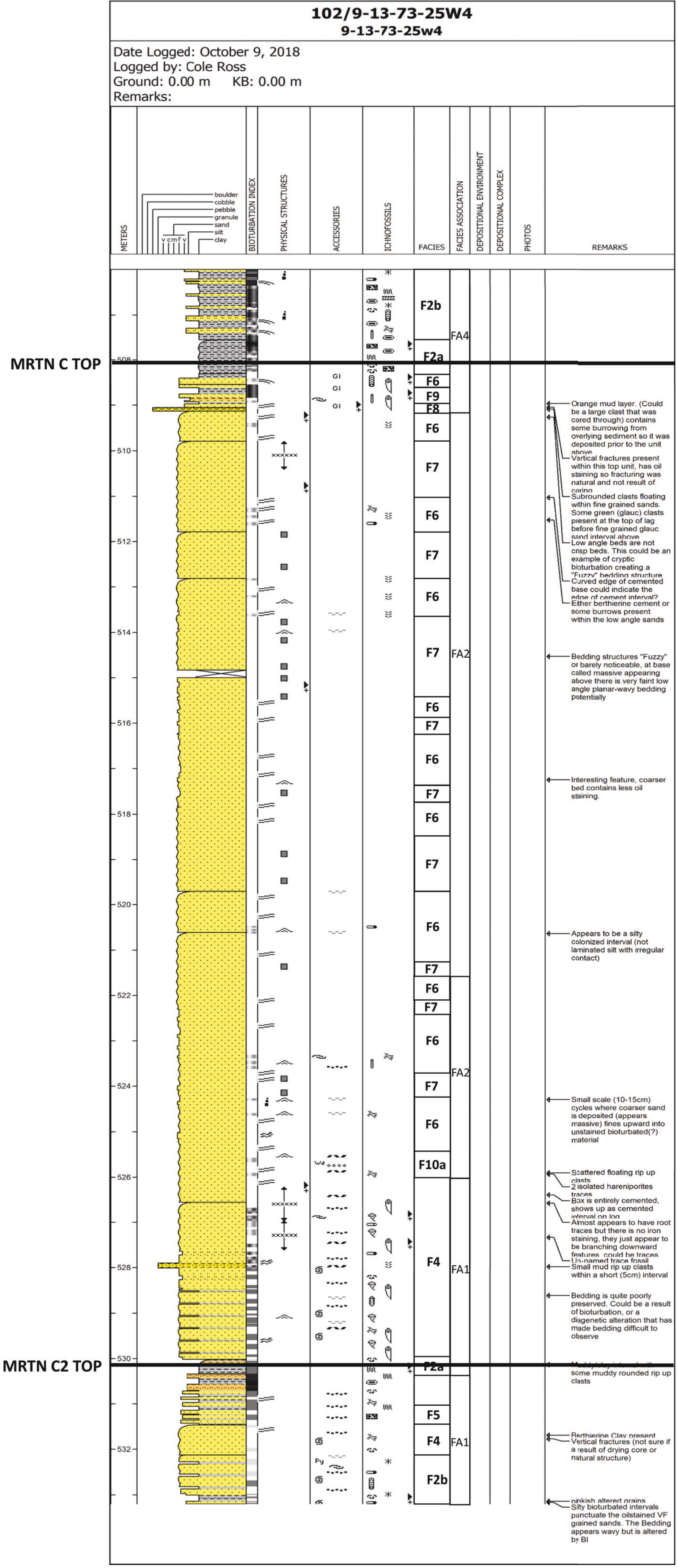
Date Logged: June 13, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:



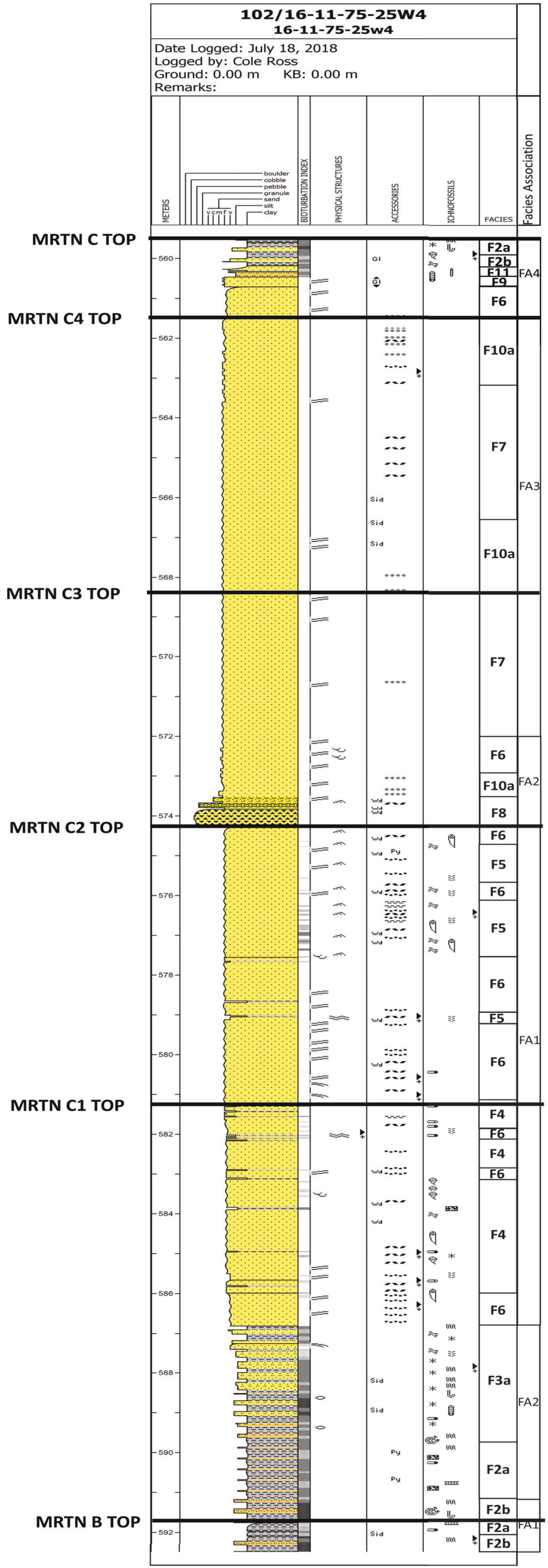
16-25-074-26W4
16-25-074-26w4

Date Logged: June 26, 2018
Logged by: Cole Ross
Ground: 0.00 m   KB: 0.00 m
Remarks:

