Sedimentology, Ichnology, and Palaeodepositional Affinity of the Cretaceous Bluesky Formation, Alberta

by

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ABSTRACT

The lower Cretaceous Bluesky Formation of Alberta comprises marginal marine to marine siliciclastic sediments deposited during transgression of the Boreal Sea. The preserved record of sedimentation represents a complex lateral and vertical architecture, making sub-surface correlation challenging. As the Bluesky Formation is the primary host to substantial bitumen deposits of the Peace River heavy oil sands, a refined interpretation of palaeodeposition is crucial to exploration activities. To achieve this objective, high-resolution sedimentological and ichnological data was recorded from a 40 core dataset within an area of approximately 215 km^2. Additionally, the process ichnology methodology was utilized to enhance the identification of physical and chemical stresses not revealed through sedimentary analysis. Eleven distinct facies are recognized within the dataset (F1-F11). These facies are the building blocks of four Facies Association (FA1-FA4), which consist of: FA1-wave-dominated, fluvially-influenced delta; FA2-bay-margin shoreface to offshore bay-margin; FA3-wave-dominated marine delta; and, FA4-wave-influenced brackish sedimentation. FA1-FA3 are considered to be coeval, and represent periodic progradation within an overall transgressive marine embayment. FA4 is considered to represent a late-stage change in relative sea-level, juxtaposing brackish-water sediments onto offshore bay-margin, and wave-dominated deltaic facies. By focusing on a relatively understudied area, this work has contributed to the broad-scale understanding of Bluesky Formation architecture. Additionally, it has helped establish the utility of applying the process ichnological methodology to core datasets. Ideally, the combined sedimentological and ichnological characteristics identified within this work will aid in recognition of similar depositional systems in the rock record.

PREFACE

This thesis represents the original work of Scott Botterill. Chapter 3 of this thesis has been submitted for publication as: Scott E. Botterill, S. Gordon Campbell, S. George Pemberton, and Murray K. Gingras, "Process Ichnological Analysis of the Lower Cretaceous Bluesky Formation, Alberta" in the Bulletin of Canadian Petroleum Geology (CSPG). The manuscript has been accepted for publication. Subsequent to the submission of this thesis, Chapter 2 will have been submitted for publication as Scott E. Botterill, S. Gordon Campbell, Eric R. Timmer, and Murray K. Gingras, "Embayment Margin Parasequences: Recognition of Wave-Influenced Deltaic and Bay-Margin Sedimentation, Bluesky Formation, Alberta". This paper will be submitted to the Bulletin of Canadian Petroleum Geology (CSPG). I am first author on both manuscripts submitted, with Dr. Murray Gingras providing the majority of editing and support. This manuscript is part of a larger project organized by Dr. Murray Gingras. I performed the data collection, interpretation and manuscript composition with the supervision and guidance of Dr. Murray Gingras and Dr. S. George Pemberton. Chapter 1 (literature review) and Chapter 4 (conclusions) are my original work.

“The only true wisdom is in knowing you know nothing”
- Socrates

DEDICATION

This thesis is dedicated to four people. First, George and Ellen Andrews. Although they are long past, their contribution to this thesis is deeply appreciated, and without them would not have been possible. It is with regret I did not have the opportunity to know them better. Second, to Dr. Murray Gingras. His belief in me was always, and still is greater than my own and without his support this thesis would not have been possible. It will never be forgotten. Finally, my wife Erin. Her support, love, generosity, patience, and understanding know no bounds and I am forever grateful to her for the opportunity to follow my dreams. I love you.

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The opportunity to undertake this thesis has been one of great enjoyment and personal fulfillment. Many people are responsible for helping me get to this place. My wife Erin, you have always believed in me, pushed and encouraged me, and really made this possible. My family, Mark, Dorothy and Ben have been supportive throughout my entire life and without such loving people, who knows how I would have turned out. I could not ask for a better family. My grandmother, Margaret (Peg) who taught me manners when I was young, now, at 90+ years of age it's my turn to make sure she minds her P's and Q's. My aunt Connie and uncle Dave, who have always been proud and supportive of me. My "second family", Ann, Dennis and Brent, who have always made me feel welcome, and supported me in many ways over the last 15 years. Rhonda Murray, obviously, this would not have been possible without your gift, I am eternally grateful for it. Dr. Reg Olson, my first "real boss" was an exceptional mentor, and even better personal friend. His love of geology is infectious, and made working in -60° weather as enjoyable as it could possibly be. Roger Paulen, who always encouraged me to pursue grad school, saying "short-term pain for long-term gain". It wasn't painful, but he was still right. My mentor Fotina Karavas at Murphy Oil, who tried teaching me to think like an industry geologist. I have a long way to go. I am thankful to many other Murphy Oil employees for their guidance and discussion of ideas.

The knowledge I have gained at Graduate School is owed to many, very smart people. I thank Dr. Murray Gingras first and foremost, for providing me with great tutelage, a great project to work on, and fighting so hard to get me accepted. It's something that will not be forgotten. He is also thanked for my now expensive taste in whiskey. Dr. S. George Pemberton and Dr. J.P. Zonneveld have taught me a great deal in a short period of time. Their doors were always open and I greatly appreciate all the knowledge they have passed on to me. Dr. Tom Chacko and Dr. Sarah Gleeson for supporting me in my ambitions. I will never forget it (even if Sarah can't remember my name). Thanks to Mike Ranger for sitting on my commitee, and for his exceptional editing! I'd wish to thank the various members of the IRG and other fellow graduate students for contributing positively to my grad school experience. I thank Gord Campbell, my brother in Bluesky, the discussions we had with our friends Glemorangie and Macallan will never be forgotten. Thank you to Ryan King for his endless help and answers to my simple questions. You deserve a medal for your patience and your willingness to help others. Your mentorship is genuinely appreciated. Thank you to Eric Timmer for all his help editing and guiding me through all things computers (and often making me feel simple minded). David Herbers, you really are one-of-a kind, and the oldest 23 year old I have ever met. Thanks for making my time in the lab so enjoyable. Thank you to Aimee Gegolick for always having a big smile on her face and having a good turtle joke to tell. Thanks to Carolyn Furlong for her help and advice in putting this thesis together, but not for introducing me to "Shock Top". Thank to Tiff Playter, a genuinely awesome person, for always helping me when I asked, and providing the lab with much amusing mischief. You prove "don't judge a book by its cover" to be absolutely correct. Thank you to the rest of the IRG: Alina Shchepetkina for always being so serious, Cheryl Hodgson, Brad Bobey, Shelby Sanders, Reed Myers, Olga Kovalchuk, Nabeel Khan, Steven Kolonesky, and Shimeng Zhang for each of you contributed positively in many ways during my time in the "Lab". Thank you Naomi Miles, Merilee Reynolds, and Morgan Snyder for making TA'ing EAS 234 field school so much fun. I know Ryan and myself will miss "girl-chat", and I am grateful for three good friends.

Finally, I would like to thank Murphy Oil Company, the Government of Canada, University of Alberta and the Department of Earth and Atmospheric Sciences for supporting and funding this research.

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CHAPTER 1: INTRODUCTION

The late Aptian to early Albian Bluesky Formation of Alberta is the primary host to the subsurface bitumen deposits of the Peace River heavy oil sands (approximately 70 billion barrels in place, Energy Resources Conservation Board, 2013). Despite this obvious economic importance, the stratigraphic architecture is, at present, poorly understood (Hubbard et al., 1999). This is undoubtedly due to the expansive geographical distribution, and complexity of processes controlling sedimentation that has resulted in a complex vertical and lateral distribution of facies. The first published data on the Bluesky Formation was that of Badgley (1952), with formal definition given by the Alberta Study Group in 1954. They defined the Bluesky Formation as the marine sandstone overlying the continental Gething Formation and underlying the marine shales of the Wilrich Member. Though this definition is broadly applicable, it falls short in accounting for the complexity of Gething and Bluesky formation deposition. Subsequent work within the Bluesky Formation has identified a complex temporal and spatial assemblage of depositional systems. These include: fluvial and estuarine valley fills (Alway, 1995; Terzuoli and Walker, 1997), wave-dominated estuary (Hubbard, 1999; Hubbard et al., 1999; Hubbard et al., 2002; Hubbard et al., 2004), tide-dominated deltaic to estuarine (Rottenfusser, 1984; Caplan and Mackay, 2007; Mackay and Dalrymple, 2005; 2011), shoreface (Moslow and Pemberton, 1988; Ranger and Pemberton, 1991; Male, 1992; Cant, 1996), and other diverse marginal marine to marine settings including lagoonal, barrier island, and tidal flat (Howard, 1976; Jackson, 1984; O'Connell, 1988; Brekke, 1995; Gordon et al., 2010). It is not surprising given the broad spatial distribution, complexity of facies relationships, and diachronous nature of the Bluesky Formation that this range of identifications exists.

The precision with which ancient depositional settings can be identified is greatly enhanced through the combination of physical sedimentology (e.g. constituent lithology, grainsize, nature of bedding) and ichnology (e.g. ethology, ichnogenera, ichno-diversity) (e.g. MacEachern et al., 2010). Through the efforts of several workers, ichnology has become an invaluable tool in interpretation, which can illuminate physical and chemical stresses present during deposition. This in turn allows for high-resolution palaeoenvironmental reconstruction (e.g. Seilacher, 1978; Pemberton et al., 1982; Frey, 1990; Pemberton and MacEachern, 1997; Bann et al., 2004; Martin, 2004; MacEachern et al., 2005a). Recent development of the Process Ichnology model by Gingras et al., (2011) has further contributed to the utility of ichnological characteristics in recognizing various physico-chemical stresses.

This study was undertaken in order to enhance the understanding of the architecture, and attempt to identify the palaeodepositional affinity of the Bluesky Formation. To achieve this goal, detailed analysis of 40 core and 21 complimentary geophysical well logs within the Peace River heavy oil sands were completed (Fig. 1-1). Documentation of lithology, sedimentology, lithologic accessories, and ichnological characteristics were completed. This work lead to the identification of 11 discrete facies (F1-F11), 4 facies associations (FA1-FA4), and a three stage evolution of the Bluesky Formation within the confines of the study area (Table 1-1). Results of this work comprise Chapter 2.

Chapter 3 focuses on using the process ichnology methodology of Gingras et al., (2011) and applying it to a sub-set of core, entirely within Range 16W5 and Township 83. The process ichnology model of Gingras et al., (2011) is built upon observations of ichnological responses to physical and chemical stresses in modern settings. This methodology treats biological structures as "biogenic sedimentary structures", and not as palaeontological entities (Gingras et al., 2011). In this method, measurements of various physical attributes are recorded at regular intervals, and when considered in combination, reveal the presence of

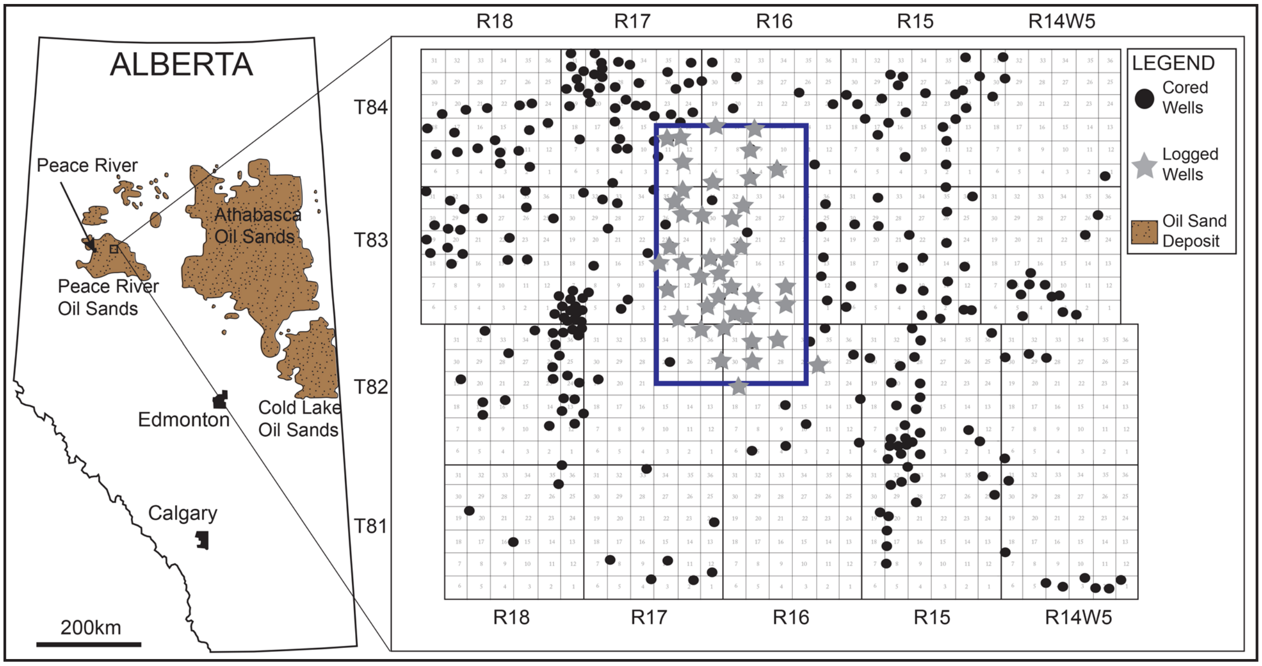


Figure 1-1. Map showing the study area and its geographical location in relation to major oil sand deposits of Alberta.

Facies	Lithology	Facies Associations	Depostitional Environment	Sequence Stratigraphy
F1	siltstone, sandstone, mudstone	Gething Fm	brackish sedimentation	lowstand/early transgression
F2 F3 F4	sandstone	FA1	wave-dominated fluvially-influenced bay-margine delta and marine delta	transgression local autocyclic regression
F5 F6 F7	heterolithic sandstone & mudstone	FA2	bay-margin shoreface to offshore	
F8 F9	mudstone			
F10	shelly, mudstone, sandstone	FA4	wave-dominated brackish sedimentation	late regression?
F11	sandstone, mudstone, siltstone	Wilrich Mbr	marine-offshore	maximum transgression

Table 1-1. Summary chart of facies, facies associations, depositional setting and sequence stratigraphic relationships.

stresses that may not be recognizable by sedimentary analysis alone (e.g. salinity fluctuation, substrate consistency). This method relies on 6 measureable or observable characteristics, which include: 1) trace fossil distribution; 2) diversity and range of ethology; 3) presence or absence of trace linings; 4) presence or absence of specific ichnogenera; 5) trace fossil size, and; 6) degree of trace deformation. This work helps to further illuminates the stratigraphic complexity within the project area.

In summary, this thesis aims to better understand the architecture, palaeodepositional setting, and evolution of the Bluesky Formation within the project limits. Detailed sedimentological, lithological, and ichnological characteristics form the core of this endeavor. This work will contribute to the current knowledge of the Bluesky Formation, by providing high-resolution mapping, facies analysis, and will ideally aid in refinement of exploration activity. Additionally, it is hoped that patterns recognized within the dataset will aid in the identification of similar ancient deposits elsewhere in the rock record.

CHAPTER 2: EMBAYMENT MARGIN PARASEQUENCES: RECOGNITION OF WAVE-INFLUENCED DELTAIC AND BAY-MARGIN SEDIMENTATION, BLUESKY, ALBERTA

INTRODUCTION

The Bluesky Formation consists of early Cretaceous marine to marginal marine siliciclastic sediments deposited during southward transgression of the Boreal sea (Fig. 2-1). The preserved record of sedimentation is characterized by a highly complex vertical and lateral architecture, making lithostratigraphic subsurface correlation impractical. This complexity is evident in the variety of depositional affinities identified by previous workers. These interpretations include: wave-dominated estuary (Hubbard, 1999; Hubbard et al., 1999; Hubbard et al., 2002; Hubbard et al., 2004); tide-dominated estuary to tide-dominated deltaic (Rottenfusser, 1984; Caplan et al., 2007; Mackay and Dalrymple, 2005; Mackay and Dalrymple, 2011); shoreface (Moslow and Pemberton, 1988; Ranger and Pemberton, 1991); and various other marginal marine to marine environments including lagoonal, tidal flat, and progradational barrier island successions (e.g. Howard, 1976; Jackson, 1984; Terzuoli and Walker, 1987; Alway, 1995; Brekke, 1995). Given the spatial complexity of many modern coastal systems, each interpretation may be correct at a given geographical location (Ainsworth et al., 2011). As the Bluesky Formation is the primary host to the Peace River heavy oil sands (~70 billion barrels in place, Energy Resources Conservation Board, 2013), a refined understanding of the depositional architecture within the project area is essential for future exploration and exploitation activities.

The recognition of ancient sedimentary environments is greatly enhanced through the combination of sedimentology and ichnology (e.g. Seilacher, 1967; Pemberton et al., 1982; MacEachern et al., 2010). This integration allows for more precise identification of constituent facies, and, in turn, more reliable paleoenvironmental reconstruction. Ichnology plays a key role in this refinement, as biological organisms are sensitive to, and reveal information about physical and chemical stresses that may otherwise leave no discernable sedimentological trace (e.g. Reineck and Singh, 1973; Seilacher, 1978; MacEachern et al., 2005b). For instance, ripple cross-lamination may form anywhere in the continuum from terrestrial through to marine settings, provided a current capable of sediment transport is present (Allen, 1968; Reineck and Singh, 1973; Collinson et al., 2006). However, along this same continuum, the archetypal ichnofacies model shows predictable changes from continental through to marine assemblages (e.g. Seilacher, 1967; MacEachern et al., 2005c; Pemberton et al., 2012). Many ichnological characteristics are easily discernable (e.g. trace fossil size, distribution, diversity), while others require slightly more advanced interpretation (e.g. ethology, ichnogenera identification). These characteristics reflect the response of organisms to various physico-chemical stresses (e.g. salinity fluctuation, sedimentation rates, water turbidity, substrate consistency, food resources, etc.) and are well documented in modern and ancient settings (e.g. Seilacher, 1978; Pemberton et al., 1982; Beynon et al., 1988; MacEachern and Pemberton, 1992; Pemberton and MacEachern, 1997; Gingras et al., 1999; Bann et al., 2004; Martin, 2004; McIlroy, 2004; MacEachern et al., 2005a; Hauck et al., 2009).

Given the diversity of previous depositional interpretations, architectural complexity, and economic importance of the Bluesky Formation, this paper aims to better understand the depositional environment within the confines of the study area. This is done through: 1) high-resolution documentation of lithological, sedimentological and ichnological characteristics; 2) combination of these characteristics into distinct facies; 3) construction of facies associations using these distinct facies, and; 4) reconstruct the depositional architecture and describe the evolution of the Bluesky Formation within the study area.

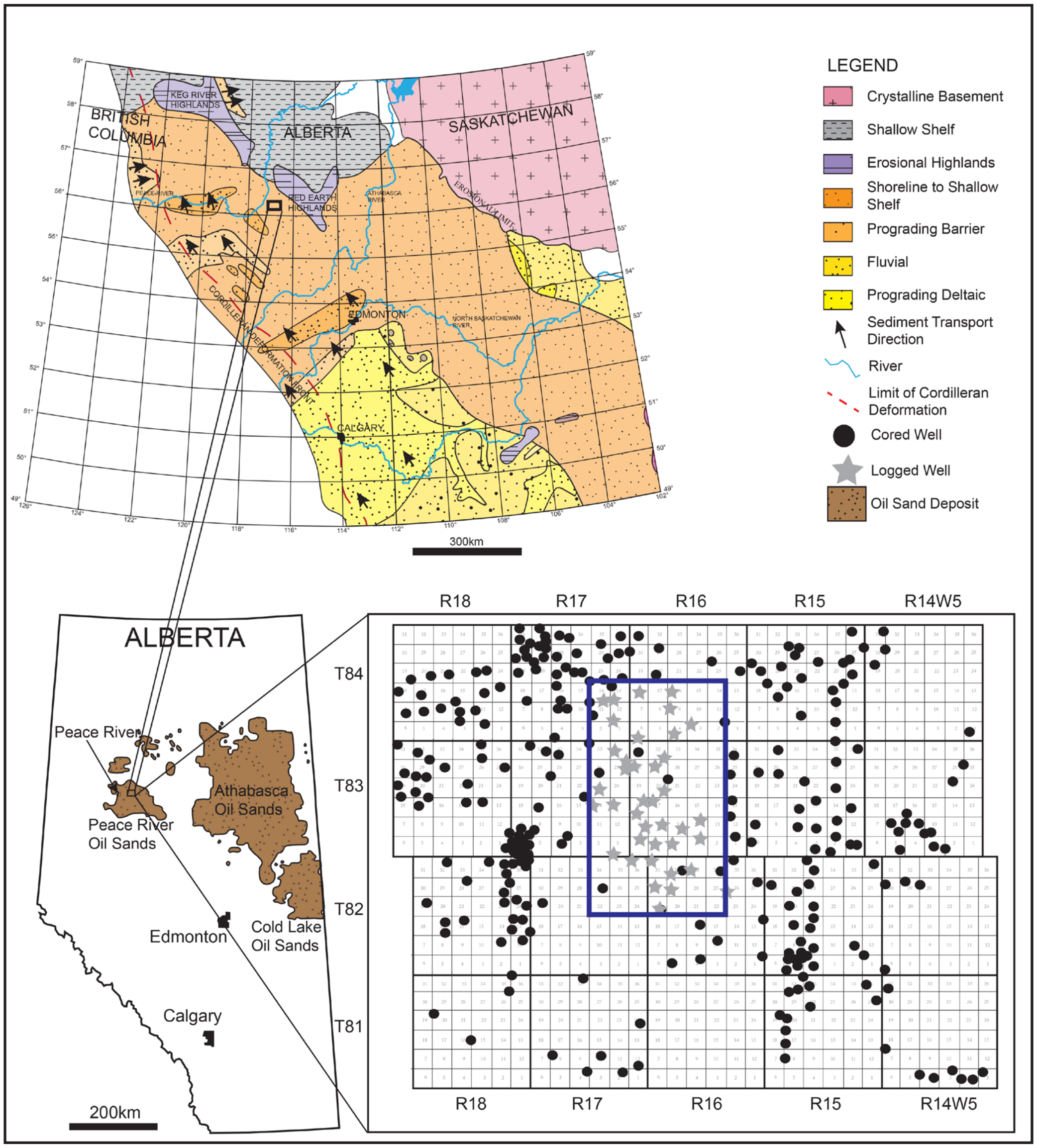


Figure 2-1. Location map showing study area with respect to early Cretaceous sedimentary deposition. Modified after Smith et al., (1994).

GEOLOGIC SETTING

The basal Cretaceous Gething and Bluesky formation deposits directly overly a sub-Cretaceous angular unconformity (Fig.2-2). The basin in which these sediments were deposited developed as a southwest dipping, asymmetrical trough in early Cretaceous time due to an over-thrusted western Cordilleran margin (Jackson, 1984; Shuquing et al., 2008). On a regional scale, basin palaeotopography and sedimentation were influenced by large-scale structural features including the Peace River Arch and the Aptian Archipelago (Williams, 1963; Jackson, 1984; Cant, 1988; O'Connell, 1988; Cant and Stockmal, 1989; Hubbard, 1999; Hubbard et al., 1999, Zhou et al, 2008). Basal Cretaceous sediments were deposited in valleys of major drainage systems cut into underlying Paleozoic rocks, and record a history of terrestrial through to marine sedimentation (Cant, 1996).

Within the project area, the Bluesky Formation lies unconformably upon the brackish-water associated Gething Formation (Fig. 2). In addition to identifying the Gething Formation, previous work by Hubbard et al., (1999; 2004) which covered an area between Range 15-20W5 and Township 83-86 (partially overlapping this study) recognized the additional presence of brackish-bay sedimentation representing the Ostracode Zone. This stratigraphy is not disputed herein, as that work covered a much greater geographical area. The Bluesky Formation is in turn overlain by the marine shales of the Wilrich Member. This stacking pattern reflects transgression of the Boreal sea from the north (Cant and Abrahamson, 1996; Hubbard et al., 1999).

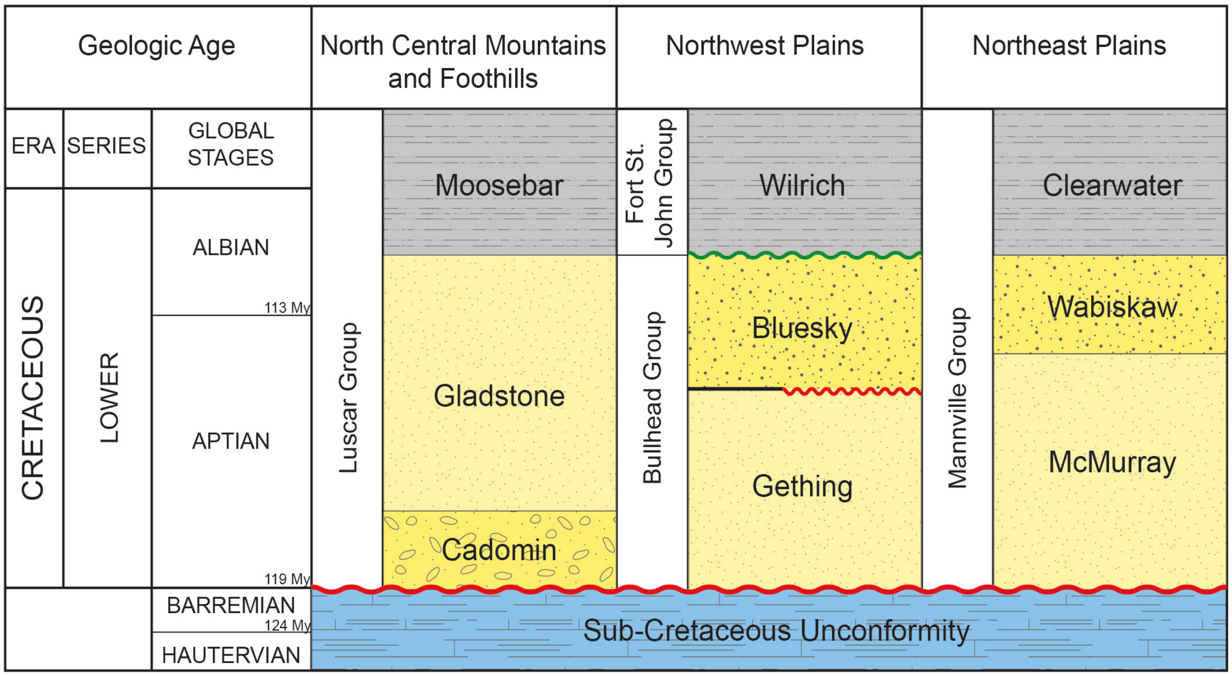


Figure 2-2. Stratigraphic chart showing the relationship of the Bluesky, Gething formations, and Wilrich Member. The green line demarcating the boundary between the Bluesky and Wilrich represents a Glossifungites demarcated surface of erosion, while the red line represents a wave-ravinement surface.

DATABASE AND METHODOLOGY

The project area is located in west-central Alberta, east of the town of Peace River, between Ranges 16 & 17W5 and Townships 82-84 (Fig. 2-1). Within this area the Bluesky Formation exists exclusively within the subsurface between depths of approximately 600 to 750 m. The dataset consists of 40 cored wells, with an additional 21 wells for which wireline logs were available (Fig. 1). Each core was logged at the individual box scale (1.5 m of core per box) with detailed documentation of: lithology, primary sedimentary structures, lithologic accessories, grain-size, and bitumen saturation. Documented ichnological characteristics consist of bioturbation intensity (following Taylor and Goldring, 1993) taken every 37.5 cm (2 measurements per core sleeve) in every well. Maximum burrow diameter and ichnological diversity were recorded for every 75 cm core sleeve in 22 wells, and were used to calculate the Size Diversity Index (SDI) (sensu Hauck et al. 2009) for each identical 75 cm interval. SDI is calculated by multiplying the observed genus-level ichnological diversity by the maximum burrow diameter within a designated interval (MBD x ID = SDI). SDI characteristics of a sub-set of wells are discussed in detail in Botterill et al., (2015, this volume).

Observed lithological, sedimentological, and ichnological characteristics were combined to delineate 11 distinct facies (F1-F11). In order to visualize the distribution of facies within the study area, a series of facies slice maps were completed. These maps were constructed by utilizing the Bluesky/Wilrich contact, interpreted to be a transgressive surface of erosion, as a datum. TSE surfaces tend to represent relatively flat lying stratigraphic surfaces with low diachroneity (Catuneanu, 2006). Facies slice maps were created using this surface as a datum (representing 0 m), at 0 m, 8 m, 12 m, and 16 m, respectively. These maps represent the facies present at these horizons, and do not represent 4 m averages. Where possible, log signatures from wells without cores were used to infer the extent of facies in a lateral direction. Though not possible to differentiate between ichnological signatures of facies, the identification of clean sandstone, heterolithic sandstone and mudstone, and mudstone was apparent on well logs.

To aid in the identification of primary, secondary, and tertiary physical processes affecting sedimentation, the ternary framework of Ainsworth et al., (2011) was applied to selected wells within the dataset (Fig. 2-3). This methodology provides a framework in which the effects of waves, tides, and fluvial processes are plotted based upon their overall normalized abundance.

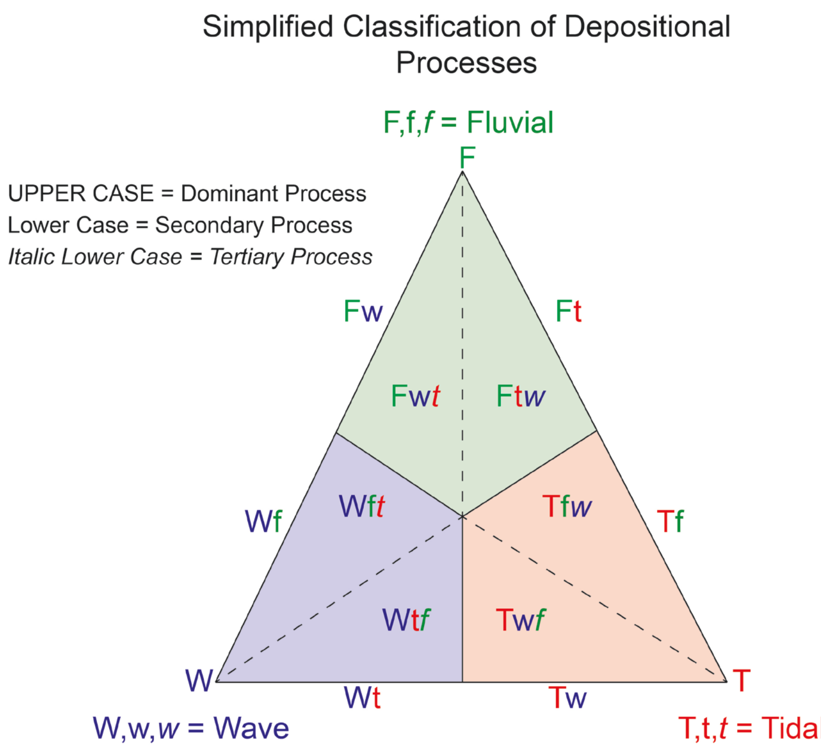
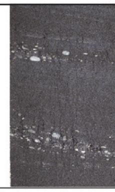
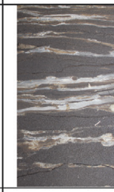
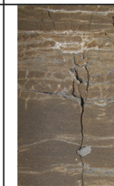
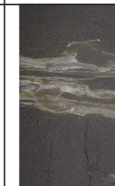
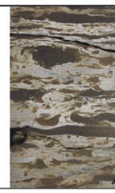


Figure 2-3. Tertiary diagram utilized to identify and classify depositional systems based upon the percentage of wave, fluvial, and tidal processes preserved in a sedimentary succession. Modified after Ainsworth et al, (2011).

FACIES DESCRIPTIONS

Eleven distinct facies were identified in core, F1-F11, with F4 and F7 sub-divided into F4a,b,c, and F7a,b, respectively. These facies are summarized in Table 2-1. Facies divisions were based upon dominant lithology (i.e. sandstone vs. mudstone ratio), grain-size, primary sedimentological character, and ichnological character. Individual facies contacts are often gradational, and the absolute contact placement between two facies (e.g. F5 and F6, F2 and F3) is, in many instances, subjective. This is compounded by the perva-

Facies	F1	F2	F3	F4a	F4b	F4c	F5	F6	F7a	F7b
Typical Core Expression										
Sedimentary Characteristics	PL, LAP, RxL,Fl, Lent,	HAP, LAP, TxB, GS, RxL, RS, TRhy	LAP, PL, PBW, NPBW RxL, HCS, QPL,	RxL, OsR, PBW, NPBW, LAP, PL	LAP, HCS, PBW, NPBW, RxL, PL	PBW, Bio Bd	LAP, HAP, TxB, HCS, RxL, WP, Sc Surf, HBxL, GS	WP, RxL, OsR, LAP, HAP, TxB, Sc Surf, SSD.	WP, FL, Bio Bdd, Cnvt, LAP	WP, FL, Bio Bdd, Cnvt, LAP
Ichnogenera	*Cy, Pl, Po, Sk, Te, Th*	*Cy, Di, Ma, Pa, Pl, Sk, Te*	*Ma, Pa, Pl, Te*	*As, Cy, Di, Pa, Pl, Sc, Te, fu*	*As, Di, Ma, Ro, Sc,*	*Pl, Sk, Undiff.Bio*	*As, Cy, Di, Ma, Pa, Pl, Ro, Si, Sk, Te, Th*	*Ar, As, Cy, Di, Pa, Pl, Sc, Sk, Te, Th*	*Ar, Cy, Pl, Te, Undiff.Bio*	*Ar, As, Cy, Pa, Pl, Ro, Rz, Sc, Sk, Te, Th, Zo*
Ichnological Characteristics	Low-mod diversity, Sporadic Dist, BI 0-6	Low diversity, Sporadic Dist, BI 0-2	Low diversity, Sporadic Dist, BI 0-3	Low-mod diversity, Sporadic Dist, BI 0-6	Low-mod diversity, Sporadic Dist, BI 0-2	Low diversity, Homogeneous Dist, BI 4-6	Low-mod diversity, Sporadic Dist, BI 0-3	Low-mod diversity, Sporadic Dist, BI 0-3	Low-mod diversity, Sporadic-Homogeneous Dist. BI 2-5	Mod-high diversity, Sporadic-Homogeneous Dist, BI 3-5
Accessory Features	Bio Clst, C Frag, C Lam, Py	MClst, MBrec, Py/C, G-PLg, Bio Clst, MDrps	MDrps, Py/C, MClst, C Frag,	C Lam, C Frag, Py, Bio Clst, Org.Lam	C Lam, C Frag, Py	C Lam, C Frag, Py, Bio Clst	M Clst, Bio Clst, Py/C, C Lam	M Clst, C Frag, Bio Clst, Py, Sh Lam	Py, Bio Clst, C Frag, G-PLag	Py, Bio Clst, C Frag, G-PLag

Facies	F8	F9	F10	F11
Typical Core Expression				
Sedimentary Characteristics	Lent, WP, OsR, CuR	Lent, WP, Bio Bd	WP, HoWP, LAP, PL, Cnvlt, L.C, Lent	PL, Bio Bd
Ichnogenera	*As, Pl, Si, Sk, Th, Zo*	*Ar, As, Ch, Cy, Di, Pa, Pl, Ro, Rh, Si, Sc, Sk, Te, Th, Zo, Undiff.Bio*	*Di, Pl, Sk, Th*	*As, Di, Pl, Sk, Th*
Ichnological Characteristics	Low-mod diversity, Sporadic Dist, BI 0-3	Mod-high diversity, Homogeneous Dist, BI 3-6	Low diversity, Sporadic to Homogeneous Dist, BI 0-6	Mod diversity, Homogeneous Dist, BI 3-6
Accessory Features	Sd Lam, Py, Bio Clst, C Frag	Sd Lam, Py, Bio Clst	Abnt Gastropods, Bivalves, Bio Clst, Py, C Frag, Calc Cmt	Abnt Gl, Py, M Clst

Abbreviation Key

Sedimentary Structures

Bio Bd- Bioturbated Bedding
Cnvlt- Convolute Bedding
CuR- Current Ripple
FL- Flaser Bedding
GS- Grain Striping
HAP- High Angle Planar Bedding
HCS- Hummocky Cross-Stratification
HBxL- Herringbone Cross-Stratification
LAP- Low Angle Planar Bedding
LC- Load Cast
Lent- Lenticular Bedding
NPWB- Non-Parallel Wavy Bedding
OsR- Oscillation Ripple
PL- Planar Lamination
PWB- Planar Wavy Bedding
QPL- Quasi-Planar Lamination
RxL- Ripple Cross-Lamination
Sc Surf- Scour Surface
SSD- Soft Sediment Deformation
TRhy- Tidal Rhythmite
TxB- Trough Cross-Bedding
WP- Wavy Parallel

Ichnogenera

Ar- Arenicolites
As- Asterosoma
Ch- Chondrites
Cy- Cylindrichnus
Di- Diplocraterion
Ma- Macaronichnus
Pa- Palaeophycus
Pl- Planolites
Po- Polykladichnus
Rz- Rhizocorallium
Ro- Rosselia
Sc- Scolicia
Si- Siphonichnus
Sk- Skolithos
Te- Teichichnus
Th- Thalssinoides
Zo- Zoophycos
Undiff. Bio- Undifferentiated Bioturbation
fu- fugichnia

Accessory Features

Abnt- Abundant
Bio Clst- Bioclastic Debris
C Frag- Coal Fragments
C Lam- Coal Lamina
Calc.Cmt- Calcareous Cement
Gl- Glauconite
G-PLag- Granule to Pebble Lag
MBrec- Mudstone Breccia
MClst- Mudstone Clast
MDrps- Mudstone Drapes
Org Lam- Organic Rich Laminae
Py- Pyrite
Py/C- Pyritic Coal laminae
Sd Lam- Sand Laminae
Sh Lam- Shale Laminae
Sid- Siderite Nodule

Table 2-1. Summary table of all observed facies identified within the core dataset with visual example of typical facies expression.

sive bitumen saturation, which obscures certain features, making contact placement difficult.

FACIES 1: MUDSTONE, SILTY MUDSTONE AND SANDSTONE

Description:

Sedimentology: within the project area, a complex assemblage dominated by mudstone and siltstone lithology, with subordinate very-fine to fine-grained sandstone, characterizes F1. Bedding ranges from cm- to dm-scale, with common laminae (<1 mm). Physical sedimentary structures present include: planar lamination, low-angle planar lamination, ripple cross-lamination, flaser bedding, soft sediment deformation, and lenticular bedding. Lithologic accessories consist of locally abundant bioclastic beds (up to several dm thick), coal fragments and laminae, and diagenetic pyrite. Where present in core, the contact between F1 and overlying sediments is erosional, and clasts of F1 are often entrained in overlying facies.

Ichnology: F1 is characterized by low to locally moderate diversity, sporadic trace fossil distribution and BI (0-6). Ichnogenera observed include abundant diminutive *Cylindrichnus* (locally monospecific), *Gyrolithes*, and *Planolites*, with lesser *Teichichnus, Skolithos, Thalassinoides* and *Polykladichnus.*

Interpretation:

Based on the overall fine-grained nature, low-energy sedimentary structures, and local rhythmicity of mudstone/sandstone beds, F1 is inferred to represent deposition within a shallow sub-tidal to inter-tidal, brackish-water setting. Ichnological evidence to support this interpretation is given by the appearance of archetypal brackish-water trace fossil suites (Pemberton et al., 1982; Buatois and Mángano, 2011). These consist of nearly monospecific, diminutive suites of *Cylindrichnus* and *Gyrolithes*, which suggest persistent brackish-water conditions. These associations represent r-selected population dynamics, a strategy commonly employed by organisms capable of filling an unexploited niche (e.g. Grassle and Grassle, 1974; Pemberton and Wightman, 1992). The erosive nature of the upper contact of F1 is interpreted to represent a wave-ravinement surface, where higher energy, increasingly marine sediments are superimposed on lower energy, shallow, brackish-water deposits.

FACIES F2: MEDIUM-FINE GRAINED SANDSTONE

Description:

Sedimentology: facies F2 (Fig. 2-4) consists of clean sandstone with mm-cm thick laminae and beds comprising bed sets of up to approximately 30 cm. Physical sedimentary structures include: abundant high-and low-angle planar bedding, planar bedding, trough cross-stratification, grain-size striping, ripple cross-lamination, hummocky cross-stratification (HCS), parallel to non-parallel wavy bedding (sensu Reineck and Singh, 1973), local reactivation surfaces and local rhythmicity. Grain-size is predominantly upper-fine to lower-medium, with local beds containing coarse sand-pebble caliber sediment. Lithologic accessories include local rounded mud clasts and mud breccia, mm-cm thick pyritic/coal beds referred to as “coffee ground” texture (sensu Broughton, 2013), granule-pebble lags, bioclastic fragments, and rare mm thick mud drapes. Facies F2 is widely distributed across the project area, with the thickest accumulations occurring at lower stratigraphic intervals. The thickest continuous vertical occurrence is approximately 15 m. Most commonly, F2 erosionally overlies F1, or gradationally overlies F5. F2 often gradationally passes into F3.

Ichnology: F2 is characterized by low diversity, highly sporadic trace fossil distribution and BI (0-2). Ichnogenera observed include *Planolites*, and *Palaeophycus* with very rare occurrence of *Cylindrichnus, Diplocraterion, Macaronichnus, Rosselia, Skolithos* and *Teichichnus*. Traces are confined to rare mudstone beds, with the exception of *Macaronichnus* and *Palaeophycus*.

Interpretation:

Facies F2 is interpreted to represent sediment deposited in high-energy, periodically brackish-water conditions dominated by uni-directional flow with secondary wave-reworking and tertiary tidal influence. This interpretation is based upon the primarily uni-directional appearing nature of bedding (i.e. high-angle and low-angle planar bedding), and overall upper fine-medium sediment caliber, suggesting significant current velocities (Reineck and Singh, 1973). Grain-size striping, and local, cyclic fining upward sequences from coarse-grained sand bases to fine-grained sand upper contacts suggest periodic fluctuations in flow strength, and/or gravity flows. Reworking by waves is inferred from the common occurrence of low-angle to planar parallel bedding, interpreted as HCS, and parallel to non-parallel wavy bedding,and quasi-planar lamination (*sensu* Arnott, 1993). The presence of "coffee ground" beds suggest fluvially influenced deposition in a more proximal setting. Periodic brackish-water conditions are inferred by the presence of an impoverished marine assemblage, and overall diminution of trace fossils compared to other facies within the dataset. However, *Macaronichnus* is indicative of near to fully marine salinity conditions (Pemberton et al., 2012). Finally, high deposition rates are inferred by the sporadic nature of trace distribution, and decimeter scale fining upward sequences.

FACIES F3: FINE-VERY FINE GRAINED SANDSTONE

Description:

Sedimentology: facies F3 (Fig 2-4) is differentiated from F2 based upon grain-size and the primary nature of sedimentary structures. Bedding consists of mm-cm thick laminae and beds, with bed sets up to a few dm. Physical sedimentary structures include: common low-angle to planar bedding, rare high-angle planar bedding, HCS, quasi-planar lamination, and parallel to non-parallel wavy bedding with local ripple cross-laminations. F3 displays local scour surfaces and faint grain-size striping. Grain-size is predominantly lower-fine to upper very-fine sand, with local beds of medium to coarse calibre sediment. Lithologic accessories include rare mudstone drapes, mm thick pyrite/coal laminae, rare mud clasts, and coal fragments. F3 has a wide geographical distribution within the study area and has a broader stratigraphic occurrence than F2 (i.e. occurs from lowest to uppermost stratigraphic levels). It commonly overlies F2 gradationally at lower stratigraphic intervals, but is also observed sharply overlying heterolithic and mudstone facies (e.g. 04-13-084-16W5).

Ichnology: F3 is the least ichnologically diverse facies. It is characterized by low diversity, highly sporadic distribution and BI (0-3). Ichnogenera observed include common *Macaronichnus*, with rare *Planolites, Palaeophycus,* and *Teichichnus. Macaronichnus* and *Palaeophycus* occur in clean sandstone beds while Planolites and Teichichnus occur in sporadically distributed mudstone beds.

Interpretation:

Facies F3 is considered to represent sediment deposited in a moderate to periodically high-energy, wave-dominated, and storm-influenced shallow water setting. This interpretation is based on the overall moderate- to high-energy nature of sedimentary structures (i.e. planar parallel, low-angle planar bedding, ripple cross lamination, local high-angle planar bedding) and fine sediment calibre. Planar parallel bedding, HCS, quasi-planar lamination, and the very clean nature of F3 suggest constant wave reworking and storm influence, as wave action winnows mud from the underlying substrate (MacEachern et al., 2005a). Ichnologically, the presences of local clusters of *Macaronichnus* are suggestive of high-energy, wave-reworked conditions connected to near marine to marine basinal waters (e.g. Clifton and Thompson, 1978; Saunders, 1989; Saunders et al., 1994; Pemberton, et al., 2012).

FACIES F4: VERY FINE-FINE GRAINED SANDSTONE

Description:

Sedimentology: facies F4a,b, and c (Fig. 2-4) are differentiated from F2 and F3 based upon grain-size, nature of primary sedimentology, and ichnological characteristics. Internal subdivision into a, b and c is based upon overall ichnological character. Individual beds and laminae are on the scale of mm-cm in thickness, with bed sets reaching as much as 10 cm. Primary sedimentary structures include: common ripple cross-lamination, oscillation ripples, and parallel to non-parallel wavy bedding with local low- to high-angle planar bedding, HCS, QPL, and mudstone flasers. Grain-size is predominantly very-fine to coarse silt, with rare occurrence of fine-grained sand. Lithologic accessories consist of rare coal lamina and fragments, pyrite, shell fragments (F4c) and dark grey-black (?organic rich) laminae. Facies F4 is more limited in occurrence than F2 or F3, and occurs predominantly at the upper levels of stratigraphy in contact with the overlying Wilrich Member. Where present, F4 is either gradational upward from F3, or erosively overlies heterolithic or mudstone dominated facies.

Ichnology: F4a and F4b are characterized by low to locally moderate diversity, sporadic distribution, and BI of (0-6). Ichnogenera observed include: *Asterosoma, Cylindrichnus, Diplocraterion, Macaronichnus, Palaeophycus, Planolites, Rosselia, Scolicia, Teichichnus,* and fugichnia. F4b is differentiated from F4a by the robustness of traces (of the same ichnogenus), which are up to roughly two times larger in maximum trace diameter. Traces occur in sandstone, and are often lined despite the lack of mud sized particles within surrounding sediment. F4c comprises moderate to high density, homogeneous distribution, and BI (4-6). Bioturbation intensity often masks identifiable ichnogenera, making reliable identification difficult.

Interpretation:

Facies F4a is considered to represent deposition in a near to fully marine, moderate- to low-energy environment. Expressions of F4a with higher bioturbation intensities and ichnological diversity may represent low-energy conditions, while diminished expressions of these ichnological characteristics may represent moderate-energy settings. This interpretation is based upon the overall fine sediment caliber, predominance of wave-generated sedimentary structures, and overall low mudstone content. The ichnological character of F4a supports this interpretation as abundant *Asterosoma*, and *Scolicia* are documented to require near fully marine salinities (e.g. Pemberton et al., 1992; MacEachern et al., 2005b; Gingras et al., 2011; Buatois and Mángano, 2011). F4b is considered to represent deposition in moderate energy, fully marine deltaic conditions. This interpretation is based upon the dominance of wave-generated and storm-generated structures (i.e. HCS, QPL, low-angle planar bedding) and an ichnological signature similar to, but more robust than F4a. In both facies, mud lined burrows including *Cylindrichnus, Diplocraterion*, and *Rosselia*, suggest suspension of fine-grained material in the water column, attributable to particle suspension by wave action. F4c is interpreted to represent deposition in brackish-water conditions under low rates of sedimentation. This is based upon the highly bioturbated, low to monospecific diversity, and intense mottling of sediment.

FACIES F5: MEDIUM-FINE GRAINED HETEROLITHIC SANDSTONE AND MUDSTONE

Description:

Sedimentology: Facies F5 (Fig. 2-5) consists of inter-bedded medium- to fine-grained sandstone and mm-cm thick mudstone laminae and beds. Bed-sets range from cm scale (sand-mud couplets) to sev-

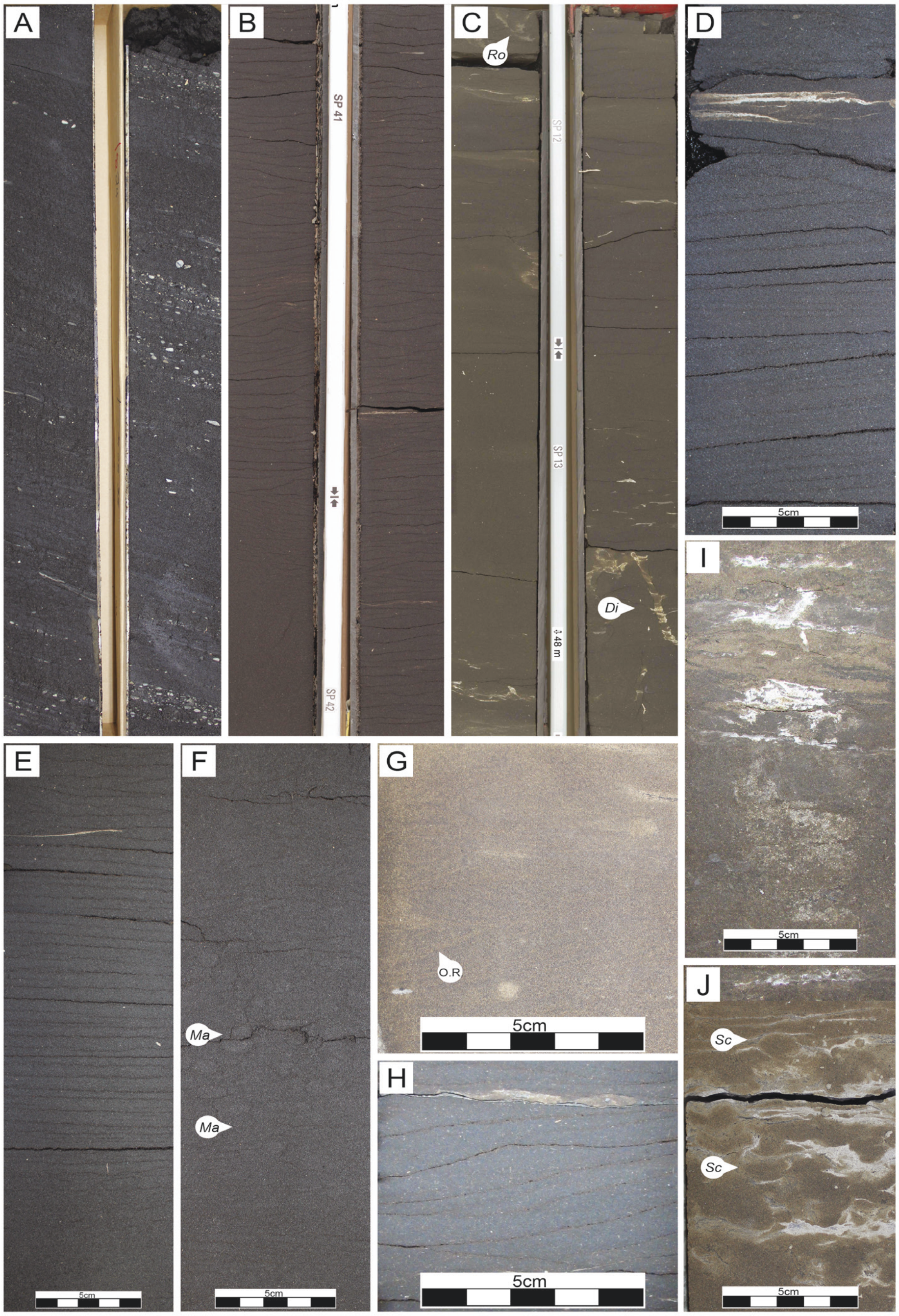


Figure 2-4. Sandstone dominated facies F2-F4. A) Typical core expression of F2 showing high-angle planar bedding, abundant pebble lags and coal debris. Well 10-18-084-16W5, depth 691.1-692.6m. B) Typical core expression of F3 showing wavy bedding, QPL, and trace mud drapes. Well 03-18-083-16W5, depth 669.25-670.75m. C) Typical core expression of F4b, with robust *Rosselia*, and *Diplocraterion* (in comparison to other facies identified). Well 06-04-084-16W5, depth 646.65-648.15m. D) Low-angle planar bedding and trough cross-bedding of F2. Well 03-32-082-16W5, depth 669.4m. E) Low-angle and planar parallel bedding indicating wave-reworking of F3 sandstone. 10-08-083-16W5, depth 658.0m. F) Cluster of *Macaronichnus* traces in clean sandstone of F3. Well 10-08-083-16W5, depth 657.55m. G) Oscillation ripples in very fine sandstone of F4. Well 08-07-083-16W5, depth 657.3m. H) Ripple foresets and homogeneous wavy parallel bedding in very fine-grained F3. Well 12-13-083-17W5, depth 659.0m. I) Highly bioturbated (BI 5-6) expression of F4c. Note the degree of bioturbation makes ichnogenera un-identifiable. Well 16-25-083-17W5, depth 618.9m. J) Highly bioturbated expression of F4a with abundant *Scolicia* traces. Well 08-20-083-16W5, depth 621.8m.

eral dm. Individual sandstone beds vary from ~5 mm to dm thick, apparently structureless beds. Mudstone layers range from mm to cm scale and show both internal lamination and massive texture, and are seen to locally truncate ripple laminae within underlying sandstone beds. Physical sedimentary structures include: common low- to high-angle planar bedding, trough cross-bedding, ripple laminations, wavy parallel bedding, parallel to non-parallel wavy bedding, HCS, scour surfaces, possible herringbone cross-stratification, and grain-size striping. Grain-size is predominantly medium to fine sand, with local granule to pebble caliber sediment. Lithologic accessories consist of common rounded to angular mudstone clasts, locally abundant shell fragments, "coffee ground" beds, and coal lamina. F5 has a wide distribution within the study area and invariably occurs within the lowest levels of stratigraphy. F5 is commonly situated above an erosive contact with the underlying sediments of F1, gradationally overlying F2, or grading transitionally into F2 or F6.

Ichnology: F5 is characterized by low to locally moderate diversity, sporadic distribution and BI (0-3). Ichnogenera observed include *Arenicolites, Asterosoma, Cylindrichnus, Diplocraterion, Macaronichnus, Palaeophycus, Planolites, Rosselia, Siphonichnus, Skolithos, Teichichnus,* and *Thalassinoides*. Traces occur predominantly within mudstone beds but are also found within clean sandstone as well (i.e. *Macaronichnus, Palaeophycus, Rosselia*).

Interpretation:

Facies F5 is interpreted to result from moderate- to high-energy deposition, within a wave-influenced, fluvial and locally tidally influenced setting. This interpretation is based on several criteria. The nature of bedding (i.e. low-angle planar to high-angle planar bedding, HCS, parallel to non-parallel wavy bedding) indicate deposition primarily within high-energy, wave-reworked conditions, while fluvial influence is inferred from the local presence of trough cross-bedding, grain-size striping, and ripple cross-laminations. Additional evidence of fluvial influence is given by the presence of erosive based, massive to graded mudstone beds, and rare "coffee ground" texture. These are interpreted as hyperpycnal flows, resulting from freshet discharge during periods of high flow in adjacent distributary channels (Bhattacharya and MacEachern, 2009). Apart from the heterolithic nature of F5, which is inferred to result from fluvial influx of suspended sediment, tidal signatures appear scarce. Instances of double mud-drapes, grain-size striping, and possible rare herringbone cross-lamination indicate local tidal influence. From an ichnological perspective, Asterosoma, Macaronichnus, and Rosselia, further suggest high-energy, near marine conditions of deposition (Clifton and Thompson, 1978; Saunders, 1989; Saunders et al., 1994; Pemberton et al., 2012).

FACIES F6: FINE-MEDIUM GRAINED HETEROLITHIC SANDSTONE AND MUDSTONE

Description:

Sedimentology: facies F6 (Fig. 2-5) consists of inter-bedded, fine- to locally medium-grained sandstone and mm-cm thick mudstone laminae and beds. Bed-sets range from cm scale (sand-mud couplets) to approximately 20 dm. Sandstone beds vary from thinly bedded to massive. Mudstone layers range from mm to cm scale, displaying fine internal lamination to apparently structureless texture. These mudstone beds are typically thinner than in F5, and lack erosive bases. They also more convoluted than those of F5. Physical sedimentary structures consist of: common heterolithic wavy bedding, non-parallel wavy bedding, ripple cross-laminations, oscillation ripples, low-angle planar to rare high-angle planar bedding, rare trough cross-bedding, QPL, soft sediment deformation, convolute bedding, and rare scour surfaces. Grain-size is predominantly lower- to upper-fine sand, with local coarse sand-granule caliber sediment. Lithologic accessories consist of mud rip-up clasts, coal fragments, local bioclastic debris, pyrite nodules, and shale laminae. F6 has a wide distribution throughout the dataset, and typically occurs in the middle to upper levels of stratigraphy. Facies F6 commonly grades upward from F5 and often grades into F7a.

Ichnology: F6 is characterized by low to moderate diversity, sporadic distribution and BI (0-3). Ichnogenera observed include *Arenicolites, Asterosoma, Cylindrichnus, Diplocraterion, Palaeophycus, Planolites, Scolicia, Skolithos, Teichichnus*, and *Thalassinoides*. Traces occur predominantly within mudstone beds, with the exception of *Palaeophycus*.

Interpretation:

Facies F6 is interpreted to represent deposition under more distal or sheltered conditions than F5, in an environment subject to wave-influence, periodic rapid deposition, hypopycnal mud plumes, and generally stable salinity levels. Wave influence is inferred from the dominantly non-parallel wavy nature of bedding, and presence of QPL, local oscillation ripples, and local very thin and well defined planar lamination. A more distant/protected geographical location is inferred by the overall finer sediment caliber, and non-erosive nature of mudstone beds. Ichnologically, the presence of *Asterosoma*, and *Scolicia* are associated with relatively stable, near-marine salinities (e.g. Pemberton et al., 1992; MacEachern et al., 2005b; Gingras et al., 2011).

FACIES F7a: LOW-DIVERSITY HETEROLITHIC SANDSTONE AND MUDSTONE

Description:

Sedimentology: facies F7a (Fig. 2-6) is similar in many respects to F6. Bed sets consist of cm to dm thick, fine-grained sandstone layered with cm to dm thick inter-laminated silty mudstone and fine-grained sandstone. Bed sets displaying this pattern are typically several dm thick. Primary sedimentary structures are dominated by: wavy parallel to flaser bedding, bioturbated bedding, convolute mudstone laminae and local low-angle planar bedding. Grain-size is predominantly lower fine-upper very-fine, with rare occurrence upper-fine to medium sand grains. Common lithological accessories include pyrite nodules, rare bioclastic debris, coal fragments, and rare granule to pebble lags. F7a has a wide distribution within the study area, and is typically located at upper stratigraphic intervals. F7a is commonly gradational from and into F6, as well as into and from F8.

Ichnology: F7a is characterized by low to moderate diversity, sporadic to locally homogeneous distribution, and displays BI (2-5). Ichnogenera observed include common diminutive to locally robust *Cylindrichnus,* and *Planolites*, with subordinate *Arenicolites, Teichichnus,* and *Thalassinoides*. In some expressions (e.g. 03-18-083-16W5) associations of diminutive monospecific *Cylindrichnus* occur, while in others (e.g. 10-18-084-16W5) the intensity of bioturbation makes species identification impractical.

Interpretation:

F7a is interpreted to be the result of deposition under relatively low-energy conditions with overall low sedimentation rates and periodic to locally persistent brackish-water conditions. This interpretation is based primarily on the fine grained nature of sediment and, in particular, mudstone content (up to 85% locally). Additionally, the dominance of heterogeneous wavy parallel bedding and lack of high-energy physical structures suggests overall low-energy conditions. Ichnological evidence suggests persistent brackish-water conditions, as diminutive monospecific assemblages of *Cylindrichus, Gyrolithes, Planolites*, or *Teichichnus* are considered a diagnostic characteristic of such chemical conditions (e.g. Pemberton et al., 1982; Wightman et al., 1987; Buatois and Mángano, 2011; Gingras et al., 2011; Gingras et al., 2012).

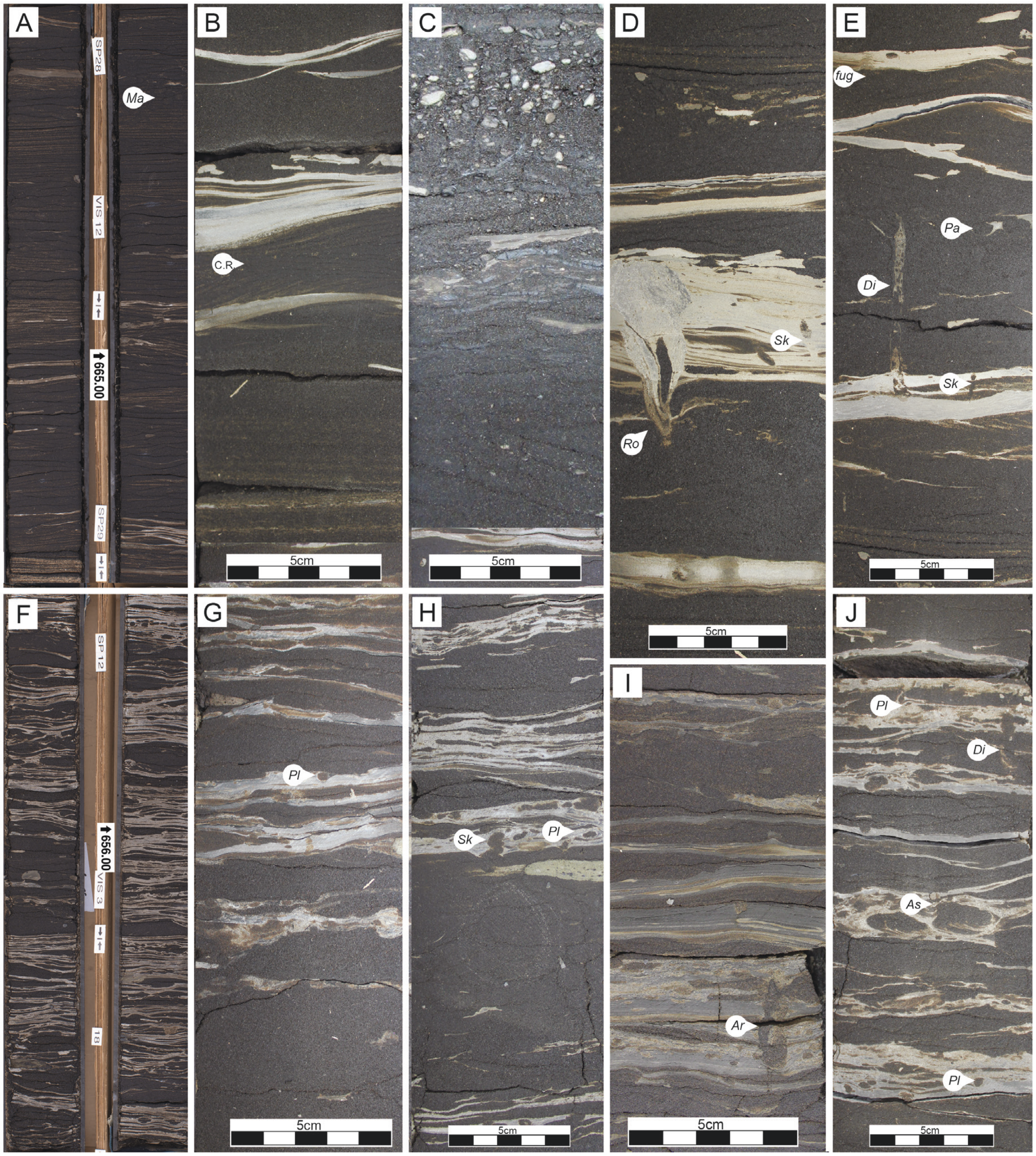


Figure 2-5. Heterolithic sandstone and mudstone facies F5-F6. A) Typical core expression of F5, with abundant low-angle planar bedding, mud-drapes and local *Macaronichnus* traces. Well 05-33-082-16W5, depth 664.6-666.1m. B) F5 displaying current ripples, planar parallel bedding, wavy parallel bedding, and fluid mudstone bed. Well 10-08-083-16W5, depth 665.8m. C) Scour interval containing pebble caliber sediment and coal debris. Well 10-36-083-17W5, depth 631.4m. D) Bioturbated mudstone bed with *Rosselia,* and *Skolithos* with heterolithic wavy parallel bedding at top of photo. Well 10-08-083-16W5, depth 661.9m. E) Wavy parallel bedded F5 with *Diplocraterion, Palaeophycus, Skolithos*, and fugichnia. Traces suggest high rates of deposition. Well 10-08-083-16W5, depth 665.3m. F) Typical core expression of F6, showing hi-frequency lamination of mudstone and sandstone. Well 05-33-082-16W5, depth 655.7-657.2m. G) F6 with low incidence of bioturbation with thin un-laminated mudstone laminae. Well 04-01-083-17W5, depth 688.5m. H) F6 with trace *Planolites*, and deformed *Skolithos* which may represent sediment compaction. Well 16-18-083-16W5, depth 650.0m. I) *Arenicolites* burrow in interbedded sandstone and internally massive grey mudstone bed. Well 12-09-084-16W5, depth 672.2m. J) Relatively robust *Asterosoma* traces showing compression in the vertical direction. Depth 16-18-083-16W5.

FACIES F7b: HIGH-DIVERSITY HETEROLITHIC SANDSTONE AND MUDSTONE

Description:

Sedimentology: facies F7b (Fig. 2-6) is lithologically very similar to F7a in terms of grain-size, and sedimentary structures, but typically displays higher silty mudstone content. In addition, these mudstone beds tend to be slightly thicker than in F7a, on the scale of a few to several cm instead of mm. Massive fine-very fine-grained sandstone beds of cm to dm scale are locally common in F7b. Distribution of F7b occurs predominantly at the uppermost stratigraphic levels, and is gradational into and from F9. It is also more common to the west half of the study area.

Ichnology: There is a marked contrast in the ichnological character of F7b with respect to F7a. F7b consists of moderate to high diversity, sporadic to homogeneous distribution, and BI (3-5). Ichnogenera observed include common *Asterosoma*, with subordinate *Arenicolites, Cylindrichnus, Palaeophycus, Planolites, Rhizocorallium, Rosselia, Scolicia, Skolithos, Teichichnus, Thalassinoides*, and *Zoophycos*.

Interpretation:

F7b is interpreted to represent deposition under relatively low-energy conditions with overall low sedimentation rates, periods of prolonged ambient conditions, and overall stable, near to fully marine salinity, with periodic storm influence. This interpretation is based on the fine- to very-fine, silty to muddy sediment caliber, predominance of low-energy sedimentary structures, and overall elevated mudstone content. Storm influence is inferred by the local presence of truncated, highly bioturbated mudstone beds by massive fine-very fine-grained sandstone beds. Ichnological evidence for prolonged periods of unstressed conditions comes from the high bioturbation intensity and deposit feeding dominated assemblage of mudstone beds. Fully to near fully marine salinities are indicated by the presence of characteristic ichnogenera including robust and abundant *Asterosoma, Rhizocorallium, Scolicia,* and *Zoophycos*.

FACIES F8: LAMINATED MUDSTONE

Description:

Sedimentology: facies F8 (Fig. 2-7) consists predominantly of light grey-brown muddy siltstone to grey silty-mudstone. Individual mudstone beds and laminae range from mm to dm scale. Thin, mm-cm scale fine-grained sandstone and silty-sandstone beds and laminae are common throughout, but overall mudstone content is >90%. The mudstone beds are both laminated and massive in texture. Physical sedimentary structures are dominated by: lenticular bedding, with subordinate heterolithic wavy bedding, planar lamination, soft sediment deformation, and local mantle and swirl texture. Within silty-sandstone lenses, oscillation and current ripple laminae are locally preserved. Lithological accessories consist of sand laminae, common pyrite nodules, local bioclastic shell accumulations, and coal fragments. F8 typically occurs in the middle to upper levels of stratigraphy, and commonly grades into and from F6 and F7a. The distribution of this facies has a wide range in a north-south orientation, but is largely restricted to the eastern half of the study area.

Ichnology: F8 is characterized by low diversity, sporadic heterogeneous distribution and BI (0-3). *Planolites, Siphonichnus, Skolithos, Teichichnus,* and *Thalassinoides*, with rare diminutive *Asterosoma, Zoophycos,* and fugichnia, represent the ichnogenera observed. Traces occur as both sand filled tubes within mudstone beds, and as mottled zones within thin sandstone beds.

Interpretation:

Facies F8 is interpreted to represent deposition in two distinct environments: 1) high-energy environment prone to elevated sedimentation rates, common hyperpycnal mud flows, storm deposition, and

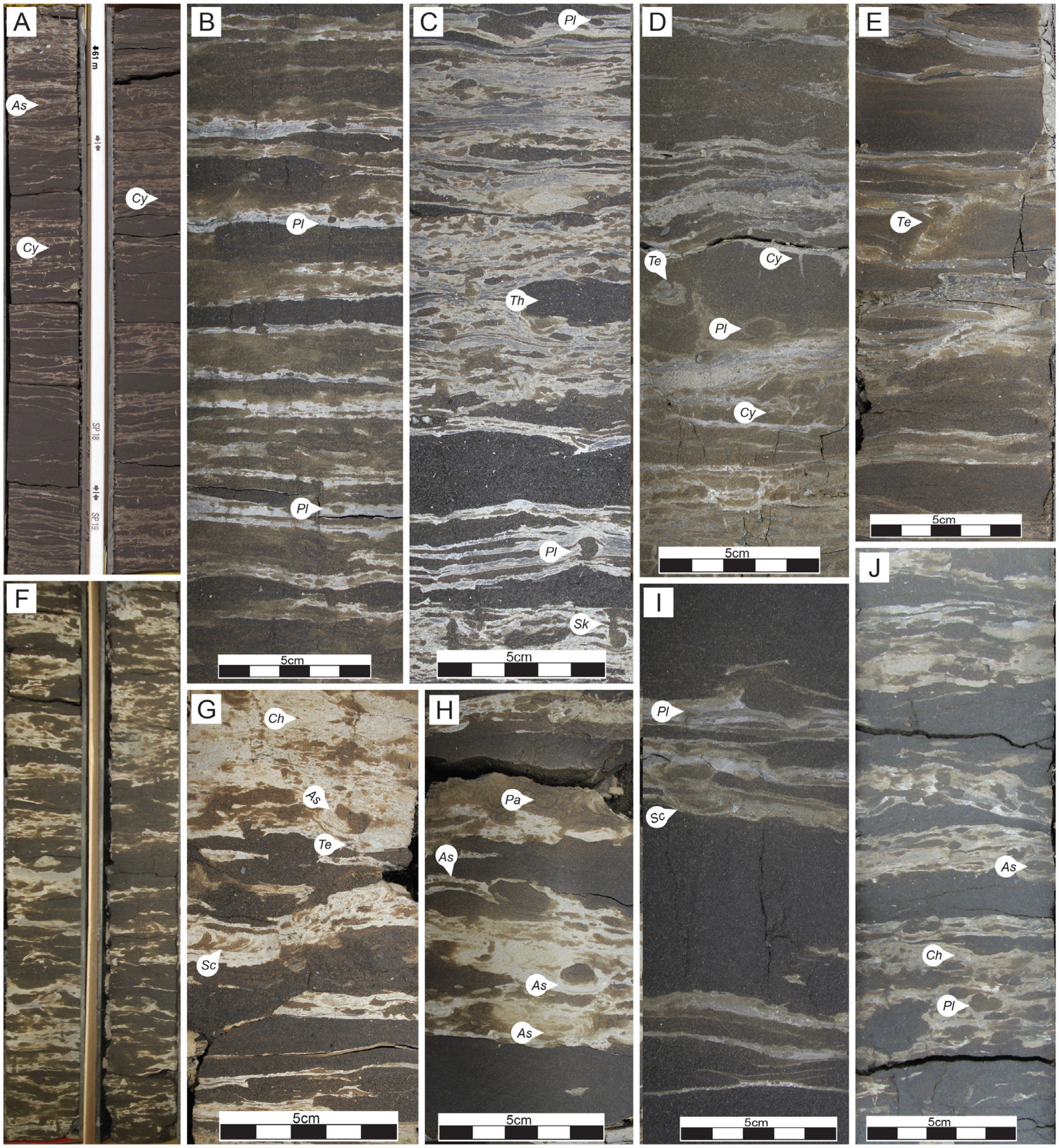


Figure 2-6. Bioturbated heterolithic sandstone and mudstone facies F7a and F7b. A) Typical core expression of F7a showing abundant *Cylindrichnus*, with subordinate *Asterosoma,* and *Planolites*. Assemblage is interpreted to represent brackish-water conditions. Well 03-18-083-16W5, depth 660.2-661.7m. B) Highly bioturbated interval of F7a with *Planolites* and mottling of sediment. Well 10-18-084-16W5, depth 671.5m. C) Bioturbated muddy expression of F7a with abundant *Planolites* and subordinate *Skolithos*, and *Thalassinoides*. Well 05-29-082-16W5, depth 671.1m. D) *Cylindrichnus* dominated assemblage with subordinate *Teichichnus*, and *Planolites*. Well 08-07-083-16W5, depth 659.2m. E) *Teichichnus* within interbedded sandstone and mudstone of F7a. Well 01-32-083-16W5, depth 640.2m. F) Typical core expression of F7b displaying highly bioturbated mudstone beds. Assemblage is interpreted to represent relatively stable, near marine salinity conditions. Well 16-18-083-16W5, depth 638.3-639.8m. G) *Scolicia, Chondrites, Asterosoma*, and *Teichichnus* within highly bioturbated F7b. Well 15-10-083-16W5, depth 629.0m. H) Dense assemblage of robust *Asterosoma*, with subordinate *Palaeophycus,* and *Planolites*. Well 15-10-083-16W5, depth 626.0m. I) *Scolicia*, and *Planolites* in mudstone bed of F7b. Well 11-29-083-16W5, depth 642.8m. J) Typical core expression of F7b. Well 10-36-083-17W5, depth 625.5m.

periodic salinity fluctuations; and, 2) low-energy, shallow subtidal to intertidal environment with periodic to persistent salinity stress. Sedimentologically, the rapid deposition and hyperpycnal mud flow interpretation is based on the locally thick, apparently structureless to graded texture, and erosive nature of mudstone beds with local fugichnia. Additionally, mantle and swirl texture suggests deposition of mud lacking sufficient cohesion for the preservation of traces, a feature common to hyperpycnal mud (MacEachern et al., 2005a; Bhattacharya and MacEachern, 2009; Tonkin, 2012). Storm influence is inferred from the presence of oscillation rippled sandstone lenses within mudstone, and the presence of local thick (cm scale) fine-grained, ripple laminated sandstone beds, interpreted as tempestites. Finally, the interpretation of fluctuating, but at least periodic near normal salinity levels is based on the presence of *Asterosoma* and *Zoophycos*. In the second facies expression, low-energy, salinity stressed conditions are inferred from the dominance of planar lamination, rare to absent bioturbation, and the highly diminutive nature of ichnogenera (Tonkin, 2012).

FACIES F9: BIOTURBATED MUDSTONE

Description:

Sedimentology: facies F9 (Fig. 2-7) consists of predominantly light grey-brown muddy-siltstone to silty-mudstone with local interbedded very fine-grained sandstone. Mudstone beds constitute greater than 90% of the facies and sandstone beds are typically thin (mm to a few cm). Physical sedimentary structures are dominated by lenticular to local wavy parallel bedding, much of which is partially or completely disrupted by bioturbation. Lithologic accessories include pyrite nodules, rare bioclastic debris, and trace coarse sand-granule caliber sediment. F9 predominantly occurs in the upper levels of stratigraphy and commonly grades into and from F7b. This facies occurs locally across most of the study area, but shows a higher concentration along the western extent (i.e. within Range 17).

Ichnology: F9 is characterized by moderate to high diversity, homogeneous distribution, and BI (3-6). Ichnogenera observed include abundant *Asterosoma*, with sub-ordinate *Arenicolites, Chondrites, Cylindrichnus, Diplocraterion, Palaeophycus, Planolites, Phycosiphon, Rosselia, Rhizocorallium, Siphonichnus, Scolicia, Skolithos, Teichichnus, Thalassinoides*, and *Zoophycos*. Traces occur predominantly within mudstone and extend into surrounding sandstone beds, destroying primary sedimentary structures.

Interpretation:

Facies F9 is interpreted to represent sedimentation under low-energy, temporally stable chemical conditions with abundant food resources. Sedimentological evidence for this interpretation is derived from the heterogeneous wavy parallel to discontinuous nature of sandstone beds, lack of observable high-energy current bedforms, and the dominance of silty mudstone. Ichnologically, the highly diverse, robust nature of traces, and dominance of deposit feeding ethologies suggest abundant food resources within the substrate (MacEachern et al., 2010, Gingras et al., 2011). Additionally, stable chemical conditions are inferred from the presence of abundant (locally monospecific) *Asterosoma*, with lesser *Rhizocorallium, Scolicia,* and *Zoophycos* indicating near fully to fully marine salinities (e.g. Pemberton et al., 1992; MacEachern et al., 2005b; Gingras et al., 2011; Buatois and Mángano, 2011; Tonkin, 2012).

FACIES F10: BIOCLASTIC SANDSTONE AND MUDSTONE

Description:

Sedimentology: facies F10 (Fig. 2-8) consists of various proportions of bioturbated to laminated mudstone, and bioclastic sandstone. Mudstone beds are typically dm thick, while bioclastic beds are cm to dm thick. Primary physical structures consist of: wavy parallel to low-angle planar parallel bedding, local

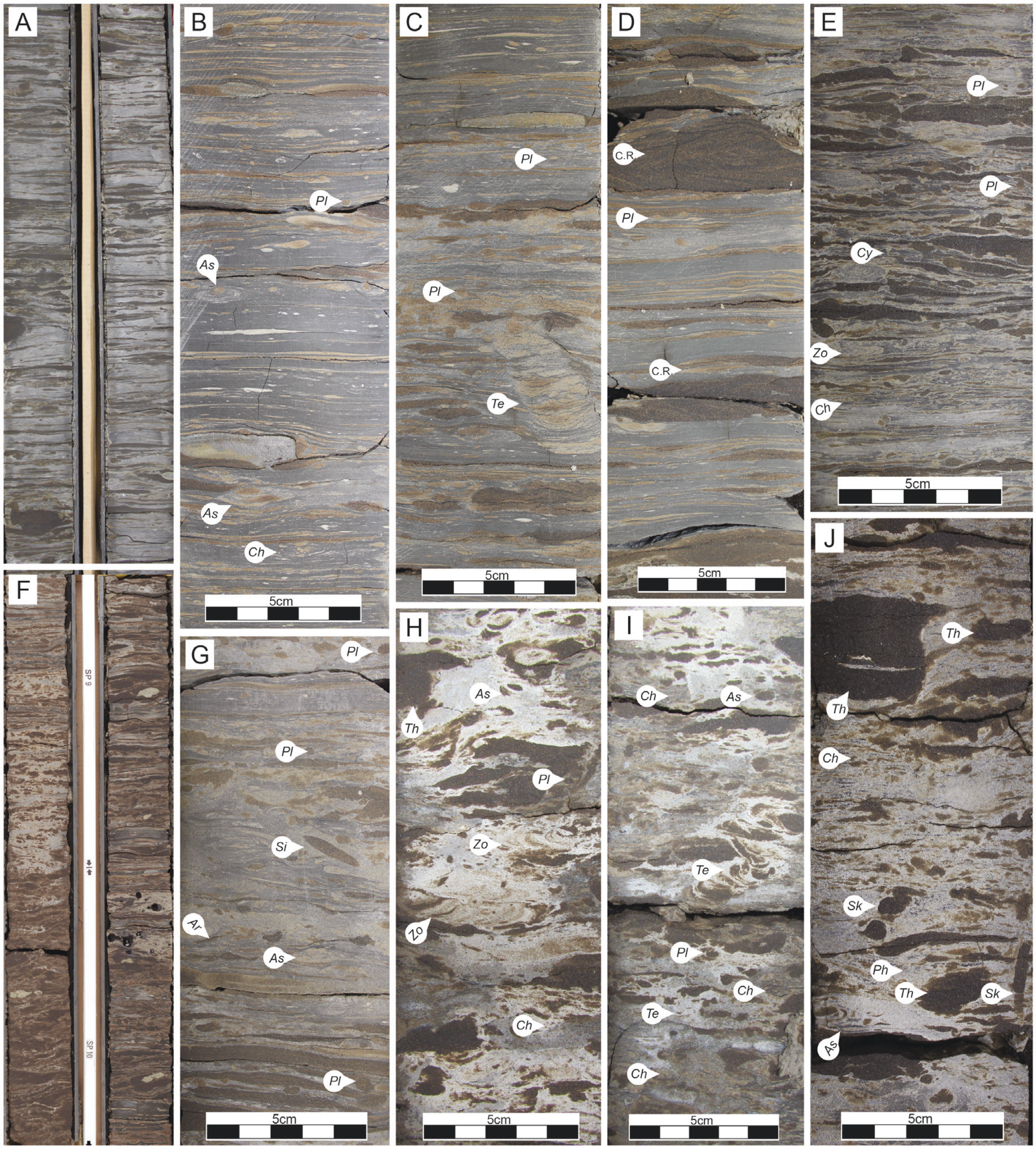


Figure 2-7. Mudstone dominated facies F8 and F9. A) Typical core expression of F8. Well 13-03-084-16W5, depth 642.5-644.0m. B) Massive to laminated mudstone of F8 with thin very fine-grained sandstone lenses. Trace fossils are diminutive and rare, and include *Asterosoma, Chondrites,* and *Planolites*. Well 12-09-084-16W5, depth 666.1m. C) Robust *Teichichnus* within F8, suggesting elevated depositional rates. Well 12-09-084-16W5, depth 664.7m. D) F8 with thick sandstone inter-bed displaying current ripple-lamination suggestive of deposition by current transport. Well 12-09-084-16W5, depth 667.5m. E) F8 with elevated bioturbation and presence of marine-indicative traces of *Zoophycos* and *Chondrites*. Well 05-29-082-16W5, depth 671.1m. F) Typical core expression of F9. Well 03-18-083-16W5, depth 656.3-657.8m. G) Highly bioturbated, moderate diversity expression of F9, including *Asterosoma, Arenicolites, Planolites*, and *Siphonichnus.* Well 11-16-084-16W5, depth 668.9m. H) Highly bioturbated expression of F9 with robust *Zoophycos*, and subordinate *Asterosoma, Chondrites, Planolites,* and *Thalassinoides*. Well 10-36-083-17W5, depth 625.1m. I) Highly bioturbated expression of F9 with robust *Teichichnus,* and subordinate *Asterosoma, Chondrites,* and *Planolites*. Well 10-36-083-17W5, depth 625.8m. J) Robust *Thalassinoides* with subordinate *Chondrites, Phycosiphon*, and *Skolithos*. Well 03-32-082-16W5, depth 660.1m

convolute bedding, load casts, and local lenticular bedding. Lithological accessories consist of abundant gastropod, bivalve, and bioclastic debris, pyrite nodules, coal fragments and local calcite cemented zones. This facies is restricted to the upper most levels of stratigraphy, in the west-central portion of the study area. It appears to be unconformable above F4a,b, and F9 in all occurrences.

Ichnology: F10 is characterized by low diversity, sporadic heterogeneous to homogeneous distribution, and BI (0-6). Ichnogenera identified include *Planolites, Skolithos*, trace *Diplocraterion*, and local pitted surfaces. In many of the sandstone beds, bioturbation is intense, making recognition of individual ichnogenera impossible.

Interpretation:

Facies F10 is interpreted to represent deposition in an environment prone to periodic high sedimentation rates, storm- and wave- reworking, and persistent brackish-water conditions. High sedimentation rates are inferred from local load casting, and common, well developed convolute structures. Brackish-water conditions are inferred from the very low-diversity, and diminutive trace sizes present. However, intensely mottled sandstone beds suggest colonization of opportunistic organisms, a feature common to brackish-water conditions (Pemberton et al., 1982; Buatois and Mángano, 2011).

FACIES F11: GLAUCONITIC SANDY MUDSTONE

Description:

Sedimentology: facies F11 (Fig. 2-8). consists of a mixture of sediment ranging in grain-size from pebble to mud caliber. Bedding is often completely mottled by bioturbation, but where preserved, is dominated by planar lamination. Common lithological accessories include abundant glauconite grains, minor pyrite nodules, mud clasts, and siderite nodules.

Ichnology: Bioturbation intensity is predominantly high with very robust *Diplocraterion*, and *Asterosoma*, with subordinate *Planolites, Skolithos,* and *Thalassinoides*. Ichnological diversity is likely under-represented due to the pervasive nature of mottling. This facies occurs at, and defines the contact between the Bluesky Formation and the overlying Wilrich Member, and characterizes a regional Glossifungites surface representing a marine flooding surface.

Interpretation:

F11 is interpreted to represent a transgressive lag deposit in fully marine, low energy setting with consistent chemical conditions. This interpretation is consistent with that of O'Connell (1988) and is based on the ubiquitous occurrence of glauconite, high degree of bioturbation, robustness of traces, and the stratigraphic location directly underlying the marine shales of the Wilrich Member.

FACIES ASSOCIATIONS

The architecture of siliciclastic marginal marine to marine systems is directly controlled by depositional process (i.e. wave, tidal, fluvial forces) acting upon the shoreline (Howell et al., 2008; Ainsworth et al., 2011; Tonkin., 2012). Throughout the evolution of a given system, each process may dominate at different times, or, two or three processes may co-effect sedimentation. This results in mixed-process systems, which have been identified in the rock record (e.g. Ainsworth, 2003; Bhattacharya and Giosan, 2003; Willis, 2005; Yoshida et al., 2007; Ainsworth et al., 2008; Charvin et al., 2009). In addition to wave, tide and fluvial processes, Ainsworth et al., (2011) identify four additional key parameters for the identification and prediction

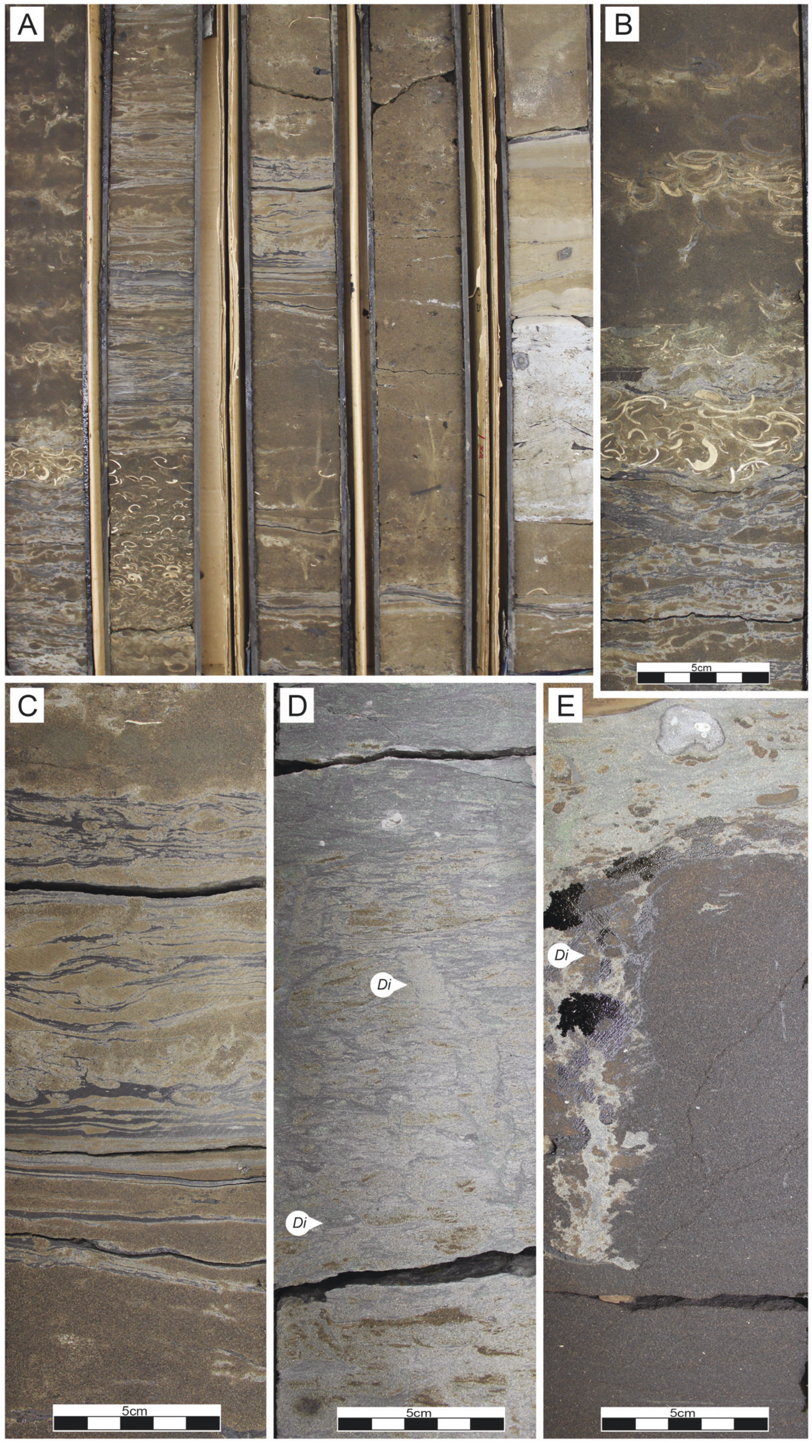


Figure 2-8. Bioclastic sandstone and mudstone of F10 and *Glossifungites* contact between the Bluesky Formation and Wilrich Member. A) Core expression of inter-bedded bioclastic sandstone, siltstone and silty sandstone. Well 10-23-083-17W5, depth 630.8-634.5m. B) Close-up showing bioclastic accumulations, and intense bioturbation of inter-bedded sandstone. Well 10-23-083-17W5, depth 634.3m. C) Close-up of load casting and convolution of mudstone layers within sandstone of F10. Well 10-23-083-17W5, depth 632.5m. D-E) Typical expression of *Glossifungites* contact between the Bluesky Formation and Wilrich Member, displaying very robust *Diplocraterion* traces. Wells 05-29-082-16W5, depth 668.0m and Well 13-03-084-16W5, depth 634.9m

of depositional systems. These are: 1) likelihood of wave vs. fluvial effectiveness; 2) influence of coastal morphology; 3) influence of shelf width or basin geometry on tidal resonance; and, 4) the influence of accommodation/sedimentation ratio. Additionally, Ainsworth et al., (2011) provide a framework in which the observations of dominant physical processes can be used to more accurately identify depositional systems. Figure 2-3 presents a modified version of this framework, and in combination with observed ichnological characteristics, provides a basis for interpretation of the Facies Associations described below. Given the relatively limited spatial extent of the project area, shelf width and basin morphology is difficult to assess. Additionally, directly assessing the accommodation/sedimentation ratio in the rock record is not possible (Ainsworth et al., 2011). However, in addition to the relative influence of wave, tide and fluvial processes, determination of the likelihood of wave vs. fluvial effectiveness, and influence of coastal morphology on tidal amplification was considered.

Four distinct facies associations (FA1-FA4) were identified within the confines of the study area (Table 2-2). These associations are based upon the combination and distribution of individual facies identified through core analysis. These include: FA1- wave/storm-dominated and fluvially-influenced delta; FA2-bay-margin through to distal bay-margin shoreface to offshore; FA3- wave-dominated marine delta, and; FA4-wave influenced brackish sedimentation. FA1, FA2 and FA3 are interpreted to represent continual evolution of the same depositional system based upon vertical and lateral core relationships. The contact between FA4 and underlying facies association is interpreted to represent a late-stage change in relative sea-level prior to complete inundation and deposition of the marine Wilrich Member.

FA1: WAVE DOMINATED, FLUVIALLY INFLUENCED BAY-MARGIN DELTA

FA1 represents the largest volume of sediment within the study area, and is interpreted to represent deltaic sedimentation in a moderate- to high-energy, wave-dominated, fluvially-influenced marine embayment setting. This interpretation is based on several criteria. Sedimentation is dominated by fine- to medium-(occasionally coarse grained) sandstone, hyperpycnal to hypopycnal mud bearing heterolithic sandstone and mudstone, and sparsely bioturbated massive mudstone, characteristics common to deltaic settings (Mutti et al., 2000; Coates and MacEachern, 2005; MacEachern et al., 2005; Bhattacharya and MacEachern, 2009; Bhattacharya, 2010). In several wells, particularly in southern locations (i.e. 03-32-082-16W5, 05-29-082-16W5, 05-04-083-16W5, and 07-09-083-16W5), a discernable cleaning/coarsening upward trend is present (Fig. 2-9, 2-10). In these wells, hyperpycnal mudstone bearing F5 is gradationally overlain by clean, medium- to locally coarse-grained sandstone of F2. In these instances, there is a decrease upward in bioturbation (trace size, BI, and ethological diversity), and an increase upward in the frequency and amount of terrestrial derived material (i.e. pyritized coal beds, “coffee ground” texture, wood and coal debris). This relationship suggests progradation with an increasing proximity to fluvial influence. Although this cleaning upward trend is not present in all wells, wave-dominated deltas are complex systems and need not show progradation in all locales (Bhattacharya and Giosan, 2003). F2 and F5 are interpreted to represent deltaic distributary channel, proximal delta front and proximal to distal delta front environments, respectively. The interpretation of wave and fluvial action as primary controls on sedimentation is inferred from the abundance of parallel to non-parallel wavy bedding, low-angle planar bedding, HCS, QPL, common normally graded beds, and abundance of trough cross-bedding. Signatures that could be considered tidal in origin, such as tidal rhythmites, and double mud drapes occur only locally, particularly within the southern and east-central study area. This may reflect slight confinement and tidal amplification due to underlying palaeotopography.

Facies Association	Associated Facies	Depositional Affinity	Sub-Environments
FA1	F2, F3, F5, F6, F7a, F8	Fluvial to Wave/Storm-Influenced Delta	proximal to distal delta front, prodelta
FA2	F3, F4a, F7b, F9	Bay-margin Shoreface to Offshore	upper, lower bay-margin shoreface, distal bay
FA3	F3, F4b	Wave-Dominated Delta	proximal delta front
FA4	F4c, F8, F10	Brackish Sedimentation	bayhead delta?, tidal flat, tidal creek, lagoon

Table 2-2. Summary table showing constituent facies comprising facies associations FA1-FA4, with interpreted sub-environments.

The overall absence of strong tidal indicators may be attributed to non-preservation of such structures due to reworking by waves, fluvial processes, or tidal forces (Davis, 2012).

The ichnological signature of FA1 compliments sedimentary characteristics in the interpretation of deltaic conditions. Trace fossil distribution within each component facies is highly sporadic, and displays low BI. This is suggestive of rapid fluctuations in physico-chemical stresses such as salinity, water turbidity, and depositional rates, all of which are common to deltaic settings (MacEachern et al., 2005a). The presence of interpreted hyperpycnal muds, and thick sandstone beds present in F5 and F2 support the presence of such stresses (MacEachern et al., 2005a; Bhattacharya and MacEachern, 2009). Additionally, certain ichnogenera within FA1 may help constrain the geographical position of the deltaic complex with respect to the shoreline. *Macaronichnus* is present in several wells throughout the study area, and its association with high-energy, wave-influenced conditions has been well documented (e.g. Clifton and Thompson, 1978; Saunders, 1989; Saunders et al., 1994; Pemberton el al., 2012). The combined presence of *Asterosoma* and *Rosselia* within F5 is suggestive of a lower shoreface/delta front depositional setting in near normal marine salinities (Gingras et al., 2011, Tonkin, 2012).

The nature of underlying Gething Formation sediments (F1) must also be considered when interpreting the depositional affinity of FA1. Though not studied in detail, Gething strata within the project area shows strong indications of brackish-water conditions (i.e. archetypal brackish-water trace assemblage, fine-grained sedimentation, possible tidal rhythmicity). These features contrast markedly with the grain-size, sedimentation style and ichnology of the overlying Bluesky Formation. This is suggestive of an environmental progression from sheltered, lower energy conditions (Gething Formation) where wave action is diminished, to less sheltered, moderate- to locally high-energy conditions (Bluesky Formation). The contact between the Gething and Bluesky formations within the confines of the study area represents a transgressive wave ravinement surface with local tidal modification (Catuneanu, 2006). This is confirmed by the highly erosional nature of this contact, where large (cm-dm scale) mud clasts and shell fragments reflecting Gething lithology are commonly entrained in Bluesky sediments of F2 and F5.

FA2: WAVE-INFLUENCED BAY-MARGIN

FA2 is, proportionally, the second most common depositional environment identified within the study area. It is interpreted to represent bay-margin shoreface through to distal bay-margin deposition, and is locally intercalated with FA1 (e.g. 11-30-083-16W5, 15-10-083-16W5, 16-18-083-16W5, 08-35-083-

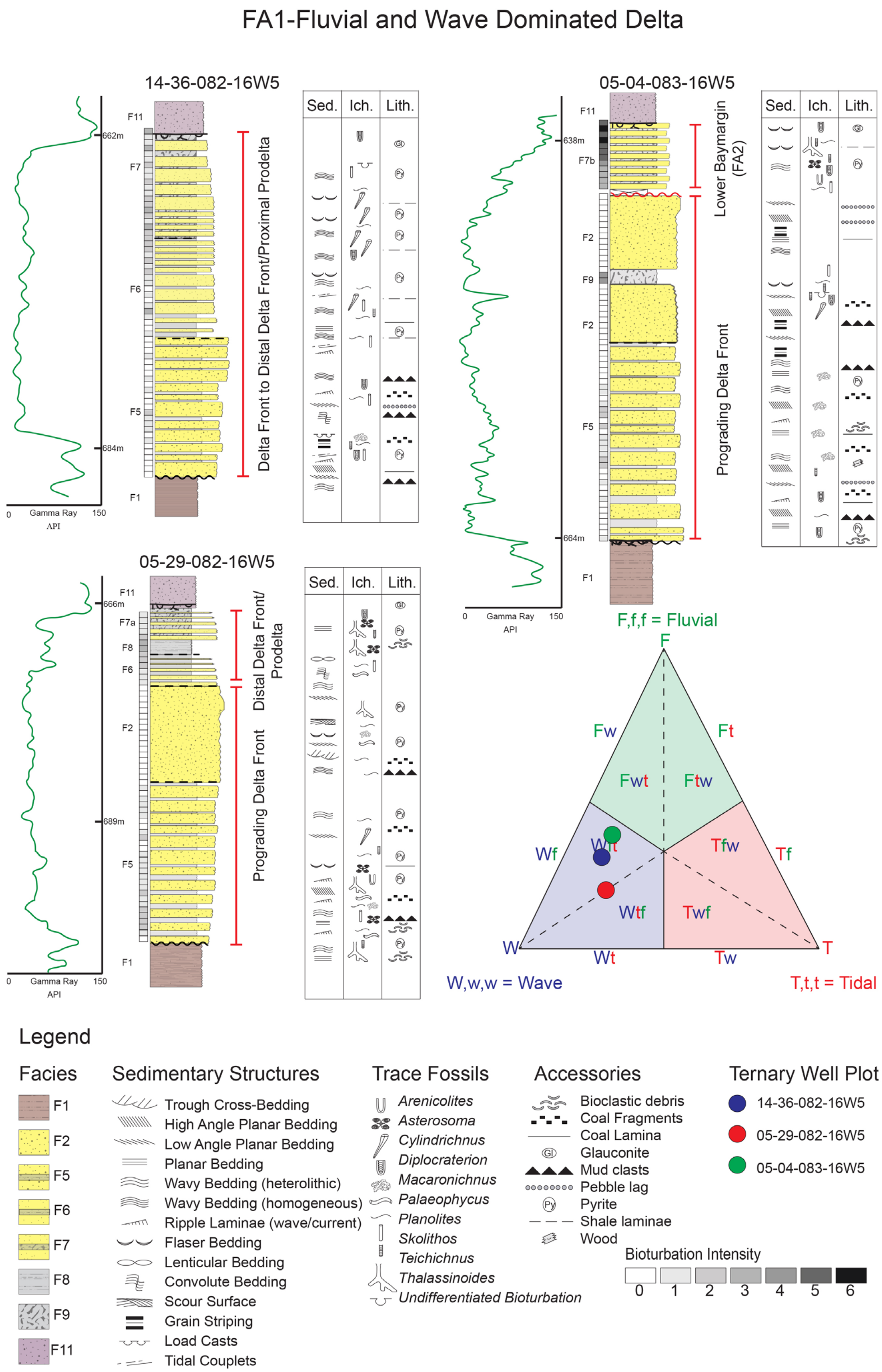


Figure 2-9. Sample core expression of FA1. 14-36-082-16W5 shows delta front to distal delta front sedimentation, while 05-04-083-17W5 and 05-29-082-16W5 show progradation of fluvial and wave dominated clean sandstone over heterolithic sandstone and mudstone. Location of each well on the ternary diagram was calculated by recording the dominant process for every 75 cm core sleeve and deriving the overall percentage based on the number of core boxes. Ternary diagram modified after Ainsworth et al., (2011).