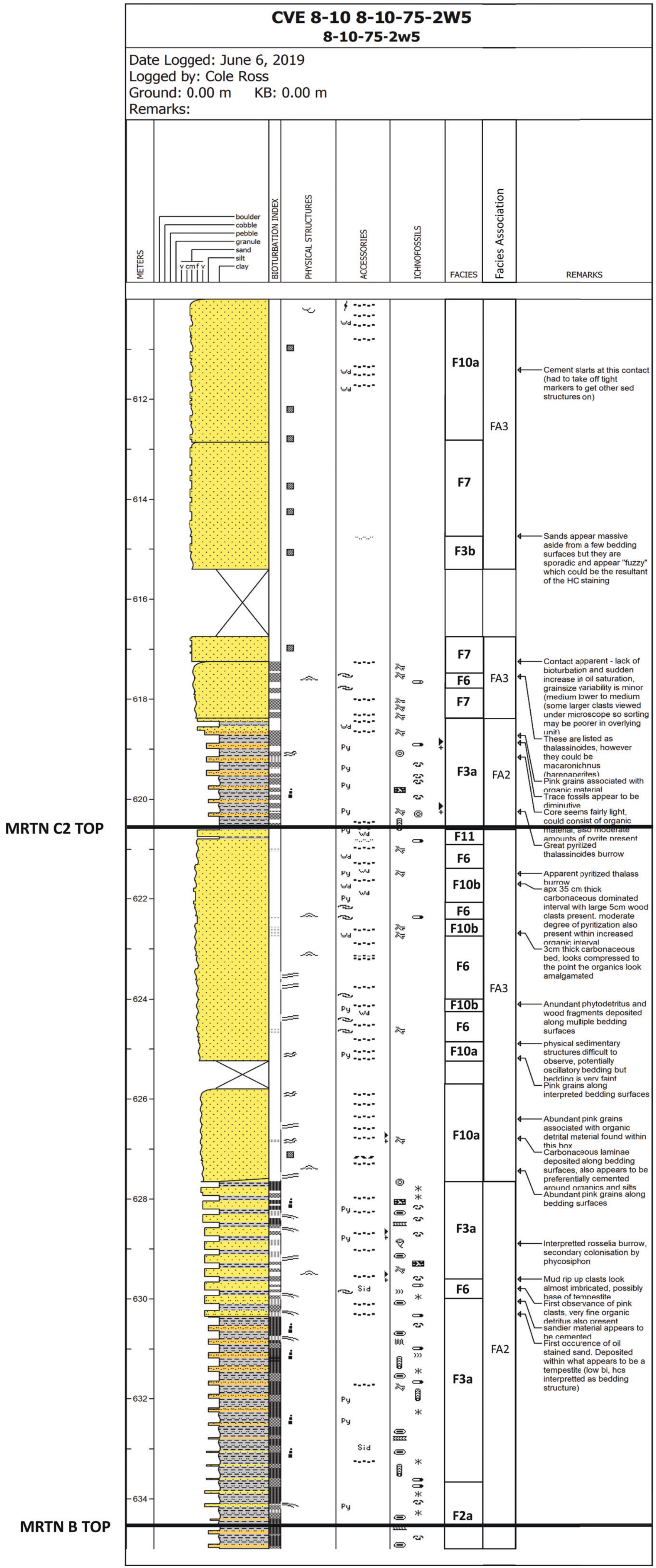




102/9-13-73-25W4
9-13-73-25w4
Date Logged: October 9, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:
METERS
boulder
cobble
pebble
granule
sand
silt
clay
v c m f v
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
DEPOSITIONAL COMPLEX
PHOTOS
REMARKS
MRTN C TOP
MRTN C2 TOP
508
510
512
514
516
518
520
522
524
526
528
530
532
F2b
F2a
F6
F9
F8
F6
F7
F6
F7
F6
F7
F6
F7
F6
F7
F6
F7
F6
F7
F6
F7
F6
F7
F6
F10a
F4
F2a
F5
F4
F2b
FA4
FA2
FA2
FA1
FA1
Gl
Gl
Gl
w/d
Py
Orange mud layer. (Could be a large clast that was cored through) contains some burrowing from overlying sediment so it was deposited prior to the unit above
Vertical fractures present within this top unit, has oil staining so fracturing was natural and not result of coring
Subrounded clasts floating within fine grained sands. Some green (glauc) clasts present at the top of lag before fine grained glauc sand interval above
Low angle beds are not crisp beds. This could be an example of cryptic bioturbation creating a "Fuzzy" bedding structure
Curved edge of cemented base could indicate the edge of cement interval?
Either berthierine cement or some burrows present within the low angle sands
Bedding structures "Fuzzy" or barely noticeable, at base called massive appearing above there is very faint low angle planar-wavy bedding potentially
Interesting feature, coarser bed contains less oil staining.
Appears to be a silty colonized interval (not laminated silt with irregular contact)
Small scale (10-15cm) cycles where coarser sand is deposited (appears massive) fines upward into unstained bioturbated(?) material
Scattered floating rip up clasts
2 isolated hareniporites traces
Box is entirely cemented, shows up as cemented interval on log
Almost appears to have root traces but there is no iron staining, they just appear to be branching downward features, could be traces
Un-named trace fossil
Small mud rip up clasts within a short (5cm) interval
Bedding is quite poorly preserved. Could be a result of bioturbation, or a diagenetic alteration that has made bedding difficult to observe
Muddy/clay interval with some muddy rounded rip up clasts
Berthierine Clay present
Vertical fractures (not sure if a result of drying core or natural structure)
pinkish altered grains
Silty bioturbated intervals punctuate the oilstained VF grained sands. The Bedding appears wavy but is altered by BI