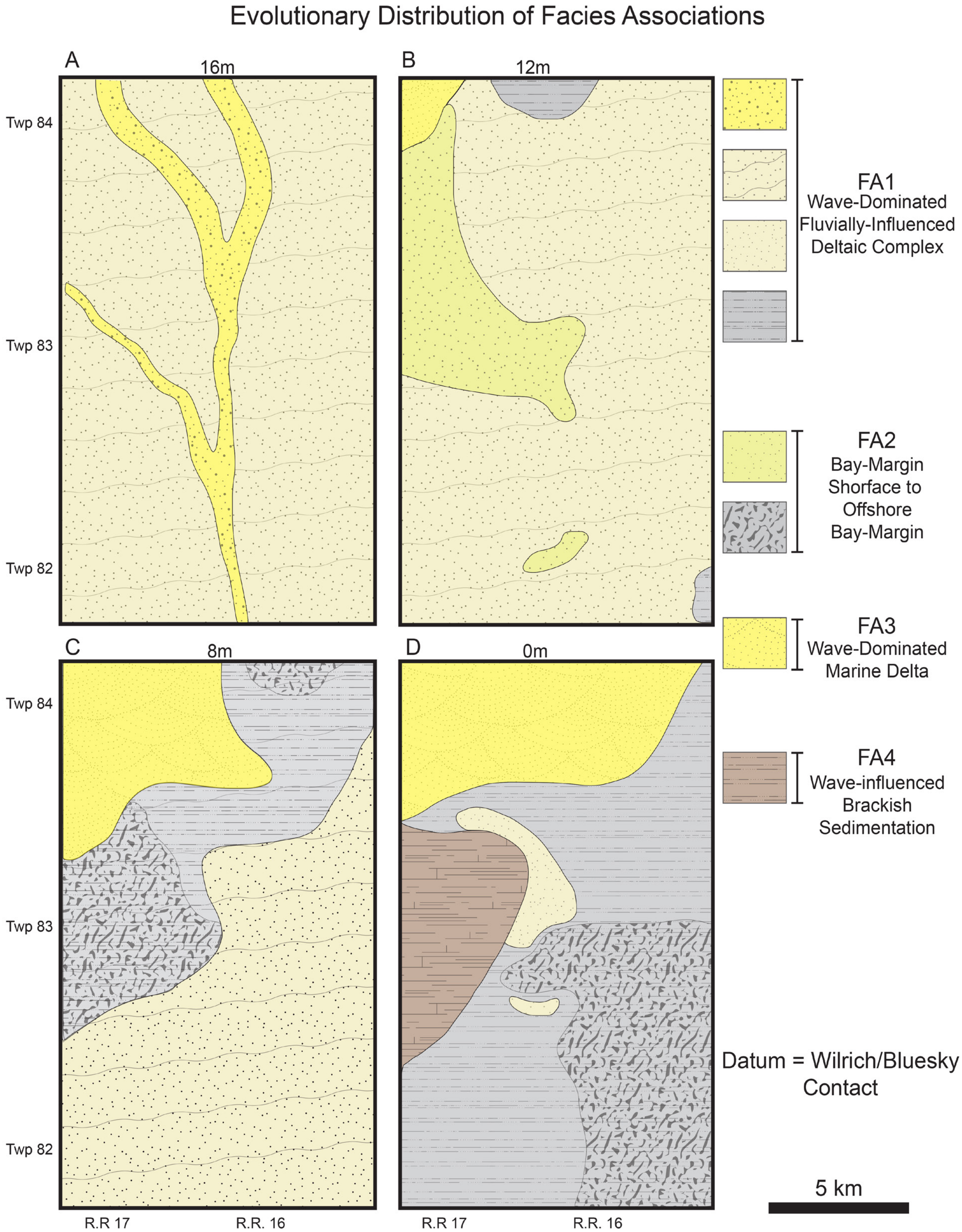


Figure 2-10. Distribution of facies associations within the project area. The Bluesky/Wilrich contact was utilized as a datum and represents 0 m. C, B, and A represent progressively deeper slices through the Bluesky Formation.

17W5) (Fig. 2-10, 2-11). Broadly speaking, facies of FA2 show a transgressive stacking pattern wherein clean, fine-grained sandstone of F3 and F4a transition into bioturbated heterolithic F7b, into bioturbated mudstone of F9. A wave/storm-influenced environment within an open embayment is interpreted based upon the following criteria. Sandstone of FA2 are predominantly mud-laminae free, and dominated by planar parallel bedding, QPL, HCS, and parallel to non-paralllel wavy bedding suggesting constant winnowing and reworking by wave/storm action (e.g. Reineck and Singh, 1973; Arnott, 1993; MacEachern et al., 2005a; Ainsworth et al., 2011). Wavy parallel bedding and fine to very fine grain-size, with occasional coarse lags, dominate heterolithic deposits of F7b. These suggest overall low-energy conditions with episodic storm influence. Mudstone deposits of F9 are overall very fine-grained, with rare truncational fine-grained sandstone inter-beds, suggesting episodic storm deposition. These sedimentary features are not normally expected within a wave-dominated estuary, for which sub-areal barriers or spits very effectively prevent wave energy from entering the estuary (Dalrymple et al., 1992).

The ichnological signature of FA2 compliments the sedimentary characteristics described above, and are the main criteria for distinguishing between heterolithic and mudstone deposits of FA1. Sandstone of FA2 displays sporadic to locally homogeneous distribution, dominated by deposit feeding ethologies (i.e. *Macaronichnus, Planolites, Scolicia*). Heterolithic F7b and mudstone F9 deposits display moderate to high BI, and contain a diverse ichnological assemblage, with a number of ichnogenera common to the *Cruziana* ichnofacies (e.g. *Asterosoma, Phycosiphon, Rhizocorallium, Scolicia,* and *Zoophycos*). The ichnological character of these sediments suggests deposition in a comparably open, marine embayment setting. These environments are virtually unrestricted in their connection to the open sea, and thus salinity stress is significantly lower than in restricted embayment settings (MacEachern and Gingras, 2007; Buatois and Mángano, 2011). Although sedimentation appears to reflect relatively calm ambient conditions, the presence of highly bioturbated mudstone beds truncated by fine-grained sandstone further suggests periodic storm influence. These conditions appear to contrast with those of central estuary environments and tidal flats, where processes such as fluvial input (freshets), brackish-water and temperature stresses produce conditions un-attractive to substrate colonization (Gingras et al., 2012).

FA3: WAVE-DOMINATED MARINE DELTA

FA3 represents a small proportion of sedimentation, and is restricted to the northern portion of the study area (Range 16 & 17W5, Township 84, Fig 10, 12). However, the apparent southeastward migration of this facies association suggests extension in a northwestern direction is highly probable. FA3 is interpreted to represent deposition in a storm- and wave-dominated marine delta setting. Sedimentation is dominated by fine- to very fine-grained, clean sandstone with abundant low-angle planar bedding, parallel to non-parallel wavy bedding, HCS, and ripple cross-lamination. This suggests constant reworking by wave-action. FA3 strongly resembles bay-margin shoreface deposits of FA2, but is distinguished based upon its ichnological character. Traces are significantly larger in sandstone of FA3, with robust *Rosselia, Diplocraterion*, and *Scolicia*. Additionally, significant intervals of sandstone in FA3 display robust, dense assemblages of *Macaronichnus*. The relationship of FA3 deltaic deposits to those of FA1 and FA2 appears erosional, and is well developed on gamma ray logs (Fig. 2-11). This contact is interpreted to represent a wave-ravinement surface (WRS) as wave action erodes embayment and deltaic deposits during a transgressive phase. However, given that sedimentation of FA1 and FA2 persists during FA3 migration (as shown of facies slice maps of Fig. 2-10), these facies associations are considered to be temporally related.

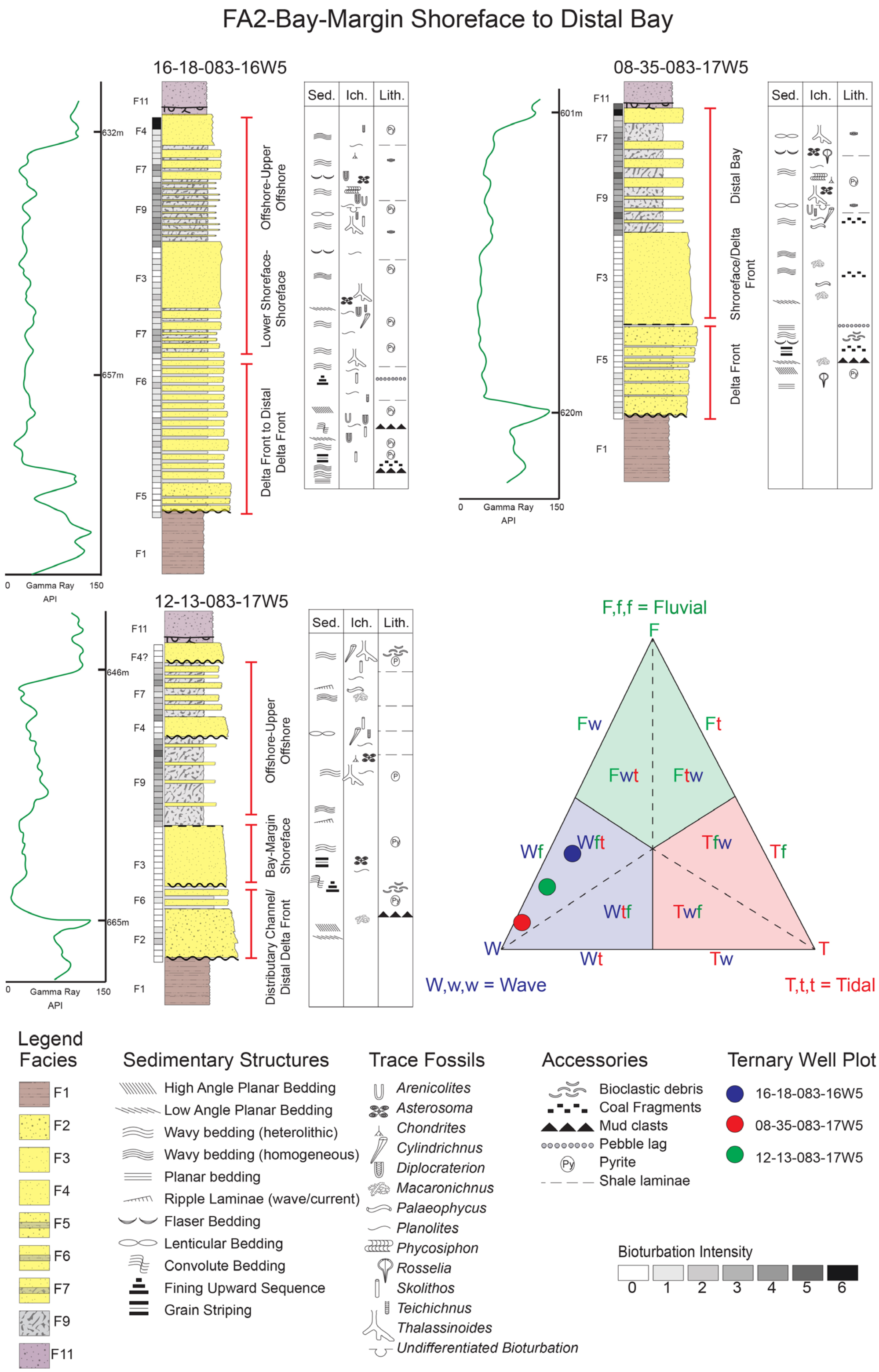


Figure 2-11. Sample core expression of FA2. Note that all wells show an overall transgression from bay-margin shoreface deposition to distal-bay mudstone and heterolithic sandstone and mudstone. 12-13-083-17W5 displays at least two sequences from proximal to distal bay sedimentation. Location of each well on the ternary diagram was calculated by recording the dominant process for every 75 cm core sleeve and deriving the overall percentage based on the number of core boxes. Ternary diagram modified after Ainsworth et al., (2011).

FA4: WAVE-DOMINATED BRACKISH SEDIMENTATION

FA4 represents a juxtaposition of brackish-water over marine embayment sedimentation in the west-central portion of the study area (Range 17W5 & Township 83, Fig. 2-10, 2-13). FA4 represents a small proportion of overall sedimentation, and the juxtaposition of brackish-water trace assemblages on significantly more marine assemblages of FA2 can be used to infer a discernable shift in relative sea level (MacEachern et al., 2012). A brackish-water interpretation of FA4 is based upon several criteria. Locally, sandstone packages showing well developed load casting, and soft sediment deformation of inter-bedded mudstone layers suggest periodic rapid deposition. Coupled with an almost complete lack of bioturbation, this suggests deposition in an high-energy, brackish-water environment (e.g. bay-head delta). In other locations, thick accumulations of laminated to locally massive mudstone (> 1 m thick bed-sets in places) suggest conditions with physical and chemical parameters non-conducive to bioturbating organisms such as salinity and oxygen fluctuations, substrate consistency, food distribution, etc. (e.g. Pemberton et al., 1982; Buatois and Mángano, 2011; Gingras et al., 2011; Gingras et al., 2012a). Local dense accumulations of bioclastic debris, inter-bedded with bioturbated silty-sandstone and muddy-siltstone are interpreted to represent tidal creek and tidal flat sedimentation, respectively (Reineck and Singh, 1973; Desjardins et al., 2012). Bioturbation, which is locally too intense to allow for trace identification, appears to be dominated by monospecific, relatively diminutive structures. This suggests deposition in persistently brackish-water conditions. While the density of data is not conducive to correlation, each characteristic described above is possible within various sub-environments of a brackish, wave-influenced, sheltered setting (e.g. upper delta plain, upper estuary).

PALAEOTOPOGRAPHIC CONTROLS ON SEDIMENTATION

In addition to the effects of waves, tides and rivers, palaeotopography is intricately associated with, and may control sedimentation (e.g. Dalrymple et al., 1992; Ainsworth et al., 2011; Leeder, 2011). Thus, palaeotopographic relief may be partially responsible for whether deltaic or estuarine environments form at the seaward termination of a fluvial system. In a transgressive setting, an estuary would form at the mouth of the fluvial incised valley. Conversely, in an unconfined termination, a tide- or wave-dominated delta would likely be constructed (Catuneanu, 2006; Leeder, 2011). Within the study area, the palaeotopography of the Gething/Bluesky contact appears to suggest the presence of a funnel shaped incised valley, where areas of non-deposition flank the progressive infilling of Bluesky Formation sediment (Fig. 2-14). This could suggest the Bluesky Formation to be estuarine in origin, and given the apparent topographic shape, tidal amplification could be predicted (Dalrymple et al., 1992; Dalrymple, 2010; Ainsworth et al., 2011; Longhitano et al., 2012). This, combined with the largely heterolithic nature of lithologies could reasonably lead to the interpretation of a tide-dominated to –influenced system, within an estuarine setting.

The data from this study appears to contradict this interpretation. The presence of a funnel-shaped, slightly incised valley is misleading, as the actual difference in topographic relief from the highest occurrence of the Gething Formation (from the Bluesky/Wilrich contact) to the lowest is approximately 10 m vertically, over a 5 km horizontal distance (slope of 0.002°). This is shown in Fig. 2-14, where even a vertical exaggeration of 25x, reveals the broadly unconfined nature of palaeotopography. The palaeotopographic relief can be combined with the observations of: 1) deltaic-style sedimentation with abundant evidence of wave-reworking, even at the lowest stratigraphic intervals; 2) the apparent brackish-water affinity of the underlying Gething Formation, with the contact representing a transgressive wave ravinement surface, and

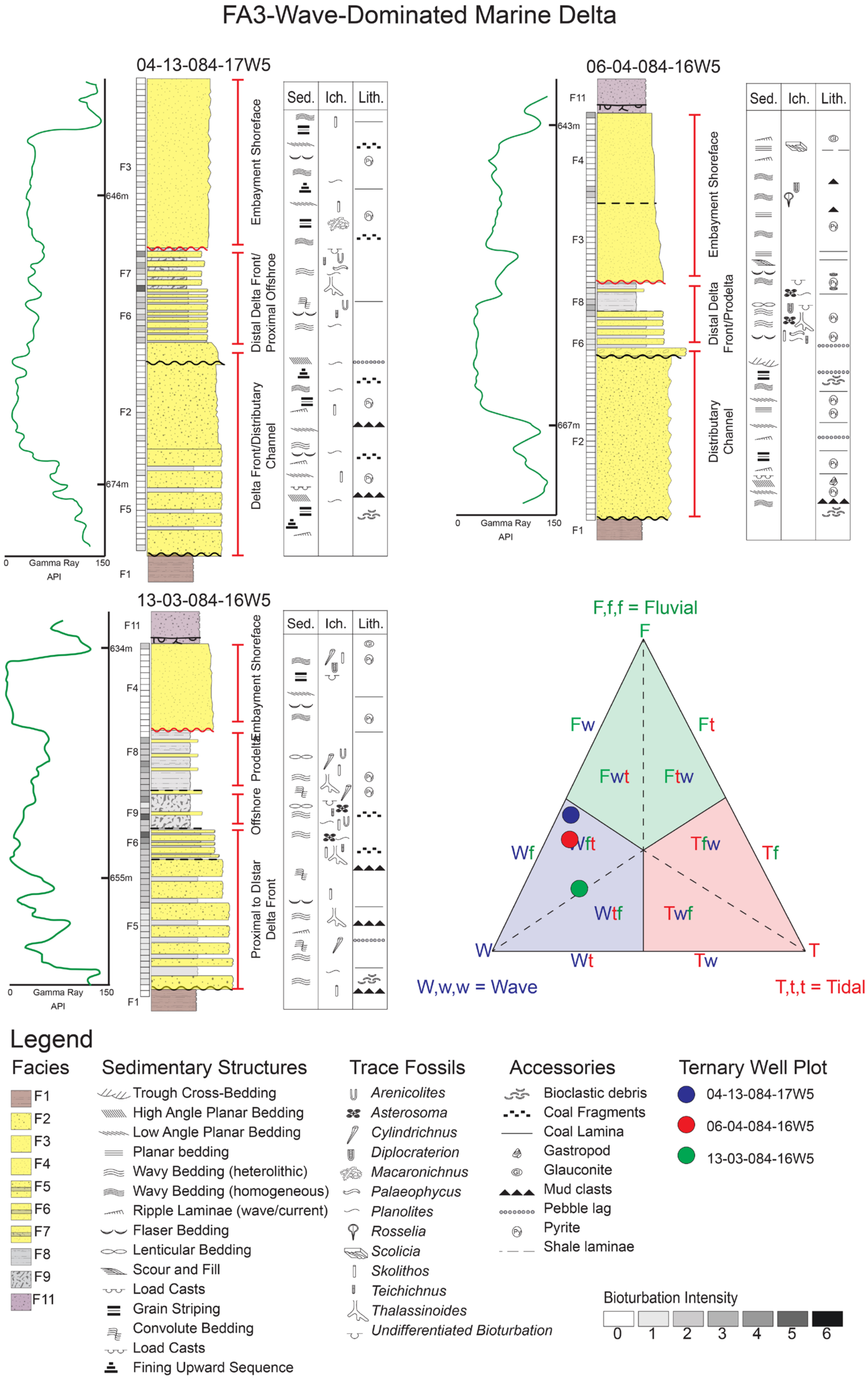


Figure 2-12. Sample core expression of FA3. The contact between marine shoreface and bay-margin/wave-dominated delta appears erosive. Location of each well on the ternary diagram was calculated by recording the dominant process for every 75 cm core sleeve and deriving the overall percentage based on the number of core boxes. Ternary diagram modified after Ainsworth et al., (2011).

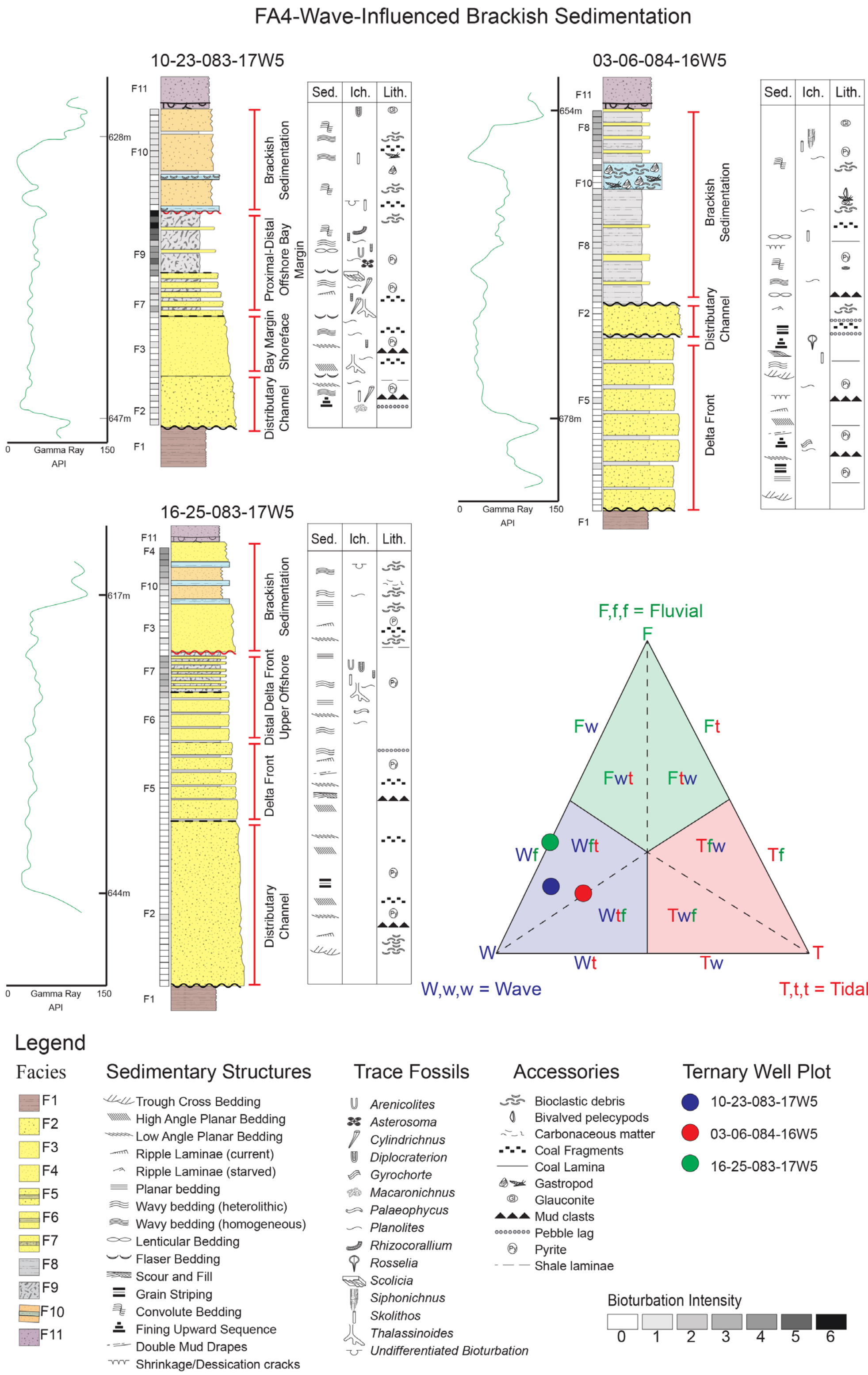


Figure 2-13. Sample core expression of FA4. The contact between FA4 and underlying units is erosive, and superimposes sediments of significantly more brackish character over significantly marine character facies. Location of each well on the ternary diagram was calculated by recording the dominant process for every 75 cm core sleeve and deriving the overall percentage based on the number of core boxes. Ternary diagram modified after Ainsworth et al., (2011).

3) the relatively marine nature of trace fossils (i.e. *Asterosoma, Macaronichnus, Rosselia, Scolicia*), even in the lowest stratigraphic intervals. Given this, it appears that initial Bluesky sedimentation took place in near marine, wave-influenced conditions and that the lack of sedimentation in surrounding areas may represents erosion by marine processes (i.e. waves). As discussed above in the interpretation of FA1, this suggests the contact between Gething and Bluesky formations represents a transgressive surface of erosion. In this interpretation, the Gething Formation, at least within the confines of the project area need not represent interfluve conditions, and the system as a whole shows a back-stepping architecture.

SIGNIFICANCE WITH RESPECT TO RELATED STUDIES

Of the previous studies conducted on the Bluesky Formation, those of Hubbard et al., (1999; 2002; 2004), Caplan et al., (2007), and Mackay and Dalrymple (2011) can be most closely compared to this work, due to their proximal geographical locations. This section discusses the key differences between these studies and provides rationale for differing interpretations. It is worth noting that there is little overlap in study areas between this and previous work. The differences discussed below are not intended to challenge these studies, but instead, contribute to the broad-scale knowledge of depositional architecture and affinity characterizing the Bluesky Formation.

Sedimentologically, the dataset of this study is characterized by wave-influenced to wave-dominated sedimentation, with secodary fluvial and tertiary tidal influence (e.g. low-angle planar to parallel bedding, HCS, QPL, oscillation ripples, trough cross-bedding, double mud drapes). Studies immediately north of this project area indicate greater tidal influence (Caplan et al., 2007; Mackay and Dalrymple, 2011). Importantly, this study also contains tidal indicators (e.g. double mud drapes, apparent rhythmicity). Hubbard et al., (1999; 2004) recognized a mappable tripartite wave-dominated estuary, that to the west (where they indicate greater wave-influence), bears similarities to the wave-reworked strata presented herein. Thus, we see the present study area as an along-shore unit that lacks an estuary and may have, in the past sourced the sediment that formed the bar of the estuary of Hubbard et al., (1999; 2004).

From an ichnological perspective, certain facies within this study (e.g. F7b, F9) display higher diversity and increased abundance of ichnogenera associated with nearly marine salinities (e.g. common *Asterosoma*, large *Rosselia*, and subordinate *Rhizocorallium, Scolicia, Zoophycos*). Additionally, *Macaronichnus* is relatively common within this dataset, even at the lowest stratigraphic horizons. This again provides evidence of wave-influenced sedimentation (*Macaronichnus* are only reported from wave-influenced zones in both modern and ancient datasets) and a reasonably open connection to the boreal sea. Notably, Hubbard et al., (1999; 2004) also recognized a more marine-influenced trace fossil assemblage to the west, albeit lacking many of the marine-associated ichnofauna reported herein.

In addition to these sedimentological and ichnological differences, the stratigraphic relationships and nomenclature differs between studies. Stratigraphy within this paper has been divided into four distinct intervals. These are, from oldest to youngest: 1) undifferentiated Gething/Ostracode Zone facies characterized by brackish-water sedimentation; 2) lower Bluesky Formation, consisting of sandstone, heterolithic, and mudstone deposits of coeval wave-influenced deltaic, embayment, and marine deltaic sedimentation; 3) upper Bluesky Formation, consisting of brackish-water sedimentation; and 4) marine shales of the Wilrich Member representing complete transgression. Mackay and Dalrymple (2011) do not discuss stratigraphy in detail, but do identify a stratigraphic relationship from Gething Formation, to Bluesky Formation, to Wilrich Member marine shales. Caplan et al., (2007) recognize the same stratigraphic relationships as

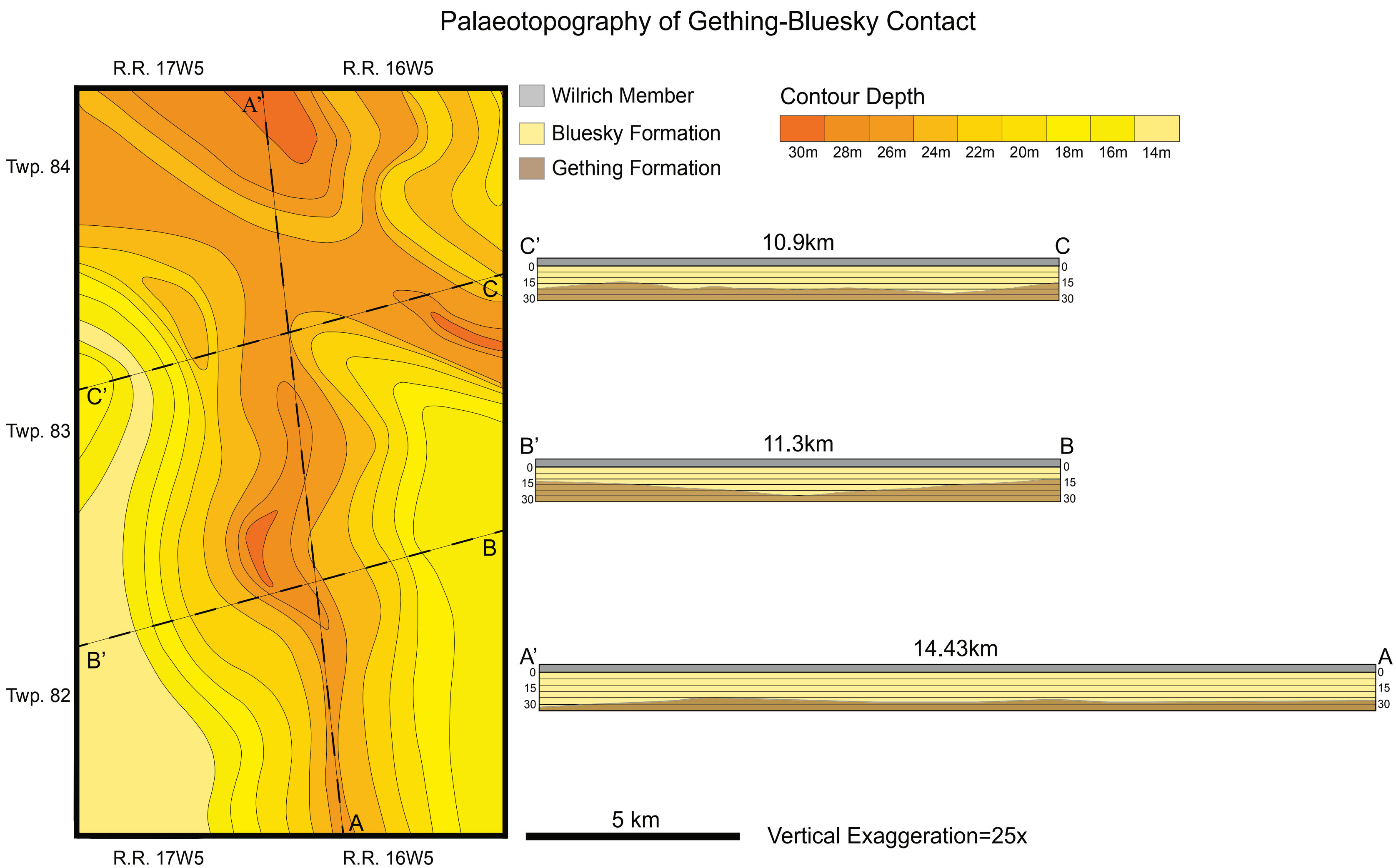


Figure 2-14. Palaeotopographic map of the Gething-Bluesky contact. Cross-sections A-A', B-B', and C-C' show the relatively unconfined, low-relief nature of this surface. This surface is interpreted as a transgressive surface of erosion (WRS) with wave-dominated deltaic deposits overlying estuarine deposits of the Gething Formation. Surface was plotted using all core and well-log data available within the project limits.

those documented herein, including from oldest to youngest: Gething Formation, lower Bluesky Formation, upper Bluesky Formation, and Wilrich Member. Hubbard et al., (1999) identified a three stage stratigraphy. These are from oldest to youngest: Ostracode Zone, Bluesky Formation, and Wilrich Member. We interpret high-energy sandstone deposits overlying the Gething Formation to belong to the lower Bluesky Formation. This interpretation is based upon the erosive nature of this contact, the marked change in sedimentary character (increased grain-size, high-energy sedimentary structures), ichnological differences (increase in near-marine and high-energy forms), and the predominance of gradational facies transitions present.

PALAEOENVIRONMENTAL EVOLUTION

Given the observed facies associations, stratigraphic relationships, and contact types, a three-stage evolution from base to top is proposed for the Bluesky Formation within the confines of the project area. Deltaic sedimentation related to FA1 and bay-margin shoreface elements of FA2 were deposited in a wave-dominated, locally fluvially-influenced marine embayment setting. An embayment setting is inferred due to: 1) dominant physical processes (e.g. wave-reworking, storm influence), suggesting a setting open to these forces; 2) the ichnological signature (e.g. common *Macaronichnus, Scolicia,* and *Asterosoma*) which indicate near marine salinity, but diminution of these traces with respect to FA3 suggest the conditions do not represent a completely open marine setting. The contact between FA1 and the underlying Gething Formation is interpreted as a transgressive surface of erosion (WRS), where deltaic and embayment facies are superimposed upon brackish-water facies. Wells within the southern project area (16 m slice map, Fig 2-9, 2-10a) show evidence of progradation in a roughly north-northwest direction. This relationship is also illustrated in Figure 2-15. Sedimentation within this initial stage of overall transgression represents distributary channel, delta front and bay-margin shoreface environments. As relative sea-level rose, distal deltaic and intertidal flat sediments of F6 and F7a, and prodeltaic mudstone of F8 begin to inundate the region from the northwest. Coupled with this trend is an increase in appearance of embayment shoreface through bioturbated upper-offshore deposits of FA2. This relationship is shown in the 12 m facies slice map of Figure 2-10b, and the SW-NE cross-section in Figure 2-15. As transgression continues, bioturbated distal bay margin deposits of FA2 and prodeltaic facies of FA1 dominate the central, western, and northeastern portions of the area (Fig. 2-10c, Fig. 2-15). This same slice shows the continued southeastward migration of more marine deltaic sandstone of FA3. This is interpreted to represent the encroachment of more open-marine deltaic conditions into the embayment, as evidenced by the increasingly marine ichnological signature. The uppermost slice map (Fig. 2-10d, Fig. 2-15) shows complete transgression of distal bay deposits over the southern study area and a continued southeast migration of FA3 sandstone. Present in the uppermost slice (Fig. 2-10D, Fig. 2-15) in the west-central project area are the facies comprising FA4. The sharp basal contact of FA4 with underlying facies, and the juxtaposition of brackish-water over a marine ichnological assemblage suggests a late-stage change in relative sea level is preserved in this area (MacEachern et al., 2012) . It is unknown as to the true areal extent of FA4, as erosional truncation of all facies associations occurs with maximum transgression of the Wilrich Member over the area.

This evolution, although transgressive in overall character, is not without local autocyclic variation. These autocyclic changes are most visible within the heterolithic facies of FA1 and FA2. Several examples exist wherein upper-offshore embayment facies of F7b transition into lower-offshore embayment facies of F9, with subsequent transition back into F7b. This relationship may indicate local fluctuations in the proximity of these deposits to the shoreline, which may be attributed to local sea-level fluctuations or proximity to

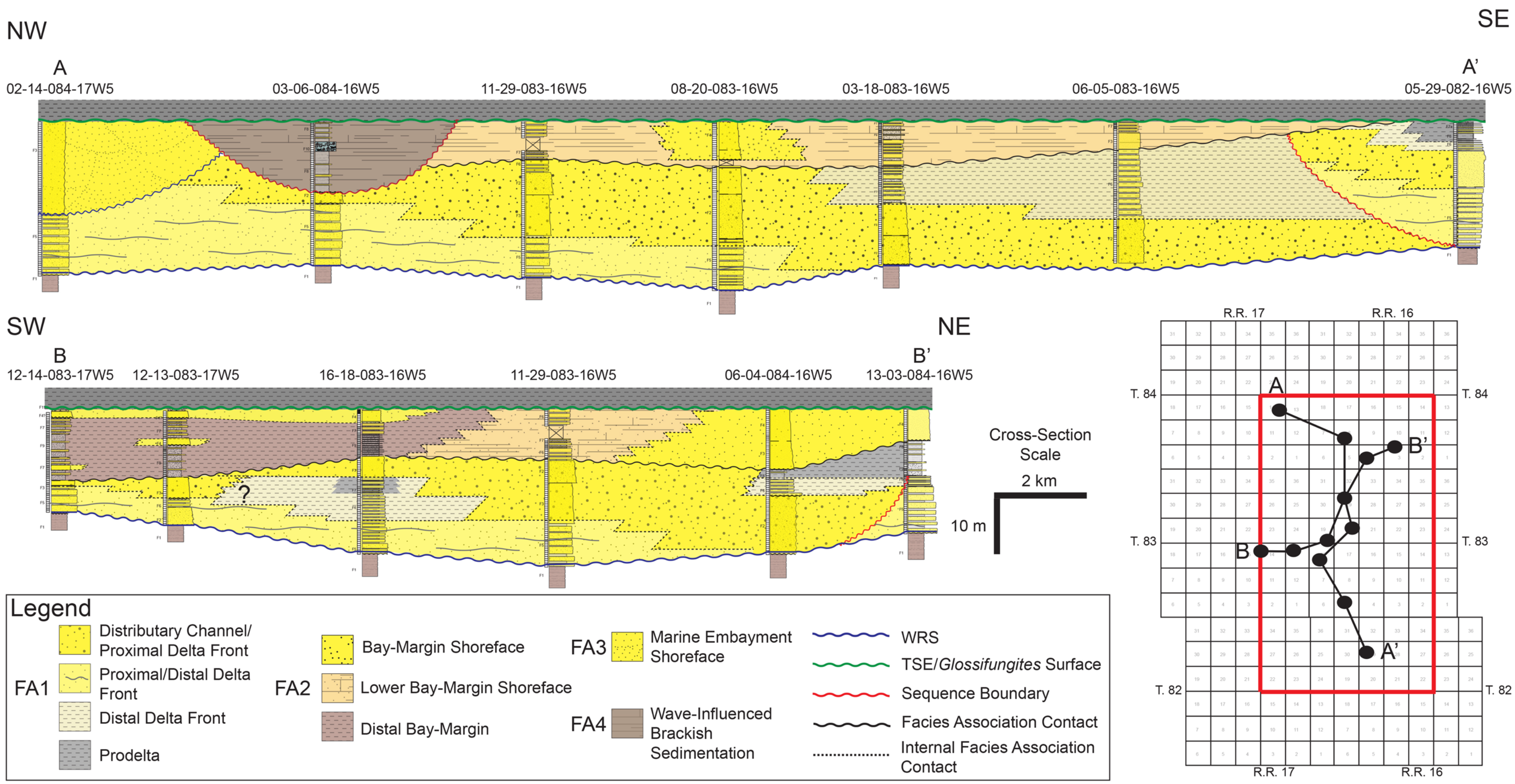


Figure 2-15. Cross-section illustrating the distribution of depositional elements comprising the Bluesky Formation. Note the progradational nature of FA1 (deltaic deposits) and the transgressional nature of FA2 and FA3 (bay-margin and marined embayment deposits). The contact between FA4 and underlying sediments represents a sequence boundary.

active delta lobes. Additionally, within FA1 the apparent migration of channels can be interpreted. Here, delta front deposits of F5 may overly distributary channel deposits of F2, which are in turn overlain erosively by a second distributary channel expression. Botterill et al., (this volume) performed a high-resolution process ichnological analysis of core within Range 16W5 and Township 83 with results mirroring the same overall transgressive nature with local autocyclic variations in sedimentation.

CONCLUSIONS

Through detailed sedimentological, ichnological, and lithological analysis a three-stage evolution of the Bluesky Formation within the project area is proposed. These stages represent deposition within a wave-dominated, fluvially-influenced, and locally tidally-influenced embayment, marine embayment, and brackish-water setting, respectively. These interpretations are based on several criteria. A wave-dominated, fluvially- and locally tidally influenced deltaic and embayment setting is inferred based upon:

1) High-energy sedimentation with primary wave and storm generated structures (i.e. HCS, low-angle planar bedding, QPL, parallel and non-parallel wavy bedding, planar parallel lamination), secondary fluvially- and tertiary tidal-generated structures (i.e. grain-size striping, terrestrial input, trough cross-bedding, double mud drapes).
2) An apparent scarcity of definitive tidal influence (i.e. rhythmic bedding, bi-modal current direction), as heterolithic bedding is not strictly confined to tide-dominated settings (e.g. Reineck and Singh, 1973; Dalrymple, 2010)
3) Ichnological characteristics consistent with deltaic conditions in a high-energy, near marine settings (i.e. *Macaronichnus* assemblages), sporadic distribution and low density of traces.
4) Ichnological character of embayment shoreface through distal bay-margin sediments. These closely resemble the characteristics of normal marine shoreface settings, reflecting persistent access to marine salinity (e.g. Pemberton et al., 2001; MacEachern and Gingras, 2007; Buatois and Mángano, 2011; Tonkin, 2012). Traces significant to this interpretation include abundant, robust *Asterosoma*, with *Phycosiphon, Rhizocorallium, Scolicia, Zoophycos*, and Chondrites.
5) The open marine deltaic character of FA3, which is dominated by planar parallel bedding, low-angle planar bedding, parallel to non-parallel wavy bedding, and HCS, and contains robust ichnogenera characteristic of marine conditions (i.e. *Scolicia, Macaronichnus, Rosselia*).
6) The presence of a transgressive surface of erosion (WRS) demarcating the contact between the underlying, brackish-water Gething and overlying Bluesky Formation.

A late-stage, relative sea-level change representing deposition of FA4 is based upon:

1) Low-energy, mudstone to muddy siltstone and silty sandstone deposits sharply overlying sandstone, heterolithic assemblages and mudstone of FA1 and FA2.
2) Distinct and sharp contrast of ichnological assemblages of FA4 and FA2, wherein archetypal brackish-water assemblages directly overly a marine *Cruziana* ichnofacies assemblage.
3) Low deposition rates as indicated by intense bioturbation of sediments (BI 4-6), and low to monospecific ichnological assemblages.

Finally,

1. Inundation of the entire area by transgression of the marine Wilrich Member. This surface is characterized by a regionally extensive, *Glossifungites* surface interpreted to represent a transgressive surface of erosion.

The ichnological character of the dataset plays a crucial role in the above-discussed interpretations. Ichnological characteristics such as trace distribution, overall size, ethology, and specific ichnogenera have shown predictable and reliable relationships to physico-chemical stresses in modern settings. Application of these characteristics to the dataset allowed for the identification of stresses such as salinity fluctuation, substrate migration, water turbidity, rapid sedimentation, and storm deposition. These, when combined with physical sedimentation and lithology have allowed for the identification of previously un-recognized wave-dominated deltaic and embayment sedimentation within the Bluesky Formation. These characteristics may, in turn, aid in the identification of similar depositional systems elsewhere within the rock record.

CHAPTER 3: PROCESS ICHNOLOGICAL ANALYSIS OF THE LOWER CRETACEOUS BLUESKY FORMATION, ALBERTA

INTRODUCTION

Integration of ichnology with physical sedimentology has proven to be a valuable tool in the refined identification of facies and interpretation of paleo-depositional affinities (e.g. Ranger and Pemberton, 1991; Pemberton, 1992; MacEachern and Pemberton, 1994; Hubbard et al., 1999, 2004; McIlroy, 2004; Caplan et al., 2007; Mackay and Dalrymple, 2011; Knaust and Bromley, 2012). More specifically, ichnology has proven effective in the identification of physico-chemical stresses affecting trace making organisms within sedimentary environments at the time of deposition (e.g. Seilacher, 1978; Beynon et al., 1988; Savrda and Bottjer, 1989; Hubbard et al., 2004; Bann et al., 2004; Martin, 2004; MacEachern, 2005a).

Common physico-chemical stresses in marginal marine settings include: rapid deposition rates, fluctuating to persistent salinity reduction, event bed cyclicity, water turbidity, fluid muds, and reduced oxygenation of bottom and/or interstitial water (MacEachern et al., 2005b). Trace fossil suites that record these physico-chemical stresses show departures from archetypal ichnofacies associations (MacEachern et al., 2005b). For instance, rapid sedimentation rates have been shown to result in decreased bioturbation intensity and a dominance of mobile or deposit feeding, and suspension feeding structures (e.g. Howard, 1975; Leithold, 1993; Leithold and Dean, 1998). Fluctuating or persistently brackish conditions lead to reduced ethological diversities, an impoverished marine assemblage, size reduction, preponderance of infaunal over epifaunal organisms, dominance of trophic generalists, occasionally large biomass, and predominantly r-selected population dynamics (e.g. Milne, 1940; Slobodkin and Sanders, 1969; Grassle and Grassle, 1974; Barnes, 1989; Pemberton and Wightman, 1992, Gingras et al., 2012). Event beds typically record partial to complete extermination of the pre-event ichnological suite, colonization of the event bed by opportunistic organisms and a subsequent return to representative fair weather suites (Pemberton and MacEachern, 1997; MacEachern, 2005b). Heightened water turbidities result in reduced abundance, diversity and limitation of ethological behavior to locomotion, deposit feeding, resting and grazing behaviors (MacEachern, 2005b). Fluctuations in bottom water and pore water oxygen levels lead to an overall decrease in size, diversity, abundance and tier depth of the ichnological assemblage (e.g. Bromley and Ekdale, 1984; Ekdale and Mason, 1988; Savrda and Bottjer, 1989; Martin, 2004; Savrda, 2007).

The concept of process ichnology utilizes trace fossils as biogenic sedimentary structures and provides a framework in which physico-chemical stresses can be identified in both modern and ancient environments (Gingras et al., 2011). This framework relies on careful observations of: 1) the distribution of trace fossils; 2) the diversity and range of ethological characteristics; 3) presence or absence of trace linings; 4) the presence or absence of specific ichnogenera; 5) the size of trace fossils; and 6) degree of deformation of traces (Gingras et al., 2011). Bioturbation intensity and Size Diversity Index can be combined to the process ichnological methodology for more refined interpretations. Individually, no single above listed characteristic is diagnostic, but when combined with sedimentological observations and compared to archetypal ichnofacies associations, reliable recognition of physico-chemical stresses become possible (MacEachern et al., 2005b).

This study focuses on applying the process ichnological model to a core dataset from the late Aptian-early Albian Bluesky Formation, Alberta (Fig. 3-1). Within the study area, the Bluesky Formation is bounded between the underlying Gething Formation and the overlying Wilrich Member of the Spirit River

Formation (Fig. 3-2). The Bluesky Formation consists of marginal marine to marine siliciclastic sediments deposited during overall transgression of the Boreal sea. Stratigraphic correlation based solely on lithostratigraphy proves extremely difficult, owing to the lateral and vertical complexity of lithologies. This has led workers to recognize various depositional affinities for the Bluesky Formation, including incised valley fill (Alway, 1995; Terzuoli and Walker, 1997), wave-dominated estuary (Hubbard et al., 1999, 2002), shoreface and strandplain (Moslow and Pemberton, 1988; Ranger and Pemberton, 1991; Male, 1992; Gordon et al., 2010), and tide-dominated deltaic and estuarine settings (Mackay and Dalrymple, 2005; Caplan et al., 2007; Mackay and Dalrymple, 2011). In order to refine the paleoenvironmental conditions present within the study area, this work aims to: 1) identify physico-chemical stresses affecting Bluesky Formation deposition utilizing the process ichnologic framework; 2) combine these observations with sedimentologic data in the construction of facies associations and physico-chemical implications; and 3) identify ichnological and sedimentological patterns that can be used to identify similar environments in the rock record.

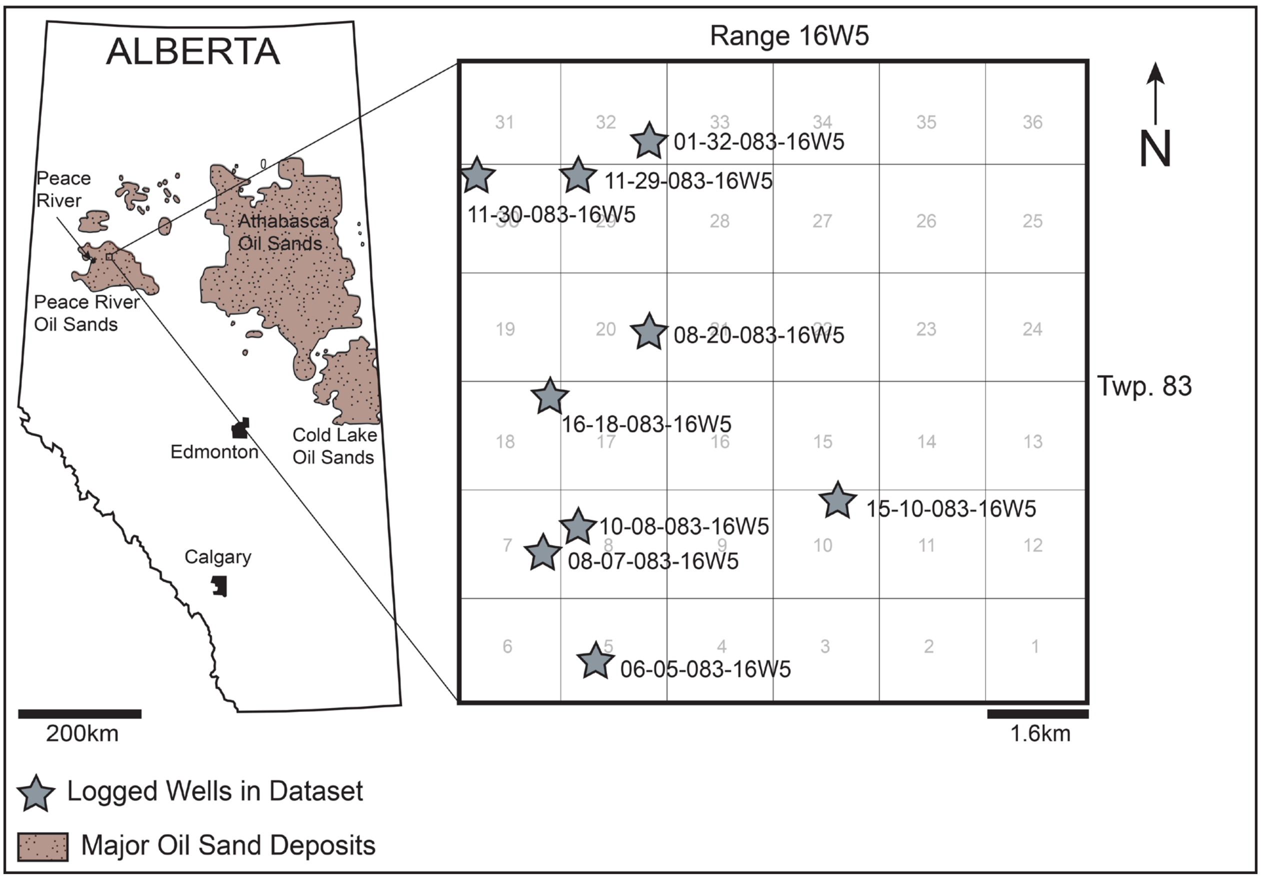


Figure 3-1 . Location map showing wells logged within the study and their relation to major oil sands deposits in Alberta.

PREVIOUS WORK

The most complete ichnological analysis of the Bluesky Formation is that of Hubbard et al., (1999; 2004). In this analysis, integration of sedimentological and ichnological characteristics helped identify the upper, middle and lower portions of a fossil wave-dominated estuary. Included in this analysis were the

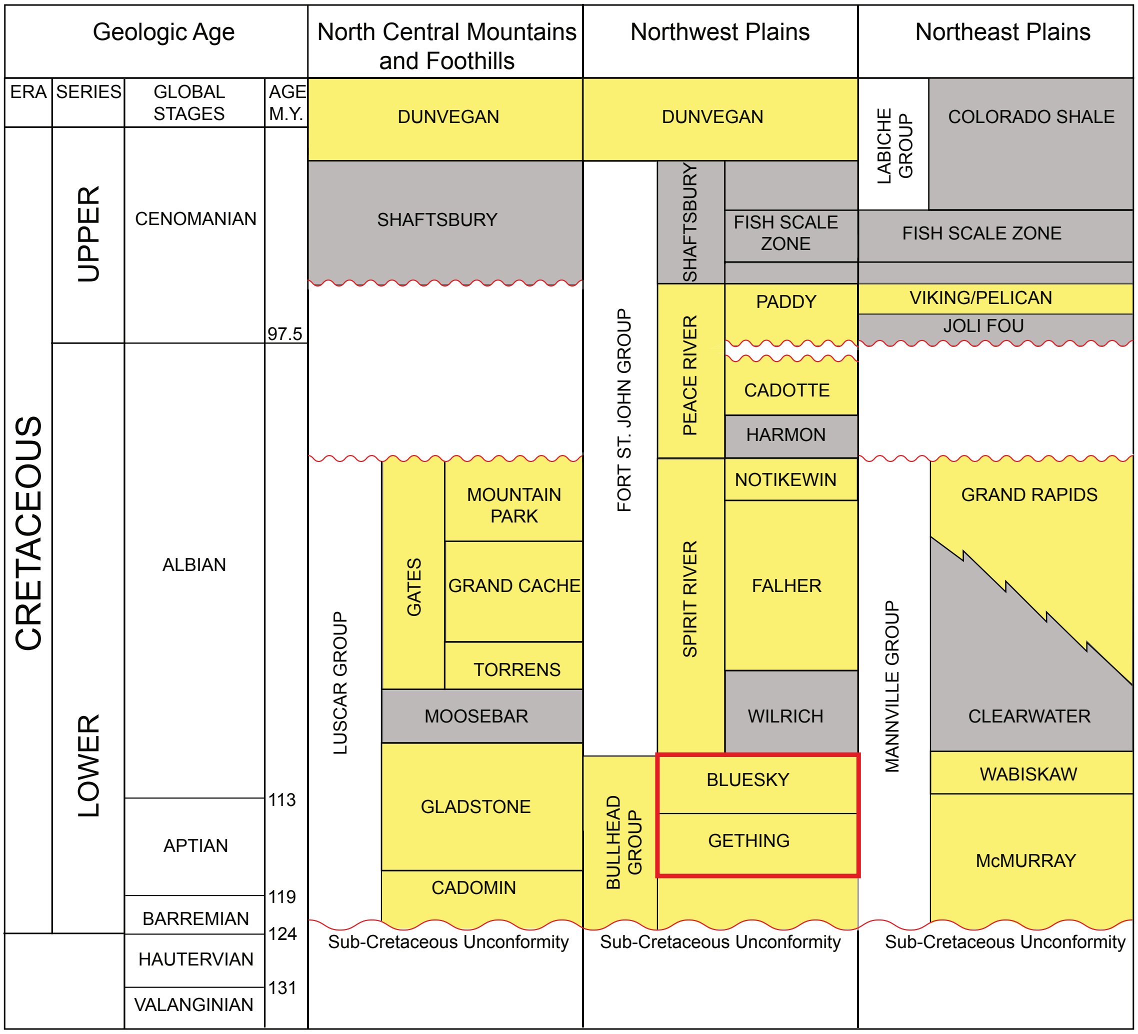


Figure 3-2. Chart showing the stratigraphic relationship of the Bluesky Formation within the lower Cretaceous, and age equivalent formations across Alberta. Modified after Core Laboratories Stratigraphic Correlation Chart, Calgary.

identification of several estuarine sub-environments (e.g. bayhead delta, tidal flat, quiescent bay, flood tidal delta, etc.). Using ichnological characteristics, the authors mapped longitudinal salinity gradients within bay facies, and from bayhead delta through to flood- and ebb-tide deltaic deposits. As will be shown below, certain facies between that study and our paper do exist: in these instances the broad observations of Hubbard et al., (2004) support the observations presented herein. It is not possible, however, to directly incorporate their findings as trace diameter, SDI, bioturbation intensity, and ichnodiversity were not recorded at a systematic level. In a stratigraphic context, Hubbard et al., (1999) separate the sediments described herein to lower Ostracode Zone (brackish bay) and upper Bluesky (bayhead delta, central bay). It is not the intention of this paper to contradict this division, but given the sedimentological, ichnological, and geophysical characteristics of this particular dataset, discussed below, a separation into lower and upper Bluesky is preferable. A comprehensize discussion of the stratigraphy of the project area is given in Botterill et al., (this volume). Figure 3-3 illustrates this stratigraphy and shows the gamma-ray signature of each surface. We emphasize that this dataset contains only one core from Hubbard et al., (1999; 2004) earlier work and that stratigraphic continuity between the two locales has not been attempted.

DATABASE AND METHODOLOGY

Data collected for this study is comprised of nine wells containing Bluesky Formation core within Twp. 83 and R.R. 16W5 east of the northern Alberta town of Peace River (Fig. 3-1). Here, the Bluesky Formation hosts the Peace River heavy oil sands at subsurface depths between 621 m and 684 m TVD (true vertical depth). Maximum thickness of the Bluesky Formation within the dataset is 29 m.

Each core was logged at the individual box scale (1.5 m core length) using AppleCore© logging soft-

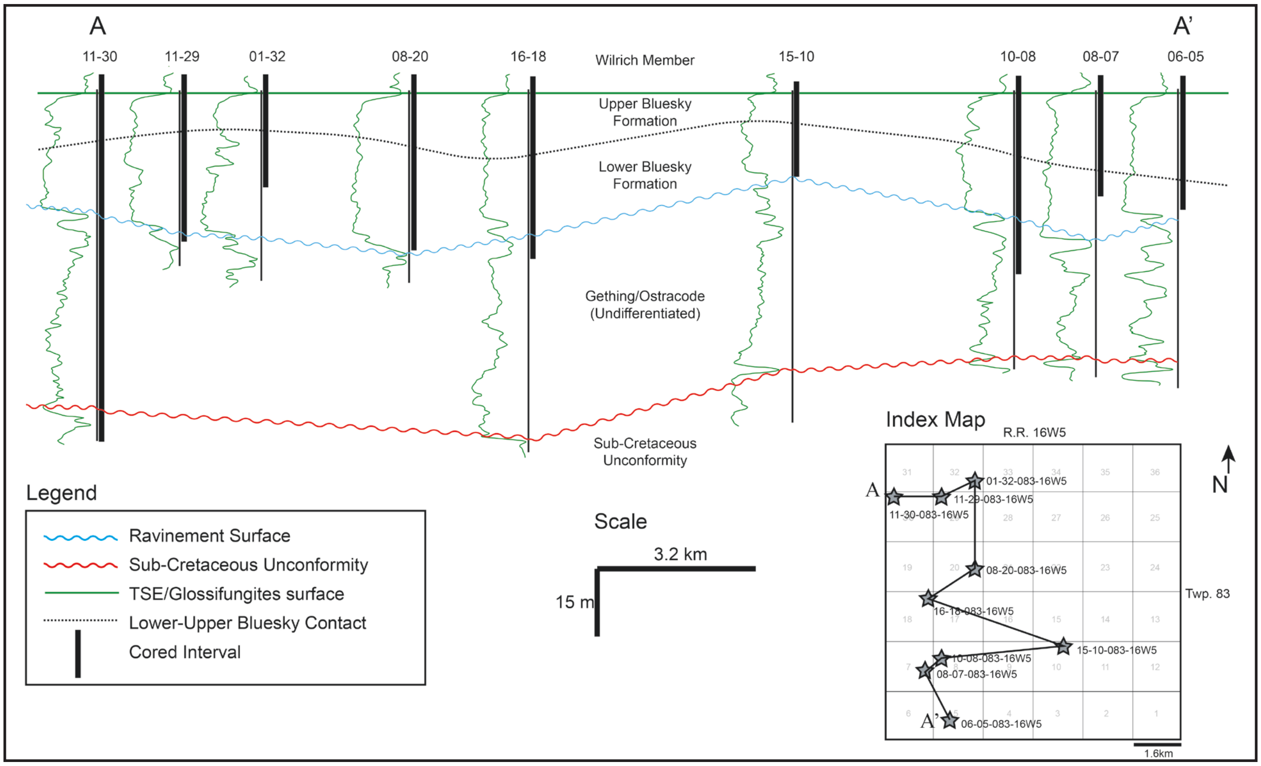


Figure 3-3. Gamma ray cross-section through the study area showing the sharp nature of the contact between the Gething and Bluesky formations.

ware. Detailed documentation of data included: lithology, nature and occurrence of contacts, sedimentary structures, lithologic accessories, body fossils, ichnogenera, bioturbation intensity, average grain size, and bitumen saturation. This data was used to create striplogs at the 1:50 scale. Figure 3-4 illustrates the detail at which these various core properties were collected. Bioturbation intensity (BI) was averaged at 20 cm intervals for each core following Taylor and Goldring (1993). This is a semi-quantitative method for assessing bioturbation intensity on a 0-6 scale, where 0 represents un-burrowed media and 6 represents complete homogenization of sediment. Although semi-quantitative data may pose problems for subsequent statistical analyses, we chose this method of assessing BI because it is widely accepted, and for this study BI is only used comparatively. Maximum burrow diameter (smallest axis in deformed burrows) was recorded for every 75 cm core length. This data was then graphed vs. depth from the top of the Bluesky Formation (representing 0 m) to show the vertical distribution of maximum burrow size (Fig. 3-5). Size Diversity Index (SDI) was calculated for each of the same 75 cm core intervals as maximum burrow diameter (Fig. 3-6). SDI is a

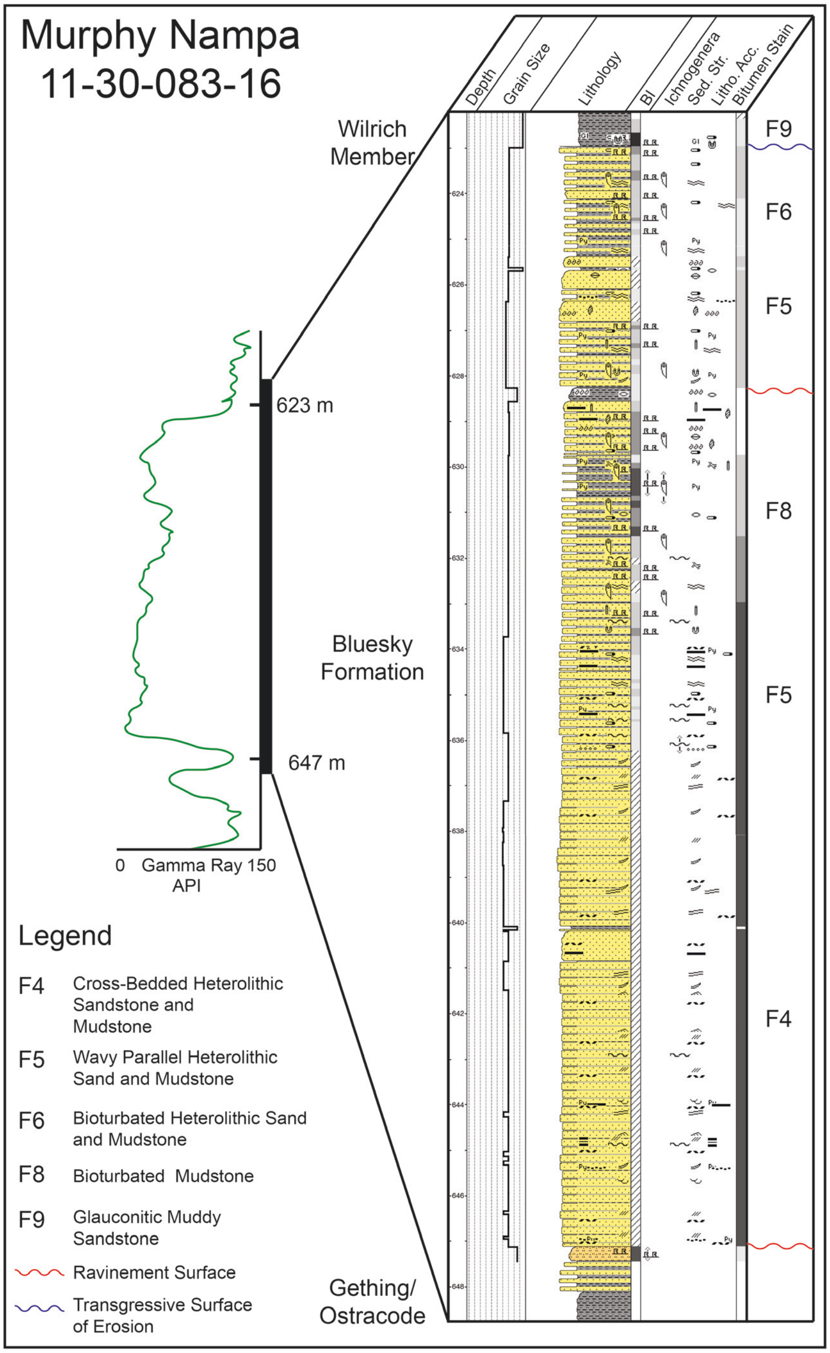


Figure 3-4. AppleCore© log for well 11-30-083-16W5 showing the detail at which lithology, sedimentary structures, ichnological characteristics, lithological accessories, grainsize, and bitumen saturation were recorded.

statistical value obtained by multiplying maximum burrow diameter by the diversity of observed macroscopic fauna (SDI=Maximum Burrow Diameter x Ichnologic diversity). Ichnological diversity to the genus level was determined (Fig. 3-7) and a subsequent ethological classification of filter/suspension feeder, deposit feeder and active carnivore was assigned to each ichnogenus. Additional ichnological information recorded consists of relative burrow deformation, and distribution of traces as either sporadic heterogeneous, regular heterogeneous or homogeneous (Fig. 3-8).

PROCESS ICHNOLOGICAL ANALYSIS OF FACIES

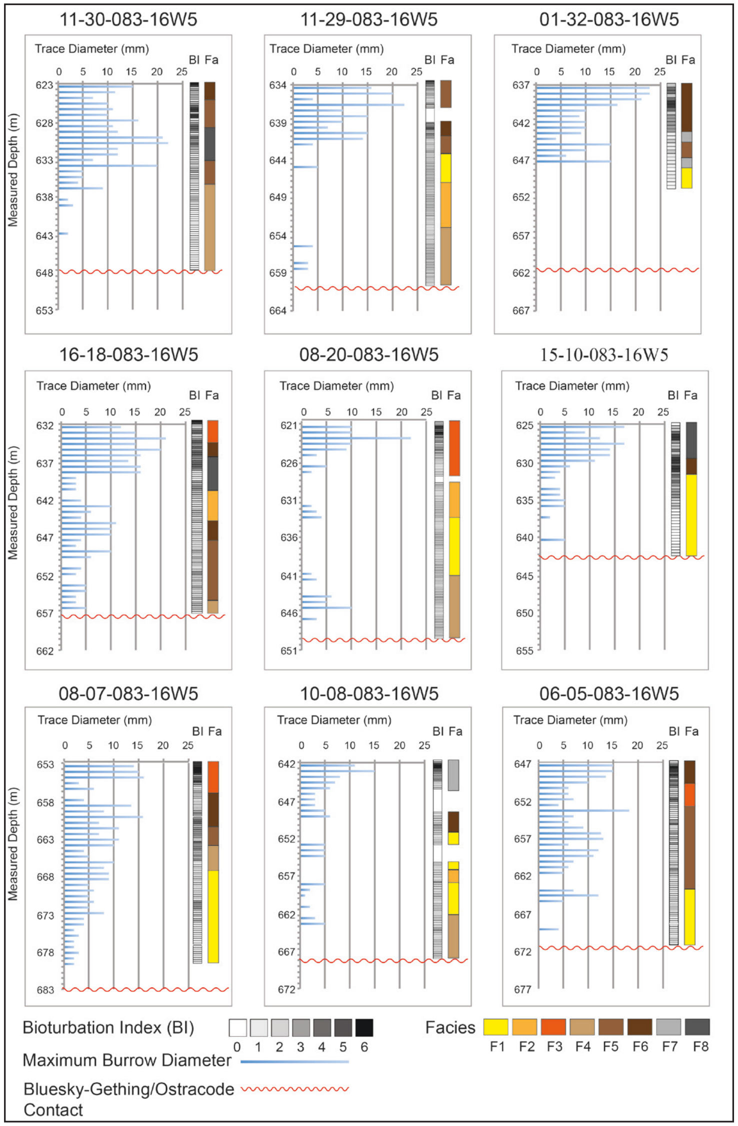


Figure 3-5. Graphical representation of maximum burrow diameter taken at 75 cm intervals from base to top of Bluesky core, with the Bluesky-Wilrich contact used as a datum. Note the overall increase in burrow diameter at progressively higher stratigraphic intervals.

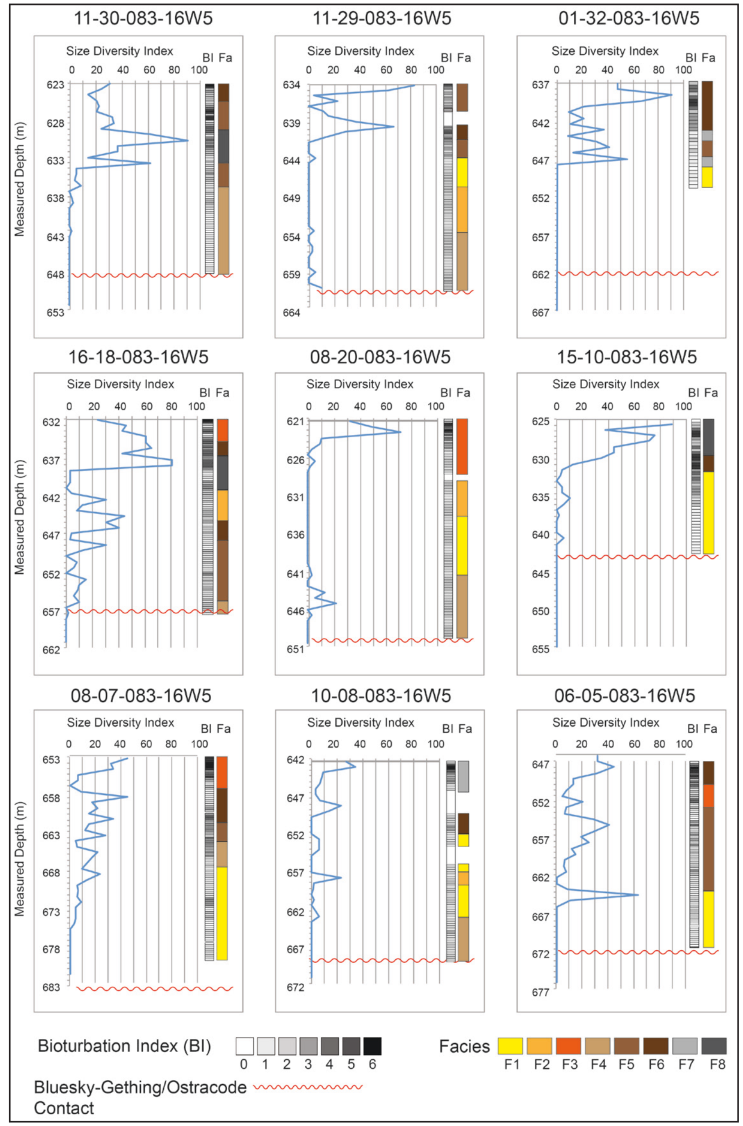


Figure 3-6. Graphical representation of Size Diversity Index (SDI) at identical intervals as those shown in figure 3-5. SDI is calculated by multiplying maximum burrow diameter by the total number of ichno-genera observed within a given interval.

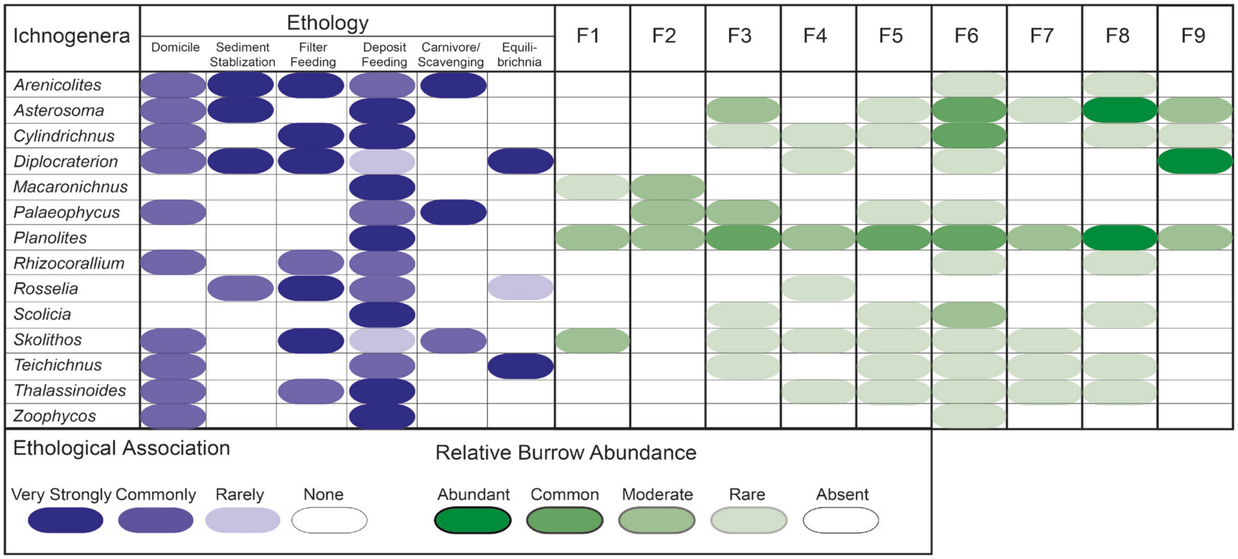


Figure 3-7. Distribution, facies abundance, and range of ethologies of ichnogenera identified in core. Modified after Davidson and MacEachern (2007), and MacEachern et al., (2010).

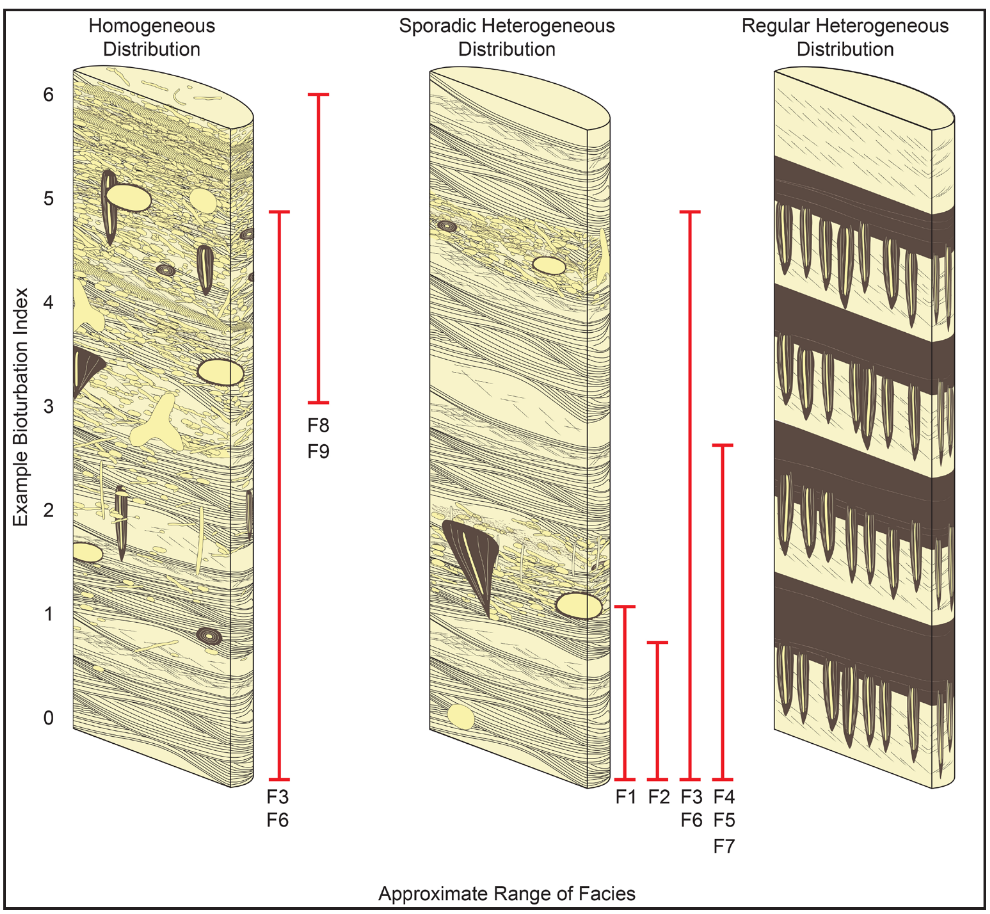


Figure 3-8. Schematic of bioturbation distribution types and the approximate range of occurrence in individual facies. Modified after Gingras et al., (2011).

Based upon the combination of lithology, sedimentary structures, and ichnology, nine facies are designated within the dataset. Table 3-1 provides a summary of the properties for each facies. Sandstone dominated facies (F1-F3, Fig. 3-9) were separated based upon primary physical structures and grain size. Heterolithic sandstone and mudstone facies (F4-F6, Fig. 3-10) were separated based upon primary physical structures, grain size, bioturbation intensity, and ichnological diversity. Mudstone and sandy mudstone facies (F7-F9, Fig. 3-11) were separated based upon bioturbation intensity, ethology and ichnological diversity. As the focus of this paper is to describe the detailed ichnological character of these facies, only brief descriptions of sedimentology will be given below. Detailed sedimentological analysis of these facies are provided in Botterill et al., (this volume).

FACIES DESCRIPTIONS

FACIES 1: HIGH-ANGLE PLANAR BEDDED SANDSTONE

Description:

Facies F1 (Fig. 3-9) consists of medium to fine-grained, high- to low-angle planar bedded sandstone, with rare parallel wavy bedding (*sensu* Reineck and Singh, 1973) with less than 10% mud content. Bioturbation is sporadically heterogeneous, and has low bioturbation intensity (BI 0-2). Trace-fossil diversity is low, consisting of primarily *Planolites* with rare occurrences of *Skolithos* and *Macaronichnus.* Burrows are largely confined to thin mudstone beds or flaser bedding, with the exception of *Macaronichnus*, which occurs as mantled traces within clean sand intervals. Traces are unlined, with the exception of mantled *Macaronichnus,* show slight deformation in the vertical direction, and have a maximum burrow diameter of 12 mm. A poorly developed trend of upward increasing BI and ichnological diversity is locally observed, particularly where F1 grades into F5. This occurs on the dm scale, and is predominantly gradual, as F1 is often gradational into F5.

Interpretation:

Facies F1 is interpreted to record deposition in an environment with persistently shifting substrates and sporadically high current energies (e.g. distributary channel, delta front). Sedimentological evidence consists of predominantly fine- to medium-grained sand, high-angle planar bedding style, and numerous scoured contacts with underlying units. The presence of *Macaronichnus,* which has been shown to form under high-energy conditions (Clifton and Thompson, 1978; Saunders, 1989; Saunders et al., 1994; Pemberton et al., 2012), also supports such an interpretation. Other ichnological data, including diminution of burrow diameter, low BI and low ichnological diversity, indicate that fluctuating or persistently low salinity levels accompanied the energetic sedimentary conditions.

FACIES 2: LOW-ANGLE PLANAR BEDDED SANDSTONE

Description:

Facies F2 (Fig. 3-9) consists of fine- to very fine-grained, low-angle planar, parallel to non-parallel wavybedded, and hummocky cross-stratified sandstone with less than 10% mud. Bioturbation is sporadically heterogeneous, and has low bioturbation intensity (BI 0-1). Ichno-diversity is low and consists of *Planolites* with rare *Macaronichnus* and *Palaeophycus.* Burrows are confined to mudstone beds, with the exception of *Macaronichnus* and *Palaeophycus,* which occur in clean sands. Traces show slight deformation in the vertical direction and have a maximum burrow diameter of 10 mm. A slight increasing upward trend

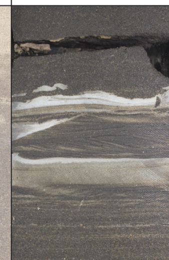
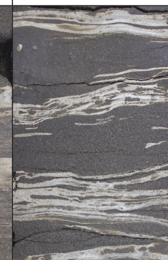
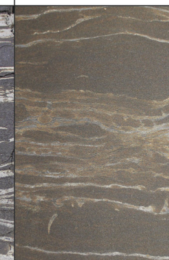
Facies	F1	F2	F3	F4	F5	F6	F7	F8	F9
Core Expression									
Lithologic Description	Cross-Bedded Medium-Fine Sandstone	Fine-Very Fine Sandstone	Very Fine-Silty Sandstone	Cross-Bedded Medium-Fine Heterolithic Sandstone and Mudstone	Wavy Parallel Fine-Very Fine Heterolithic Sand and Mudstone	Bioturbated Heterolithic Sand and Mudstone	Laminated Mudstone	Bioturbated Mudstone	Glauconitic Muddy Sandstone
Ichnological Assemblage	*Pl, Sk, Ma*	*Pl, Pa, Ma*	*Pl, Pa, Cy, Te, As, Sc fugichnia*	*Pl, Di, Cy, Sk, Th, Ro*	*Pl, As, Sk, Cy, Te, Ar, Th, Pa, Sc*	*Pl, Ar, As, Sk, Sc, Th, Pa, Rz, ?Zo*	*Sk, Pl, As, Te, Th, Zo, fugichnia*	*As, Pl, Th, Te, Cy, Ar, Sc, Rz*	*Di, Sk, As, Th, Pl, Cy*
Bioturbation Index	0-2	0-1	0-5	0-3	0-3	0-5	0-3	3-6	3-6
Max Burrow Diameter	12 mm	10 mm	22 mm	10 mm	22 mm	22 mm	15 mm	24 mm	15 mm
Primary Physical Structures	HAP, LAP, X-Strat, graded bedding, SSrf	LAP, WP, SSD, OR, SSrf, CR, con bdd, rare X-Strat, rare mud flasers, HCS	CR, OR, rare mud flasers, rare HAP, grain striping	HAP, LAP, OR, CR, SSD, SSrf, Con bdd, grain striping, ?HCS, LC	LAP, WP, SSD, LC, Con bdd	WP, Bio. bd, con. bdd, SSD.	WP laminae, SSD, OR, LC, SSrf, lenticular bedding, ?Tempestites.	Bio bd, WP, Con bdd, lenticular bedding, LC	Bio bd, laminated bedding
Lithological Accessories	coal lam., mud pbl, py, pbl & grn lags, shell frags, gastropod shells, siderite nodules	coal lam., mud pbl, mica flakes, py, shale lam, shell frags, coal frags.	coal lam, py, coal frags, silt lam, shell frags, calc cmt.	Mrups, py, coal frags, shell frags, coal lam, shale lam, gastropod shells	Mrups, py, coal frags, shell frags, coal lam, shale lam, gastropod shells	Mrups, coal frags, py, calc mud drapes, shell frags, mica flakes	sand lam, py, shell debris, coal frags.	py, sand lam, calc cmt.	abundant glauconite grains, Mrups, pbl, py
Grain Size	upper fine-lower medium, common granule-pebble	fine-upper very fine, occasional medium	very fine-lower fine	fine-medium, rare coarse	fine-very fine, occasional medium	very fine-fine, occasional mud and silt	mud-silt, very fine sand in lenses	mud-silt, very fine sand in lenses	mud to very coarse sand and pebbles
Inferred Environmental Stresses	persistently shifting substrate, high current energy, fluctuating salininty, rapid deposition	fluctuating salinity, wave reworking, storm influence	wave reworking, rare event bed deposition	persistently shifting substrates, high current energy, fluctuating salinity, rapid deposition, hyperpycnal flows, tidal currents	wave reworking, periodic rapid deposition, periodic fluctuating salinity	periodic fluctuating salinity, event bed deposition	rapid deposition, periodic hyperpycnal flows, event bed deposition, salinity fluctuation	event bed deposition.	none inferred.

Table 3-1. Summary of lithologic, ichnologic and sedimentologic attributes of distinct facies.

Abbreviation Key

Ichnology

Ar-Arenicolites
As-Asterosoma
Cy-Cylindrichnus
Di-Diplocraterion
Ma-Macaronichnus
Pa-Palaeophycus
Ph-Phycosiphon
Pl-Planolites
Ro-Rosselia
Rz-Rhizocorallium
Sc-Scolicia
Sk-Skolithos
Te-Teichichnus
Th-Thalassinoides
Zo-Zoophycos

Physical Structures

Bio bd-Bioturbated Bedding
Con bd-Convolute Bedding
CR-Current Ripple
HAP-High Angle Planar Bedding
HCS-Hummocky Cross-Stratification
LAP-Low Angle Planar Bedding
LC-Load Cast
OR-Oscillation Ripple
SSD-Soft Sediment Deformation
SSrf-Scour Surface
WP-Wavy Parallel Bedding
X-Strat-Cross Stratification

Lithological Accessories

calc cmt-Calcareous Cement
Mrup-Mud Rip Up Clasts
grn-Granule
pbl-Pebble
py-Pyrite
lam-Lamina
frags-Fragments

Bioturbation Index

0-Bioturbation Absent
1-Sparse Bioturbation (distinct bedding, few traces)
2-Uncommon Bioturbation (bedding distinct, low trace density)
3-Moderate Bioturbation (bedding observeable, traces discrete)
4-Common Bioturabation (bedding indistinct, high trace density)
5-Abundant Bioturbation (bedding highly disturbed, just visible)
6-Complete Bioturbation (complete homogenization, no bedding visible)

Table 3-1-1. Abbreviation key for Table 3-1.

of BI and ichno-diversity occurs when F2 is succeeded by heterolithic sand and mud of F4, or mudstone of F7.

Interpretation:

Facies F2 is interpreted to represent an environment prone to fluctuating salinity, under conditions of wave energy and storm influence (e.g. shoreface, delta front). Sedimentological evidence includes the presence of hummocky cross-stratification, low-angle planar parallel bedding and very low mud content (i.e. mud winnowed by wave action). Ichnological evidence for these conditions is, as with F1, supported by the presence of a *Macaronichnus*–dominated assemblage. Additionally, BI and ichnodiversity are low, with sporadic distribution, further indicating the temporally consistent nature of high-energy conditions and possible fluctuating salinity.

FACIES 3: RIPPLE LAMINATED SILTY SANDSTONE

Description:

Facies F3 (Fig 3-9) consists of very fine- to silty-, ripple to planar laminated sandstone with less than 10% mudstone. Bioturbation distributions are sporadically heterogeneous to locally homogeneous, and display low to locally high bioturbation intensity (BI 0-5). Ichnological diversity is moderate and consists of *Planolites* with less common *Cylindrichnus, Palaeophycus, Scolicia, Teichichnus, Asterosoma* and fugichnia. Burrowing is present in both sandstone and mudstone beds. Burrows are occasionally lined and un-deformed with a maximum burrow diameter of 22 mm. F3 is present in two wells, and is characterized by an upward increase in bioturbation intensity and ichnological diversity over the dm scale.

Interpretation:

Facies F3 is interpreted have formed in an environment subjected to lower intensity of physico-chemical stress than F1 and F2, under conditions of wave-reworking, and periodic rapid deposition (e.g. lower shoreface, delta front). Very fine to silty sediment caliber and the presence of wave ripple-laminae (*sensu* Reineck and Singh, 1973; Fig. 3-8G) suggest influence by wave action, but in a more distal setting compared to F2. Ichnological evidence for an increasingly stable environment includes increased homoge-

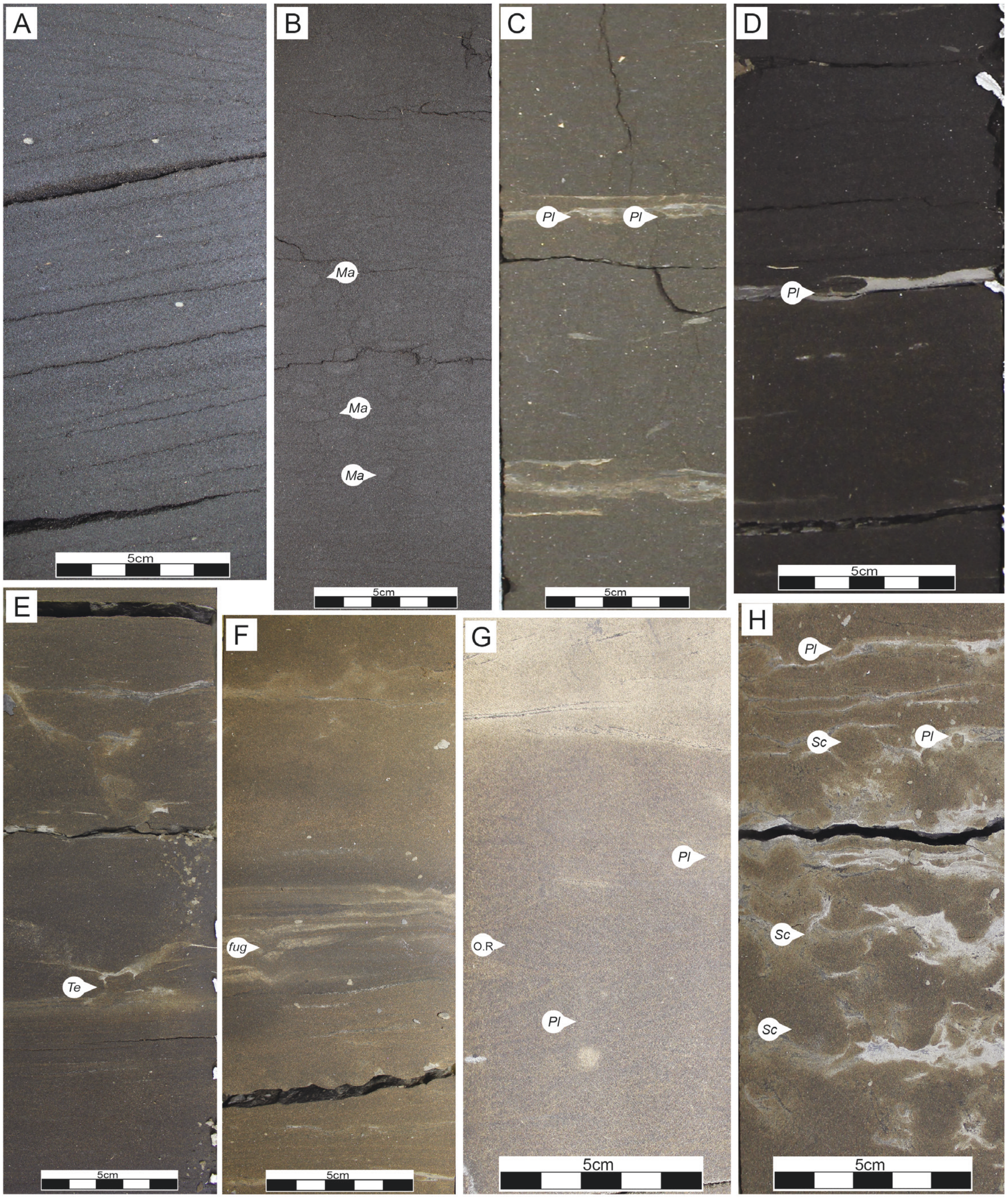


Figure 3-9. Sandstone dominated facies F1 (A,B), F2 (C,D) and F3(E-H). A) High-angle planar and trough cross-bedding with rare granules in fine to medium grained sandstone of facies F1. Well 10-08-083-16W5, depth 651.9m. B) Macaronichnus in fine sandstone showing low angle planar parallel bedding in facies F2. Well 10-08-083-16W5, depth 656.5m. C) Diminutive *Planolites* in rare mudstone beds within fine to very fine grained sandstone of facies F2. Well 06-05-083-16W5, depth 651.0m. D) Moderately robust *Planolites* in fine to very fine grained sandstone facies F2. Well 08-20-083-16W5, depth 627.9m. E) *Teichichnus* burrows in very fine-silty sandstone facies F3. Well 08-20-083-16W5, depth 624.4m. F) Fugichnia (escape trace) in very fine-silty sandstone facies F3 indicating rapid deposition of sediment. Well 08-20-083-16W5, depth 623.7m. G) Ripple laminated very fine-silty sandstone facies F3 with rare Planolites. Well 08-07-083-16W5, depth 657.3m. H) Bioturbated interval within facies F3 containing elevated mud content with *Planolites*, and *Scolicia*. Well 08-20-083-16W5, depth 623.6m.

neous distribution of traces, higher overall BI values and increased ichnological diversity (i.e. *Asterosoma, Teichichnus, Cylindrichnus, Scolicia and Palaeophycus*). Additionally, salinity stress can be inferred to be diminished from F1 and F2 due to the presence of an increasingly marine assemblage including *Scolicia* and *Asterosoma,* two ichnogenera that are indicative of environmental stability and normal marine salinities (Gingras et al., 2011; Buatois and Mángano, 2011). The presence of fugichnia indicates sporadic sedimentation, and rapid deposition.

FACIES 4: HIGH-ANGLE PLANAR BEDDED HETEROLITHIC SANDSTONE AND MUDSTONE

Description:

Facies F4 (Fig. 3-10) consists of fine- to medium-grained, low- to high-angle planar bedded heterolithic sandstone and mudstone with local current ripples. Bioturbation is sporadically heterogeneous in distribution, displays low density and has low to moderate bioturbation intensity (BI 0-3). Ichnological diversity is moderate, consisting of common *Planolites, Diplocraterion* and *Cylindrichnus* with subordinate *Asterosoma, Skolithos, Thalassinoides,* and *Rosselia.* Burrows are present in both mudstone beds and clean sandstone. Burrows display slight deformation and a maximum burrow diameter of 10 mm. No apparent upward trend in ichnological diversity or bioturbation intensity occurs within this facies, with the exception of well 10-08-083-16W5.

Interpretation:

Facies F4 is interpreted to record high-energy conditions, persistently shifting substrates, hyperpycnal mud flows (*sensu* Bhattacharya and MacEachern, 2009; Fig. 3-10C), high deposition rates , and wave-influence on sedimentation (e.g. delta front). Sedimentological evidence for this interpretation is based on the fine to medium sediment, high-angle planar to trough cross-bedding, and heterolithic nature of sedimentation. Ichnologically, the overall low BI, sporadic distribution and occurrence of lined trace fossils further imply shifting substrates and high-energy conditions. High deposition rates are inferred by the presence of burrows showing retrusive spreite (*Diplocraterion,* Fig. 3-10E), while hyperpycnal mud flows are represented by un-burrowed, massive to graded mudstone and silty sandstone beds (Bhattacharya and MacEachern, 2009; MacKay and Dalrymple, 2011). However, the localized presence of moderately bioturbated mudstone intervals and increased ichnological diversity suggest periods of relatively stable physico-chemical conditions where organisms are able to exploit food resources (Howard, 1975; MacEachern and Pemberton, 1992; Buatois and Mángano, 2011).

FACIES 5: WAVY PARALLEL HETEROLITHIC SANDSTONE AND MUDSTONE

Description:

Facies F5 (Fig. 3-10) consists of fine to very fine, wavy parallel to non-parallel bedded sandstone and mudstone (Fig 10D,E). Bioturbation is sporadically heterogeneous in distribution, and has overall low to moderate bioturbation intensities (BI 0-3) . Ichnological diversity is moderate to high, consisting of common *Planolites* and *Asterosoma* with subordinate *Skolithos, Cylindrichnus, Teichichnus, Arenicolites, Thalassinoides, Palaeophycus,* and rare *Scolicia.* Traces are commonly confined to mudstone beds and flaser bedding. Trace fossils show moderate degrees of deformation and a maximum burrow diameter of 22 mm. In each occurrence, bioturbation intensity and ichnological diversity increase upward into facies F7 and F9.

Interpretation:

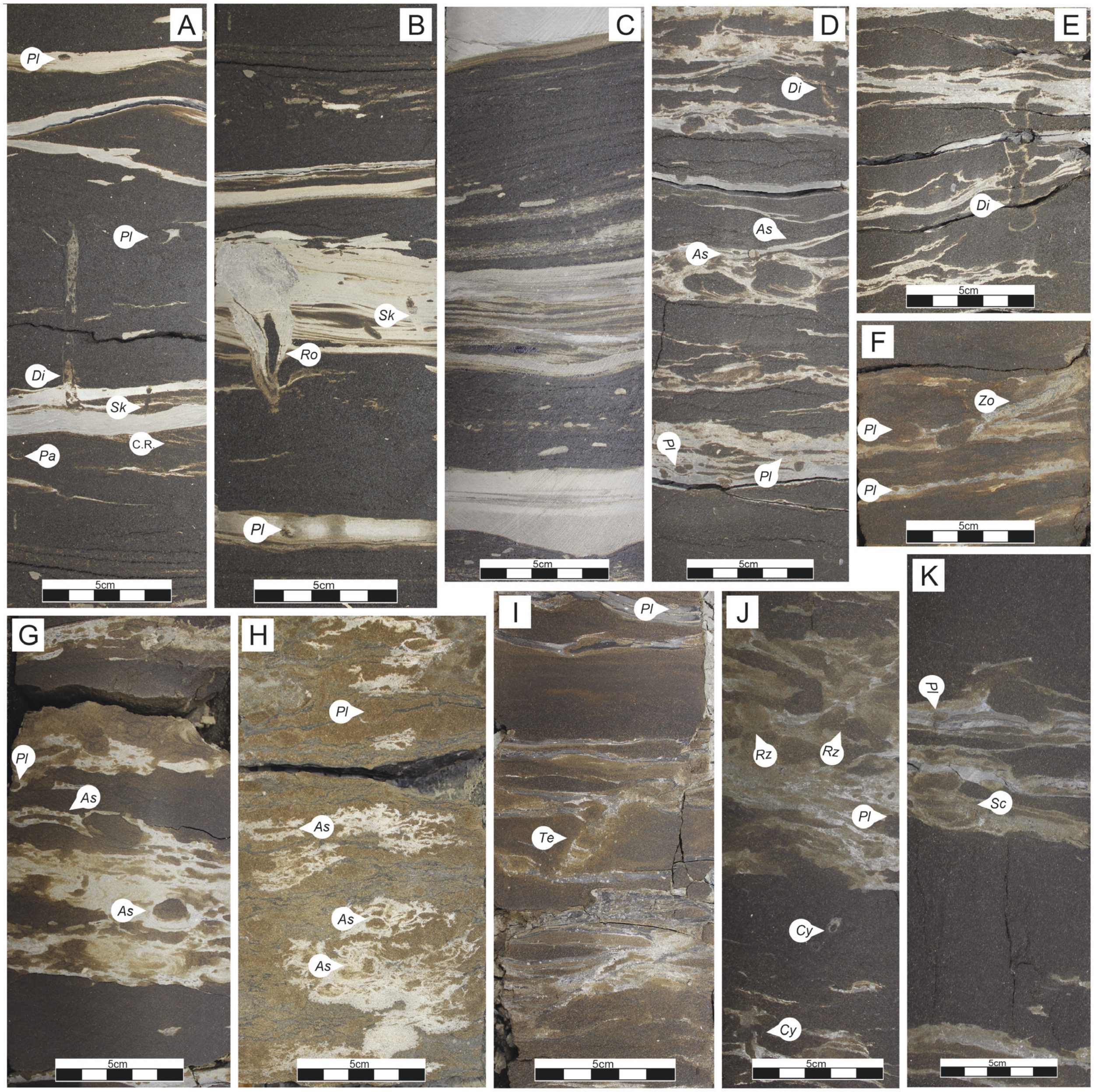


Figure 3-10. Heterolithic sandstone and mudstone facies F4-F6. A) Sporadically distributed *Diplocraterion, Skolithos, Planolites* and *Palaeophycus* in fine-medium grained facies F4. Note current ripple foresets and un-laminated mud bed possibly representing a hyperpycnal flow. Well 10-08-083-16W5, depth 661.6m. B) Sporadically distributed trace fossil assemblage consisting of *Rosselia, Skolithos* and *Planolites* in facies F4. Well 10-08-083-16W5, depth 656.5m. C) Thick, massive to graded mudstone beds interpreted to represent hyperpycnal mud deposition during high fluvial discharge. Well 11-29-083-16W5, depth 661.1 m D) *Asterosoma, Diplocraterion, Planolites* and *Palaeophycus* in facies F5. Note the deformed and convolute appearance of thin mud beds. Well 16-18-083-16W5, depth 639.5m. E) Lined, slightly deformed *Diplocraterion* trace in heterolithic facies F5. Well 16-18-083-16W5, depth 639.5. F) *Planolites* and *?Zoophycos* traces in thin mudstone beds. Well 01-32-083-16W5, depth 642.5m. G) Common *Asterosoma* with rare *Planolites* in mud rich interval of facies F6. Well 15-10-083-16W5, depth 626.7m. H) Highly bioturbated interval (BI 5) from facies F6 with abundant *Asterosoma* and lesser *Planolites*. Bioturbation has caused almost complete homogenization of sediment. Well 06-05-083-16W5, depth 650.1m. I) *Teichichnus* trace with *Planolites* in facies F6. Well 01-32-083-16W5, depth 638.1m. J) Highly bioturbated interval (BI 4) with *Rhizocorallium, Cylindrichnus* and *Planolites* in facies F6. Well 11-29-083-16W5, depth 641.6m. K) Bioturbated muddy interval with *Scolicia*, and *Planolites* in facies F6. Well 11-29-083-16W5, depth 641.5m.