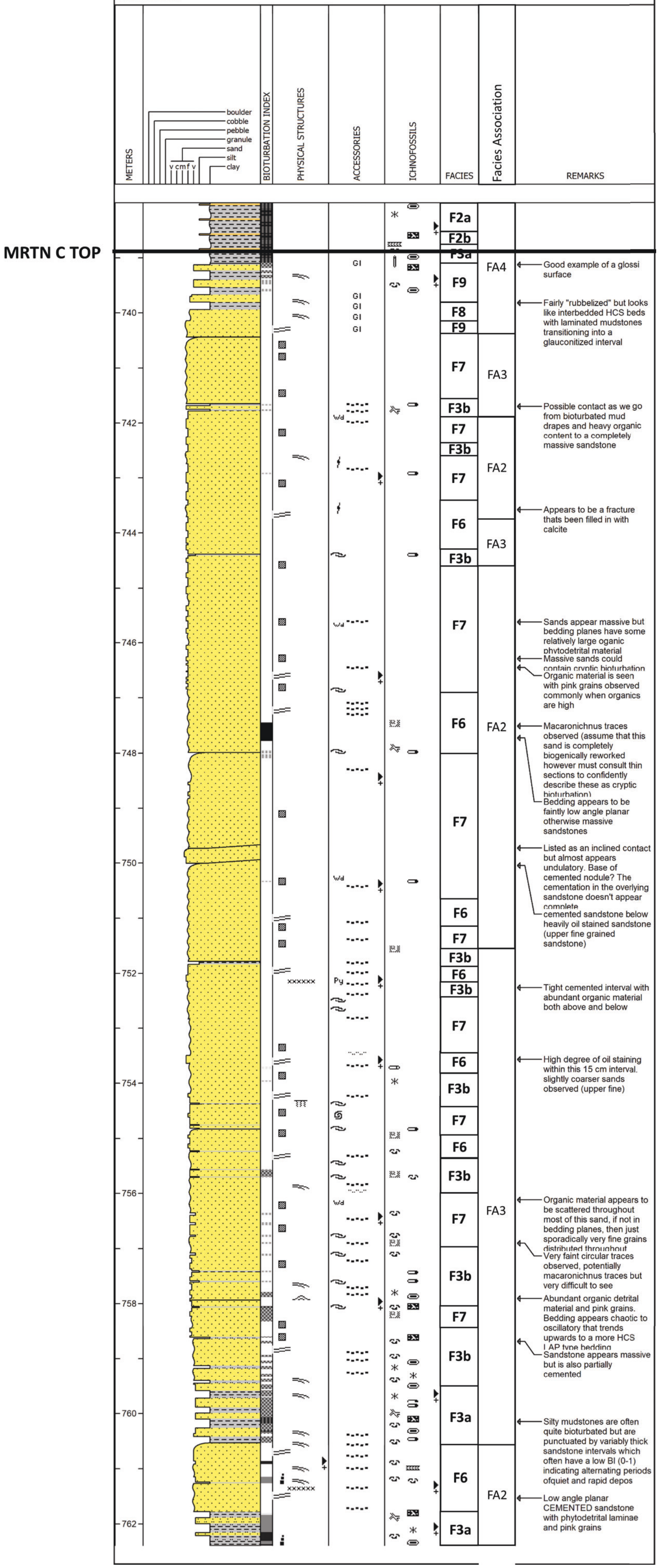
102/16-11-75-25W4
16-11-75-25w4
Date Logged: July 18, 2018
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:
METERS
boulder
cobble
pebble
granule
sand
silt
clay
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FACIES
Facies Association
MRTN C TOP
MRTN C4 TOP
MRTN C3 TOP
MRTN C2 TOP
MRTN C1 TOP
MRTN B TOP
560
562
564
566
568
570
572
574
576
578
580
582
584
586
588
590
592
F2a
F2b
F11
F9
F6
F10a
F7
F10a
F7
F6
F10a
F8
F6
F5
F6
F5
F6
F5
F6
F4
F6
F4
F6
F4
F6
F3a
F2a
F2b
F2a
F2b
FA4
FA3
FA2
FA1
FA2
FA1
Gl
Sid
Wd
Py