Facies F5 is interpreted to record sediments subject to wave-reworking, periodic high sedimentation rates, and hypopycnal mud plumes with relatively stable overall salinity levels. Sedimentological evidence of wave action is shown in the overall parallel and non-parallel wavy bedding in clean sandstone intervals, and periodic rapid sedimentation is inferred by the presence of convolute bedding structures and soft-sediment deformation. The ichnological character of F5, as evidence by the presence of *Scolicia* and *Asterosoma* (Gingras et al., 2011, Buatois and Mángano, 2011; Gingras et al., 2012a), indicates near to normal marine salinities. F5 is inferred to be influenced by decreased persistence of rapid sedimentation as compared to F4. Evidence for this includes a more regular exploitation of mudstone beds, which suggests increasingly prolonged periods of increased stability.

FACIES 6: BIOTURBATED HETEROLITHIC SANDSTONE AND MUDSTONE

Description:

Facies F6 (Fig. 3-10) comprises fine to very fine, bioturbated heterolithic sandstone and mudstone. Sedimentation is characterized by wavy parallel bedding, with local convolute and soft sediment deformation. Bioturbation is sporadically heterogeneous to locally homogenous in distribution, and low to very high bioturbation intensity (BI 0-5). F6 contains the highest ichno-diversity of observed facies with common *Planolites, Cylindrichnus, Teichichnus* and *Asterosoma* with subordinate *Arenicolites, Skolithos, Scolicia, Thalassinoides, Palaeophycus, Rhizocorallium* and *Zoophycos.* Traces occur within mudstone beds and extent out from these beds into the surrounding sandstone. Burrows are lined and unlined, dominantly un-deformed and the maximum burrow diameter recorded was 22 mm. An upward increasing trend of bioturbation intensity and homogeneous distribution of traces occurs in wells where F6 is gradational upwards into F8 or F9. These contacts are gradational, and this increase takes place on the dm scale.

Interpretation:

Facies F6 is interpreted to record low energy sedimentary conditions with relatively stable salinity and oxygen content (e.g. lower bay-margin shoreface, distal bay-margin). Sedimentological evidence consists of very fine-silt sediment caliber and low-energy, wavy parallel bedding. Ichnologically, the assemblage is relatively diverse, evenly distributed and contains ichnogenera common to fully or near fully marine conditions, including *Scolicia, Rhizocorallium, Zoophycos* and *Asterosoma* (Gingras et al., 2011, Buatois and Mángano, 2011; Gingras et al., 2012). Additionally, the largest observed burrow diameter of 25 mm (in relation to other facies in the study, with the exception of F8) provides further evidence of increasingly stable conditions as diminution of trace diameter has been linked to persistent salinity or oxygenation stresses (e.g. Pemberton et al., 1982; Bromley and Ekdale, 1984; Gingras et al., 2007).

FACIES 7: LAMINATED MUDSTONE

Description:

Facies F7 (Fig. 3-11) is present in only two wells and consists of laminated to massive grey mudstone with thin beds and lenses of fine to very fine-grained sandstone. These sandstone beds are predominantly mm to locally cm thick. Bioturbation is sporadically heterogeneous in distribution, displays low to locally high density and low to moderate bioturbation intensity (BI 0-3). Ichnological diversity is low, consisting of *Planolites, Skolithos* and rare *Teichichnus, Asterosoma, Zoophycos*, *Thalassinoides* and fugichnia. Traces are rare within mudstone beds, with higher occurrence in sandstone beds and lenses. Burrows are lined and unlined, relatively un-deformed and the maximum burrow diameter recorded was 15 mm. F7 shows a slight upward trend in BI as it grades into F6.

Interpretation:

Facies F7 indicates high depositional rates, periodic hyperpycnal flows (massive mudstone with normal and reverse graded profiles, absent bioturbation), possible storm event beds and periodic fluctuating salinity conditions (e.g. prodelta). Sedimentological evidence consists of the presence of thick (cm-dm), massive-appearing to very faintly laminated mudstone beds interpreted to represent hyperpycnal mud deposits and the presence of sporadic sandstone beds containing current ripple lamina. Ichnologically, the low to absent BI within these mudstone beds attests to very soft substrate consistency, as fluid muds are rarely burrowed (MacEachern et al., 2005a; Bhattacharya and MacEachern, 2009). High sedimentation rates are inferred by the presence of fugichnia (escape traces). The presence of marine trace fossils (i.e. *Zoophycos* and *Asterosoma)* indicate periods of near normal marine salinities.

FACIES 8: BIOTURBATED MUDSTONE

Description:

Facies F8 (Fig. 3-11) consists of bioturbated mudstone with less than 10% fine- to very fine-grained sandstone beds and lenses. Bioturbation is predominantly homogeneous in distribution, and moderate to locally intense bioturbation intensity (BI 3-6). Ichnological diversity is moderate to high, consisting of abundant *Asterosoma, Planolites, Thalassinoides, Scolicia* and secondary *Teichichnus, Cylindrichnus, Arenicolites, Skolithos, Thalassinoides,* and *Rhizocorallium.* Traces are abundant within mudstone and extend into sandstone beds and lenses. Traces are relatively un-deformed and maximum burrow diameter measured was 25 mm. In both occurrences, F8 shows an upward decrease in bioturbation intensity as it grades into F5 and F6 respectively.

Interpretation:

Facies F8 records an environment of low energy, relatively stable chemical conditions and abundant supply of food resources (e.g. distal bay-margin). Sedimentological evidence consists of the dominance of mud content and low-energy wavy parallel to lower flow regime horizontal bedding (where preserved). Ichnologically, the high BI and homogenous distribution of traces suggest persistently low sedimentation rates. Stable chemical conditions are evidenced by the abundance of marine associated trace fossils (i.e. *Asterosoma, Rhizocorallium* and *Scolicia*) (MacEachern et al., 2010; Gingras et al., 2012a).. Abundant marine food resources can be inferred by the dominance of deposit feeding ethologies (MacEachern et al., 2010).

FACIES 9: GLAUCONITIC MUDDY SANDSTONE

Description:

F9 consists of muddy, glauconitic sandstone largely homogenized by bioturbation. Bioturbation is homogenous in distribution, and has moderate to intense bioturbation intensity (BI 3-6). Ichnological diversity consist of large (several cm in vertical axis) *Diplocraterion* and smaller *Skolithos, Asterosoma, Thalassinoides, Planolites* and *Cylindrichnus.* This assemblage may be an underrepresentation of ichnological diversity as complete homogenization often makes individual forms difficult to identify. Burrows are lined and unlined, relatively un-deformed and the maximum diameter measured is 15 mm. F9 decreases in bioturbation intensity and ichnological diversity upward as it is transitional with the Wilrich Member shales above.

Interpretation:

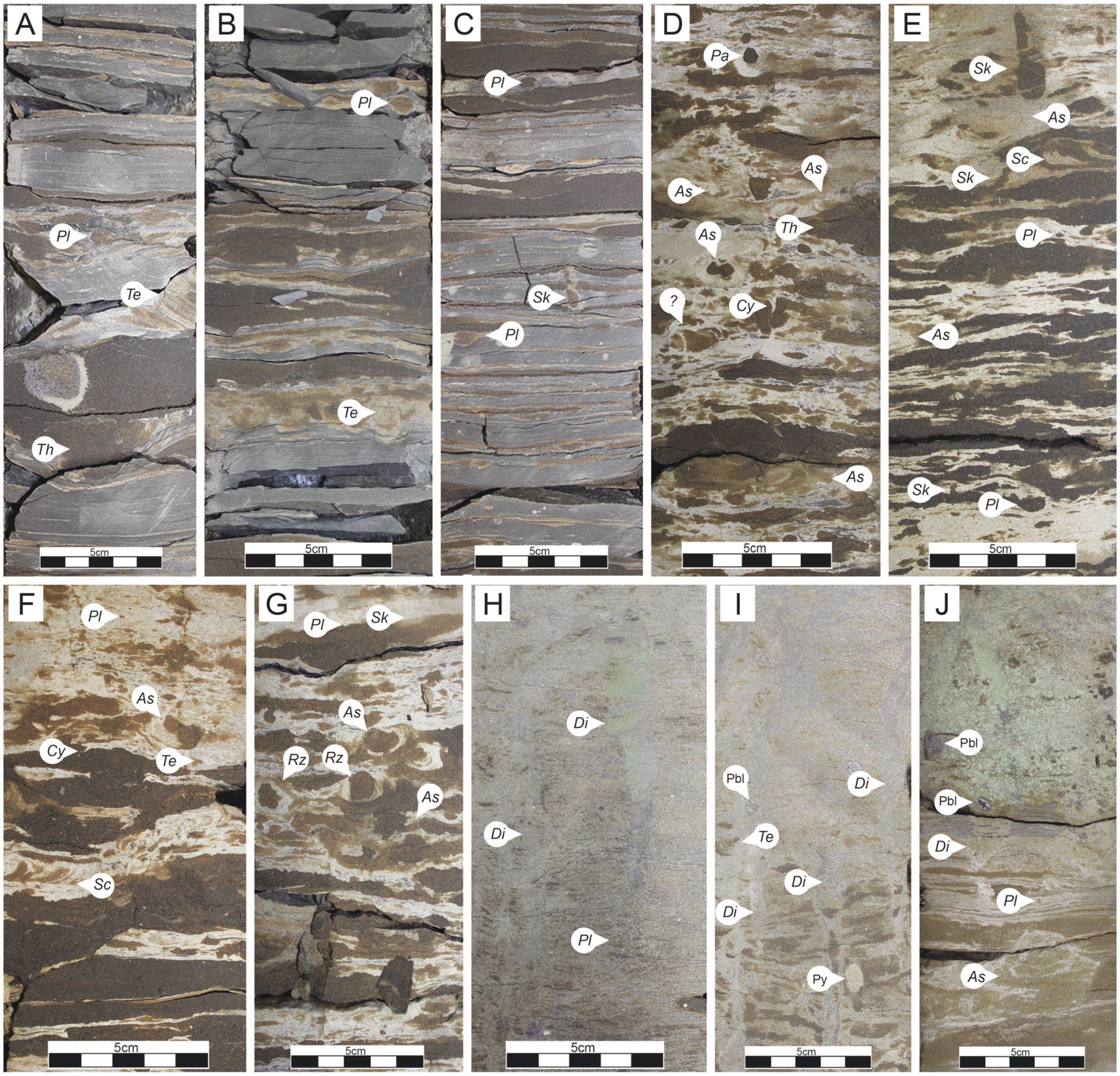


Figure 3-11. Mudstone dominated and muddy sandstone facies F7 to F9. A) *Planolites, Thalassinoides* and T*eichichnus* in laminated mudstone facies F7. Note bioturbation is largely confined to sandstone beds. Well 01-32-083-16W5, depth 647.9m. B) Bioturbated sandy interval with *?Teichichnus* in relatively un-burrowed mudstone of facies F7. Well 01-32-083-16W5, depth 643.7m. C) Rare, diminutive *Planolites* and *Skolithos* in mudstone facies F7. Well 01-32-083-16W5, depth 647.3m. D) Highly bioturbated mudstone (BI 4-5) of facies F8 with common *Asterosoma* and lesser *Cylindrichnus, Thalassinoides* and *Palaeophycus*. Well 15-10-083-16W5, depth 627.5m. E) Moderately bioturbated interval (BI 3-4) consisting of *Asterosoma, Planolites Scolicia,* and *Skolithos* in mudstone dominated facies F8. Well 10-08-083-16W5, depth 650.0m. F) Moderately bioturbated interval (BI 3) with increased sandstone content and containing of *Asterosoma, Scolicia, Planolites* and *Cylindrichnus* in mudstone dominated facies F8. Well 15-10-083-16W5, depth 629.0m. G) Abundant *Asterosoma* with lesser *Skolithos, Rhizocorallium*, and *Planolites* in modererately to strongly (BI 3-4) bioturbated mudstone interval in facies F8. Well 15-10-083-16W5, depth 628.1m. H-J) Muddy glauconitic sandstone of facies F9 representing a highly bioturbated (BI 4-6) *Glossifungites* surface with robust *Diplocraterion, Asterosoma* and *Planolites*. Well 08-07-083-16W5, depth 654.6m (H), Well 16-18-083-16W5, depth 631.3m (I) and Well 11-30-083-16W5, depth 622.9m (J).

This facies is interpreted to represent largely unstressed, fully marine conditions. Sedimentological evidence for this interpretation is based upon the homogenized nature of sediment, the abundance of glauconitic grains and the transition into marine shales above. Ichnologically, the complete homogenization of sediment and overall large traces (*Diplocraterion* reaching several centimeters in the vertical axis) indicate stable physical and chemical conditions. In addition, F9 is part of an regionally extensive *Glossifungites* surface that marks a transgressive surface of erosion (O'Connell, 1988).

PROCESS ICHNOLOGICAL CHARACTER OF THE BLUESKY FORMATION

As described, applying the process ichnological methodology to the dataset allows for the possible identification of physico-chemical stresses present during deposition within individual facies. The vertical and horizontal relationships of these observations are considered in this section, and illustrated in Figure 3-12.

TRACE DISTRIBUTION

The distribution of burrows within the dataset can be used to infer the stability and temporal persistence of physico-chemical stress within the environment (Gingras et al., 2011). Facies F1, F2, F4 and F7 (with inferred rapid sedimentation rates, high water turbidity, persistently shifting substrates, and salinity fluctuations) are characterized by sporadically distributed intervals of bioturbation, indicating persistent temporal variability in physico-chemical conditions. Such fluctuations are common to environments where waves, storms, and fluvial forces influence environments of deposition (MacEachern et al., 2005a). Facies F3 and F5 also display sporadic distributions of traces, but to a lesser degree than F1, F2, and F4, which indicates an overall decrease in the intensity and/or temporal duration of physico-chemical stresses. These facies are commonly found in lower stratigraphic intervals within the dataset, suggesting early deposition of the Bluesky Formation occurred in energetic conditions with fluctuating to locally persistent salinity reduction. F6, F8, and F9 are characterized by moderately sporadic to homogenous distributions that can be inferred to represent stable food and oxygen resources and probable slow, steady sedimentation rates (Gingras et al., 2011). These facies are invariably found at higher stratigraphic intervals within the dataset, suggesting a further overall decrease in the temporal persistence and/or intensity of physical and chemical stresses with respect to lower facies.

TRACE DIAMETER, DIVERSITY, AND SDI

Maximum trace diameter, ichnological diversity, and Sized Diversity index within the dataset displays an overall increasing upward trend (Fig. 3-5, 3-6). In facies that tend to occur lower within the stratigraphic framework, trace fossils have a small overall maximum diameter (predominantly less than 10 mm). These facies are also characterized by low ichnological diversity (1-3 forms), and low SDI values in relation to other facies in the dataset. Facies occurring at higher levels within stratigraphy attain larger diameters (up to 25 mm), are characterized by higher ichnological diversity (6-9 forms), and significantly higher SDI values (Fig. 3-6). Gingras et al., (1999) and Hauck et al., (2009) have shown in modern environments that a relationship exists between overall salinity and the size of traces, where higher salinity environments typically display larger burrow diameters. The pattern observed within the data set can be used to show an increase in salinity towards marine chemistry in an upward stratigraphic direction within the study area.

Variations in Size Diversity Index could also result from other depositional controls (e.g. substrate consistency, sedimentation rates, dissolved oxygen concentration). However, the pervasive nature of brackish-water assemblages (e.g. low diversity *Planolites, Cylindrichnus,* and *Thalassinoides*) in lower facies, and more marine assemblages (e.g. diverse *Scolicia, Rhizocorallium, Asterosoma, Zoophycos* and *Diplocraterion*) in higher facies, strongly suggests salinity is a primary control on SDI (e.g. Pemberton et al., 1982; MacEachern and Gingras, 2007).

Additionally, it may be contended that trace diameter is only meaningful within a single ichnogenera. We avoid that approach for several reasons: 1) that method assumes all examples of a single ichnogenera are made by the same type of animal, which is untrue; 2) single ichnogenera are commonly too sporadic in distribution to produce an analytical dataset; and 3) some types of animals show no response to salinity levels (e.g. Gingras et al., 1999; 2011). Thus, SDI considers population response to salinity fluctuations, not those of individual forms. This allows for more reliable indications of salinity levels and salinity fluctuations (Gingras et al., 1999; Hauck et al., 2009). Gingras et al. (2011) discuss this concept in detail, and recognized two types of diminution trends: "facultative diminution", which is an animal size response to osmotic stress; and more commonly "enforced diminution", wherein salinity stress may lead to shortened life cycles and exclude animals that are poor osmoregulators. Enforced diminution results in larger animal species being absent from the burrowing community. SDI includes observations of all trace diameters in an interval, in recognition that facultative diminution cannot be unwound from enforced diminution.

TRACE DEFORMATION

Burrow deformation can be used in conjunction with trace-fossil distribution in order to enhance the recognition of high sedimentation rates, deposition in a sloped environment (i.e. delta front or tidal bar), and substrate cohesiveness (Gingras et al., 2011). However, post-burial compaction of soft substrate may also be responsible for this phenomenon. In facies with lower burrow densities (F1, F2, F4), burrows tend to show evidence of compaction (attributed to burial) and lateral strain (attributed to deposition on a sloped surface). In F5, burrows within mudstone beds are likewise deformed, and associated with soft-sediment deformation and convolution of mudstone lamina. An example can be seen in figure 3-10D, where *Asterosoma* burrows show flattening and elongation in a horizontal direction. These features could suggest exploitation of food resources from hypopycnal mud deposited during high discharge periods (Gingras et al., 2011). The overall trend of burrow deformation is observed to decrease in facies containing higher mud content (except F7), further indicating the slower sedimentation rates experienced at higher stratigraphic levels.

TRACE LINING

Burrow linings can be useful in recognizing shifting substrates and water turbidity within a particular location. However, caution must be exercised as organisms may line burrows for various reasons (Gingras et al., 2011). Within this dataset, the presence of dominantly lined burrows in heterolithic F4 deposits (including *Skolithos* that may not normally possess a lining) can be used to infer persistently shifting substrates. These linings act to stabilize burrow walls and prevent collapse of the central shaft (Gingras et al., 2011). Additionally, the presence of *Rosselia and Diplocraterion,* which contain linings (*Rosselia*) and linings with spreite (*Diplocraterion),* can be used to infer pronounced water turbidity (Gingras et al., 2011). This is based on the interpretation that the trace makers likely collected the mud from the water column or at the sediment-water interface. The ichnological characteristics, in combination with the presence of hyperpycnal mud beds within F4, suggest turbid conditions existed during deposition.

Burrow linings are less relevent in higher stratigraphic facies within the dataset (F5, F6, F8) as several trace making organisms within these zones possess burrow linings, that are, in fact the basis for some individual taxonomy (e.g. *Arenicolites* vs. *Diplocraterion*).

BIOTURBATION INTENSITY

Bioturbation intensity can be used to infer depositional rates and the abundance of food resources. Low-energy environments connected to marine waters tend to show higher bioturbation intensities than those deposited under conditions of higher-energy or in fresh-water (Gingras et al., 2011). It should be noted, however, that some high-energy deposits (e.g. foreshore sands) can be completely bioturbated by *Macaronichnus* or cryptically bioturbated by meiofauna (Pemberton et al., 2012). Within this dataset there is strong relationship between bioturbation intensity and silt/mud content (with the exception of F7). This can be used to infer overall slower rates of deposition and/or increased biomass in an upward stratigraphic direction. Ethology of trace makers is a critical observation, as Gingras et al., (2008) showed that deposit feeding organisms are able to completely bioturbate sediments in shorter time spans than filter/suspension feeders. The traces present within the reported mudstone-dominated facies appear to predominantly comprise deposit-feeding ethologies. Thus, while low sedimentation rates may be inferred within these facies (i.e. F8), it is likely that these fabrics developed over weeks or months, but they do not represent years of bioturbation (Gingras et al., 2008, Figure 14). These observations help refine possible environments of deposition. Normal offshore deposits and micro to mesotidal intertidal flats commonly represent years of colonization. Thus, deposition may be narrowed to a sub-tidal, embayment setting where sedimentation rates are relatively slow, and overall salinity levels remain stable.

CHARACTERISTIC ICHNOGENERA

While characteristic ichnogenera are empirically based and therefore not absolutely diagnostic, this observation, coupled with other ichnological data can be informative (Gingras et al., 2011). The presence of *Scolicia, Zoophycos,* locally abundant *Asterosoma,* and *Rhizocorallium* in facies F3, F5, F6, F7 and F8 suggest deposition in fully to near fully marine chemistry (Gingras et al., 2011; Buatois and Mángano, 2011; Gingras et al., 2012). Forms more characteristic of brackish-water (e.g. *Cylindrichnus, Teichichnus* and *Palaeophycus*), although present in the upper marine facies, are more common in facies at lower stratigraphic intervals. This infers conditions of lower overall and/or consistently fluctuating salinity levels in lower stratigraphic intervals. This is consistent with the findings of Hubbard et al., (1999; 2004), where low diversity, typical brackish-water trace fossil assemblages were observed in facies at lower stratigraphic intervals.

DISCUSSION

PALAEOENVIRONMENTAL IMPLICATIONS

This paper sets out to explore the significance of the different ichnological expressions of Bluesky

Formation facies in the study area, but it is worth discussing some of the broader observations that may be extracted from the detailed ichnology. For a detailed interpretation of palaeodepositional setting and the stratigraphic relationship of facies, the reader is referred to Botterill et al., (this volume). First, although core spacing is only 1.4 to 4.5 km, each of the 5 vertical successions shown in Figure 3-12 are, to varying degrees, different. However, three vertical trends can be generalized.

1. Cross-bedded sandstone and/or heterolithic sand/mudstone that transitions into brackish-water mudstones and then marine mudstones. This succession is observed in the north of the study area (01-32 and 11-30, Fig. 3-12) and likely represents progressive transgression of marine influenced environs.

2. Persistently cross-bedded sandstones and heterolithic sandstones with an abrupt transition to brackish-water to marine influenced strata at the top of the Bluesky succession (i.e. 08-20, Fig. 10).

3. Cross-bedded sandstone and/or heterolithic sand/mudstone that transitions into brackish-water mudstones and then marine mudstones, capped with wave-influenced brackish-water units (i.e. 08-07 and 06-05). This succession is similar to Succession 1 (above) and may represent the same transgression mentioned therein, but in a more proximal position.

Broadly speaking, ichnological data show a trend wherein the depositional setting evolves from sedimentation dominated by near marine to locally brackish-water salinity, wave and current action and/or hyperpycnal flow to wave-influenced bay-margin and marine-embayment conditions. In the most general terms, the strata reflect a change from wave-dominated deltaic sedimentation into a more open marine embayment setting. While these core are confined to a relatively small area, the findings are consistent with those of the more broad scale, detailed depositional interpretations of Botterill et al., (2015, this volume).

CONCLUSIONS

The utility of combining ichnological and sedimentological characteristics to facies analysis and the recognition of physico-chemical stresses within the rock record cannot be over-stated. The ichnological response to various stresses provides information about depositional conditions that are not discernable through sedimentary analysis alone (e.g. Schäfer, 1956; Reineck and Singh, 1973; Seilacher, 1978; Hubbard et al., 2004; Lettley et al., 2005; MacEachern et al., 2005c). The combined ichnological and sedimentological character of this dataset show: 1) overall increase in density and regularity in distribution of trace fossils in an upward stratigraphic direction; 2) an upward increase in maximum burrow diameter; 3) decrease in burrow deformation in an upward stratigraphic direction; 4) dominance of lined burrows in lower, higher energy facies; 5) overall upward increase in bioturbation intensity; 6) upward increase in ichnological diversity and preponderance of deposit feeding ethologies; and; 7) upward increase in Size Diversity Index values. These observations correlate to the sedimentological observations of: 1) overall upward decrease in grainsize; 2) overall upward decreased energy of physical sedimentary structures, and; 3) overall increase in mud content in an upward stratigraphic direction.

These trends are not without local variation, as autocyclic events are identifiable in certain wells (e.g. 06-05-083-16W5 where sandstone of F3 overlies heterolithic deposits of F5 and 08-20-083-16W5 where F1 overlies F4). However, the observations noted above can be used to show an evolution of the Bluesky Formation from:

1. High energy, shore proximal wave-influenced setting characterized by persistently shifting substrates, periodic rapid deposition, elevated water turbidity and persistent to temporal salinity fluctuations. This suggests deposition in a wave-influenced proximal delta front and/or proximal bay-maring shoreface setting.
2. Moderate energy, wave-influenced setting characterized by periodic hypopycnal mud plumes and periodic high deposition rates. This suggests deposition in a wave-dominated shoreface and/or distal delta front setting where salinity levels are characterized predominantly by near to fully marine water chemistry.
3. Low energy, temporally stable distal setting where food resources are abundant, deposition rates are slow and chemical conditions are relatively stable. This suggest deposition in a marine, distal embayment setting.
4. Fully marine deposits consisting of abundant food resources and low physico-chemical stress condition

Different environments are subject to a unique set of physical and chemical conditions (e.g. tidal forces, wave energy, storm influence, fluvial input, salinity and/or oxygen fluctuation, etc.). As such, the precision with which these stresses can be identified is crucial to refined environmental interpretation. Process ichnology is a valuable tool which, when applied properly, can greatly enhance our ability to recognized the discussed physico-chemical stresses, and thus increase confidence in paleoenvironmental interpretation.

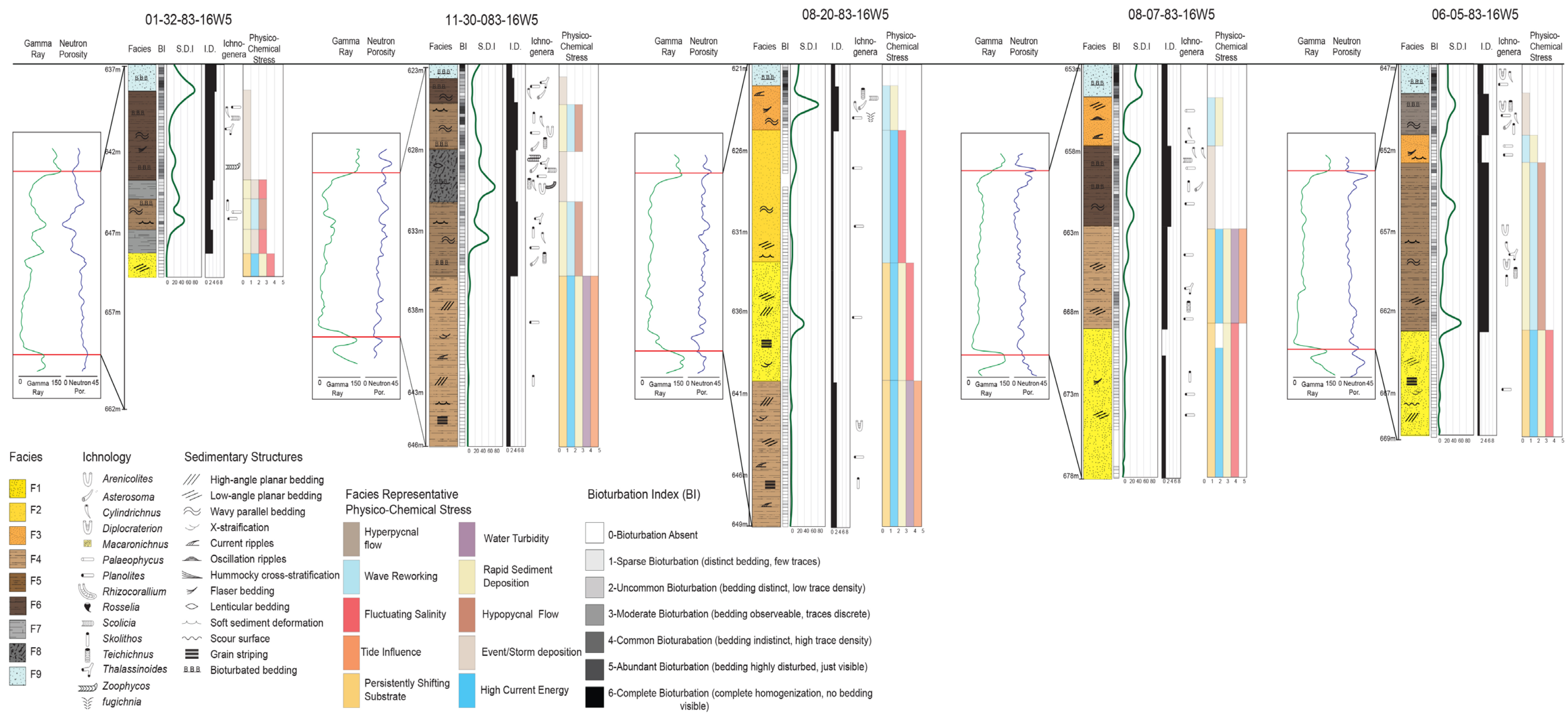


Fig. 3-12. Cross-section sumarizing the trends in SDI, BI, ichnological diversity, and proposed physical and chemical stresses. Note, the stresses indicated need not all be present, but can be inferred based upon the ichnological signature of each facies.

CHAPTER 4: SUMMARY AND CONCLUSIONS

Reconstruction of ancient depositional environments based on core datasets is, in many cases, highly difficult. This results from the complex lateral distribution of depositional elements within whole systems (i.e. deltas, estuaries, shoreface systems, etc.). This difficulty is exacerbated by the fact that many physical sedimentary features (e.g. cross-bedding, ripple lamination, flaser bedding, etc.) and sedimentary facies (e.g. sandstone, mudstone, heterogeneous sandstone and mudstone, etc.) are not unique to one particular system. The Bluesky Formation is no exception to these realities, as it is characterized by a highly complex lateral and vertical facies architecture. The concept of ichnology has a long and well established history, and provides an additional set of observations, that when used in conjunction with sedimentology can greatly enhance the precision and reliability of interpretation. Characteristics such as ethology, distribution, diversity, ichnogenera, bioturbation intensity, trace diameter, and Size Diversity Index (SDI) can elucidate the presence of various physical and chemical stresses not necessarily recognized though sedimentology alone (e.g. salinity fluctuation, dissolved oxygen, substrate consistency). Thus, the purpose of this thesis was to combine detailed observations of lithology, physical sedimentology and ichnology in order to better understand the palaeodepositional setting of the Bluesky Formation. As the Bluesky Formation contains substantial economic bitumen deposits, a more precise understanding of the distribution of reservoir facies is of primary importance to exploration and exploitation activity.

Data collected for this thesis was comprised of 40 logged wells, with supplementation of an additional 21 wells with geophysical well logs. Detailed documentation consisted of: lithology, nature of contacts, sedimentary structures, lithologic accessories, body fossils, grain-size, and bitumen saturation. Ichnological observations included ichnogenera present, diversity, distribution, trace size, bioturbation intensity, trace deformation, and ichnological assemblages. SDI was calculated for 22 wells by multiplying [maximum burrow diameter x ichnological diversity]. Additionally, the ternary framework of Ainsworth et al., (2011) was utilized to aid in quantifying the magnitude of depositional forces present during depositional evolution. A series of facies slice maps and two cross-sections were created to better visualize the distribution of facies within the dataset. The contact between the Bluesky Formation and the overlying Wilrich Member was utilized as a datum in the construction of these maps and cross-sections. Finally, the palaeotopography of the Bluesky and underlying Gething Formation contact was completed to understand possible topographic controls on Bluesky Formation sedimentation. This was completed by mapping the thickness of Bluesky sediment from the Wilrich Member to the contact with the underlying Gething Formation. This data constitutes the descriptions and interpretations presented in Chapter 2.

A subset of data (9 wells) within Township 83 and Range 16W5 was chosen in order to test the applicability of the process ichnology method of Gingras et al., (2011), to core dataset. This methodology constitutes observations of: 1) trace diameter; 2) diversity and range of ethological characteristics; 3) presence or absence of trace linings; 4) presence or absence of specific ichnogenera; 5) trace distribution; and, 6) degree of trace deformation. This framework allows for the identification of physical and chemical stresses present during deposition. This analysis led to the identification of an overall increasing upward trend in salinity level, decreasing upward tend in rates of sedimentation, and an overall increase upward in MBD and SDI values. This work constitutes the content of Chapter 3.

Overall, this work has lead to the identification of 11 distinct facies (F1-F11), 4 Facies Associations (FA1-FA4), and a three-stage depositional evolution of sediments within the confines of the study area. These Facies associations constitute various elements of a relatively unrestricted, wave-dominated marine embayment setting, and include: FA1-wave-dominated, fluvially-influenced delta; 2) FA2-bay-margin shoreface through to distal bay-margin; 3) FA3-wave-dominated marine delta; and, 4) FA4-wave-influenced brackish-water sedimentation. An illustration of the theoretical distribution of these elements is shown in Figure 4-1. The overall evolution of sedimentation is interpreted as follows, and core examples are shown in Figure 4-2:

1. Initial Bluesky sedimentation resulted from transgression of high-energy delta front and bay-margin shoreface sediments over the brackish-water sediments of the Gething Formation. The surface demarcating the contact is erosive, and represents a wave-ravinement surface (WRS). This sedimentation was dominated by wave processes, with secondary fluvial, and tertiary tidal influence.
2. Continued transgression, with local autocyclic regressive pulses resulted in the deposition of distal delta front, intertidal flat, and prodelta facies over proximal delta front facies, and distal bay-margin sediments over bay-margin shoreface deposits. This sedimentation was dominated by wave processes, with secondary storm influence, and local tidal/fluvial influence. During this phase, marine deltaic facies inundated the area from a northwest to southeast direction.
3. An apparent late change in relative sea level, wherein wave-influenced, brackish-water sediments are erosively juxtaposed on distal bay-margin and distal delta front facies.
4. Finally, the area was completely inundated by transgression of the Boreal sea, resulting in deposition of the marine Wilrich Member shale. This surface is characterized by a regional *Glossifungites* surface, and is interpreted to represent a transgressive surface of erosion (TSE).

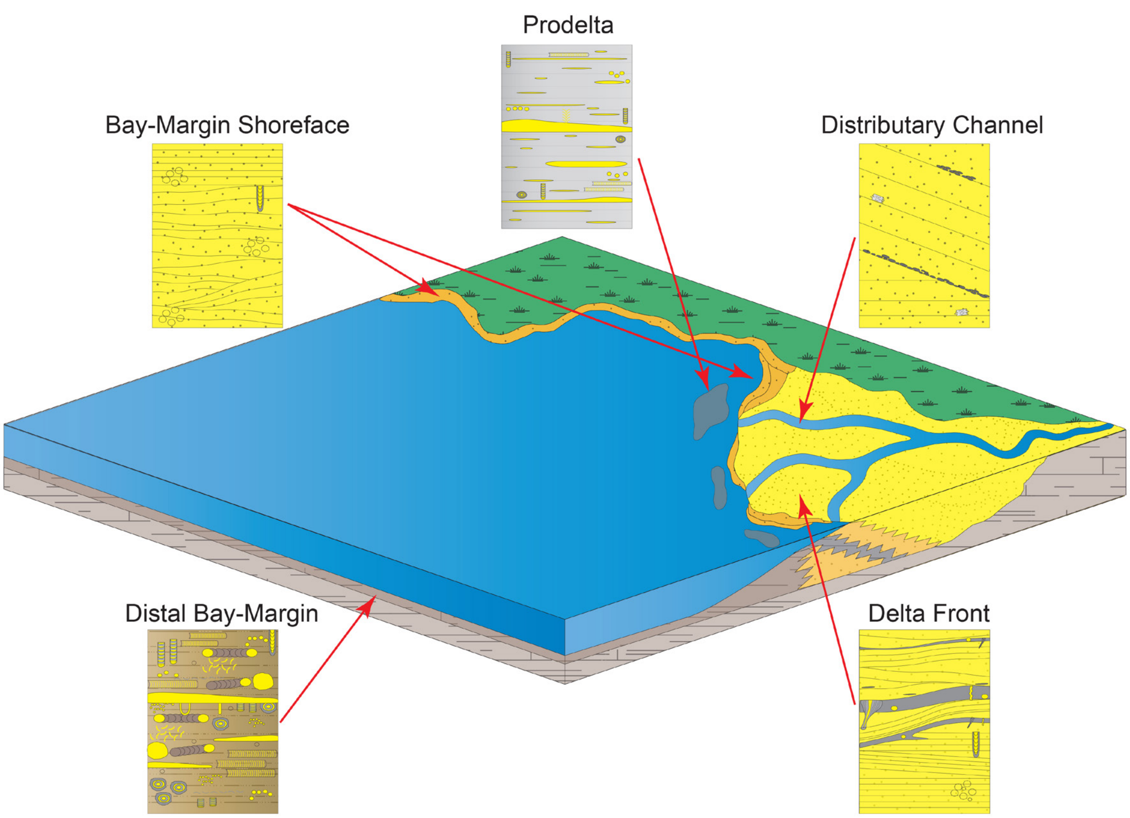


Figure 4-1. Illustration of a theoretical depositional setting and the location of select facies within the dataset.

In addition to the interpreted facies associations and depositional evolution, important observations about reservoir distribution can be made. Well spacing is often on the scale of a few km's, yet correlation of individual facies from well to well is often problematic. This indicates a highly variable lateral architecture. Reservoir facies are predominantly limited to FA1 and FA3, as these Facies Association contain the highest proportion of clean, bitumen saturated sandstone. However, clean reservoir facies within FA1 appear relatively limited in lateral extent, confined to deltaic distributary channel deposits. The majority of sedimentation appears to be heterogeneous with locally abundant hyperpycnal mudstone beds. Unfortunately, given the well spacing and lack of outcrop data, the lateral extent of these mudstone beds can not be reliably determined. Sediments from the upper stratigraphic intervals of FA1, and the majority of FA2 and FA4 do not appear to constitute quality reservoir. This is due to the moderate to high mudstone content (upper FA1 and FA4). Although FA2 does posses localized, clean shoreface/delta front sandstone bodies, these appear to limited in lateral extent with the remaining deposits characterized by heterolithic and mudstone lithology.

Description of embayment facies are not abundant in the literature, and have often in the past been mistaken as estuarine in origin (Yoshida et al., 2007). Additionally, the recognition of wave-dominated deltas in the rock record may have been underestimated in the past (Bhattacharya and Giosan, 2003). Through the combination of sedimentological and ichnological characteristics, this work has led to the identification of wave-influenced deltaic deposition in a marine embayment setting for the Bluesky Formation. This work fills a geographical gap where limited work has been completed. It is hoped that the combined sedimentological and ichnological characteristics described herein will lead to the identification and/or re-interpretation of other ancient, wave-influenced deltaic and marine embayment settings in the rock record. Additionally, it is intended that the interpretations of this research may be utilized for more efficient reservoir prediction in future exploration activities.

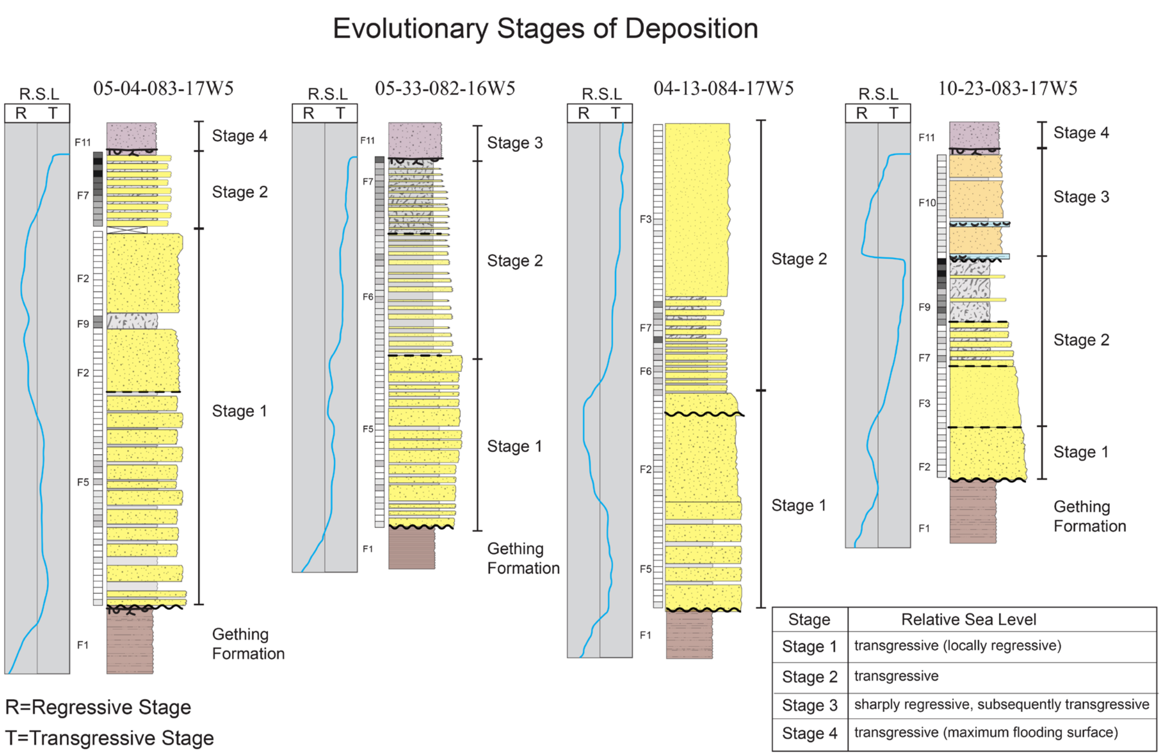


Figure 4-2. Schematic diagram of relative sea level during the four stage depositional evolution interpreted from the dataset. R.S.L. is relative and does not represent actual measured levels of rise or fall.

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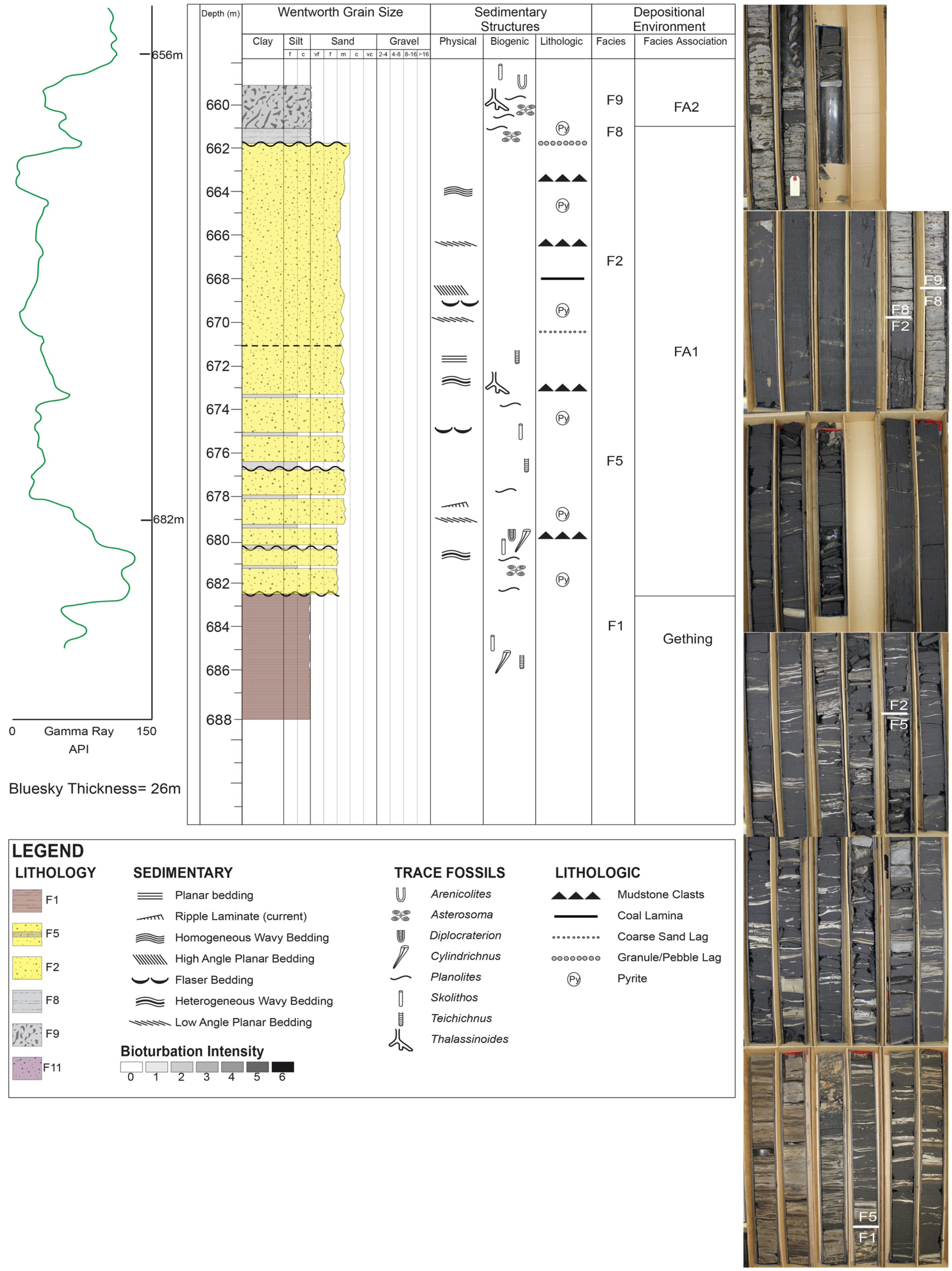
APPENDIX I

CORE LOGS

03-32-082-16W5



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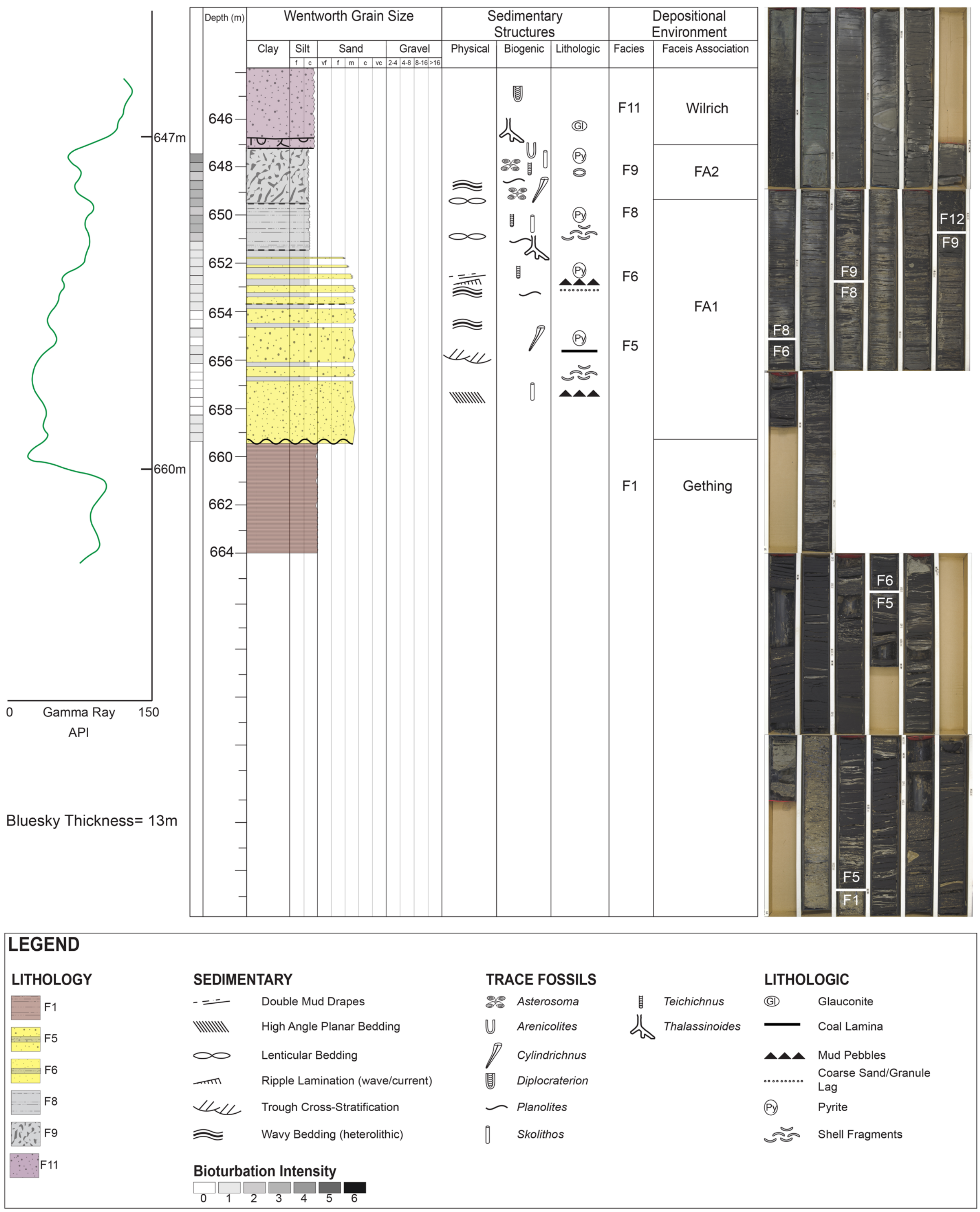
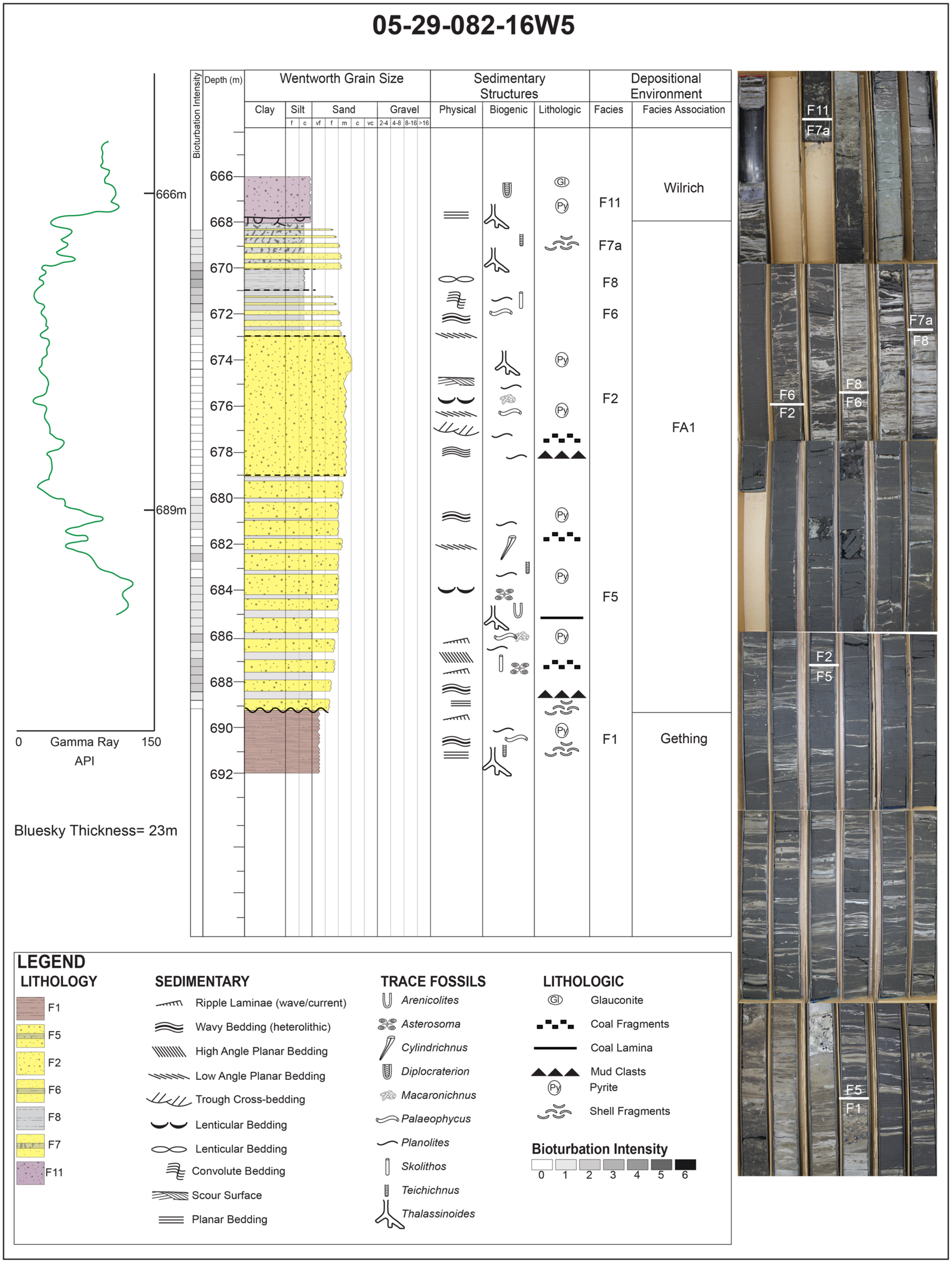
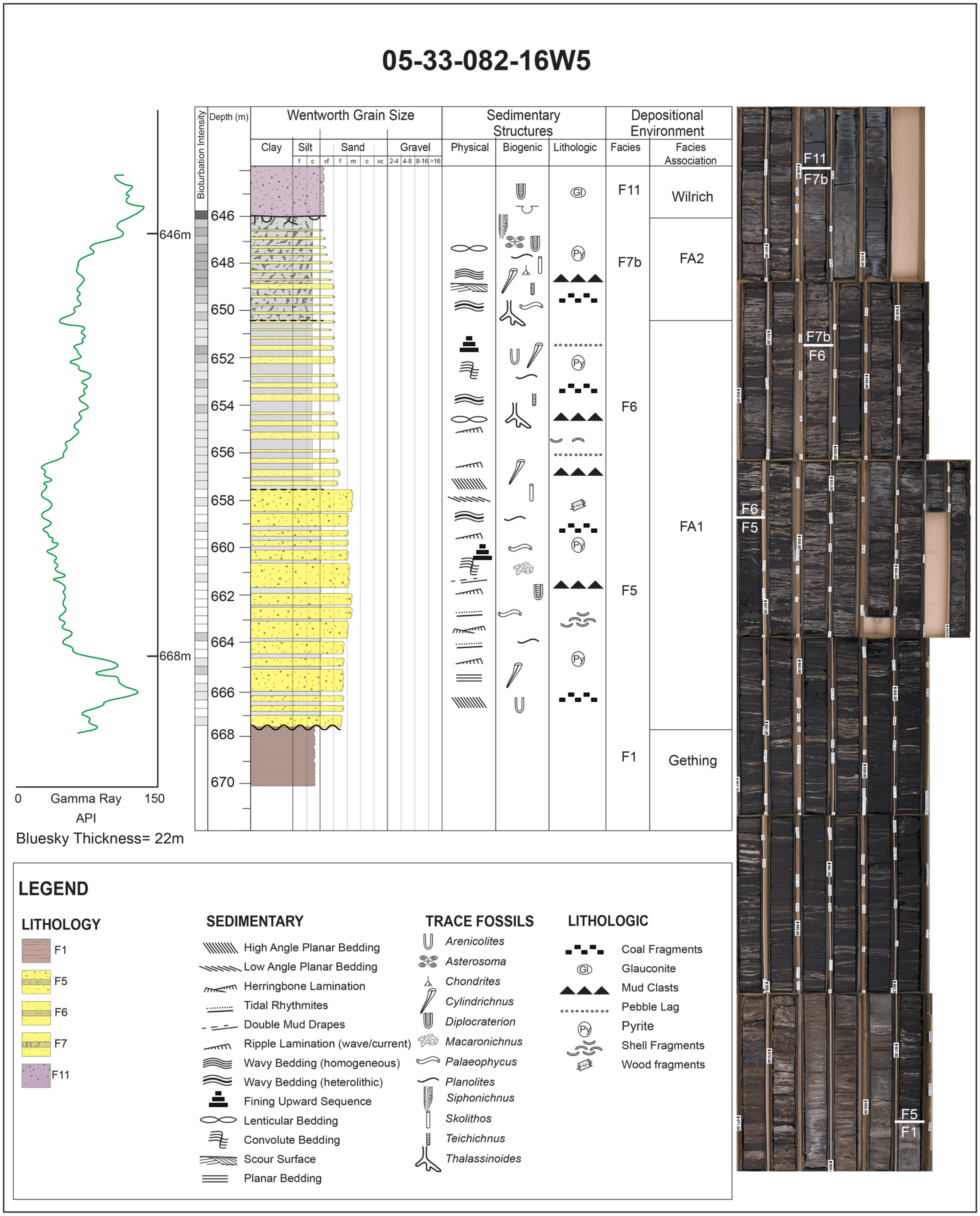
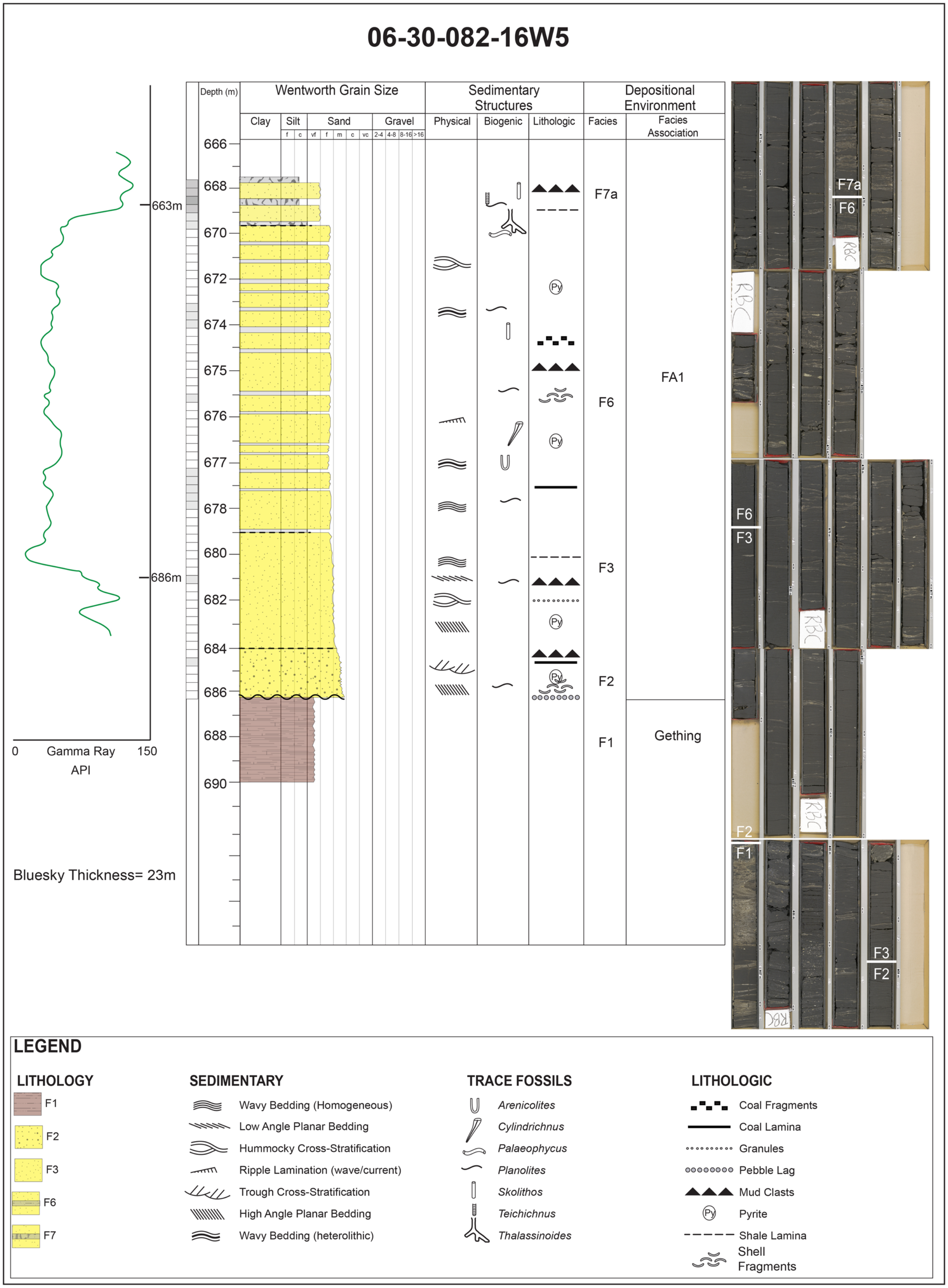
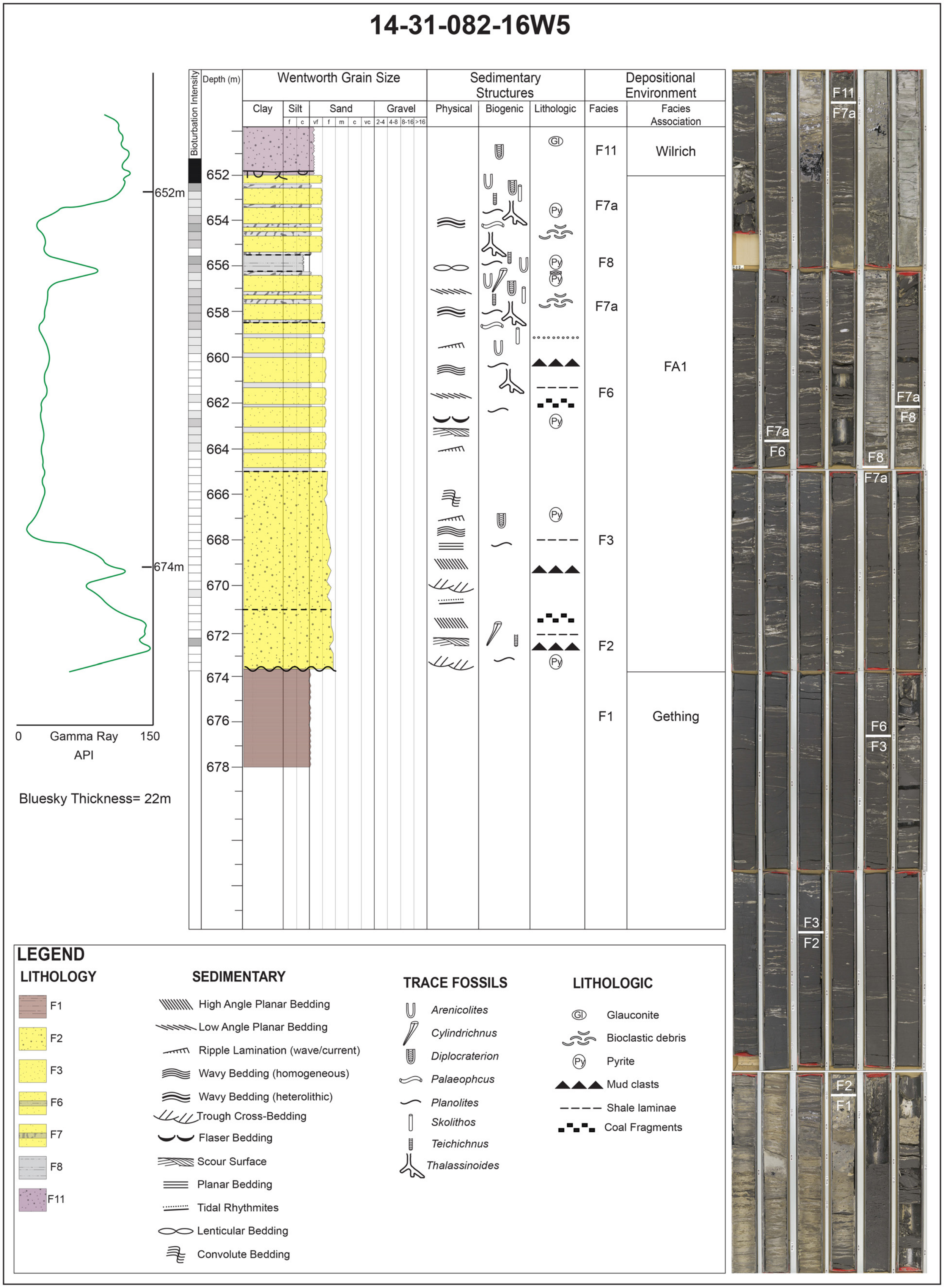



05-29-082-16W5
Bioturbation Intensity
Depth (m)
Wentworth Grain Size
Clay
Silt
Sand
Gravel
f c vf f m c vc 2-4 4-8 8-16 >16
Sedimentary Structures
Physical
Biogenic
Lithologic
Depositional Environment
Facies
Facies Association
666
668
670
672
674
676
678
680
682
684
686
688
690
692
666m
689m
0 Gamma Ray 150
API
F11
F7a
F8
F6
F2
F5
F1
Wilrich
FA1
Gething
Bluesky Thickness= 23m
F11
F7a
F6
F2
F8
F6
F7a
F8
F2
F5
F5
F1
LEGEND
LITHOLOGY
F1
F5
F2
F6
F8
F7
F11
SEDIMENTARY
Ripple Laminae (wave/current)
Wavy Bedding (heterolithic)
High Angle Planar Bedding
Low Angle Planar Bedding
Trough Cross-bedding
Lenticular Bedding
Lenticular Bedding
Convolute Bedding
Scour Surface
Planar Bedding
TRACE FOSSILS
Arenicolites
Asterosoma
Cylindrichnus
Diplocraterion
Macaronichnus
Palaeophycus
Planolites
Skolithos
Teichichnus
Thalassinoides
LITHOLOGIC
Glauconite
Coal Fragments
Coal Lamina
Mud Clasts
Pyrite
Shell Fragments
Bioturbation Intensity
0 1 2 3 4 5 6

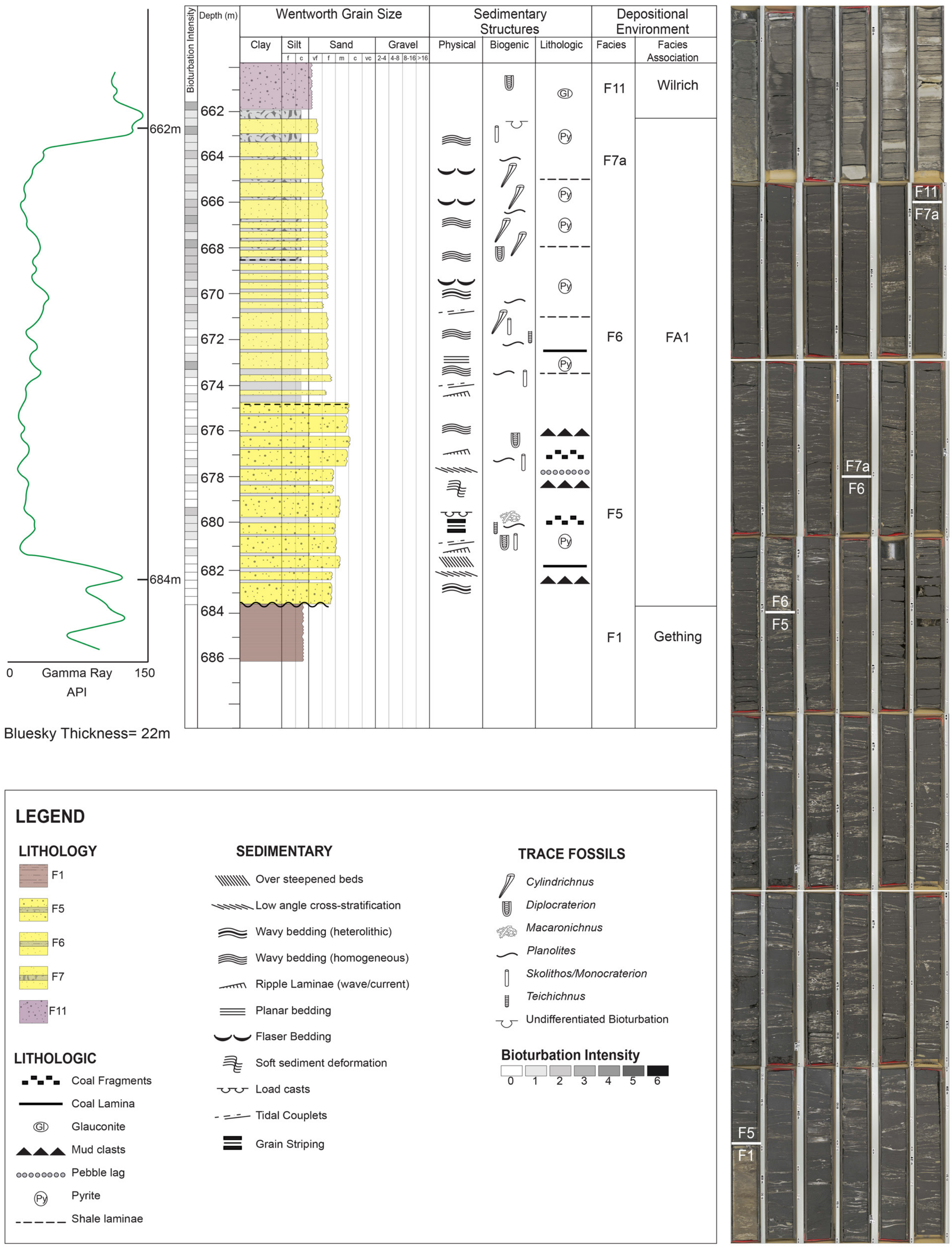

05-33-082-16W5
Bioturbation Intensity
Depth (m)
Wentworth Grain Size
Clay
Silt
Sand
Gravel
Sedimentary Structures
Physical
Biogenic
Lithologic
Depositional Environment
Facies
Facies Association
646m
668m
0
Gamma Ray
150
API
Bluesky Thickness= 22m
F11
Wilrich
F7b
FA2
F6
FA1
F5
F1
Gething
LEGEND
LITHOLOGY
SEDIMENTARY
High Angle Planar Bedding
Low Angle Planar Bedding
Herringbone Lamination
Tidal Rhythmites
Double Mud Drapes
Ripple Lamination (wave/current)
Wavy Bedding (homogeneous)
Wavy Bedding (heterolithic)
Fining Upward Sequence
Lenticular Bedding
Convolute Bedding
Scour Surface
Planar Bedding
TRACE FOSSILS
Arenicolites
Asterosoma
Chondrites
Cylindrichnus
Diplocraterion
Macaronichnus
Palaeophycus
Planolites
Siphonichnus
Skolithos
Teichichnus
Thalassinoides
LITHOLOGIC
Coal Fragments
Glauconite
Mud Clasts
Pebble Lag
Pyrite
Shell Fragments
Wood fragments

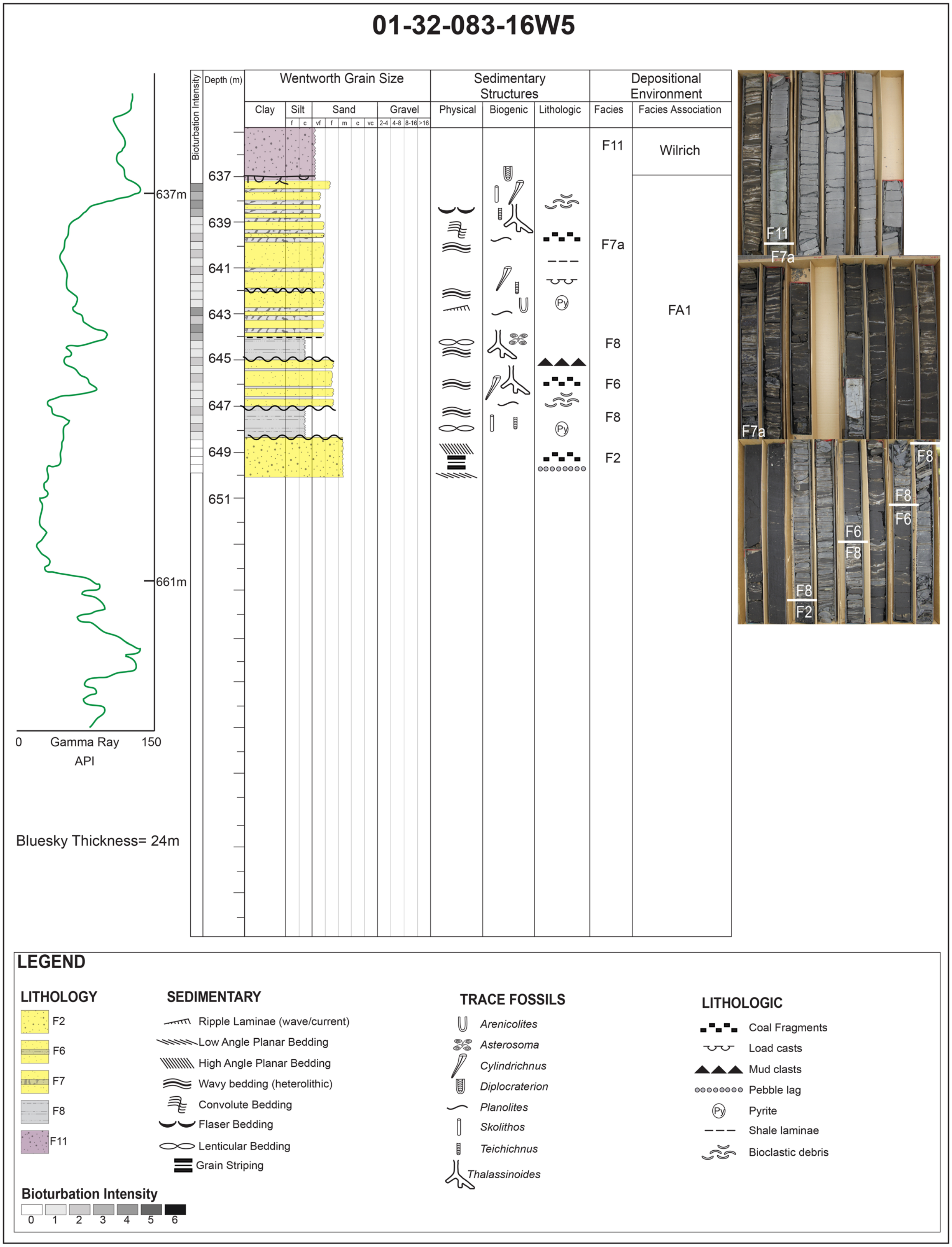

06-30-082-16W5
Depth (m)
Wentworth Grain Size
Clay
Silt
Sand
Gravel
f c vf f m c vc 2-4 4-8 8-16 >16
Sedimentary Structures
Physical
Biogenic
Lithologic
Depositional Environment
Facies
Facies Association
666
668
670
672
674
675
676
677
678
680
682
684
686
688
690
663m
686m
0
Gamma Ray
API
150
F7a
F6
F3
F2
F1
FA1
Gething
Bluesky Thickness= 23m
F7a
F6
RBC
F6
F3
F2
F1
F3
F2
LEGEND
LITHOLOGY
F1
F2
F3
F6
F7
SEDIMENTARY
Wavy Bedding (Homogeneous)
Low Angle Planar Bedding
Hummocky Cross-Stratification
Ripple Lamination (wave/current)
Trough Cross-Stratification
High Angle Planar Bedding
Wavy Bedding (heterolithic)
TRACE FOSSILS
Arenicolites
Cylindrichnus
Palaeophycus
Planolites
Skolithos
Teichichnus
Thalassinoides
LITHOLOGIC
Coal Fragments
Coal Lamina
Granules
Pebble Lag
Mud Clasts
Pyrite
Shale Lamina
Shell Fragments



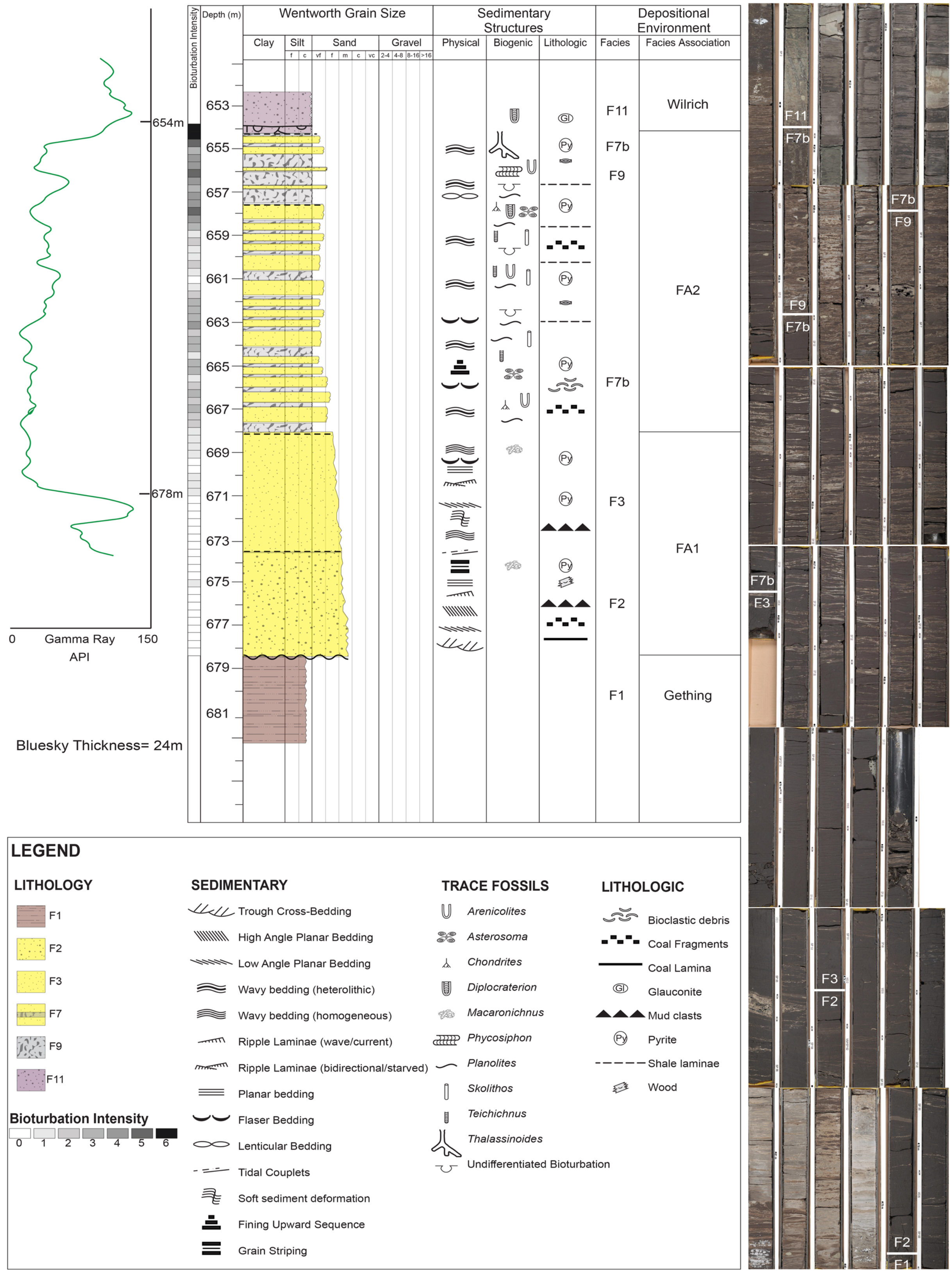
14-31-082-16W5
Gamma Ray API
0
150
652m
674m
Bluesky Thickness= 22m
Bioturbation Intensity
Depth (m)
Wentworth Grain Size
Clay
Silt
Sand
Gravel
f c vf f m c vc 2-4 4-8 8-16 >16
Sedimentary Structures
Physical
Biogenic
Lithologic
Depositional Environment
Facies
Facies Association
652
654
656
658
660
662
664
666
668
670
672
674
676
678
F11
Wilrich
F7a
F8
F7a
F6
F3
F2
F1
FA1
Gething
LEGEND
LITHOLOGY
F1
F2
F3
F6
F7
F8
F11
SEDIMENTARY
High Angle Planar Bedding
Low Angle Planar Bedding
Ripple Lamination (wave/current)
Wavy Bedding (homogeneous)
Wavy Bedding (heterolithic)
Trough Cross-Bedding
Flaser Bedding
Scour Surface
Planar Bedding
Tidal Rhythmites
Lenticular Bedding
Convolute Bedding
TRACE FOSSILS
Arenicolites
Cylindrichnus
Diplocraterion
Palaeophcus
Planolites
Skolithos
Teichichnus
Thalassinoides
LITHOLOGIC
Glauconite
Bioclastic debris
Pyrite
Mud clasts
Shale laminae
Coal Fragments
F11
F7a
F7a
F6
F8
F7a
F7a
F8
F6
F3
F3
F2
F2
F1

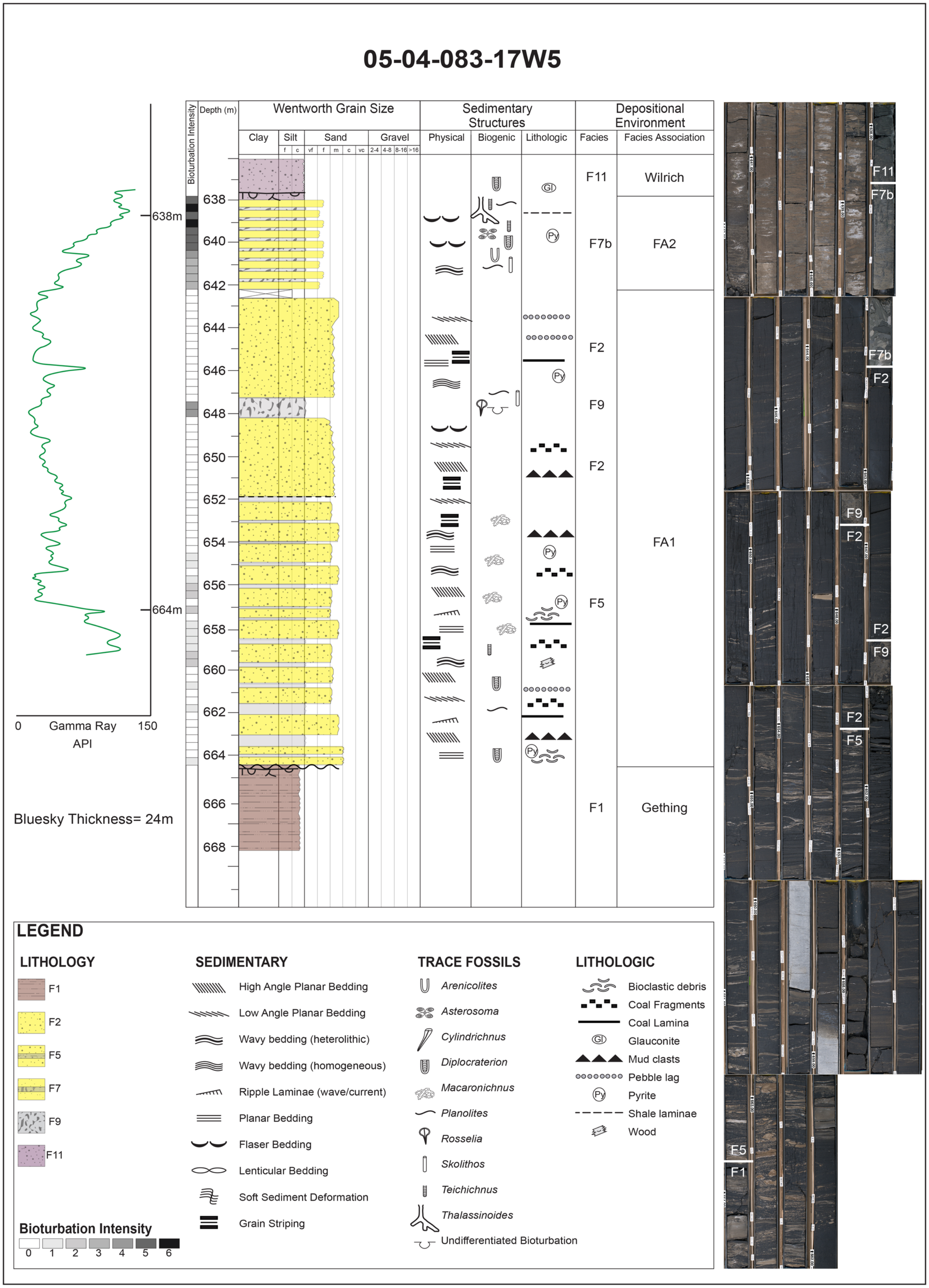
14-36-082-16W5




01-32-083-16W5
Bioturbation Intensity
Depth (m)
Wentworth Grain Size
Clay
Silt
Sand
Gravel
Sedimentary Structures
Physical
Biogenic
Lithologic
Depositional Environment
Facies
Facies Association
637
639
641
643
645
647
649
651
637m
661m
0
Gamma Ray
API
150
F11
Wilrich
F7a
FA1
F8
F6
F8
F2
F11
F7a
F7a
F8
F8
F6
F6
F8
F8
F2
Bluesky Thickness= 24m
LEGEND
LITHOLOGY
F2
F6
F7
F8
F11
SEDIMENTARY
Ripple Laminae (wave/current)
Low Angle Planar Bedding
High Angle Planar Bedding
Wavy bedding (heterolithic)
Convolute Bedding
Flaser Bedding
Lenticular Bedding
Grain Striping
TRACE FOSSILS
Arenicolites
Asterosoma
Cylindrichnus
Diplocraterion
Planolites
Skolithos
Teichichnus
Thalassinoides
LITHOLOGIC
Coal Fragments
Load casts
Mud clasts
Pebble lag
Pyrite
Shale laminae
Bioclastic debris
Bioturbation Intensity
0 1 2 3 4 5 6

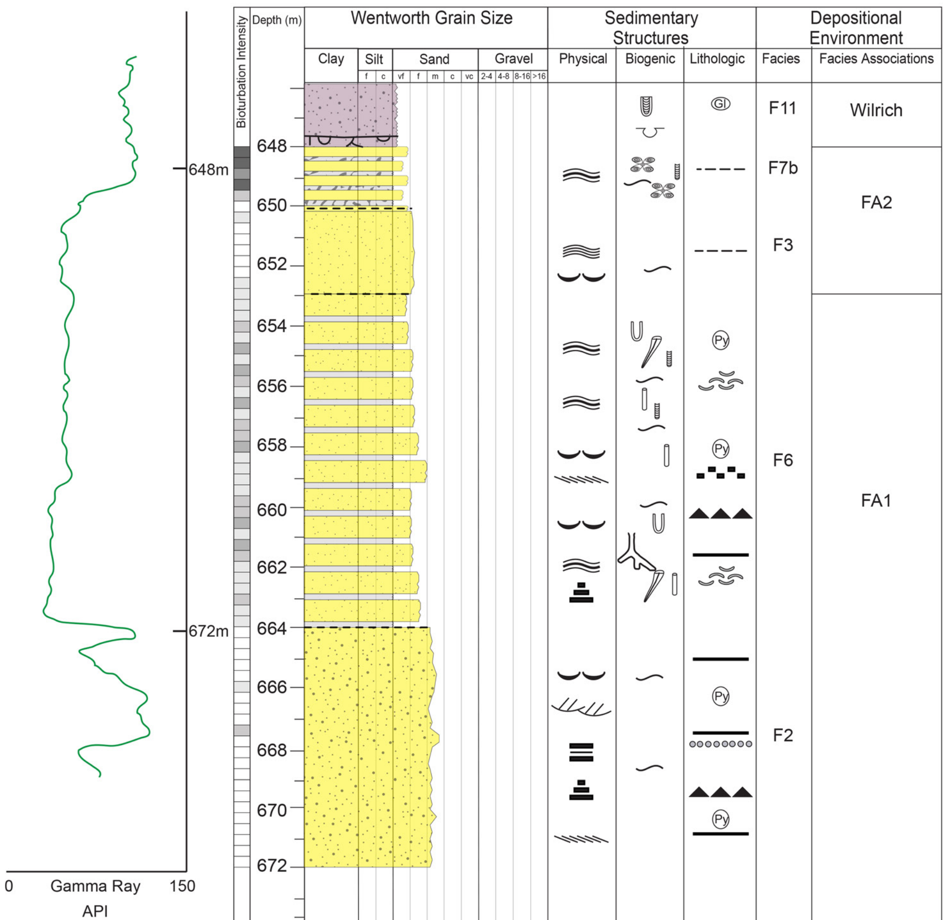
03-18-083-16W5





05-04-083-17W5
638m
664m
0
Gamma Ray
150
API
Bluesky Thickness= 24m
Bioturbation Intensity
Depth (m)
Wentworth Grain Size
Clay
Silt
Sand
Gravel
Sedimentary Structures
Physical
Biogenic
Lithologic
Depositional Environment
Facies
Facies Association
638
640
642
644
646
648
650
652
654
656
658
660
662
664
666
668
F11
Wilrich
F7b
FA2
F2
F9
F2
FA1
F5
F1
Gething
LEGEND
LITHOLOGY
F1
F2
F5
F7
F9
F11
SEDIMENTARY
High Angle Planar Bedding
Low Angle Planar Bedding
Wavy bedding (heterolithic)
Wavy bedding (homogeneous)
Ripple Laminae (wave/current)
Planar Bedding
Flaser Bedding
Lenticular Bedding
Soft Sediment Deformation
Grain Striping
TRACE FOSSILS
Arenicolites
Asterosoma
Cylindrichnus
Diplocraterion
Macaronichnus
Planolites
Rosselia
Skolithos
Teichichnus
Thalassinoides
Undifferentiated Bioturbation
LITHOLOGIC
Bioclastic debris
Coal Fragments
Coal Lamina
Glauconite
Mud clasts
Pebble lag
Pyrite
Shale laminae
Wood
Bioturbation Intensity
0 1 2 3 4 5 6
F11
F7b
F7b
F2
F9
F2
F2
F9
F2
F5
F5
F1

06-05-083-16W5



Bluesky Thickness= 24m

LEGEND

LITHOLOGY

- F2
- F3
- F6
- F7
- F11

SEDIMENTARY

- Low Angle Planar Bedding
- Wavy Bedding (heterolithic)
- Wavy Bedding (homogeneous)
- Flaser Bedding
- Trough Cross-Bedding
- Graded Bedding (Normal)
- Grain Striping

TRACE FOSSILS

- *Arenicolites*
- *Asterosoma*
- *Cylindrichnus*
- *Diplocraterion*
- *Planolites*
- *Skolithos*
- *Teichichnus*
- *Thalassinoides*
- Undifferentiated Bioturbation

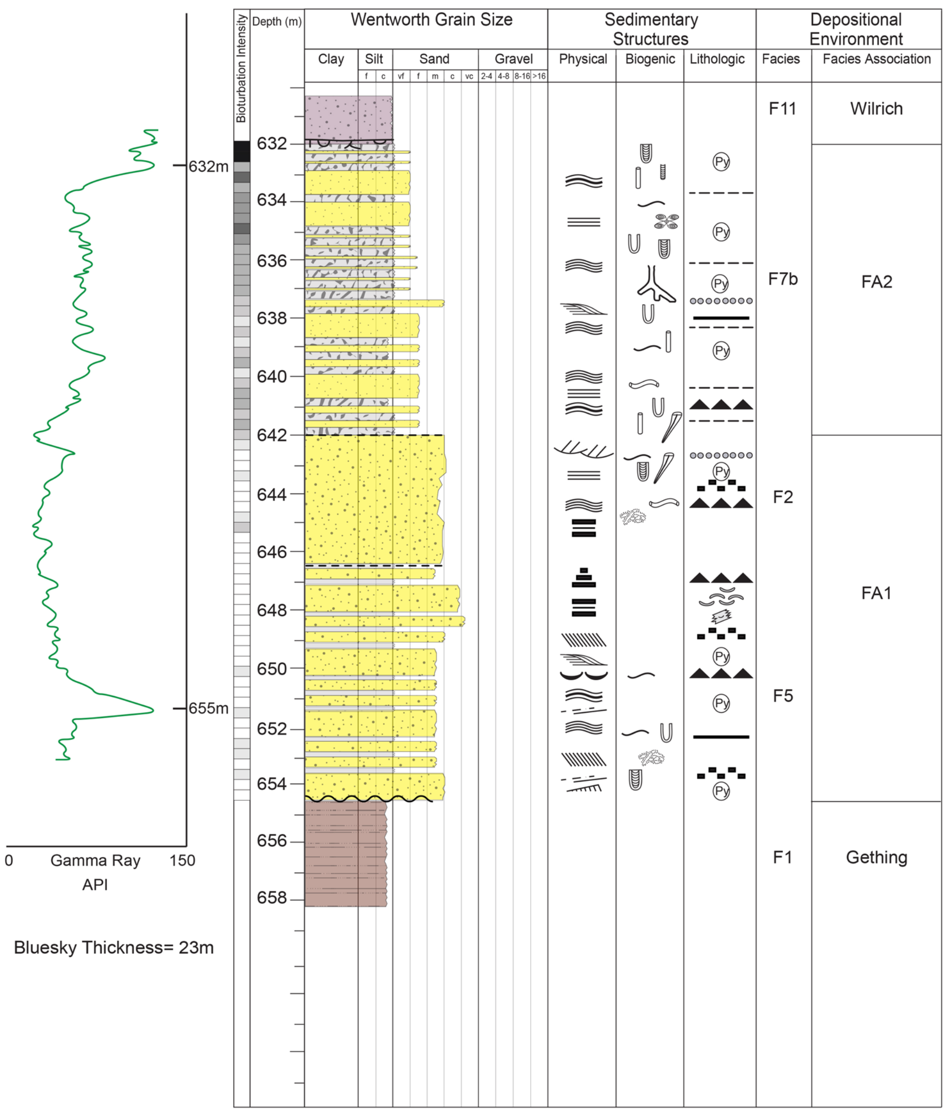
LITHOLOGIC

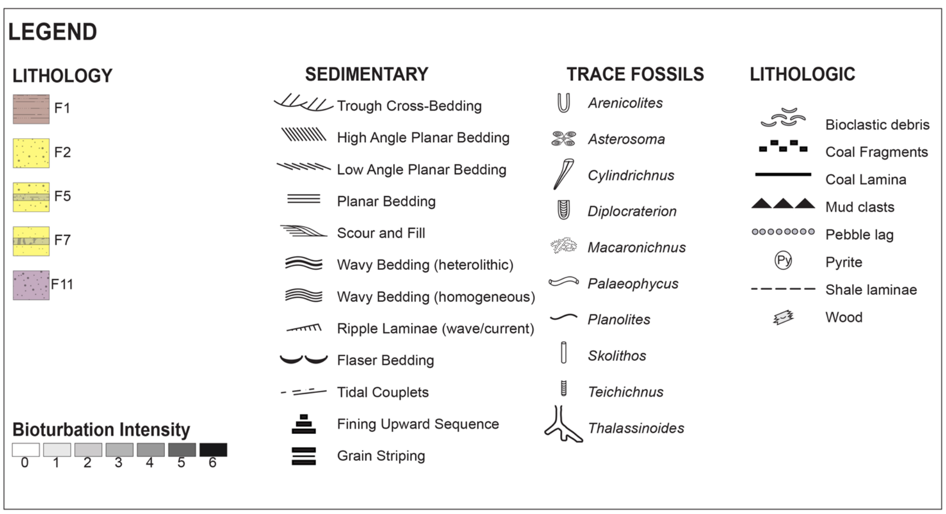
- Bioclastic debris
- Coal Fragments
- Coal Lamina
- Mud clasts
- Pebble lag
- Pyrite
- Shale laminae

Bioturbation Intensity

0 1 2 3 4 5 6

07-09-083-16W5





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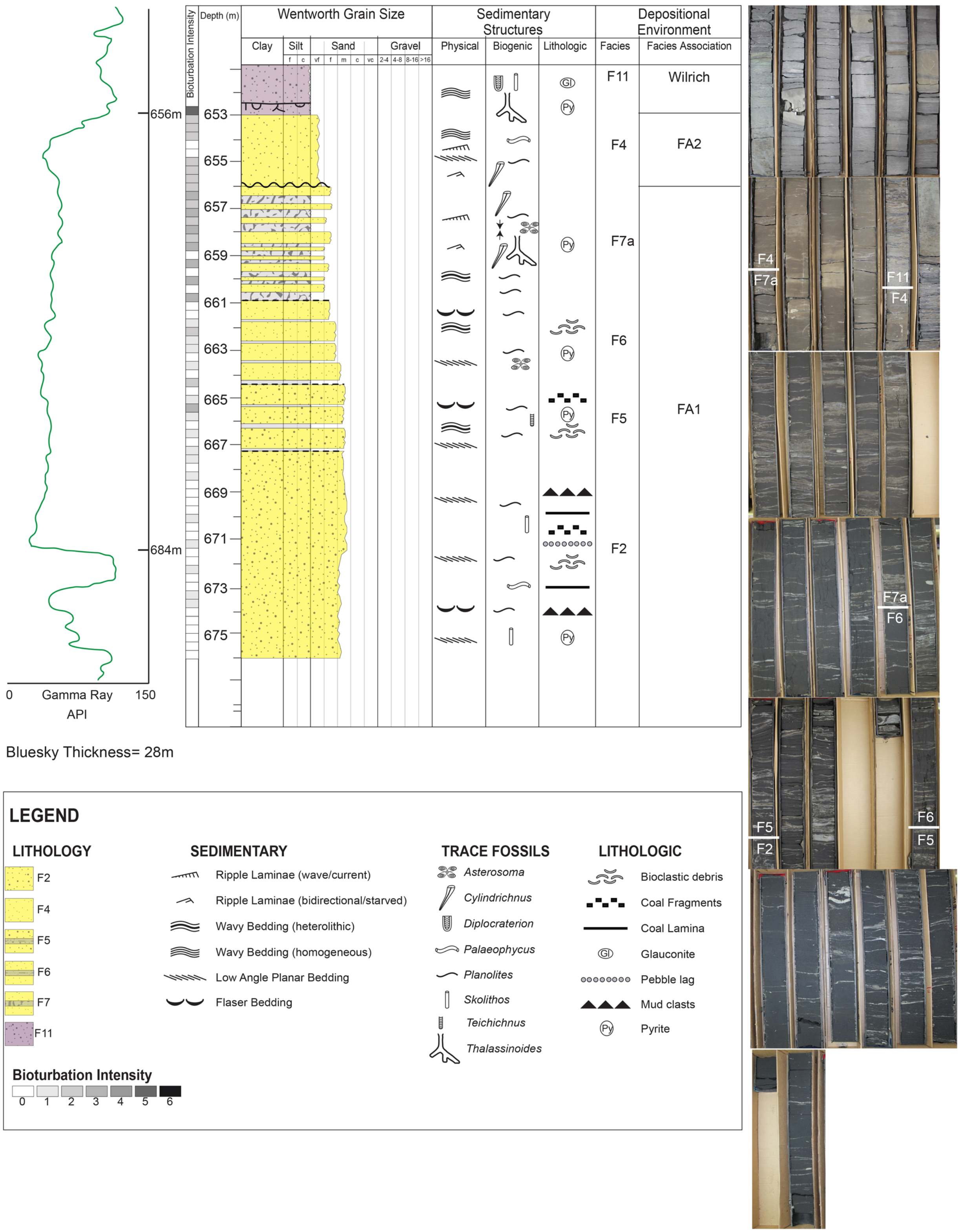