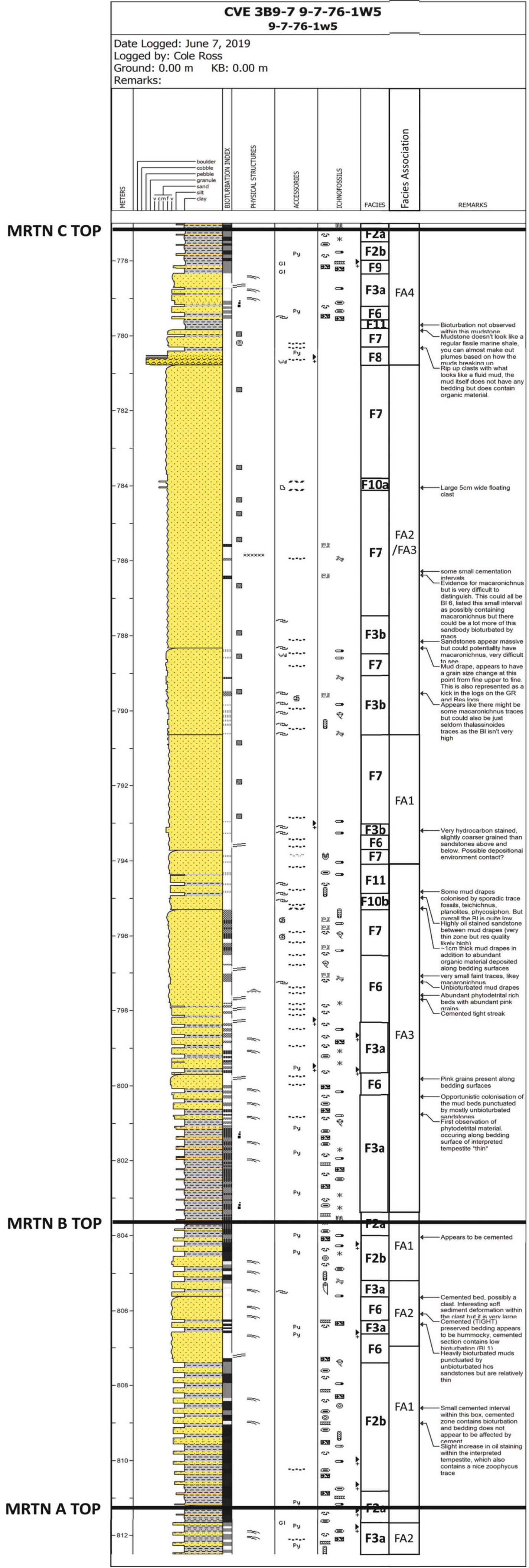


CVE 8-10 8-10-75-2W5
8-10-75-2w5
Date Logged: June 6, 2019
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:
METERS
boulder
cobble
pebble
granule
sand
silt
clay
v c m f v
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FACIES
Facies Association
REMARKS
612
614
616
618
620
622
624
626
628
630
632
634
F10a
F7
F3b
F7
F6
F7
F3a
F11
F6
F10b
F6
F10b
F6
F10b
F6
F10a
F10a
F3a
F6
F3a
F2a
FA3
FA3
FA2
FA3
FA2
MRTN C2 TOP
MRTN B TOP
Cement starts at this contact (had to take off tight markers to get other sed structures on)
Sands appear massive aside from a few bedding surfaces but they are sporadic and appear "fuzzy" which could be the resultant of the HC staining
Contact apparent - lack of bioturbation and sudden increase in oil saturation, grainsize variability is minor (medium lower to medium (some larger clasts viewed under microscope so sorting may be poorer in overlying unit)
These are listed as thalassinoides, however they could be macaronichnus (harenaperites)
Pink grains associated with organic material
Trace fossils appear to be diminutive
Core seems fairly light, could consist of organic material, also moderate amounts of pyrite present
Great pyritized thalassinoides burrow
Apparent pyritized thalass burrow
apx 35 cm thick carbonaceous dominated interval with large 5cm wood clasts present. moderate degree of pyritization also present within increased organic interval
3cm thick carbonaceous bed, looks compressed to the point the organics look amalgamated
Anundant phytodetritus and wood fragments deposited along multiple bedding surfaces
physical sedimentary structures difficult to observe, potentially oscillatory bedding but bedding is very faint
Pink grains along interpreted bedding surfaces
Abundant pink grains associated with organic detrital material found within this box
Carbonaceous laminae deposited along bedding surfaces, also appears to be preferentially cemented around organics and silts
Abundant pink grains along bedding surfaces
Interpretted rosselia burrow, secondary colonisation by phycosiphon
Mud rip up clasts look almost imbricated, possibly base of tempestite
First observance of pink clasts, very fine organic detritus also present
sandier material appears to be cemented
First occurence of oil stained sand. Deposited within what appears to be a tempestite (low bi, hcs interpretted as bedding structure)