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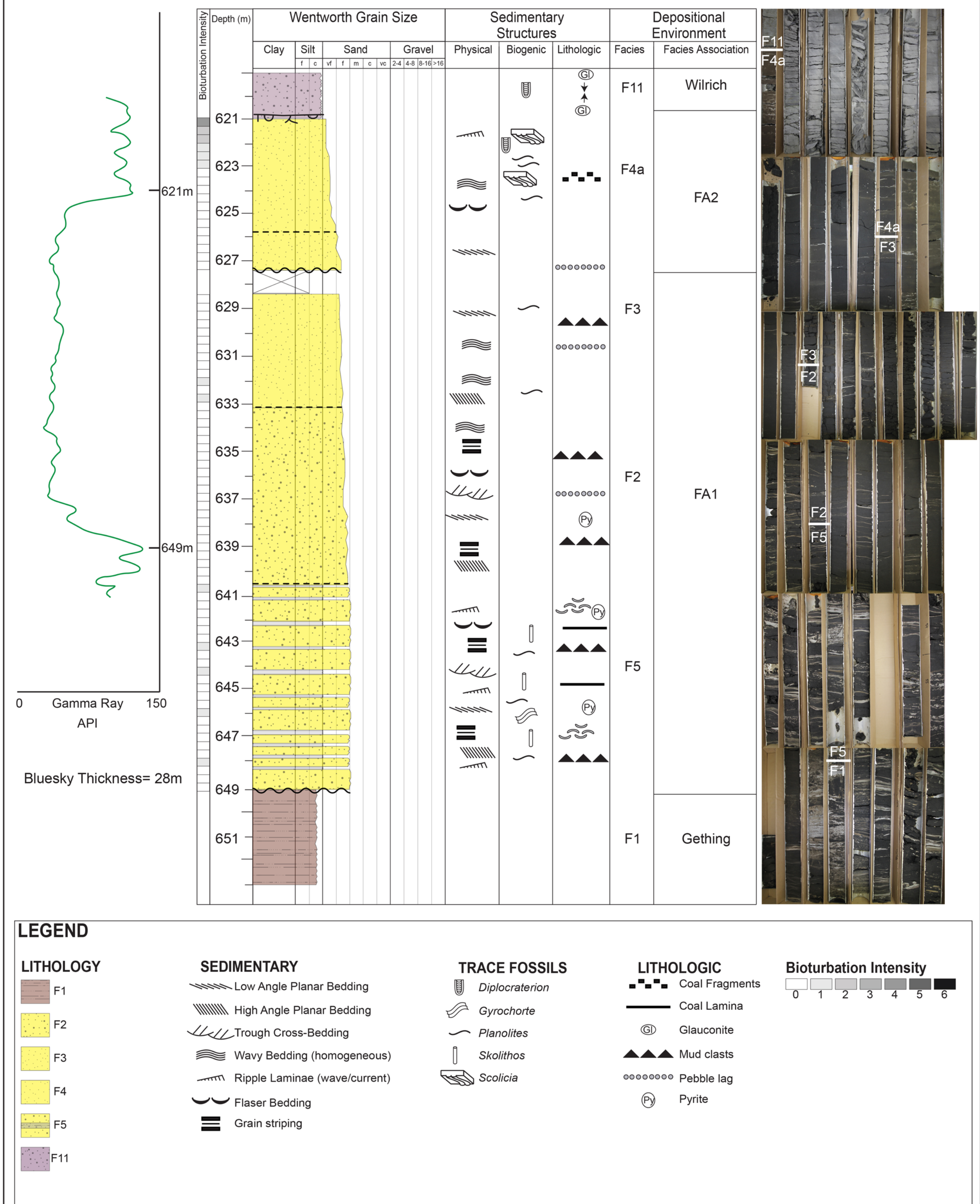

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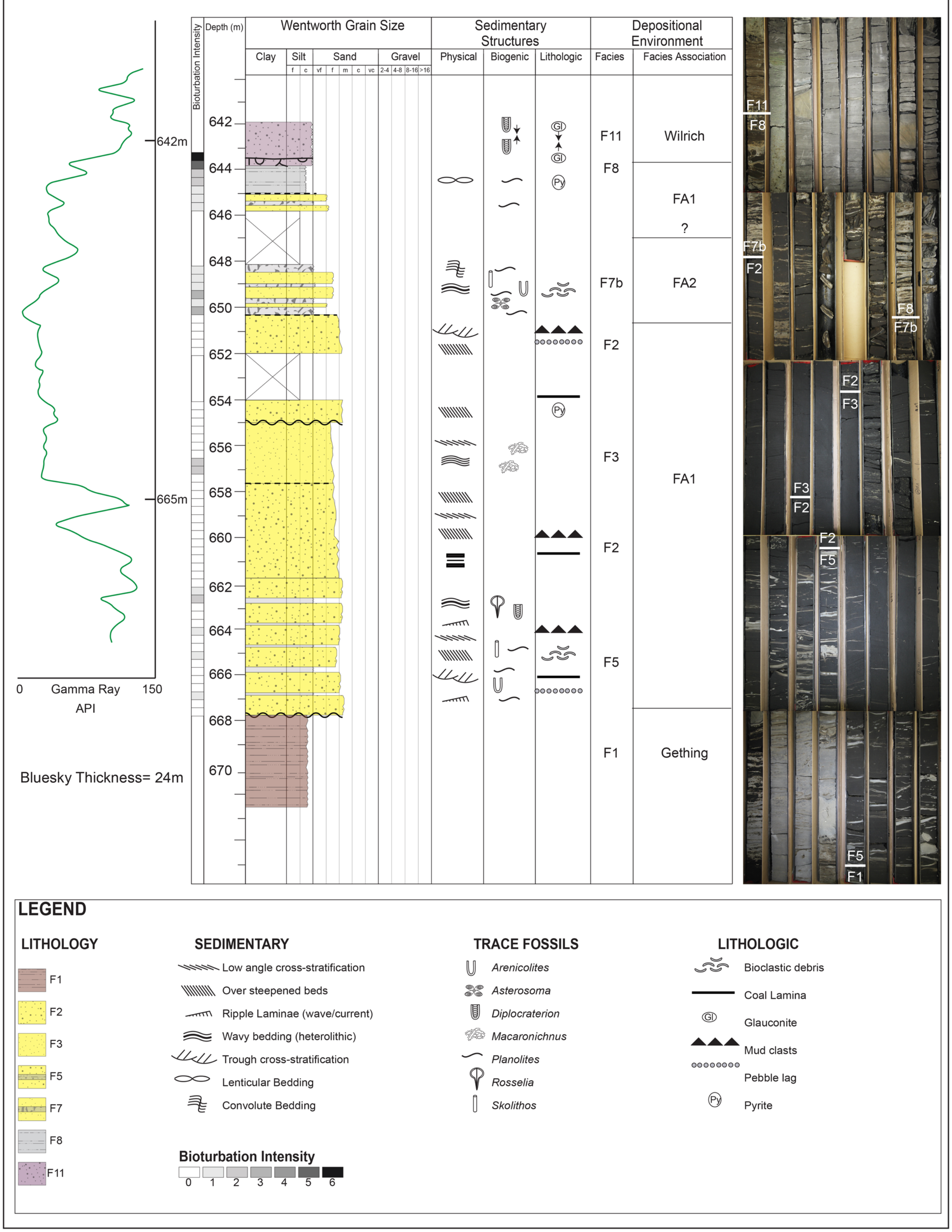

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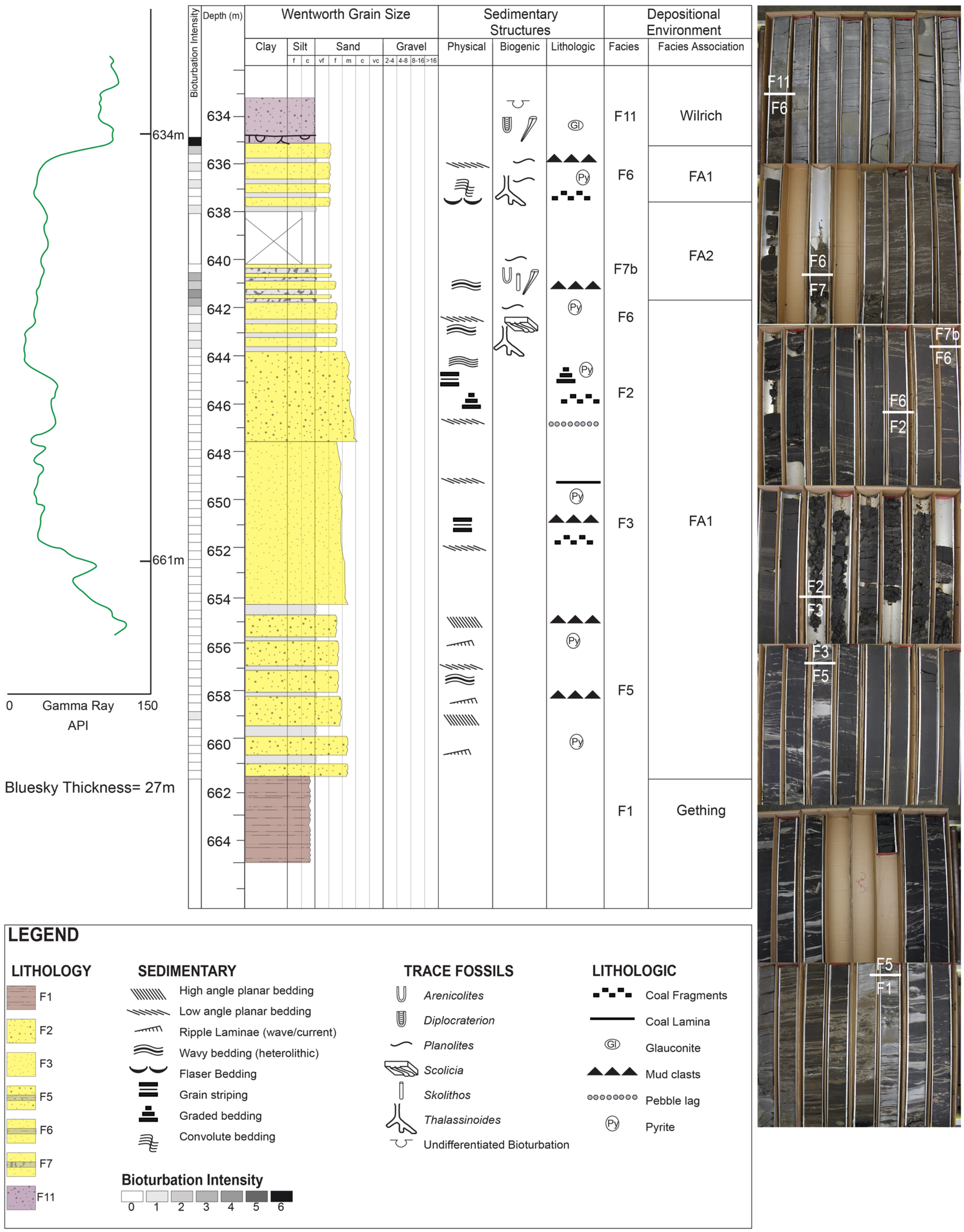

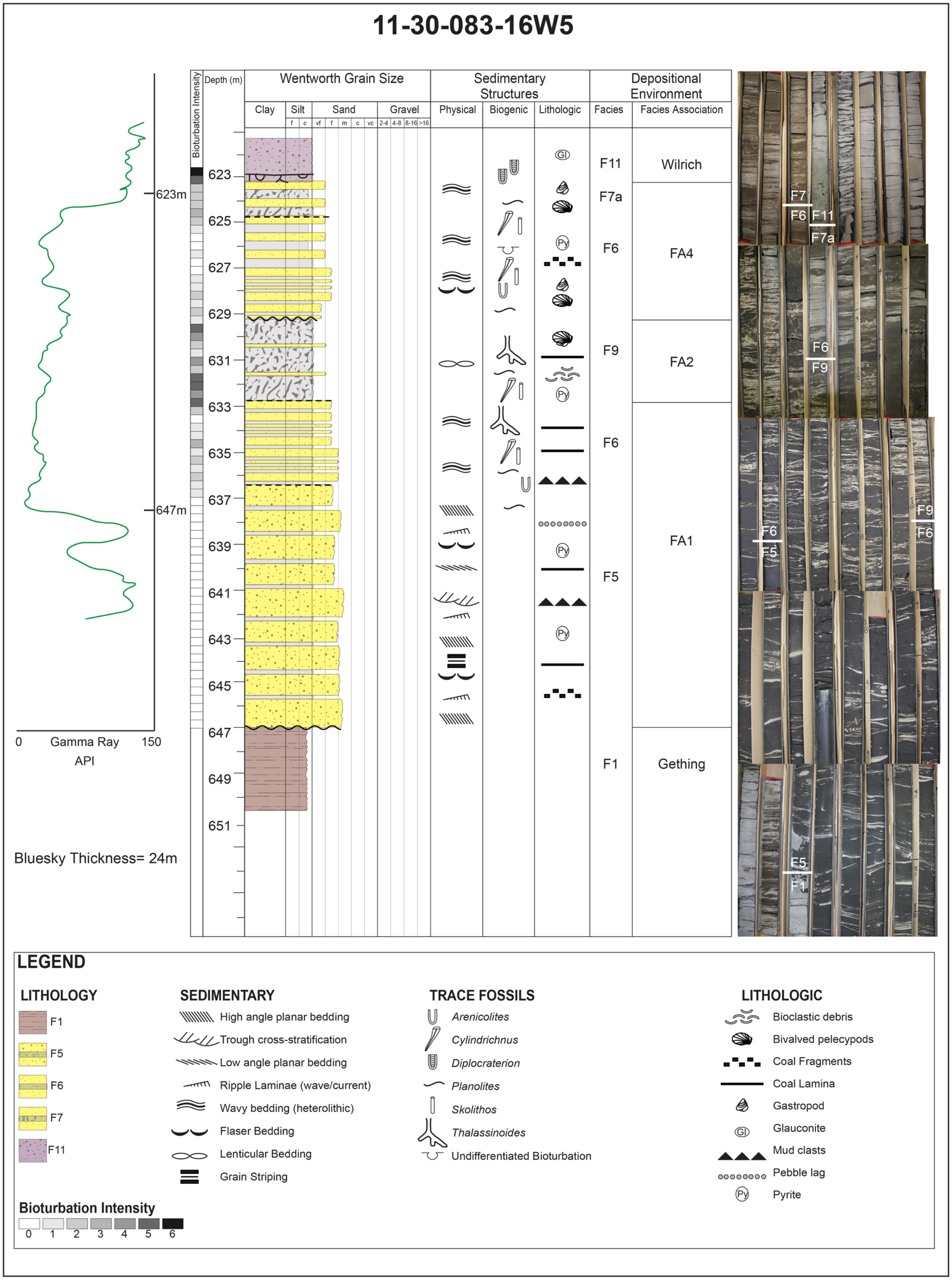
11-30-083-16W5
Bioturbation Intensity
Depth (m)
Wentworth Grain Size
Clay
Silt
f
c
Sand
vf
f
m
c
vc
Gravel
2-4
4-8
8-16
>16
Sedimentary Structures
Physical
Biogenic
Lithologic
Depositional Environment
Facies
Facies Association
623
625
627
629
631
633
635
637
639
641
643
645
647
649
651
623m
647m
0
Gamma Ray
150
API
F11
Wilrich
F7a
F6
FA4
F9
FA2
F6
FA1
F5
F1
Gething
Bluesky Thickness= 24m
F7
F6
F11
F7a
F6
F9
F6
F5
F9
F6
F5
F1
LEGEND
LITHOLOGY
F1
F5
F6
F7
F11
SEDIMENTARY
High angle planar bedding
Trough cross-stratification
Low angle planar bedding
Ripple Laminae (wave/current)
Wavy bedding (heterolithic)
Flaser Bedding
Lenticular Bedding
Grain Striping
TRACE FOSSILS
Arenicolites
Cylindrichnus
Diplocraterion
Planolites
Skolithos
Thalassinoides
Undifferentiated Bioturbation
LITHOLOGIC
Bioclastic debris
Bivalved pelecypods
Coal Fragments
Coal Lamina
Gastropod
Glauconite
Mud clasts
Pebble lag
Pyrite
Bioturbation Intensity
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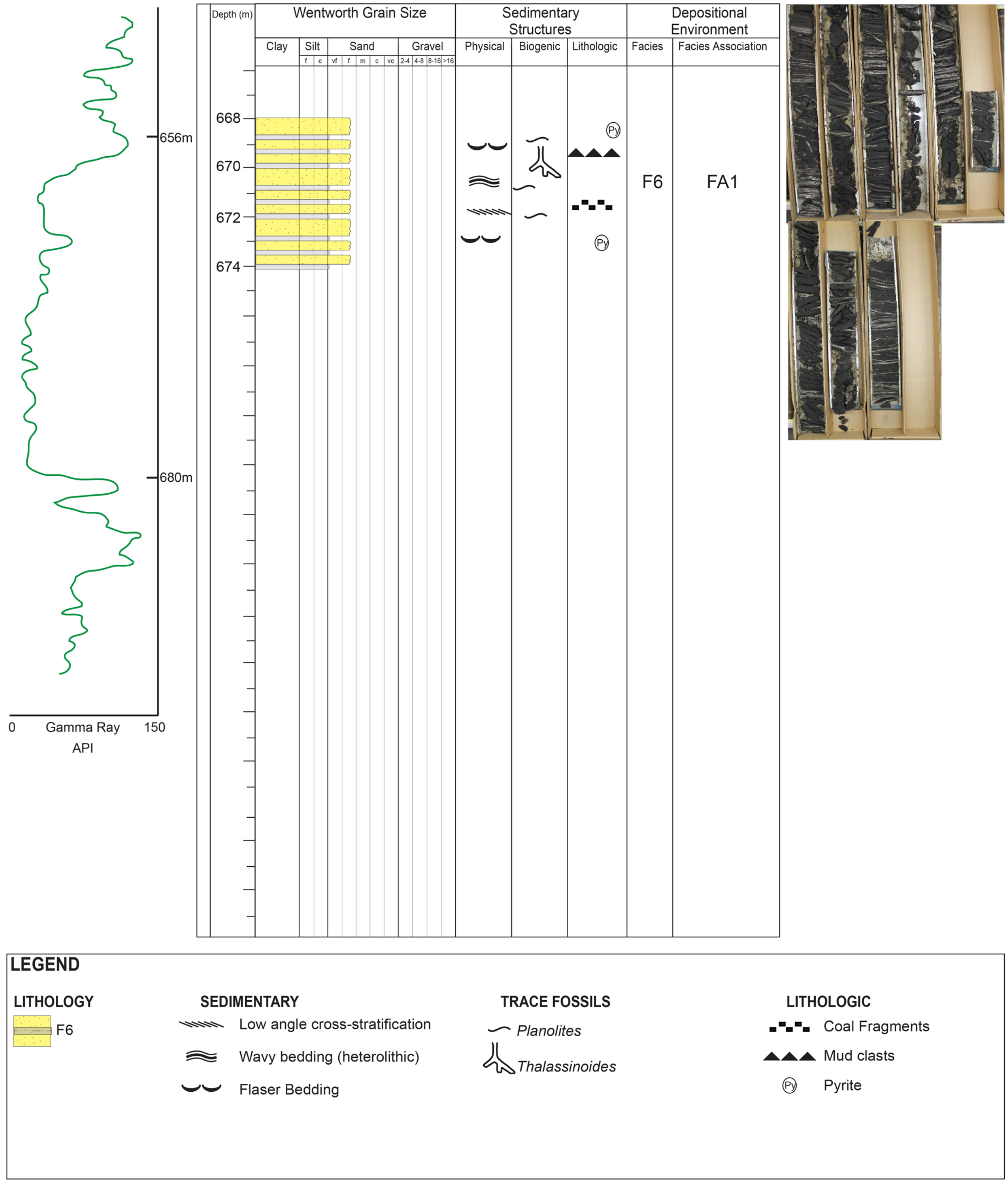
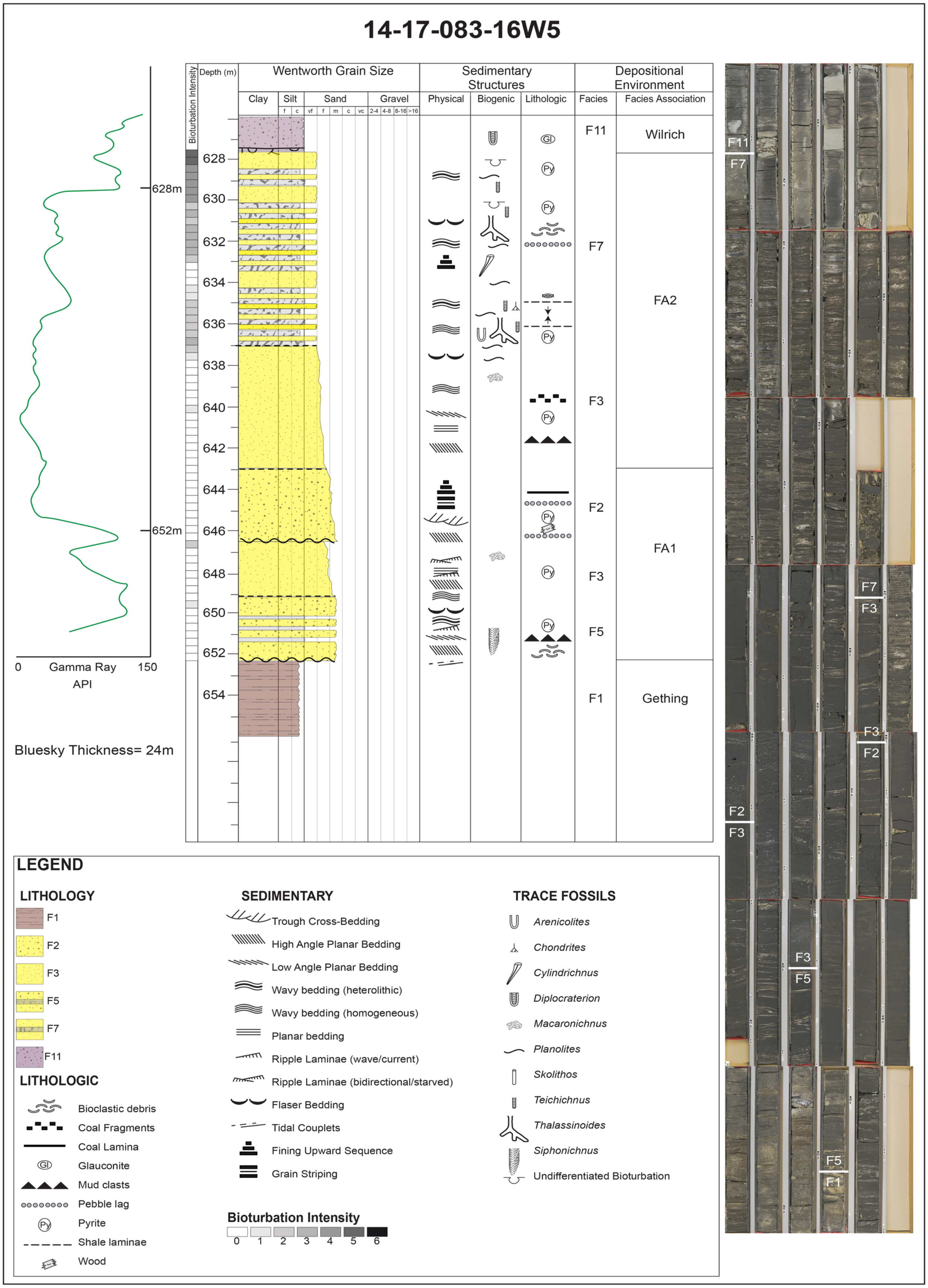
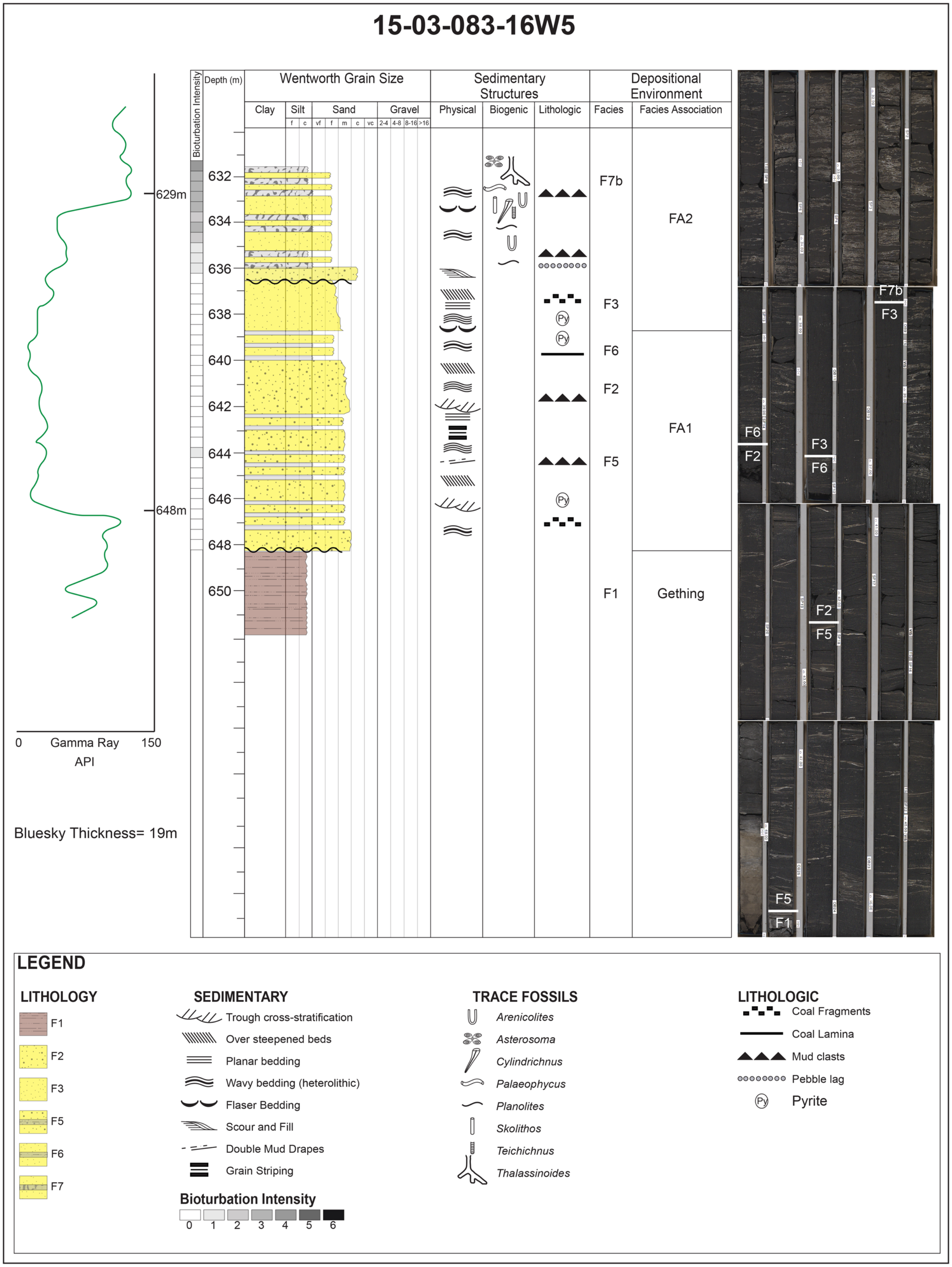
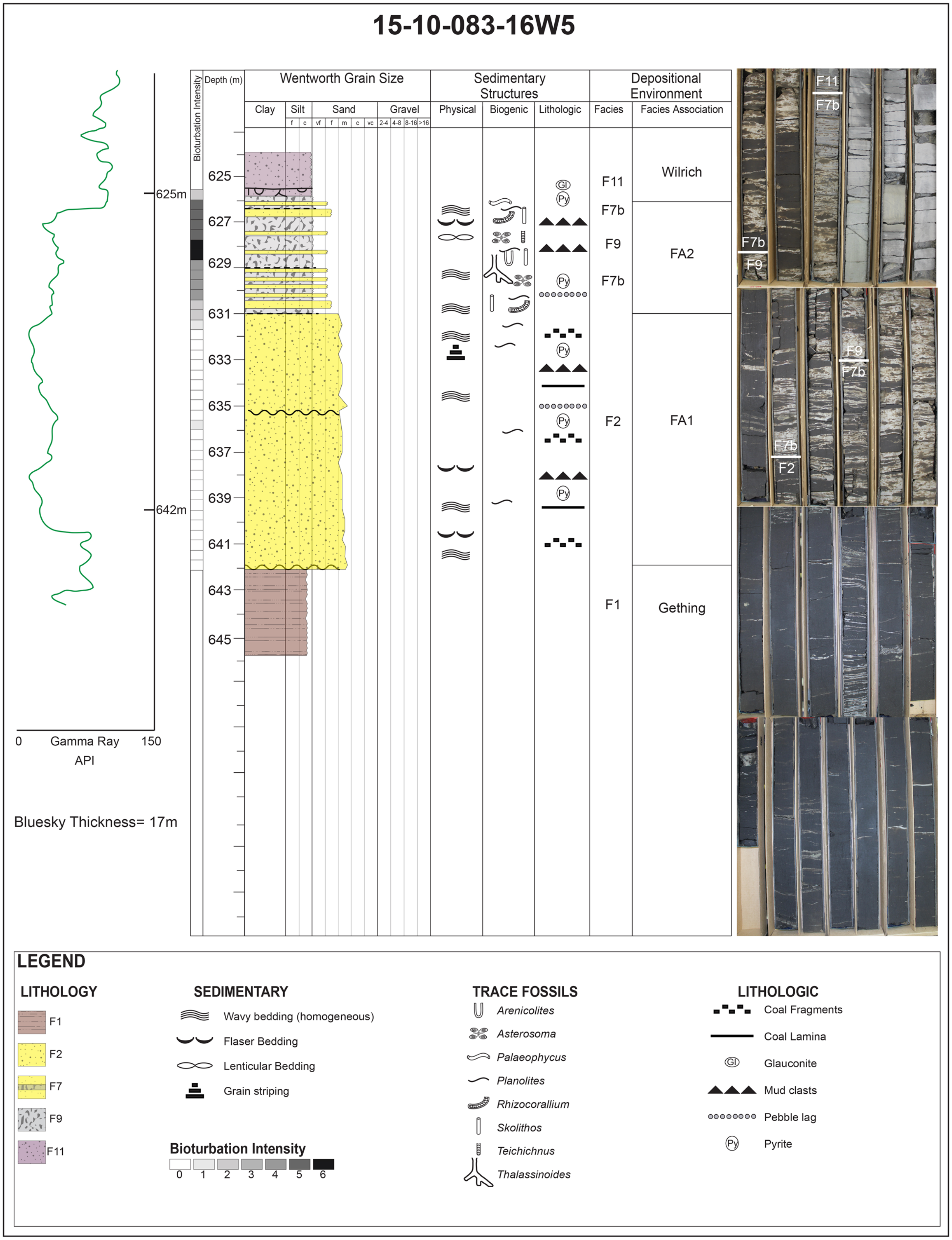
1
2
3
4
5
6

14-06-083-16W5

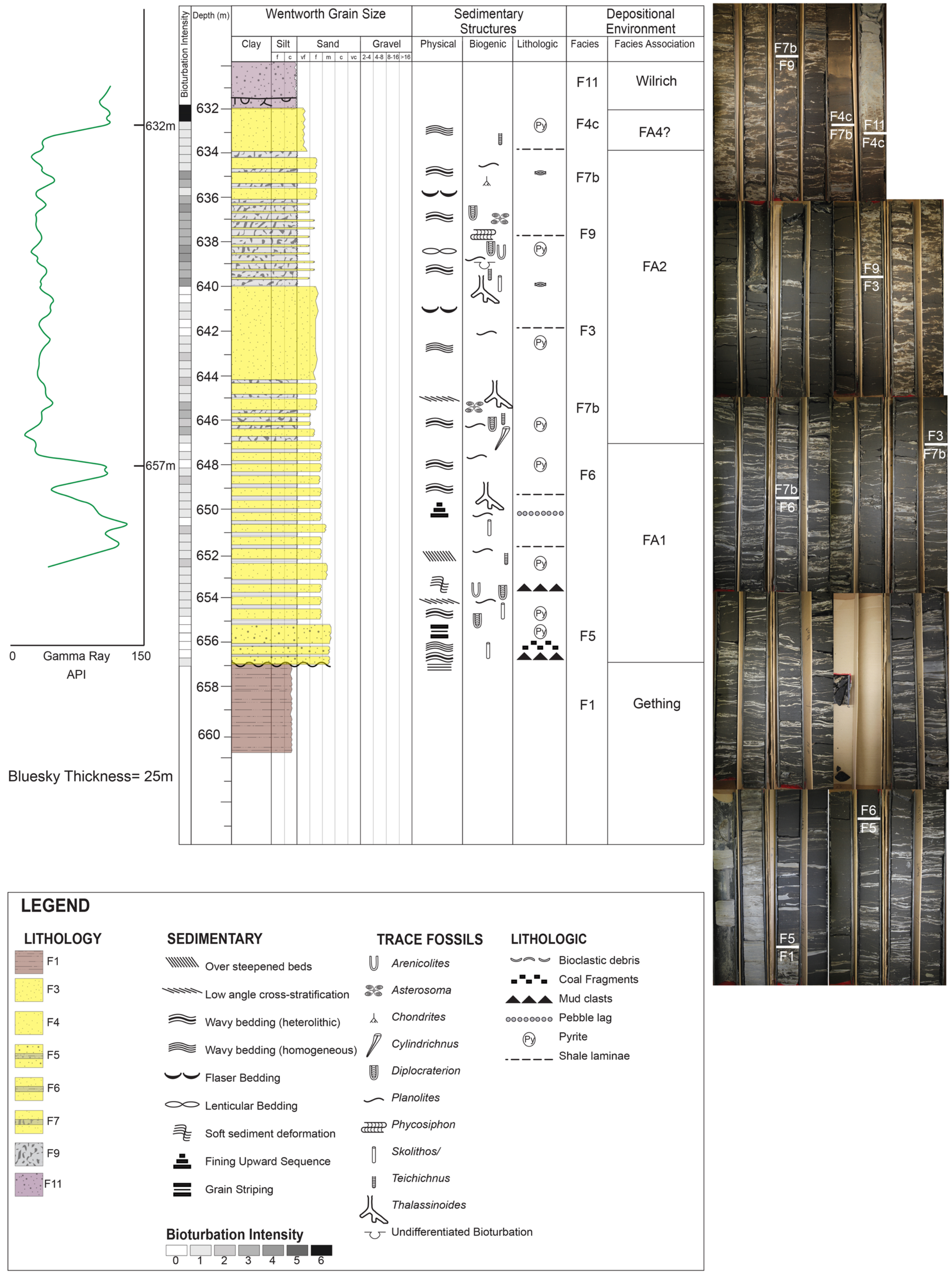



14-17-083-16W5
Bioturbation Intensity
Depth (m)
Wentworth Grain Size
Clay
Silt
Sand
Gravel
f c vf f m c vc 2-4 4-8 8-16 >16
Sedimentary Structures
Physical
Biogenic
Lithologic
Depositional Environment
Facies
Facies Association
628
630
632
634
636
638
640
642
644
646
648
650
652
654
628m
652m
0 Gamma Ray 150
API
Bluesky Thickness= 24m
F11
F7
F3
F2
F3
F5
F1
Wilrich
FA2
FA1
Gething
LEGEND
LITHOLOGY
F1
F2
F3
F5
F7
F11
LITHOLOGIC
Bioclastic debris
Coal Fragments
Coal Lamina
Glauconite
Mud clasts
Pebble lag
Pyrite
Shale laminae
Wood
SEDIMENTARY
Trough Cross-Bedding
High Angle Planar Bedding
Low Angle Planar Bedding
Wavy bedding (heterolithic)
Wavy bedding (homogeneous)
Planar bedding
Ripple Laminae (wave/current)
Ripple Laminae (bidirectional/starved)
Flaser Bedding
Tidal Couplets
Fining Upward Sequence
Grain Striping
Bioturbation Intensity
0 1 2 3 4 5 6
TRACE FOSSILS
Arenicolites
Chondrites
Cylindrichnus
Diplocraterion
Macaronichnus
Planolites
Skolithos
Teichichnus
Thalassinoides
Siphonichnus
Undifferentiated Bioturbation
F11
F7
F7
F3
F3
F2
F2
F3
F3
F5
F5
F1

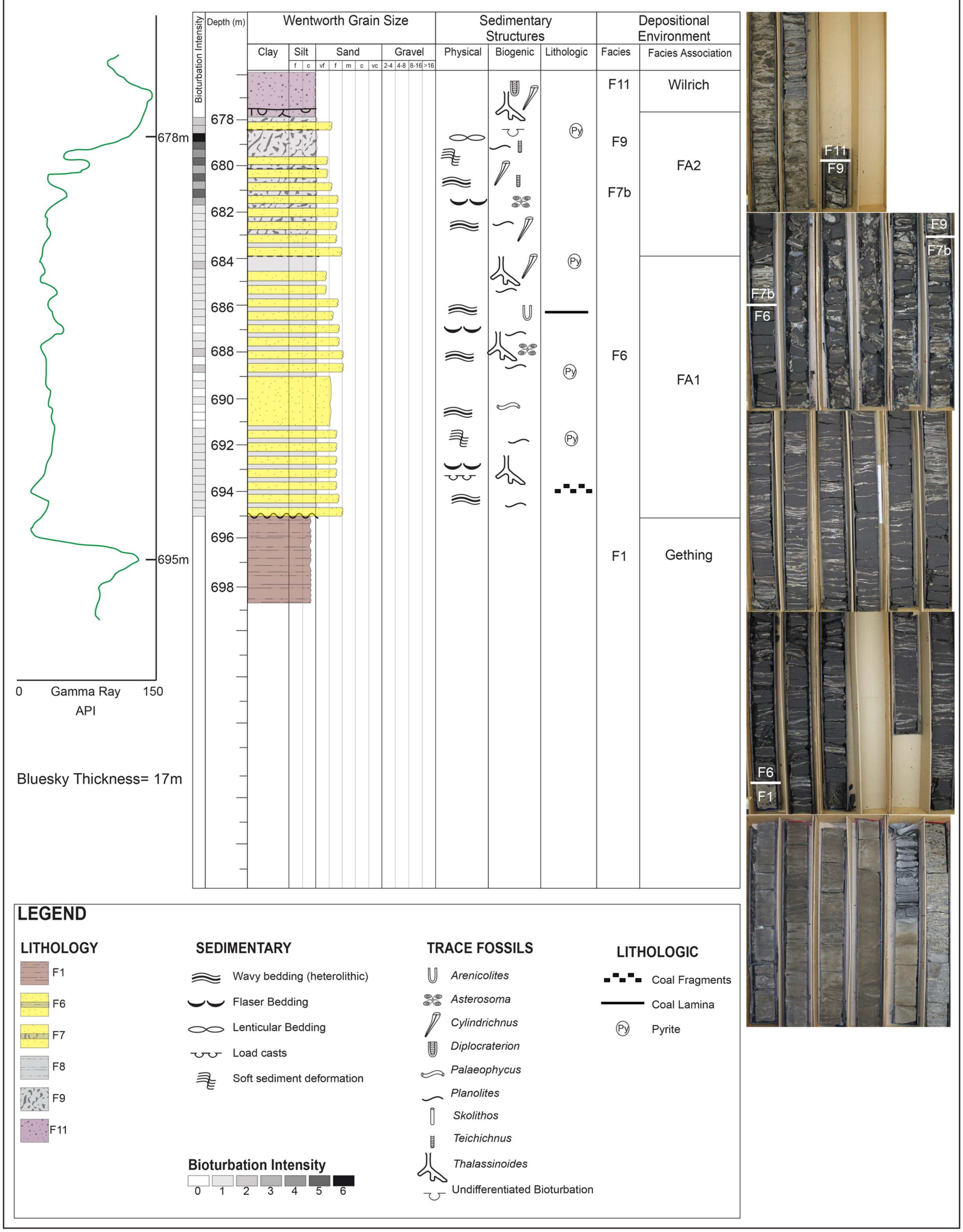

15-03-083-16W5
Bioturbation Intensity
Depth (m)
Wentworth Grain Size
Clay
Silt
Sand
Gravel
f c vf f m c vc 2-4 4-8 8-16 >16
Sedimentary Structures
Physical
Biogenic
Lithologic
Depositional Environment
Facies
Facies Association
632
634
636
638
640
642
644
646
648
650
629m
648m
F7b
F3
F6
F2
F5
F1
FA2
FA1
Gething
0 Gamma Ray 150
API
Bluesky Thickness= 19m
LEGEND
LITHOLOGY
F1
F2
F3
F5
F6
F7
SEDIMENTARY
Trough cross-stratification
Over steepened beds
Planar bedding
Wavy bedding (heterolithic)
Flaser Bedding
Scour and Fill
Double Mud Drapes
Grain Striping
Bioturbation Intensity
0 1 2 3 4 5 6
TRACE FOSSILS
Arenicolites
Asterosoma
Cylindrichnus
Palaeophycus
Planolites
Skolithos
Teichichnus
Thalassinoides
LITHOLOGIC
Coal Fragments
Coal Lamina
Mud clasts
Pebble lag
Pyrite


15-10-083-16W5
Bioturbation Intensity
Depth (m)
Wentworth Grain Size
Clay
Silt
Sand
Gravel
f c vf f m c vc 2-4 4-8 8-16 >16
Sedimentary Structures
Physical
Biogenic
Lithologic
Depositional Environment
Facies
Facies Association
625m
642m
625
627
629
631
633
635
637
639
641
643
645
F11
F7b
F9
F7b
F2
F1
Wilrich
FA2
FA1
Gething
0 Gamma Ray 150
API
Bluesky Thickness= 17m
F11
F7b
F7b
F9
F9
F7b
F7b
F2
LEGEND
LITHOLOGY
F1
F2
F7
F9
F11
SEDIMENTARY
Wavy bedding (homogeneous)
Flaser Bedding
Lenticular Bedding
Grain striping
Bioturbation Intensity
0 1 2 3 4 5 6
TRACE FOSSILS
Arenicolites
Asterosoma
Palaeophycus
Planolites
Rhizocorallium
Skolithos
Teichichnus
Thalassinoides
LITHOLOGIC
Coal Fragments
Coal Lamina
Glauconite
Mud clasts
Pebble lag
Pyrite

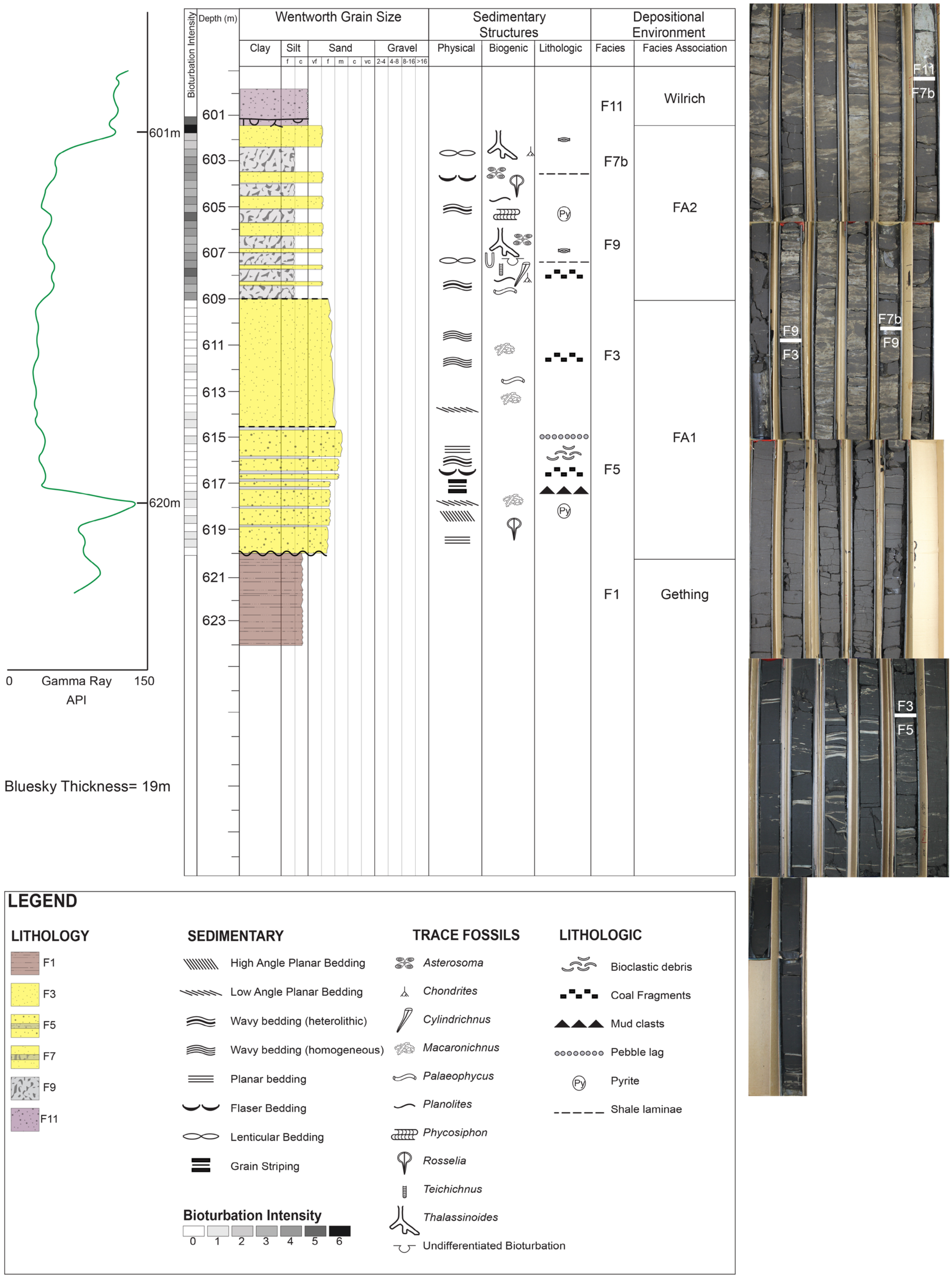
16-18-083-16W5

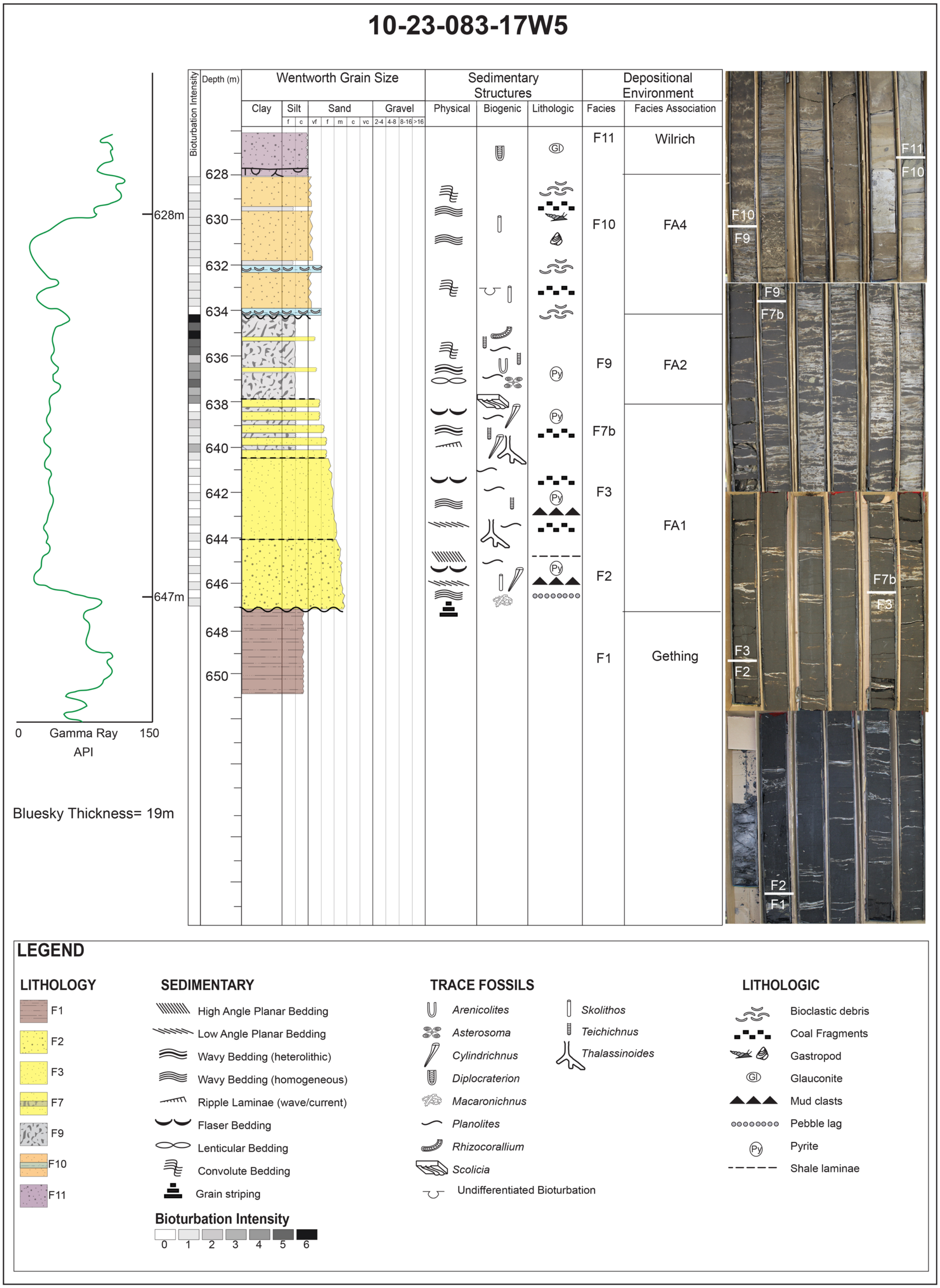


04-01-083-17W5

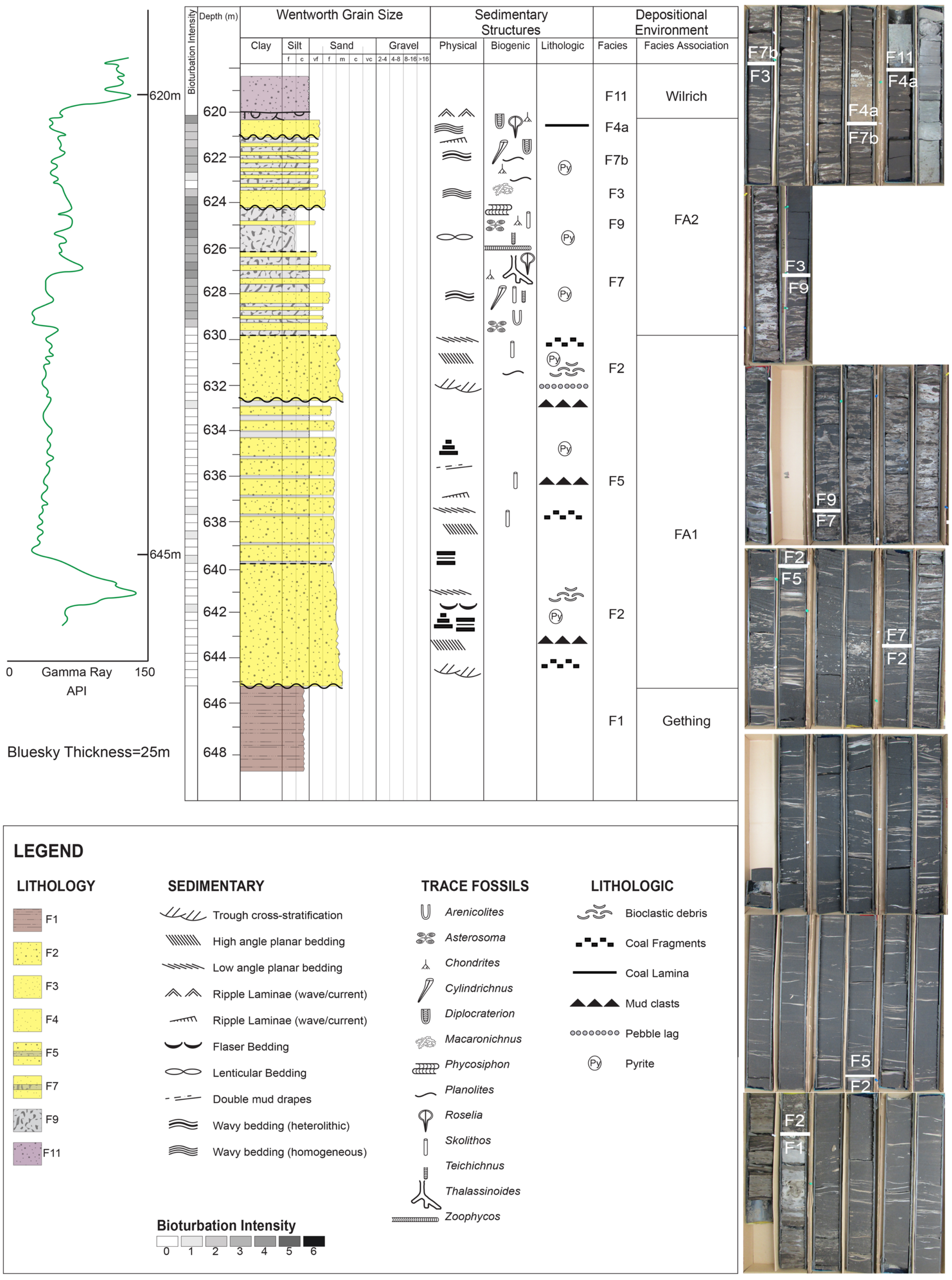


08-35-083-17W5

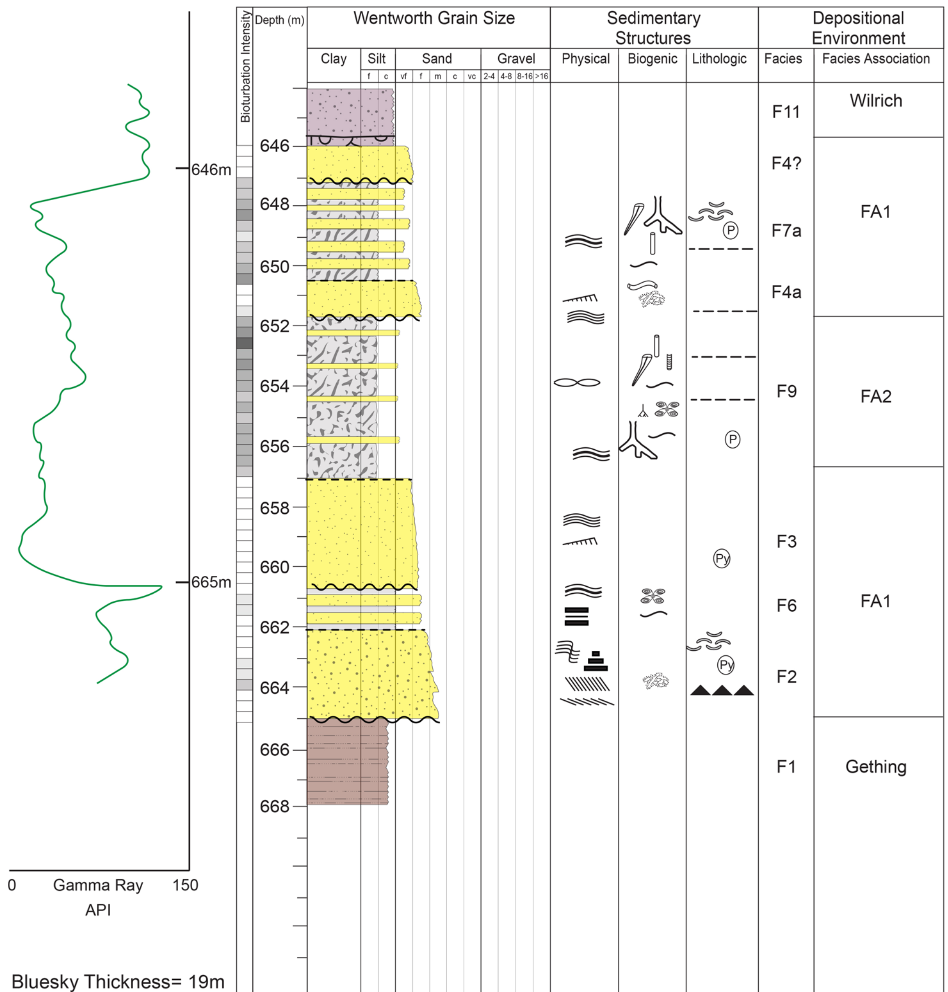


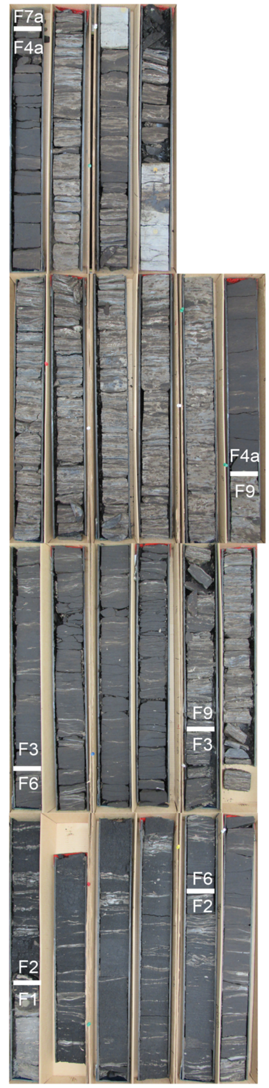

10-23-083-17W5
628m
647m
0
Gamma Ray
150
API
Bluesky Thickness= 19m
Bioturbation Intensity
Depth (m)
628
630
632
634
636
638
640
642
644
646
648
650
Wentworth Grain Size
Clay
Silt
Sand
Gravel
f
c
vf
f
m
c
vc
2-4
4-8
8-16
>16
Sedimentary Structures
Physical
Biogenic
Lithologic
Depositional Environment
Facies
Facies Association
F11
Wilrich
F10
FA4
F9
FA2
F7b
F3
FA1
F2
F1
Gething
F11
F10
F10
F9
F9
F7b
F7b
F3
F3
F2
F2
F1
LEGEND
LITHOLOGY
F1
F2
F3
F7
F9
F10
F11
SEDIMENTARY
High Angle Planar Bedding
Low Angle Planar Bedding
Wavy Bedding (heterolithic)
Wavy Bedding (homogeneous)
Ripple Laminae (wave/current)
Flaser Bedding
Lenticular Bedding
Convolute Bedding
Grain striping
Bioturbation Intensity
0
1
2
3
4
5
6
TRACE FOSSILS
Arenicolites
Asterosoma
Cylindrichnus
Diplocraterion
Macaronichnus
Planolites
Rhizocorallium
Scolicia
Skolithos
Teichichnus
Thalassinoides
Undifferentiated Bioturbation
LITHOLOGIC
Bioclastic debris
Coal Fragments
Gastropod
Glauconite
Mud clasts
Pebble lag
Pyrite
Shale laminae