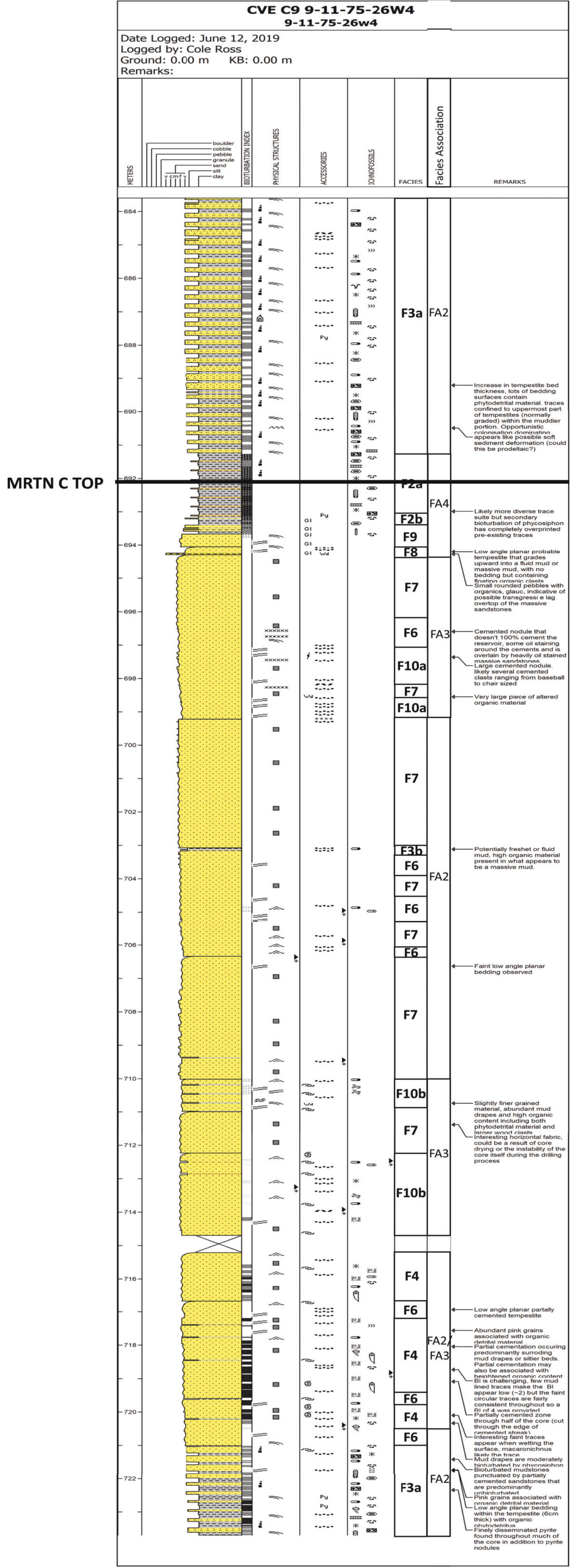
CVE 7-31 8-32-75-1W5
8-32-75-1w5

Date Logged: June 11, 2019
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:



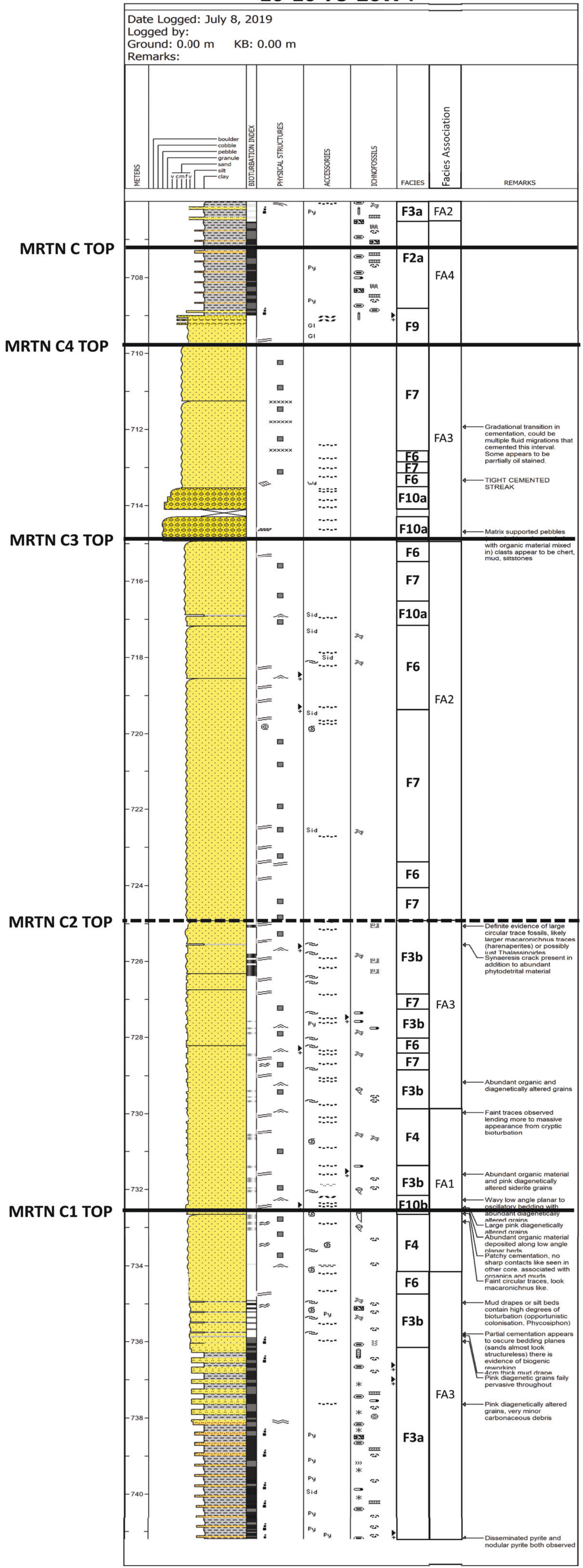


CVE 3B9-7 9-7-76-1W5
9-7-76-1w5
Date Logged: June 7, 2019
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:
METERS
boulder
cobble
pebble
granule
sand
silt
clay
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FACIES
Facies Association
REMARKS
MRTN C TOP
MRTN B TOP
MRTN A TOP
778
780
782
784
786
788
790
792
794
796
798
800
802
804
806
808
810
812
F2a
F2b
F9
F3a
F6
F11
F7
F8
F7
F10a
F7
F3b
F7
F3b
F7
F3b
F6
F7
F11
F10b
F7
F6
F3a
F6
F3a
F2a
F2b
F3a
F6
F3a
F6
F2b
F2a
F3a
FA4
FA2
/FA3
FA1
FA3
FA1
FA2
FA1
FA2
Bioturbation not observed within this mudstone
Mudstone doesn't look like a regular fissile marine shale, you can almost make out plumes based on how the muds breaking up
Rip up clasts with what looks like a fluid mud, the mud itself does not have any bedding but does contain organic material.
Large 5cm wide floating clast
some small cementation intervals
Evidence for macaronichnus but is very difficult to distinguish. This could all be BI 6, listed this small interval as possibly containing macaronichnus but there could be a lot more of this sandbody bioturbated by macs
Sandstones appear massive but could potentiallty have macaronichnus, very difficult to see
Mud drape, appears to have a grain size change at this point from fine upper to fine. This is also represented as a kick in the logs on the GR and Res logs
Appears like there might be some macaronichnus traces but could also be just seldom thalassinoides traces as the BI isn't very high
Very hydrocarbon stained, slightly coarser grained than sandstones above and below. Possible depositional environment contact?
Some mud drapes colonised by sporadic trace fossils, teichichnus, planolites, phycosiphon. But overall the BI is quite low
Highly oil stained sandstone between mud drapes (very thin zone but res quality likely high)
~1cm thick mud drapes in addition to abundant organic material deposited along bedding surfaces
very small faint traces, likey macaronichnus
Unbioturbated mud drapes
Abundant phytodetrital rich beds with abundant pink grains
Cemented tight streak
Pink grains present along bedding surfaces
Opportunistic colonisation of the mud beds punctuated by mostly unbioturbated sandstones
First observation of phytodetrital material. occuring along bedding surface of interpreted tempestite *thin*
Appears to be cemented
Cemented bed, possibly a clast. Interesting soft sediment deformation within the clast but it is very large
Cemented (TIGHT) preserved bedding appears to be hummocky, cemented section contains low bioturbation (BI 1)
Heavily bioturbated muds punctuated by unbioturbated hcs sandstones but are relatively thin
Small cemented interval within this box, cemented zone contains bioturbation and bedding does not appear to be affected by cement
Slight increase in oil staining within the interpreted tempestite, which also contains a nice zoophycus trace