10-36-083-17W5



12-13-083-17W5



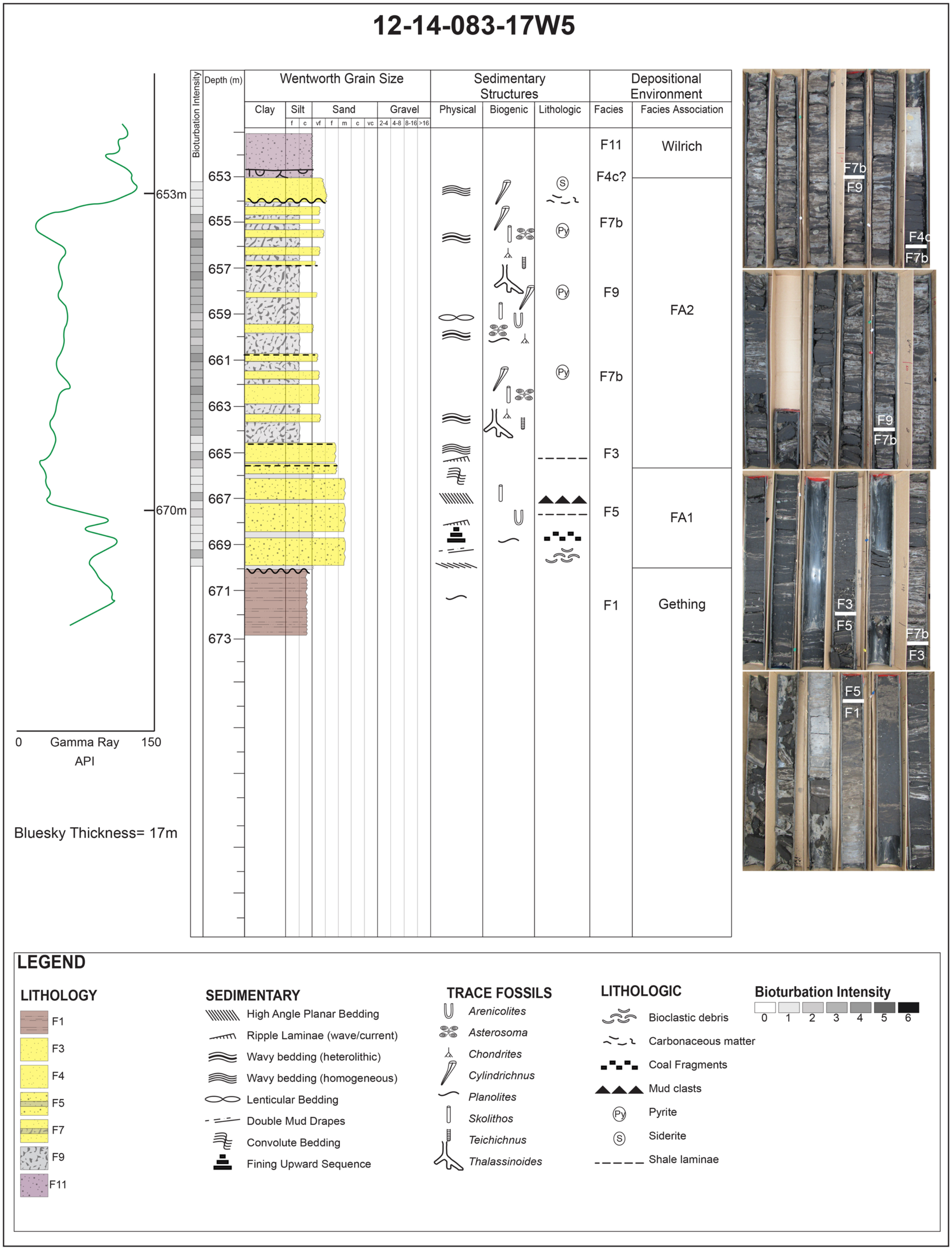


LEGEND

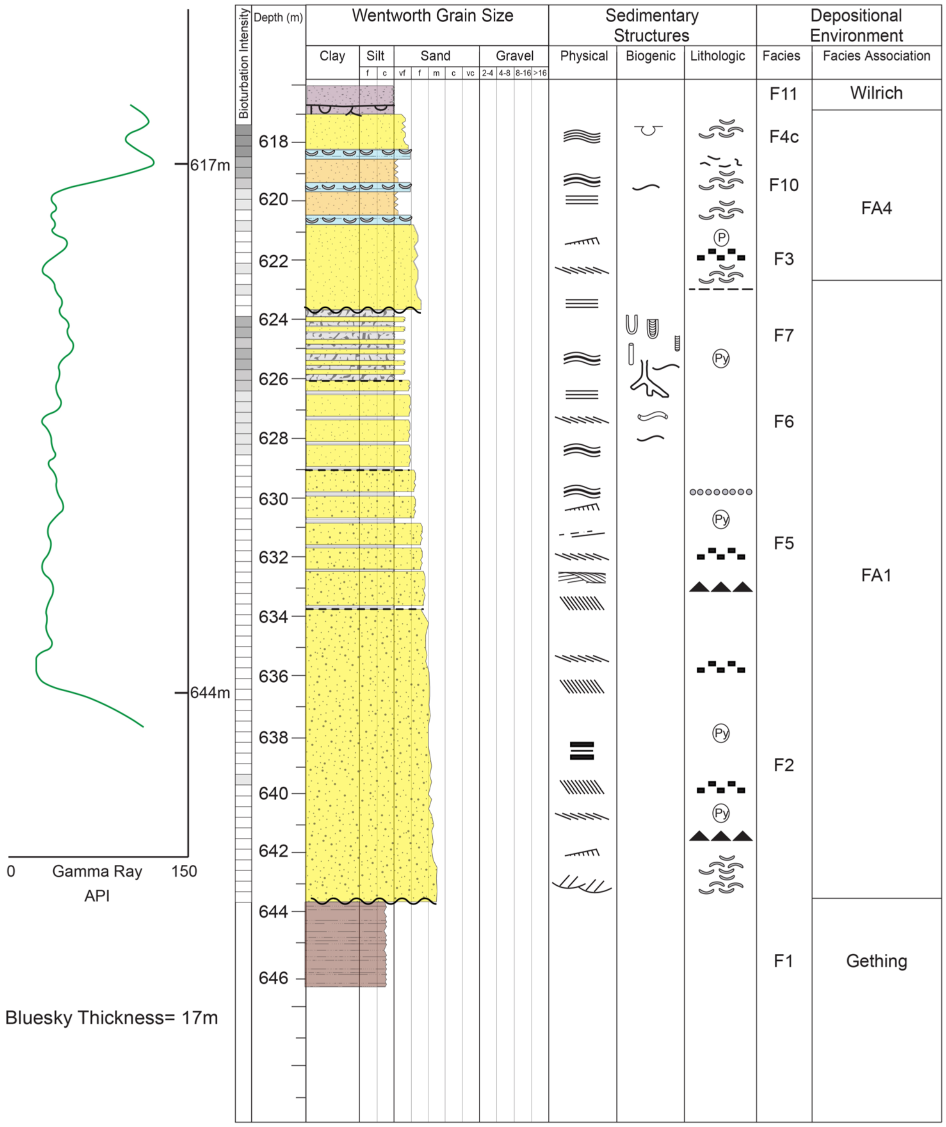
LITHOLOGY	SEDIMENTARY	TRACE FOSSILS	LITHOLOGIC
F1	High Angle Planar Bedding	*Asterosoma*	Bioclastic debris
F2	Low Angle Planar Bedding	*Chondrites*	Mud clasts
F3	Ripple Laminae (wave/current)	*Cylindrichnus*	Pyrite
F4	Lenticular Bedding	*Macaronichnus*	Shale laminae
F6	Wavy Bedding (heterolithic)	*Palaeophycus*	
F7	Wavy Bedding (homogeneous)	*Planolites*	
F9	Convolute Bedding	*Skolithos*	
F11	Fining Upward Sequence	*Teichichnus*	
	Grain Striping	*Thalassinoides*	

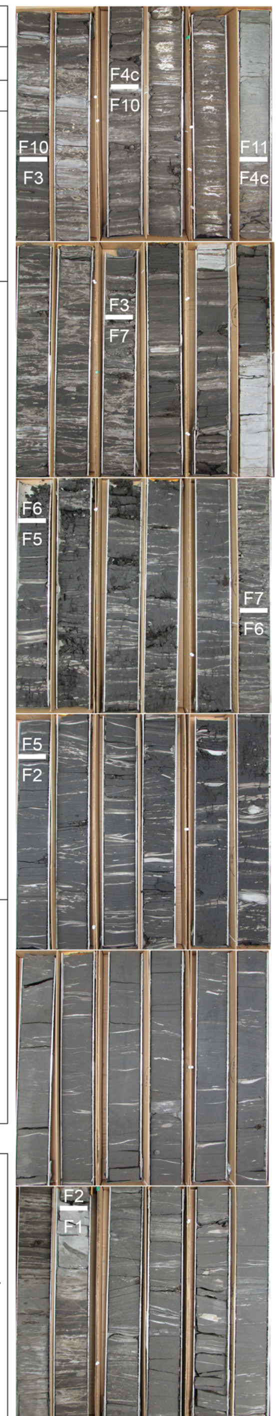
Bioturbation Intensity

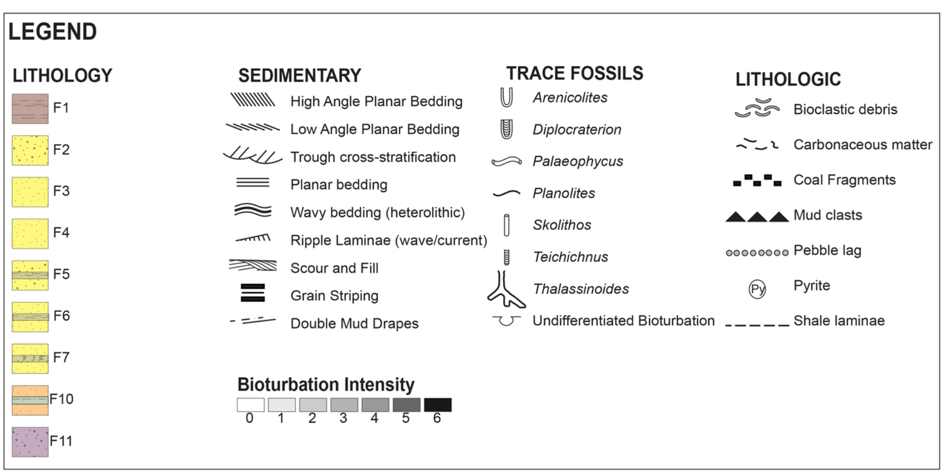
0 1 2 3 4 5 6


12-14-083-17W5
Gamma Ray API
0
150
653m
670m
Bluesky Thickness= 17m
Bioturbation Intensity
Depth (m)
Wentworth Grain Size
Clay
Silt
Sand
Gravel
f c vf f m c vc 2-4 4-8 8-16 >16
Sedimentary Structures
Physical
Biogenic
Lithologic
Depositional Environment
Facies
Facies Association
653
655
657
659
661
663
665
667
669
671
673
F11
F4c?
F7b
F9
F7b
F3
F5
F1
Wilrich
FA2
FA1
Gething
F7b
F9
F4c
F7b
F9
F7b
F3
F5
F7b
F3
F5
F1
LEGEND
LITHOLOGY
F1
F3
F4
F5
F7
F9
F11
SEDIMENTARY
High Angle Planar Bedding
Ripple Laminae (wave/current)
Wavy bedding (heterolithic)
Wavy bedding (homogeneous)
Lenticular Bedding
Double Mud Drapes
Convolute Bedding
Fining Upward Sequence
TRACE FOSSILS
Arenicolites
Asterosoma
Chondrites
Cylindrichnus
Planolites
Skolithos
Teichichnus
Thalassinoides
LITHOLOGIC
Bioclastic debris
Carbonaceous matter
Coal Fragments
Mud clasts
Pyrite
Siderite
Shale laminae
Bioturbation Intensity
0 1 2 3 4 5 6

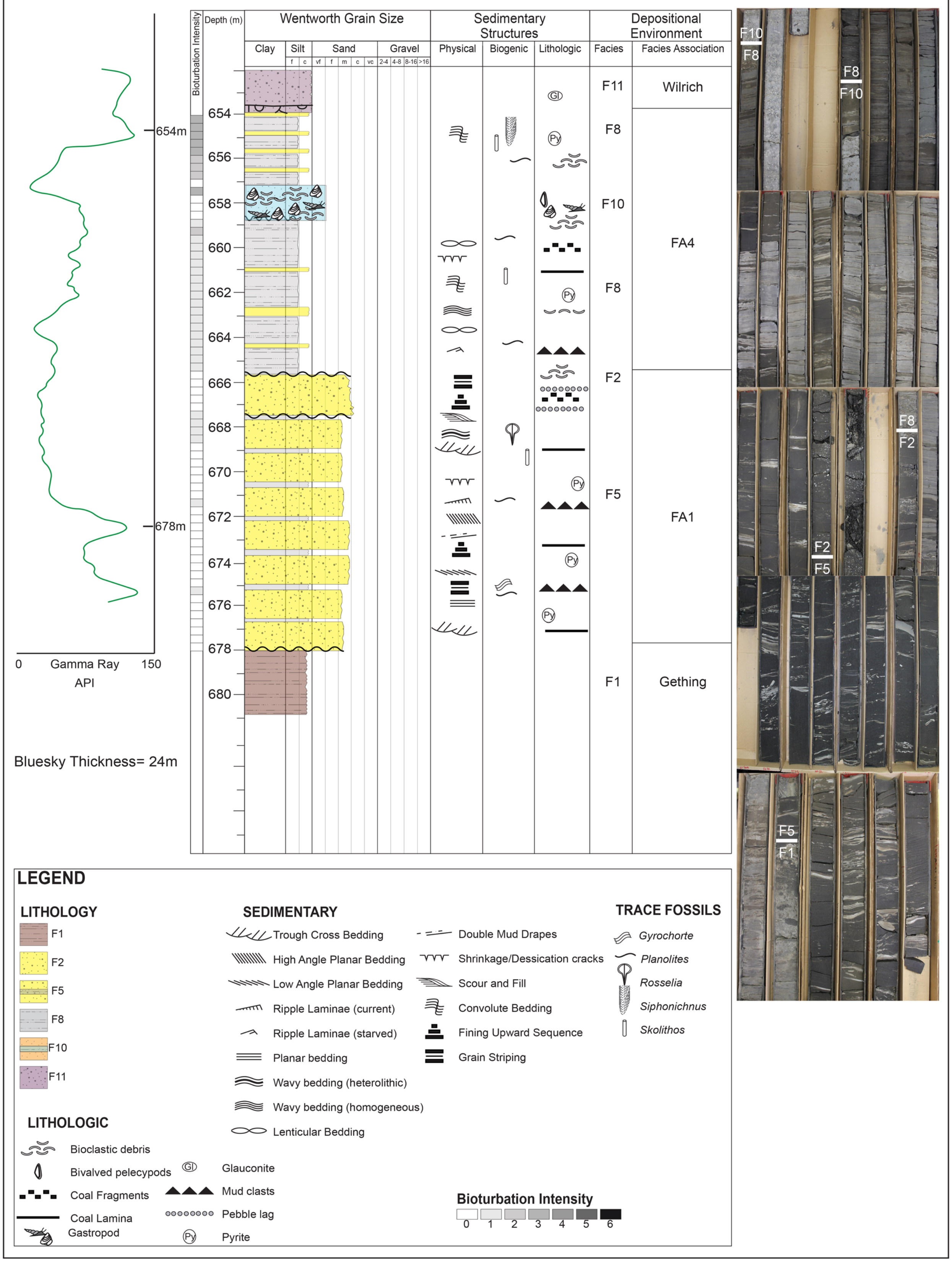
16-25-083-17W5



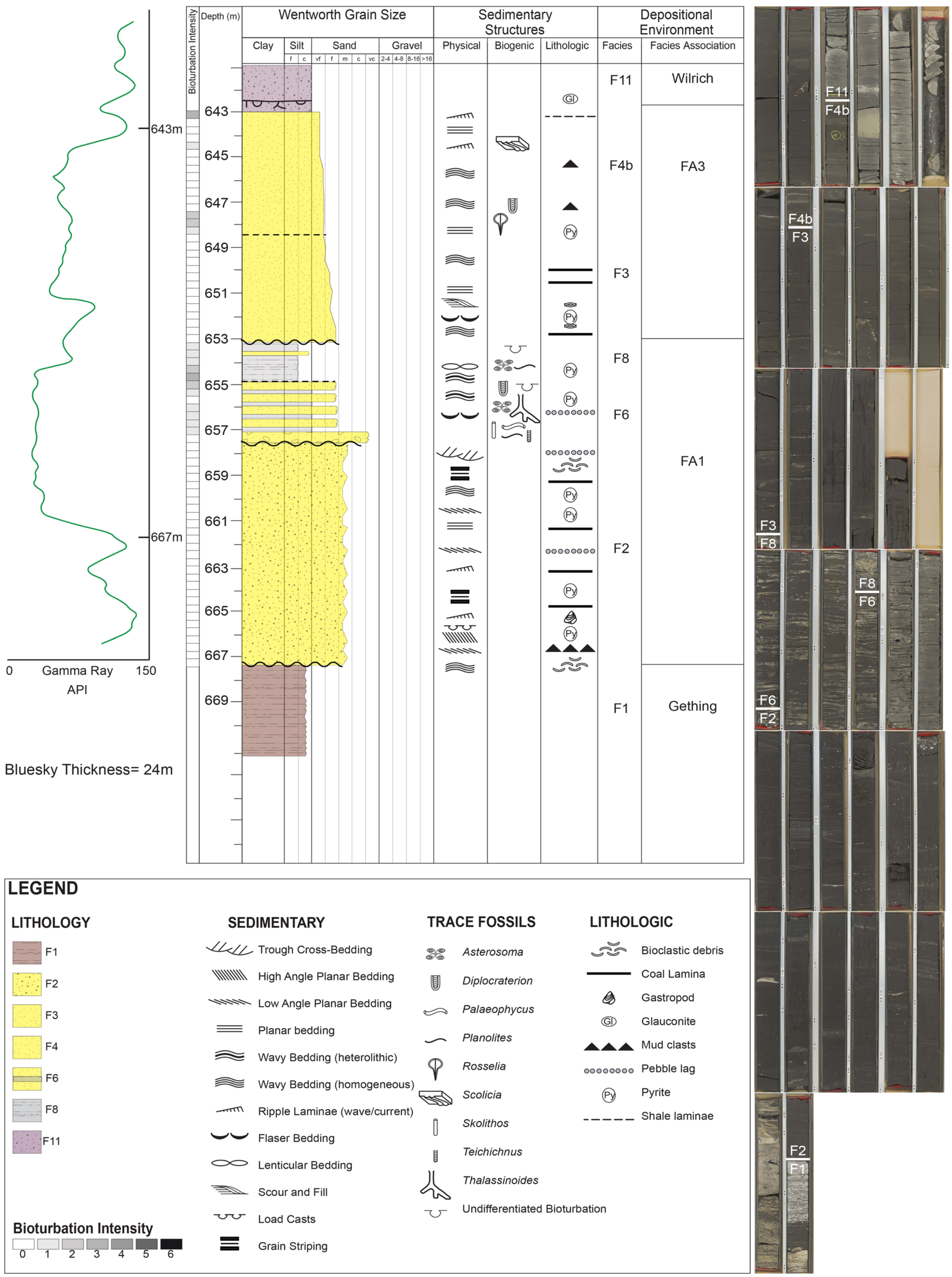




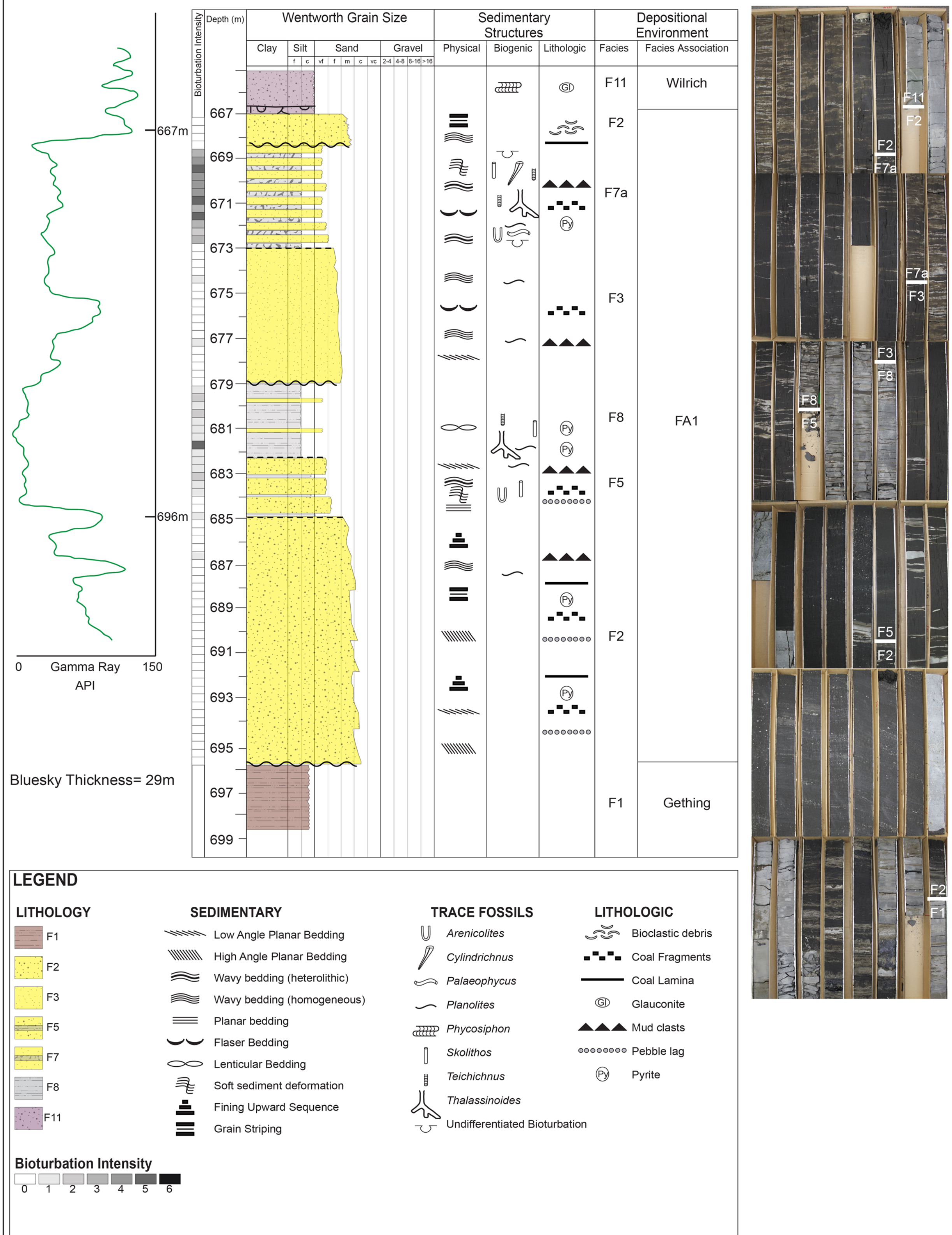
03-06-084-16W5



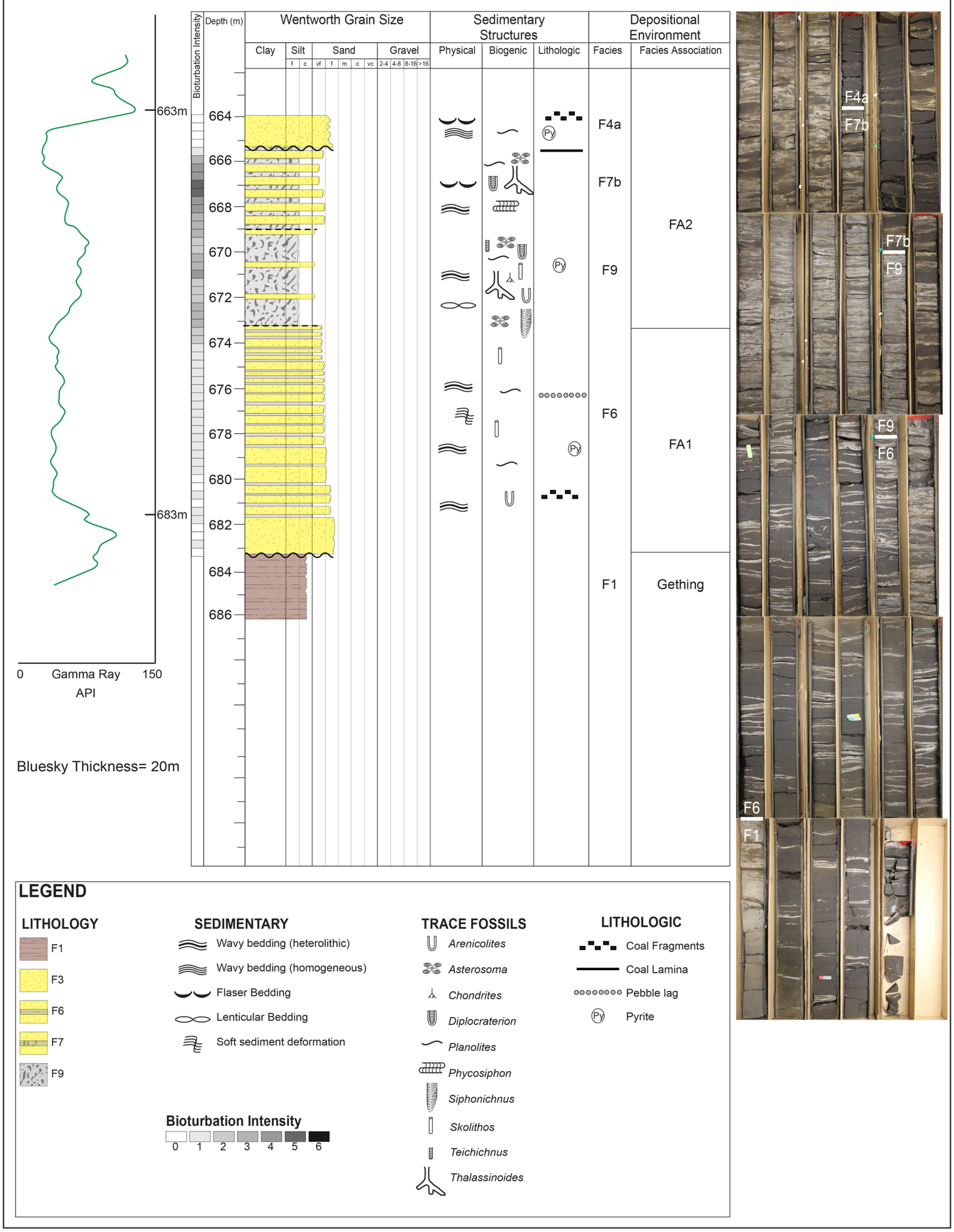
06-04-084-16W5



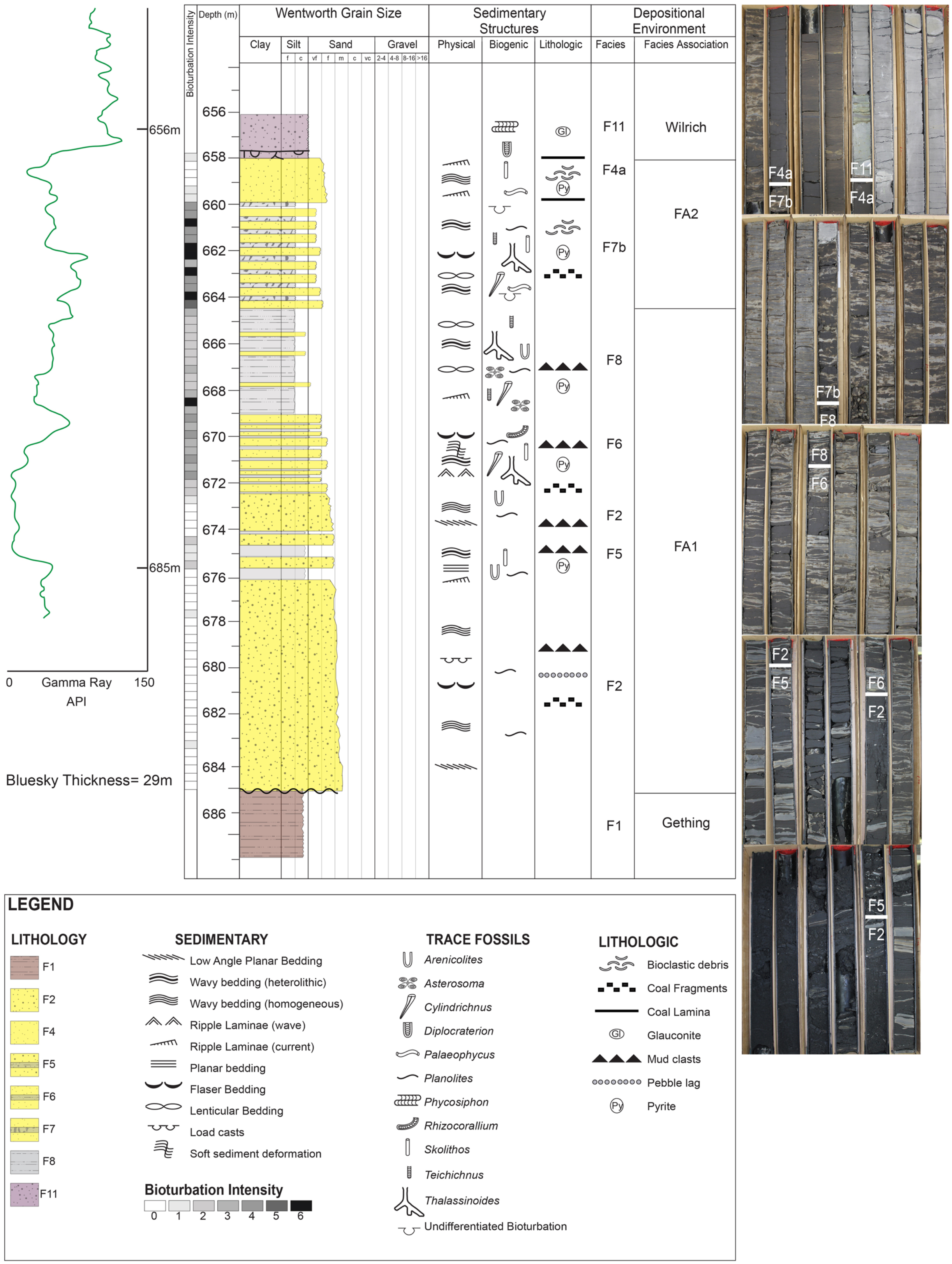
10-18-084-16W5



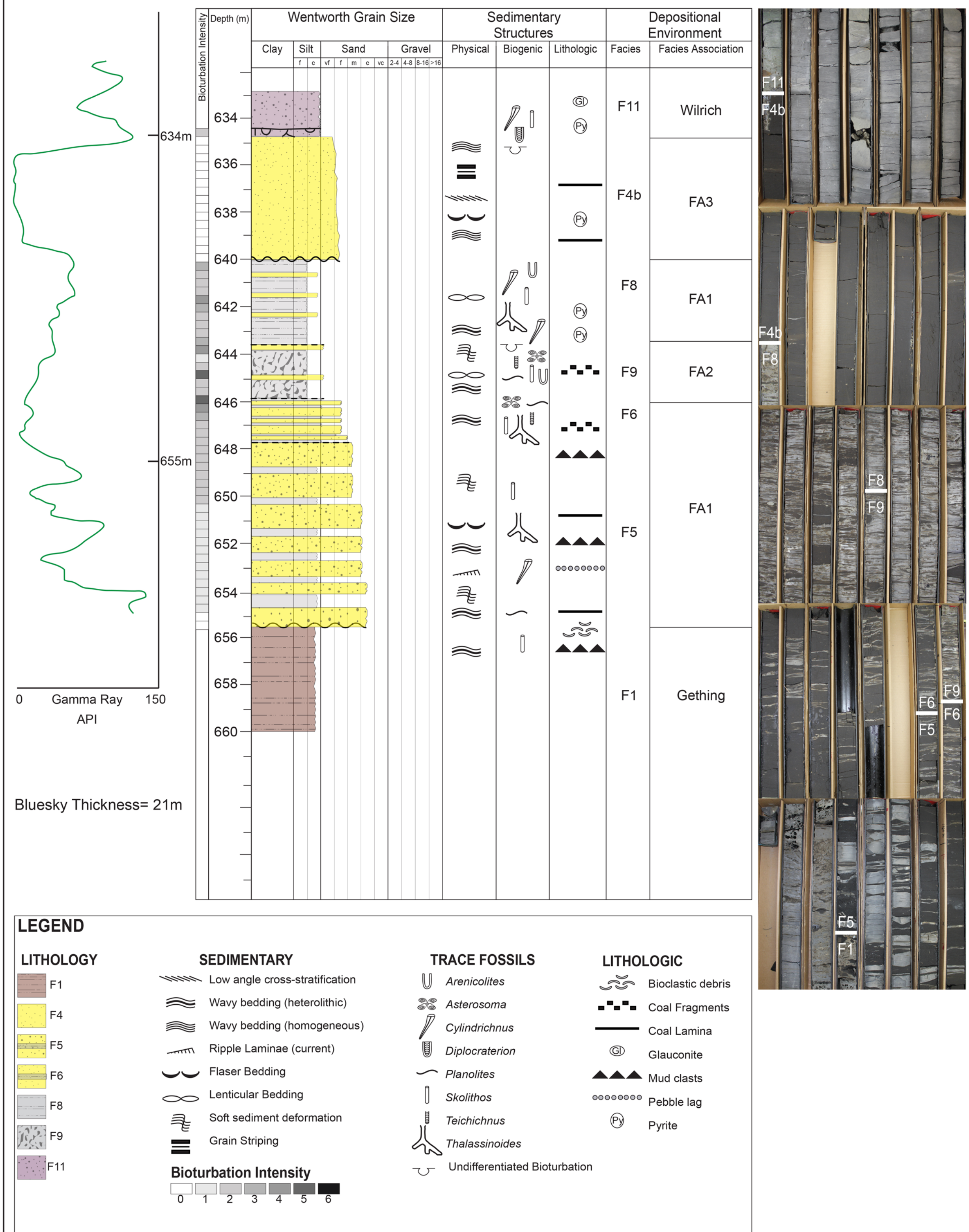
11-16-084-16W5



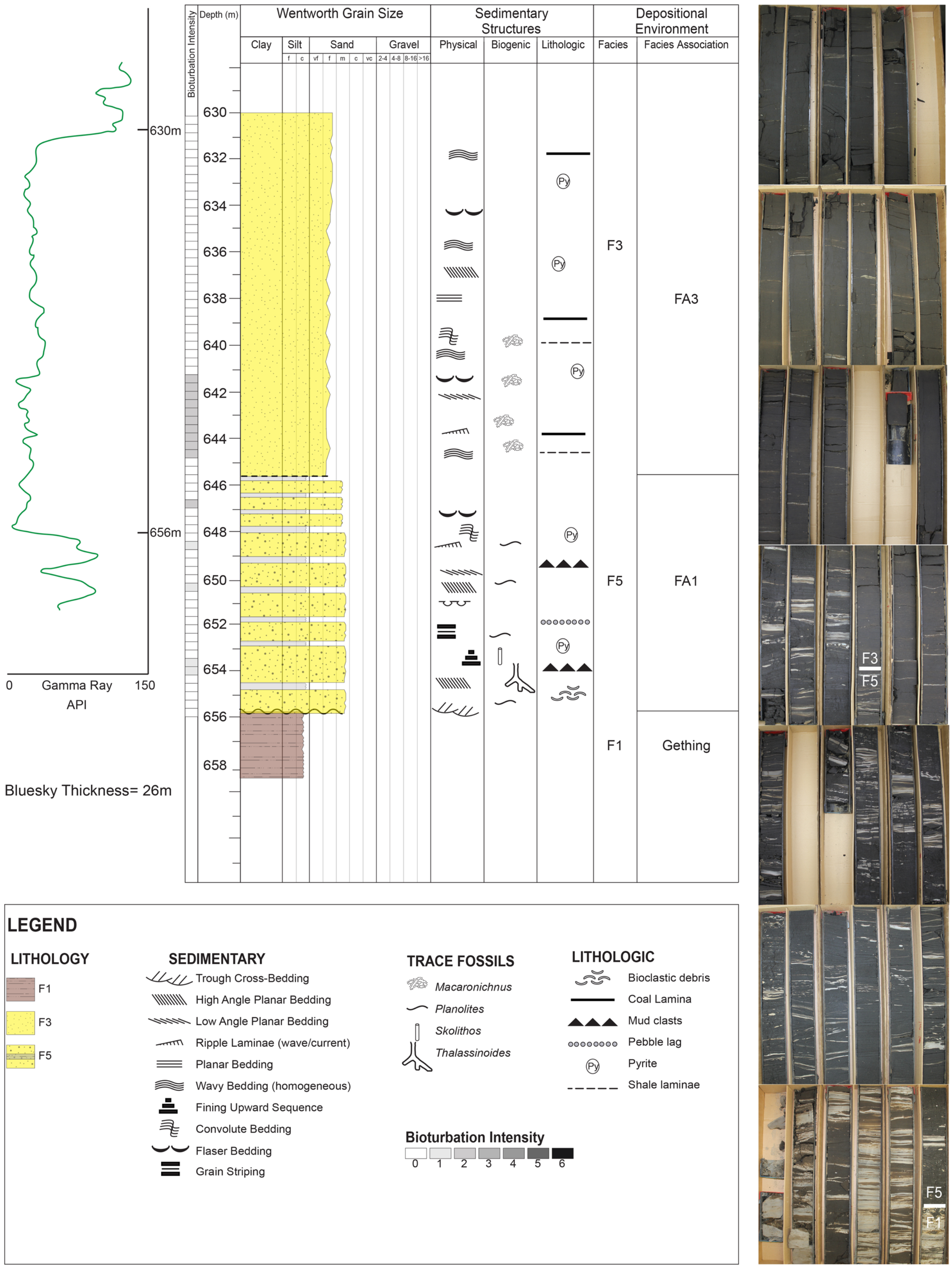
12-09-084-16W5



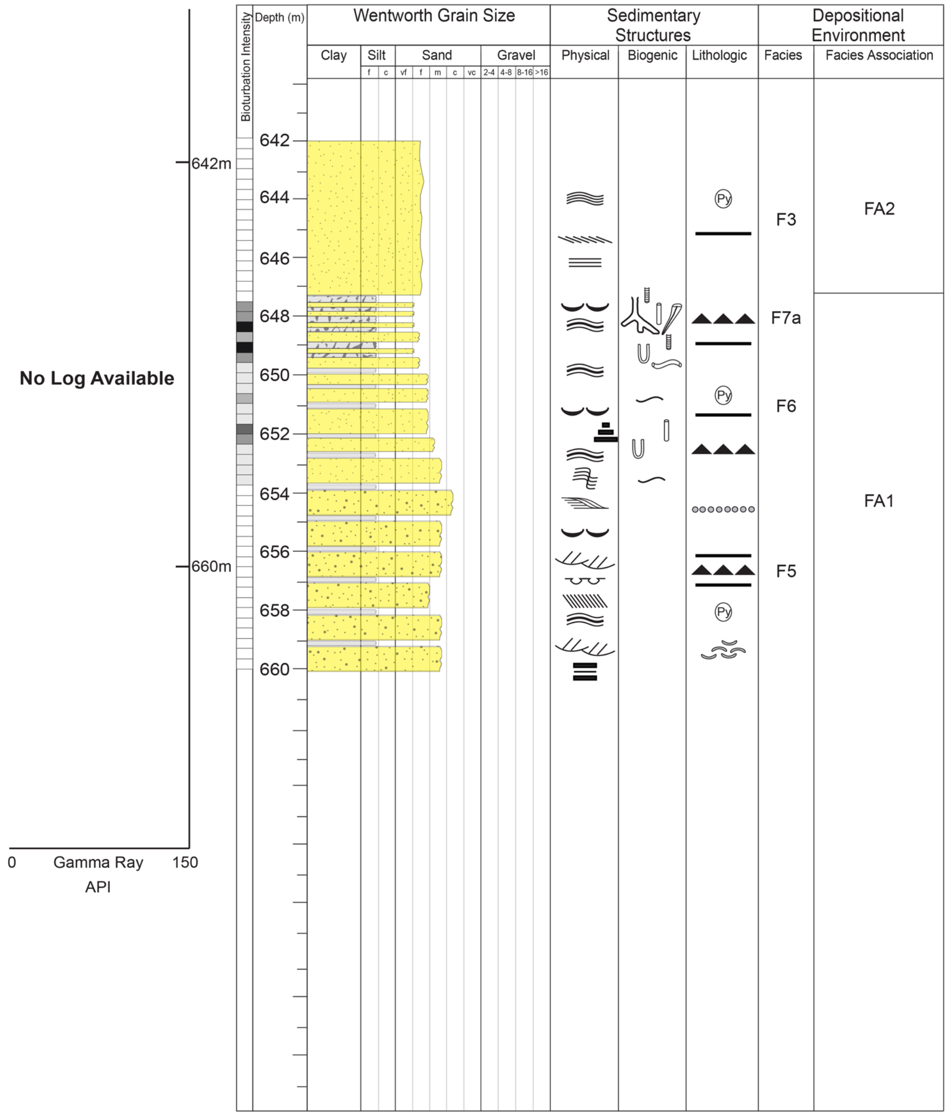
13-03-084-16W5

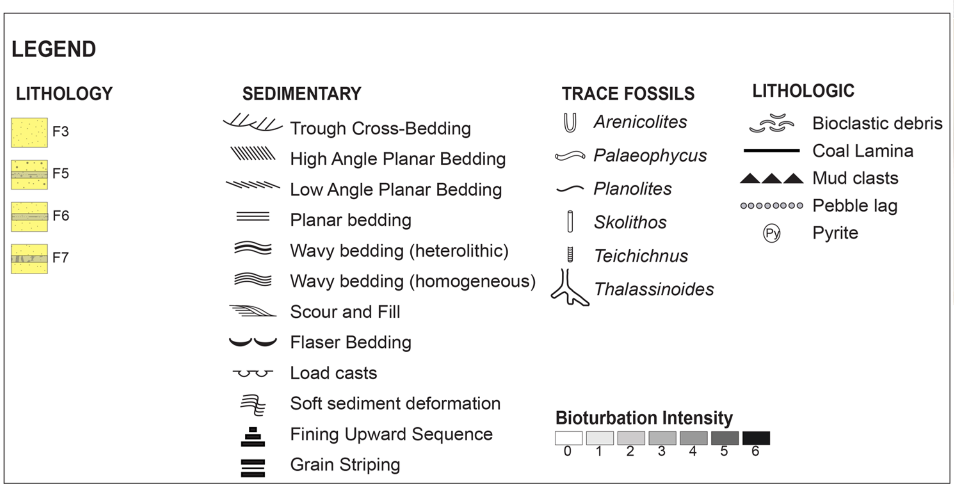


02-14-084-17W5



04-12-084-17W5





04-13-084-17W5