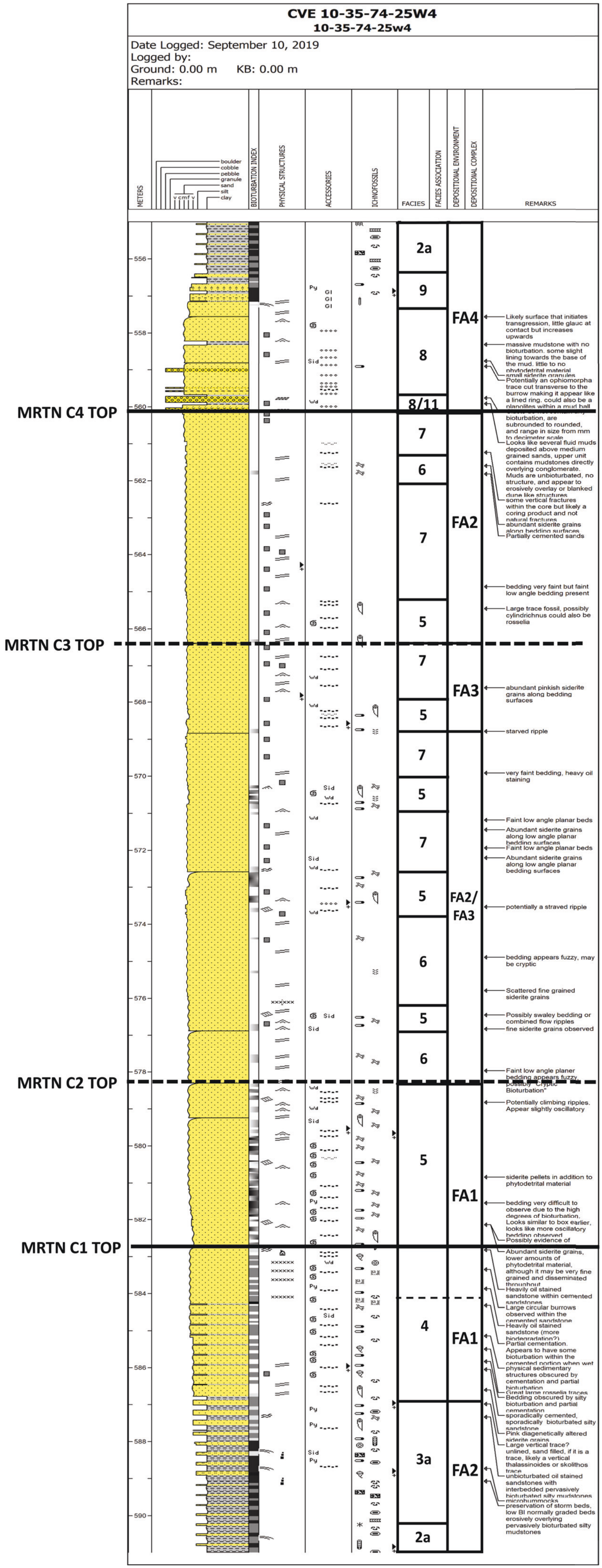


CVE C9 9-11-75-26W4
9-11-75-26w4
Date Logged: June 12, 2019
Logged by: Cole Ross
Ground: 0.00 m KB: 0.00 m
Remarks:
METERS
boulder
cobble
pebble
granule
sand
silt
clay
v c m f v
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FACIES
Facies Association
REMARKS
MRTN C TOP
684
686
688
690
692
694
696
698
700
702
704
706
708
710
712
714
716
718
720
722
F3a
FA2
F2a
FA4
F2b
F9
F8
F7
F6
FA3
F10a
F7
F10a
F7
F3b
F6
F7
FA2
F6
F7
F6
F7
F10b
F7
FA3
F10b
F4
F6
FA2/
FA3
F4
F6
F4
F6
F3a
FA2
Py
Gl
Increase in tempestite bed thickness, lots of bedding surfaces contain phytodetrital material. traces confined to uppermost part of tempestites (normally graded) within the muddier portion. Opportunistic colonisation dominating
appears like possible soft sediment deformation (could this be prodeltaic?)
Likely more diverse trace suite but secondary bioturbation of phycosiphon has completely overprinted pre-existing traces
Low angle planar probable tempestite that grades upward into a fluid mud or massive mud, with no bedding but containing floating organic clasts
Small rounded pebbles with organics, glauc, indicative of possible transgressi e lag overtop of the massive sandstones
Cemented nodule that doesn't 100% cement the reservoir, some oil staining around the cements and is overlain by heavily oil stained massive sandstones
Large cemented nodule. likely several cemented clasts ranging from baseball to chair sized
Very large piece of altered organic material
Potentially freshet or fluid mud, high organic material present in what appears to be a massive mud.
Faint low angle planar bedding observed
Slightly finer grained material, abundant mud drapes and high organic content including both phytodetrital material and larger wood clasts
Interesting horizontal fabric, could be a result of core drying or the instability of the core itself during the drilling process
Low angle planar partally cemented tempestite
Abundant pink grains associated with organic detrital material
Partial cementation occuring predominantly surroding mud drapes or siltier beds. Partial cementation may also be associated with heightened organic content
BI is challenging, few mud lined traces make the BI appear low (~2) but the faint circular traces are fairly consistent throughout so a BI of 4 was provided
Partially cemented zone through half of the core (cut through the edge of cemented streak)
Interesting faint traces appear when wetting the surface, macaronichnus likely the trace
Mud drapes are moderately bioturbated by phycosiphon
Bioturbated mudstones punctuated by partially cemented sandstones that are predominantly unbioturbated
Pink grains associated with organic detrital material
Low angle planar bedding within the tempestite (6cm thick) with organic phytodetritus
Finely disseminated pyrite found throughout much of the core in addition to pyrite nodules

10-10-75-26W4



Date Logged: July 8, 2019
Logged by:
Ground: 0.00 m KB: 0.00 m
Remarks:
METERS
boulder
cobble
pebble
granule
sand
silt
clay
v c m f v
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FACIES
Facies Association
REMARKS
MRTN C TOP
MRTN C4 TOP
MRTN C3 TOP
MRTN C2 TOP
MRTN C1 TOP
708
710
712
714
716
718
720
722
724
726
728
730
732
734
736
738
740
Py
Gl
Sid
F3a
FA2
F2a
FA4
F9
F7
F6
F7
F6
F10a
F10a
FA3
F6
F7
F10a
F6
F7
F6
F7
FA2
F3b
F7
F3b
F6
F7
F3b
FA3
F4
F3b
F10b
FA1
F4
F6
F3b
F3a
FA3
Gradational transition in cementation, could be multiple fluid migrations that cemented this interval. Some appears to be parrtially oil stained.
TIGHT CEMENTED STREAK
Matrix supported pebbles
with organic material mixed in) clasts appear to be chert, mud, siltstones
Definite evidence of large circular trace fossils, likely larger macaronichnus traces (harenaperites) or possibly just Thalassinoides
Synaeresis crack present in addition to abundant phytodetrital material
Abundant organic and diagenetically altered grains
Faint traces observed lending more to massive appearance from cryptic bioturbation
Abundant organic material and pink diagenetically altered siderite grains
Wavy low angle planar to oscillatory bedding with abundant diagenetically altered grains
Large pink diagenetically altered grains
Abundant organic material deposited along low angle planar beds
Patchy cementation, no sharp contacts like seen in other core. associated with organics and muds
Faint circular traces, look macaronichnus like.
Mud drapes or silt beds contain high degrees of bioturbation (opportunistic colonisation, Phycosiphon)
Partial cementation appears to oscure bedding planes (sands almost look structureless) there is evidence of biogenic reworking
4cm thick mud drape
Pink diagenetic grains faily pervasive throughout
Pink diagenetically altered grains, very minor carbonaceous debris
Disseminated pyrite and nodular pyrite both observed



CVE 10-35-74-25W4
10-35-74-25w4
Date Logged: September 10, 2019
Logged by:
Ground: 0.00 m KB: 0.00 m
Remarks:
METERS
boulder
cobble
pebble
granule
sand
silt
clay
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
DEPOSITIONAL COMPLEX
REMARKS
MRTN C4 TOP
MRTN C3 TOP
MRTN C2 TOP
MRTN C1 TOP
556
558
560
562
564
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2a
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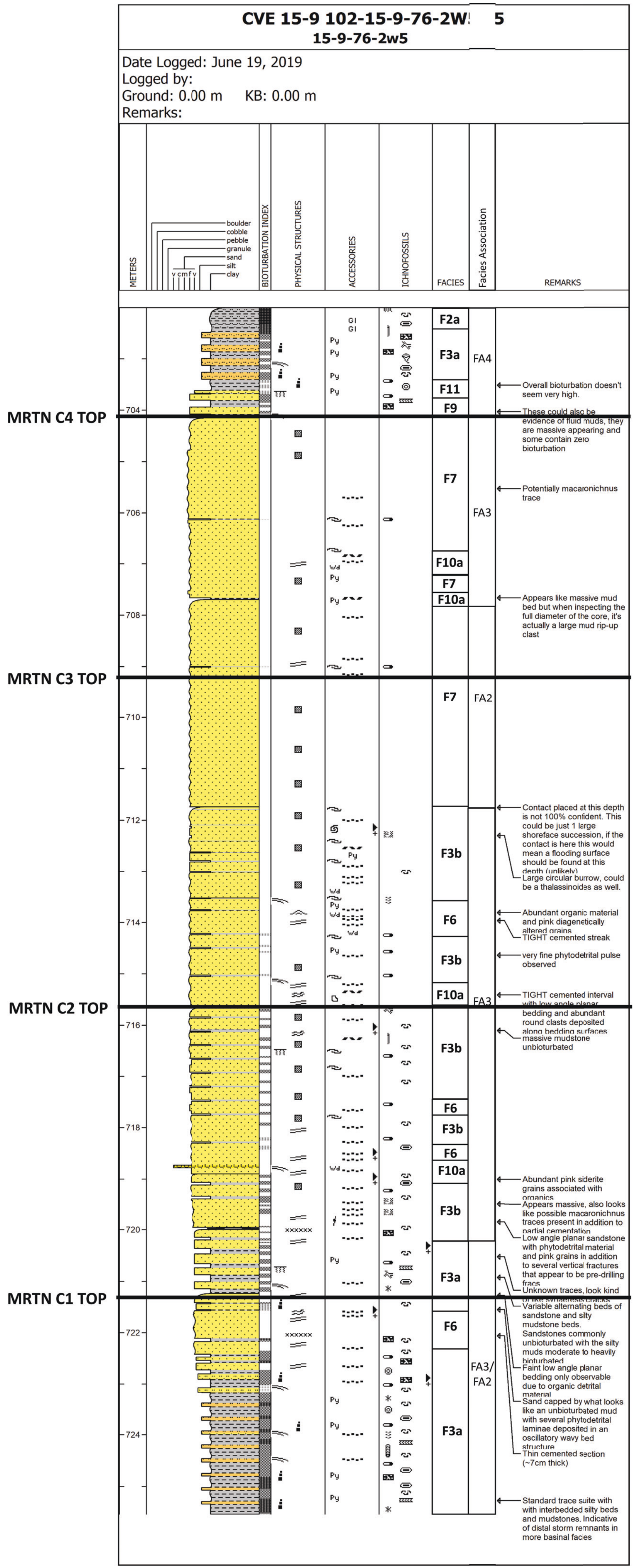
8/11
7
6
7
5
7
5
7
5
7
5
6
5
6
5
4
3a
2a
FA4
FA2
FA3
FA2/
FA3
FA1
FA1
FA2
Likely surface that initiates transgression, little glauc at contact but increases upwards
massive mudstone with no bioturbation. some slight lining towards the base of the mud. little to no phytodetrital material
small siderite granules
Potentially an ophiomorpha trace cut transverse to the burrow making it appear like a lined ring. could also be a planolites within a mud ball
bioturbation, are subrounded to rounded, and range in size from mm to decimeter scale
Looks like several fluid muds deposited above medium grained sands, upper unit contains mudstones directly overlying conglomerate. Muds are unbioturbated, no structure, and appear to erosively overlay or blanked dune like structures
some vertical fractures within the core but likely a coring product and not natural fractures
abundant siderite grains along bedding surfaces
Partially cemented sands
bedding very faint but faint low angle bedding present
Large trace fossil, possibly cylindrichnus could also be rosselia
abundant pinkish siderite grains along bedding surfaces
starved ripple
very faint bedding, heavy oil staining
Faint low angle planar beds
Abundant siderite grains along low angle planar bedding surfaces
Faint low angle planar beds
Abundant siderite grains along low angle planar bedding surfaces
potentially a straved ripple
bedding appears fuzzy, may be cryptic
Scattered fine grained siderite grains
Possibly swaley bedding or combined flow ripples
fine siderite grains observed
Faint low angle planer bedding appears fuzzy
Potentially climbing ripples. Appear slightly oscillatory
siderite pellets in addition to phytodetrital material
bedding very difficult to observe due to the high degrees of bioturbation.
Looks similar to box earlier, looks like more oscillatory bedding observed
Possibly evidence of
Abundant siderite grains, lower amounts of phytodetrital material, although it may be very fine grained and disseminated throughout
Heavily oil stained sandstone within cemented sandstones
Large circular burrows observed within the cemented sandstone
Heavily oil stained sandstone (more biodegradation?)
Partial cementation. Appears to have some bioturbation within the cemented portion when wet
physical sedimentary structures obscured by cementation and partial bioturbation
Great large rosselia traces
Bedding obscured by silty bioturbation and partial cementation
sporadically cemented, sporadically bioturbated silty sandstone
Pink diagenetically altered siderite grains
Large vertical trace? unlined, sand filled, if it is a trace, likely a vertical thalassinoides or skolithos trace
unbioturbated oil stained sandstones with interbedded pervasively bioturbated silty mudstones
microhummocks
preservation of storm beds, low BI normally graded beds erosively overlying pervasively bioturbated silty mudstones



CVE 15-9 102-15-9-76-2W5
15-9-76-2w5
Date Logged: June 19, 2019
Logged by:
Ground: 0.00 m KB: 0.00 m
Remarks:
METERS
boulder
cobble
pebble
granule
sand
silt
clay
v c m f v
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FACIES
Facies Association
REMARKS
704
706
708
710
712
714
716
718
720
722
724
MRTN C4 TOP
MRTN C3 TOP
MRTN C2 TOP
MRTN C1 TOP
F2a
F3a
F11
F9
F7
F10a
F7
F10a
F7
F3b
F6
F3b
F10a
F3b
F6
F3b
F6
F10a
F3b
F3a
F6
F3a
FA4
FA3
FA2
FA3
FA3/
FA2
Overall bioturbation doesn't seem very high.
These could also be evidence of fluid muds, they are massive appearing and some contain zero bioturbation
Potentially macaronichnus trace
Appears like massive mud bed but when inspecting the full diameter of the core, it's actually a large mud rip-up clast
Contact placed at this depth is not 100% confident. This could be just 1 large shoreface succession, if the contact is here this would mean a flooding surface should be found at this depth (unlikely)
Large circular burrow, could be a thalassinoides as well.
Abundant organic material and pink diagenetically altered grains
TIGHT cemented streak
very fine phytodetrital pulse observed
TIGHT cemented interval with low angle planar bedding and abundant round clasts deposited along bedding surfaces
massive mudstone unbioturbated
Abundant pink siderite grains associated with organics
Appears massive, also looks like possible macaronichnus traces present in addition to partial cementation
Low angle planar sandstone with phytodetrital material and pink grains in addition to several vertical fractures that appear to be pre-drilling fracs
Unknown traces, look kind of like synaeresis cracks
Variable alternating beds of sandstone and silty mudstone beds. Sandstones commonly unbioturbated with the silty muds moderate to heavily bioturbated
Faint low angle planar bedding only observable due to organic detrital material
Sand capped by what looks like an unbioturbated mud with several phytodetrital laminae deposited in an oscillatory wavy bed structure
Thin cemented section (~7cm thick)
Standard trace suite with with interbedded silty beds and mudstones. Indicative of distal storm remnants in more basinal faces